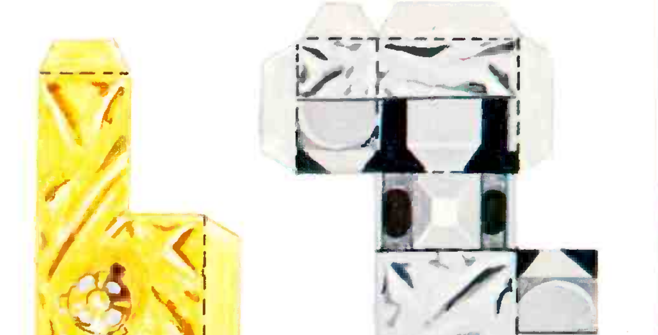
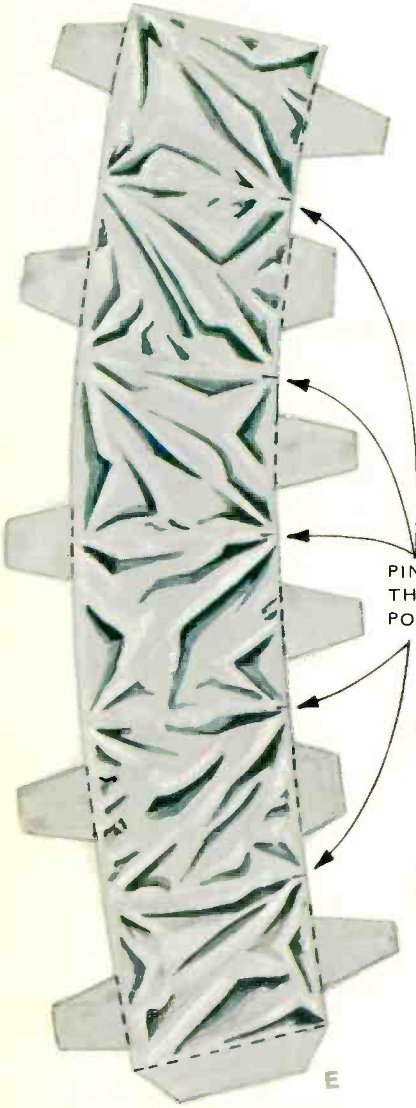
RCA Engineer

Vol 24|No 2 Aug|Sep 1978

TIROS-N





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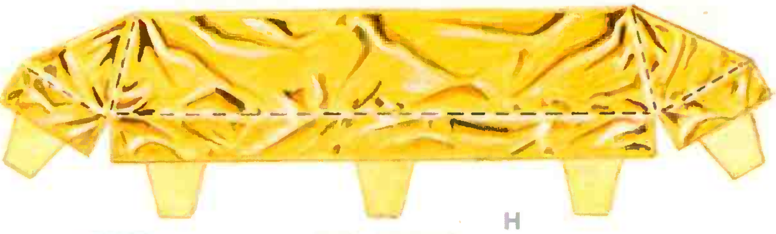
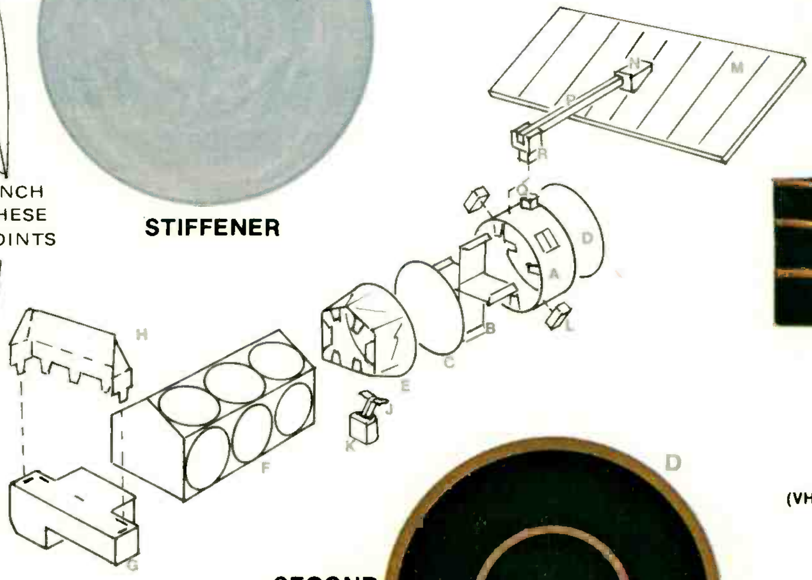


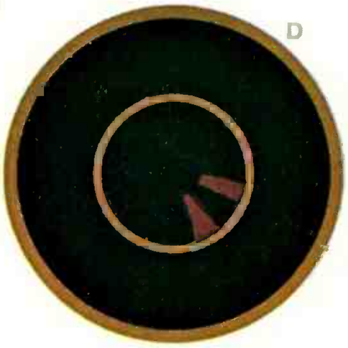
SUN SHIELD

**VRA
BRACKET**

STIFFENER



VRA
(VHF REAL-TIME ANTENNA ASSEMBLY)



**SECOND
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AREAS WHERE
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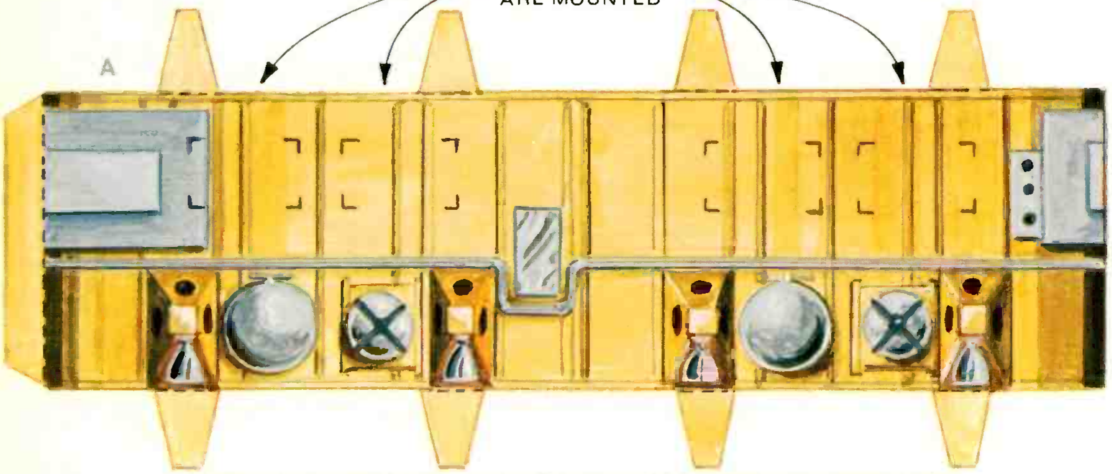
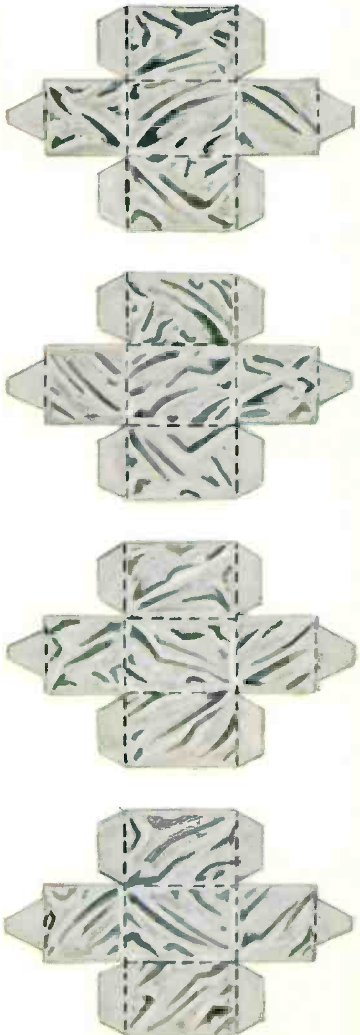


SUPPORT STRUCTURE FOR REACTION CONTROL SUBSYSTEM

STIFFENERS



BATTERIES

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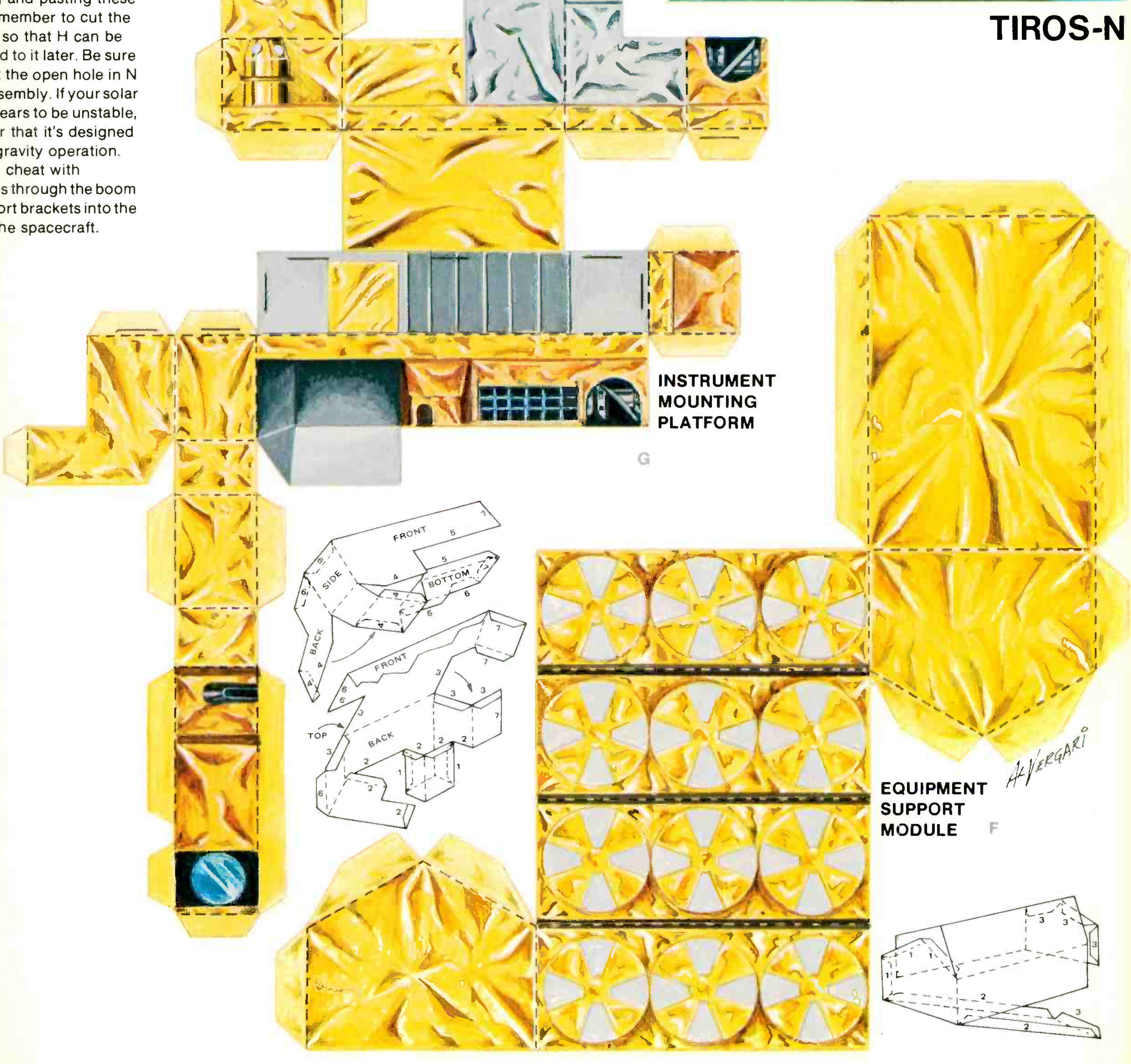
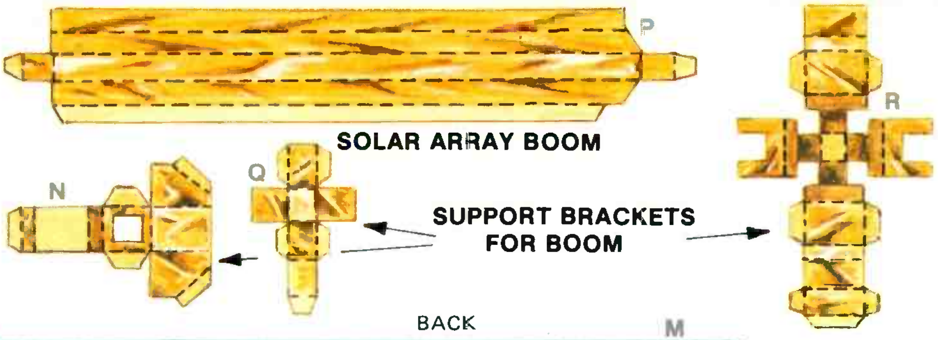
as complicated as it looks. For best results, cut out the parts with a sharp knife and hem together by using rubber cement on both sides of mating surfaces.

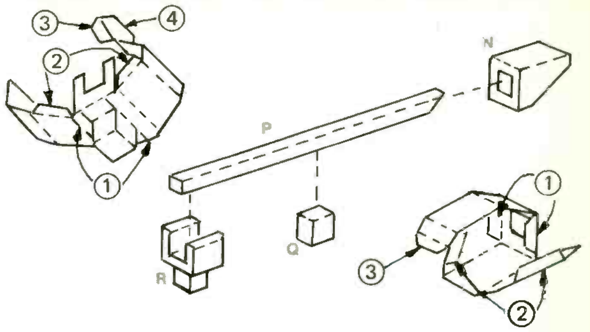
siest way to build TIROS-N is to start with part A, ɔle B to it, and work your way through to part R. This ch saves the most difficult parts, G and R, until late assembly, and also lets the e "grow" before your eyes.

l hints: When you ɔle A to E, putting the f A at the bottom will ne solar array boom tteries properly. The rs on the diagrams for G show the best order ing and pasting these Remember to cut the G so that H can be ɔled to it later. Be sure ɔut the open hole in N assembly. If your solar ppears to be unstable, ber that it's designed ɔ-gravity operation. th, cheat with icks through the boom pport brackets into the f the spacecraft.

TIROS-N




P
SOLAR ARRAY BOOM
N
Q
SUPPORT BRACKETS
FOR BOOM
R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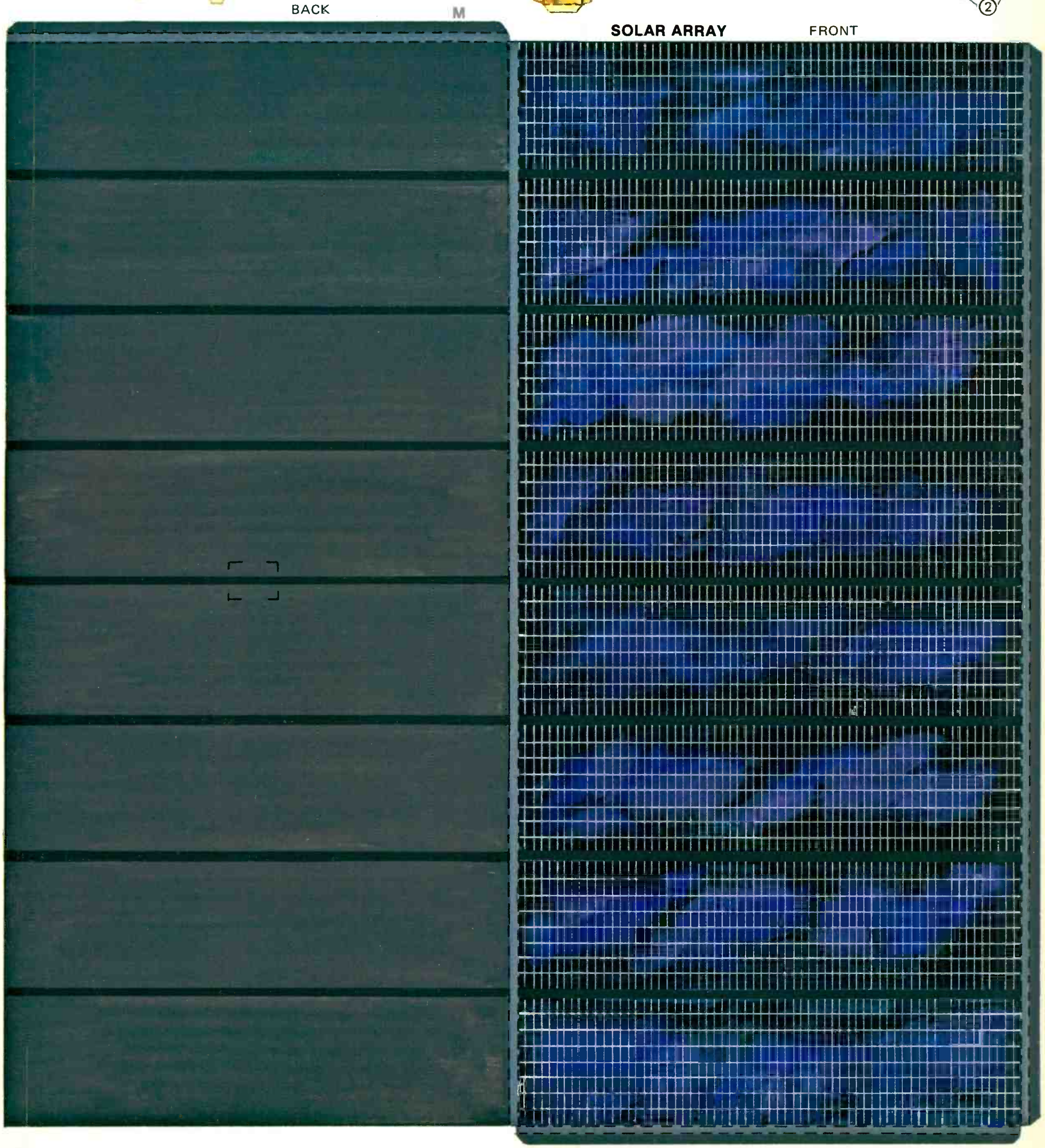
BACK
M
SOLAR ARRAY
FRONT

RCA Engineer

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- To disseminate to RCA engineers technical information of professional value
- To publish in an appropriate manner important technical developments at RCA, and the role of the engineer
- To serve as a medium of interchange of technical information between various groups at RCA
- To create a community of engineering interest within the company by stressing the interrelated nature of all technical contributions
- To help publicize engineering achievements in a manner that will promote the interests and reputation of RCA in the engineering field
- To provide a convenient means by which the RCA engineer may review his professional work before associates and engineering management
- To announce outstanding and unusual achievements of RCA engineers in a manner most likely to enhance their prestige and professional status.

Even an editor can do it. Associate Editor Bill Lauffer produced this TIROS-N model without help and had no pieces left over.

Our cover: Build your own TIROS-N weather satellite. The real thing, built by RCA Astro-Electronics, will be launched this fall. Be sure to build your satellite from the enclosed insert and not the cover, which is missing the solar array. Remember, when all else fails, read the instructions.

Design and illustration: Al Vergari, RCA Astro-Electronics, Princeton, N.J.

Turning the exceptional into the routine

Taking the perspective we had at the time of the launch of the first Sputnik, October 4, 1957, the accomplishments of the past 20 years in space seem nothing short of miraculous.

We have explored space, even taking men to the moon and back. The knowledge gained from our early explorations has helped us build and use unmanned satellites for important practical missions—communications, navigation, weather observation, and surveying earth resources. What was once considered near-impossible has become routine—Americans now see nothing exceptional about being able to watch a live broadcast of Jack Nicklaus winning his fourth British Open at St. Andrews.

Although most Americans now routinely benefit from satellite communications and other space applications, few of them realize that space technology is entering a period of radical transition, stimulated by the development of the space shuttle.

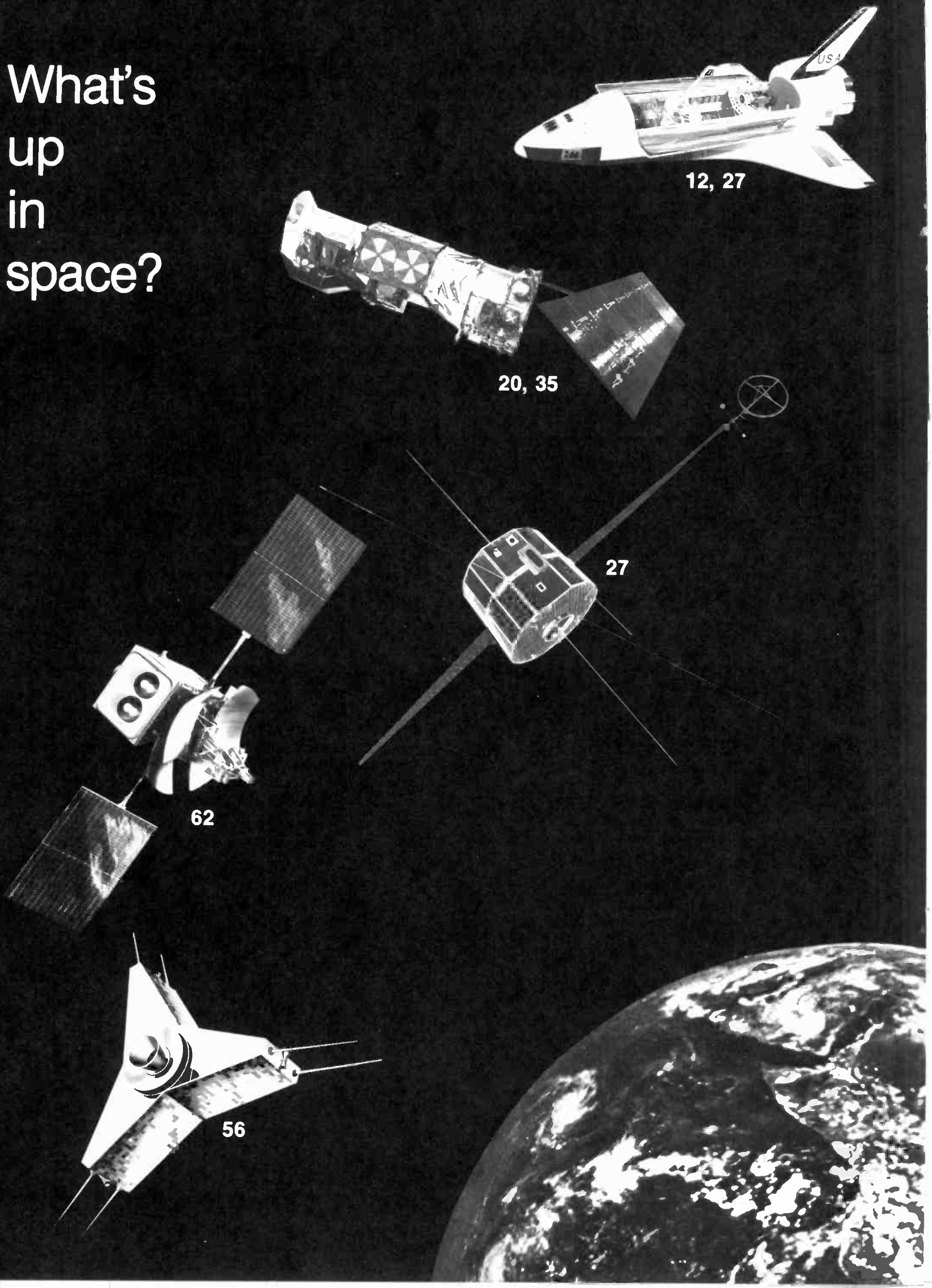
When the shuttle transportation system becomes fully operational by, say, the mid-80s, entirely new kinds of missions and payloads will become possible. The idea of assembling extremely large structures in space is particularly exciting. Huge antennas with multiple steerable spot beams will lead to entirely new communications systems and services. Significant sums of money are already being spent investigating the technology required for collecting solar energy in space and relaying it to earth as microwave energy. Also, since the shuttle will give us the opportunity to repair and/or retrieve satellites, even the economics and operating concepts behind spacecraft use will change.

There is every prospect that the shuttle will make the next 20 years in space even more exciting than the last 20. What dreams of today will become routine by then?

Warren P. Manger

Warren P. Manger
Chief Engineer
Astro Electronics
Government Systems Division
Princeton, N.J.

What's up in space?



RCA Engineer

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space technology

engineer and the corporation

on the job|off the job

space technology

departments

Space applications for the benefit of man

J.F. Clark

Space has moved from the decade of exploration to the decade of application.

> *"We who inhabit the Earth are like frogs at the bottom of a pool. Only if man could rise above the summit of the air could he behold the true Earth, the world in which we live."*
>
> —Socrates, circa 400 B.C.

Nearly half a century ago, Robert Goddard, the American father of liquid-fueled rockets, wrote to the noted historian H.G. Wells, "Space flight is a problem to occupy generations, so that no matter how much progress one makes, there is always the thrill of just beginning."

In the thirties, Wernher Von Braun was one of the very few who understood and shared Goddard's dream. Von Braun's World War II V-2 rocket was literally the embodiment of Goddard's concepts. Starting in 1946, the rocket's use at White Sands, New Mexico for upper-atmospheric research marked the beginning of the Space Age for hundreds of us who shared in that government-sponsored program.

For most people, the dawn of the Space Age was defined by the 1957 Russian launch of Sputnik 1. RCA was first in the electronics industry to commit itself to a major space role. It was in March 1958 that the Astro-Electronics Products Division was established, six months before the birth of NASA. That same year, RCA's orbiting transmitter beamed President Eisenhower's recorded message of peace back to Earth in the first of many precursors to our present-day operational communications satellite systems.

Through the end of the sixties, several hundred American space missions were launched. Their overall success rate was about 80%. Only about 20 missions were manned, but these produced the spectacularly successful first step on the moon by Neil Armstrong. The overwhelming majority of launches involved unmanned satellites and space probes that explored between the orbits of Venus and Mars, particularly within the Earth-Moon system.

The scientific results from experiments and observations carried out on these missions have literally revolutionized our understanding of astronomy and astrophysics, and of our solar system (see the companion paper by deBastos). But our focus here is on *applications* of space research and space systems for the benefit of man. From this viewpoint, the most useful results of that first Decade of Exploration came from satellites in sun-synchronous and geostationary orbits. These are the two important approaches to achieving the global view of our home planet foreseen by Socrates almost 24 centuries ago.

The first of these was used in 1960, when NASA launched RCA's TIROS 1, the world's first weather satellite. This type of satellite traverses a near-polar circular orbit some 700 kilometers above Earth, to photograph narrow swaths of the Earth's surface and its cloud cover. As Earth rotates beneath the orbiting satellite in the latter's nearly-fixed plane, images of the entire globe are built up during each 24-hour day. Earth's equatorial bulge is used (see Fig.1) to precess the satellite's orbital plane nearly 1° eastward each day, thus maintaining the images' local sun time constant from day to day. It is this characteristic that defines the sun-synchronous orbit. Landsat, Seasat, and NOAA weather satellites are important users of this type orbit.

The geostationary applications orbit was first achieved in 1964 by the Hughes-built synchronous communications satellite Syncom 3. Injected into an equatorial 35,803-km circular path, it rotated about Earth's polar axis in synchronism with Earth's own rotation once every 23-hr 56-min sidereal day. Syncom thereby remained fixed above a particular point on the equator, and always saw the same area. Intelsat and all western-hemisphere domestic communications satellites use assigned longitude "slots" along the geostationary arc. The other important user of this orbit is the Geostationary Orbiting Environmental Satellite (GOES) series of NOAA, whose images on tv weather shows are familiar to all.

Fig. 1
A satellite's orbital plane does not remain constant, but precesses because of Earth's nonspherical shape. Earth has a slight bulge at the Equator, induced by the centrifugal force of Earth's rotation, and so has a stronger pull of gravity there.

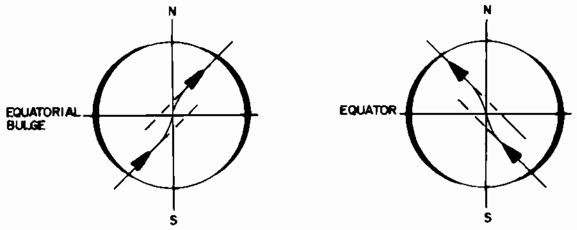


Fig. 1a
A prograde orbit has an eastward velocity component. South of the Equator, the satellite is pulled to the north of its unperturbed orbital path by the equatorial bulge, and north of the Equator, it experiences a southward pull. The net result is an elongated S-curve orbit symmetric about its equatorial crossing and a westward rotation of the satellite's orbital plane, in celestial coordinates.

Fig. 1b
A retrograde orbit has a westward velocity component, and its orbital plane precesses to the east. By choosing an appropriate combination of satellite orbital attitude and inclination, this eastward precession can be matched to the apparent annual rotation rate of the Sun about the Earth, in celestial coordinates. Such a "sun-synchronous" orbit has the same local (sun) time for each equatorial crossing.

Finally, during the Decade of Exploration we learned that the space environment is relatively benign, once the spacecraft survives the shaking, heating, acceleration, and depressurization of the launch environment. Meteoroid densities are too low to be hazardous. Differential electrical charging of spacecraft surfaces can be readily controlled by bonding exposed conductors to the spacecraft frame and minimizing the area and resistivity of exposed insulators. Virtually the only remaining adverse effect of the space environment is the limited, slow, predictable degradation of solar cells by the geomagnetically-trapped energetic particles.

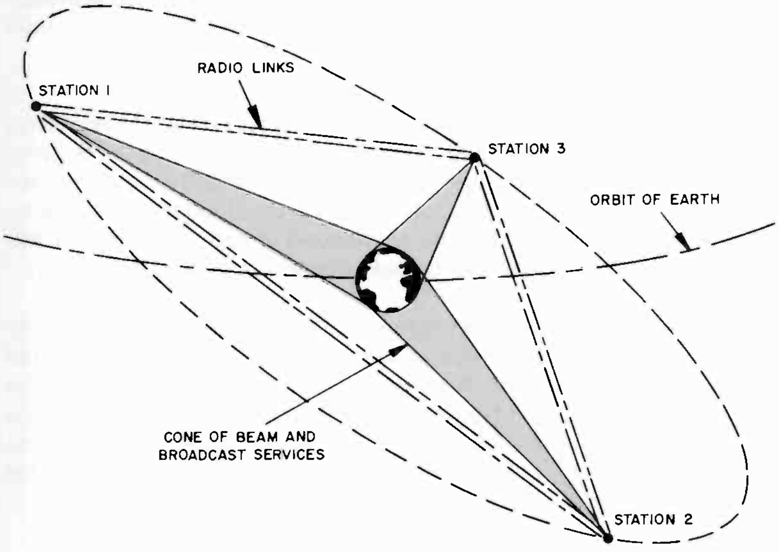
Now we are nearing the end of our second ten years since Sputnik, the Decade of Applications. Commercial satellite communications is a billion-dollar industry. Two operational systems of weather satellites are providing improved, worldwide forecasts. Landsat has been joined by Seasat in surveying our resources. Let us look more closely at some of the results and future promises of such space applications.

Communications

In 1945 Arthur Clarke (Fig. 2) was the first to publish the geostationary orbital elements and point out the advantages of a world-wide communications system employing three geostationary satellites, one over each major ocean (Fig. 3). Our technology caught up with Clarke's concept 24 years later.

Fig. 2
Arthur Clarke was years ahead of his time—he was the first to publish the geostationary orbital elements and point out the advantages of a worldwide geostationary-satellite communications system. (AIAA photo.)

Fig. 3
Clarke's geostationary communications satellite system uses three satellites, one over each ocean for worldwide coverage. Because these satellites have no apparent motion to an earth observer, they do not require complicated tracking systems for the ground antennas.



The first step was the Army's Project SCORE (Signal Communications by Orbiting Relay Equipment), which in 1958 orbited the RCA package mentioned earlier to broadcast the President's holiday message. Next came ECHO, the 30-meter passive balloon. In part because of its weak radio echo, proportional to the inverse fourth power of its distance, it proved to be an impractical technique for operational communications.

In 1962, NASA launched Telstar for AT&T and Relay 1, built by RCA. These satellites pioneered the use of solar cells to recharge their batteries, and were the first to relay tv between Europe and America. But, like ECHO, their low-altitude orbits required sophisticated tracking antennas on the ground. One operational system would have required an impractically large number of satellites to avoid lengthy gaps in communications.

The answer came in 1963, when Syncom 2 was launched into the first diurnal geosynchronous orbit. This orbit differs slightly from the first geostationary orbit achieved the following year by Syncom 3. A geostationary orbit is simply an equatorial diurnal geosynchronous orbit (Fig. 4). The ground track of a diurnal geosynchronous satellite executes a north-south figure eight whose maximum latitude equals the orbital inclination. The ground track of a truly geostationary orbit is, therefore, a fixed point on the equator. In practice, all "geostationary" satellites will drift out of their assigned positions when they run out of their station-keeping propellant, and oscillate about one of the three equatorial geopotential minima at the geostationary altitude.

Mention should be made of one other geosynchronous satellite orbit, pioneered by the Soviets for communications within their high-latitude land mass. Their Molniya I and II satellites are placed in 12-hr (actually 11-hr 58-min) orbits to be geosynchronous at half of Earth's sidereal rotation period. Highly-inclined (65°) elliptic orbits are used so that every other apogee occurs over the Soviet heartland. To provide around-the-clock operation, three spacecraft are phased to provide about 8 hours each of continuous coverage. This system requires two tracking antennas at each ground station to execute three synchronized hand-

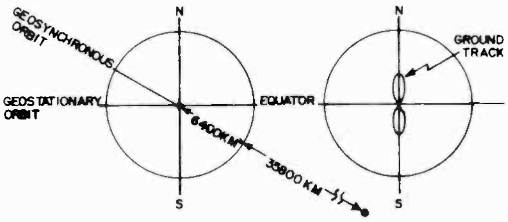


Fig. 4
Ground track of a diurnal geosynchronous satellite executes a north-south figure eight whose maximum latitude equals the orbital inclination. Since a geostationary orbit is simply an equatorial diurnal geosynchronous orbit, its ground track is a fixed point on the equator.

overs daily, when each satellite descends toward the horizon as its replacement emerges.

In America, Syncom's success led directly to the formation of the Communications Satellite Corporation. By 1969, Comsat had placed Intelsat "birds" over each of the three major oceans. Currently the Intelsat system uses some 25,000 channels to connect users in some 80 countries through more than 150 ground stations. This system produces annual revenues well over $100 million on an investment of more than $1 billion.

Private industry sent up its first domestic communications satellite in 1972, when NASA launched Anik-1 for the Canadian Telesat Corporation. RCA Globcom initiated the first phase of its own satellite communications system using leased Anik transponders shortly thereafter. Western Union launched its satellite system, Westar, in 1974. One year later, RCA Americom took control of its satellite from the NASA/McDonnell Douglas launch team. The Americom satellite, built by RCA Astro-Electronics, is unusually cost-effective because it carries twice as many transponders as any other Delta-launched spacecraft. This mission used the first commercially-funded upgraded Delta 3914 launch vehicle, which increased the Delta capability from 1500 to 2000 pounds of payload into geostationary transfer orbit.

In 1976, AT&T leased its first of three domestic communications satellites, Comstar, from Comsat. Indonesia, the fifth-largest country in the world, leaped in one giant step to a country united by tv, radio, telephone, and record services, through its Palapa satellite. Intelsat leased capacity to Arabia, Brazil, France, Malaysia, Mexico, Nigeria, Norway, Saudi Arabia, and Spain, each for its own internal domestic communications. 1976 also saw the deployment of the three-satellite $110-million Marisat maritime communications system, which is owned 86.3% by Comsat General, with participation by ITT Worldcom, RCA Globcom, and WUI. This system appears to be passing its first marketplace test of economic viability.

Japan passed a significant milestone last year, with its launch of its first geostationary payload, ETS 2. This satellite carries microwave transponders for propagation experiments. Last year, Italy achieved its first experimental geostationary communications capacity, at l8 and 12 GHz. Earlier this year, the European Space Agency (ESA) launched its OTS 1, with 14- and 11-GHz links.

The next decade promises to be one of extraordinary activity and growth. The total number of communications satellites should triple. Perhaps the largest growth rate will occur in domestic satellites for data communications, teleconferencing, telephony, and television. This is already putting more pressure on higher frequencies. Canada's Anik B, Intelsat V, Western Union's Advanced Westar, NASA's tracking and data relay satellite system (TDRSS), and Satellite Business System's SBS satellites will all be using frequencies above 10 GHz for at least a large fraction of their future capacity. Multiple spot beams will provide better frequency re-use, but will require satellite "switchboards" to restore the connectivity which had been automatically provided by wide-area, hemispheric coverage. The space shuttle orbiter, with its substantial reduction in launch costs, will permit much larger and heavier satellites which, in turn, will cut the costs of ground facilities substantially.

The shuttle is now (August 1978) scheduled for its first orbital test in the last half of 1979, with commercial operations beginning one year later. This timing could present some problems for the next generation of communications satellites, if development or test problems cause these dates to slip further. TDRSS, SBS, Anik C, and the third RCA Americom satellite are all presently scheduled for shuttle launch in 1980 or 1981. Should the shuttle slip too long, expendable launch vehicles such as the Delta 3910 will be used for backup. The following generation of satellites will be able to take better advantage of the shuttle, once they are relieved of the need for compatibility with the smaller diameter and lower weight constraints of expendable launch vehicles. The Hughes "tuna can" Syncom 4 is an example of a satellite concept specifically designed to efficiently use the occupied length in the shuttle cargo bay.

Navigation

The concept of using satellites for navigation dates back to Sputnik I in 1958, when engineers tracking the satellite observed that the doppler shift of the received telemetry signal could be used to determine the satellite's orbit. Conversely, they concluded, if the orbit were known, a receiver's position on Earth could be determined. After several years of work at Johns Hopkins University's Applied Physics Laboratory, the Transit satellite series, and satellite navigation, was born.

Satellite navigation systems operate in a manner somewhat analogous to land-based hyperbolic navigation systems such as LORAN, which use the differential time delay between synchronized transmissions from pairs of fixed land-based transmitting stations. Each value of time delay corresponds to a unique hyperbolic line of position. In the Transit satellite navigation system, the land-based transmitters are replaced by a sequence of successive positions of a single orbiting satellite. The satellite's ephemeris (location and time information), which is broadcast as part of its signal, is determined by a land-based tracking network.

The user determines his latitude and longitude by receiving four successive satellite broadcasts, computing the doppler hyperboloid of position for each one, and then solving four simultaneous equations to give a point location. (Actually, only three broadcasts are needed to solve for position, but the redundant fourth measurement improves accuracy.)

Satellite navigation systems of the first generation typically have a location accuracy of 0.1 km or better. Their initial application was for the Polaris submarine fleet and the system is still Navy-owned and operated. But today there are also thousands of commercial satellite navigation receivers in use, on merchant ships and oil-drilling rigs, for example.

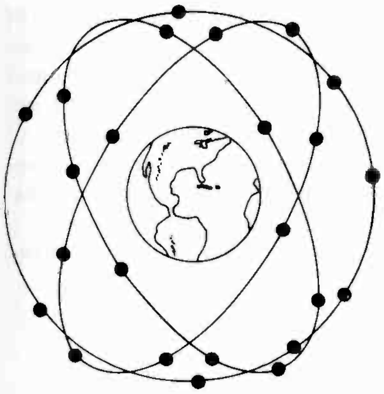


Fig. 5

Highly accurate navigation is possible with Navstar (Global Positioning System). It uses 24 satellites to provide three-dimensional positioning (latitude, longitude, altitude) to within 10 meters, as well as velocity to 3 cm/s.

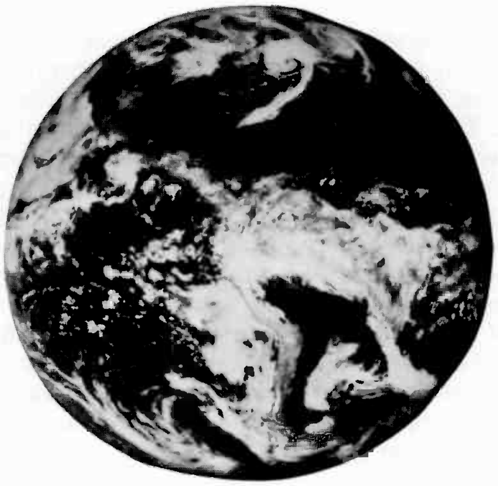


Fig. 6

Earth view from SMS (Synchronous Meteorological Satellite). (NOAA photo.)

Fig. 7

Hurricane Carmen was tracked by SMS every thirty minutes for twelve days in 1974, warning of her approach into the Gulf of Mexico and Texas. Before satellites, weather-tracking planes, with less coverage area and longer times between coverage, were used. (NOAA photo.)

The next-generation satellite navigation system is now undergoing early testing in the field. Called Navstar, or Global Positioning System (GPS), it provides three-dimensional position accuracies (latitude, longitude, and altitude) of 10 meters, velocity of 3 cm/sec, and time. GPS receivers can be made small and lightweight, and will be able to be carried in aircraft, missiles, ground vehicles, and even manpacks, in addition to ships.

Each Navstar satellite will complete two revolutions of the Earth each day. Broadcast coverage will be complete and continuous by the 24 satellites (Fig. 5), so users will not have to wait for the proper satellite to be in position. Another advantage of GPS is that it can be used more easily in combination with other systems because of the additional altitude and velocity outputs. Aircraft and missiles will be able to sense and display position, altitude, ground speed, direction of travel, rate of climb, and time of day—all from the same passive GPS receiver. These data could also be used as inputs to the plane's autopilot or the missile's guidance system.

GPS is currently scheduled for full 24-satellite operational capability by the mid-80s. This assumes that no intractable development problems will be encountered, and that requested funding will be available.

Earth observations—weather forecasting

Probably our most obvious world-wide system is our atmosphere, whose movements and changes we call weather. What happens locally depends on what has happened far away, so only a satellite can give us the global view needed to analyze, predict, and perhaps some day manage this global system.

The sun-synchronous TIROS weather satellite system and its follow-on ITOS and NOAA advanced versions are described in the companion paper by Schnapf. Nowadays, a complete global field of atmospheric temperature is fed into NOAA's forecasting computers every 12 hours. RCA Astro-Electronics also designed and built a similar Department of Defense system to meet this nation's military requirements for world-wide weather information.

Four years ago, Americans achieved the ultimate view of our weatern hemisphere when NASA launched Ford Aerospace's first Synchronous Meteorological Satellite into geostationary orbit. Fig. 6 is a view from SMS. It produces images like this every half hour, both day and night, employing infrared and visible light sensors. SMS also receives weather information by radio from up to 10,000 data collection platforms such as flood gauges, buoys, and remote unattended weather stations.

Now there are seven such satellites in orbit, five American, one Japanese, and one French. The Soviet Union had planned to launch its counterpart satellite by 1980, but because of Soviet satellite delays one of the U.S. "birds" will be used to complete the network. The most important objective of this satellite network is to obtain wind velocities over the entire globe by tracking cloud positions on successive images. The program goal is to build a precise computer model of the atmosphere so that, using such data, accurate forecasts of local weather can be made as long as one or even two weeks in advance. How would you like to have such information—as a farmer, a builder, a shipper, or as a resort manager?

Fig. 7 pictures hurricane Carmen, with dangerous 300 km-per-hour winds just outside of her tiny eye. Such images were obtained by SMS every thirty minutes for twelve days in 1974, from Carmen's birth off the northwest coast of Africa, across the Atlantic Ocean and the Gulf of Mexico, into Texas, where she died in a final flurry of intense rain. There is a tremendous advantage in such improved accuracy of forecasting the position of dangerous storms, because it costs a city the size of Miami some $2 million to "batten down the hatches" and evacuate its population. More accurate forecasts save this money when the population may remain, and give increased credibility to forecasts that require evacuation. In either case, the public benefits. The next generation of geostationary weather satellites will have an important improvement—a vertical temperature sounder that will further improve the forecasting power of the computer model.

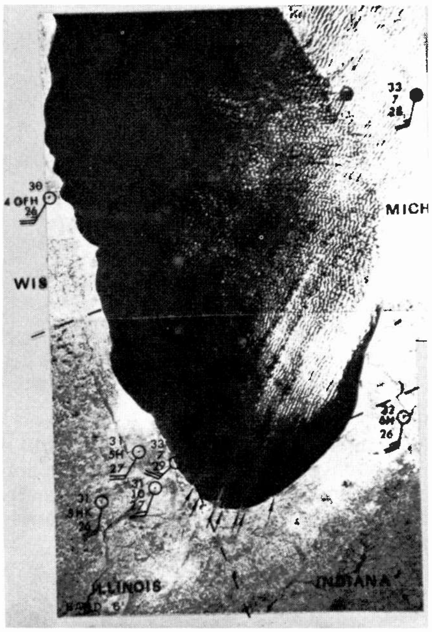


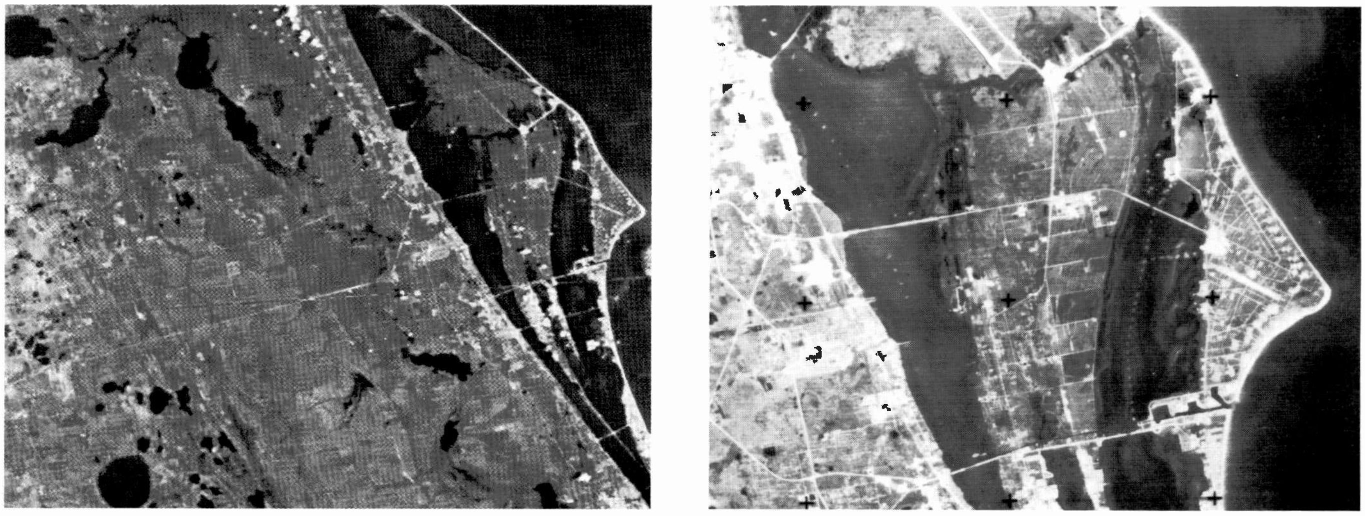
Fig. 8
Detecting man-made weather from space. This Landsat picture of the southern Lake Michigan area shows a deep snowfall produced by steel-mill smoke from Chicago that picked up moisture while crossing the lake. (NASA photo.)

In Fig. 8 we see a Landsat picture of the southern portion of Lake Michigan at a time when smoke from the Chicago steel mills picked up moisture while crossing the lake and produced a snowfall on the Michigan shore some 25 cm deep. The issue is no longer whether man is capable of weather modification, but rather how we can avoid unfavorable modifications while encouraging favorable ones. Even the answer to the question of what constitutes a "favorable modification" depends on the viewpoint of the answerer.

Earth resources detecting and monitoring

For six years, multispectral images of Earth's land and water surface have been transmitted electronically by one of three Landsat satellites. These platforms are each in a 900-km circular, sun-synchronous, mid-morning orbit, whose sub-satellite track moves westward 160 km each day, so that the ground track repeats itself every eighteen days. The scanned path is 185 km wide, providing 25 km of overlap (at the Equator) between passes on successive days. Thus, with two properly-phased satellites, any cloud-free location on Earth may be viewed every nine days.

Landsat 3, launched last March, differs from its two predecessors in one important respect. The RCA return-beam vidicon (RBV) camera installation has been modified to provide one-half of the lineal Earth surface coverage, at twice the resolution of the earlier Landsat RBV cameras. (See Fig. 1 of the companion paper by Soltoff.) Figs. 9a and 9b, two images of the Cape Canaveral, Florida, vicinity, show the striking difference in information available from these cameras. The Landsat 3 RBV resolution is approximately 40 meters, compared with the Landsat 1 and 2 multispectral scanner (MSS) and RBV resolution of 80 meters.



Landsat 1

Landsat 3

Fig. 9
Resolution of space images has improved. These images of the Cape Canaveral area were both taken by return-beam vidicon tv cameras. For Landsat 3, the Landsat 1 camera was modified so that it covered half the distance at twice the resolution. Linear resolution improved from 80 meters to 40 meters, with a consequent 4X improvement in area resolution. (NASA photo.)

Many observers are convinced that satellite data is useful both in exploring for non-renewable resources like minerals and petroleum, and in managing renewable resources like land, water, crops, and forests.

The use of observations from space, to identify potential non-renewable resource (minerals, gas, oil) locations in Earth's crust, is still in its infancy. Studies of Landsat data have revealed some surface features that have been correlated with entrapment of minerals, petroleum, and geothermal sources. Last year, the Geosat Committee, Inc. was formed with the support of many energy-resource companies to provide a unified voice for industrial exploration geologists. The recommendations of this organization are providing a basis for the future NASA efforts in this field.

For example, the concept of remote sensing in an additional spectral band at 2.2 micrometers has been tested in aircraft flights and may be incorporated into the Landsat D system. This band provides maximum rock-type discrimination for mineralogical reasons.

NASA is also pursuing the use of spaceborne radar techniques for geologic mapping and exploration. Because microwaves can penetrate clouds, such techniques can be particularly useful in making maps of polar and tropical regions. A single-frequency synthetic-aperture radar is scheduled to be flown on the second shuttle Orbital Flight Test (OFT 2) for this purpose.

Fig. 10 gives a good idea of the impressive mapping accuracy available from computer-processed Landsat data. Such accuracy can be very important; the Brazilian government reportedly spent some $20 million extra on the Trans-Amazon Highway because the exact courses of several tributaries of this giant river were not known. Subsequently Brazil has installed a Landsat ground station and has made its data available to its neighbors.

Figs. 11 through 15 show examples of space imagery being used for agriculture, forestry, water resources, and land use. These images are providing previously unavailable information to researchers and policy-makers on such

Fig. 11
Land-use puzzle. In this portion of the Sahel region of Central Africa, a drought had persisted for years and former grazing lands had been regressing into arid desert. The darker, five-sided patch in the south central region of the Landsat image is an area of many hundreds of square kilometers within which the vegetation is vigorous enough to support grazing. Why? Poachers put up a single-strand barbed-wire fence to keep out the nomad herds. This picture and its lesson have made a profound impression on the local governments. Here is a superb example of the direct and inexpensive benefits that can accrue to developing nations from space systems and technology. (NASA photo.)

Fig. 10
Space portrait of the 48 contiguous states is made up of 569 selected Landsat images. It illustrates the beauty and versatility of montages made up of images taken at the same local sun time, at the same season of the year, and printed on the same scale. (This map was funded by the National Geographic Society, and is printed as a full-color centerfold in their July 1976 Bicentennial issue.)

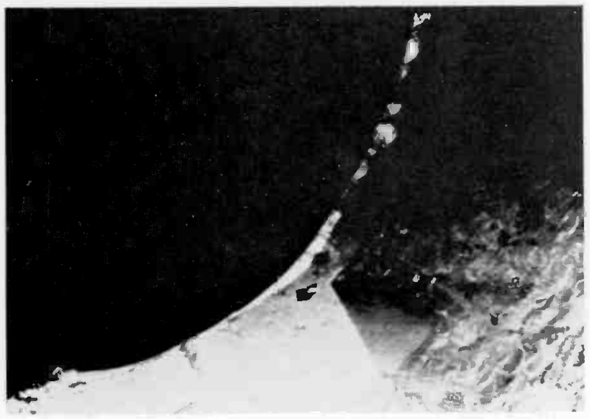


Fig. 12
Visible border. This image of the southeastern Mediterranean area shows a distinct southeast-to-northwest line—the boundary between Israeli- and Egyptian-occupied land at the time. Why is the northeast side darker than the other? The Israeli side is irrigated, productive land—the Egyptian side, a virtually uninhabited desert. (NASA photo.)

diverse areas as the effects of grazing on vegetation, the effects of clear-cutting, forest fires, and air pollution on timber resources, and the extent of flood damage.

This year marks the completion of a 3-year USDA/NASA/NOAA Large Area Crop Inventory Experiment (LACIE). Through this experiment, we learned that it is technically feasible to achieve the goal of 90% accuracy in world-wide wheat estimates by using Landsat remote-sensing data. LACIE results are consistently good in areas where the wheat fields are large compared with the 80-meter resolution of the Landsat MSS. This includes winter-wheat regions of the American Great Plains, and Soviet spring- and winter-wheat areas. More difficulty has been encountered with the spring crop in the U.S. Great Plains, because of the use of narrow-strip fallow fields. Here, the improved resolution of Landsat 3 and follow-on Earth Resources missions should reduce these "edge-of-field" errors substantially. Next year, USDA and NASA plan to begin production estimates of other crops such as soybeans, corn, or rice.

Ocean resources

Earlier this year, Landsat was joined in orbit by its ocean-going companion, Seasat. It is too early to cite specific results, but a pre-launch quote from Princeton's ECON, Inc. is pertinent:

> "The cumulative gross (civilian) benefits that may be obtained through the use of data from an operational Seasat system to provide improved ocean condition and weather forecasts is in the range of \$859M to \$2.7B in 1975 dollars at a 10% discount rate."

This is on a postulated 3-6 spacecraft system, operating from 1985-2000. The postulated benefits break down as follows:

- one-third ocean fishing—ocean currents, temperatures, safety
- one-fifth tanker operations—improved ocean and weather forecasts
- one-fifth marine transportation—improved forecasts
- one-sixth offshore oil and gas activities—production platform installation savings
- one-tenth arctic operations—ice information for ice-breaking tankers

Earth observations outlook

The next step in earth resources sensors is the Thematic Mapper, to fly on the follow-on Landsat D in the early 80s. The geometric resolution will be improved from 80 to 30 meters and the spectral bands will be sharpened and increased in number, probably from 4 to 7. Note the increased data bandwidth requirement of a factor of 12 caused by these two changes alone.

Another limitation, that of cloud cover, may be overcome by looking at thermal emission from Earth in the microwave spectrum. Fig. 16 shows two images of Antarctica taken 6 weeks apart during the ice breakup of the Southern Hemisphere summer—both through thick clouds.

In the mid-eighties, the next-generation weather satellites (NOAA Tiros-O, DMSP Block VI) and the follow-on Seasat will be lofted from the Western Test Range shuttle launch facility. These missions will not be defined until the early

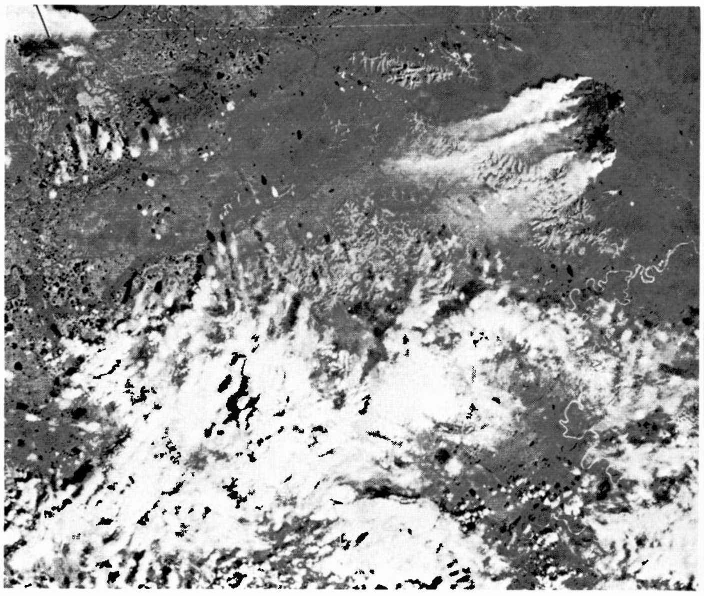


Fig. 13

Spotting fires. Timber resources are difficult to estimate in remote areas. This Landsat image of a portion of North Alaska is typical of ones that have proved timber resources to be some 30% less than earlier estimates. The cause of the shortage is the prevalence of major forest fires such as the one in the upper right-hand corner of the photo. The very existence of many such lightning-initiated fires in this sparsely-populated region was not even known prior to Landsat. (NASA photo.)

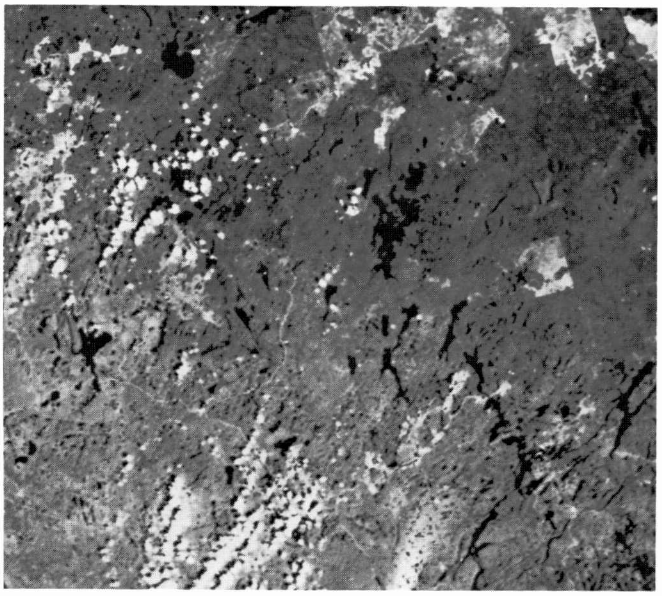


Fig. 14

Man's effect on forests. This Landsat image of south-central Canada shows large rectangular patches of "clear-cut" forest (top right and middle right). Almost as visible is the light-colored north-heading plume (bottom of photo to right of clouds) that marks the detrimental effects on vegetation of sulphur-dioxide pollution. This effluent is coming from a steel mill located just off the southern edge of the figure. (NASA photo.)

80s. They might even be candidates for consolidation, because of the similarity of their orbits and many of their sensors. Their time phasing is such that they can be designed to take full advantage of the shuttle launch capability, since operating experience will have been gained from East Coast shuttle launches before these new missions have been fully defined.

Conclusion

This is the end of this article, but the end of this story will never be written. New uses for space keep appearing—productive uses, humanitarian uses. The humanitarian face of space shows itself whenever you consider violent weather, floods and other natural disasters; pollution and energy shortages; and flight safety and communications. Add medicine, for in orbit we may be able to manufacture special vaccines of a purity that cannot be obtained on Earth. I close with a favorite quote from Arthur Clarke:

> "Our grandchildren's consciousness will flicker like lightning back and forth across the face of this planet. They will be able to go anywhere and meet anyone, without stirring from their homes. All knowledge will be open to them. All the museums and libraries of the world will be extensions of their living rooms."

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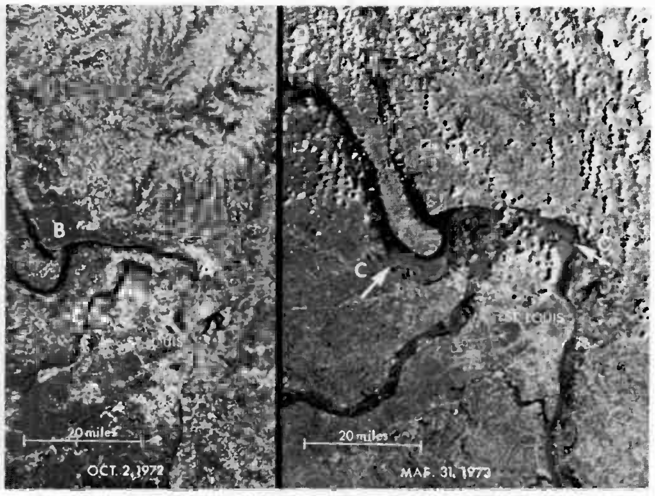

Fig. 15
Flood management. Time changes are frequently crucial in the management of water resources. This pair of Landsat images of the St. Louis area of the Mississippi River are on the same scale. The left panel shows normal conditions, and the right panel was taken during the great flood of 1973. It is apparent that the dikes through the city held, in contrast to the extensive upstream flooding. Such images permit relief agencies to focus their efforts on areas hardest hit by floods, and have already provided substantial help in the fair settlement of flood-damage claims. (NASA photo.)

Fig. 16
Following the ice breakup. Taken six weeks apart, these images show how the spring ice breakup takes place around Antarctica. Such images are useful to shipping and military users. (NASA photo.)

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Mechanical engineering of unmanned spacecraft: textbook solutions are hard to find

W. Metzger

Designing for space involves precise analytical work and down-to-earth common sense.

For 20 years, engineers at RCA Astro-Electronics have been building satellites to perform various missions: communication, physical measurement, meteorology, planetary missions and navigation, for example. As these spacecraft have become larger and more complicated, they have become more demanding with respect to the complexity and performance of their mechanical systems. Their mechanical engineering requirements include the basic structure, mechanisms for deploying appendages, and thermal control of the spacecraft.

Bill Metzger has over twenty years experience in the engineering of mechanical systems for aerospace vehicles. Since 1972, he has worked at Astro-Electronics where he is currently Manager, Mechanical Engineering. In this position, he has initiated new methods in finite-element analysis of structures, advanced composite materials applications to spacecraft structures, normal-mode vibration testing of structures, thermal analysis of spacecraft components, and compact electronic packaging.

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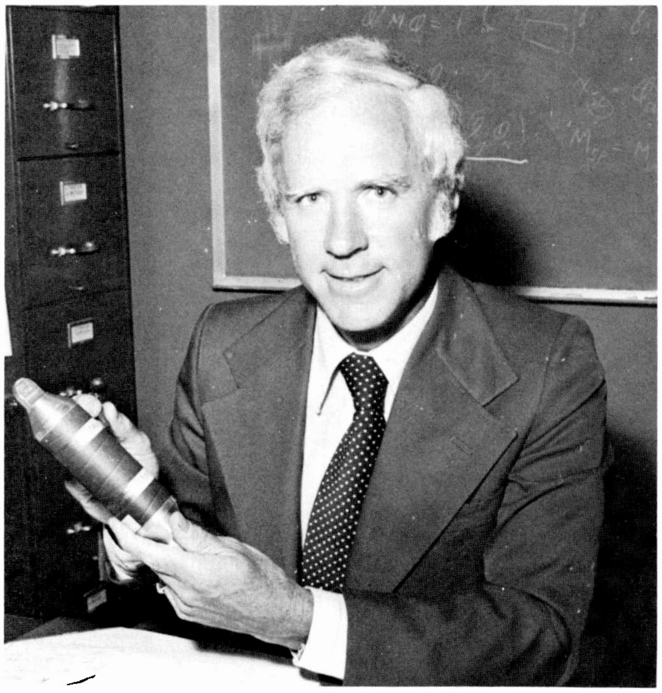
Bill Metzger and a graphite-filled epoxy composite test specimen. This advanced material is stronger per unit weight than steel and does not expand and contract with temperature changes.



The space environment imposes certain mechanical constraints on these spacecraft as they travel through it. However, it also relaxes certain other constraints which dictate the mechanical designs of more familiar earth-based systems. On the other hand, the nature of the spacecraft mission, originating on earth, enduring the rocket ride to space, and the robot-like years of life in space, creates other special requirements for the mechanical systems of the spacecraft.

This paper discusses the mechanical systems of the unmanned spacecraft built at Astro-Electronics. It shows how the space environment and the spacecraft mission impose unique requirements on the spacecraft mechanical systems. It also discusses these requirements as the basis for the challenge to mechanical engineering for designing, building, and testing these spacecraft.

At Astro-Electronics, we are now working on at least eight different satellites (communication, meteorological, navigation, scientific) and one major space subsystem (shuttle tv cameras), each of which carries electronic payloads into space. Mechanical engineering plays an essential role in the creation of these electronic systems and in providing the mechanical systems which are necessary for the satellite to reach orbit and to function. In today's jargon, the whole satellite certainly qualifies as a super-system.

Mechanical engineers traditionally have worked on harnessing energy (water, wind, and fire) through machines (engines, turbines) to do useful work. The latter requires special-purpose machinery, from automobiles or airplanes to electric-power generating stations. The skills developed in these efforts find applications to new technologies, such as spacecraft, as they arise. The name aerospace engineer was created by some engineering schools for those mechanical engineers who apply their skills to aircraft and spacecraft. In fact, many civil engineers, too, apply their structural skills to spacecraft.

Thus, in this article, the focus is on certain skills, mechanical in nature, as they are applied to the creation of satellites. What are the categories of mechanical skills

Recently, an electrical engineer told me, "All failures are mechanical."

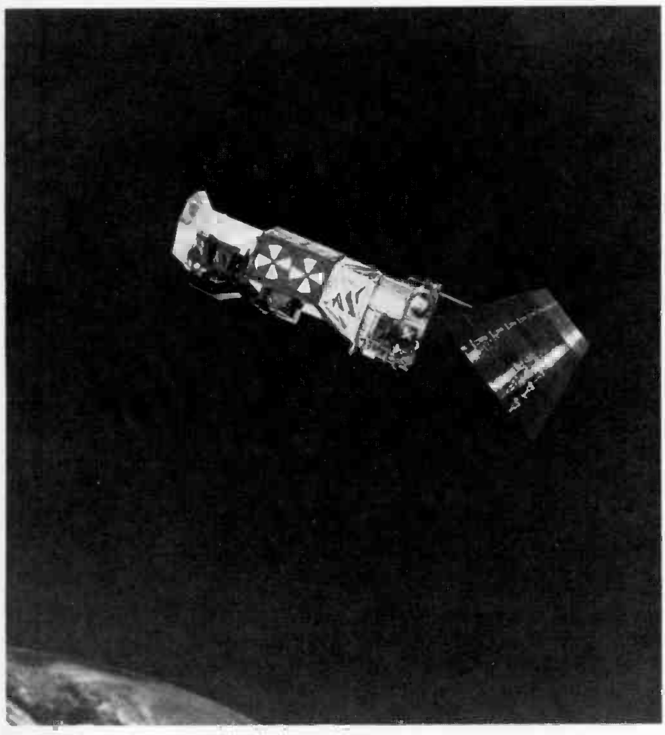


Fig. 1
Once in space, satellites operate in a relatively benign environment. This Air Force weather satellite, shown with its solar panels deployed, is in a polar orbit 350 miles above the earth.

included? Recently, an electrical engineer told me, "All failures are mechanical." And, ultimately, all material things are mechanical in that they have mass and structure. But, here we are concerned with those things which depend primarily on specific mechanical engineering skills.

Six subject areas are identified as falling within the province of mechanical engineering as practiced at the RCA Space Center: loads; structures; mass properties; mechanisms; electronic packinging; and thermal control. Although any list may appear arbitrary, this grouping has evolved from the arena of our activity.

Another author may have organized this article around analysis, design, and development—the traditional three-legged stool approach to engineering. Clearly, all three phases must occur in each of the above six subjects. It is our organizational goal to have analysis, design, and development integrated to the largest extent possible into a single process. Then each of these three legs represents an evolution of changing emphasis rather than an organization specialization.

Spacecraft requirements and constraints

Engineering has been defined as the art of building a device and making it work. The "make it work" part imposes certain requirements which are characteristic of the device. In aircraft, speed, range, and cargo weight are requirements. Spacecraft mechanical design requirements are orbital position, pointing accuracy, payload size and weight, and long life. As the mission becomes more demanding, so do the requirements.

The interaction between the requirements and the environment imposes certain constraints within which engineers must work. Spacecraft are subject to harsh loading during launch, they're exposed to hard vacuum and varied radiation, including the sun, in orbit, and are inaccessible to inspection or repair during their long lives. The latter is a mind-boggling constraint to any experienced mechanical engineer, especially when applied to the first item. By way of comparison, when the Boeing 747 was first introduced it spent 8 hours per day in service and 12 hours per day in repair, a grueling schedule which continued for months.

On the other hand, certain commonly imposed constraints are relieved by the special environment of space. The comparison between spacecraft and aircraft is illustrative. Aircraft carry people and therefore must be structurally enclosed, have cabin pressurization, and limit accelerations to human allowables. All three are relieved in spacecraft. Aircraft mechanical systems (engines, pumps, compressors, structure) operate for thousands of hours at very high performance levels fighting to stay up and with the cabin pressurized; all in the earth's corrosive atmosphere. On the other hand, mechanical systems never had it so good as in satellites while operating in the benign environment of space; see Fig. 1. This weightless vacuum environment permanently unloads all supporting structures and frees them from corrosion and wind forces.

Spacecraft mechanical engineering specialties

In the next sections each of six mechanical engineering skill specialties will be examined to explore what is special about its application to satellites. Each case generally covers the following order of presentation: requirements, constraints, methods of solution, test, and special problems.

The techniques and the mathematics used in the analysis of each of these specialties are quite sophisticated and sometimes complex; they are necessary to optimize both performance and weight. However, the basic concepts are simple. In my experience, the most costly test and service problems involving mechanical systems have resulted from oversights or errors of an elementary nature. With the broken pieces in hand, or the machine that won't go, and 20-20 hindsight, the failure is correctable by the application of sound judgment and basic principles as taught in undergraduate courses. This is not to say that advanced analysis embodied in massive computer printouts is not necessary; rather it says that advanced analysis does not relieve us of the need for a broad command of basic principles.

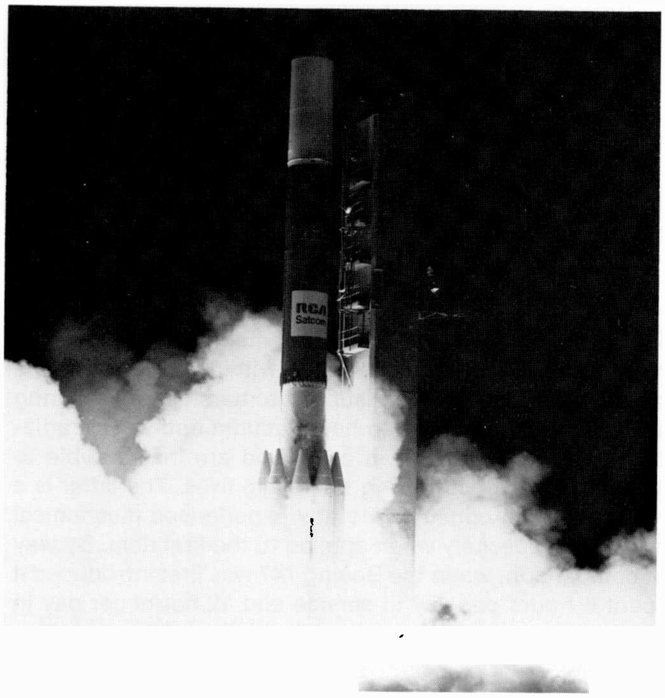


Fig. 2
Launch loads are severe. The RCA communications satellite at the top of the rocket must withstand high acceleration and tremendous acoustic noise and vibrations.

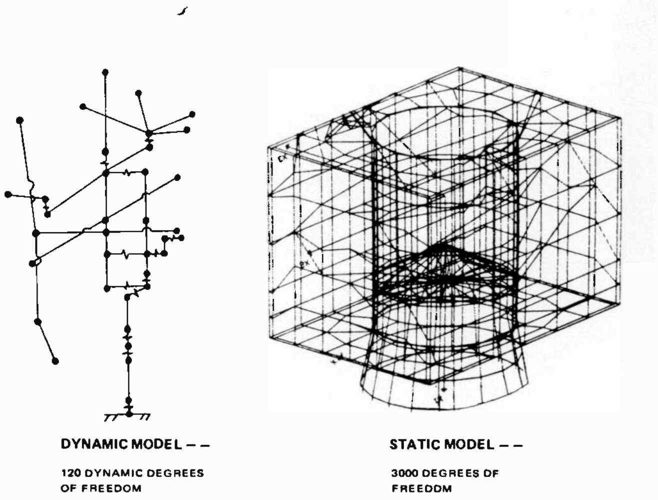


Fig. 3
Spacecraft loads must be predicted in advance. These finite-element models of the Telesat communications satellite were used as part of the design process. The number of degrees of freedom is so high that the analysis must be done by computer.

Loads

Loads present a paradox to the satellite structure.

The rocket ride into space is a short, but harsh, few minutes, the likes of which few structures must endure; whereas the years in space are more gentle than for any earthbound structure. The beginning of these loads is shown in Fig. 2 where the 2000-lb RCA domestic communication satellite is contained within the nose cone at the top 17 feet of the 116-ft-high launch vehicle. At the instant shown, the main engine, together with nine solid strap-on rockets, is producing maximum thrust to accelerate the entire launch vehicle away from earth. The satellite is subject to acoustic noise coming directly from the turbulent burning and reflected from the earth to the forward heat shield and transmitted inside to give a deafening noise around the satellite. This noise excites flat panels and vibrates electronic equipment mounted to them.

In addition, load transients caused by the thrust buildup and by lateral steering functions excite harmonic responses at resonances of the vehicle. These loads in combination reach a climax just before main engine cut-off (MECO) where the thrust acceleration is a maximum (8-12 g), because of high thrust and reduced total mass; the acoustic excitation is also a maximum at this point because of the supersonic buffeting of the heat shield.

The rocket ride into space is a short, but harsh, few minutes, the likes of which few structures must endure; whereas the years in space are more gentle than for any earthbound structure.

The above load sequence has been measured by the launch vehicle contractor and NASA, using accelerometers mounted to the structure along the length of the vehicle and on the satellite during similar previous flights. This prior experience is used to determine design loads and test loads.

Since each satellite has structural or mass differences, an analytical model of the entire launch vehicle is constructed and subjected to a computer-simulated launch sequence in advance of the final approval of the structure. The dynamic model of the Telesat communication spacecraft is shown in Fig. 3. In addition to the launch-vehicle analysis, the dynamic model is analyzed at RCA in a computer simulation of the vibration tests of the spacecraft. These tests include base excitation sine-vibration as illustrated in Fig. 4, and acoustic testing in our steel-walled reverberant acoustic chamber. The computer analysis predicts response loads in the primary structure and responses at box mounts, which represent predicted input vibration to electronic boxes. The latter are used to establish box design load requirements.

The special problem in load analysis lies in understanding the variability and different combinations of the loads. For example, one given load case, maximum lateral vibration at lift-off, has a likely variation of ±20 percent to ±50 percent. Therefore, qualification test loads are commonly 1.5 times flight measured loads. The 1.5 factor does not cover overlooked load combinations that may result from excitations not present in the flight measurements or from dynamic interactions not present in the configuration measured. In my experience, errors in loads analysis are the most common cause of structural failures. Experience, diligence, and a sharp wit are necessary to prevent them.

Structures

Space structures have difficult strength, weight, alignment, and stiffness requirements.

The structure is required to support the satellite equipment without failure during prelaunch handling, and during launch with its deployable equipment stowed. Then it must support the deployables in orbit. The structure must keep various instruments and attitude-control devices aligned to provide the required pointing accuracy. And it must have proper stiffness (greater than some minimal amount) to keep resonant frequencies separated from each other during launch and separated from any on-orbit excitations caused by rotating equipment.

Size and weight constraints are imposed on the satellite by the limitations of the selected launch vehicle. A specific example will illustrate some ways in which these requirements are satisfied within the above constraints.

The precision mounting platform (PMP) of the Air Force weather satellite is mounted on a test fixture in Fig. 5. It supports several instruments that must be precisely aligned at assembly and remain aligned in space. In the satellite shown in Fig. 1, the PMP is at the left, concealed by thermal shields and blankets. In the flight spacecraft it is made of aluminum with maximum stress limited below the micro yield level to prevent distortion caused by launch loads. In orbit, thermal distortion is prevented by maintaining the structure at constant temperature. Further, its ball-joint supports do not transmit redundant loads caused by distortions of the mating structure. Finally, the eggcrate construction gives a stiff, strong structure at low weight within minimum space.

The developmental PMP in Fig. 5 is made of graphite-filled epoxy composite (GFEC). This advanced aerospace developed material is composed of many tiny graphite filaments embedded in epoxy and laminated into plates. It is stronger and stiffer per unit weight than steel and it does not expand and contract with temperature changes. It has been developed as a direct replacement for the aluminum one at lower weight and with relaxed thermal-control requirements.

The most demanding strength requirements imposed on the PMP take place during launch, as a result of the steady acceleration combined with harmonic vibrations. The test shown in Fig. 4 is designed to simulate this vibratory loading on the whole spacecraft structure, including the PMP. To analyze the response loading of the structure under these flight and test excitations, the engineer must be able to predict the structural response magnification at resonance, alternately referred to as Q, or damping. This factor is derived solely from experience, except in the most ideal cases of hydraulic dashpots or completely rigid structures. Even for structures which are similar to ones with which engineers have past experience, this elusive damping factor may differ with subtle changes in support conditions, attached equipment, load level, or frequency.

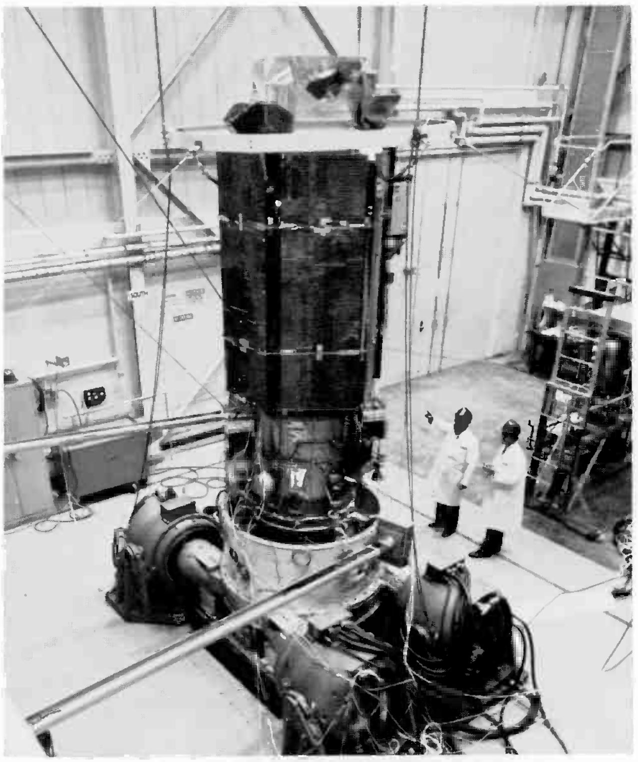


Fig. 4
Vibration testing is necessary to check out the results of the simulations shown in Fig. 3. Here, an Air Force weather satellite, with its solar panels stowed for the launch, is mounted on its base to a four-input shaker for lateral sine-vibration qualification.

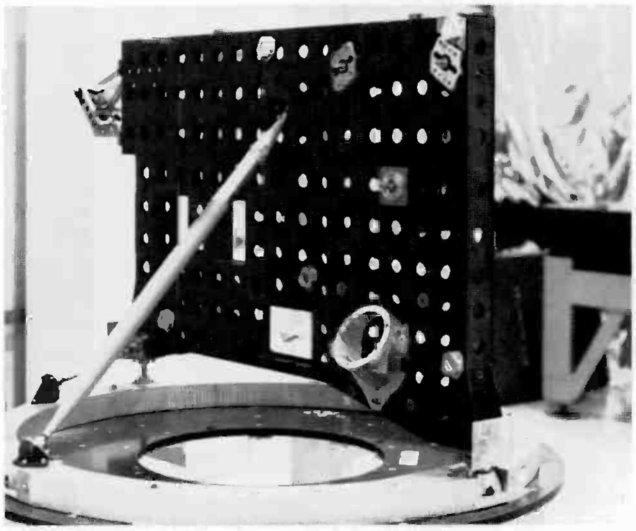


Fig. 5
Innovative structures are necessary in space. This precision mounting platform (developmental part for possible future flight of the weather satellite of Fig. 1) is made of a graphite-epoxy composite that has essentially zero thermal expansion and contraction. The ball-joint struts do not transmit redundant loads between the platform and its mating structure.

Difficult problems require calculus, extremely difficult problems require a computer, but impossible problems in addition require common sense.

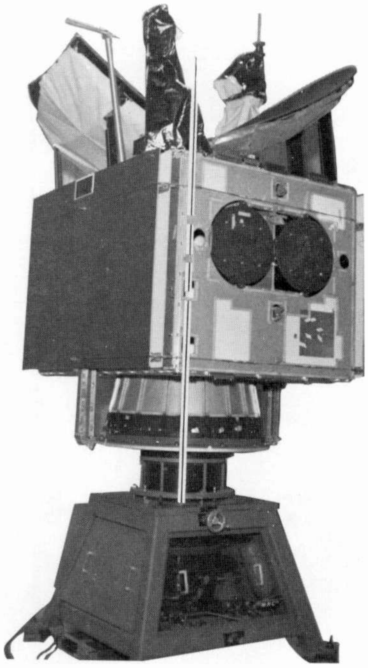


Fig. 6
Precise balancing is necessary so that the axis of the spacecraft's booster rocket (concealed in center, pointing down) coincides with the spacecraft's spin axis through the center of gravity (dashed line).

Mass properties

Weights and moments must be determined to very high accuracies.

The booster shown in Fig. 2 will boost only 2000 lb into the required elliptical transfer orbit. Therefore it is necessary to accurately control the satellite weight. Also, in this transfer orbit the spacecraft is spun about its thrust axis (vertical in Figs. 2 and 6) to prevent tumbling. For stable spinning, the mass moment of inertia about the spin axis must be higher than about any cross axis. Thus the shape of a pancake is ideal, but this is difficult to accomplish in an instrument-filled satellite. Designing for stable spinning therefore requires precise computations of moments of inertia—all the weights and their distances from the thrust and lateral axes must be known accurately.

The RCA-built communication satellites, for RCA Americom and Telesat Canada (see Fig. 6), use a 1000-lb solid rocket, concealed in the center with business end down, to boost them from relatively low elliptical transfer orbits into geosynchronous orbits 22,000 miles above the equator. For this rocket to push the spinning satellite precisely in the desired direction, the rocket thrust axis must coincide with the spin axis through the spacecraft center of gravity. This will be the case only if the spacecraft is statically and dynamically balanced about the desired spin axis.

These mass requirements are satisfied by design analysis using a computer program which sums the weight and computes inertia contributions for every item right down to nuts and bolts. Thus a computer mass model is created.

Before launch, the actual satellite is precisely balanced by adding small weights in locations indicated electronically by the balance machine shown in Fig. 6. In this machine the satellite is supported on air bearings which constrain it to spin about its geometric axis (also the solid-rocket thrust axis).

This same machine is used to measure the spacecraft polar moments of inertia about thrust and lateral axes. This is done by measuring the torsion pendulum frequency of the satellite when supported on the air bearing and grounded through a calibrated torsion spring.

In principle, determining mass properties is a simple problem. It presents a crucially challenging engineering problem because of three factors: 1) The enormous number of items which must be counted, computed and summed—the Air Force weather satellite in Fig. 1 has 700 entries in its mass-properties computer listing. 2) The precision of these computations, which must be summed up for the whole spacecraft, is very high. 3) The final balance and mass measurements are made just prior to shipping the satellite, when there is little time and great urgency.

Mechanisms

Designing mechanisms for satellites presents some unusual requirements.

The solar panels of the Air Force weather satellite are stowed for launch in Fig. 4 and are deployed for space operations in Fig. 1. Moving the panels from stowed to deployed requires the action of several mechanisms:

1) preloaded restraint bands or cables (see Fig. 4);

2) pyrotechnically actuated cutters;

3) hinges that may incorporate springs, dampers, stops, and latches;

4) connecting support arms (see Fig. 7 for view of these devices on a different spacecraft); and

5) a drive system to rotate the panels in orbit so they continuously face the sun.

These devices are required to give:

1) strong, rigid support when stowed;

2) reliable one-time deployment when commanded;

3) long life in space (eight years for the Americom communications satellite);

4) light weight; and

Engineering is the most fun while working at the cutting edge of an advancing new technology where the problems are new—and the opportunity for originality is greatest.

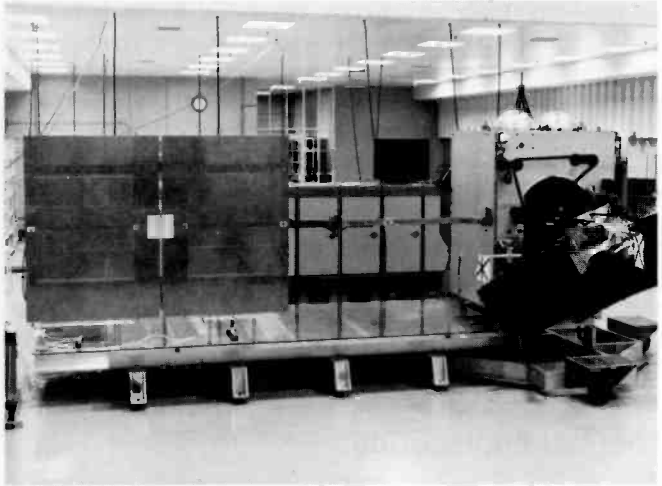


Fig. 7
On-earth testing of structures designed for space can prove difficult because of the presence of gravity. The RCA communications satellite here has its solar panels deployed; they are supported by air bearings on a flat table for this test.

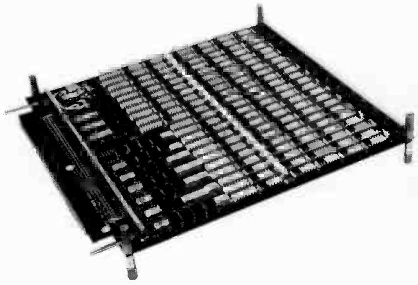


Fig. 8 (left)
Electronics must be packaged so components can withstand vibration without failure. Components on this memory module must withstand as much as 50 *g* during resonance. The trend to making connections within the microcircuits rather than on the circuit board has helped increase reliability and reduce size.

Fig. 9 (right)
Spaceborne computer performs 80,000 operations per second while consuming only 6.5 W. Computer consists of four circuit boards (including the one of Fig. 8) mounted within this box. Connections to rest of satellite are at top.

5) specified stiffness in orbit ($f_1 \pm 0.5$ Hz for the Americom satellite) to keep the panels dynamically isolated from the satellite guidance system and from excitations produced by on-board equipment (separated from 6.0-Hz scanner speed on the Air Force weather satellite).

The stiffness-in-orbit specification further requires:

6) zero backlash in the hinges; and

7) latches for the deployed position also with zero backlash.

These requirements must be satisfied within the constraints:

1) the mechanisms must be stowed within the space of the nose cone;

2) they must operate in the hard vacuum of space;

3) outgassing of lubricants and damping fluids must be near zero;

4) they must operate over a wide temperature range;

and probably the most difficult of all constraints,

5) the device must be demonstration-tested in the earth's gravity.

Why so difficult for number 5? This test is illustrated in Fig. 7. In it, the deployed panels are supported on a flat airbearing table (like air hockey). The table must be precisely flat. Unfortunately, air bearings cannot be used in a vacuum chamber. For the Air Force weather satellite, roller casters were used as supports so it could be tested in the vacuum chamber, but they introduced friction. Thus, the test in the earth's gravity becomes an overwhelming requirement which either drives the design (make the structure self-supporting or make the springs big enough to power the test) or results in a costly precision rig development program (shown in Fig. 7).

The above discussion presents one way in which one type of mechanism is implemented. The solar array is similar in principle to a wide variety of antennas, gravity-gradient booms, and other extensions deployed from satellites. The pyro release, spring, damper, stop, and latch is only one sequence for deployment, which can be accomplished by any number of alternative arrangements of linkages, cables, motors, springs, and dashpots. Friction between sliding surfaces is present in many ways in all of these devices. It is the elusive variable which complicates analyses—look in a text in mechanics to see how few example problems include friction. It is unpredictable—coming on strong when it interferes and vanishing when it is needed; varying widely in tests, but being precisely repeatable in certain devices. In coping with friction, there is no substitute for experience on the part of the mechanical engineer.

Electronic packaging

The packaging of electronic equipment for spacecraft combines mechanical analysis, thermal analysis, and configuration design into a unique mechanical engineering specialty.

The circuit board shown in Fig. 8 is one of four which comprise a programmable digital computer with 16k word memory. This computer performs 80k operations per second using only 6.5 watts of power. The boards are assembled into the box shown in Fig. 9. Two of these units fly with the new Air Force weather satellite, similar to Fig. 1.

The mechanical requirements and constraints for this package are much the same as for mechanisms discussed in the previous section. Some special comments on the size of the box and on vibration are appropriate.

The desirability of small size and low weight for a spaceborne computer is obvious. But how small? And at

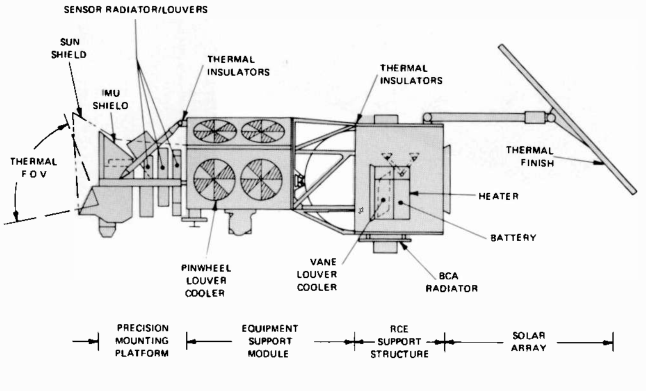


Fig. 10
Thermal control system has to keep temperatures constant in bright sunlight and in the earth's shadow. Active controls (louvers and heaters) and passive (shields and insulators) controls are used in this Air Force weather satellite.

what cost? These become very complicated questions which have probably never been completely analyzed quantitatively. The parts mounted on the boards are interconnected through a system of leads, printed circuits, soldered joints, pins through the boards, and a network of wire welded to one end of the pins in a prescribed pattern called the buttonhead weld technique. The four boards are interconnected through a bottom edge connector (see left front edge in Fig. 8) that plugs into a harness board. The boards are connected to the satellite through top connectors (see Fig. 9 for harness wires into connectors). No need to understand the details of this scheme for this discussion. The size of the package is mostly determined by the number and size of connections. The number can be reduced by including more connections on the microcircuits mounted on the boards. This has been the big breakthrough of the past decade and no doubt it will continue. But with today's parts, as shown in Fig. 8, the size of the present circuit board is limited by the size of the pins, 0.05 inch in diameter, and the spacing between them, an 0.075 x 0.05-inch staggered grid. These sizes are determined by the wire-weld machine, which has developed through experience to be somewhat of an industry standard. Thus, the constraint on size is imposed by the selection of available pins and weld machines.

In the past, we built a similar package that was 30 percent smaller. We took this size penalty in order to have the benefits of plug-in boards (adds a harness board) and of buttonhead welding (more automated and more reliable manufacturing processes). Actually, the box in Fig. 9 is half again as large so it can house two more boards for computer growth.

The vibratory loads experienced by boards depend upon the box resonance, and the loads on parts depend on board resonances. The box in Fig. 9 resonates from 200 to 400 Hz, with force magnifications of 6 to 10. For the boards, the first plate resonant frequencies are 80 to 100 Hz and the magnification is 4 to 6. A typical vibration test of the box (determined from spacecraft response measurements) would require 10-*g* excitation up to 50 Hz, and 5 *g* above 50 Hz. Thus, at 100 Hz, the parts on boards see (5 *g*) (6) = 30 *g*, and at 200 Hz the boards and parts on boards may see (5 *g*) (10) = 50 *g*. In the latter case, the board may give some isolation to parts by virtue of its in-plane sliding fit in its slide supports. Now these results present an anomaly with respect to the loading of parts on boards: many parts are qualified only by steady loading in a centrifuge and few are qualified for ± 30*g* vibration. Thus, normal package design imposes loads on parts in excess of their qualification levels. Fortunately, parts are seldom sensitive to vibration below about 1000 Hz.

Thermal engineering

In space, wide temperature variations are possible, from near absolute zero, -273° C when shadowed from the sun, to several hundred ° C for some bodies when exposed to the sun.

Temperature control of the satellite is necessary since some items would be destroyed by such temperature extremes. Further, most electronic equipments have a preferred temperature for efficient operation and long life; for example, batteries prefer 10° C. Therefore, the satellite is designed to provide a near-ideal temperature for all equipment.

The space environment imposes a wide variety of heating and cooling conditions. Most often, energy from the sun heats one side of the spacecraft while the opposite side is cooled by radiating to space. Then, suddenly, the sun input may be shut off as the spacecraft passes through the earth's shadow. These conditions produce severe temperature gradients and rapid transients. The thermal-control system must maintain prescribed spacecraft temperatures during these conditions.

On the other hand, the space environment is very kind to eliminate virtually all atmosphere so that there is no convection (boundary-layer) heat transfer to cope with.

The thermal engineering task involves three parts: design of the thermal system; analysis of spacecraft temperatures; and tests to make final adjustments of control systems and to prove the proper temperature control. The thermal control systems of the Air Force weather satellite are shown in Fig. 10. Active control is done by heaters and louvers, which are electronically controlled. Passive control is accomplished by special finishes, insulators, sun shields, radiators, and multi-layer insulating blankets (not shown in Fig. 10) that entirely enclose the equipment support module and precision mounting platform.

The thermal analysis is acccomplished on a computer model which defines each spacecraft element and each equipment as a body. The thermal model for Fig. 10 contains 400 bodies—no way this could be analyzed without a large computer! Radiation couplings and conductive couplings are determined for each body relative to all other bodies. Radiation inputs and outputs with space are determined. Electrical power dissipation (heat generation) is determined for each body. With all of these inputs, the computer solves for temperature profiles for each body for a large number of space and test conditions.

Final verification of the thermal system is done by placing the entire spacecraft into a space simulation chamber, a hard-vacuum chamber with cold black walls to simulate space. Then, with the spacecraft electrical systems operating, for about three weeks around the clock, the test continues. Temperatures are measured and final adjustments for electronic heater and louver controls are made.

Temperature predictions require accurate descriptions of material surface properties with respect to emissivity (radiation away to space) and absorptivity (radiation in from the sun and earth). During the 1960s much effort was invested in measuring these properties and in developing materials with special properties. This technology is now well developed. Conduction through joints remains an elusive characteristic which, like structural damping and friction, is determined by tests and experience.

Technicalities not taught in school

A professor once told me, "Difficult problems require calculus, extremely difficult problems require a computer, but impossible problems in addition require common sense." Unfortunately, common sense is actually quite uncommon and what is meant by common sense is really good judgment based on experience. In each technical area covered here, I've singled out at least one aspect or parameter required to "make the design work," but which is based on experience. These factors are the cornerstones of mechanical judgment and are summarized here for emphasis:

Loads—combinations

Structure—damping

Mass properties—tolerances

Mechanisms—friction

Electronic packaging—vibration sensitivity of parts

Thermal—conduction through joints and radiation characteristics of surfaces

The satellite as a system

Considering the complexity of the satellite mission, the number of systems which must operate simultaneously, and the total isolation of the entire satellite in space, the satellite is rightly referred to as a super system.

This article has been organized around technical specialties. The boundaries that separate them are largely arbitrary and shouldn't be taken too seriously. For in this super system, nothing can be separated without jeopardizing the whole. Some examples will illustrate the interdependence of the different technical areas of the satellite.

The relation between the thermal control and the electric power systems is obvious. All electric power is dissipated someplace in the satellite, where it becomes heat and is included in the thermal model.

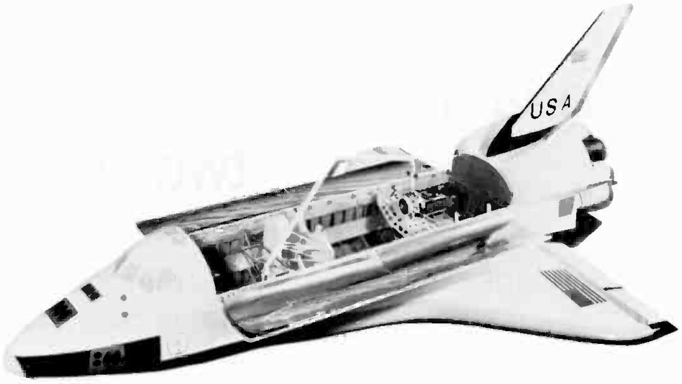


Fig. 11
The space shuttle will change the design requirements for launching satellites, and will also open up the possibility of recovering them from orbit for service and renewal. Model shows an Air Force weather satellite ready for deployment from the shuttle launch bay.

A relation between the structural, attitude-control, thermal, and propulsion systems is described with reference to Fig. 7. The long arms support the solar panels some 4 ft away from the satellite, removing them from the plumes of four north-side thrusters. These thrusters, centered around the spacecraft center of gravity, are computer controlled about once per month to translate the satellite southward to its assigned position. If the plume strikes the array, it will overturn the satellite. The long arms are also designed for stiffness so that the deployed array's bending flexibility will not couple with the attitude-control system in an unstable way. When deployed in space, the arms must not bend as a result of one-sided thermal heating, since this would shift the spacecraft center of gravity and cause attitude-control errors. Thus, at least four systems—structural, propulsion, attitude-control, and thermal—affect the design of the arms.

Conclusion

Engineering is fun! That's why we became engineers and that's why we stay at it. It's the most fun while working at the cutting edge of an advancing new technology where the problems are new—and the opportunity for originality is greatest. Satellites are still on the ascending slope of this advancing technology in the area of new applications and changing constraints.

The space shuttle, now only 18 months away from its first launch, will change some of the ground rules. It will present a whole new set of launch requirements, as illustrated in Fig. 11. It will make it possible to retrieve satellites from orbit for service and renewal. It may relieve weight limitations and it will promote greater numbers of satellites in orbit. Finally, it will carry men into orbit and open up possibilities for human interaction with satellites in space. All of this will make new requirements on mechanical engineering of satellites, from the construction of shuttle interface structures to the mechanisms for deploying and retrieving them. Mechanical engineering of space applications is still alive with fresh new ideas that make it an exciting place to work.

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Global weather satellites— two decades of accomplishment

A. Schnapf

Weather-satellite data has become so useful and reliable that meteorologists consider it indispensable.

What have the benefits been?

Over the past 18 years the quantity, quality, and reliability of weather satellite coverage have improved greatly. Since 1966 the entire earth has been photographed at least once daily on a continuous basis. From its inception as a new research tool with its potential not fully realized, satellite data has steadily increased in importance. It is now being used by meteorologists and environmental scientists on a widespread basis in routine operations throughout the world, and is considered almost indispensable for analyses and short-range forecasts.

The meteorological data from around the earth is received at the National Environmental Satellite Service (NESS) near Washington, transformed into a broad variety of products and distributed throughout the world. Selected images from several satellites currently in use are shown in Fig. 1. Although these images lose some detail in being transferred to the printed page, their scope and potential usefulness are readily apparent.

The satellite information has proven extremely useful in two broad types of situations. First, extensive areas of the earth cannot regularly provide

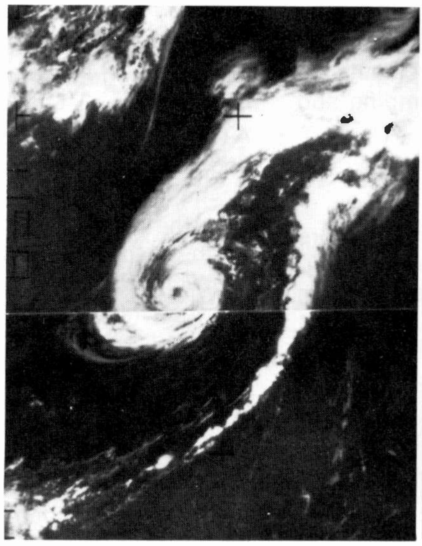

Fig. 1a
Tropical storm Amy as imaged by ESSA-8 on July 2, 1975, when the satellite had been in orbit over seven years.

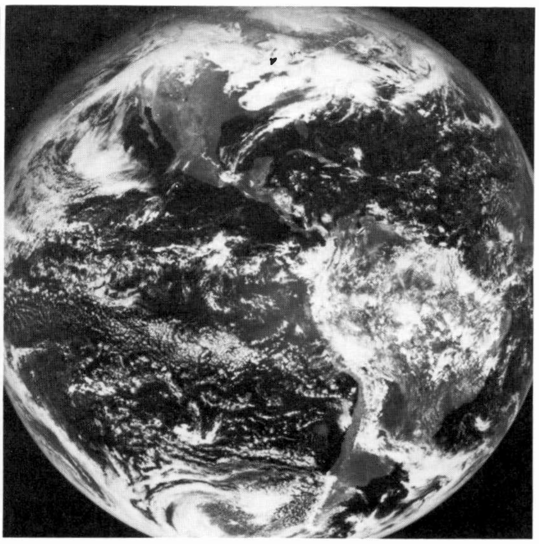

Fig. 1c
Western hemisphere in a visible-spectrum image taken by SMS-2.

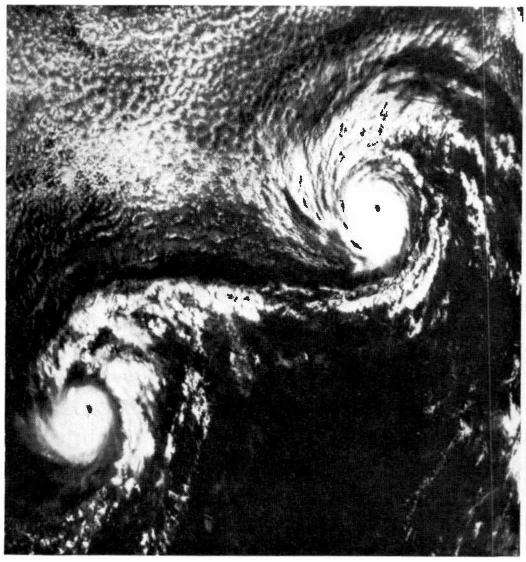

Fig. 1b
Hurricanes Ione and Kirsten, August 24, 1974, in a NOAA-3 visible spectrum image.

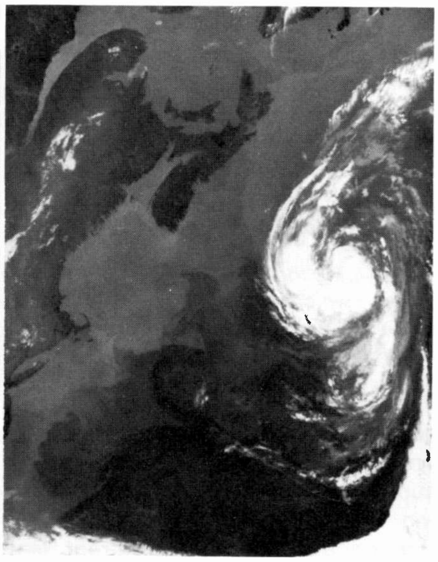

Fig. 1d
Hurricane Candice off the east coast of the United States, August 21, 1976; infrared image from NOAA-5.

conventional weather reports, namely, the oceanic regions of the northern and southern hemispheres, deserts, and the polar regions. Satellite information fills these voids by locating the large-scale features depicted by the cloud formations. These features include storm systems, fronts, upper-level troughs and ridges, jet streams, fog, stratus, sea-ice conditions, area of snow cover, and to some extent upper-level wind directions and speeds. The satellite data is also used in conjunction with other data to provide quantitative heights of constant-pressure surfaces as inputs to conventional analyses.

The second type of situation to which satellite data is usefully applied is the location and tracking of hurricanes, typhoons, and tropical storms. Coastal and island stations with little or no adjacent conventional weather information can make maximum use of APT (automatic picture transmission) data and the processed stored data from facsimile circuits. The satellite data provides information on the presence and position of frontal patterns, storms, and general cloud cover.

Satellite information has had a great impact on the routine surveillance and tracking of tropical storms. Since 1966, when coverage of the world by the TIROS-series satellites on a daily basis became complete, no tropical storm has escaped detection and daily tracking. Storms are usually spotted in their developing states, often beyond the normal range of weather reconnaissance aircraft. The APT, direct readout infrared, and processed stored visible and infrared data are available at most offices with tropical-storm forecast responsibilities. All the tropical regions of the world are completely monitored through satellite data received by the National Environmental Satellite Service.

The infrared data from the ITOS/NOAA satellites can be used to produce charts showing the sea-surface temperature over a larger area and with more frequency than is possible from any other source. This information is useful to shipping interests and the fishing industry, and is a vital input to meteorological forecasts.

Satellite pictures display the extent and character of ice fields in the Arctic and Antarctic Oceans, and on the Great Lakes, with a frequency and geographic coverage never before approached.

Worldwide atmospheric-temperature soundings provided by satellite help produce more complete and accurate analyses for use in weather forecasts because they cover oceans and remote areas not covered by conventional sounding instruments. The continual soundings also help locate atmospheric temperature gradients for use in studying atmospheric phenomena.

What are the satellites that have made this possible?

The TIROS system and its successor, ITOS, have been the principal global operational meteorological satellite systems for the United States over the past 18 years.

These systems started as a research and development program, marked by the successful mission of the first TIROS (Television and Infra-Red Observation Satellite) in April 1960. They eventually matured to a semi-operational satellite system in which nine additional TIROS satellites were successfully launched between 1960 and 1965. Each satellite carried a pair of miniature television cameras, and approximately half of the missions also included scanning infrared radiometers.

The ESSA satellites were the next step.

The commitment to provide routine daily worldwide observations without interruption in data was fulfilled by the introduction of the TIROS Operational System (TOS) in February 1966. This system employed a pair of ESSA (Environmental Science Services Administration) satellites, each configured for its specific mission. One satellite provided global weather data to the Department of Commerce's National Environmental Satellite Service at Suitland, Maryland, for processing and forwarding to the major forcasting centers of the United States and to nations overseas. The second satellite provided direct real-time readout of its APT television pictures to simple stations located around the world. Nine ESSA satellites were successfully launched between 1966 and 1969. One of them, ESSA-8, remained in operation until March 1976. Larger television cameras (1-inch vidicons) developed for the Nimbus satellite program were adapted for use on the ESSA series, significantly increasing the quality of the cloud cover pictures over that obtained from the earlier TIROS cameras, which used ½-inch vidicons.

The ITOS series began the second generation of operational weather satellites.

The second decade of meteorological satellites was introduced by the successful orbiting on January 23, 1970, of ITOS-1 * (Improved TIROS Operational System). This satellite dramatically surpassed the capabilities of the predecessor ESSA satellites, moving rapidly closer toward the objectives of the National Operational Meteorological System (discussed later in this paper). ITOS-1 provided in a single spacecraft the combined capability of two ESSA spacecraft—the direct-readout automatic picture-transmission system, and the global stored images for later transmission and processing. Additionally, ITOS-1 provided, for the first time, day-and-night radiometric data in real time or stored for later playback. Global observation of the earth's cloud cover was provided every 12 hours with the single ITOS spacecraft as compared to every 24 hours

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* This spacecraft was originally designated TIROS-M. After being placed into orbit, it was redesignated ITOS-1. Subsequent spacecraft in this series were named NOAA-1, NOAA-2, etc. by the National Oceanic and Atmospheric Administration, the successor to ESSA as operator of the system.

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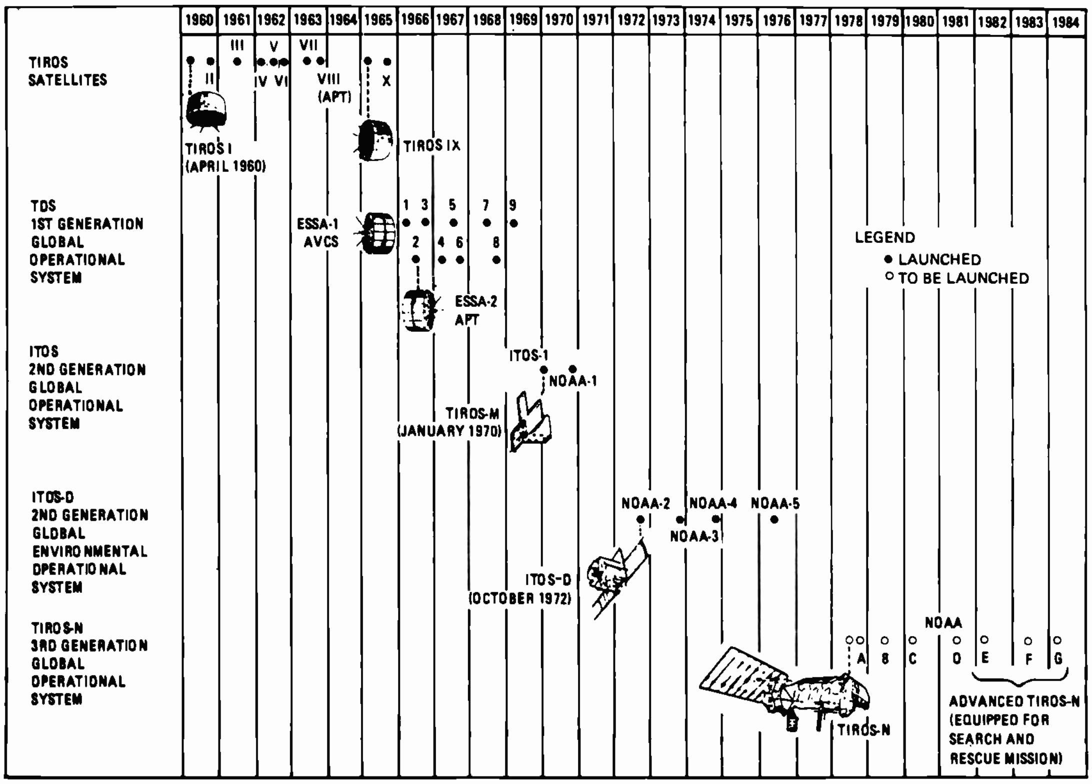
Fig. 2
The TIROS family (TIROS-ESSA-ITOS-NOAA) has been the principal operational satellite weather system for the United States for almost twenty years. This evolutionary family was designed and built by RCA Astro-Electronics under the technical management of NASA, and operated by the National Oceanic and Atmospheric Administration.



with two of the ESSA satellites. A second ITOS spacecraft, NOAA-1 (ITOS-A), was launched on December 11, 1970.

As the ITOS system evolved to become the ITOS-D system, the flexibility inherent in the spacecraft design permitted a broader and more sophisticated array of environmental sensors to be carried, with only minor changes to the spacecraft. This new sensor complement provided day-and-night imaging by means of very-high-resolution radiometers and medium-resolution scanning radiometers. It also included vertical temperature profile radiometers for temperature soundings of the atmosphere and a solar proton monitor for measuring proton and electron flux. Six spacecraft (ITOS-D, E-2, F, G, H, and I) were planned for the ITOS-D series. NOAA-2 (ITOS-D), the first satellite in this series, was successfully launched on October 15, 1972. Three additional satellites of this type (NOAA-3, -4, and -5) were placed into orbit in 1973, 1974, and 1976, respectively. The ITOS system, as it matured, brought the goals of the National Operational System closer to realization.

The ITOS satellite system evolved from the proven technology of the TIROS and ESSA spacecraft. Many devices and techniques employed on the earlier series were enhanced and used on the ITOS spacecraft. This orderly evolution permitted growth from a spin-stabilized spacecraft to a 3-axis stabilized earth-oriented despun platform.

The principal objectives of this growth pattern during the evolvement from an R&D satellite to a global operational system were improved performance, the provision for increased quality and more frequent acquisition of meteorological data, and more timely dissemination of the processed data to the users. The evolving system had to be compatible with the global ground network of local receiving stations as well as the two principal command and data-acquisition sites. Finally, the operational system had to be cost-effective and have the capacity for future growth.

TIROS-N will start the third generation this year.

TIROS-N, an operational polar-orbiting environmental satellite system, is currently under development and will be placed into operational service late in 1978. Eight spacecraft in this series will provide global observations from 1978 through 1984. This new series will have a new complement of data-gathering instruments. One of these instruments, the advanced very-high-resolution radiometer, will increase the amount of radiometric information available for more accurate sea-surface temperature mapping and identification of snow and sea ice, in addition to day-and-night imaging in the visible and infrared bands. Other instruments will improve vertical sounding of the atmosphere.

A data-collection system will receive environmental data from fixed or moving platforms such as buoys or balloons and retain it for transmission to the ground stations. A solar environmental monitor will be included to measure proton, electron, and alpha-particle densities for solar-disturbance prediction. Fig. 2 depicts the evolution of the TIROS-ESSA-ITOS-NOAA family of satellites.

The Nimbus satellites have been our principal program for remote-sensing research.

The Nimbus satellite program was initiated by NASA in the early 1960s to develop an observational system capable of meeting the research and development needs of the nation's atmospheric and earth scientists.

Originally, Nimbus was conceived as an operational system but was redirected to be

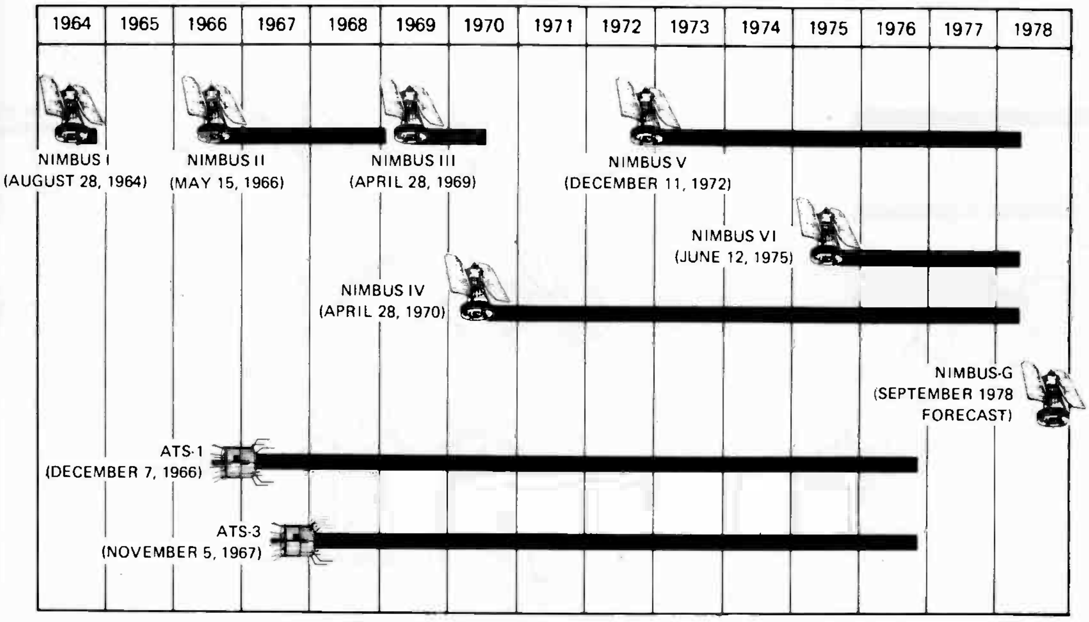


Fig. 3
Nimbus and ATS satellites have been used for research and as test beds for advanced concepts such as high-resolution television cameras and sounding instruments. Both were developed under NASA management, with General Electric as the main contractor for the Nimbus series and Hughes Aircraft as the prime contractor for ATS.

1) the test bed for advanced instruments for the future operational TIROS polar-orbiting satellites and 2) the research system for remote sensing and data collection. The project has matured to become the nation's principal satellite program for remote-sensing research. Each new satellite in the Nimbus series has represented significant growth in sophistication, complexity, weight, capability, and performance.

Six Nimbus spacecraft were successfully placed into orbit from 1964 through 1975. The final spacecraft, Nimbus G, scheduled for launch in 1978, will be instrumented with sensors to monitor atmospheric pollutants. The Nimbus program has provided advanced television cameras, high-resolution radiometers, temperature-sounding instruments, microwave sensors, a data collection system, and a data relay experiment.

Geostationary satellites such as ATS and SMS/GOES improved coverage greatly.

The increased launch-vehicle capabilities available during the middle 1960s permitted satellites to be placed at geostationary altitudes and thus provided atmospheric scientists with a new dimension in observations, namely: continuous observations of almost one-third of the earth's surface. A NASA research program involving geostationary satellites was implemented in the Applications Technology Satellite (ATS) series. Although primarily designed to demonstrate communications satellite technology, several of the ATS series carried high-resolution cameras for atmospheric observation.

On December 7, 1966, ATS-1 was placed into geostationary orbit. This technology satellite showed, as one of its functions, that it was possible to provide a picture of the western hemisphere every 20 minutes through the use of a spin-scan camera. Useful data was provided from approximately 55° N to 55° S latitude. The ability to receive sequential photographs of the same area improved the possibility of early detection of severe storms and tornadoes, and provided real-time data of cloud and frontal movements.

A second technology satellite, ATS-3, was launched in November 1967. This satellite, using a multispectral spin-scan camera, returned the first color images of the full earth disc. Copies of these pictures have been used for many applications in addition to meteorology. The performance history of the Nimbus and ATS technology satellites is shown in Fig. 3.

The successful application of atmospheric observations from geostationary altitudes led to NASA's development of a satellite designed specifically for that purpose. The prototype for the SMS/GOES series (for Synchronous Meteorological Satellite/ Geostationary Operational Environmental Satellite), was called SMS-1 and was designed and integrated by the Aeroneutronic Ford Corporation. This satellite was successfully launched in May 1974. Placed over the equator at 45° W longitude, it provided continuous hemispheric coverage. The principal instrument for SMS is a 16-inch aperture telescope for visible and infrared scanning. Built by Hughes Aircraft Company and called the visible and infrared spin scan radiometer, this sensor permits day and night observation of clouds and the determination of temperatures, cloud heights, and wind fields.

The SMS also relays data received from remotely located data-collection platforms such as river gauges, ocean buoys, ships, balloons, and aircraft. Its space environmental monitor (consisting of an X-ray sensor, an energetic particle sensor, and a magnetometer) detects unusual solar activity, such as flares, and measures the flow of electron and proton energy and changes in the geomagnetic field. Observation and forecasting of atmospheric phenomena not specifically related to meteorology are thus possible on an operational basis.

Three additional satellites of the SMS design have been launched: SMS-2 on February 6, 1975; the first operational version, GOES-1, on October 16, 1975; and GOES-2 on June 16, 1977.

After being positioned at 45° W longitude (off the west coast of Africa) to support the international experiment called GATE

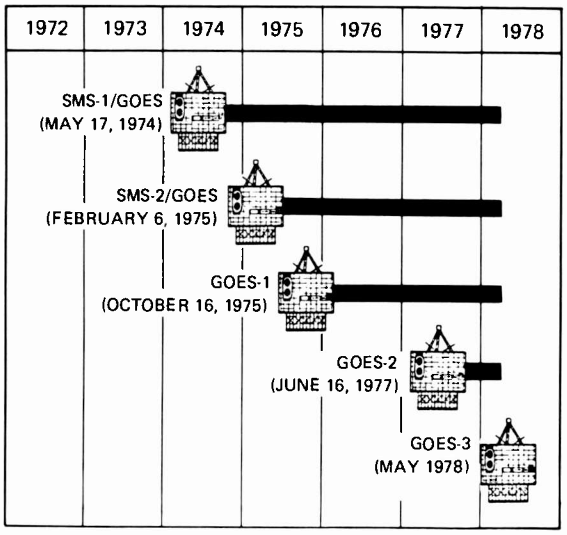


Fig. 4
SMS/GOES series was the first to use geostationary satellites as part of an operational weather system. These satellites have relayed data from remote earth-bound stations as well as their own weather data.

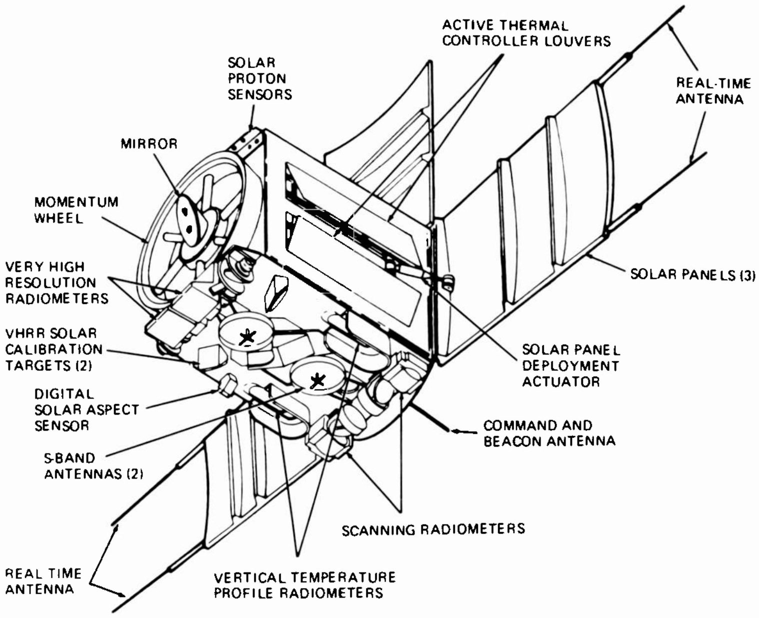


Fig. 5
ITOS satellite is an evolutionary improvement to the TIROS series.

during the summer of 1974, SMS-1 was moved to 75 °W, where it provided routine images until replaced by GOES-1. SMS-2 is still in service at 135° W, providing coverage of the Pacific Ocean and the western United States. The performance history of the SMS/GOES satellites is shown in Fig. 4.

Today's weather systems

The U.S. now has a fully operational satellite weather system.

The U.S. National Operational Meteorological System has achieved full capability in the second decade of space operations. The system required, in addition to the polar-orbiting TIROS satellites, continuous views of the earth's cloud cover, a data relay for weather facsimile to users, and the ability to collect data from remote sensor platforms. The research and development that produced these current observational systems evolved out of the TIROS, Nimbus, and Advanced Technology Satellites. The system can be divided in terms of its two satellite types—polar-orbiting (ITOS and TIROS) and geostationary (SMS/GOES).

The ITOS satellites operate in a sun-synchronous near-polar circular orbit at an altitude of 1463 kilometers.

During the satellite's 115-minute orbital period, the earth rotates 28.5 degrees. The sensor view angles give contiguous coverage between adjacent orbits as well as observation in the orbit track, providing global imaging during the 12.5 orbits daily.

The ITOS/NOAA system provides both real-time direct data to automatic-picture-transmission receiving stations throughout the world and stored data to the two U.S. command and data-acquisition stations for retransmission to the National Environmental Satellite Service, at Suitland, Maryland, for processing and distribution. The real-time data provided to local users consists of: visible and infrared data with a resolution of 3.7 and 7.4 km, respectively; infrared and visible data from the very high resolution radiometer, with a resolution of 0.9 km; and vertical temperature profiles from the surface of the earth to about 30,500 meters.

The ITOS system continuously orients the spacecraft surface containing the primary sensors, and maintains three-axis orientation of the spacecraft to better than ±1 degree at all times.

Fig. 5 shows the general physical configuration of the ITOS satellite. The satellite is a rectangular, box-shaped structure, approximately 101.6 cm by 101.6 cm by 121.9 cm long. On the bottom of the structure, a cylindrical transition section attaches to the 94-cm-diameter adapter section of the launch vehicle. The ITOS-D series spacecraft weigh approximately 340 kg.

TIROS-N, the third-generation operational meteorological polar-orbiting satellite, will be introduced in the fall of 1978.

This spacecraft (Figs. 6 and 7) will be equipped with improved sensors and instruments, and its data-collection system will permit it to gather data from balloon and buoy platforms deployed about the planet. The TIROS-N satellite, in conjunction with two GOES satellites, will constitute the U.S.'s contribution to the World Weather Watch.

The data collected by the satellite's advanced instrument complement will be processed and stored on board for transmission to earth stations for retransmission to the central processing facility at Suitland, Maryland. Data will also be transmitted in real time to remote stations distributed about the globe.

The TIROS-N satellite will operate in a near-polar circular sun-synchronous orbit with a nominal altitude of either 833 or 870 km. In the operational configuration, two satellites positioned with a nominal orbit-plane separation of 90 degrees will be used.

The instrument payload for TIROS-N consists of:

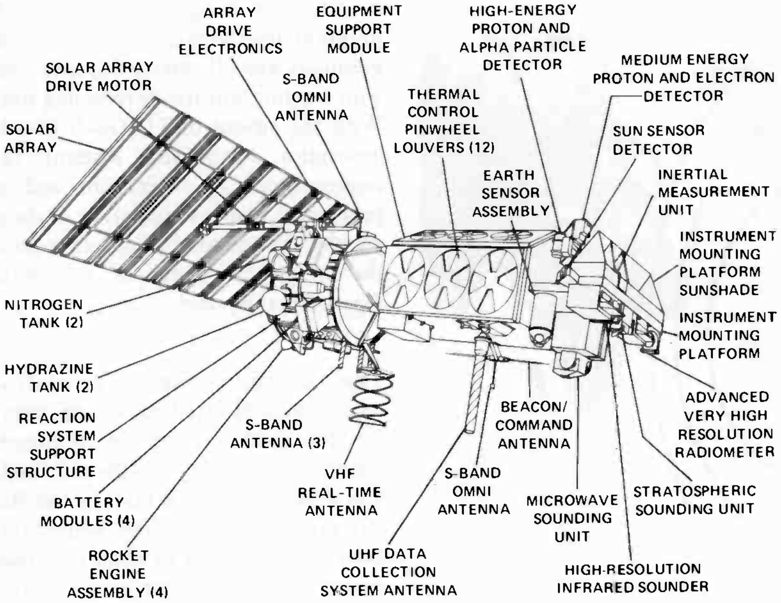


Fig. 6
TIROS-N is the start of the third generation of operational polar-orbiting meteorological satellites. It will be launched in the fall of 1978.

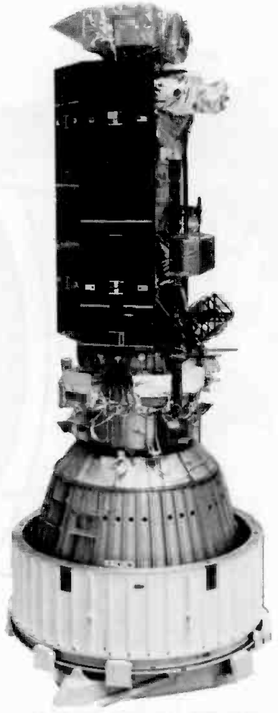


Fig. 7
TIROS-N mounted on its launch-vehicle adapter at RCA Astro-Electronics.

1) The advanced very high resolution radiometer, a four-channel, cross-track scanning instrument providing image and radiometric data in the visible, near-infrared, and far-infrared portions of the spectrum.

2) The TIROS Operational Vertical Sounder, a subsystem consisting of:

- The high-resolution infrared sounder, a 20-channel, step-scanned, visible and infrared spectrometer, used to produce tropospheric temperature and moisture profiles.
- The stratospheric sounding unit, a 3-channel, pulse-modulated, step-scanned, far-infrared spectrometer, used to produce temperature profiles of the stratosphere.
- The microwave sounding unit, a 4-channel, step-scanned spectrometer with response in the 60-GHz O_2 band, used to produce temperature profiles of the atmosphere in the presence of clouds.

3) The data collection system, a random-access system for collecting meteorological data from *in-situ* platforms, both movable and fixed, such as buoys, balloons, and remote weather stations.

4) The space environment monitor, a multidetector unit used to monitor solar particulate energies in the vicinity of the satellite.

In addition to this basic complement, a list of growth sensors anticipated for future requirements was used in developing the requirements for the spacecraft's support subsystem. This resulted in a satellite design with inherent growth capabilities for continued orderly evolution. Thus, NOAA-E, the sixth spacecraft in the TIROS-N series, will be an advanced configuration equipped for search-and-rescue work. It will be used in a joint U.S.-Canadian program to perform an experimental mission that will provide data for identifying and locating downed aircraft and ships in distress.

The SMS/GOES satellites can track destructive storms in real time.

The capabilities of the SMS/GOES system include day-and-night earth imaging, retransmission of imaged data, data collection and relay from terrestrial data collection platforms, and space environmental monitoring. However, the geostationary satellite's most important contribution may be its ability to show, in virtual real time, destructive natural events at several scales of size and motion.

Fig. 8 shows the image coverage area and communications range of two GOES satellites stationed at approximately 75° W longitude and 135° W longitude. From these vantage points, they view all of North and South America and the adjacent ocean areas.

The SMS/GOES spacecraft consists of a visible and infrared spin-scan radiometer for high-resolution visible imagery and lower-resolution infrared imagery, a communications subsystem for data collection and relay, and a space environment monitoring subsystem. The spacecraft is spin-stabilized for proper earth imaging by an attitude-control subsystem that aligns the spacecraft's spin axis parallel to the earth's polar axis and thus perpendicular to the orbital plane. The satellite rotates at 100 revolutions per minute, and the radiometer scanning mirror scans the earth for about one-twentieth of each complete 360-degree rotation. Scanning is from west to east in eight identical visible channels and two redundant infrared channels. While the spacecraft is completing its revolution, the mirror moves to the next southward step and acquires and transmits data again when it is looking at the earth. The radiometer accomplishes the 1821 scan steps required to provide a high-resolution image of nearly one quarter of the earth's surface within 18.2 minutes. The resulting visible images contain 14,568 lines and

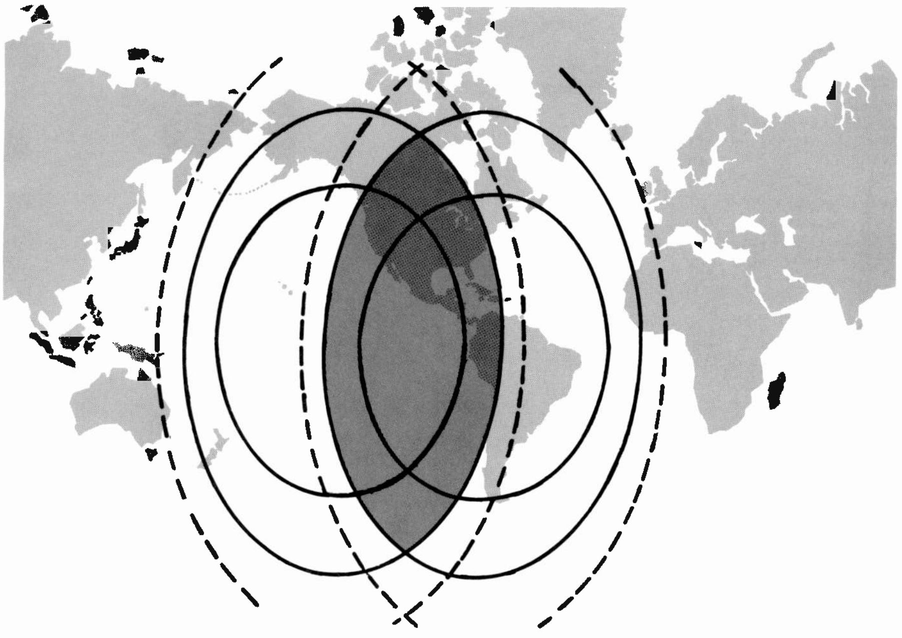


Fig. 8
Image coverage for two geostationary GOES satellites (outer solid oval). Inner solid oval is useful area for wind measurements, and dashed line shows communication range for 3½° elevation angle.

have a resolution of nearly 0.8 km. The infrared images have a total of 1821 lines with a 6.4-km resolution.

The GOES data-collection system collects and distributes environmental data acquired by remotely located, attended and unattended data collection platforms located on land, at sea, or in the atmosphere. The data-collection platforms are environmental sensing devices with radio transmission and reception capabilities for relaying data as required. These platforms include instrumented buoys, river gauges, automatic weather stations, seismic and tsunami stations, and manned ships. Some examples of their uses are: 1) fixed stations in remote land areas send information on earthquakes, wind direction and velocity, humidity, and amount of rainfall; 2) river platforms measure currents, water levels, and temperatures; 3) marine platforms (either fixed or floating) measure tides, water and air temperatures, and provide tsunami warnings.

Many photographic and computer-generated products are derived from SMS/GOES images. One that is unique to geostationary satellite data comes from the ability to generate time-lapse movies from a series of registered GOES images (visible or infrared) of the full earth disc. By using both manual and computer techniques, selected cloud tracers are tracked in successive GOES images to determine wind speeds and directions.

Three additional GOES satellites of more advanced design are planned. These satellites, GOES-D, E, and F, will use a visible-infrared spin-scan radiometer atmospheric sounder to obtain simultaneous imaging in the visible and infrared portions of the spectrum, with a resolution of 0.9 km in the visible band and a resolution of 6.9 km in the infrared. Additionally, it will obtain radiometric data in the earth's atmosphere water vapor and CO_2 absorption band and will thus make it possible to determine the three-dimensional structure of the atmosphere with respect to temperature and humidity.

Future expectations

The TIROS-ESSA-ITOS-NOAA polar-orbiting meteorological satellites have been the mainstay of the U.S. meteorological satellite programs; the forthcoming TIROS-N satellite series will assume this mission. The TIROS-ESSA-ITOS-NOAA family of satellites has fulfilled U.S.A. operational requirements by providing a reliable in-orbit system that transmits routine observations on a timely basis without interruptions in service. Its evolutionary design has helped achieve program objectives cost-effectively and has gradually and effectively improved service with existing worldwide receiving stations. With the advent of TIROS-N (the third-generation operational system), further improvements in observation and in the processing and dissemination of data will provide the polar-orbiting data required by the long-term goals of the National Operational System.

The complementary geostationary environmental satellites will be improved by the addition of an atmospheric-sounding capability on the GOES-D, E, and F satellites (to be built by the Hughes Aircraft Company). The soundings obtained will be used to identify conditions under which short-term severe storms are generated. Real-time temperature and thermal gradient data is expected to contribute significantly to the understanding of these meso-scale phenomena and, in time, improve the meteorologist's ability to forecast the areas where severe thunderstorms and tornadoes are likely to occur.

As part of the international cooperation and participation within the World Meteorological Organization, Japan, the European Space Agency (ESA), and the U.S.S.R. planned to launch their own geostationary environmental satellites within this decade. Japan's satellite (Himwari-1) was launched on July 14, 1977, and positioned over the western Pacific Ocean. The ESA's satellite (METEOSAT) was launched on November 23, 1977, and positioned over the eastern Atlantic Ocean. Both were launched by NASA Delta launch vehicles from Cape Canaveral, Florida. The U.S.S.R. deferred the launch of its satellite; therefore, the U.S. (NOAA) filled the gap by launching GOES-3 in June 1978 and moving GOES-1 to a position over the Indian Ocean, where India operates it with a U.S.-loaned ground station.

These geostationary satellites will be complemented by the polar-orbiting TIROS-N satellite series, which will provide the global data, particularly filling in the data for the far polar regions.

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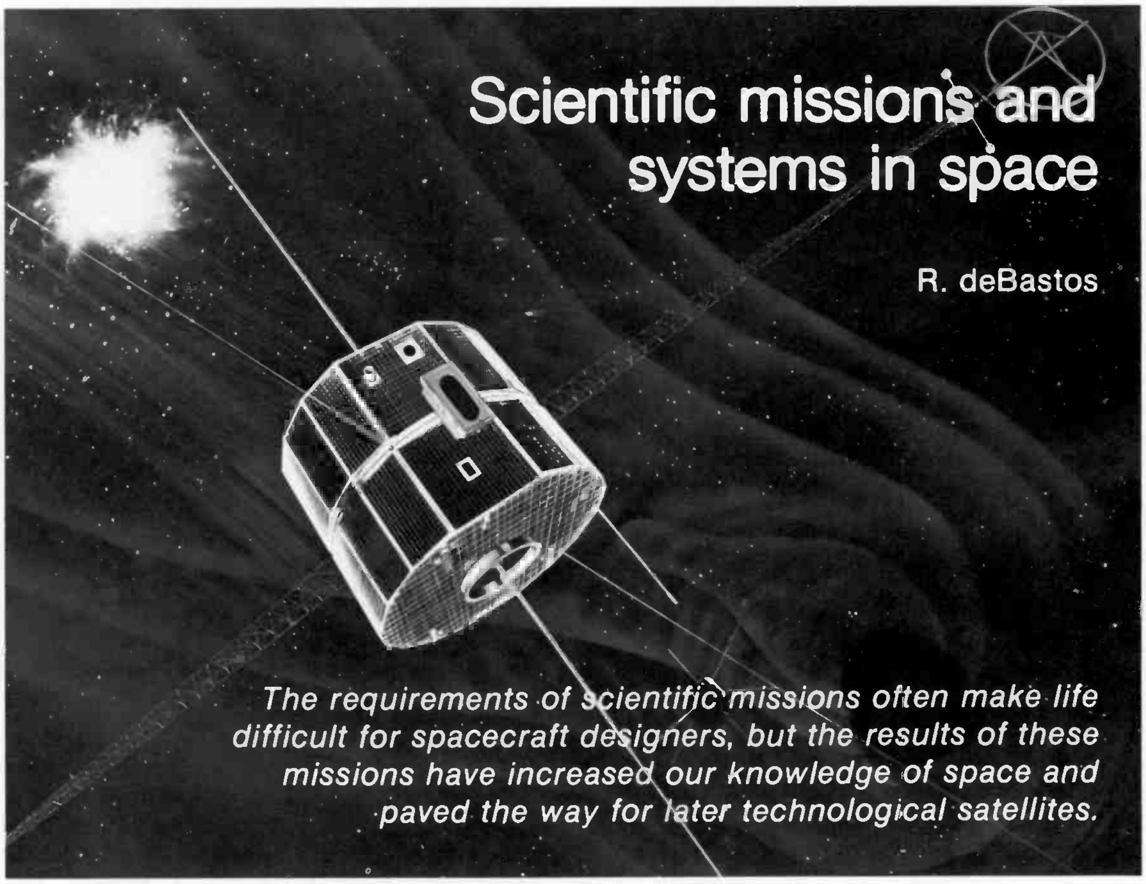
Scientific missions and systems in space

R. deBastos



The requirements of scientific missions often make life difficult for spacecraft designers, but the results of these missions have increased our knowledge of space and paved the way for later technological satellites.

In an 1870 adventure story, Edward Hale described a huge water wheel that could be used to fling a communications and navigational satellite into earth orbit. Later, Jules Verne wrote of a giant cannon that could shoot an object into terrestrial orbit. On October 4, 1957, Russia astounded the world's scientific and technical community by placing Sputnik I, man's first artificial satellite, into orbit. Weighing 184 lb and transmitting scientific data via telemetry for 23 days, the feat demonstrated the practicality of artificial earth satellites.

As it is sometimes hard to separate the "science" from "science fiction" and determine which ideas belong to which category, it is also hard to separate scientific accomplishments from the high-technology accomplishments of engineering. As science attempts to discover and explain the physical processes of the universe, in many cases, the engineering technology required to make the scientific measurements and demonstrate the scientific principles is indistinguishable from the basic science itself. Just as the scientific theories, models, and predictions defined the engineering requirements and efforts necessary to develop the first man-made satellite 21 years ago, science and engineering are inseparable in the most advanced science missions of today.

Early scientific objectives

The scientific objectives of early satellites were constrained in part by the limited abilities of the spacecraft support systems.

Early launch-vehicle performance severely limited the spacecraft weight. The United States' first attempt to launch a satellite, if successful, would have orbited a 3¼-lb satellite whose primary scientific objective was to demonstrate that a man-made satellite was possible. The onboard instrumentation consisted of two small transmitters used to send measurements of the spacecraft temperature.

Even a device this simple can provide basic scientific information by allowing scientists to study its orbital behavior. Such data can be used to model atmospheric-density profiles, and to predict and refine the models of the earth's gravitational field.

Early scientific satellites made measurements that eventually led to an understanding of space, which led to models that could be used as routine engineering tools.

The first successful American satellite, Explorer 1, was launched February 1, 1958. It weighed 31 lb, and carried a more capable payload than the Vangard series of spacecraft. Its scientific objectives included the measurement of cosmic radiation, micrometeorite impacts, and spacecraft temperatures. Curiously, ear-

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ly spacecraft measurements of temperature provided a fundamental parameter for scientific analysis of incident solar flux, spacecraft surface properties, and earth albedo, whereas the current generation of spacecraft primarily uses spacecraft temperature measurements as health or diagnostic checks. Similarly, the study of spacecraft orbit perturbations to deduce or refine earth gravitational models is no longer of prime scientific interest; orbital predictions are accurately made using computerized predictive capabilities developed over the years of spaceflight. These are two simple examples of the developmental pattern of space science. Early speculation is followed by theorizing of physical principles. Further study leads to predictive modeling based on theory. Experimental results then lead to verification and adjustment of the predictive models. Finally, after many measurements, a quantitative data base establishes confidence in the understanding of the phenomena, and a new routine engineering tool is established.

Early RCA science participation

Early scientific satellites determined the feasibility of later technological satellites.

RCA entered the space age at a time when many of the spaceflight engineering tools were being established from results of scientific missions. In 1958, hardware was developed for Project Score, an early experiment in spacecraft communications. Many of us will recall the unforgettable experience of hearing the voice of President Eisenhower beaming a holiday message from space. Just a scant 10 years later, astronaut Frank Borman beamed a live holiday message from space, from the Apollo 8 spacecraft in orbit about the moon.

RCA also provided a beacon transmitter for Project Echo in August, 1960. Echo was a balloon, 100 feet in diameter, whose scientific purpose was to determine the feasibility of using a satellite as a passive communications reflector. The successful tests using passive satellites as a means of providing long-range radio and television transmission led to the investigation of multiple active repeater satellites in low earth orbit. The RCA Relay satellite was successfully launched in December 1962, one of the first successful low-orbit communications repeater satellites. Although the prime objective of the program was to demonstrate the practicality of intercontinental satellite-borne communications, in keeping with the demand for basic science knowledge, instrumentation was carried on the satellite to measure cosmic radiation and space degradation and damage to solar cells and diodes.

Many early spacecraft were designed to develop engineering technology in support of a basic mission. Some of these engineering and operational satellites were configured to carry simple scientific instrumentation packages in addition to the basic payload. The opportunity for spaceflight, and the attendant acquisition of scientific data from a space observational platform, led many universities and research laboratories to propose and develop unique instrumentation integrated on a host spacecraft, or, in some cases, ejected as a complete spacecraft package after hitchhiking a ride into orbit. The scientific instrumentation in this category generally consisted of simple sensor and electronics packages, with support systems (power, telemetry, commands) provided by the host system.

The first TIROS meteorological satellites were built by RCA in 1960. TIROS was designed to transmit television pictures of the earth's cloud cover from a 400-mile altitude. In addition to the television system, radiometers were carried to measure the earth's radiation in 5 spectral bands, and to study the earth's overall heat budget. From the developments which had their start with these simple scientific measurements of the earth's radiation, the meteorological satellites of today routinely obtain cloud patterns on a global scale, daily, day or night, using complex multi-spectral-region high-resolution IR scanning sensors. Again we have a fundamental RCA role in all aspects of the scientific process, from theory, to feasibility, to data collection, and finally, to routine engineering practice.

Atmosphere Explorer—RCA's first all-science spacecraft

Throughout the rapid development of space science in the sixties, the RCA participation focused on developing the engineering technologies necessary to provide reliable, high-performance spacecraft and spacecraft subsystems necessary to perform the basic space missions. Late in the sixties, in cooperation with NASA-Goddard Space Flight Center, RCA began studies of an all-scientific satellite designed to probe the lower atmosphere. The scientific need for an aeronomy satellite, designed to make direct, *in-situ* measurements of atmospheric temperatures, densities, winds, and populations of neutral and ionized particles in all regions of the lower thermosphere, led to the development of the Atmosphere Explorer C, D, and E spacecraft series, shown in Fig. 1.

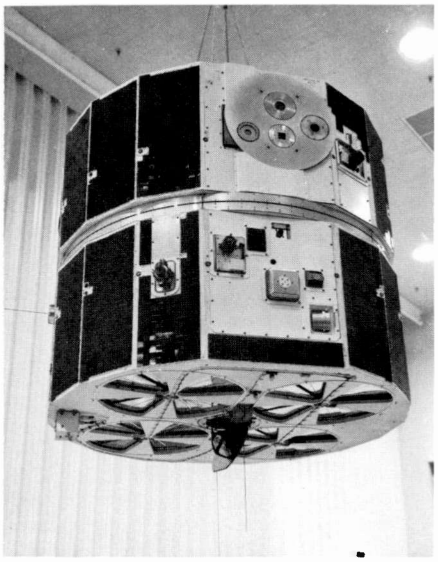


Fig. 1
The Atmosphere Explorers were RCA's first all-science spacecraft. These satellites used varying orbits to obtain data on conditions in the upper atmosphere.

Before the Atmosphere Explorer aeronomy mission, little was known about the causes and effects of upper-atmosphere phenomena.

The variations in atmospheric pressure, density, temperature, and compositional characteristics are reasonably well known at low altitudes, and the variation of these parameters with respect to time is relatively minor below an altitude of 100 km. Above 100 km, though, variations in the ultraviolet radiation received from the sun, differences in the solar wind, and electromagnetic couplings within the ionosphere cause large variations in the atmospheric particle constituents and population. Atmospheric density at sea level may vary because of the slowly changing extremes of weather conditions, but in the upper atmosphere, a density variation of a factor of 4 or more may exist between the daylight side and night side of the earth. Atmospheric temperature may vary, in the extremes, by 100° K from sea level to 100 km altitude. Above 100 km, solar-flare activity and day-night variations can cause upper-atmospheric temperatures to change by 1000°K or more. The close relationship between upper-atmospheric conditions and solar activity led to the scientific objective of explaining and quantizing the relationships between these observable phenomena.

The upper-atmospheric regions of the earth can be explored by aircraft to an altitude of 20 km or so, and by ballons to about 35 km. Sounding rockets can take simple payloads to 250 km, but the useful measurement period lasts only for a few minutes. The maximum solar absorption and most of the energy-transfer processes occur in the 100- to 250-km region of the atmosphere. A spacecraft was needed to take measurements at these altitudes. It had to be capable of operating in this altitude range, be designed to measure energy inputs from the sun, and at the same time, determine the atmospheric constituents in the vicinity of the spacecraft. Thus, the resulting Atmosphere Explorer spacecraft was configured as a low-altitude orbit "cause and effect" aeronomy laboratory in space.

A spacecraft capable of making systematic measurements in the upper atmosphere requires many unique characteristics.

The most demanding requirement on the spacecraft design is the ability to operate controllably and repeatedly in low-altitude, high-atmospheric-density conditions. Although at altitudes of 120-150 km the atmospheric density is only one hundred millionth of the density at sea level, a satellite collides with the relatively few air molecules there at 19,000 mi/hr; the resulting disturbance has a dramatic effect on the spacecraft. The large atmospheric disturbances at low altitudes require several major spacecraft design features: the attitude-control system must be able to tolerate high disturbances; there must be a means to restore lost altitude and forestall re-entry into the atmosphere; and the profile, or projected area, of the spacecraft must be small, to reduce the effect of the drag forces.

Operating a spacecraft in the low-altitude, high-atmospheric-density region creates unique technical spacecraft design considerations. Since the objective is not to provide just an operating spacecraft design, but to provide a useful orbiting aeronomy laboratory, the requirements for an *in-situ* scientific measurement capability are factored in as well, along with the additional orbital operating requirements and mission time lines required to perform the mission science.

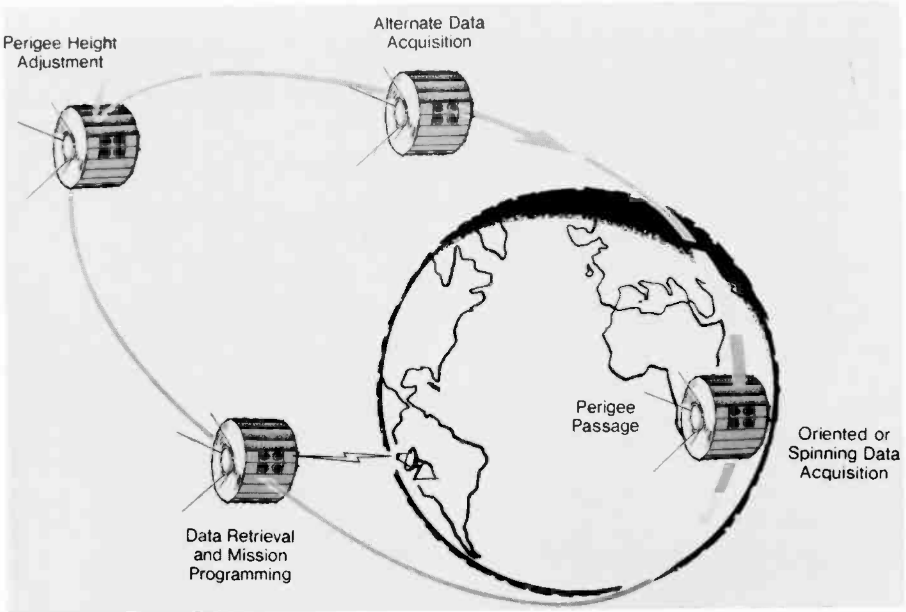


Fig. 2
Mission profile of the Atmosphere Explorer required continued passage through the earth's upper atmosphere. Because atmospheric drag would otherwise produce a loss in altitude, the satellite's on-board propulsion system was needed to boost the altitude.

The scientific objectives require a flexible spacecraft design, capable of supporting a data-gathering mission on a global scale. As the scientific mission requirements are studied in depth, spacecraft technological requirements begin to unfold. Many of the design requirements dictated by operational constraints and scientific objectives are conflicting, and careful consideration of compromise solutions, closely negotiated with the science community, is necessary to achieve a successful solution.

The spacecraft had three different types of orbits during its time in space.

The aeronomy mission planned for the three Atmosphere Explorer spacecraft required operations in orbits at mid inclinations (68.4°), near-polar inclinations (104°), and near-equatorial inclinations (22.5°). These orbits were chosen to provide data on the atmospheric characteristics and variations caused by diurnal effects (day/night changes), longitudinal and latitudinal variations, and seasonal changes. Each spacecraft orbit mission consisted of three phases. In the first phase, the perigee (orbital low point) of the spacecraft was established at a nominal 150-km altitude. During this phase, the apogee (orbital high point) was maintained at 4000 km. Because the spacecraft would otherwise lose altitude because of atmospheric drag in the low portion of its orbit, altitude restoration was necessary. It was provided by using an on-board propulsion system (Fig. 2), the first application of this technology at RCA-AE. Periodically, during the elliptical phase of the mission, the perigee was temporarily lowered for a series of orbits to obtain data at lower atmospheric regions. The spacecraft's survivability limit was a perigee of 120 km; the atmospheric drag and aerodynamic heating effects below 115 km would have destroyed the solar array, tumbled the spacecraft, and produced rapid re-entry into the atmosphere.

In the second or transition phase of the mission, the apogee was allowed to slowly decay over a period of 6 months to approximately 300 km. During this phase, data was collected over a wide range of atmospheric conditions and solar cycles. In the last phase of the mission, the circular phase, the spacecraft's on-board propulsion was used to produce and maintain a circular orbit at 300 km. Atmospheric Explorer-C and -E are currently operating in this mission phase, well beyond the planned mission life of one year.

The scientific payload determined many design parameters.

The scientific payload, listed in Table I, comprised three basic instrument types:

Table I

Scientific payload of Atmosphere Explorer consisted of three types of instrumentation—charged-particle instruments, neutral-particle instruments, and optical devices. Scientists responsible for these instruments and experiments came from a wide range of universities, government laboratories, and industry.

Instrument	*Parameters*
Solar EUV spectrometer	140Å to 1850Å
Solar EUV filter photometer	40Å to 1300Å
UV nitric oxide	2150Å, 2190Å
Airflow photometer	6300, 5577, 4278, 3371, 5200, 7319 to 7330Å
Open-source neutral mass spectrometer	1 to 46 AMU
Closed-source neutral mass spectrometer	1 to 46 AMU
Neutral atm. temp. exp.	T_g, N_2
Atm. density accel.	Neutral density
Planar ion trap	T_i, N_i, M_i, drift velocity
Cylindrical electrostatic probe	T_e, N_e, N_i, M_i
Magnetic-ion mass spectrometer	1 to 64 AMU
Positive-ion mass spectrometer	0.5 to 72 AMU
Low-energy electron exp.	0.2 to 25 keV
Photoelectron spect.	Photo electron spect.
Three-axis fluxgate magnetometer	Magnet variations
Capacitance manometer	Pressure
Cold-cathode ion-gauge range	Pressure
Temperature alarm	Aerodynamic heating

T_e = electron temperature
T_i = ion temperature
T_g = gas temperature

N_e = electron density
N_i = ion density
M_i = ion mass

charged-particle instruments for the measurement of ion concentrations and temperatures, electron temperatures and particle fluxes; neutral-particle instruments configured to measure neutral-particle composition, temperature, and total atmospheric density; and optical devices to measure solar energy, airglow intensity, and nitric-oxide profiles. This instrument complement required orientation knowledge and control with respect to the earth, the sun, and the orbital velocity vector. In addition, the desired operating modes required periods when instrument sensor axes were fixed relative to the orbital velocity vector, and other periods when the instrument sensor axes were slowly scanned through the spacecraft "ram" and "wake" directions.

To satisfy the scientific objective of measuring the incoming solar flux and determining if it causes atmospheric variations, a solar spectrophotometer was used. This instrument is capable of measuring solar flux in the ultraviolet spectrum from 140 to 1850 Å, in discrete spectral intervals. The solar ultraviolet flux is measured from various orbital locations. Measurements are made during periods when the instrument can view the sun directly, without atmospheric attenuation, from the perigee region in combination with the other instruments, and during periods coinciding with maximum atmospheric attenuation or optical path length. Since the sun can be at any elevation or azimuth angle relative to the spacecraft throughout the orbital mission, a two-axis gimballed platform was designed to acquire and orient the instrument toward the sun, independent of spacecraft attitude, orientation, spin rate, or nutational motion.

The instruments flown on the Atmosphere Explorer spacecraft were designed and developed by universities and research laboratories throughout the country. The efforts and capabilities of the participating scientists were combined into an "aeronomy team," which configured an instrument payload, individually contributed specific instruments, and managed and directed the science mission operations throughout the spacecraft life.

To complement this joint team effort, NASA developed a computerized data collection, processing, and distribution system. All of the data collected by the spacecraft was sorted, processed, and reduced with a central computer facility located at NASA's Goddard Space Flight Center in Greenbelt, Maryland. Each principal investigator was able to access reduced scientific data collected by any or all of the instruments via a computer terminal located at his facility, usually within 24 to 48 hours of the time the raw data was measured on board the orbiting satellite. By sharing this data, each scientist was able to maximize the correlative and collective scientific returns from the system. This "near-real-time" availability of reduced data was a "first" in the annals of scientific-mission spacecraft.

The Atmosphere Explorer spacecraft, (Fig. 1), was shaped as a sixteen-sided polyhedron, 53.5 inches in diameter and 45 inches high. The weight at launch was approximately 1500 lb. The satellite's surface was used to mount the solar cells necessary to produce the system power. An S-band antenna mounted at the girth of the spacecraft formed a continuously radiating slotted surface on the periphery of the spacecraft. The antenna configuration allowed data transmission at any spacecraft orientation or spin rate. The instrument complement required viewing access to the external environment for particle sampling or optical measurements, so apertures were provided in the solar array for this purpose. The predominant instrument cluster was located on the surface of the spacecraft that would be normal to the orbital velocity vector at perigee.

The internal configuration, shown in Fig. 3, was densely packaged to minimize the spacecraft's external frontal area. The instruments and spacecraft components were mounted on two equipment platforms, or baseplates, as shown in Fig. 4 and 5. The tanks of the propulsion system, Fig. 6, were sandwiched between the equipment baseplates at the center of mass of the spacecraft assembly, reducing the unbalance effects caused by fuel use. A large flywheel, spinning at 360 r/min, provided the momentum storage used for stabilization and control.

Data collected from the instruments and spacecraft housekeeping telemetry cannot be sent to the ground in real time because of the lack of communication with the spacecraft during perigee passages. Likewise, commands cannot be transmitted to the spacecraft during all points in the orbit. To allow for remote operations, data storage aboard the spacecraft was provided in two forms, stored command sequences for spacecraft control in remote operation, stored in a magnetic core memory, and instrument and spacecraft telemetry data, stored in on-board tape recorders.

An S-band link with the spacecraft was used for communicating for commands and playback of data. A vhf link was provided for backup for real-time telemetry data and beacon tracking. All communications links were operable with the spacecraft despun (oriented with respect to the velocity vector) or spinning at rates from 0.5 to 10 r/min. A range and range-rate transponder was used to aid in orbit and position determination.

The near-equatorial inclination and high-apogee altitudes of the AE-E mission meant that the spacecraft circuit components had to be protected from the damaging environment of the Van Allen radiation belts. All sensitive circuit elements were radiation-hardened and shielded to preclude damage or degradation beyond acceptable limits.

The program has been highly successful and the satellites continue to supply data from orbit.

The three spacecraft of the Atmosphere Explorer series (AE-C, D, and E) were launched in December 1973, October 1975, and November 1975. Originally designed to operate for a one-year mission, AE-C, now designated Explorer 51, and AE-E, now designated Explorer 55, continue to operate daily to support an expanded scientific mission. The results of the mission have been gratifying—as of July 1977, over 130 technical papers had been published, and 228 talks had been given at meetings and symposia in 11 countries. The scientific return from the Atmosphere Explorer program has been outstanding, and the RCA-designed and-built spacecraft has had a remarkable performance record.

Figs. 3-6 (top to bottom)

Scientific instruments for sampling charged and neutral particles can be seen clustered on the "ram"-facing portion of the spacecraft. Instruments visible include the open-source and closed-source neutral mass spectrometers, the planar ion trap, the positive-ion and magnetic-ion mass spectrometers, the photo-electron spectrometer, the temperature alarm, the capacitive manometers, and the pressure sensor.

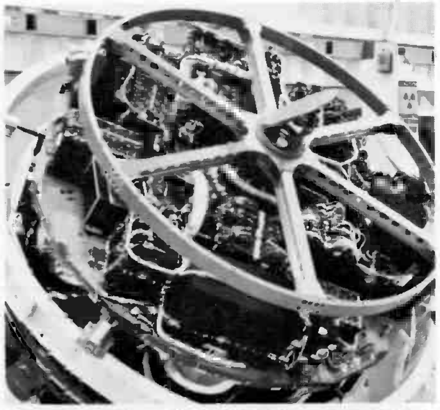


Fig. 3

The Atmosphere Explorer's low-altitude mission required dense instrument packaging so the frontal area, and thus atmospheric drag, would be as low as possible.

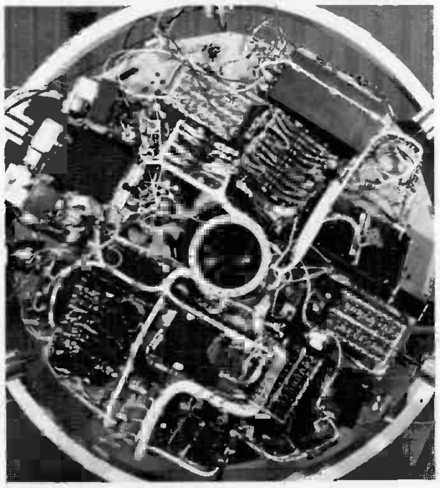


Fig. 4

Instrumentation mounted on the Atmosphere Explorer upper baseplate.

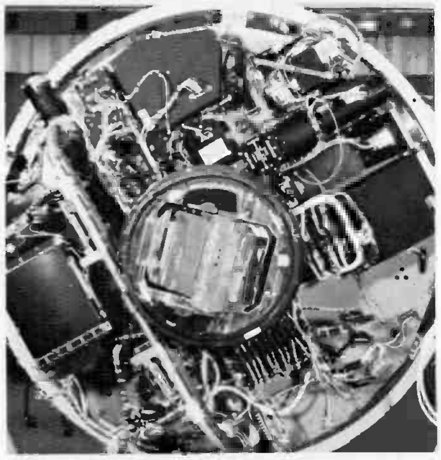


Fig. 5

Instrumentation mounted on the Atmosphere Explorer lower baseplate.

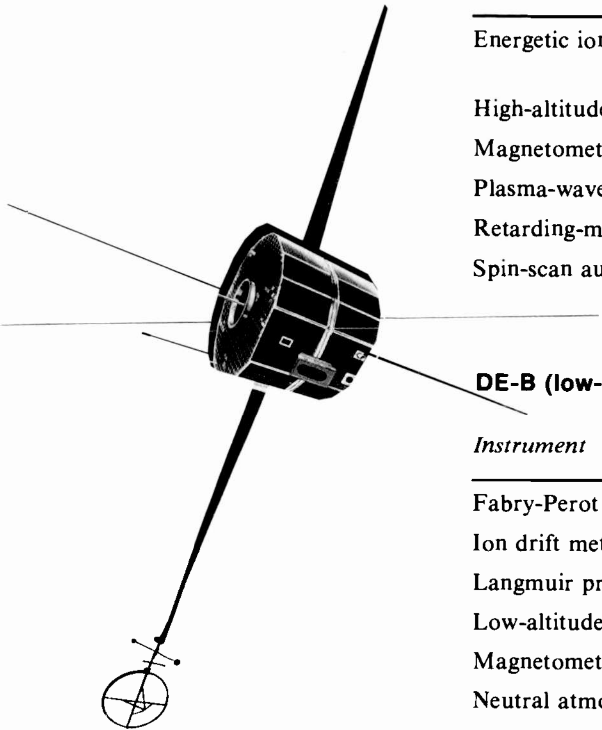
Fig. 6

Propulsion system for the Atmosphere Explorer was needed to adjust the orbit of the satellite.

Dynamics Explorer—the next step

Prior to the completion of the Atmosphere Explorer spacecraft series, a group of scientists began to consider studying atmospheric reactions of a different type. The earth's upper atmosphere and magnetosphere form a blanket or boundary region between our planet and the hostility of outer space. The study of the processes that transpire in this protective blanket have been the object of scientific curiosity through the ages. The processes that take place in the lower boundary of this protective blanket are familiar to mankind in the form of weather and climatic changes. Processes in the upper atmosphere, however, are known directly to mankind only in the form of visible auroral events and radio disturbances, and are controlled by earth's magnetic field and the extremes in solar activity, manifested in the form of sunspots. Although both of these control mechanisms can be observed and recorded, their interactions and effects on the upper atmosphere can only be determined by scientific study and measurement.

Table II
Dynamics Explorer mission will divide its scientific payload between two coplanar-orbiting satellites. Dynamics Explorer A will have an orbit ranging from 275 to 30,000 km, and Dynamics Explorer B will have an orbit of 275 to 1100 km. The two satellites will thus be able to measure magnetic-field and plasma properties simultaneously at two altitudes on a common magnetic-field line of flux.



DE-A (high-altitude satellite)

Instrument	*Measurement*
Energetic ion composition	Ion energy 0 - 17 eV Ion mass 1 - 138 AMU
High-altitude plasma	Positive ions and electrons 5 eV - 25 keV
Magnetometer	3-axis magnetic fields in auroral oval
Plasma-wave instrument	ELF, VLF, HF spatial and temporal measurements
Retarding-mass ion spectrometer	Density of ions ionosphere, plasmasphere
Spin-scan auroral imager	Aurora measurements at visible and UV wavelengths

DE-B (low-altitude satellite)

Instrument	*Measurement*
Fabry-Perot Interferometer	Neutral and ionic atomic oxygen
Ion drift meter	Bulk motion of ionospheric plasma
Langmuir probe	Electron temperature and ion concentration
Low-altitude plasma	Positive ions and electrons 5 eV to 25 keV
Magnetometer	3-axis magnetic field in auroral oval
Neutral atmosphere composition	Composition of neutral atmosphere
Retarding potential analyzer	Ion temperature, composition, concentration, bulk velocity
Wind and temperature spectrometer	Neutral wind and neutral particle temperature
Vector electric fields	3-axis measurement of dc electric field

This mission will study how the earth's ionosphere and magnetosphere interact with each other.

The earth's ionosphere, consisting of ionized gases created primarily by solar ultraviolet radiation, forms the layered concentrations of charged particles that allows radio signals to be "bounced" beyond the line of sight. The composition and strength of the layers of the ionosphere is directly related to solar activity. This interaction was studied by the Atmosphere Explorer program. The sun is also the source of the solar wind, a continuous rapidly flowing stream of magnetized plasma. The solar wind interacts with the earth's magnetic field, forming a magnetospheric sheath around the earth. The interaction between the solar wind and the magnetosphere is also a cause-and-effect relationship now being studied by the International Sun Earth Explorer program. A third element of scientific interest in this atmospheric-process investigation is the interaction between the charged particles of the upper atmosphere and ionosphere, which rotates with the earth, and the charged plasma of the magnetosphere, which is fixed with respect to the sun. Both the ionosphere and magnetosphere are directly affected by the two forms of energy that emanate from the sun, electromagnetic energy and the plasma flow of the solar wind. The interactions between the ionospheric and magnetospheric regions create large current systems, release large quantities of energy, and create mass flows. The results of these interactions create intense local heating, neutral winds, atmospheric composition changes, and a variety of other effects.

To study these interactions, a Dynamics Explorer mission was evolved to obtain detailed correlative measurements in the proper regions of space to determine the various coupling processes. RCA has a contract to develop and produce two satellites to perform the Dynamics Explorer mission, to be launched in early 1981. Results of the study are expected to add to our store of knowledge on the atmospheric environment and help extrapolate data to other planetary atmospheres within the solar system.

The mission requires two spacecraft to make simultaneous measurements at vastly different altitudes.

To accomplish the scientific objective, an instrumented spacecraft must be capable of measuring not only atmospheric constituents such as charged particles and neutral particles, but it must also be able to determine electric fields, magnetic fields, plasmas, and characteristic emissions. Of prime importance is the ability to measure magnetic field and plasma parameters simultaneously at two altitudes on a common magnetic-field line of flux. To meet this requirement, the Dynamics Explorer mission uses two spacecraft flying in coplanar polar orbits at two vastly different altitudes.

The high orbiter, designated DE-A, will have a perigee of 275 km and an apogee of 30,000 km. It is designed to make measurements in the hot magnetospheric plasma region down to the cooler ionospheric region. The orbital path will coincide with a geomagnetic flux line for a significant period of time, providing temporal measurements of the earth's magnetic field along a line of flux.

The orbital altitude and instrumentation complement will provide an optical global auroral image for detailed macroscopic auroral studies. The low orbiter spacecraft, designated DE-B, will have a perigee of 275 km and an apogee of 1100 km. It will obtain scientific data in the cooler ionospheric region and upper atmosphere, measuring neutral winds, suprathermal ions, and plasma flow.

To measure the scientific parameters in two disciplines of aeronomy, particles and fields, two types of instruments must be accommodated on the same spacecraft. The Dynamics Explorer instruments are listed in Table II. Preliminary engineering feasibility studies established that an Atmosphere Explorer spacecraft design approach was the ideal system configuration to perform the complex mission. An artist's concept of the spacecraft is shown alongside Table II. The prime consideration for the low-orbiting spacecraft, DE-B, is that it must accommodate and orient a group of particle sampling instruments, oriented along the velocity vector, or slowly scanning the surrounds. The Atmosphere Explorer attitude control system is ideally suited to this application.

A large momentum wheel is used to store the required momentum, and by varying the wheel speed, body rates can be adjusted to provide a "slow-scan" mode. The attitude-control system also has the inherent ability to "lock on" any of 360 desired azimuth pointing locations, for specific instrument operation modes.

The technology used for the Atmosphere Explorer must be extended for the Dynamics Explorer.

As a scientific requirement, the magnetic- and electric-field instruments require long booms and antennas to physically separate their sensors from the spacecraft. Two appendage types are employed, a rigid structure and furled tubular elements. Both types fold into the spacecraft during launch and are deployed on command after orbit is achieved. For the DE-B spacecraft, the rigid boom places a sensitive magnetometer 6 meters away from the body of the spacecraft, minimizing magnetic disturbances from the spacecraft electronics that would contaminate the scientific data. Six 1-1/8-inch-diameter furled tubes, each 11 meters long, are used to obtain 3 orthogonal-axis measurements of electric fields.

To make sure that these additional flexible appendages do not dynamically couple with the active attitude-control system and produce an unstable design, the technology used with the Atmospheric Explorer series must be extended. Another extension of Atmosphere Explorer technology appears in the communication system. The spacecraft data retrieval is required to go through NASA's Tracking Data Relay Satellite System (TDRSS), the expected replacement of the STADAN network in the 1980s. To be compatible with this system, the spacecraft must orient a high-gain antenna toward the orbiting TDRSS relay satellite. The ability of the attitude-control system to point the spacecraft body along any desired azimuth orientation is used to advantage, as a body-mounted, fan-beam, high-gain antenna can be employed, eliminating the requirement and cost of a two-axis steerable antenna.

The DE-A spacecraft, orbiting through the boundaries of the magnetosphere, requires a much longer antenna sensor to determine plasma wave characteristics. The antenna sensors for this experiment use 0.020-inch-diameter wires, each 100 meters long, extending from the spacecraft body. To keep the wires extended out from the spacecraft, the spacecraft is spin-stabilized at 10 r/min. Two rigid booms of the type used on DE-B provide sensor locations remote from spacecraft-produced electromagnetic disturbances. Rotating this complex and high-inertia assembly at 10 r/min results in a large system momentum, and so precludes reorienting the spacecraft to track a favorable solar aspect angle for solar-array and thermal-design considerations. Again, Atmosphere Explorer technology was expanded to design a completely solar-symmetrical spacecraft, allowing the spacecraft power supply and thermal design to operate at any solar aspect angle.

Extending the Atmosphere Explorer technology to the Dynamics Explorer mission, while at the same time maintaining the cost constraints of the program, requires a close accommodation analysis and tradeoff study. Engineers and scientific investigators must maintain a strong cooperative interface relationship so that compromise solutions can be made when conflicting requirements exist. The key to the ability to extend the Atmosphere Explorer technology to successive mission applications is the flexibility of the basic design of the spacecraft. A second fundamental requirement for successfully reusing previous developments in future applications is the understanding of the basic science and the implications to the spacecraft ability to accommodate, or stretch to accommodate, the scientific requirements.

Future scientific missions

The scientific instrumentation flown to date in rockets and satellites have had one significant feature in common—they were designed to collect the desired scientific data remotely and without guidance or interaction from an operator or the interested scientist. In many instances, perhaps inability to control the spacecraft in real time is a system simplification, rather than a complexity. However, the need to program and compute mission operating sequences days in advance of execution does limit the ability to investigate specific spontaneous short-lived phenomena such as magnetic storms and auroral events.

With the space shuttle, scientists will be able to work directly alongside their experiments in space.

The space shuttle is the space transportation system of the 1980s. The shuttle will be used in two basic operating modes—as a launch vehicle for free-flying payloads and as an orbiting space lab. This second configuration will have the necessary basic instrumentation and sensors to conduct a wide range of scientific missions. Instrumented payloads are being designed to conduct basic scientific investigations in fields of solar, stellar, and atmospheric sciences, along with earth resources. In

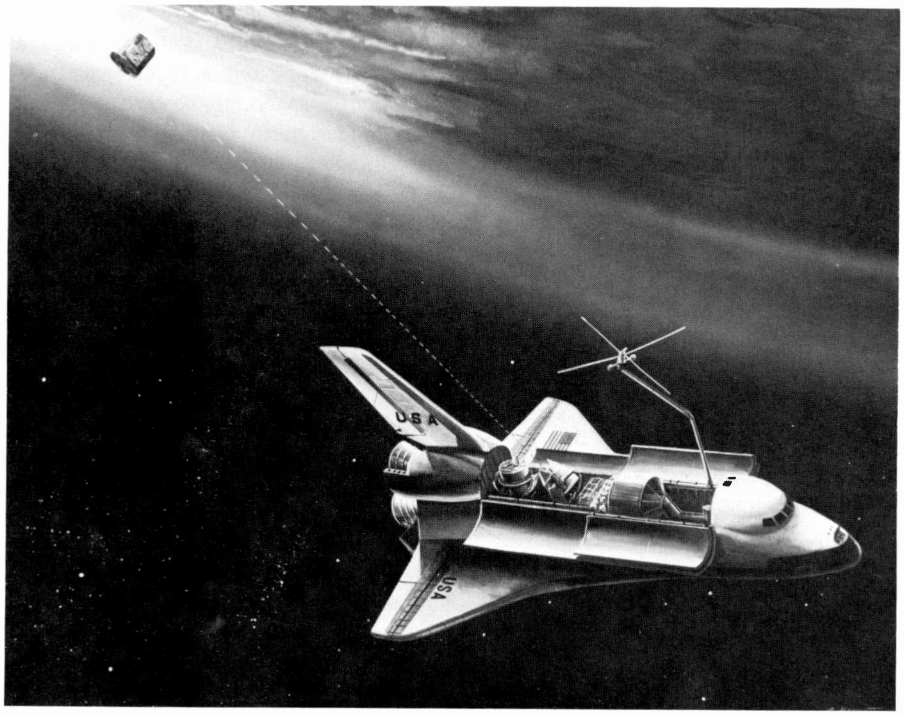


Fig. 7
Subsatellites will support scientific missions in the era of the space shuttle, measuring at a distance interactions that take place at the shuttle laboratory. After completion of the mission, the subsatellite would be retrieved and brought back to earth for refurbishment.

addition to the magnitude and complexity of the instruments which can be accommodated on the shuttle, the most exciting innovation of spacelab payloads is the ability to support a man in the loop. Spacelab payloads can carry a manned laboratory, with scientists working in a shirt-sleeve environment, in direct support of their scienctific endeavor. After a mission of 7 to 30 days, the shuttle returns to earth with its crew and cargo, and is refurbished for another flight.

Subsatellites will be able to support scientific experiments taking place on the shuttle.

The possibilities for scientific studies are enormous. RCA has an active role in helping to define a support subsatellite to be carried by the shuttle. (Fig. 7 is an artist's concept of the spacecraft.) The subsatellite will be released by the shuttle and used in direct support of a scientific mission. Upon completion of the mission, the subsatellite will return to the shuttle, be retrieved, stowed, and brought back to earth for refurbishment and a future mission. Using a subsatellite in support of a shuttle spacelab payload extends the capability of the science payload. The main shuttle payload can be used to inject particle beams, or to release chemical materials, and a suitable instrumented subsatellite can measure the resulting interactions at their place of occurence. The subsatellite position can be moved to observe spatial or time variation of the interaction characteristics. Another use of a subsatellite would be to actively probe the plasma "wake" of the large shuttle body, to study the interaction of the ionosphere with bodies of varying size, shape, or electromagnetic properties. Measurements of the natural orbital environment with the accuracy and sensitivity desired must be made *in situ*. To avoid contaminating the environment to be measured, the subsatellite must be separated from the shuttle by at least 1 km.

The subsatellite science mission envisioned represents an extension of the Dynamics Explorer technology that now is just being extended from the Atmosphere Explorer program. The subsatellite must be capable of being launched from the shuttle, controlled in real time, programmed by scientists in a nearby orbiting vehicle, and be able to change and adjust its orbit parameters. For true *in-situ* measurement, the spacecraft must accommodate the instrument payload without compromise to the science. After completion of its mission, the subsatellite must return to the shuttle, be safely captured, and then return to earth with the shuttle. To be economically feasible, a rapid and simple change of the subsatellite instrument scientific payload must be accomplished, allowing the sequence to start over.

The challenges of being able to accomplish the design objectives for the subsatellite are enormous. Developing engineering solutions during the same time period that shuttle and spacelab system philosophies, ground rules, and objectives are emerging will be a return to the exciting early days of space, where science and engineering technology were intermingled and inseparable from each other. RCA has contributed heavily to space science technology in the past, and we shall continue to be pioneers in the future developments in space technology.

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Ricardo deBastos is the Program Manager for the Dynamics Explorer spacecraft. Since joining RCA Astro Electronics in 1960, he has participated in the development of spacecraft technology from its infancy to today's state of the art. He played a key role in the system conceptual design of Atmosphere Explorer, and during the hardware design, was responsible for coordinating the scientific payload.

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"Lazarus" sleeps no more— satellite recovered from tumble

J.R. Staniszewski

Shortly after the Air Force's first DMSP Block 5D satellite was launched, it began to tumble out of control. A combined Air Force/contractor team, using extraordinary analysis and control techniques, recovered the satellite after six months of effort.

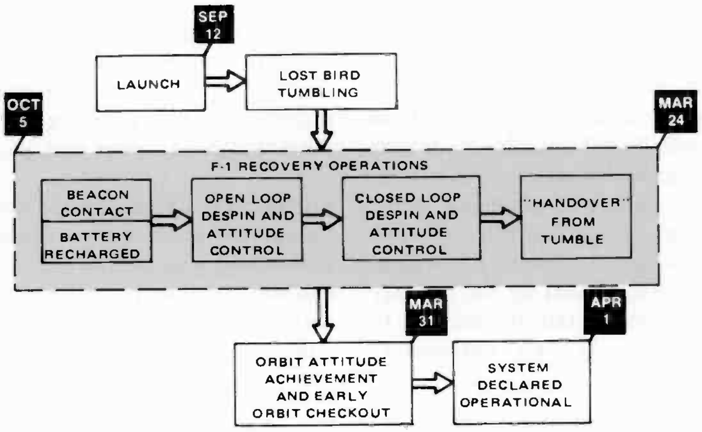

Fig. 1
Recovery took six months. Each step toward recovery represented a higher level of operational sophistication.

"Lazarus, our friend, sleeps. But I go that I may wake him from sleep."—John 11:1 - 11:44

Introduction

For over a decade, RCA Astro-Electronics has been a partner with the United States Air Force, providing weather satellites that have had a remarkable record of performance and reliability. With the launching of the first DMSP Block 5D satellite, they faced a new challenge, as the satellite tumbled out of control shortly after achieving orbit on September 12, 1976. In all prior satellite designs, a tumbling satellite would have been given up as a "lost bird" if its control authority was not manageable by ground command. Block 5D, Flight 1 became the first exception—a combined Air Force and contractor engineering team, using the combined strength of their analytical and design skills, fully recovered the tumbling spacecraft. Even then, this feat would have been impossible without new system technology available on board the DMSP satellite, in the form of two reprogrammable computers, (RCA's SCP-234s).

This unique effort eventually spanned six calendar months (October 5, 1976 to April 1, 1977) and involved several organizations throughout the United States. Block 5D-F1 (nicknamed "Lazarus") was eventually brought into operation and continues to provide useful data today. The successful recovery of this valuable national resource (replacement cost of a DMSP satellite has been estimated at $15 million and the need for timely high-quality meteorological data for use by military planners is essential) vindicated the Air Force management office decision to press for a "safe" recovery.

Three weeks after the satellite's launch and apparent loss, contact with the satellite was re-established on October 5, when the satellite's position in space became such that power was again available from the solar array. The satellite's initial output from the renewed telemetry transmission was discovered by the 4000th Aerospace Application Group in Omaha, Nebraska. The Air Force immediately organized a dedicated team of engineers to develop the detailed means to restore the weather satellite's operation. The contributing agencies and companies are listed in Table I. At their earliest planning meetings, this group began to evolve a strategy for the recovery; the essence of this strategy is summarized in Table II.[1]

The analysis/design arm of the team prepared the logic for recovery and the operations arm converted the logic into satellite command messages and operational scenarios. Returning the tumbling satellite to operation involved the entire DMSP Command and Control System, augmented by the Air Force's Satellite Control Facility tracking stations and the Air Defense Command's space object identification radars. The F1 recovery operations flow diagram (Fig. 1)

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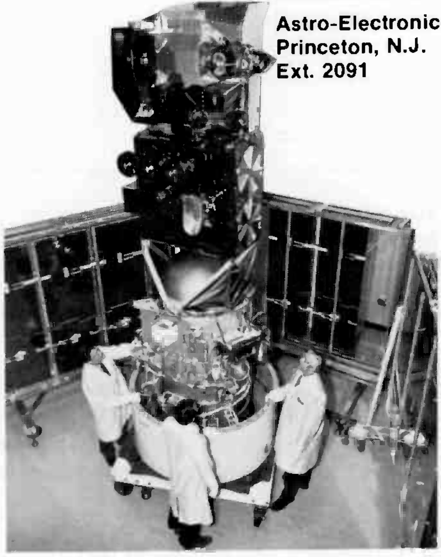

Joe Staniszewski (right) and the DMSP-5D Flight 1 satellite at Astro Electronics.

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describes the major epochs in the recovery activity; each block in the sequence represents a higher level of operational sophistication. Each step of this recovery plan demanded a high probability of success prior to moving on to the next level of complication. Also, each control scheme had to be verified and independently validated, the systems designed had to be configured from available hardware, and the required recovery logic had to be implemented by the operational group at Omaha.

The most difficult task, then, was the search for an invention to insure a reasonable risk in moving the satellite from its gyroscopically stable tumble mode to its normal designed orbital mode as a zero-momentum, three-axis-stabilized body. The boundary region between these two modes, when the satellite would become destabilized, was viewed by the recovery team as an uncharted territory that had to be crossed with the very rudimentary control equipment available in the tumbling spacecraft.

Modeling and environment simulation proved to be essential in developing the recovery logic and scenario to cope with this situation. Successful recovery was achieved by following the strategy shown in Table II. The design team insured the correctness of the models by independent validation techniques and used orbital tests for model calibration. The next steps were to develop appropriate control laws and to define the required software. Before the computer code with the recovery logic was transferred to operational routines, comprehensive testing, planning, and full-scale dress rehearsals always took place.

Full maturity of this doctrine was required for success, as adverse environmental exposure had a damaging effect on critical hardware such as the delicate gyroscopes that were essential to establish the correct attitude operation. The team's patience was eventually rewarded when the satellite was fully recovered on March 24, 1977 and declared operational on April 1, 1977.

Table I
The engineering team dedicated to restoring DMSP, F-1 to operation came from a number of agencies and companies.

Air Force

  Space and Missle Systems Organization (SAMSO0—Satellite Control Facility, Defense Meteorological Satellite Program

  Strategic Air Command—4000th Aerospace Applications Group

  Air Defense Command—Space Object Indetification Radars

Aerospace Corp.

RCA Astro-Electronics

Barnes Engineering

Honeywell, Inc.

C. Stark Draper Laboratories

Table II
The initial recovery strategy was followed until analyses and simulations (the fourth step) showed that reducing momentum to near zero could produce problems.

- Establish a favorable power balance by developing an algorithm that uses the spacecraft's magnetic coils to control the precession of its spin vector.
- Using the immediate past history of the spin-axis precession, validate the presumed torques, (gravity gradient, magnetic dipole, solar pressure). Successful validation will permit future prediction of spin-axis precession.
- Develop a spacecraft algorithm to despin using magnetic coils.
- Demonstrate analytically that a favorable spin axis can be maintained as the angular momentum is decreased to zero.

Launch—everything fine

When the first Block 5D satellite was quietly rolled out of the Astro Electronics plant on its way to the Air Force's Western Test Range (WTR) at Vandenberg Air Force Base, it took with it the hopes of RCA AE employees and Air Force program managers, as it was the pathfinder for future weather satellites. Six additional spacecraft of this third-generation design were waiting in line to be assembled and deployed for operation at a later date. This first Block 5D satellite carried the latest designs in meteorological and environmental sensors. The weather data gathered would increase the effectiveness of our military's strategic and tactical planners located the world over. All the effort behind the 5D-1 reached a climax late at night on the 11th of September 1976, with a successful countdown and launch.

Satellite "lost"

Twenty-five minutes after lift-off from WTR, the satellite was successfully placed into a 450-nautical-mile, nearly circular, sun-synchronous orbit. The launch team retired to toast the latest launching with the traditional barrel of beer while the operations team continued its tense watch of the spacecraft's behavior through the first orbit. The spacecraft successfully completed its required orbit-injection sequence of heatshield separation, stage 2 and stage 3 propulsion, and mission deployment, under the control of the spacecraft's miniature but powerful computer. These events were recorded as nominal by the pursuing telemetry-tracking ARIA aircraft flying out of Papeete, Tahiti. Shortly after reaching orbit the satellite's computer signaled that "handover" had been achieved and the control of the spacecraft's attitude was transferred from the high-pressure nitrogen gas system used exclusively during ascent to the reaction wheels and magnetics system used in orbit.

Momentum started increasing—a potential disaster.

After an additional 25 minutes of flight time, as Flight 1 was heading north over the Indian Ocean Tracking Station, telemetry signals indicated that the system momentum, and consequently the corrective reaction-wheel speeds, were increasing rapidly, although the satellite was main-

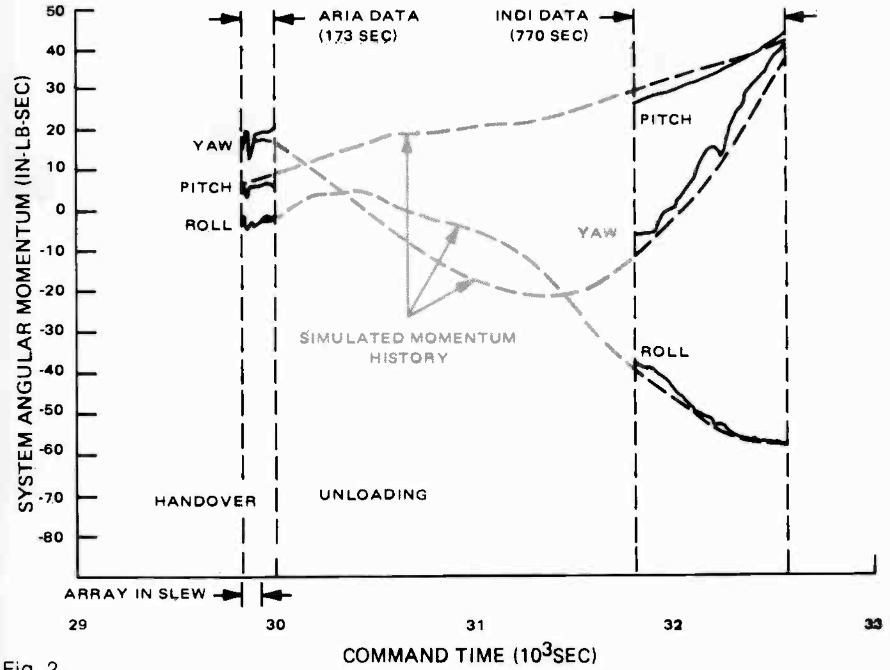

Fig. 2
Momentum history shortly after handover showed dramatic increase in angular momentum (shaded area is from simulated history). Engineers recognized this symptom as potentially disastrous—the control system would eventually become saturated, the spacecraft would tumble, and the solar array could potentially become de-oriented and stop producing power.

taining its proper three-axis attitude. This information was quickly sent to the early-orbit analysis team at Vandenberg and at the Satellite Command and Control Center in Omaha, Nebraska. The team recognized this symptom as a potentially disastrous control problem if it should persist—with the increasing spacecraft angular momentum, the prospect of a saturated control system seemed high. At the next spacecraft sighting at Cook Tracking Station in California, some fifty minutes later, all reaction wheels were at maximum speed (10,000 rpm), the control system was saturated, and the spacecraft was beginning to tumble (Fig. 2).[2] The engineers knew that if the tumbling continued, the spacecraft's solar array would not be oriented properly and the batteries would lose charge rapidly.

"Safing" attempts weren't enough to keep the satellite under control.

The satellite operations team went immediately into emergency action to try to "safe" the spacecraft while they considered what corrective commands they should use to arrest the tumble. ("Safing" consists of reducing all unnecessary power consumption in the satellite to preserve the battery.) With the passing of each of those early orbits, a sense of loss began to permeate the operation as the seriousness of the satellite's condition came into focus. The spacecraft continued to tumble at an increasing rate, the programmed orbital control authority was saturated, and the battery began to lose ground in its struggle to maintain an adequate state of charge. Visions of cycling the spacecraft computer logic back to its ascent mode and using the nitrogen thrusters to control the tumble raced through the minds of the desperate operations team when, on the 13th orbit, the battery gave up its last bit of charge. DMSP Block 5D Flight-1 was silent, failing to respond to ground commands.

What went wrong?

This was the end of the disappointing launch and orbit-injection phase for Flight-1. The launch and operations support teams returned home, haunted by the thought that, if they had had more time, they might have been able to reprogram the spacecraft's computer to arrest the tumble and recover the operation of the spacecraft's control system. Putting the thoughts of the launch events behind them, the analysis team set forth on a thorough review of all of the recovered telemetry. Reconstruction of the anomaly that precipitated the tumble was paramount in everyone's mind in order to prevent any recurrence of such an accident. By using a computer model of the spacecraft dynamics and control system, a plausible accident scenario began to emerge. Using the available data, the analysts concluded that the spacecraft was in control as it completed its orbit injection and deployment.

A bit of telemetry taken during the sixth revolution of the spacecraft, however, indicated that the reservoir of nitrogen was substantially depleted and that the spacecraft was tumbling at a rapid rate. This led to a possible failure scenario suggesting that escaping gas from a high-pressure nitrogen line struck the solar array, spinning up the spacecraft. As the nitrogen gas continued to leak, the system angular momentum continued to increase. The tumbling spacecraft's attitude then provided the solar array with only abbreviated views of the sun. Eventually, the lowered array current could not maintain a charged battery and sustain the spacecraft's equipment load.

Back to life

More than three weeks after the satellite had apparently gone out of control, it suddenly started sending telemetry signals.

While the accident investigation was in progress back at Astro Electronics, the DMSP Satellite Control Agency at Omaha (Strategic Air Command; 4000th Aerospace Application Group) maintained a faithful vigil. At every opportunity they attempted to have the silent spacecraft respond to its commands. They were rewarded on October 5th when signals were received from Flight-1's telemetry transmitter. The signals were alternately strong and weak with a period of approximately eighteen seconds during the satellite's overflight of the Control Readout Sites (CRS) in the states of Maine and Washington. A similar scintillation period was being observed by the Air Defense Command's skin-tracking space object identification radars. This strong correlation between the two independent observations confirmed the analysis that the satellite was tumbling at a rate of approximately 3.1 revolutions per minute.

Additionally, the telemetry responses during the daylight overflights of the control sites indicated the array was receiving enough illumination during the sunlit portion of the orbit to power the transmitter, command receiver, and decoder equipments. Loss of command response during the eclipse portion of the orbit indicated the battery state of charge was not sufficient to carry this minimum load. These early diagnostics set the tone for the initial Flight-1 recovery activity, Fig. 3, which was dominated by nursing the battery back to a healthy state of charge.

Power-management techniques brought the battery charge back to normal.

On October 11th pre-packaged command lists were made available to the remote tracking sites in Guam and in the Indian Ocean to manage the satellite's equipment configurations. In that way excess array current was made available during the sunlit portion of the orbit to recharge the battery and noncritical components were turned off during the orbit eclipse. This arrangement was continued until October 16th, when the battery was brought back to nearly a normal state of charge. As a consequence, the power system could now maintain the load throughout a tumble period and subsequently through the satellite's eclipse period.

Hence, in its first ten days of new-found life, the satellite had been brought safely through this most primitive state of recovery. The computer memories were reloaded with the command software and a power-management algorithm, and the satellite's tape recorders were brought online to continuously record satellite telemetry. This first blush of operational success gave the analysis team the incentive to seek the means of using the on-board computers (SCP-234s) to further stabilize the spacecraft.

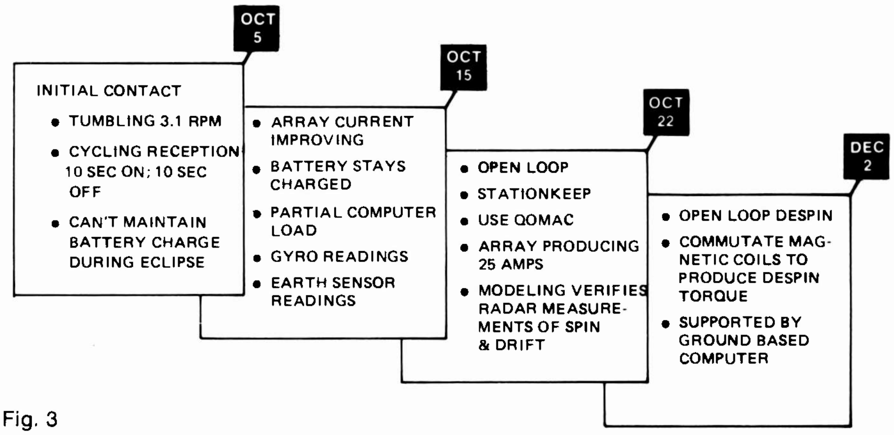

Fig. 3
Early recovery activity centered on bringing the battery system to a normal state of charge. Once that was accomplished, roughly two weeks after the initial re-contact, the recovery team was ready to despin the satellite.

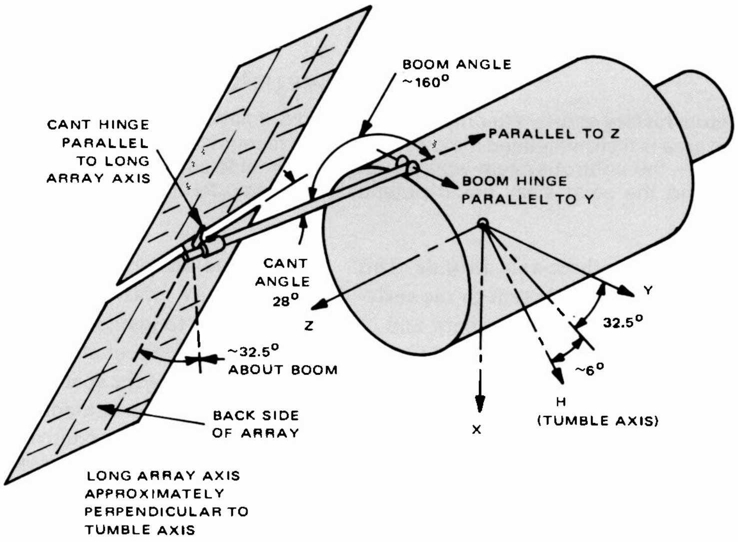

Fig. 4
Initial tumble configuration was determined by taking telemetry of gyro readings and earth-sensor horizon crossings, then combining them with the known mass properties of the satellite.

Slowing the spin

Before the spacecraft could be stabilized, its exact behavior and positioning had to be determined. The actual methods used by the analysis team included interpretations of ground-based radar observations, earth-sensor horizon crossings, and the high-rate, ascent-mode, gyro readings (the latter two data were available from the satellite's telemetry). When the body rates were combined with the known mass properties of the satellite, the location of the axis of tumble in body coordinates was defined. The addition of orbit-long recordings of earth-horizon crossings defined the satellite's orientation in inertial coordinates. The radar observations corroborated the earth-sensor readings. From this data the schematic of the spacecraft shown in Fig. 4 was synthesized.[3]

The tumble was far beyond the spacecraft's attitude-control system's ability to control.

Several facts and realizations emerged from these early analyses. First, the satellite, tumbling at 3 r/min, had developed an angular momentum of 2800 inch-pound-seconds—two orders of magnitude above the satellite reaction wheels' ability to control. The satellite, as discovered early in October, was behaving as a gyroscopically stiff body spinning about its maximum principal moment of inertia axis, approximately parallel to the normal to the plane of solar array.

Attitude-control techniques from the "early days" of space were used to stop the spacecraft's precession.

Second, the satellite's spin axis, because of its large moments of inertia and high tumble rate, would remain inertially fixed in the short term, but would precess in the longer term because of natural disturbances, primarily those caused by gravity-gradient and magnetic torques. The analysts recognized this dynamic behavior as similar in nature to the earlier "spin-stabilized" Block IV spacecraft first launched and operated in 1965. They quickly realized that magnetic coils in the spacecraft were available to control the attitude of the spin axis precisely in the same manner as the Block IV system with the use of QOMAC, (Quarter Orbit Magnetic Attitude Control).[4] These techniques were successfully employed on the 22nd of October by the Operations Group at Omaha to arrest the drift of the spin axis.

By controlling the spin axis, the solar array, which is coupled to the spacecraft by a direct-drive motor (not operated during

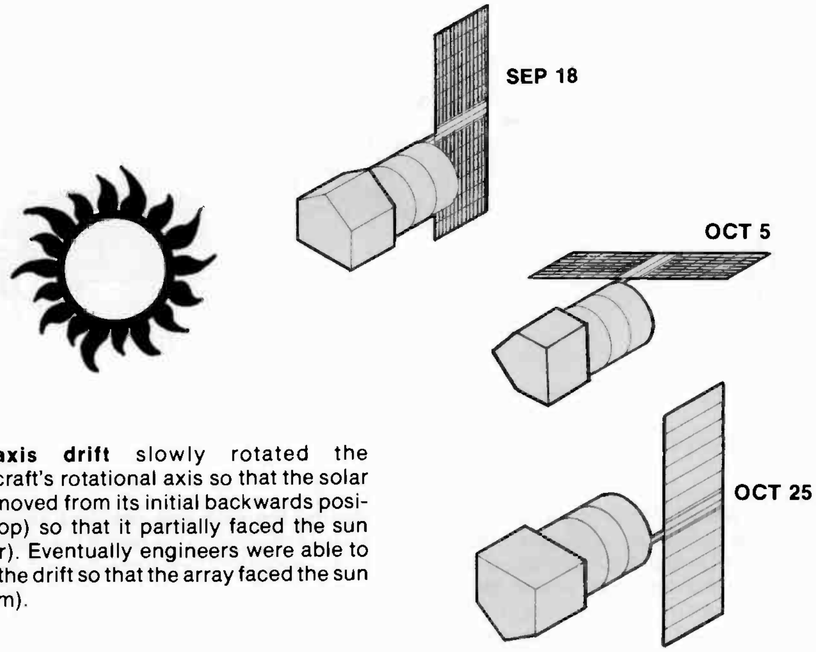

Fig. 5
Spin-axis drift slowly rotated the spacecraft's rotational axis so that the solar array moved from its initial backwards position (top) so that it partially faced the sun (center). Eventually engineers were able to arrest the drift so that the array faced the sun (bottom).

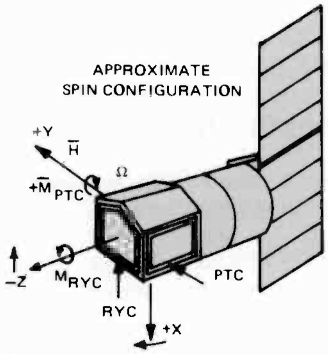

Fig. 6
Magnetic coils on board the spacecraft were used to create a magnetic dipole that interacted with the earth's magnetic field and produced a torque. This torque, which was used to slow down the satellite's spinning, was kept continuously opposing the spin by switching the current direction in the coil as the spacecraft spun through the earth's magnetic field.

this early recovery phase), was directed toward the sun to maximize the available energy, thus providing more than 25 amperes of current for battery and load management. Through the remainder of October and early into November, QOMAC was frequently used as a stationkeeping program to maintain this favorable orientation.

The spacecraft's changing orientation with regard to the sun, caused by the drift of the spacecraft's spin axis, is shown in Fig. 5. These attitudes were determined by running the spacecraft dynamic model on an Astro Electronics ground-support computer and bootstrapping the model's starting points to measurements made of the inertial attitude of the satellite from radar observations on September 18 and October 16, 1976. The data obtained clarified the satellite's early behavior, including the sudden response to commands on October 5th after three weeks of silence. The analysts reasoned that when the satellite was lost, the backside of the solar array was directed at the sun and the solar-cell side of the array received no energy. They further argued that the array, because of its large moment of inertia, remained fixed with this relationship to the sun until the spin-axis precession brought the solar cells into a grazing view of the sun on October 5, the day of first command contact. From that day until October 22, the natural precession continued to improve the solar array's view of the sun. After the 22nd of October, the Operations Group could use QOMAC with confidence to compensate for the natural drift tendency of the satellite's spin axis and so maintain this favorable view of the sun.

Open-loop despinning was the next step.

At Astro Electronics, effort was under way to develop an open-loop despin algorithm. The first demonstration of this algorithm, on December 5th through 8, reduced the satellite's momentum, and hence its tumble rate, by fifteen percent. The despin algorithm used the principle of generating an on-board magnetic dipole that could be interacted with the earth's magnetic field to create a despin torque. To effectively reduce angular momentum and hence spin rate, the torque (T_D) needed to be directed collinearly but of opposite sign to the momentum or spin vector (ω_s). In its initial spin configuration, the correctly arranged coil was the spacecraft's roll-yaw coil (RYC)—its plane was nearly parallel to the spin axis and thus could provide a magnetic dipole M_D transverse to the spin axis ω_s. Coupling the M_D with the earth's magnetic field B resulted in the appropriate torque T_D for despin.

Because the RYC coil was spinning with the tumbling spacecraft, the current flow through the coil had to be commutated synchronously with the passing of the magnitude dipole (M_D) (Fig. 6) through the (B) earth's field, in order to create a net despin torque ($T = M \times B$) during each spin. (This action is equivalent to the commutation in a dc motor.) A signal from the sky-earth-sky crossing of a particular earth-sensor (ESA) quadrant was used to synchronize the clocking of each spin period with respect to the geomagnetic field. (As the inertially fixed spacecraft moved through its orbit, at least one of the earth sensor's four quadrants was available for synchronizing.) Working with the known geometric relationship of the RYC coils, the ESA quadrant line of sight and at an appropriate time (phase) from the alignment of the ESA line of sight and the spacecraft's local vertical, the despin algorithm logic required the current to flow in one direction in the RYC coil. One-half spin period later the logic would reverse the direction of coil current flow; this coil-current commutation created a net despin torque.

The algorithm and computations were shared between the spacecraft computer and the ground-operations computers. The more sophisticated geometric calculations were conducted on the ground, where present spin rates, spin-axis location in body coordinates, and spin-axis location in inertial coordinates were analyzed along with the earth's magnetic-field model and the satellite's ephemeris. From this data a table of parameters was generated to drive the despin algorithms located in the spacecraft's computer. The table contained the correct earth-sensor quadrant to be selected for generating the synchronizing signal and designated the effective despin region of the orbit as clocked from the ascending node of the orbit. The spacecraft's onboard computer calculated the local vertical from these selected earth-sensor quadrant signals and timed out from the point of the local vertical the correct phase angle of spin prior to driving the coil with current. The system proved to be quite effective, eventually reducing system momentum by approximately 40 inch-pound-seconds per orbit. The open-loop precession control or stationkeeping program and the open-loop despin torquing program were independently managed.

Studies foretell danger ahead

Success in lowering the spin rate would bring problems in other areas.

With these control techniques in hand, it became urgent to press on with the despin programming to reduce the spacecraft angular momentum to the neighborhood of 20 inch-pound-seconds, where the spacecraft's normal attitude-control equipment and algorithms could take over. Several concerns emerged at this time. One result of the modeling studies conducted at RCA in December of '76 (Fig.7) showed that the spin vector developed large nutation angles at low momentum levels when excited by natural disturbances. An equally important result, reported in December from the Aerospace Corporation's supporting modeling studies, was that a level of momentum compatible with the spacecraft's normal control system (30 inch-pound-seconds) could not be reached with the open-loop despin algorithm.

Continuing the open-loop despin operation would not be successful—the result instead would be increased nutation, loss of power reserve, and finally imminent failure. In addition, other study results confirmed the analysts' hunches that at the lower momentum levels much more frequent attitude control would be required, thus creating undue demands on the Operations Group. The risk of an early recovery under these conditions was considered too high, so the despin activity was slowed down until an "end-game" algorithm with less risk could be developed and demonstrated.

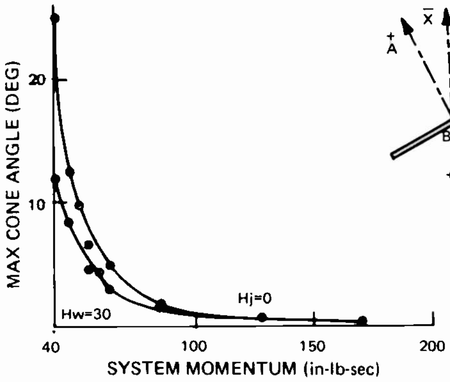

Fig. 7
Trouble ahead. Modeling studies showed that large nutations could take place if the spacecraft's angular momentum dropped to 20 inch-pound-seconds, where the normal attitude-control system could work successfully. These findings forced the engineers to slow down the de-spinning until a solution to this problem could be found.

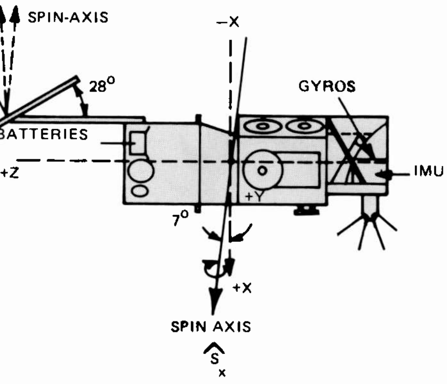

Fig. 9
Moving the spin axis required moving the array in relation to the rest of the spacecraft. New orientation put batteries and gyros in more direct view of the sun. Engineers had to use the QOMAC routine deftly to avoid dangerous overheating of these components.

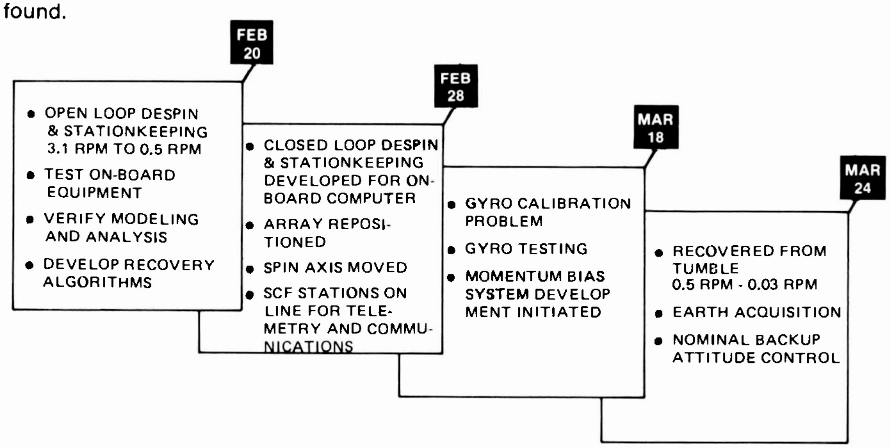

Fig. 8
De-spinning and attitude control took place in two major epochs—open-loop and closed-loop. For the closed-loop operation to be successful, the solar array and spin axis had to be moved. Then, gyro problems occurred, and gyroless attitude-control methods had to be developed.

A new attitude and despin scenario

The spin axis had to be realigned by moving the solar array.

The attitude and despin control scenario broke into two major design and operational epochs (Fig. 8). The first, which featured open-loop control, was applied to the spacecraft in the attitude in which it was discovered, with the spin axis near the spacecraft's y axis. This method proved to be effective and adequate until the momentum had been reduced to the region of 700 inch-pound-seconds (ω_S = 0.83 r/min). This momentum level became a clear break point at which to adopt the closed-loop despin and attitude-control method. First, an innovative design began to emerge; it used the earth sensor to automatically synchronize the commutation of the magnetic coils (PTC and RYC) to produce despin and attitude control. This concept required the spin axis to be located as close to the x axis as possible, and hence to bisect the optical lines of sight of the earth sensor's quadrants, in order to be effective. Secondly, to move the spin axis it would be necessary to rotate the array so that the principal moment of inertia of the spacecraft, which is collinear with the normal to the plane of the array, would be aligned with the x axis (Fig. 9).

The array could not be moved reliably, however, until the spin rate dropped below 0.9 r/min, where the inertial forces acting on the motor shaft would be substantially below the array drive motor's delivered torque. Because the array had significantly more inertia than the main body of the spacecraft, the array remained inertially fixed when the array drive motor was energized, and the main body of the spacecraft rotated, instead, about its long (z) axis. The net effect was to relocate the spin axis to the desired body axis.

But, engineers knew that moving the array would produce temperature problems.

An anticipated unfortunate consequence of this new orientation placed the batteries and gyros into a more direct view of the sun, causing their temperatures to rise. The gyros momentarily reached 62°C, their maximum design limit. The Operations

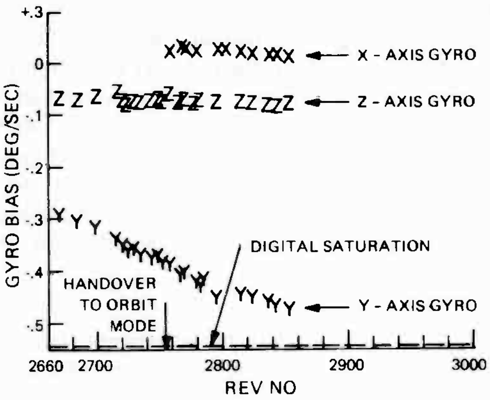

Fig. 10
Gyro behavior became erratic because of the difficult environment to which they had been exposed. Unpredictable behavior stopped initial recovery attempt until a gyroless attitude-control algorithm could be developed.

Team had to use all of their skills in operating QOMAC to simultaneously maximize the array current and to shade the batteries and gyros to normalize their temperatures. (Thermal radiators on the batteries and gyros are shielded from sunlight in a normally operating 5D spacecraft.) To achieve these results, the team had to keep the spin axis closely aligned with the sun line (Fig. 9). Throughout the month of February the Operations Group and the Analysis Group reviewed every detail of the recovery algorithms, operational scenarios, and contingency plans.

During February of 1977 numerous simulations of the recovery control system were operated, testing a variety of initial conditions and modifications to the baseline design. These operations were conducted to determine an optimally "safe" starting point and the sensitivity of the control system to parameter variations. As these studies were in progress at RCA and at the Aerospace Corp., the Operations Group prepared to flight-test elements of the recovery scenario and to generally prepare themselves for the recovery operation. A break in final-phase design activity was taken and the analysis teams joined the Operations Team at Omaha on February 19 for these flight-test operations. The spacecraft momentum was reduced to 1400 inch-pound-seconds (ω_S = 1.64 r/min), where the reaction wheels were satisfactorily operated and the communication system was tested. The open-loop despin algorithms were further operated to reduce the angular momentum to 800 inch-pound-seconds (ω_S = 0.7 r/min). On the 20th of January, at this lower spin rate, the spin axis had been successfully relocated to the spacecraft's x axis by operating the solar array drive motor.

Initial recovery attempt—trouble with failing gyros

On the 28th of February, the final despin operation began at the 425 inch-pound-second momentum level. The group had high expectations that the spacecraft would be captured by the following morning. Momentum reduction progressed on schedule and with a remarkable correlation to the simulations. The drama and significance of the objective infected all the personnel participating in the recovery, as everyone alertly scanned each word of telemetry. There was, however, concern about the health of the gyros, which had been exhibiting signs of erratic behavior since early December. In all complex orchestrations to each theme there is a counterpoint; hence, as midnight of February 28th stretched into the dawn of March 1st, the recovery theme was dominated by the disturbing behavior of the gyros (Fig. 10).

Nearly successful, the team had to temporarily stop recovery and spin the satellite up again.

As the spin rate was reduced to 0.2 r/min, independent measurements of gyro biases were made. The inordinately high and varying bias of the y-axis gyro was alarming and destroyed our confidence in predicting a successful recovery that had been based on prior measurements, analysis, and simulations. After an urgent counsel of key personnel, the despin procedures were terminated, even though the objective was within view. Walking away from the summit was a bitter pill to swallow after five months of preparation, but it was clearly the prudent thing to do. The spacecraft was then spun up to a more docile momentum level (using the inverse of the logic for despin), where its station could be routinely maintained while the impact of the gyro performance on recovery was carefully evaluated.

For successful orbital operation the gyros were essential to accomplishing the initial steps of earth acquisition, rate nulling, and gyrocompassing of the normal attitude control. All of the gyros had been exposed to extreme hot and cold temperatures during their powered-down stage, as they were at times viewing the cold sink of space and at times directly in view of the sun. Ground tests and analysis indicated that irreversible damage may have been suffered to all of the gyros throughout that early post-launch era. The situation was assessed as follows: if the recovery were not accomplished soon, the gyro drift increases may make them unuseable, delaying the recovery operation indefinitely; on the other hand, moving onto recovery without a contingency plan to cope with a sudden loss of one or more of the three operating gyros would most certainly result in a permanent loss of spacecraft.

Gyroless control was obviously needed, but not yet available.

To assure that the recovery would be successful, RCA, assisted by the Draper Laboratories, set out on an emergency task to design an attitude-control algorithm that would not require the gyros. This system was called MOBACS, an acronym for a Momentum Bias Attitude Control System. The spacecraft normally operates as a zero-momentum system.

Final recovery

The recovery operation began again before the MOBACS design was available, because it was always possible to send a "spinup" command to "safe" the satellite or to compensate for the excessive and varying gyro drift via ground command. Without these abilities, recovery would have had to wait for MOBACS.

Three weeks after the initial recovery attempt, on the 20th of March, RCA and SAMSO recovery teams again joined the Operations Group at Omaha. Special telemetry links were provided from the satellite control sites at Guam and the Indian Ocean to Omaha to augment the normal telemetry from receiving stations in Maine and Washington state. A telemetry transfer system was also provided for the RCA Astro Electronics standby engineering group at Princeton. The Aerospace Corporation group installed a terminal at Omaha linked to their computer facilities at El Segundo, from which to operate the simulations in support of the despin operations. Meanwhile, Draper Labs continued with their analysis tasks in Cambridge, Massachusetts. A senior scientist (K. Ward) was on hand from the Barnes Engineering Company, under subcontract to RCA, to interpret and operate the earth-sensor data processing for attitude information. All of these resources were at the command of the DMSP Program Director and his Deputy for Operations.

The pre-recovery events began when the software algorithms for despin and attitude control were uplinked to the spacecraft computers and verified. In addition, the normal orbit attitude-control system software was also installed in the spacecraft computer. The automatic despin system included a nutation damper implemented with the *y*-axis gyro and the *z*-axis reaction wheel with alternate configurations available by command. It also provided a 10 inch-pound-second momentum bias with the appropriate operation of the *x*-axis reaction wheel. The two pitch torquing coils (PTC) and the one and one-half roll-yaw torquing coils (RYC) were configured for despin and for attitude-control torquing. (One half of a RYC coil had been lost early in the recovery operation.) The planned initial conditions, which had been thoroughly simulated, were a starting angular momentum of 450 inch-pound-seconds with "handover" set to be automatically switched when the measured angular momentum reached 30 inch-pound-seconds.

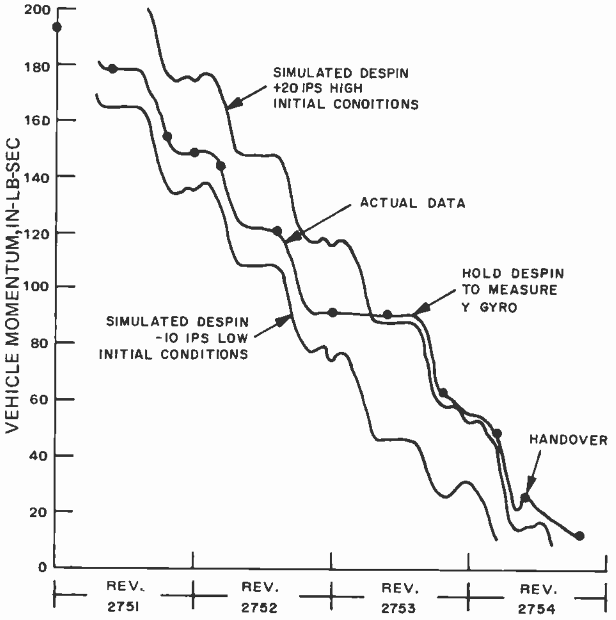

Fig. 11
Actual despin events followed predictions closely.

With a final drift measurement of the *x*-and *z*-axis gyros, the required gyro biases were calculated, as shown in Fig. 10, and the data entered into the spacecraft's computer software. Then, on the evening of March 23, the recovery operation was re-visited. The predicted and actually achieved despin scenarios correlated closely (Fig. 11). Telemetry messages received at Omaha from all the tracking sites were scrutinized for indications of spacecraft equipment health. The automatic operation was interrupted momentarily as the angular momentum of 70 inch-pound-seconds was reached to measure data from the *y*-axis gyro. This would be the last gate to pass prior to automatically proceeding to "handover." The reading, made early in the morning of March 24, indicated a useable bias term and the message was passed that the *y*-gyro was still functioning. This final gyro bias term was inserted into the despin software program and the spacecraft was released to continue its despin operation.[5]

"Handover" was achieved at 0912 local Omaha time as the spacecraft was flying

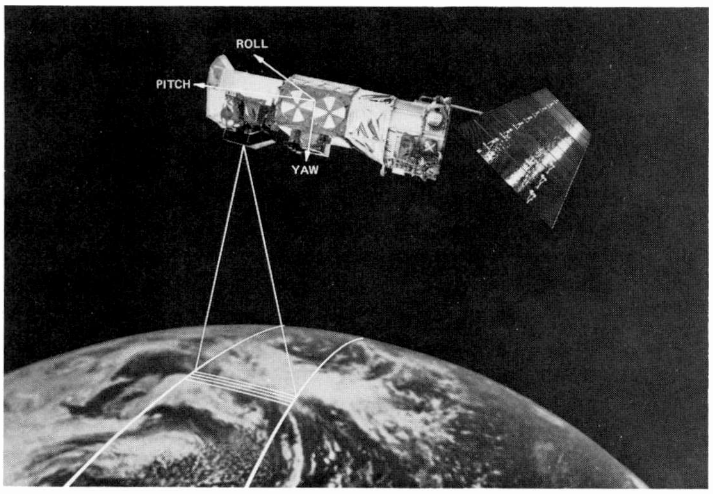

Fig. 12
Operational satellite flew at its normal attitude and began producing cloud-cover images as in Fig. 13.

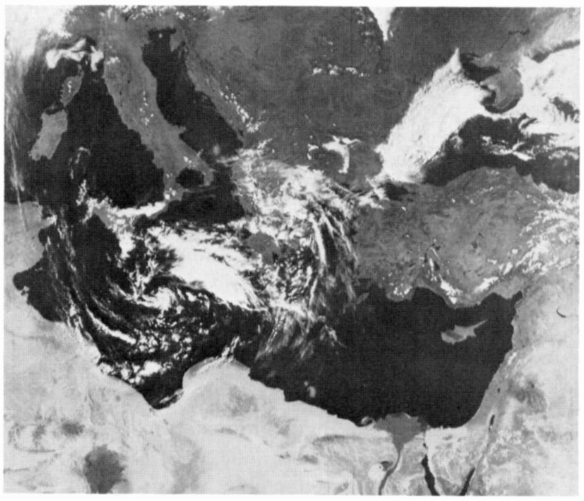

Fig. 13
Cloud-cover images from March 25, 1977, just after "handover" of the satellite. The boot of Italy is visibile at the upper left, and the Nile delta and the Red Sea are at the lower right.

over the Guam station. During the next fifty minutes the spacecraft control system successfully performed its earth-acquisition, rate-nulling, and gyrocompassing control modes, essentially repeating the routines accomplished on the day of its launch. This time, however, as the spacecraft rose over the Liza, Maine, site, it was noted to be in full three-axis control with reaction wheels holding at a nominal speed.

Early orbit checkout

The first line of the "recovery" team stepped aside for a needed rest and the back-up team assumed control to perform the planned early-orbit testing of the satellite equipment. The director of operations kept his finger on the "spin-up" command as the *y*-gyro drift continued in its inextricable growth toward saturation. During these earliest operational orbits the spacecraft continued to fly in its normal attitude (Fig. 12) and the weather sensors produced the high-quality cloud cover images as shown in Fig. 13.

During this period, the team received a proposal from Draper Labs to use the output of the earth sensor as a substitute for the deteriorating *y* gyro. This system was called ESARD (Earth Sensor Roll Determination). A software module was quickly put together at Draper Labs and verified at RCA Astro Electronics. The software was loaded into the spacecraft computer on March 26, only 36 hours after "handover," in a virtuoso performance of software development engineering. The ESARD was substituted for the *y*-axis gyro with hardly a reactive ripple noticeable in the attitude-control telemetry.

Over the three or four days following "handover" the recovery team was confident that they had met their objective of preserving the Air Forces' satellite. The 5D-1 spacecraft was producing useful cloud cover data and more and more of the data analysis and normal operational decisions were being assumed by the 4000th AAA and the DMSP Deputy for Operations. On April 1st the various elements of the recovery team in concert recommended to the DMSP Program Director that he declare the Block 5D Flight 1 satellite operational.

As the team returned to their respective home bases, the effort was continued to complete the development of the MOBACS System (implemented by May 21) and to prepare for the launching of Block 5D Flight 2, with the knowledge that the equipment and talent provided by the combined Air Force-contractor team had well served the DMSP Block 5D Flight 1 pathfinder.

Benefits of the recovery

Saving a $15-million spacecraft is obviously worth the effort expended during the recovery operations, but other benefits have also resulted. First, design and manufacturing technology improvements were subsequently incorporated in the spacecraft design to eliminate any potential source of high-pressure leaking in follow-up spacecraft. Additionally, procedures and software developed during the recovery operations influenced the development of future launch and orbit scenarios to better insure their success. The effort also provided the basis of a valuable repertoire of procedures to cope with future emergencies, thus reducing their impact on satellite data-gathering operations.

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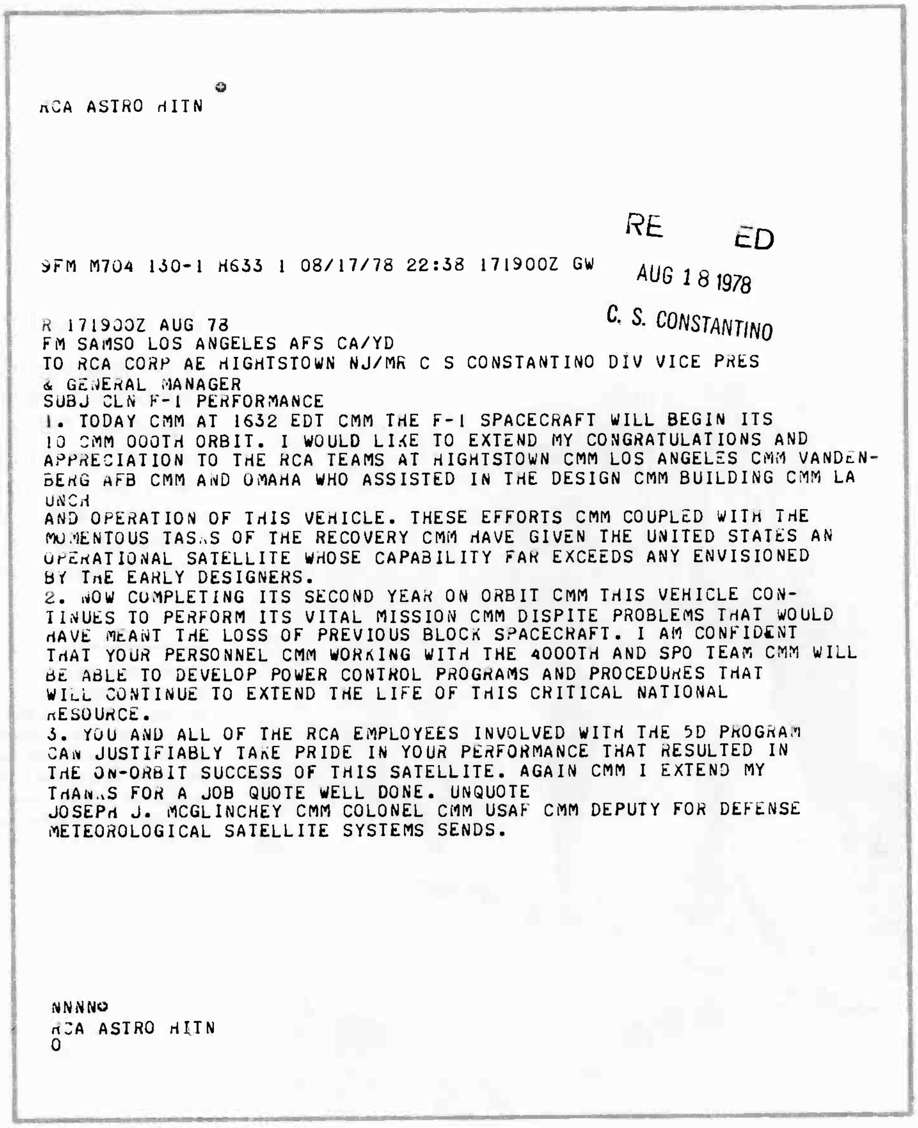
2. Internal Memorandum—L. Muhlfelder to W. Manger, Status Summary of 5D1-F1 Failure Analysis and Recovery Effort, and 5D1-F2 Design Considerations Oct. 28, 1976.
3. Drawn by G. Beck, Nov. 5 1976.
4. Lindorfer, W., and Muhlfelder, L.; "Attitude and spin control for TIROS wheel," AIAA/JACC Guidance & Control Conference (Aug 1966).
5. Greip, D., and Skrinska, R.; "Simulation of final despin," Aerospace Corp. (Mar 24, 1977).

A job "well done." This recent telex shows the Air Force's appreciation of RCA's work in the Block 5D-F1 recovery. The satellite continues to operate today, returning weather data to earth.



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TO RCA CORP AE HIGHTSTOWN NJ/MR C S CONSTANTINO DIV VICE PRES
& GENERAL MANAGER
SUBJ CLN F-1 PERFORMANCE
1. TODAY CMM AT 1632 EDT CMM THE F-1 SPACECRAFT WILL BEGIN ITS
10 CMM 000TH ORBIT. I WOULD LIKE TO EXTEND MY CONGRATULATIONS AND
APPRECIATION TO THE RCA TEAMS AT HIGHTSTOWN CMM LOS ANGELES CMM VANDEN-
BERG AFB CMM AND OMAHA WHO ASSISTED IN THE DESIGN CMM BUILDING CMM LA
UNCH
AND OPERATION OF THIS VEHICLE. THESE EFFORTS CMM COUPLED WITH THE
MOMENTOUS TASKS OF THE RECOVERY CMM HAVE GIVEN THE UNITED STATES AN
OPERATIONAL SATELLITE WHOSE CAPABILITY FAR EXCEEDS ANY ENVISIONED
BY THE EARLY DESIGNERS.
2. NOW COMPLETING ITS SECOND YEAR ON ORBIT CMM THIS VEHICLE CON-
TINUES TO PERFORM ITS VITAL MISSION CMM DISPITE PROBLEMS THAT WOULD
HAVE MEANT THE LOSS OF PREVIOUS BLOCK SPACECRAFT. I AM CONFIDENT
THAT YOUR PERSONNEL CMM WORKING WITH THE 4000TH AND SPO TEAM CMM WILL
BE ABLE TO DEVELOP POWER CONTROL PROGRAMS AND PROCEDURES THAT
WILL CONTINUE TO EXTEND THE LIFE OF THIS CRITICAL NATIONAL
RESOURCE.
3. YOU AND ALL OF THE RCA EMPLOYEES INVOLVED WITH THE 5D PROGRAM
CAN JUSTIFIABLY TAKE PRIDE IN YOUR PERFORMANCE THAT RESULTED IN
THE ON-ORBIT SUCCESS OF THIS SATELLITE. AGAIN CMM I EXTEND MY
THANKS FOR A JOB QUOTE WELL DONE. UNQUOTE
JOSEPH J. MCGLINCHEY CMM COLONEL CMM USAF CMM DEPUTY FOR DEFENSE
METEOROLOGICAL SATELLITE SYSTEMS SENDS.



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New Patent Office regulations and the inventor's duty to disclose

E.J. Norton

Inventors should complete a "prior art" statement as part of their duty to disclose information material to their patent applications.

Ed Norton is the Director of Patent Planning and Administration for RCA's Patent Operations. He is a Registered Patent Attorney before the U.S. Patent and Trademark Office and is a Member of the Bar of the U.S. Supreme Court and of other federal and state courts.

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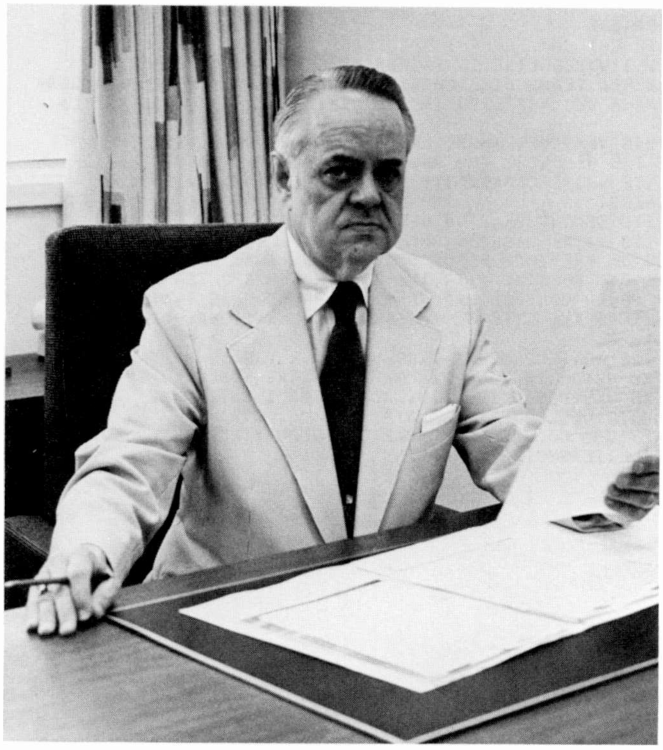
Reprint RE-24-2-1
Final manuscript received January 9, 1978.



Inventors who file patent applications must, as part of their applications, sign a statement which sets forth that they believe themselves to be the original, first, and sole or co-inventor of the invention covered by the application.[1] This statement can take the form of an oath by which the inventor, being duly sworn, pledges before someone authorized to accept oaths that the statements made are true. Also, the statement can take the form of a declaration by which the inventor affirms that the statements made are true and are made with the knowledge that willful false statements are punishable by fine or imprisonment.[2] Whether an oath or declaration is used, the inventor is exercising a duty of good faith and candor. That is, the inventor is indicating, by signature on the oath or declaration, an honest belief in the accuracy of the statements made.

What is "duty of good faith and candor?"

In considering this duty of good faith and candor, it is significant to recognize that the United States Patent and Trademark Office has no procedure to challenge or even question, as a regular matter, the truth of the statements made by the inventor in the oath or declaration. The inventor is assumed to be truthful. As a practical matter, the Patent Office must work in this way. In fact, however, the oath or declaration signed by a particular inventor may

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[1] Additionally, the inventor must state that he/she has read the specification and claims of the accompanying patent application; that he/she does not know and does not believe that the invention was ever known or used in the United States of America before his/her invention thereof, or patented or described in any printed publication in any country before his/her invention thereof or more than one year prior to the application, or in public use or on sale in the United States of America for more than one year prior to the application; that the invention has not been patented or made the subject of an inventor's certificate issued before the date of the application in any country foreign to the United States of America on an application filed by him/her or legal representatives or assigns more than twelve months before the application; and that no application for patent or inventor's certificate on the invention has been filed by him/her or representatives or assigns in any country foreign to the United States of America, prior to the application, except as identified.—Title 35, United States Code; Title 37, Code of Federal Regulations, Section 1.65.

[2] A declaration will include, for example, the following paragraph: "The undersigned petitioner declare(s) further that all statements made herein of his/her own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon."

contain an inaccurate statement. This inaccuracy can be caused by an oversight or a misunderstanding, or it can be a deliberate effort to trick or deceive. The result has been the development of a body of case law directed to the treatment of patents issuing on patent applications where such inaccuracies have been made. Whether the wrong statement was made intentionally or unintentionally, the patent can be held to be unenforceable and/or invalid, depending upon the circumstances of the particular case.

An inventor who has signed an oath or declaration can be accused of having made mistakes or misrepresentations ranging from what appear to be trivial and incidental errors to grave misrepresentations. Actually, such accusations can span the entire field of contacts between the inventor as a patent applicant and the U.S. Patent and Trademark Office, as summarized in the following outline.

1) Misjoinder or non-joinder of inventors.

2) The derivation from or appropriation by the inventor of the work of others.

3) Failure to make known the inventor's own relevant prior printed publications, including a patent that preceded the invention or is a time bar.[3]

4) Failure to make known a printed publication, including a patent by others which preceded the invention and could be anticipatory of the invention.

5) The existence of a public use, sale, or offer for sale which could be a bar to patenting.[3]

6) Deliberate obscuring of the invention covered by the patent application.

7) Misrepresentation of the prior art, whether deliberate or not, brought to the attention of the Examiner in the patent specification or in some other manner.

What is the new Patent Office ruling?

Public notoriety has been brought to patent litigation where allegations have been made that the inventor has violated the duty of good faith and candor in dealing with the U.S. Patent and Trademark Office. Such publicity creates a challenge adverse to the development of the U.S. patent system and, in fact, to the patent system's very existence. The United States Patent and Trademark Office, mindful of this challenge, has recently modified certain of its rules and procedures in an effort to strengthen the patent system. Effective January 1, 1978, the inventor is required by the Patent Office to include in the oath or declaration accompanying a patent application the following statement:

> "That he/she acknowledges a duty to disclose information of which he/she is aware which is material to the examination of the application."

The Rules of the Patent Office have been further amended to define this duty to disclose.[4] The Rules restate the longstanding, judicially created duty of good faith and candor required of all who deal with the Patent Office and provide for the striking of a patent application, if it is established that fraud was practiced or attempted on the Patent Office or that the duty of disclosure is violated through bad faith or gross negligence. The duty rests on every individual who is substantially involved in the preparation or prosecution of a patent application. The word "substantially" is meant to include persons such as the inventor and the patent attorney with whom the inventor works and to exclude persons such as typists, clerks and similar individuals. The inventor's duty to disclose can be discharged through the patent attorney or agent having the responsibility for the preparation or prosecution of the patent application.

What information is considered important?

Information is considered "material" when there is a substantial likelihood that a reasonable Examiner at the Patent Office would consider it important in deciding whether to allow the patent application to issue as a patent.

Such information may include references found in a preliminary search, information known to the inventor or brought to the inventor's attention by others, or information which should be known to the inventor as one skilled in the art. Note that "information" refers not only to patents and publications, but also includes acts such as public use, sales, offering for sale, etc. But, information that has been determined to be trivial need not be included. *The inventor should not rely on his own judgment, but should consult with his patent attorney before such a determination is made.* Note that the Patent Office has stated that bad faith is not present if information is withheld as a result of an honest error in judgment.

The inventor and the prior art statement

In order to provide a standardized mechanism by which patent applicants can comply with the duty to disclose, the Patent Office has further provided for the filing of a prior art statement with or within three months of the filing of a

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[3] See footnote 1 for statement of one-year grace period.

[4] 37 CFR Sec 1.56

patent application.[5] Although filing a prior art statement is voluntary, it is strongly encouraged as one way of meeting the duty to disclose by those involved in the preparation and prosecution of a patent application. The prior art statement serves as a representation that the prior art or other information listed therein includes, in the opinion of the person filing it, the closest prior art of which that person is aware. But, the statement will not be construed as a representation that a search has been made or that no better art exists. Copies of the pertinent portions of all listed documents must be supplied along with the prior art statement.

Generally, the prior art statement can include a listing of patents, publications, or other items of information.

The submitter is not required to identify which items he considers to be the closest art. It is important to note that the Patent Office Rules do not prescribe which among the available references should be selected for submission or exclusion or which circumstances possibly affecting patentability should be discussed. It is left to the inventor and patent attorney or agent to decide.

A concise explanation is required of the relevance of each item listed in the prior art statement. The explanation of relevance may be nothing more than identification of the particular figure or paragraph of the patent or publication which may be considered to have some relation to the claimed invention. An explanation of why the invention is believed patentable over the cited art is not required. However, it is permissible to include a discussion of the difference between the prior art and the claimed invention. The Rules also provide for an updating of the prior art statement by information which has become known subsequent to the filing thereof. The additional information should be submitted with reasonable promptness, and can be included in a supplemental prior art statement or may be incorporated in other communications to be considered by the Examiner in the Patent Office.

The standard of conduct

The reader may now well ask, "Exactly what standard of conduct does the U.S. Patent and Trademark Office require of patent applicants? What are the consequences if an applicant fails to meet that standard?"

Suffice it to say, much has been written on the subject, both by the Courts and in the literature. Perhaps no subject in patent law has stirred up as much discussion and even heated controversy as this. A thorough review of this subject is beyond the scope of this paper. However, certain observations and conclusions can be made as to the present state of the law in this area.

Faced with allegations that a patent applicant has failed to meet the required standard of conduct and, thus, has not shown the duty of good faith and candor necessary to the existence of a valid and enforceable patent, the Courts have examined whether or not the questioned acts of the applicant constitute inequitable or fraudulent conduct. An allegation of inequitable or fraudulent conduct in connection with the obtaining of a United States patent is always a matter which must be taken seriously. Generally, where inequitable conduct is found, the patent is simply held to be unenforceable. Where fraudulent conduct is found, the patent is held to be invalid and any attempt by the patent owner to enforce the patent against others can result in severe penalties. The Courts tend to decide whether the offending act or omission establishes either inequitable or fraudulent conduct by measuring the extent to which the presence of the act or omission was material to the issue of patentability. In other words, to what extent did the applicant's conduct enter into and otherwise affect the Examiner's deliberations as to the patentability of the invention?

Court decisions have created the concept of "uncompromising duty."

The U.S. Supreme Court decisions, *Precision Instrument Mfg. Co. v. Automotive Maintenance Machinery Co.*[6] (1945), and *Kingsland v. Dorsey*[7] (1949) contributed significantly to the judicial creation of a standard against which the applicant's conduct before the U.S. Patent and Trademark Office is to be measured. The Court in the *Precision Instrument Mfg. Co.* case stated:

> "Those who have applications pending with the Patent Office or who are parties to Patent Office proceedings have an *uncompromising duty* to report to it all facts concerning possible fraud or inequitableness underlying the applications in issue." (Italics added.)

Thus, the *Precision Instrument Mfg. Co.* case established an "uncompromising duty" standard. This standard was expanded upon by the U.S. Supreme Court in the *Kingsland* case wherein the Court stated that those dealing with the Patent Office must act with the "highest degree of candor and good faith."

U.S. Supreme Court Justice Potter Stewart, unable to define hard-core pornography, is quoted as having said, "I know it when I see it." A similar situation exists in the efforts by the Courts to apply the "uncompromising duty" standard. To what extent is a lapse in memory, a neglectful omission, or a deliberate act permissible? Generally, it is up to each Court, given the particular fact situation of the case before it, to decide whether the standard has been violated by the acts or omissions of the applicant. Deliberate omission of relevant information concerning the prior work of others, failure to call relevant references to the attention of the Examiner, misrepresentation of the nature of the prior art, failure to reveal publications which the inventor authored and a research thesis which he supervised, and failure to make known the existence of foreign patents

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[5] 37 CFR Sec 197, 198, 199

[6] 324 U.S. 806

[7] 338 U.S. 318

which bore directly on the issue of patentability have all been held to render a patent unenforceable.

It is, therefore, the intention of the Patent Office, by specifically requiring the inventor to acknowledge a duty to disclose, to make each inventor aware of the existence of this "uncompromising duty," and to codify the existing case law. There can be no doubt that such a duty exists. In fact, some Courts have gone so far as to state that this obligation extends to not only what the inventor knows, but also to that which the inventor suspects or believes. In short, the inventor and those representing him before the patent Office must reveal their uncertainties as well as their convictions regarding a claimed invention. The duty is indeed a heavy one. However, as stated by the Court in *Xerox Corp. v. Dennison Mfg. Co.*:[8]

> "... an applicant for a patent should be accorded the right to exercise good faith judgment in deciding what matters are and are not of sufficient relevance and materiality to require disclosure. Only when he is guilty of fraud, willfulness or recklessness indicating a disregard for his duty of frankness should enforcement of the patent be barred."

Intent is generally considered a necessary element of fraud.

What are the penalties for misconduct?

Patents can be found invalid, attorney fees may be awarded, and, in severe cases, violators can face fines or imprisonment.

What then are the available penalties against a patentee who has been found guilty of misconduct in dealing with the Patent Office? As above, a finding of inequitable or fraudulent conduct can cause the patent to be held unenforceable against an infringer. A finding that the patent is invalid can make the patent forever valueless to the owner. Further, courts may, in exceptional cases, award reasonable attorney fees to the prevailing party.

In one case, a court awarded attorney fees of more than one million dollars to an accused infringer forced to defend the action where the patentee was found to have obtained the patent by knowingly and deliberately misrepresenting material facts to the Patent Office. Except for exceptional cases of obvious, excessive misconduct, it is considered discretionary with the court as to whether the findings of the case warrant the awarding of attorney fees.

In *Walker Process Equipment Inc. v. Food Machinery and Chemical Corp.*[9] (1965), the U.S. Supreme Court introduced a new dimension to the remedies available to an accused infringer of a patent found to have been improperly obtained. In finding that the patent in question had been fraudulently obtained by knowingly and willfully misrepresenting facts to the Patent Office, the U.S. Supreme Court held that such a finding could form the basis for a treble-damages anti-trust claim, under Section 2 of the Sherman Act, assuming that the other elements required to prove a violation of the Act were present. Severe, gross misconduct in obtaining a patent can therefore subject a patent owner to the extremely serious, far-reaching consequences of a charge of creating or attempting to create an illegal monopoly in violation of the Sherman Act.

Increasing attention is being given to the possibility of applying the provisions of the federal criminal law against patent fraud. The Federal Criminal Code[10,11] provides that anyone who acts in a manner in violation of Section 1001 in any matter within the jurisdiction of any department or agency of the United States is subject to punishment by imprisonment of up to five years and/or a fine of up to $10,000. This provision has not up to now been invoked in patent cases to any significant extent. The attention being given to the possibility of using the criminal code to punish the more flagrant violators of the standards of the patent system suggests that much more will be heard from this area in the future.

Summary

An inventor is required to exercise a duty of good faith and candor in dealing with the U.S. Patent and Trademark Office. To further ensure that this duty is recognized, the Patent Office now requires the inventor to exhibit an understanding of this duty by stating in writing over the inventor's signature that the inventor acknowledges a duty to disclose information of which the inventor is aware which is material to the examination of the patent application.

RCA inventors will be queried by their patent attorneys as to whether they are aware of any information which is responsive or could be responsive to this duty to disclose. This query must be accepted as an extremely serious matter, warranting the full attention and thought of the inventor. Any judgment decisions as to whether something is or is not responsive to the duty to disclose should not be made by the inventor alone. Rather, it behooves the inventor to be completely open and thorough in providing all the information of which he is aware bearing on the creation and development of the invention. In this manner, the inventor can be assured that the duty of good faith and candor has been met.

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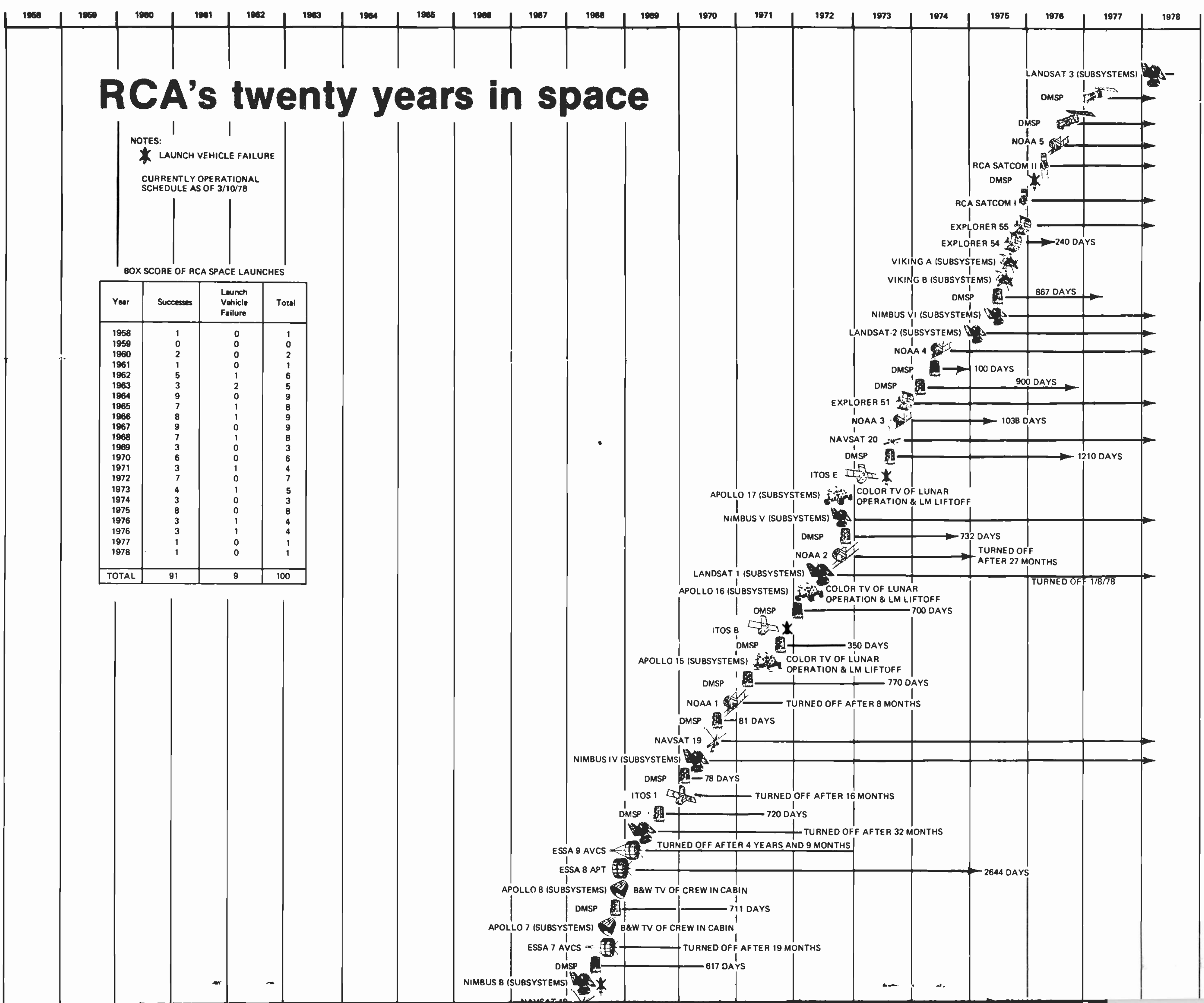
[8] 322 F. Supp. 963 (S.D.N.Y. 1971)

[9] 382 U.S. 172

[10] See footnote 2.

[11] 18 U.S.C. 1001. Statements or entries generally "Whoever, in any matter within the jurisdiction of any department or agency of the United States knowingly and willfully falsifies, conceals or covers up by any trick, scheme, or device a material fact, or makes any false fictitious or fraudulent statements or representations, or makes or uses any false writing or document knowing the same to contain any false, fictitious or fraudulent statement or entry, shall be fined not more than $10,000 or imprisoned not more than five years, or both."

RCA's twenty years in space



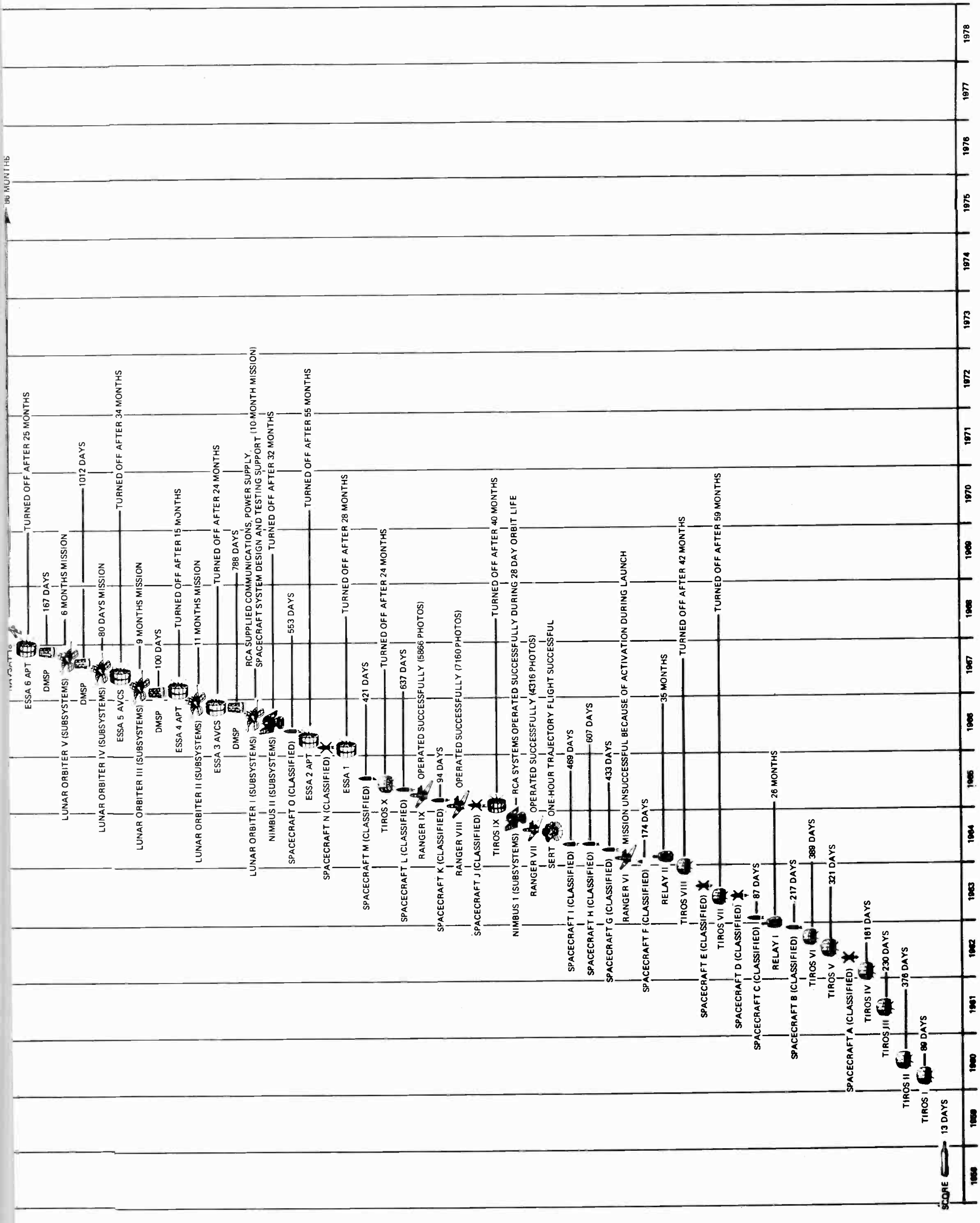
NOTES:

✱ LAUNCH VEHICLE FAILURE

CURRENTLY OPERATIONAL SCHEDULE AS OF 3/10/78

BOX SCORE OF RCA SPACE LAUNCHES

Year	Successes	Launch Vehicle Failure	Total
1958	1	0	1
1959	0	0	0
1960	2	0	2
1961	1	0	1
1962	5	1	6
1963	3	2	5
1964	9	0	9
1965	7	1	8
1966	8	1	9
1967	9	0	9
1968	7	1	8
1969	3	0	3
1970	6	0	6
1971	3	1	4
1972	7	0	7
1973	4	1	5
1974	3	0	3
1975	8	0	8
1976	3	1	4
1976	3	1	4
1977	1	0	1
1978	1	0	1
TOTAL	91	9	100


1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
SCORE — 13 DAYS
TIROS I — 80 DAYS
TIROS II — 376 DAYS
TIROS III — 230 DAYS
TIROS IV — 161 DAYS
SPACECRAFT A (CLASSIFIED)
TIROS V — 321 DAYS
TIROS VI — 389 DAYS
SPACECRAFT B (CLASSIFIED) — 217 DAYS
RELAY I — 26 MONTHS
SPACECRAFT C (CLASSIFIED) — 87 DAYS
SPACECRAFT D (CLASSIFIED)
TIROS VII — TURNED OFF AFTER 59 MONTHS
SPACECRAFT E (CLASSIFIED)
TIROS VIII — TURNED OFF AFTER 42 MONTHS
RELAY II — 35 MONTHS
SPACECRAFT F (CLASSIFIED) — 174 DAYS
RANGER VI — MISSION UNSUCCESSFUL BECAUSE OF ACTIVATION DURING LAUNCH
SPACECRAFT G (CLASSIFIED) — 433 DAYS
SPACECRAFT H (CLASSIFIED) — 607 DAYS
SPACECRAFT I (CLASSIFIED) — 469 DAYS
SERT — ONE-HOUR TRAJECTORY FLIGHT SUCCESSFUL
RANGER VII — OPERATED SUCCESSFULLY (4316 PHOTOS)
NIMBUS 1 (SUBSYSTEMS) — RCA SYSTEMS OPERATED SUCCESSFULLY DURING 28 DAY ORBIT LIFE
TIROS IX — TURNED OFF AFTER 40 MONTHS
SPACECRAFT J (CLASSIFIED)
RANGER VIII — OPERATED SUCCESSFULLY (7160 PHOTOS)
SPACECRAFT K (CLASSIFIED) — 94 DAYS
RANGER IX — OPERATED SUCCESSFULLY (5866 PHOTOS)
SPACECRAFT L (CLASSIFIED) — 637 DAYS
TIROS X — TURNED OFF AFTER 24 MONTHS
SPACECRAFT M (CLASSIFIED) — 421 DAYS
ESSA 1 — TURNED OFF AFTER 28 MONTHS
SPACECRAFT N (CLASSIFIED)
ESSA 2 APT — TURNED OFF AFTER 55 MONTHS
SPACECRAFT O (CLASSIFIED) — 553 DAYS
NIMBUS II (SUBSYSTEMS) — TURNED OFF AFTER 32 MONTHS
LUNAR ORBITER I (SUBSYSTEMS) — RCA SUPPLIED COMMUNICATIONS, POWER SUPPLY, SPACECRAFT SYSTEM DESIGN AND TESTING SUPPORT (10-MONTH MISSION)
DMSP — 788 DAYS
ESSA 3 AVCS — TURNED OFF AFTER 24 MONTHS
LUNAR ORBITER II (SUBSYSTEMS) — 11 MONTHS MISSION
ESSA 4 APT — TURNED OFF AFTER 15 MONTHS
DMSP — 100 DAYS
LUNAR ORBITER III (SUBSYSTEMS) — 9 MONTHS MISSION
ESSA 5 AVCS — TURNED OFF AFTER 34 MONTHS
LUNAR ORBITER IV (SUBSYSTEMS) — 80 DAYS MISSION
DMSP — 1012 DAYS
LUNAR ORBITER V (SUBSYSTEMS) — 6 MONTHS MISSION
DMSP — 167 DAYS
ESSA 6 APT — TURNED OFF AFTER 25 MONTHS

Engineering undergraduate education in the 70s—closing the loop

J.J. Karakash

Today's engineering students must learn to practice "assessment before the fact" as they cope with a broader range of technologies and become more aware of the consequences of their technical proposals.

In broad terms, the engineering function has evolved through four major stages as shown in Fig. 1. Specific dates for each stage are unnecessary, beyond saying that the third stage grew gradually until World War II at which time it burst into growth. As with the other three stages, the fourth stage—closing the loop—also starts with the identification of need. But unlike the other stages, the loop is closed with an assessment of the quality of the need—in terms of its impact on the human condition. We must learn how to close the loop. If we fail, instead of technology enabling us to implement national purpose, it will be permitted to dictate it by default. We are virtually being forced by events to think in terms of closing the loop. We should have taken this matter seriously, but did not choose to until compelled to do so by the threat to life, both in terms of the biological compatibility of the planet and also the social stability of organized community life.

Today, we try to educate within the context of the fourth stage, within the closed loop.

If a student develops a specific interest, for example, in research, development, design, production, or operational management, we are responsible as educators to help that student develop competence in that one function, but also understand the essential role of that function in the context of the entire sequence. And beyond all this, a student must be taught to think in terms of the consequences of technical developments.

Great as the need for stressing this latter parameter may be, our ability to do the job in our classrooms is limited. We just do not know how to inspire technically curious students to become increasingly society-oriented and to want to become increasingly human in all their interactions with society. This is as true in the education of lawyers, legislators, bankers, or physicians as it is in the education of future engineers; it applies to all professions.

Engineering degree programs

Present-day four-year engineering degree programs generally include four components:

1) basic science and mathematics
2) humanities and social sciences—including economics
3) engineering sciences—corresponding to selective extensions of applied science and mathematics
4) applications to engineering design.

These four components are required by the ECPD (Engineer's Council for Professional Development)—our accrediting agency. Beyond this formal requirement, of course, these components are essential in promoting total student growth. The relative weight or credit hours allotted to each of the four components within four-year programs varies somewhat among student curricula in different colleges and even among individual student programs within one college or one curriculum. Normalizing to the two-semester-per-year four-year program, the requirements range from around 120 to 140 credit hours. Wide as this range may appear, there are often valid reasons for the variation. Entrance requirements and range of qualifications of incoming classes are among the reasons; also, summer field work receives credit in some instances.

Within these credit-hour graduation requirements, the four components are identifiable in terms of the following credit-hour ranges:

component	*credits*
basic science and mathematics	35 - 45
humanities and social sciences	18 - 35
engineering sciences	25 - 40
applications to design	15 - 30

The first component— basic science and mathematics

The mathematics requirement continues to include the calculus, linear mathematics (including matrices and ordinary differential equations) and a course in probability (including some statistical inference). This package at Lehigh amounts to 18 credit hours and is usually completed

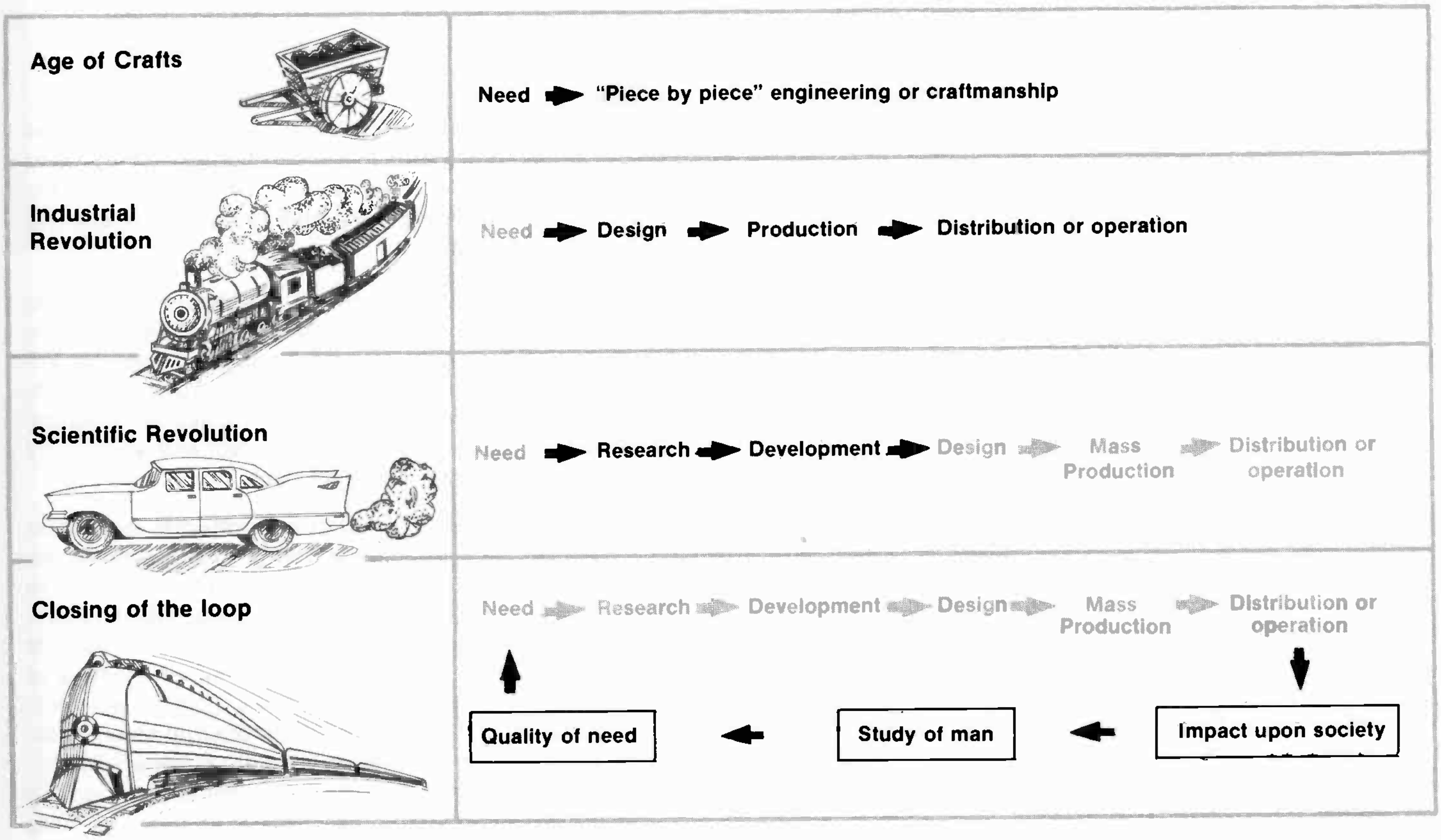


Fig. 1
Evolution of the engineering function. All four stages start with an identification of a need. It is only recently, however, that we have begun to evaluate the **quality** of the need. (From "Education through Engineering"; J.J. Karakash, Middle States Report, 1966).

during the first five semesters. Some engineering degree programs, electrical engineering, for example, require additional courses in mathematics. One or two of our programs where analytical work is not a major common requirement have a minimum requirement of 15 credit hours; students in such programs may graduate without a full course on probability or linear mathematics. However, these students will probably learn to use the techniques of linear mathematics by working out engineering problems in their departmental courses.

Every engineering student completes "freshman chemistry" which includes atomic structure and bonding, stoichiometry, and an exposure to kinetics, chemical equilibrium, acid-base theories, oxidation-reduction reactions, and galvanic cells. Quite a few students will not stop there. An electrical engineering student, for example, interested in the theory of solid-state devices (not circuits) would learn some fundamentals of "solid state chemistry" which is an application of physical chemistry. Chemical engineers must complete at least three more chemistry courses, in organic and physical chemistry.

In physics, all engineering programs continue to require kinematics—laws of motion in Newtonian Theory and conservation laws as applied to mechanics of mass points. Laws of thermodynamics—heat, temperature and some kinetic theory of gases—follow. Upon completion of the above, the required program continues with electrostatics, magnetostatics, and electric currents. Maxwell's equations and waves precede an exposure to physical and geometrical optics. In some institutions, the common physics requirement includes exposure to modern physics. As with chemistry, some engineers have additional program requirements beyond the minimum—for example, introduction to quantum mechanics for some electrical engineers and materials science students.

Two developments within this entire component deserve noting. First, greater reliance has been placed on the use of mathematics in physics courses. Second, we have introduced the computer, not merely as a programmable calculator, but also as an entirely new approach to the engineering method. This introduction starts during the first year.

The second component—humanities and social sciences

The program in the humanities and social sciences for engineering students is a *de facto* admission that we must educate within the closed loop of our fourth stage (Fig. 1). At Lehigh, this component is called General Studies. It requires two courses in English and literature and one in economics. Students also choose at least five courses from offerings in history, philosophy, religion, fine arts, government, international relations or classics. More recently, we have attempted to develop and teach "impact" courses—social perspectives on technology. I find it difficult to comment intelligently on such efforts beyond saying that they constitute an honest intent, within the constraint of the four years and staff resources, to organize programs that will help students develop personal values that are consistent with the "closed-loop" responsibilities of the engineering profession.

When it comes to measuring the effectiveness of this component we face a difficult task. As is the case with all formative education, grading of examinations is a reading on classroom assignments, not a true measurement of attitude or conviction. The situation is comparable to teaching a course in ethics. Students who complete the course will not necessarily adopt a personal code of ethics commensurate with their grades. The least we can do for, and with, engineering students is to prepare them to face the world of contradictions which characterizes our society and challenge them to help overcome its weaknesses while preserving its values.

The third component—engineering sciences

The third component, the engineering sciences, constitutes the "muscle" of engineering programs. Interpreted more generally, this component extends into modern applied science and applied mathematics. This wide umbrella component includes such areas as solid mechanics, thermodynamics, heat transfer, fluid mechanics, circuit theory, field theory, electromagnetic theory, elasticity, materials science, linear systems, logic, computer and computing science, information science, optics, solid-state physics, partial differential equations (applied), and statistical methods. The above list is quite descriptive but by no means complete. On occasion biophysics and geophysics are also chosen.

For any particular degree program, some of these courses are, of course, required. On the other hand, no student can complete the degree program without including courses from this group beyond those required by the degree. For instance, a student majoring in mechanical engineering may choose the circuit theory course as part of an engineering science requirement; the electrical engineer, however, is required to take it, the same being true of electromagnetic theory. To satisfy this component, however, the electrical engineering student will have to include courses such as dynamics, thermodynamics, materials science, fluids, or optics.

This flexibility is both an asset and a liability. It is an asset if the individual student advisors are both fully informed as well as student-oriented. To be effective, advisors must be familiar with the level of difficulty and actual work requirements of courses in and outside their own department, as well as with the potential of the students they advise.

The fourth component—applications

Applications to design takes up a good part of the senior year, and the courses in this component have prerequisites that are satisfied by courses from component three. If we were to view the first two years as "body building," and the third as "muscle building"—then the fourth year is learning to apply this muscle.

Many larger colleges have shifted to a senior year that is mostly elective; this is perhaps the most significant recent development in engineering programs, in colleges that are large enough to afford it. This shift recognizes the reality that, even within a particular engineering degree program, we cannot do justice to student interests and abilities by using the same course recipe for each student.

Present-day realities require that a fourth-year student be given choices among several fields. For example, an electrical engineering senior ought to have opportunities to take anywhere between six and eight courses dealing with applications. The fields of such applications could include computers, solid-state devices, communication theory and communication systems, microwaves, control systems, power systems, instrumentation, or industrial electronics. Hence, a senior, even if unable to specialize in one field (this is to be discouraged even if it were possible) can, on the average, attain essential competence in as many as three possibly interrelated fields. Such an educational policy has practical advantages when one considers prospects of employment of graduating seniors.

At Lehigh, electrical engineering students select their senior electives from among a variety of offerings in their own department and the offerings of other academic units. They choose from among electrical engineering courses such as pulse and digital circuits, control systems, power systems, communication theory, transistor circuit applications, compiler design, computer architecture, digital system design, digital signal processing, microwave circuits and techniques, microelectronics technology, or applied integrated circuits. There are some twenty such electives open to seniors, or about 10 per term. The idea is to accommodate the individual needs and interests of as many seniors as our resources will allow. They also look into, and choose, upper-level courses offered by other academic units such as the Departments of Engineering Physics, Mechanical Engineering, Materials Science or Industrial Engineering. Thus, when we refer to the senior electives of the fourth component as "application to design," the implication is that we return to principles already identified in the engineering science component, extend them, and apply them in developing design principles for devices, circuits, instruments, or systems.

In the teaching of senior-year design courses, there is need for some vigilance—to avoid the practice of teaching design courses as "revealed systems"—where the course is a faithful, step-by-step repetition of some design worked out by the professor a decade ago. It is not enough to help students understand how a particular design approach developed and how to practice it: they must be educated with the idea that they will also contribute to the knowledge which will cause a change in that practice.

In essence, the third and fourth components together acquaint engineering students with a wide range of physical laws, principles and phenomena, along with course opportunities where students acquire methods, approaches, and techniques in applying these principles. **Thus, ideally, it is the mastery of methods and techniques, based on principles, that becomes part of the student's education, not the designs themselves.** On this account, we often refer to education *through* rather than *in* engineering. Unfortunately, this is not understood well enough by some among our peers who point to specific design work by our seniors and who conclude that we are "specializing." They fail to see that designs of specific items in our courses are the means *through* which we educate, not our prime academic objectives. Thus, when an electrical engineering senior spends some time organizing for, and putting together, an integrated circuit operational amplifier, the academic gain is not the "how to do it" part of the venture, but rather the grasp of the elements and principles involved which are based upon the knowledge acquired from engineering science courses and their translation into a functional unit.

The most visible recent course entries into the elective system of the fourth component have been courses related to computers. The design of a computer-controlled distillation column in a chemical engineering laboratory is no longer a novelty any more so than courses including computer-aided design or manufacture for industrial engineers. With the advent of minicomputers and microprocessors, applications and design courses are providing new challenges to those professors who use their courses as vehicles to introduce new technology or instrumentation. Along with the many positive challenges generated by the entry of the computer into engineering programs, there is one possible negative aspect. This refers to the tendency in some programs to use computer-related courses as an excuse to reduce emphasis in actual laboratory work. The reason in such instances may be economics. But the result is unfortunate. All engineering students *must* be taught principles and learn first how to measure, second what they need to measure, and third (in their upper level work) how to make use of the measurement. Instrumentation remains a dominant part of engineering curricula. The computer is a superposition to, not a substitute for, the lab.

Four consequences

The effectiveness of education is not measured in terms of what we do to, for, or with students, but rather by what happens to them as a result of what we do.

There are four invariant consequences we try to achieve through our programs—whether we specifically say so or not:

- Help students develop intellectual capacity—the ability to think, think clearly to the point where thinking becomes a habit;
- Encourage and stimulate—we cannot compel—students to develop a sense of values and live by them;
- Require that students master the intelligent application of knowledge in the solution of problems and last, but not least;
- Insist on the acceptance of work as a vehicle for service to society and the will to work as a self-discipline for life.

No absolute one-to-one correspondence exists between these four consequences and the four components comprising our programs. There are some definite connecting links, of course. For instance, we do stress and expect students to develop "the intelligent application of knowledge" in our "applications to design" courses just as we hope our General Study program will stimulate engineering students to think in terms of human values as they take into account implications of technological innovations in which they play a role. Perhaps more than any other academic group, engineering colleges stress the importance of the fourth consequence, namely, the will to work.

The students

Engineering colleges continue to attract students from among the most competent high school seniors.

In a medium-sized private institution such as Lehigh, the present-day combined mean math-verbal SAT score is around 1200-1210, with Math 665 to 660, and Verbal 545 to 550. The trends in SAT scores, as far as our own college is concerned (and this is not atypical), show a peak in 1965 when the mean math scores were in the 680-685 range and verbal 600 to 605 range for a mean combined score of 1285. Since then, the trend has been monotonically downward for about eight years to a low of 1180 in 1973. Since then, there has been a gradual upward swing to the current 1200-1210 range. It is important to note that the recent upward trend continued despite increased enrollments in our college of the order or 25%.

Even if SAT scores do not measure precisely any one thing (or measure any one thing precisely), motivation, industriousness, imagination, and creativity are more prevalent among the higher brackets of test scores. This does not mean that every now and then a freshman with a combined score of 1050 will not rise to the occasion, overcome background difficulties—attributable to high school conditions and motivation, rather than to low innate ability—and end up in the upper quarter of the graduating class. Nevertheless, in the same class group, there will have been quite a number of students with scores above 1400 and some approaching 1500 who need just as much attention in the sense their programs need to be individually designed if they are to profit optimally from their education. We find that the availability on a campus of professors carrying on research with their graduate students is an invaluable asset in keeping up the motivation of the gifted undergraduate, even if the contacts between them are not through the formality of a scheduled course.

The problem we'd like to face in connection with gifted students is how to help them invest productively four years on the campus and not how to help them finish the degree work program in three years. The latter approach, namely, the accelerated pace to the diploma, has obvious economic advantages. However, beyond the acquisition of credits, the completion of courses, there is such a thing as striving for growth toward the realization of a person's full potential. Difficult as this intangible may be to measure, it is quite a challenge for those who face it.

Some student attitudes and program trends

A number of issues relating to students and student attitudes and expectations deserve attention.

The number of engineering students thinking seriously about graduate school is currently below what may be required for our national interest.

We should admit that there was a time, some two decades or so ago, when graduate school was the stated objective of a few too many—including those for whom it was not an optimal investment of their time. Perhaps the draft was a factor at the time.

During the current decade, initially as part of the Vietnam-related student activism, which reacted negatively to what some called the "military-industrial" complex—engineering and indeed the entire profit-motivated free-enterprise system came under attack. Even though this situation did not last more than five or six years, high school student attitudes were nevertheless affected. Increasingly greater numbers of qualified students were "turned off" by engineering as well as physics. Eventually, of course, this affected the graduate school picture as well.

When, within the same decade, the government terminated its large R & D programs, many industries released a large number of professionals while at the same time drastically reducing or completely arresting hiring engineers, both at the BS and graduate levels. The brightest BS students with an eye to the market became most eager to accept offers from the few employers who were still hiring, rather than go to graduate school.

There are signs of a gradual improvement during the last year or so. However, salaries now offered by industry to qualified seniors are too tempting for many to resist. Our own attitude in advising students regarding graduate school must be based on student growth—not market expediency. Certainly, we should not want to accept, let alone encourage, the "two degrees are better than one" concept of earlier years. Some students because of natural inclinations and range of intellectual ability benefit far more from direct exposure to the world of work following graduation. And, of course, there are others for whom full-time graduate school is by far the better alternative. Effective advising of seniors means trying to optimize the growth path for each undergraduate student while keeping in mind that there are effective part-time graduate programs, especially for MS level work.

Because of trends in undergraduate engineering programs, it is no longer sufficient or desirable to identify specific industrial needs in terms of strictly departmental designations.

An employer interested in a qualified undergraduate with some heat transfer background may find such a candidate among mechanical *or* chemical engineering seniors. Departmental lines break down even in considering faculty.

One will find a professor in the Department of Mechanical Engineering who earned his degrees in Chemical Engineering or a professor of Electrical Engineering with degrees in Physics. Beyond this there is the cross listing of courses among departments. For example, an upper level elective in polymers at Lehigh is entered under three different listings, in the Department of Chemical Engineering as Chem. E. 393, in Metallurgy and Materials Science as Met. 393, and in Chemistry as Chem. 393.

In the area of solid state devices and systems, an Engineering Physics senior may be just as likely to fit into a situation as an electrical engineer, the same being true in microwaves or instrumentation.

The senior elective system allows students from different departments to develop competence in the same field. Since this trend is increasing, industry may want to take this into account in its recruiting practices, and stress fields rather than just departments.

Many engineering colleges have submitted to demand pressures and established BS programs based on topical areas.

With the aerospace age and the large initial federal investments in that area, some engineering colleges organized aerospace departments and gave BS degrees. The same with other more recent topical areas, notably bioengineering and environmental engineering. Such topical degree programs can be little more than partial combinations of two or three generic degree programs—such as ME, EE, Chem E, etc.

Although such topical fields provide exceptional challenges and opportunities for *graduate* research, the justification for an *undergraduate* program is questionable. On the other hand, undergraduates interested in seeking employment in such fields can use the senior year elective system already described to come as close as any four year program can in providing a foundation for employment or for graduate work.

Private industry, by far the biggest "customer" for undergraduates, may wish to enter into a dialog with engineering schools to help them identify essential needs for programs in such non-generic areas. Of course, we must and do respond to topical needs by introducing senior-year electives in new, relevant areas. Where we lack such competence we make use of adjunct professors. However, it may not be in the long-range interest of our students or the nation to trade off analytical competence for topical range and dilute the strength of generic degree programs. This may have been one of the negative consequences of the widely proclaimed "interdisciplinary" period spanning the late 60s and early 70s. Since engineering programs were never "monodisciplinary" it is indeed difficult to interpret such terms as "interdisciplinary, multidisciplinary, or cross disciplinary" in a meaningful way.

Programs for employees

Far-sighted industrial concerns will continue to invest in their new engineers' education.

Highly qualified and motivated undergraduates contemplating employment are genuinely interested in, and influenced by, corporate policies toward programs to promote their continued growth, even when these are not degree oriented. Such students are intelligent enough to view the graduate degree as a most desirable consequence of education, but not its objective. They know that the real objective is their continued growth.

Many leading industries in our country are farsighted enough to enable continuing education of their engineers. On the other hand, there are instances when such education is viewed as an investment only when things are booming—when the dollars are there—but the time is not. When things slacken a little, the time is there but the dollars are not.

Intelligently designed educational programs for employees can be cost effective to the point that they survive even when the year end "bottom line" is less than optimal. On the other hand, there are examples of large scale expenditures by industry to launch ambitious programs with predictably unfortunate outcomes. Hybrid (both plant-based and campus-based) programs may be the optimal approach for many plants since they enable both degree and non-degree programs at minimal cost both in time and dollars, if both plant management and college are earnest in wanting to collaborate to their mutual advantage. Programs can only be optimized if each plant is able to take advantage of its size, character, geography, and proximity to a university. Too much centralization at corporate headquarters of program policy works to the detriment of optimal plant-campus working relations.

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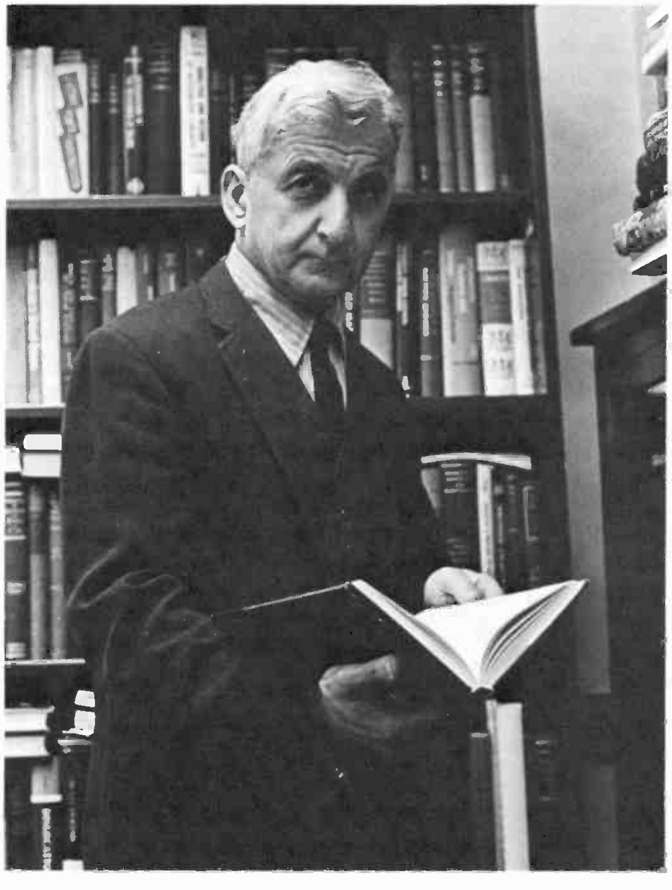

OSCAR—orbiting spacecraft for amateur communications

J.A. King
J. Kasser
W. Maxwell

The OSCAR series of communications satellites are prime examples of how radio amateurs are taking home high-level management and technology skills from offices and labs and applying them to their spare-time activities.

Many hobbies emulate a professional discipline or corporate activity (e.g., amateur astronomy; personal computing) and most are represented by local, national, or international organizations. Some hobby associations have organizational structures and financial means which generate (for the devotees, at least) real political situations which are best solved by using modern management techniques.

Few avocations are more diverse and technologically complex than the hobby of amateur radio. With more than a dozen "sub-hobbies," the "Radio Amateur Service" provides an opportunity to experiment with activities ranging from microwave engineering to providing communications in times of emergency. One particular subset of amateur radio which has emerged in the last two decades is the direct result of aerospace technology—the Orbiting Satellites Carrying Amateur Radio (OSCAR) communication systems.

Six times a day, two OSCAR spacecraft skim across North American skies on their steadfast journey around the earth. During each of the passes, amateur radio operators track the 65-pound "birds," less than 1,000 miles overhead, to communicate through them with other radio amateurs, within a range of 2,500 km.

OSCARs are the brainchildren and products of radio amateurs. As the satellites rise above the horizon for periods ranging from a few seconds to 22 minutes, they present a target traveling at about 14,000 miles per hour toward which ground-based amateur radio operators aim their messages for the spacecraft to carry to other operators within range.

Similar to the RCA-built Relay, NASA's first communications satellite, and other low-altitude communications satellites, OSCARs 7 and 8 circle the earth at nearly two-hour intervals. Radio amateurs within reach of their north-south trajectory can communicate by relaying messages received from the ground through the satellite transmitters, which operate at a power level of about one watt. This capability of OSCAR becomes more amazing when one considers that inexpensive CB radio transmitters have a power output two or three times that of the transmitter on board the spacecraft.

OSCAR history

The OSCAR program had its inception in the writings of a radio amateur in *QST*, the *Journal of the American Radio Relay League*, (ARRL), in 1960. He suggested the construction of a space satellite by radio amateurs. The idea caught on and Project OSCAR was formed in California.

The first satellite of the OSCAR family was carried into orbit on board a Thor-Agena launch vehicle, whose main payload was Discoverer XXXVI, on December 12, 1961. The launch marked 60 years to the day that Guglielmo Marconi, the world's self-professed original radio amateur, made history by receiving the first transatlantic shortwave radio signals. OSCAR 1, built by radio amateurs on the West Coast, transmitted telemetry and Morse code signals for almost three weeks until its batteries were exhausted.

But Project OSCAR was not the first time signals were acquired from space satellites by radio amateurs. When the U.S.S.R. launched Sputnik I in 1957, Russian scientists chose a beacon frequency very close to the 21-MHz amateur band. Presumably, the choice was not made by chance, for although signals from the spacecraft could be heard by anyone with a suitable receiver, radio amateurs were the people most likely to have such receivers. Within minutes of the launch, many amateurs were eagerly tuning their receivers to pick up Sputnik's signals from space.

OSCAR gains international support

OSCARs 1 through 4 were built by radio amateurs on the West Coast. It was not until 1969, that the feasibility of building, designing, and testing such satellites by the amateurs on the East Coast was recognized. Many of these amateurs were employed by government agencies (such as NASA) and commercial organizations (such as RCA). The formation of an East Coast group to conduct such a program was proposed.

The idea took hold. Discussions were held between representatives of the amateur radio clubs of COMSAT, the Johns Hopkins University Applied Physics Laboratory, IBM Federal Systems Division, Aeronautical Radio, Inc., Communications and Systems, and NASA Goddard Space Flight Center. Many of those present at the various meetings, already involved in other space programs, were interested in the idea of the Radio Amateur Satellite Program. But most important, many were in contact with officials of government and industry who could render invaluable assistance to the program.

On March 3, 1970, the Radio Amateur Satellite Corporation (AMSAT) was formed. AMSAT's first project was to manage the launch of the AUSTRALIS-OSCAR 5 spacecraft built by a group of radio amateurs at Melbourne University, Australia, (from which group the spacecraft derived part of its name).

OSCAR 5 was the beginning of international cooperation in the OSCAR series of spacecraft. As the series progressed, amateurs from several other countries became participants in the OSCAR program. Even the Soviet Union plans to enter the "amateur satellite race." The U.S.S.R. has announced its intention (via the International Telecommunications Union) to launch in 1978 a series of amateur radio satellites carrying transponders whose frequencies are compatible with the OSCARs already in orbit.

AMSAT also has a program for developing low-cost portable terminals for use with its spacecraft. These terminals cost about $1,500 and consist of commercial transceivers integrated into a portable package. They can be powered by an automobile battery and use tv-style anten-

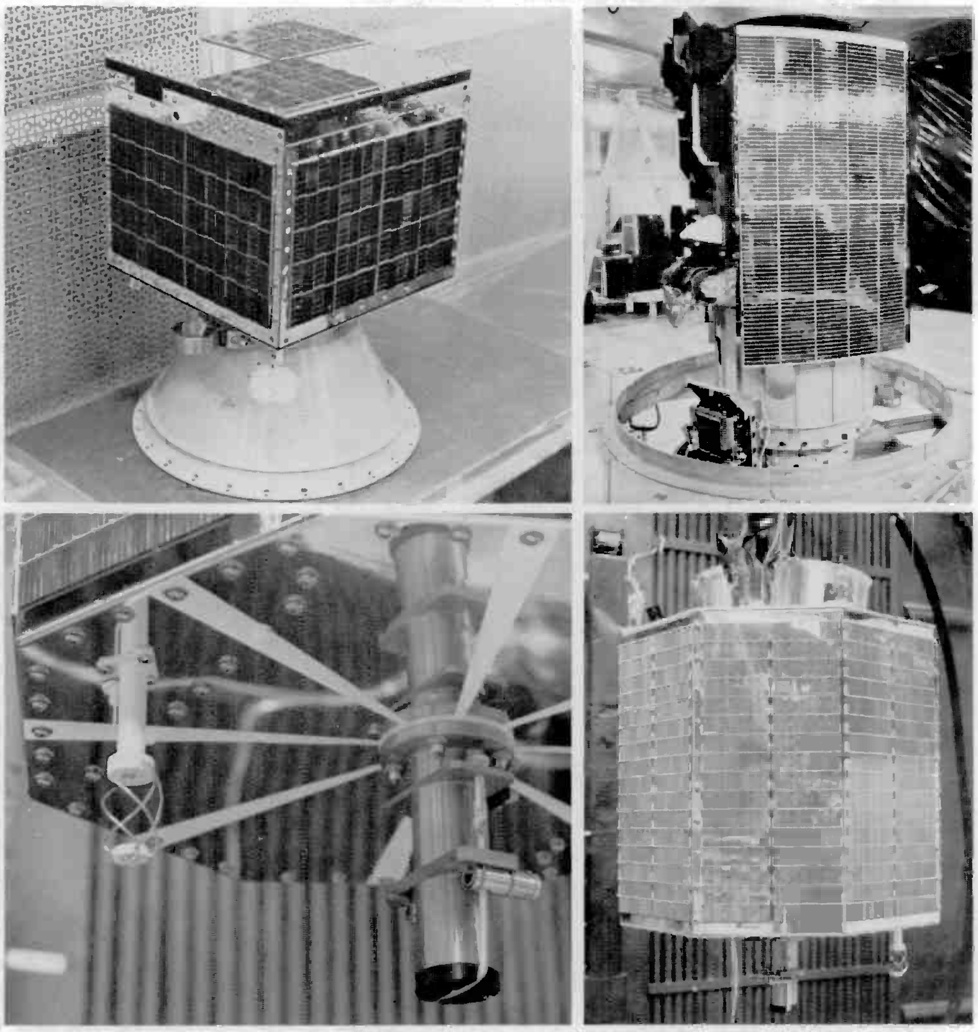

Photo montage shows several spacecraft in the OSCAR series. Starting at upper right and moving clockwise are 1) OSCAR-6 amateur radio piggyback satellite mounted on the Delta launch vehicle below the ITOS-D primary payload, 2) OSCAR-7 spacecraft, 3) closeup of RCA-donated quadrifilar antenna for OSCAR-7 (at left), and 4) OSCAR-8 spacecraft.

Walt Maxwell, W2DU, joined RCA as patent researcher at RCA Laboratories, Princeton, in 1949. He has been a member of the spacecraft antenna design group of Astro-Electronics since the Division was formed in 1958. He designed the antennas for Echo 1 and for many of the TIROS weather satellites and assisted in the design of Apollo's Lunar Rover earth-link antenna. Walt has been a licensed radio amateur since 1933. He is also a member of the FCC Advisory Committee for Amateur Radio, in preparation for the 1979 World Administrative Radio Conference, ITU, Geneva.

Contact him at:
Spacecraft Antenna Design
Astro-Electronics
Princeton, N.J.
Ext. 2109

Joe Kasser, G3ZCZ, is a member of the Technical Staff at the Communications Satellite Corporation in Clarksburg, Md. He joined COMSAT Laboratories in 1973 and is currently investigating microprocessor and distributed processing applications for automatic satellite control functions. Mr. Kasser is a member of the IERE and serves as the Editor of the AMSAT Newsletter.

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Jan King, W3GEY, for the past ten years has been an engineer with NASA's Goddard Space Flight Center in Greenbelt, Md. He is presently a member of the Communications and Navigation Division and is involved with R&D in the communications satellite area. In his amateur work he has served as AMSAT project manager for OSCARs 5, 6, 7 and PHASE III.

Above, co-author Joe Kasser. At right is the electrical test model of OSCAR-7 attached to an ITOS weather satellite in launch test configuration at Astro-Electronics. Photo shows RCA-donated 2304-MHz quadrifilar beacon antenna developed by R. Bricker (holding antenna) and co-author Walt Maxwell (standing left). Co-author Jan King is seated at right and antenna tester W. Ozman is standing at right.

nas that can be folded up and carried in a container the size of a golf bag. They are especially suited for use in disaster areas to provide reliable communications at low cost.

Amateur space techniques

With the launching of a reliable long-life radio amateur communications satellite (AMSAT-OSCAR 6) in October 1972, radio amateurs were, for the first time, free to pioneer space communication techniques in a systematic manner.

American radio amateurs are allowed to relay telephone calls ("phone patch") to certain countries through their ham equipment. The majority of such calls link American servicemen on board ships at sea, and missionaries in remote places where connections to commercial networks are non-existent, with their families at home. In September 1974, the first claimed use of a satellite for this ham service was for a "phone patch" relay between the United States mainland and Hawaii via AMSAT-OSCAR 6.

Emergency communications capability has been demonstrated by special tests organized by the ARRL which simulated disaster conditions such as earthquakes in Alaska. Occasionally, hams journey to remote places to put a rare "country" or state on the "radio map." Such journeys, called "DX-peditions," have included spending a night next to a graveyard in West Virginia, operating a portable station in the Vatican, and setting up a battery-powered station on the Mall in Washington, D.C., for the opening of the new Smithsonian Aeronautics and Space Museum in July 1976. These DX-peditions and the results of the simulated emergency tests have shown that small, low-cost (less than $1,500), low-power (10 to 100 W) stations can easily put usable signals into the OSCAR spacecraft.

In October 1975, electrocardiogram (EKG) data was transmitted from Santa Ana, California, to the National Institutes of Health Amateur Radio Club, Bethesda, Maryland, via AMSAT-OSCARs 6 and 7. The received data was an acceptable EKG pattern, closely resembling the original transmitted signal. In conjunction with the portable and mobile terminal tests, amateurs have shown that medical data can be relayed from remote areas to hospitals via low-altitude, low-cost satellites and terminals.

The AMSAT-OSCAR 6 satellite has been used by the Canadian Communications Research Center and by NASA's Goddard Space Flight Center to successfully demonstrate the feasibility of a satellite-aided search and rescue technique that can reduce the time and costs associated with conventional methods of finding downed aircraft.

It is mandatory for all aircraft in the U.S. and Canada to carry Emergency Locator Transmitters (ELTs) operating on an international distress frequency of 121.5 MHz. The ELT is designed to switch itself on at the time of a crash and transmit a signal for at least 100 hours so that search and rescue aircraft can "home in" on it.

OSCAR chronology

OSCAR 1 was launched on December 12, 1961, and operated for 18 days. Communications through the satellite resulted in more than 5,000 reception reports from amateurs in 28 countries. OSCAR 1 also introduced the concepts of "Doppler tracking" and "telemetry decoding" to the radio amateurs of the world. The satellite's telemetry system was very simple; the beacon continually transmitted the message "Hi" in Morse code. The number of "Hi's" transmitted within a 10-second time period was a function of the internal spacecraft temperature.

OSCAR 2, launched June 2, 1962, was similar to OSCAR 1 and also had an active life of 18 days.

OSCAR 3, launched March 9, 1965, was the world's first free-access communications relay satellite, having been placed in orbit one month before Intelsat launched Early Bird. OSCAR 3 contained an in-band transponder at 145 MHz, powered by silver-zinc batteries. It was active for 15 days, during which time 176 two-way communications, including a number of transatlantic contacts, were claimed by 98 participating radio amateurs, 67 in North America and 31 in Europe. Because the battery covers could not be replaced before launch, battery life was somewhat reduced. OSCAR 3 also carried a two-channel telemetry beacon, powered by solar cells, which transmitted for several months, sending back spacecraft internal temperature and voltage data.

OSCAR 4, launched December 21, 1965, was the OSCAR Program's first "misfire." The spacecraft was supposed to be injected into a near-synchronous orbit at an altitude of about 32,000 km (approximately 20,000 miles), but the third stage failed to ignite, leaving the launch vehicle in a highly elliptical transfer orbit. Consequently, OSCAR 4 was injected into an orbit with a perigee of approximately 200 km (125 miles) and an apogee of 33,000 km (20,500 miles) at zero-degree inclination.

Built by radio amateurs of the TRW Amateur Radio Club of Redondo Beach, California, OSCAR 4 carried a transponder which received signals at 144.1 MHz and transmitted them at 431.93 MHz within a 10-kHz bandwidth. Power for this spacecraft was furnished by solar cells instead of batteries. OSCAR 4 suffered from a solar array malfunction in its elliptical orbit. With its passband only 10-kHz wide and operating slightly erratically, communications through OSCAR 4 was quite difficult. However, it did provide the first direct satellite link of any kind between the United States and the U.S.S.R.

AUSTRALIS-OSCAR 5, launched on January 23, 1970, was the first international effort: the satellite had been built in Australia and space-qualified by American amateurs. It was the forerunner to achieving greater international cooperation by radio amateurs in the satellite field.

The AUSTRALIS-OSCAR mission was significant in that it utilized a command system to demonstrate that radio amateurs could successfully control the operation and transmissions of more complex long-lived spacecraft in orbit. This capability was ably demonstrated when the 28-MHz beacon was commanded "on" on Fridays and "off" on Mondays, thus confining its operations to weekends when the greatest number of amateurs would be able to monitor spacecraft signals.

AMSAT-OSCAR 6 was launched on October 15, 1972, and amateur radio contacts by satellite became everyday occurrences. OSCAR 6 carried a linear transponder relaying signals from 145.9 MHz to 29.5 MHz within a 100-kHz passband. The telemetry beacon transmitted 24 channels of data encoded in Morse code; consequently, any amateur with an understanding of the code could decode the telemetry output and determine the condition of the spacecraft. Solar cells on the spacecraft recharged its nickel-cadmium (NiCd) batteries, greatly extending the useful lifetime of the spacecraft.

The spacecraft also contained a message storage facility known as Code-store which utilized a memory that could be loaded from the ground with a message in Morse code. The message was then transmitted by the beacon instead of the telemetry data. Code-store was used by the Canadian and Australian Command Stations to exchange messages (the satellite was not within range of both stations at the same time) and by AMSAT to alert satellite communicators to changes in the operating schedule of the spacecraft.

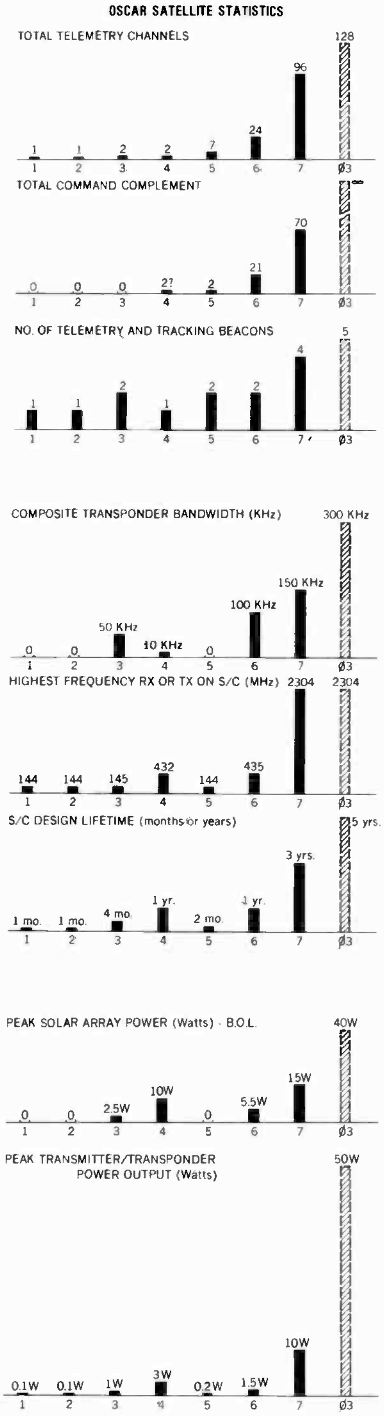
OSCAR 6 was designed and built by radio amateurs in the United States, Australia, and West Germany. Although designed for a one-year lifetime, it remained in routine usage for four and one-half years until degradation of its solar cells and NiCd batteries caused its demise.

OSCAR 7, launched on November 15, 1974, was even more of an international effort, having been built by radio amateurs in the United States, Canada, Australia, and West Germany. AMSAT-OSCAR 7 carries two transponders (432.1-MHz uplink/149.5-MHz downlink and 145.9-MHz uplink/29.5-MHz downlink, each operational at different times. Telemetry is available both in Morse code and in Baudot-coded radio teletype, and the satellite also contains a code-store facility. Solar cells are again used to recharge its NiCd batteries. Redundant command decoders, power conditioning circuitry, and under- and over-voltage protection circuits are used in the spacecraft to increase its lifetime.

Having two working satellites in space has enabled radio amateurs to make the first double-satellite communications links in which signals were uplinked to AMSAT-OSCAR 7 at 432.1 MHz, relayed to AMSAT-OSCAR 6 at 145.9 MHz and downlinked to earth at 29.5 MHz. Since the orbital period of AMSAT-OSCAR 7 is just slightly shorter than that of AMSAT-OSCAR 6, AMSAT-OSCAR 7 overtook its little brother about every six months, and it is during these periods of overlap that double-satellite contacts took place.

The AMSAT-OSCAR 7 also carries an S-band beacon operating at 2304.1 MHz as proof of the interest of radio amateurs in the use of microwaves for space communications; however, much to their dismay, they have not yet been able to obtain permission from the FCC to power it up. AMSAT-OSCAR 7 was built largely by volunteer help with a cash investment of $60,000. The funds were contributed by individuals and organizations interested in the project. If built commercially, the spacecraft would have cost nearly $2,000,000.

AMSAT-OSCAR 8 was launched as a secondary payload along with LANDSAT C on March 5, 1978. Like its predecessors, the spacecraft is an international effort involving the United States, Canada, Japan, and West Germany. Designed to replace the failed AMSAT-OSCAR 6 and to fill the gap until a new generation of amateur satellites is available, AMSAT-OSCAR 8 also contains two linear communications transponders. Amateurs from Japan have provided one of the transponders for this spacecraft, the result of over 3 years of effort. This transponder has a frequency-link combination little used by previous OSCARs. It relays 100 kHz of spectrum from 145.9 MHz to 435.1 MHz.



Growth trend of the OSCAR series of satellites shows an upward trend in all areas. This is due to increased spacecraft complexity required for longer life missions as well as the general advancement of the state-of-the-art in electronics technology since 1961. Statistics for OSCAR-8 (not shown) are similar to those for OSCAR-6. OSCAR-8 launched on March 5 of this year was intended to replace OSCAR-6, assuring the continuity of the satellite program until the first Phase III spacecraft can be launched.

Using simulated ELTs at 145.9 MHz, the satellite search and rescue concept has been proven. The position of the satellite at any instant is known because of the existence of precise orbital predictions. Computers then process the distress signals relayed by the satellite, determining the Doppler shift in the frequency of the ELT as the spacecraft passes within range of a simulated crash site. During a spacecraft pass, an immediate "position fix" accurate to within about 100 km is available. Within 15 minutes or so, after computer processing of the data, an optimized "fix" is available to locate simulated crash site to within 8 km.

Researchers are planning for an operational system that might involve three spacecraft, each having a design lifetime of 7 to 10 years, at a total cost of about $30,000,000. This is a fraction of the amount spent annually for search and rescue by the United States and Canada.

These amateur satellite ELT experiments have been an important factor in the success of a new joint Canadian/U.S. venture to develop a comprehensive search and rescue space system. The spaceborne part of the system will be flown in the early 1980s on the TIROS-N class of spacecraft designed and built by RCA.

In the United States, AMSAT has been transmitting daily educational messages and bulletins. Each year, during the hurricane season in the Caribbean, special hurricane bulletins have been relayed via the OSCAR spacecraft. At times, when propagation conditions are bad, OSCAR hurricane bulletins are the only warnings available to remote islands.

Educational usage of OSCAR

The major factor in NASAs agreement to include the AMSAT-OSCAR spacecraft in its launches was the recognition of their educational uses. Numerous schools, museums, and similar educational institutions, worldwide, use these spacecraft for teaching purposes as well as for "hands on" demonstration of space techniques.

For example, the Morse code telemetry encoder on AMSAT-OSCAR 7 can be commanded to send signals back to earth at a slow 10 words per minute. The telemetry system is designed to teach young students, in a simple way, concepts such as signal scaling, analog and digital multiplexing, analog-to-digital conversion, and code conversion.

Other physical phenomena related to the propagation of signals through the transponder can be dramatically demonstrated. Scintillation, polarization, and Faraday rotation of the downlink electromagnetic waves can be observed with simple equipment. Although somewhat more complex, distance-ranging measurements through the transponder have also been demonstrated.

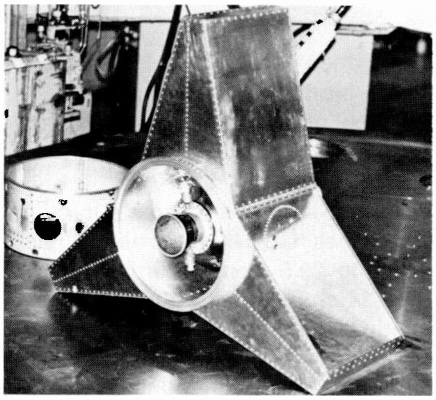


Fig. 1
AMSAT-PHASE III engineering test unit undergoing vibration testing.

The internal status of the spacecraft can be monitored by means of telemetry data, which provides information on the temperature and orientation of the spacecraft. Day-to-day variations can be recorded and students are encouraged to explain them.

Diverse applications of the space sciences can be demonstrated by use of the spacecraft in many areas. Solar radiation, Van Allen Belts, thermal balance, and system reliability are among the many concepts that can be illustrated and tied to the interpretation of the telemetry signals.

Computers and computer programming can be introduced to students by having them write programs to predict orbits or times of acquisition of signals from the spacecraft for any day or to process the telemetry.

The Crookes radiometer has long been a scientific "toy" used in schools to demonstrate the effects of light pressure. The first published practical use of the "photon pressure" effect as demonstrated by Crookes radiometer is the thermal subsystem of the AMSAT-OSCAR 7 spacecraft. The VHF/UHF antennas on the spacecraft are painted black on one side and white on the other. The sun always "sees" one black blade and one white blade and a differential transfer of photon momentum to the spacecraft occurs. Photon pressure thus causes the spacecraft to spin at a slow rate, reducing thermal gradients across the spacecraft structure. Confirmation of the fact that the spacecraft is spinning in this manner is obtained from the telemetry signals.

This is but a quick-brush treatment of the educational potential of the OSCAR spacecraft. Teachers have found that the actual experience of hearing signals live from space, of plotting Doppler curves, and of doing other basic exercises stimulates interest and enthusiasm among their students.

To encourage this interest, AMSAT arranges specific educational demonstrations. A special guide to the use of the spacecraft for educational purposes is also published by the ARRL and is available to educators, free for the asking.

The future—PHASE III

AMSAT-OSCARs 7 and 8 provide educators with a basic means for practical demonstrations of space-flight techniques and provide radio amateurs with some communications capability. AMSAT, however, is upgrading the service provided by the low-altitude spacecraft and is currently building bigger and better ones.

The AMSAT-PHASE III satellite (shown in Fig. 1) will contain a microprocessor to perform the functions of command decoding, telemetry data processing, and attitude control. The satellite will have redundant transponders operating cross band in the 145-MHz and 435-MHz bands and an S-band telemetry beacon. Fig. 2 shows some of the technological features to be incorporated in this satellite.

The European Space Agency (ESA) has agreed to launch the first PHASE III spacecraft as a passenger on the LO2 Ariane test flight in December 1979. The spacecraft will be placed into a parking orbit by the Ariane launch vehicle. Then, about 45 days later, upon receipt of a ground command, it will boost itself into a highly elliptical 12-hour orbit with an apogee above the northern hemisphere.

When the PHASE III spacecraft becomes operational, it will usher in a new era for amateur radio. For the first time, the majority of the world's radio amateurs will have reliable communications capability to any part of the northern hemisphere for hours at a time. There will be no "skip" or "dead" zones as on the conventional shortwave bands. School children in Europe, North America, and Asia could be linked together in a round-table discussion during educational demonstrations. Emergency communications capability will be available anywhere there is a suitably equipped radio amateur. The PHASE III spacecraft will provide a communications capability that does not exist

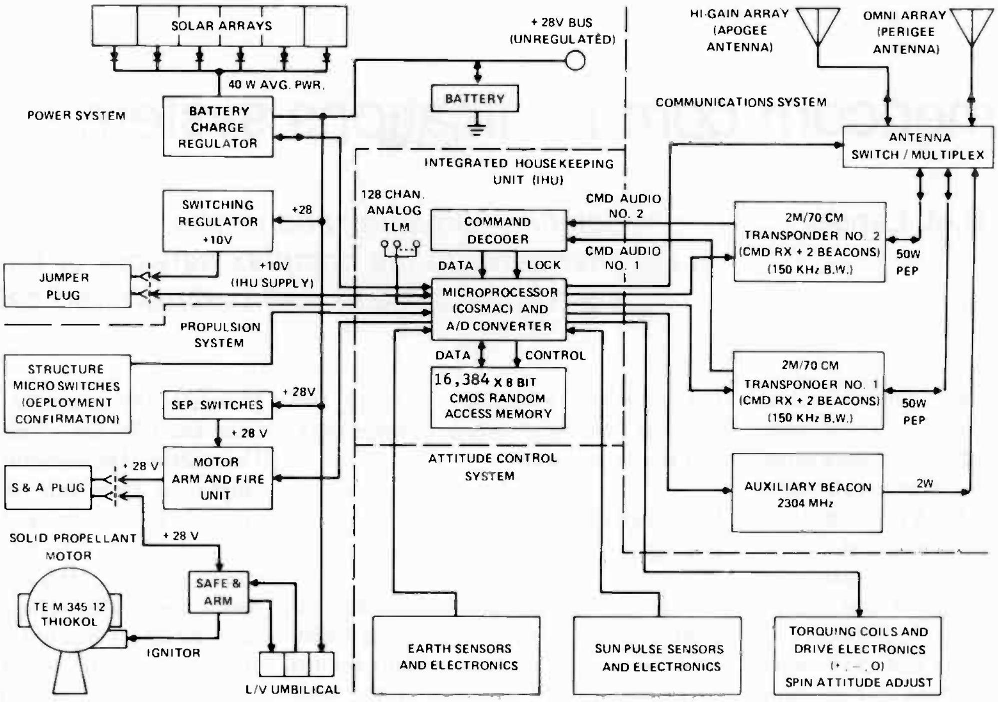


Fig. 2

Functional Block Diagram of AMSAT-PHASE III shows some major features of this new spacecraft. Central to the spacecraft design is an RCA CDP1802 microprocessor which is responsible for all on-board control functions and also acts as the command and telemetry system. Primary up- and down-link data rate is 400 bits per second.

The integrated housekeeping unit (INU) is responsible for timing and executing the burn of the kick motor. The primary task of the INU, however, is to control the attitude of the spacecraft. Using earth and sun sensor data as inputs to the microprocessor, software will "steer" the spacecraft spin axis by applying current pulses to the torquing coils at the proper phase during each rotation of the satellite.

Two linear transponders, containing both command receivers and telemetry beacons are the heart of the communications subsystem. These state-of-the-art "repeaters" utilize a modulation technique known as envelope elimination and restoration which allows the power amplifier stages to be very efficient with excellent linearity. Each transponder will handle up to 100 simultaneous true random multiple access users.

at this time and whose potential can only be guessed.

Government and industrial support

Without continued outside support, an activity of this nature could not survive long. The government and several of the aerospace companies have provided much-needed assistance to the amateur satellite effort.

The U.S. Air Force and NASA have provided launch opportunities and launch vehicle integration support for each of the OSCARs. NASA approved the launch of OSCARs 5 through 8 as secondary payloads on the Delta launch vehicle, primarily as passengers with the ITOS weather satellites. In addition, NASA has provided technical advice and consultation in a number of areas. AMSAT has made use of flight spare batteries and solar arrays from NASA space programs.

Several companies have donated high-level technology items to AMSAT that were critical to the development of the spacecraft. Of these companies RCA has played a major supportive role. In particular:

1) Solid State Division, Somerville, N.J., provided several hundred COS/MOS integrated circuits screened to hi-rel standards which were used throughout AMSAT-OSCARs 6, 7, and 8. To date, after some 35,000 orbits (70,000 hours) of in-orbit service, none are known to have failed. Prior to its battery failure AMSAT-OSCAR 6 accumulated 3.6 million COS/MOS-device hours in space. Quantitative results of OSCAR COS/MOS performance have been reported to RCA, to NASA, and in the literature.[1]

2) Astro-Electronics, Princeton, N.J., assisted AMSAT in obtaining solar arrays that were utilized on AMSAT-OSCARs 6 and 7. RCA has also provided technical support in the use of solar arrays from time to time.

3) Astro-Electronics worked together with AMSAT in the design and fabrication of an S-band quadrifilar helix antenna used on AMSAT-OSCAR 7. RCA also provided general consultation and advice regarding the antenna designs employed on the OSCAR satellites.

4) Solid State Division has provided a number of needed components for the breadboarding of a spacecraft microcomputer to be used in AMSAT-PHASE III. The computer will use the RCA CDP1802 COSMAC microprocessor and 16k of random-access memory and will control all housekeeping and command functions aboard the new satellites.

Like many other hobbyists and public service groups, AMSAT people take their activity very seriously. While this pastime provides both fun and excitement for many thousands of individuals, amateur satellite enthusiasts believe they are making a positive contribution to society by making possible demonstrations of new and different applications of space technology for use in public service.

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[1] Klein, P.I., and King, J.A.; *Results of the AMSAT-OSCAR 6 Communications Satellite Experiment*, IEEE International Convention, N.Y., N.Y. (Mar 28, 1974).

RCA Americom communications system

R. Langhans|R.M. Lansey

Satellite communications offers an effective, reliable alternative to the complex network of terrestrial microwave systems and underground cables.

The RCA Americom Communications System is a network of telecommunications facilities that provides a broad range of communications services to major cities. Linked by two RCA satellites, these facilities include commercial earth stations, terrestrial microwave extensions and local telephone loops, as well as earth stations dedicated to specific customers. At present, over 500 RCA or customer-owned earth stations are receiving transmissions from the RCA satellites. RCA Americom Communications, the owner and operator of the system, has introduced a number of innovative domestic satellite communication services, increasing versatility and reducing the cost of long-haul voice, data, and tv transmissions.

Spacecraft and tracking facilities

The two RCA spacecraft presently on-orbit are the result of a program which included the first commercially-funded development of an advanced launch vehicle and the first 24-transponder frequency-reuse satellites. RCA funded the development of the Delta 3914 launch vehicle, increasing the useful load it could put into a geosynchronous transfer orbit to 2000 lbs., from the 1500 lbs. of its predecessor, the Delta 2914. The communication satellites employ a three-axis stabilized attitude control system using a body-mounted momentum wheel to maintain gyroscopic stability. (See L. Muhlfelder's paper in this issue). The satellites (Fig. 1) are designed to have all 24 of the 6/4-GHz transponder channels operational at their specified radiated power throughout the minimum eight-year life, including full eclipse operation.

The coverage patterns for these satellites are tailored to meet the specific needs of the various services.

The spacecraft design provides effective radiated power ranging from 36 dBW at beam center to about 32 dBW at the edges of the domestic coverage pattern to both the lower 48 states and Alaska. Offset feeds in two of the reflectors also provide a spot pattern of about 26 dBW on 12 of the channels to the Hawaiian Islands (Fig. 2).

RCA satellite F2, which is located at 119°W longitude, has special-purpose beam patterns. The alternate odd transponders (3, 7, 11, . . . , 23) are canted toward Alaska and the West coast of the

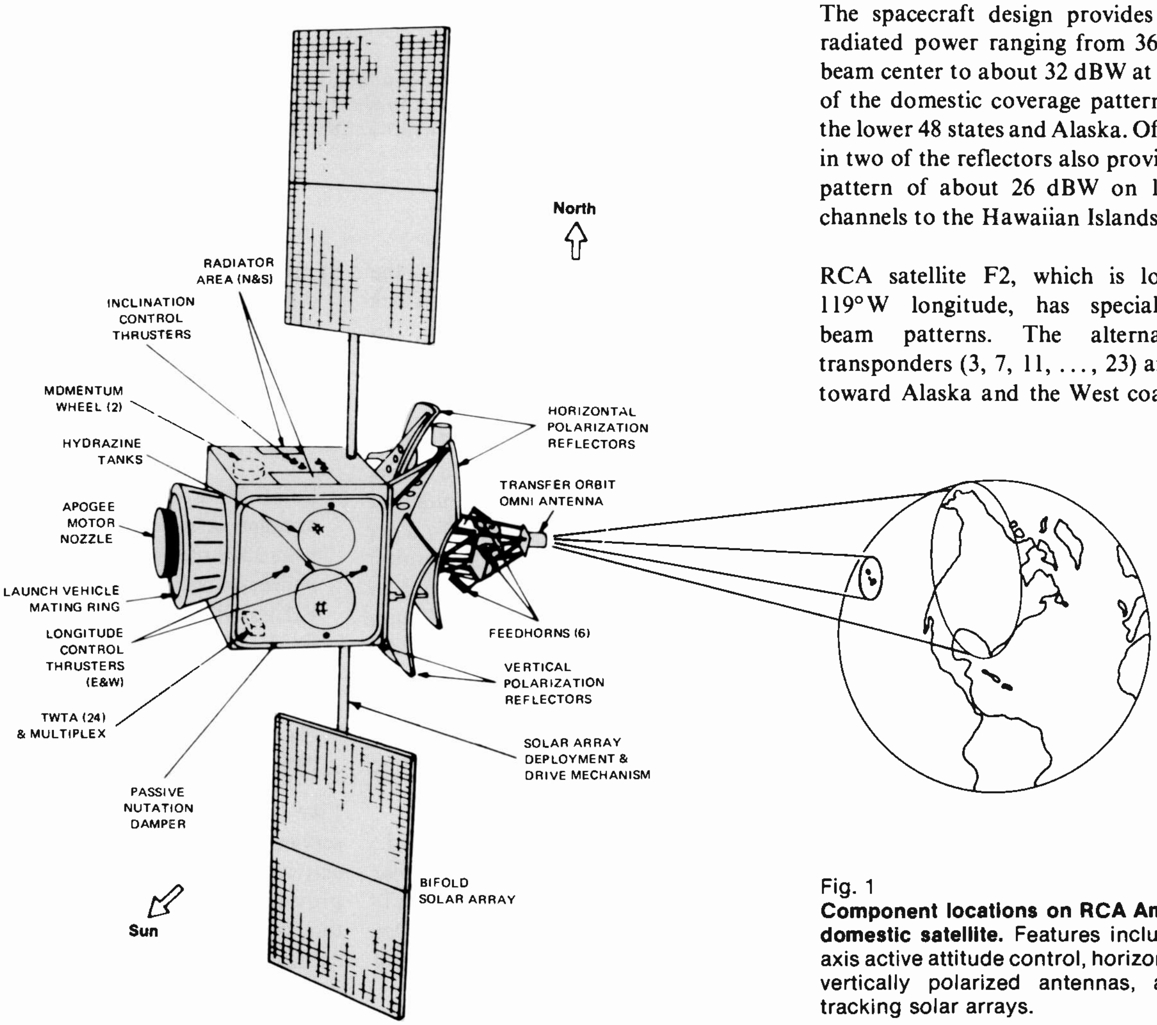

Fig. 1
Component locations on RCA Americom's domestic satellite. Features include three-axis active attitude control, horizontally and vertically polarized antennas, and sun-tracking solar arrays.

continental U.S. to provide a favorable coverage pattern for Alaskan interstate and intrastate traffic (Fig. 3). The other odd transponders (1, 5, 9, . . . , 21) have an omnidirectional beam, which is centered in the northwestern U.S. and covers the lower 48 states and Alaskan stations almost equally. Alternate even transponders (4, 8, 12, . . . , 24) have a coverage pattern that is most favorable to the lower 48, with particularly good Southeast and East coast coverage (Fig. 4). This makes these transponders particularly desirable for broadcast to CATV receive stations. The other alternate even transponders also have omnidirectional beam coverage.

RCA satellite F1, located at 135.0°W longitude, is more a general purpose satellite, with all of its transponders canted to provide optimum coverage toward the lower 48.

Both satellites have special purpose high-gain transponders in channels 1 and 3, favorable for lower-power small-aperture earth stations.

The frequency reuse design allows 24 independent channels, twice the number achievable with standard linear polarization techniques.

The 24 channels, each with 34-MHz usable bandwidth within the 500-MHz-wide domestic satellite band, are spaced on 20-MHz centers. However, they are transmitted alternately on horizontal and vertical polarizations to isolate adjacent channels. All channels have a fixed 2225-MHz down conversion between the 5.925- to 6.425-GHz uplink and the 3.7- to 4.2-GHz downlink. The high degree of polarization isolation required to support this system is achieved in the spacecraft antenna reflectors using orthogonal reflecting grids embedded in supporting dielectric surfaces. In-orbit tests show that better than 33 dB polarization discrimination, for both transmit and receive spacecraft antenna beams, has been achieved throughout the specified coverage area. The system polarization isolation includes the polarization effects of the spacecraft antennas, the earth station antennas, and the depolarizing effects contributed by the transmission medium from such phenomena as rain and Faraday rotation. Considering all these effects, the system polarization isolation is approximately 27 dB for greater than 99% of the time.

The transponder design includes separate fully redundant tunnel-diode receivers for each polarization, so that 12 of the 24 channels are supported by each receiver. The spacecraft transmitters consist of 24 TWT amplifiers with a nominal saturated power output of 5 W.

The spacecraft is controlled by two redundant Telemetry, Tracking, and Command (TT&C) ground stations.

The prime TT&C station is located at Vernon Valley, N.J. Current operational procedure is to hold each spacecraft to an orbit inclination and E-W stationkeeping accuracy of ±0.07°. These TT&C stations also contain the Satellite Operation Control Center (SOCC) which monitors and controls each of the spacecraft via a phase-modulated beacon signal transmitted at the edges of the communications band.

Alaskan services

RCA Alascom provides long-distance telephone facilities and services within the state of Alaska and between Alaska and the lower 48 states.

Private-line and message toll services are provided using various combinations of satellite, microwave, and cable facilities. RCA Americom leases satellite

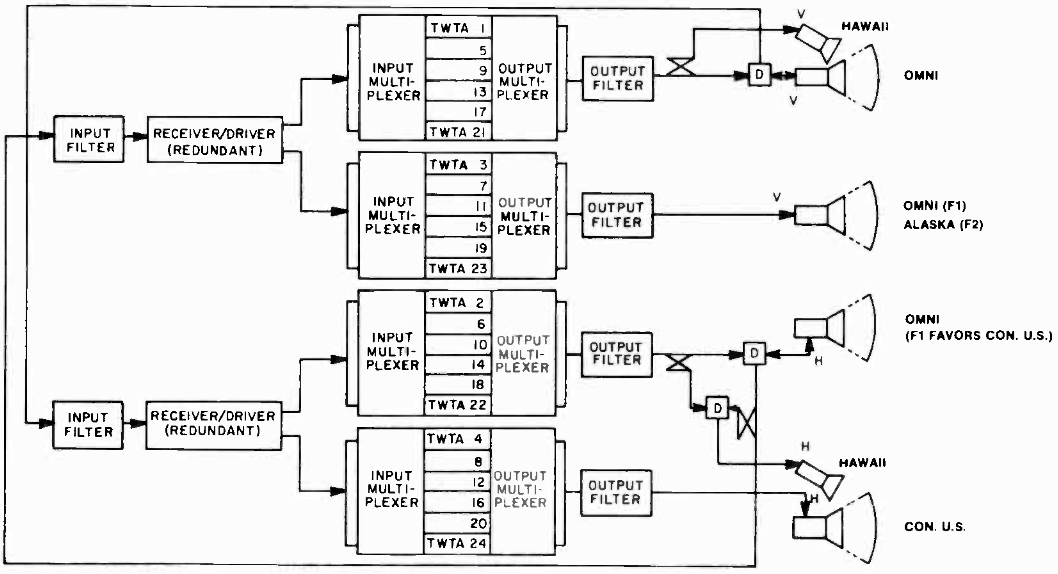

Fig. 2
Full domestic coverage provided by the 24 transponders. This coverage includes domestic private leased-channel services, voice-grade and wideband digital data services, and both point-to-point and multipoint radio and tv distribution services.

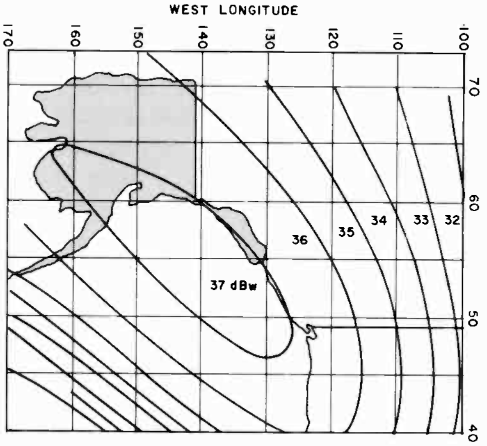

Fig. 3
Effective isotropic radiated power (EIRP) provided by Alaska-canted beam.

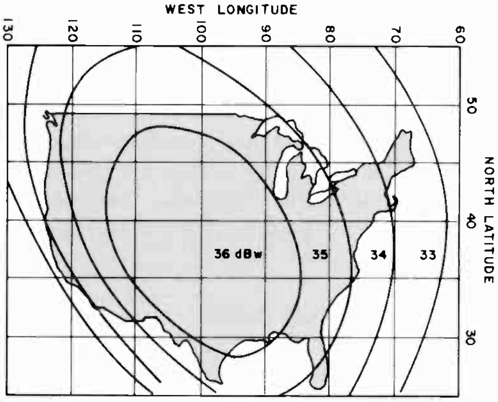

Fig. 4
Effective isotropic radiated power (EIRP) provided by the beam canted toward the lower 48 states.

Some communication terms used in this paper

C4 conditioning	a specification on group delay and amplitude linearity of a voice-band circuit. This specification is particularly important for data communications.
delta modulation	a form of pulse code modulation, in which a code representing the difference between the amplitude of a sample and the amplitude of the previous sample is sent.
dBrnC0	dB above reference noise (−90 dBm) with C-message weighting.
FDM	frequency division multiplexing—an arrangement where several message channels share a single transmission facility, each having its own frequency band.
G/T	figure of merit on the performance of an earth station, defined as: $\dfrac{\textit{antenna power gain}\ \text{(dB)}}{[\,10 \log_{10} \textit{system noise temperature}\ (^\circ\text{K})\,]}$
pWp0	picowatts psophometrically weighted with respect to the 0 transmission-level point. An 800-Hz, 1-mW tone into 600 ohms produces a psophometer reading of 0.775 V.
PSK	phase shift keying—encoding of digital information as different phases of signal elements having constant amplitude and frequency. Two variants of interest here are QPSK (quadrature PSK) and BPSK (binary PSK).
SCPC	single channel per carrier.

transponders to RCA Alascom. Presently about 20 operational heavy and mid-route earth stations and over 70 bush stations are in the Alascom network. The earth stations range from a typical mid-route station which has a 10-meter antenna and a figure of merit, or *G/T*, of about 29 dB/°K, to the Bartlett station serving Anchorage and Fairbanks, equipped with a 30-meter dish, providing a *G/T* of 41.5 dB/°K, to the bush stations serving the small rural Alaskan communities which typically have a 4.5-meter dish and a *G/T* of 19.2 dB/°K.

The Bartlett station is the largest in the Alaska satellite network, while the bush stations are so small and compact they are installed, in some cases, in grocery store basements and schoolroom closets, with the 4.5-meter antenna located in the adjacent yard. These bush stations have had a significant and beneficial impact on the communities they serve since, in most cases, they represent the first telephone communications service these villages have ever had.

The bush circuits are, in effect, long subscriber loops connected to a switch in Anchorage which automatically connect the bush subscriber to his calling party.

In general, three different types of heavy and mid-route circuits are used with three different modulation techniques:

- Toll connecting mid-routes to Juneau using FDM/FM transmission.
- Intrastate intertoll using voice-activated single-channel-per-carrier transmission (using both delta modulation and FM/SCPC) between Juneau and Anchorage.
- Interstate FDM/FM between Alaska and the RCA Americom stations in the lower 48.

Transmission performance of these heavy and mid-route circuits is characterized by the noise in a voice circuit when measured at zero test point level (0 TPL). RCA Alascom has selected for its goal, 7,500 pWp0. This is 2500 pW better than the Intelsat intercontinental circuits. This noise level includes thermal, intermodulation, and both internal and external interference contributions. Where SCPC transmission is used, a 17 dB companding advantage is included. In general, the link budgets are largely down-link thermal-noise limited, with intermodulation noise and internal interference sources causing the next largest contribution to the noise-link budget.

Of the several television services being broadcast to Alaska daily via the RCA Americom spacecraft, one is using an innovative technique that allows two video signals to transmit on a single transponder. Each video signal is transmitted as a separate carrier and is band limited to one half (17.5 MHz) of the transponder. One of the two video signals is passed through an alternate line delay which delays alternate field lines to reduce chroma crosstalk caused by the intermodulation of the color subcarriers. The video signal is then restored to normal at the receiver.

The peak-to-peak-luminance to rms-weighted-noise ratio achieved into the mid-route stations is 50 dB. The audio (15 kHz) is transmitted separately on an SCPC transponder, and achieves an rms-signal to unweighted-rms-noise ratio of 50 dB. The full transponder video transmitted to the small-aperture bush stations achieves a video signal-to-noise ratio of 49 dB.

Commercial services

RCA Americom has constructed a network of ground facilities to operate with its satellites and provide private leased-channel services to the New York, Los Angeles, San Francisco, Chicago, Philadelphia/Camden, and Houston areas (see Fig. 5, for example). Each ground segment has a CTO (Central Telecommunications Office), a terrestrial microwave link, and a commercial earth station.

The CTO, centrally located in each city, acts as a concentration point for local loops originating at customer premises. It also provides monitoring, control, alarm, and processing functions. At the CTO, the individual channels are frequency-division

Fig. 5

Ground facilities such as these located at South Mountain, Cal., provide private leased-channel and tv services to major commercial centers. Each ground segment includes a CTO, a terrestrial microwave link, and a commercial earth station.

multiplexed, using standard CCITT single-sideband multiplex plans, into a single composite baseband for transmission over the terrestrial microwave link to the earth station. The short-haul (3-hop), 1800-channel microwave system utilizes heterodyne repeaters and has redundant, hot standby, equipment with back-up battery power to assure a high system availability.

Each commercial earth station uses a 13-meter parabolic antenna equipped with a cross-polarized cassegrain feed system to permit simultaneous transmission and reception from all 24 transponder channels on the RCA satellites. All stations but one also have a second antenna to enable operation on both satellites. Step-track angle pointing control is used to maintain pointing accuracy to within 0.05° rms, and polarization tracking is used to maintain system cross-polarization isolation. A receiving system figure of merit, or G/T, of 32.4 dB/°K at 4 GHz is achieved through the use of two redundant sets of 55°K thermoelectrically cooled parametric amplifier systems, one set for each polarization.

A typical earth station distribution path would be as follows: Earth station and terrestrial microwave FDM equipment interface at the group or supergroup level at the earth station. The composite FDM baseband is frequency modulated onto a 70-MHz i.f. carrier, upconverted to the 6-GHz band, and transmitted as a multi-destination rf carrier to the satellite utilizing a 3-kW klystron high power amplifier. Each multidestination 4-GHz message carrier received at the earth station is down-converted to 70 MHz and then demodulated using fm threshold-extension demodulators. The supergroups and groups destined for that city are demultiplexed for transmission along the terrestrial microwave system.

All electronic equipment is protected by "hot-standby" back-up units, and a diesel generator provides back-up power in case of commercial power failure.

RCA provides both voice-grade and group-band private leased channel services. The voice-grade channels meet C4 conditioning standards between CTOs with C-message weighted idle channel noise lower than 40 dBrnc0. Data services are also provided within these channels supporting data rates up to 9600 b/s and at bit error rates better than 1×10^{-5}. Higher-speed data services, between 48 kb/s and 168 kb/s, can be provided within group-band channels with bit error rates better than 1×10^{-6}.

Video, audio, and broadcast services

These commercial ground facilities are also used to provide video and audio services to those major cities listed above. In addition, a television transmit and receive station is owned and operated by RCA in Atlanta, Georgia. RCA Television Operating Centers (TOC) in each city monitor and control video and audio signals going to and from that city. Audio programming is frequency modulated on subcarriers above the video baseband to form a composite baseband signal. This baseband is frequency modulated for transmission over the terrestrial microwave links and the satellite system.

At the present time, RCA Americom is providing NTSC color television signals with associated 15-kHz program audio quality channels to the networks for further distribution and broadcast. Some of the performance parameters of this service are listed below:

	Video	*TV audio*
Baseband bandwidth	4.2 MHz	15 kHz
Signal-to-noise	56 dB	65 dB
Differential phase	2°	
Differential gain	4%	

This service has been used by the tv networks for major events such as the presidential debates and the Superbowl, as well as for everyday programming like the weekend football and baseball games, and NBC's "Tonight Show."

RCA Americom can also provide two 15-kHz program-quality audio channels with each video feed for stereo programming or to allow for two separate audio commentaries to accompany each video feed.

As described previously, the State of Alaska is now being provided with two high quality, color video channels of live network programming utilizing only one satellite transponder using equipment and transmission parameters developed by RCA. This system is being modified for teleconferencing and other lower quality video uses within the continental United States. It should provide the following quality of performance:

	Video	*TV audio*
Baseband bandwidth	4.2 MHz	8 kHz
Signal-to-noise	48 dB	50 dB
Differential phase	4°	
Differential gain	8%	

General Electric used RCA's satellite to perform tests on their "sample-dot" digital video equipment.

This equipment provides a black-and-white video signal with the use of a little over 2 MHz of the 34 MHz available in a single transponder. It is only one of the many digital and analog techniques now being investigated at the RCA Laboratories to reduce the video bandwidth requirements of black-and-white and color television signals while minimizing equipment-induced distortions. Video noise reduction equipment can be used to increase low video signal-to-noise ratios to acceptable levels while reducing other video distortions. This would achieve the same effective signal-to-noise ratio using less space segment.

Four commercial radio networks are now using simplex or full duplex audio program channels provided by RCA.

RCA Americom provides these audio channels between New York, San Francisco, Los Angeles, Chicago, and Houston for network feeds. Performance specifications between RCA TOCs for these high quality program audio channels are listed below.

	8-kHz service	*15-kHz service*
Signal-to-noise	>55 dB	>55 dB
Amplitude-frequency response	50 Hz to 8 kHz ±0.5 dB	50 Hz to 15 kHz ±0.5 dB
Harmonic distortion	<1.0%	<1.0%

Perhaps the fastest-growing satellite communications market is the CATV program distribution service.

Among the CATV program distributors using the RCA spacecraft are Home Box Office and Showtime Entertainment pay tv network, Southern Satellite Systems providing the 24-hour schedule of WTCG (channel 17) in Atlanta, Christian Broadcasting Network, PTL Television Network, Trinity Broadcasting Network, and U-A Columbia/Madison Square Garden. This market was originally implemented via widespread installation of 10-meter tv receive-only earth stations, priced in the $60-70,000 range with G/Ts of

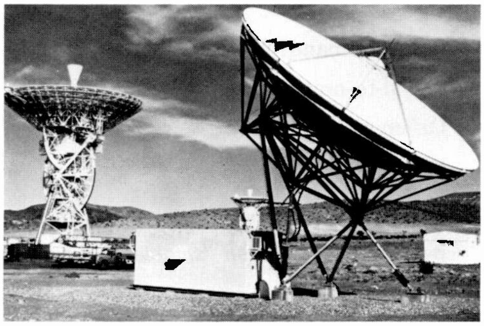

Fig. 6
Small government-dedicated earth stations such as this one at Goldstone, Cal., are part of Americom's growing government-services network.

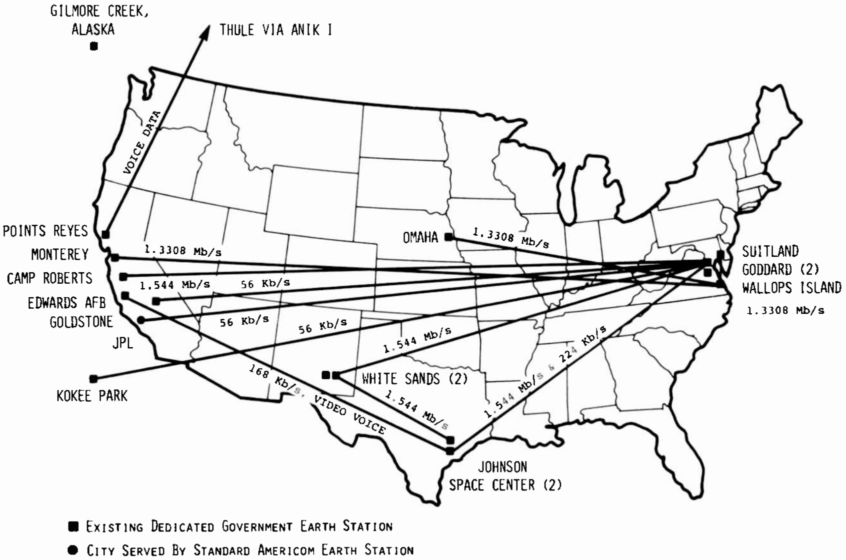

Fig. 7
Government-dedicated stations are located at Goddard Space Flight Center, Md.; Edwards AFB, Cal.; Kokee Park, Hawaii; Goldstone, Cal.; Monterey, Cal.; Wallops Island, Va.; and Suitland, Md. Stations under contract to be installed in the near future include Johnson Space Center, Tex.; White Sands, N.M.; Jet Propulsion Labs., Pasadena, Cal.; Sunnyvale AFS, Cal.; Offut, S.D.; and Dixon and Delano, Cal.

27 dB/°K. However, the market is now undergoing a major expansion triggered by the FCC announcement of routine processing of small-aperture (15-ft) receive-only stations in the $20-40,000 range with *G/T*s of 22 dB/°K. Video signal-to-noise performance for these stations varies between 48 and 54 dB, depending on the location of the station within the satellite EIRP "footprint" and the station *G/T*.

This basic system is adaptable for many other distribution-type services.

A facsimile transmission system that provides quality reproductions, up to 2,000 lines per inch, is one example. The video baseband could accommodate the transmission of up to 100 magazine-size pages an hour in an analog mode. A digital signal can also be applied to the video baseband for transmission over the satellite system. These high speed transmissions would allow the service to be time shared with video services using the same facilities (e.g., tv services between 4 p.m. and 4 a.m.; facsimile services between 4 a.m. and 4 p.m.).

RCA has pioneered the use of domestic satellites for distribution of audio and message programming to small receive-only terminals.

As early as August 1974, RCA demonstrated the transmission of a 15-kHz program audio channel into a 4-foot parabolic reflector antenna. In the last 4 years, RCA has demonstrated both SCPC and FDM/FM systems for satellite distribution into receive-only stations with antenna diameters ranging from 4 to 8 feet. One of these demonstrations provided eight 8-kHz program channels of a signal-to-noise ratio of 66 dB into a six-foot dish using a single saturated FDM/FM carrier. These systems can be used for distribution of audio programming for radio networks, and high speed data, teletype, and facsimile information for the news services. Standard tariffs for SCPC audio uplink services with baseband bandwidths ranging from 3,500 Hz to 15 kHz will soon be made available from RCA for systems based on 6-, 8-, and 10-foot receive-only stations.

The system design, in these multipoint services, is aimed at minimizing earth station costs at the expense of increased satellite power.

With higher satellite power, the cost of small-aperture earth stations can be as low as $5,000 in large quantities. The high power density and narrow bandwidth of these carriers are less susceptible to interference from conventionally modulated terrestrial and satellite signals. In addition, pseudo-random spacing of these carriers within the satellite transponder minimizes the degradation due to intermodulation distortion and permits the operation of the transponder close to saturation.

Dedicated government services

A rapidly expanding area in the RCA Americom system is the growing network of small dedicated earth stations located on the customer's premises (e.g., Fig. 6). At present, all of these stations are serving government customers such as NASA, NOAA, and DCA (Fig. 7).

These stations typically provide wideband data service between 56 kb/s and 1.544 Mb/s, but are also used for voice-grade and video communications.

A typical dedicated station carrying a moderate amount of wideband data traffic would be designed to achieve a figure of merit, or *G/T*, of 30 dB/°K at 4 GHz. This would be implemented by using a 10- or 11-meter non-tracking dish and a low cost GaAsFET amplifier. The optimum *G/T* for an earth station is arrived at by system tradeoffs involving minimizing the combination of earth station costs and required transponder power utilization, since these two factors are the major elements in determining the service tariff rate charged to the customer.

The transmission technique used for wideband data transmission is BPSK or QPSK together with error-correction encoding. The transmission modulation and coding (if any) are chosen to approximately equalize the percentage of transponder bandwidth and the percentage of transponder power used in providing the service. In this way, power and bandwidth are being used at the same rate in each transponder for more efficient operation.

To reduce the transponder power required, error-correction encoding is employed with either threshold or, the more powerful, soft-decision Viterbi decoding. The type of decoding used is determined from an economic tradeoff of transponder power savings vs. increased cost of coding and decoding.

In the RCA Americom dedicated earth station system, most stations are designed for unmanned operation with automatic switching to fully redundant "hot standby" back-up subsystems in the event of an online subsystem failure. These unmanned stations are monitored and controlled via a voice-grade dial-up line from a master station, which, in the case of the government dedicated stations, is the RCA Goddard earth station. In this way, a design goal of 99.95% system availability can be achieved. This availability level includes the effect of rain, wind, and polarization effects on the availability of the transmission medium. The master station monitors each subsystem's digital alarm indicators and controls both subsystem switching and power levels with a remote fault/monitor system which converts this data to tones transmitted via a voice-grade modem over the DDD line.

Although the dedicated station concept has been pioneered and developed in the Government Services area, this approach is applicable to many commercial applications, such as the oil industry for offshore drilling and customer-owned broadcast CATV and receive-only stations for the printing and news services. In addition, RCA Americom is providing the country's first satellite communications service to an oil drilling ship, linking the shipboard terminal to its Houston headquarters, via RCA Americom's Rayburn, Texas earth station.

Performance objectives that can be provided for wideband data are as flexible as the customer's needs. Bit error rates can range from 1×10^{-4} to better than 1×10^{-9}, with typical NASA circuits operating at 1×10^{-7}. Block throughput, or error-free-seconds is typically better than 99.5%. Bit rates can range up to approximately 60 Mb/s, with the most frequently used data rates presently being 56 kb/s and 1.544 Mb/s.

Some of the NASA/NOAA programs supported by these stations are as follows:

- The Viking Mars Exploration—RCA carried the telemetry and digitized video between JPL in California and the Goddard Space Flight Center via a duplex 56-kb/s satellite link.
- TIROS-N—Weather data from the polar-orbiting TIROS-N satellite is carried from tracking stations in Alaska and Virginia to NOAA facilities in Maryland via simplex 1.3308-Mb/s satellite data circuits.
- Seasat—Detailed mapping and surveillance of the ocean area is made possible by an RCA 1.544-Mb/s data circuit linking an Alaskan tracking station with a NOAA facility in Maryland.
- Space Shuttle—Pictures recently broadcast over commercial tv of the Space Shuttle flights were made possible by an RCA video link between the Edwards AFB testing site and NASA's Johnson Space Center in Texas.

Summary

The RCA Americom system is a versatile communications network for serving commercial requirements in the areas of telephone, television, and data communications. This satellite communications system provides a cost-effective and highly reliable alternative to the complex network of terrestrial microwave systems and underground cables.

The future of commercial satellite communications will undoubtedly bring a proliferation of small-aperture, user-dedicated stations. This will bring point-to-point and point-to-multipoint data, video and audio distribution systems within the reach of most business markets.

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Richard Langhans is responsible for the system design and technical content of all government proposals involving voice-grade, wideband data and video services via RCA Americom's satellite. He has over ten years of experience in analog avionics circuit design and satellite communications. He was project engineer on Americom's first wideband data network supporting the Viking Mars mission and the first satellite communications circuits to offshore drilling ships.

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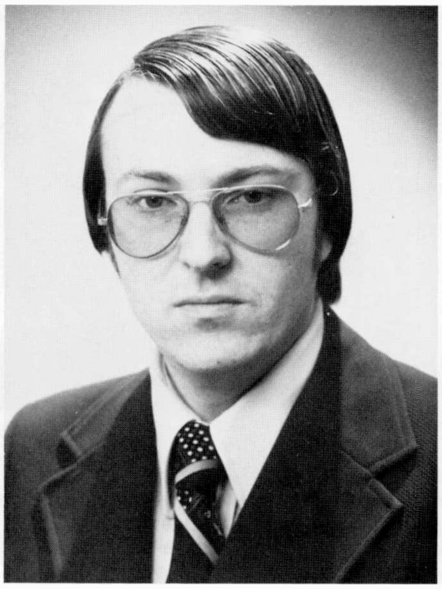

Robert Lansey is responsible for developing systems for the distribution of video and audio services via satellite and has been involved in testing and demonstration programs for audio distribution into small receive-only earth stations, four to eight feet in diameter. He has done much work in applying the broadcast capability of the communications satellite to the distribution of facsimile and data.

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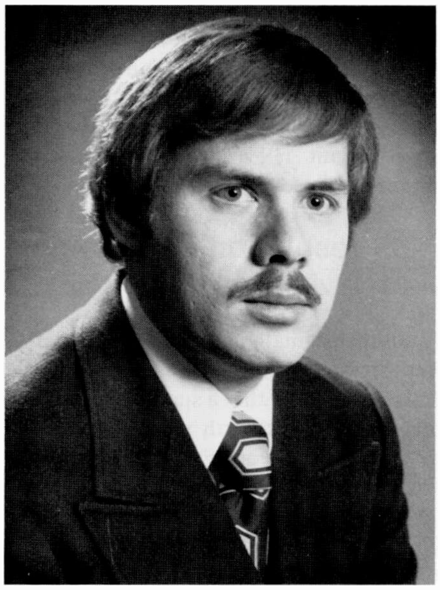

Current directions of television imaging from space

Television's adaptability, short-term picture storage, and precision make it the best sensor for some space applications; high resolution cartography from Landsat C and CCTV on the shuttle are two.

B.M. Soltoff

The first television images transmitted from a satellite were generated by TIROS-I in 1960, using a ½-inch-vidicon television camera. Since that time, a variety of special purpose tv cameras have been used in space to produce images for meteorological observations, earth resources evaluation, scientific (lunar and planetary) exploration, and public interest data dissemination (e.g., Apollo program).

As the industry has matured, mechanical scanners using resolution-element-size sensors have replaced normal television area-array sensors for many of these types of imaging applications. These scanners offer extended spectral responsivity and response uniformity within the imaged format, making it relatively easy to have multichannel instruments using a single optical system and multiple detectors. For other applications, the unique features of conventional area-array television sensors which include a wide range of useful scan rates, short-term storage of a picture frame, and precise geometric accuracy, provide the best solution.

This paper will discuss two current applications. The first is the high resolution return beam vidicon (RBV) camera system used for earth observations from the Landsat-C spacecraft. The second is the closed-circuit television (CCTV) system planned for use on the space shuttle.

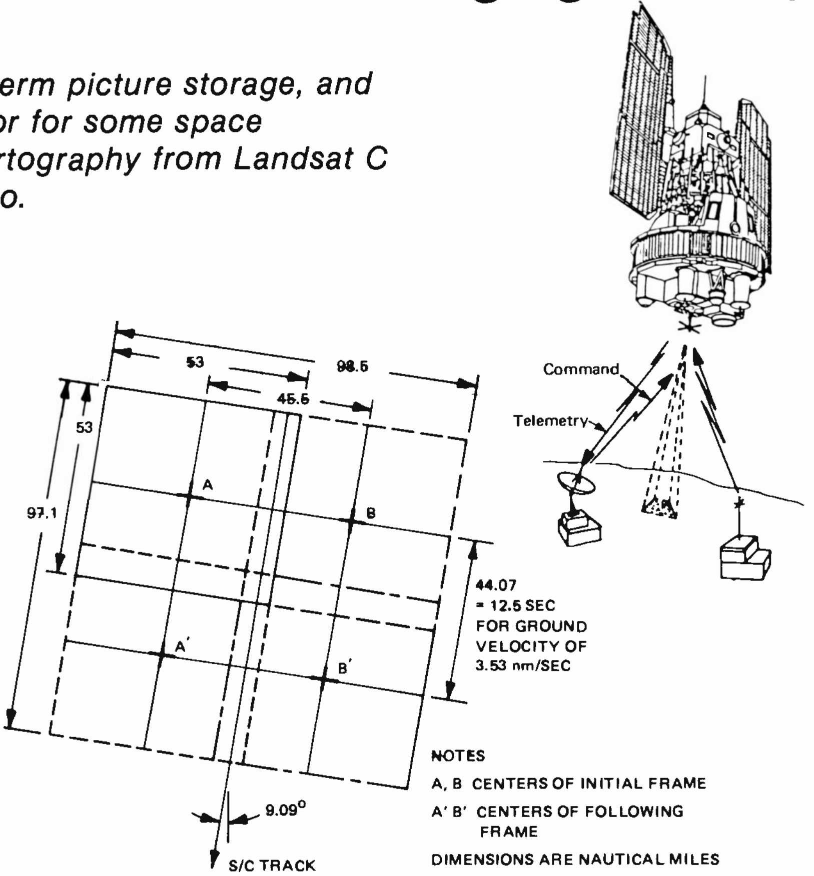

Fig. 1
Ground coverage from the Landsat C return-beam vidicon cameras which are mounted on the bottom of the spacecraft. Each of the side-by-side cameras looks at a 53-mile-square area of the earth every 12.5 seconds. As shown, the images have a 8-mile-wide overlap on two sides. The overlap at the center of the spacecraft track is determined by camera pointing angle; the overlap perpendicular to the track is a result of the 12.5-second picture-taking cycle and the spacecraft's ground speed of 3.53 nautical miles/second.

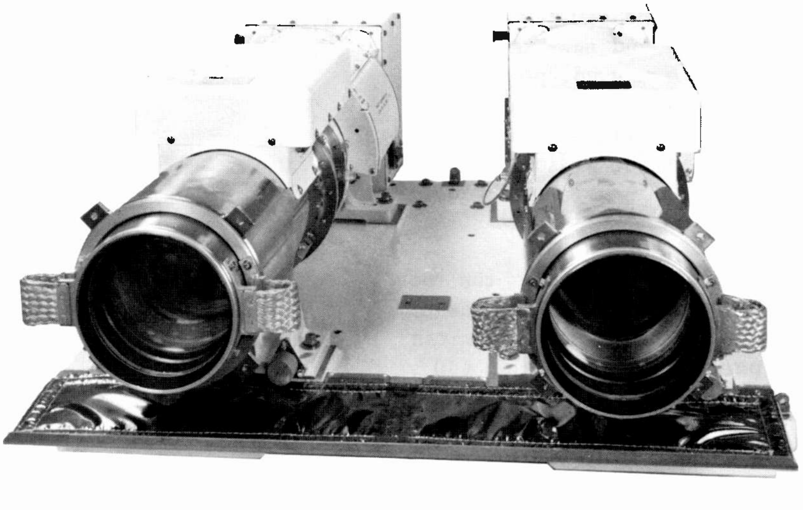

Fig. 2
RBV sensors on reference baseplate. The precise mechanical alignment translates into the precise eight-mile-wide overlap of pictures as described in Fig. 1. Also, the cameras are canted so that their picture-taking cycles can be sequential yet produce pictures of the ground that are aligned side by side.

High resolution cartography via television

Landsat (originally called ERTS or Earth Resources Technology Satellite) was designed to show that a spacecraft can be a practical tool for earth resource management. In fulfillment of this mission, three Landsat spacecraft have provided over a

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hundred thousand television images of the earth's surface in unprecidented breadth and detail (see J. Clark's article in this issue).

Landsat's imaging system is a multispectral mechanical scanner complemented by a return-beam-vidicon. The multispectral scanner provides imagery in a continuous 100-nautical-mile-wide swath, in five narrow spectral bands. Spacecraft motion generates the scan in one direction (along the orbit path), while an oscillating mirror perpendicular to the flight path scans across the 100-mile-wide swath.

Two return-beam vidicons allow Landsat C to locate ground reference points with about four times the accuracy of previous systems.

The return-beam vidicon cameras used on Landsat C are improved versions of those used in previous Landsat missions. The RBV's format has been modified so that each sensor provides a nominal 53-nautical-mile square image. The system contains two identical RBVs whose optical axes are arranged to provide adjacent, slightly overlapping images. The picture taking cycle in conjunction with the spacecraft velocity permits contiguous coverage of adjacent picture frames. As shown in Fig. 1, four RBV frames cover an equivalent 100-nautical-mile-square multispectral scanner image.

The smaller format RBV images can thus locate ground reference points about four times more accurately than previous spacecraft data. Landsat-C experiments are planned that combine the higher resolution return-beam-vidicon data with the multi-spectral color images, to provide enhanced data not otherwise available. Additionally, the RBV ground resolution should allow geometric accuracies approaching that required for 1:100,000 scale maps, i.e., about 30-meter (rms) error.

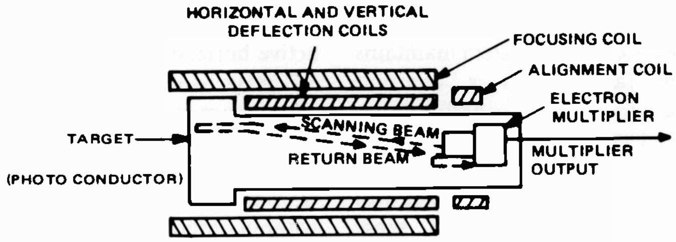
Landsat C's RBV system consists of two cameras, two camera electronics units, and one camera controller and combiner.

The cameras are mounted on a reference baseplate which serves as a precise alignment reference plane and thermal control element (see Fig. 2). As part of the optical alignment, the sensors are symmetrically tilted in the spacecraft's roll axis 2.69 degrees, and similarly canted (pitch axis) 0.71 degrees, from the nadir to provide the desired ground coverage.

How does the RBV achieve such high resolution?

The extremely high resolution of the return beam vidicon is made possible by a combination of slow scan operation, return-beam-mode of signal processing, and precise electron optics.

The spot size of the scanning beam in a vidicon is proportional to the beam current. When the scan rate is decreased, the beam current may be reduced proportionally, while maintaining a constant number of electrons landing on a unit area of the photoconductor. Thus, a smaller spot size, hence higher resolution, is obtained at slow scan rates.



In the RBV, the return beam modulates the signal source—an internal electron multiplier. This internal video signal amplifier introduces less external noise, allowing greater sensitivity to be attained in the sensor for a given signal-to-noise ratio. Thus, the RBV can be operated with lower photoconductor incident illumination than a normal vidicon. As a result, the beam current may be reduced further to improve resolution.

Precise electron optics (focus field, deflection field, and electron gun structure) further improve the high resolution response and ensure that the response can be maintained across the image format. The RBV uses the fourth node of focus, a specially designed non-uniform axial focus field, and high signal-to-noise ratio in the deflection circuits to maintain precise electron optics.

The cameras are identical—each has a return-beam vidicon, electron optics, deflection generators, electro-mechanical shutter, lens, and thermoelectric cooler.

The vidicon-type imaging tube is magnetically deflected and focused and contains an integral five-stage electron multiplier to provide low noise amplification of the return-beam signal current (see box). The 2¼-inch-diameter RBV faceplate provides a 1-inch-square usable format. A precisely located reticle pattern (termed a reseau) is deposited on the scan-beam side of the faceplate to provide a fixed geometric reference to correct scanning or optical errors.

The two-bladed shutter permits ground commandable uniform exposures at times as fast as 2.4 ms. Both blades are in motion during an exposure and serve as a moving slit. The actual exposure is determined by the time difference in the blade start commands, and thus, the effective width of the slit. The shutter design has been tested to in excess of 1 million operations.

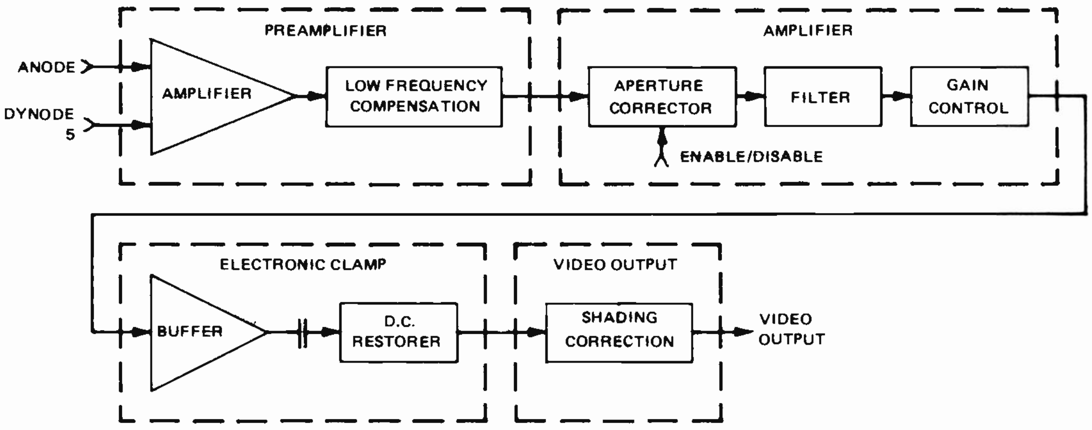


Fig. 3
RBV video processing circuits include improved shading correction.

A thermoelectric control system maintains the vidicon faceplate at a constant temperature to prevent performance degradation. Four thermoelectric (Peltier effect) modules are mounted on a copper heat sink which is in intimate contact with the faceplate. Two thermistors sense faceplate temperature and control an electronic servo, driving the modules to heat or cool as required to maintain a constant faceplate temperature. Thermal shunts attach the heat sink to the alignment baseplate which contains radiative and conductive thermal control paths.

The operational picture cycle for each camera has a duration of 12.5 seconds and includes four modes—erase, prepare, expose, and read.

Scanning parameters and readout time are compatible with ground data processing equipment used for previous RBV equipment (25 second cycle), and to permit the required picture frame overlap as shown in Fig. 1. The picture sequence starts with a 0.5 second erase cycle during which the photoconductor is uniformly discharged by lamps mounted at the edge of the faceplate; this removes any residual image. The erase is followed by a prepare cycle consisting of 16 half-second frames of photoconductor scanning to establish a uniform target potential. Symmetrical triangular horizontal deflection is used for this mode to conserve power. Following the prepare mode, the uniformly charged target is exposed to the scene illumination during a 200-ms vertical-blanking interval at the beginning of a 3.5-second readout frame. Image information is generated during the readout interval using 4125 active horizontal scan lines, resulting in a 3.2-MHz bandwidth for the video signal. The picture-taking sequence for the second camera is shifted by the duration of the readout frame to permit sequential transmission of the two video frames without intermediate signal storage. The resultant time shift of the two exposures would normally produce a vertical displacement of the adjacent ground formats. This is corrected by the previously mentioned alignment canting of the two camera sensors.

The camera electronics has improved shading correction circuitry.

The camera electronics unit for each sensor contains supporting circuitry to process the video signal, generate required power supply voltages, actuate the shutter-blade solenoids, and control the thermoelectric modules. The video processing functions are shown in the block diagram (Fig. 3). The compensation range of the shading correction circuits has been improved for the new RBV cameras, to provide greater fidelity in the transmitted image.

Shading is described as non-uniformity in the video output signal when the sensor is stimulated by a uniform scene, and is therefore undesirable as a characteristic. A number of factors contribute to shading, including uniformity of the photoconductor responsivity (sensitivity variations), non-orthogonal landing of the scanning beam, $\cos^2$ transmission fall-off in the optics, and dark-current effects. Shading is generally measured for the two extremes of the video signal; namely black level corresponding to a capped lens condition, and white level corresponding to the sensitivity to full scene luminance.

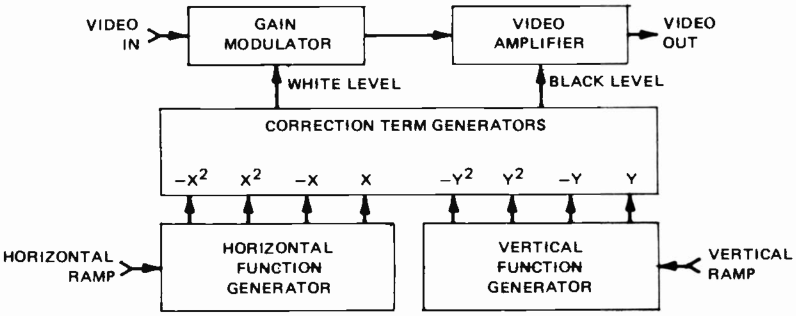


Fig. 4
Shading correction is accomplished by varying the gain of the video signal as a function of scan-beam position to reduce white-level variations and by changing the dc level of the video output to compensate for black-level changes.

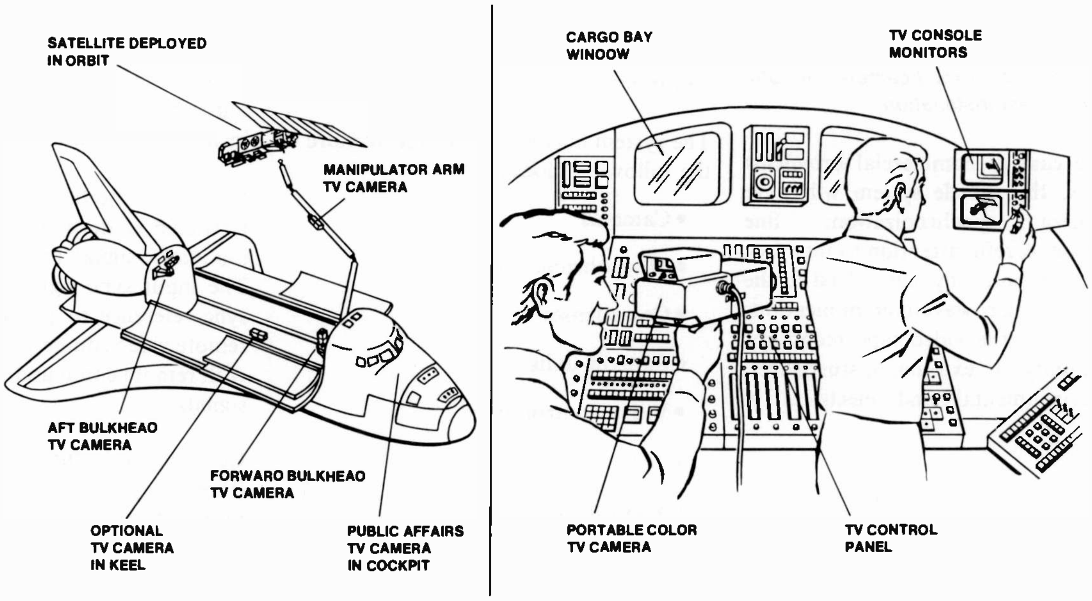


Fig. 5
Closed circuit tv system for the space shuttle.

Shading correction may be accomplished by: 1) changing the gain of the video signal as a function of scan-beam position to reduce sensitivity (white-level) variations, and 2) changing the dc level of the video output to compensate for baseline (black-level) changes. Since the sources of shading are stable with time, the correction waveform may be a predetermined complex function of the position of the reading beam. Previously, the RBV correction techniques provided fairly good correction except at the top, bottom and extreme corners of the readout. The Landsat-C camera electronics uses a new circuit that produces a baseline correction voltage which allows the horizontal correction amplitude to change as a function of the vertical position.

Sensitivity shading correction is accomplished by modulating the video signal amplitude as a function of the applied correction voltage. The correction voltage is applied to a shunt modulator which varies resistance as a function of the correction voltage. The modulator is referenced to the baseline level so that only the gain, not the baseline level, is affected by the modulator.

A block diagram of the shading correction is shown in Fig. 4. Horizontal and vertical ramp references are derived from their respective linearized deflection currents. Parabolas and ramps of standard amplitude are developed in the function generators and supplied to the correction circuits.

The camera controller and combiner uses a 1.6 MHz clock signal from the spacecraft to generate all timing signals for operation of both cameras.

The CCC receives video signals from both cameras and forms them into a serial video output containing horizontal and vertical sync, and spacecraft time code to permit picture annotation at the ground site. The CCC design is similar to previous units, with changes restricted to forming the new picture sequence cycling, together with general component upgrading.

Closed circuit tv for the space shuttle

The space shuttle, currently under development, will provide a reusable launch vehicle to transport a variety of payloads to orbit, retrieve payloads, service satellites in space, and provide a laboratory for experiments in space. The shuttle payload bay is 60 feet long and 15 feet in diameter and will be equipped with a remotely operated manipulator arm for use by the astronaut crew in handling payloads.

An on-board closed-circuit-television (CCTV) system, consisting of as many as six cameras, will provide coverage of the payload compartment, the surroundings of the shuttle orbiter, and the interior of the cabin and crew compartments (Fig. 5). The CCTV system is compatible with standard broadcast rates and quality, so that the transmissions can be used by the NASA Public Affairs Office to disseminate information of interest to the general public. It will also allow engineers and scientists on the ground to participate during experimental operations, engineering tests, and in-orbit problem solving. All on-board video signals are also ground-selectable for viewing and distribution by Mission Control and the Public Affairs Office.

The forward bulkhead of the payload bay has small windows in an otherwise solid structure which blocks most of the view of the payload bay from the crew in the command cabin. Many critical events using the manipulator arm will take place directly above the cabin or behind payload bay cargo, out of view of the operator. A CCTV system is therefore essential to ensure proper payload handling, inspection, and deployment/retrieval, and for monitoring of mission-critical activities. When direct observation is possible, closed circuit television may be used to advantage by the operator for close-up views of the end of the manipulator arm.

A wide range of operations are intended for the CCTV system on the shuttle: structure inspection; observations during in-flight servicing of spacecraft with replacement modules; payload deployment; connection and retrieval of free-flying payloads; and interior operations, including public information broadcasts as well as interior inspection.

Because of this broad range of planned use, the quality, reliability, and operational flexibility of the CCTV system must be comparable to that of a multicamera, remote-pickup broadcast installation.

As is the case in commercial broadcast operations, the shuttle system will have multi-camera synchronization; line equalization; careful attention to interface constraints imposed by signal feed to the monitor, the microwave communications processor, and the video tape recorders; and immunity to external disturbances, both environmental and electrical in origin.

Plans for the shuttle program extend through the 1990s. Thus, the CCTV system is being designed for maximum flexibility, so that a large variety of currently unspecified payloads and experiments can be accommodated with minimum system change. As one example, the CCTV hardware is modular, with brackets and cabling designed for flexibile installation and mounting.

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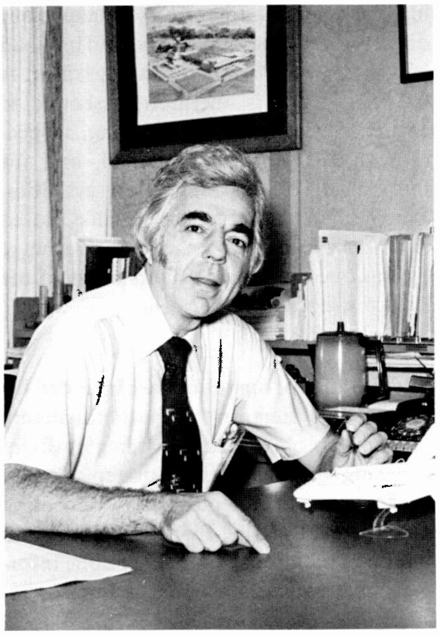

The system may consist of one or more of the following modules:

- Cameras
- Monochrome lenses
- Color lenses
- Pan/tilt units
- Video control unit
- Television monitors
- Viewfinder monitors

The general arrangement of the CCTV equipment within the space shuttle is shown in Fig. 5.

A typical mission would require the use of five cameras; one each on the forward and aft bulkheads of the payload bay, one on the manipulator arm, one in the keel of the payload bay, and one in the crew cabin. The first three of these will be mounted on pan/tilt units allowing essentially full spherical coverage. An additional camera, fixed in position at the wrist of the manipulator arm, may be used to aid in payload handling. The video control unit, located in the crew's cabin, performs all video and command routing and switching, and special video processing (e.g., split screen and special effects). The VCU contains spare channels to accommodate payload video interfaces or additional video sources within the CCTV system. Dual console monitors in the command cabin allow the operator to observe activity in the payload bay.

Wideband video processing circuits in the basic CCTV system can accommodate full color operation.

Cameras operating in the payload bay will normally be black and white, to simplify the on-board display system and conserve weight and power. However, color tv coverage within the payload bay can be provided if required for particular mission applications. The portable cameras located in the cabin areas will normally operate in color for viewing by the general public.

The camera image sensors are one-inch silicon-intensifier-target (SIT) vidicons,[1] which provide adequate sensitivity under the low light conditions that may be experienced in the payload bay. On-board supplemental lighting is provided; however, due to possible shadowing in the cargo compartment, the camera sensor must be sensitive to 10^{-3} foot-candles incident illumination.

Electrical interfaces to the camera are restricted to dc power, on/off command, input sync signal, and output video signal. The input sync signal serves as a master sync reference to permit genlock at each remote video source, and also is modulated with remote command data and video test signals.

Commandable functions include gamma (three slopes selectable), dynamic light range (three modes of automatic level control or automatic gain control), lens functions (zoom, focus, and iris), and pan and tilt controls (decoded and routed to the associated pan/tilt unit).

Commands are issued by either the on-board payload handling specialist at the display and control panel, or from the mission control center via an rf uplink. The commands, pulse-code modulated during two horizontal-line intervals in the vertical blanking period, are decoded in the camera. The decoder is designed to function in the absence of input sync or lack of genlock operation, for maximum system flexibility.

The video test signals include a modulated staircase and $\sin^2$ pulse and bar. Within the camera, these signals are stripped from the input signal and added to the output signal where they are used to provide standard reference signals for cable, video processing, and video link tests.

The video output signal is standard 525 line, 60 fields/second, interlaced EIA format. In addition to the video information, data are incorporated during the vertical blanking interval. The data include camera temperature, operating location and unit serial number, video test signals, status of the gamma and dynamic light range modes, and the encoded positions of the pan and tilt angles. The transmitted data are available for use either by the payload handling specialist on board the shuttle or by the ground controller.

The camera is designed to function with either of two lens assemblies, color or monochrome.

The color lens uses a rotating six-segment filter wheel to produce field-sequential color when used with the associated camera. The color wheel and synchronous drive are similar in design to the Apollo lunar camera unit,[2] and provide an individual color field each 1/60 second. After transmission to the ground station, scan conversion equipment stores a triad of sequential fields to generate an NTSC-compatible signal for broadcast to home viewers. The field-sequential signal may be viewed on-board the shuttle on a monochrome monitor at full resolution. The color lens is normally equipped with a 6:1 remotely actuated zoom lens. Motor drive mechanisms are pivoted to permit interchange of other lens types for particular mission application.

The monochrome lens is identical to the color lens, except that the color wheel and associated drive circuit are omitted. Both assemblies are keyed and fitted with quick-disconnect fasteners to permit interchange during mission preparation.

The pan/tilt units provide two degrees of freedom for camera mounting and pointing.

Pan and tilt motions (±170° in each of the two orthogonal axes) are driven by permanent-magnet stepper motors in response to commands decoded in the camera. Pan and tilt angles are encoded and routed to the camera where they are added to the output video signal. Adjustable limit stops are set during preparation for the particular mission. In addition, the zero reference for pan/tilt angle encoding may be reset by command during a mission operation.

The pan/tilt unit mechanical design supports the camera near its nominal c.g., to minimize motor power requirements. The design also maintains a selected angular position with power removed from the drive system.

The video switching unit (VSU) and the remote control unit (RCU) provide video control.

The VSU switches and distributes each of the video sources to any of the video output destinations. The RCU includes redundant master sync generators and controls the command interfaces between the shuttle, the uplink, and the individual cameras.

Video routing in the VSU is accomplished with a cross-point matrix of solid-state switches, feeding dedicated video line drivers which are individually compensated for their respective output cable lengths. A split screen is displayed by alternately actuating the associated source pair of switches for half the horizontal period (½H). In addition, a center split-screen mode has been incorporated. In this mode, the two sources selected for split-screen operation are delayed by an appropriate time (¾ H for the left side, ¼ H for the right side) so that the split-screen switching automatically displays the original center portion of the two sources on the left and right half of the display. This technique permits the payload handler to orient the two cameras initially for optimum views, and then select a split display of two view angles without orienting the camera from the optimum position. Rapid switching between normal and split-screen display can then be performed while maintaining the alignment between the cameras and the viewed scenes.

The VSU also generates and inserts special data in the video output to the display monitors. These data include a crosshair reticle used as a payload alignment reference, and alphanumeric annotation to display the measured pan/tilt angles, video source location, and camera temperature. The data are formatted and inserted in dot matrix form at the bottom of the raster with additional video switches.

The RCU accepts commands from the two sources previously mentioned, performs priority assessment, and reformats the command structure for transmission to the cameras during the vertical-blanking interval. It generates a full-field video test signal, which is command selectable as a video source, and the two line test signals. The selected master sync source, multiplexed with commands and test signals, is distributed to each of the video sources through dedicated sync line drivers which are cable-length compensated similar to the video drivers. Status of the commanded camera functions, decoded from the camera video output signals, as well as talkback for video source and destination selection are provided to the display and control panel by the RCU.

Dual console monitors are mounted in the cabin to display the video signals.

The monitors are 8-inch-diagonal high-quality monochrome dislays. Standard pulse cross display capability allows inspection of the sync interval, including the control command lines. One of three video sources is displayed on each monitor, selected by a front-panel switch.

A contrast-enhancement faceplate filter provides implosion protection for the cathode-ray tube while improving the scene contrast under the cabin's ambient illumination. The monitor is capable of at least 500-line horizontal resolution over the full raster area.

The viewfinder monitor is a small, low-power black and white monitor with an active 4-square-inch viewing area.

The viewfinder monitor is normally used by the astronaut in conjunction with the cabin color camera to permit adjustment of field-of-view, framing, and focus. It is equipped with mounting brackets to attach to the top or sides of the cabin camera, or to a mounting position in the cabin. An over-peaking mode, switch selectable, is available to enhance the camera focus.

Conclusion

Conventional television sensors have been used extensively in various space applications. Mechanical scanning sensors have displaced image tube devices in many of the applications; however, the unique features of image-tube devices have preserved their usefulness in certain specific NASA programs. Two primary examples are the Landsat C cameras, which offer the extremely high resolution and precise geometrical characteristics of the return beam vidicon, and the shuttle CCTV camera system which utilizes the low light sensitivity, wide dynamic range, and burn resistance of the silicon intensifier target vidicon.

Other evolving sensors may be used in space applications as their technology matures. Charge-coupled device (CCD) sensors are nearing this state of development at the present time. Offering advantages in terms of size, weight, power, and solid state reliability, they are at present limited in resolution and low light sensitivity. We anticipate that expected improvements will permit their future use in the shuttle CCTV program.

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2. Soltoff, B.M., "Apollo 15 and 16 Ground Commanded Television Assembly," *RCA Engineer*, Vol. 18, No. 3, (Oct 1972), pp. 62-67.

Spacecraft power systems—past, present, and future

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H. Bilsky
S. Gaston

A typical spaceborne electrical power plant must be maintenance-free and totally reliable for eight years. Producing such a system means bringing a number of diverse skills together successfully.

A spaceborne electric power plant requires the application of a broad spectrum of seemingly unrelated scientific and technical skills. Even if one limits the scope of interest to only the most common variety of spacecraft power systems, the photovoltaic solar-cell type, the diversity of problems confronting the designer attempting to bring about a self-contained, maintenance-free source of electric energy capable of withstanding the rigors of space environment for several years becomes immediately apparent.

Consider, for instance, the solar-cell array, which is the prime source of power in photovoltaic power supplies. Each of the typically several thousand cells is shielded from direct exposure to harmful space radiation by a thin layer of optically pure glass bonded to the cell with a transparent adhesive. Delicate silver interconnections are used to connect the cells into an electric circuit, and the assembled cells are attached to the solar panel by means of an adhesive deposited over a layer of insulating material applied to the aluminum skin of the panel's honeycomb structure. The entire assembly must be light in weight yet strong enough to resist severe strains during launch, and it must withstand hundreds of repeated thermal shocks—exposures to rapidly changing temperatures in orbit, typically from −120°C to +50°C. Special requirements are often invoked. For instance, adhesives must not emit trapped gases that could contaminate sensitive instrumentation frequently carried on board a spacecraft. Also, magnetic fields generated by the solar-cell current must be neutralized.

Solar cells produce electricity only when sunlight strikes them. If the cells are mounted on solar platforms apart from the main body of the spacecraft, motor-driven array drive mechanisms are usually provided to keep the platforms pointed at the sun.

Solar-cell output is subject to large variations caused by a combination of such influencing factors as temperature, solar incidence angle, and radiation damage. The solar-cell-generated voltage and current, therefore, must be conditioned so that they are suitable for application to electric loads. Special highly reliable regulation and conversion techniques are used for that purpose with an emphasis on minimizing heat dissipation and weight.

Since the spacecraft requires continuous electric energy, batteries charged from the solar array provide power when the spacecraft travels through the earth's eclipse. Sizing a battery for space use is a difficult design task because of the large weights involved and the need for tight temperature control. Special-purpose charging and protective circuits control the amount of charge without overcharging the battery, which can otherwise build up internal pressure and fail.

RCA's background in space power supplies

More than one hundred spacecraft, built under prime contract to RCA or subcontract to another supplier of space hardware, have been equipped with RCA-built space power systems.

Table I is a sampling of the space programs for which RCA has provided photovoltaic power supplies. A number of specialized techniques have been used to provide a reliable, self-contained, maintenance-free source of electricity in space. Generally, major components of a space power system and their functions can be described by reference to Fig. 1.

Table I
RCA photovoltaic power supplies have been used in more than 100 spacecraft; this sampling shows the diversity of RCA's effort.

Program	Year launched	For	Orbit (n.mi)	Voltage regulator
Tiros N	1978	NASA GSFC	450	Boost
Anik B	1978	Telesat of Canada	Geostationary	Partial shunt
Americom	1975-76	RCA Americom	Geostationary	Partial shunt
DMSP-5D	1976-77	USAF	450	Boost
Atmosphere Explorer	1973-75	NASA GSFC	70-2050 elliptical	Pulse-width-modulated (PWM)
ITOS	1970-73	NASA	800	Series dissipative
Landsat/Nimbus	1964-78	NASA GSFC	500-700	PWM and series dissipative
Transit (Navsat)	1968-73	US Navy	650	Series
Tiros-TOS	1960-69	NASA GSFC	500	Series dissipative
Ranger	1964-65	NASA	Lunar Flight	Series

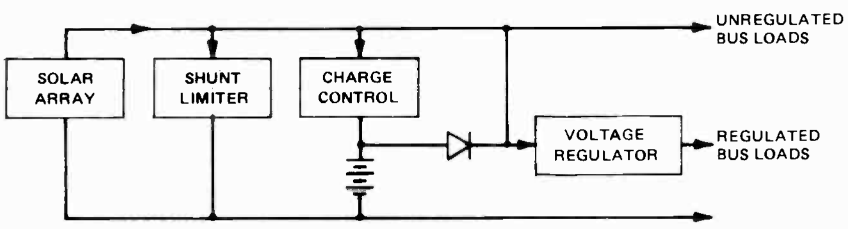


Fig. 1
Space power system in its simplest form has these subsystems. The solar array is the power source, the shunt limiter keeps the voltage below a predetermined level, the charge controller regulates charge to and protects the batteries, and the regulator controls loads to the spacecraft power bus.

The solar array is the prime source of electrical energy.

The array is a matrix of series- and parallel-connected solar cells that convert sunlight directly into electrical energy. Typically (many variations exist), a solar cell is 2 x 2 cm in size, 10 to 14 mils thick, and covered with a layer of 6 mils or more of fused silica to protect it from the effects of Van Allen Belt radiation. Again, typically, such a cell may deliver 125 mA at 0.46 V under room-temperature conditions. We connect a sufficient number of cells in series to provide a bus voltage within the working range of perhaps 25 to 35 volts, and a predetermined number of series-cell strings so as to assure sufficient power. A considerable amount of basic solar-cell research was performed at the RCA Laboratories in Princeton, leading to notable state-of-the-art advances in ultra-lightweight, high-voltage, and other areas of solar-cell technology. In the early-to-mid-sixties, RCA was also a leader in mass-produced solar cells used industrywide. Solar arrays flown on all RCA spacecraft are built and tested at the Astro-Electronics array-assembly facility in Princeton.

Referring once again to Fig. 1, the solar-array output power is divided between the loads and the battery charge. Load demands are satisfied first; any surplus power is delivered as battery charge. Any surplus over and above that is dissipated in the shunt limiter.

The charge-control circuit in its simplest form is a current limiter. In the more common version, used in the RCA Americom communication satellite, the charge current is also controlled by the battery voltage and temperature.

Nickel-cadmium batteries are used in almost all of the space power supplies used by RCA and others.

The choice is motivated by two key properties of Ni-Cd: it is durable and it lends itself to hermetically sealed packaging, the latter a significant factor for operation in the hard vacuum of space. Typically, a Ni-Cd cell develops 1.25 V under moderate discharge, and is recharged to 1.5 V. Several cells, possibly 20 to 24, are series-connected into a battery pack, and one or more packs are flown in a spacecraft. RCA has designed and built more than 250 flight battery packs, predominantly Ni-Cd, but also a limited number of specialized silver-zinc batteries, which have a weight advantage and are used when spacecraft lifetimes are very short.

The shunt limiter is a power stage placed across the solar array.

The shunt limiter protects the system by conducting once a predetermined upper-limit voltage is reached, as when solar cells generate excessive power. A more sophisticated version of this principle, the partial shunt, is flown on the RCA Americom communication satellite, giving the advantages of lower power dissipation and considerably lower weight. Several versions of the partial-shunt approach exist on the drawing board and in practice, prompted largely by the formulation of the basic partial-shunt theory at RCA in the sixties.

		Solar array		Battery		
Load power, (W)	Load voltage, (V)	No. panels	Total area (sq.ft.)	No. batteries	Capacity/battery (A-hr)	(W-hr/lb)
550	+28	8	125	2	30	12
550	+24.0 to +35.5	4	75	3	17	13
500	+24.5 to +35.5	4	75	3	12	10
450	+28	8	100	1	17	12
170	−24.5	Body-mounted	65	3	6	8
150	−24.5	3	50	2	6	9
500	−24.5	2	48	8	4.5	8
25	9.2	4	37	1	12	--
100	−24.5	Body-mounted	30	3	4	7
1000 max.	32	---	---	2	43	34

In many systems, unregulated bus voltage, varying typically within a ±15% range, is conditioned at load by regulated dc/dc converters. Such is the case, for instance, in the Americom spacecraft. In many other satellites, a centralized voltage regulator is employed, usually in a redundant configuration for added reliability. Early spacecraft used the more traditional series-dissipative form of voltage regulator with the attendant problems of high thermal dissipation and lowered efficiency. RCA pioneered the development of the highly efficient, lightweight, transformerless switching regulator now in common use, as well as its various versions, such as the buck-voltage, boost-voltage, and the buck-boost voltage-inverting variations.

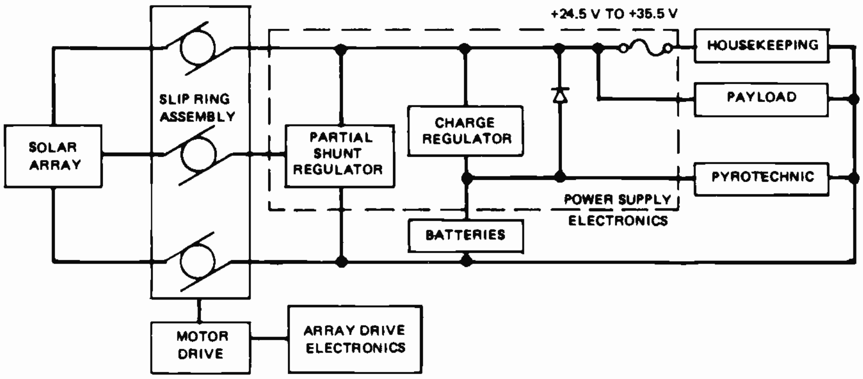


Fig. 2
Electrical power system for a specific spacecraft—the RCA Americom communications satellite. Note the similarities to Fig. 1.

A design example—the Americom communications satellite

The Americom spacecraft's power system illustrates how skills can be blended to produce a highly reliable system for an 8-year mission.

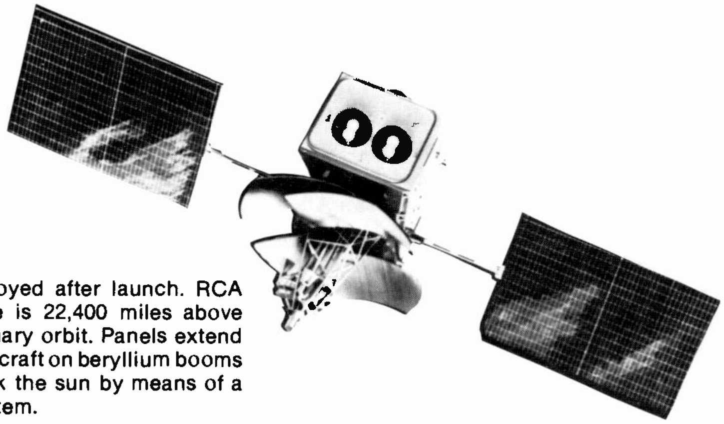


Fig. 3
Solar panels deployed after launch. RCA Americom satellite is 22,400 miles above earth in geostationary orbit. Panels extend from body of spacecraft on beryllium booms and seek and track the sun by means of a common drive system.

The Americom satellite's Electrical Power System (EPS) uses a direct-energy-transfer configuration providing a bus voltage of +24.5 to +35.5 V for operating the spacecraft support subsystems and the 24-channel communications payload.

The bus voltage is converted to specific unit voltage requirements by individual unit regulators. These distributed regulators preclude a major EPS single-point failure. The direct array-to-load connection maximizes the efficiency and minimizes the weight of the electrical power generation, storage, and regulation systems.

A single-axis clock-controlled shaft drive keeps the planar solar array oriented toward the sun. Energy from the array is transferred directly to the main bus through slip rings. Fig. 2 is a functional diagram of the EPS.

The 75-ft^2 solar array is designed to supply about 600 watts (equinox) at the end of the 8 years in orbit to the high-power communications payload and the spacecraft housekeeping loads. Excess array power is shunted by a linear-operating partial shunt regulator. The solar array consists of two paddles, each incorporating two panels, driven by a common array drive. The inboard panel of each paddle is connected to a beryllium boom that extends from the array drive outward through the north and south sides of the spacecraft, as shown in Fig. 3. For launch and transfer orbits, these panels are folded against the sides of the spacecraft.

The system uses three independently charged, 22-cell, nickel-cadmium batteries, with a total capacity of 36 A-hr. These batteries provide the payload and housekeeping power required throughout the longest eclipse periods and when higher-than-usual electrical loads are present. Should one of the three batteries be taken off-line for any reason, essential spacecraft control loads plus more than 50% of the payload can still be powered throughout eclipse by the remaining two batteries. During the non-eclipse seasons of the year, except for an occassional high-power transient load, there is no requirement for batteries.

Redundant charge regulators available for each battery provide three different charge rates, which are selected by ground command based on the operating mode of the spacecraft. Unique battery reconditioning circuits are available to execute a procedure that restores, in part, the original voltage characteristics of the batteries. Redundancy is provided for all of mission-critical functions, including the solar array drive and the pyrotechnic circuits used to initiate solar-array deployment.

After launch and injection into the transfer orbit by the launch vehicle, the spacecraft will be spinning at 60 r/min. Because the array paddles are folded against the two opposite sides of the spacecraft, with their planes parallel to the spin axis, the power output will approximate a rectified sinewave. Consequently, the batteries are alternately charged and discharged at a rate related to the spin rate (2 Hz).

After the satellite reaches synchronous altitude, the solar panels are deployed, the solar array drive is enabled, and the array is slewed toward the sun. After sun capture, the array is automatically driven to track the sun.

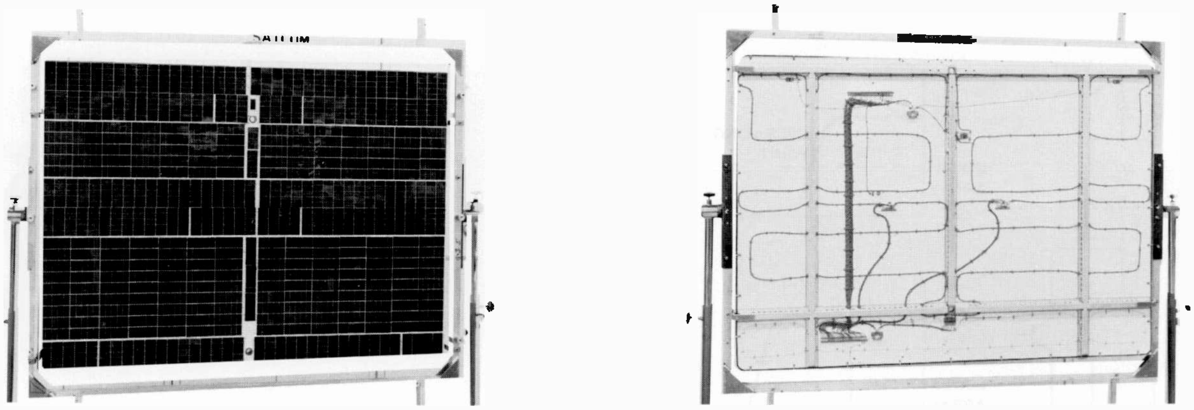


Fig. 4
Solar array supported in test fixture. Photo on left shows solar cells, photo on right shows electrical interconnections on back of panel.

The power system normally operates automatically; it requires ground control only for battery reconditioning and the initiation of battery charging before and after the eclipse seasons. However, ground override of automatically controlled functions is provided for abnormal situations. Important EPS parameters are monitored by telemetry to permit in-flight analysis and performance evaluation of the subsystem.

The use of a partial-shunt control system minimizes thermal dissipation within the spacecraft to a fraction of the unneeded power. Thermal dissipation can be controlled and reduced further by offsetting the array from the sun, thereby reducing the power generated.

Battery charge control is performed automatically by the charge regulators. During the 100-percent suntime orbits (summer and winter solstice periods) the regulators are commanded into the trickle-charge mode. In the eclipse seasons (two periods of 44 days each year; spring and fall equinox periods) the charge regulators are commanded into the normal charge mode. Normally, all batteries operate in the same mode. However, twice each year, prior to an eclipse season, each battery is individually reconditioned, a procedure that consists of a complete discharge and recharge at a rate higher than the normal charge rate.

Component descriptions

The solar array is a matrix of parallel strings of series-connected solar cells.

Electrically, the solar array (Fig. 4) is divided into two sections separated by the tap-off point for the partial shunt regulator. This solar-array arrangement was optimized by computer analysis based on lifetime requirements, environmental conditions, and electrical load.

Each solar-cell circuit of series cells is diode-isolated, including the tap-off-point inputs to the partial-shunt circuits. Redundant parallel diodes are used for circuit isolation, and are located on the backside (anti-sun side) of the solar panels. Each diode-isolated circuit provides power to the spacecraft via slip rings.

The solar-cell substrate is reinforced aluminum honeycomb on which solar cells, arranged in circuits and protected from radiation by fused silica material, are adhered.

Each of the three spacecraft batteries contains 22 series-connected, hermetically sealed, space-proven nickel-cadmium cells.

Each battery has a 12 A-hr capacity and is packaged in two 11-cell modules (Fig. 5). Battery heaters used for controlling temperature are included in the module package. Individual cell reconditioning resistors and their control relays are mounted on the battery module, but are controlled by the Power Supply Electronics (PSE).

The battery container is a four-piece structure constructed of magnesium alloy plates. This arrangement provides clamping forces to support the cells when internal pressure develops in the cells and when environmental loads are imposed. The structure provides a good thermal conduction path to the honeycomb mounting surface by allowing the cells to contact the surface through an electrical insulator. Fiberglass insulation is used between the cells and to encapsulate the redundant battery heaters. This packaging approach produces the desired average temperature and limits temperature gradients.

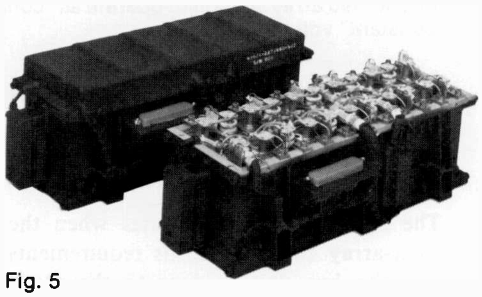
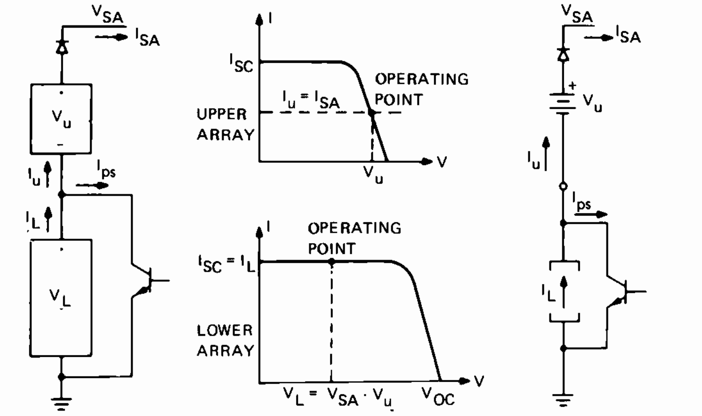


Fig. 5
Hermetically sealed Ni-Cd batteries are packed as two 11-cell modules. Spacecraft has three such batteries, weighing a total of 81 lb.

The Power Supply Electronics (PSE) unit controls the conditioning and distribution of electrical power throughout the spacecraft.

The power system monitoring and regulatory elements are housed within the PSE, with the exception of portions of the partial-shunt regulator. Although the control section of the shunt regulator and the shunt transistors function electrically as one, the shunt transistor and its driver assemblies are mounted on the relatively massive central column of the spacecraft structure. Power handling and thermal considerations make this location desirable.

Redundant configurations, included in the design for each of the major circuit elements, are activated automatically by failure-detection circuitry or by ground command.



SOLAR CELL CIRCUIT I V CURVES EQUIVALENT CIRCUIT

Fig. 6
Partial shunts prevent excess voltage across the load. When shunts are operating, they force the shunted array section to operate as "constant"-current source. Unshunted array acts as "constant" voltage.

Fig. 7
Solar array drive must have very high reliability. It uses a brushless dc motor and resolver, gold-to-gold slip-ring contacts, finely finished bearings, and special lubrication. The drive also uses a special bearing/diaphragm system to account for widely varying thermal expansion rates and temperatures found in the spacecraft.

The shunt regulator limits the load bus voltage to 35.5 V by reducing the solar-array output current to the level required by the spacecraft.

The shunt regulator operates when the solar-array current exceeds requirements and the bus voltage rises to the shunt regulator cut-in voltage, 35.30 V nominal. A control amplifier compares the bus voltage to a voltage reference and generates an error signal when the bus exceeds the cut-in voltage. Partial-shunt circuits reduce solar-array current in response to the error signal.

Excess current is controlled by the partial shunts located external to the PSE. When the shunts are operating, Fig. 6, they force the shunted array section to operate in the "constant"-current source region of its I-V characteristic, so that the net current available matches the spacecraft requirement. The operating point of the unshunted array section is in the "constant"-voltage source region of its I-V characteristic. The voltage across the shunted array section assumes the value necessary to maintain system-limited bus voltage by the current adjustment.

The control amplifiers and drivers are redundant and both circuits are normally connected. Should either set fail "open," then the other will be on-line to limit the load bus voltage. Each set is provided with a failure detection feature which will disconnect a failed "short" amplifier. The failure detectors and control amplifier switching are configured so that one amplifier is always connected.

The battery charge regulators control and regulate battery charging current, protecting the batteries from overcurrent, overvoltage, and excessive overcharge.

To perform these functions, battery charge current, battery voltage, and battery temperature are monitored continually and compared with preset references to provide the necessary feedback signals for each mode of charger operation. Each of the spacecraft batteries has primary and backup charge regulators that can operate in three current-limiting modes, as noted previously. When a failure detector senses excess charge current, a relay disconnects the charger from the bus and the backup charger is connected by ground command.

The solar array drive rotates the array to acquire and track the sun.

The motor (Fig. 7), which is coupled directly to the solar array, rotates the array at one of two speeds (in either direction) against the friction torque of the bearings and brushes on the slip rings. The array normally rotates at one revolution per solar day, but can also slew at 27 times this rate for sun acquisition. The system uses two motors and two synchro resolvers for redundancy. Integral slip rings transfer power from the array across the rotating interface to the spacecraft. Angular position of the array is determined by the resolver. The entire drive weighs only 10 lb and is roughly six inches in diameter and 12 inches long.

The solar array acquires and continually tracks the sun by a ground-commanded clock-driven controller. Based on the orbital position of the satellite relative to the sun and the telemetered position of the array relative to the spacecraft, the array is slewed by ground command to the desired orientation with respect to the sun, and then switches to its normal operation of 1 revolution per solar day. The control system's accumulated error is corrected periodically.

Power subsystem performance analysis

The EPS furnishes electrical power to the spacecraft subsystems during all phases of the 8-year mission, including a short period on the launch pad, during transfer orbit, and final attitude-control maneuvers. The power required for the pre-operational phases of the mission is 70 watts (nominal) and less than 600 watts for the 8-year operational phase (during equinox periods).

The size of the solar array was determined by the spacecraft power required and by several factors that influence power generation. The analysis took into account radiation damage to the array, the major cause of reduced power. To shield the array from this radiation environment, which includes electrons, protons, and alpha particles, the cells are covered with highly transparent fused silica platelets. This radiation-protection scheme is not absolute and the solar-array power does decrease measurably with time. This estimated degradation was used in the prediction for the array behavior, along

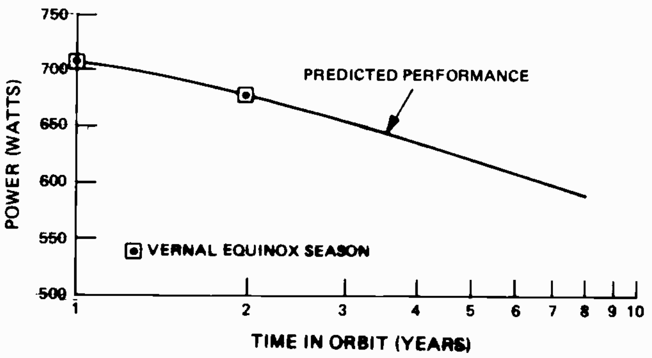


Fig. 8
Performance so far for Americom F-2 satellite agrees with initial predictions. Decay in power available is mainly a result of slow buildup of radiation damage to array.

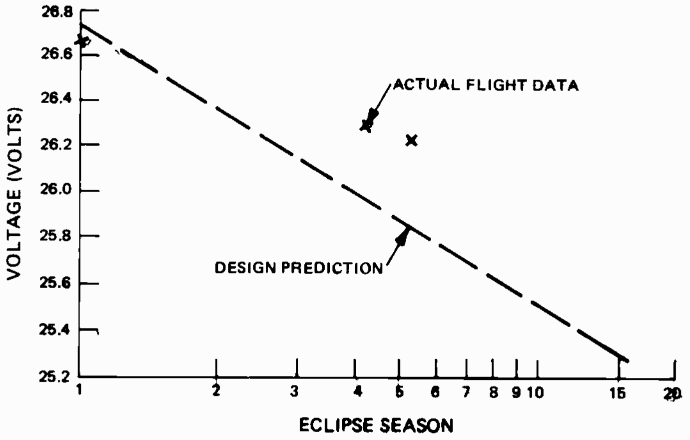


Fig. 9
Battery discharge voltage decreases with time because of battery aging. Performance for Americom satellite, however, shows higher voltage than predicted.

with power distribution losses, ultraviolet-radiation damage, cell and coverglass optical-properties degradation, and manufacturing losses.

Using these factors, the predicted array power through 8 years is given in Fig. 8. Thus far, array performance agrees with the initial predictions. Battery discharge voltage, because of aging, reduces with the number of eclipse seasons in orbit. However, the batteries (Fig. 9) show a distinctly higher voltage than the predicted value through five eclipse seasons. A substantial voltage margin is present and is likely to continue.

A look at the future

Solar cells and arrays are increasing in efficiency.

For nearly a decade the silicon solar-cell efficiency, or ability to convert sunlight to electricity, was a more or less constant eleven percent following the initial state-of-the-art advances of the early sixties. A significant improvement took place in 1972 with the development of the "violet" cell, which is much more sensitive to solar irradiance in the blue and ultraviolet spectral regions. The currently available mass-production version of the "violet" cell generates 25% more power per unit area than the old conventional cell, and is the prime power source on the RCA-built Anik B spacecraft.

Development of still more efficient cells is continuing. The improved output power of the back-surface-field cell, for instance, is attributed to the presence of an electric field produced by certain impurities diffused or alloyed at the rear surface of the cell. The so-called black or textured-surface cell promises to deliver still more power; its surface is specially treated to reduce reflectivity to such an extent that the cell appears velvet black. Solar cells combining the attributes of both the "black" and back-surface-field technologies have also been considered.

Aside from efficiency, other improvements have been made, such as the development of very light-weight, ultra-thin solar cells (2 mils vs. 10 to 14 mils in the more conventional versions). Solar cells made of exotic materials are also being developed, among them the gallium-arsenide cells with very high efficiencies (of the order of 18.5 percent). These cells will be more radiation-resistant and will perform better at high temperatures than their silicon counterparts.

Array technology is also being advanced. Thus, flexible arrays with special provisions to withstand extreme exposures to radiation are scheduled for flight in 1981. Similarly, an ultra-lightweight, high-power array will be flight-tested in one of the space shuttle flights in the not-too-distant future.

Lighter and longer-life nickel-cadmium batteries are on the horizon.

Better charge-control methods, tighter cell-manufacturing controls, and design improvements such as Teflonated negative electrodes (as used in the Americom satellite) mean that less gas pressure will be produced during battery operation, so the stainless-steel container can be made substantially thinner. The RCA-patented in-orbit battery reconditioning technique has proven very effective and should extend battery performance life. Further cell-design improvements are taking place. An electrochemically impregnated positive electrode, for example, with a better-controlled uniformity and higher active material utilization, has shown less electrode swelling with aging and also should extend performance life substantially. Further development on this space battery cell will continue—a 1982 goal is to double its energy density. A novel approach taken is to replace the stainless-steel cell housing with a carbon-fiber composite to decrease its weight significantly.

New storage systems—the nickel-hydrogen cell and the fuel cell—are part of the search for longer life and lower cost.

The nickel-hydrogen battery cell couple has an inherently longer performance life than the Ni-Cd cell. The cadmium electrode with its associated material penetration through the separator, forming an internal short circuit, has been replaced by an inert electrode. This couple permits higher depths of discharge and so yields higher effective energy densities. In June 1977, the U.S. Navy launched its Navigation Technology Satellite (NTS-2), containing a 35 A-hr nickel-hydrogen battery in addition to a conventional nickel-cadmium battery. The Ni-H_2 battery has performed well since. Nickel-hydrogen cells with 50 A-hr capacity have been developed and will receive extensive life evaluation testing shortly. This potentially longer-mission battery will ultimately result in lower total cost over its performance life.

The search for longer life, larger capacity, higher-energy-density and lower-cost electrical energy storage devices will continue beyond the immediate future in space applications since NASA is planning large space bases requiring from 25 to 100 kW power. These future storage devices might consist of fuel-cell types, or the alkaline-metal (lithium or sodium) battery cells. Fuel cells were developed and flown on the Apollo command capsule and will be flown on the space shuttle. They are electrochemical devices that operate by taking hydrogen and oxygen gases under pressure, combining them, and producing an electric current and a water by-product. Large progress has been made over the years to increase the fuel cell's performance life and efficiency. Recently an electrolysis cell was developed to recharge this system by means of solar cells.

The alkaline-metal rechargeable battery with its 100-200 W-hr/lb energy density has been under development for a number of years for use in electric vehicles. This effort has intensified recently with the realization that petroleum reserves are limited and material is too valuable just to be burned to obtain energy. These battery couples have shown very good results but still require longer life for successful terrestrial and space use.

Power-supply electronics subsystems will use more modern power conditioning and energy management techniques.

Advancements in the field of spaceborne power-supply electronics will continue to be made. One of the most significant improvements in the near future is energy management. Under this concept, the on-board energy generated and the load energy expanded will be carefully compared, with the computed results telemetered to the user on the ground. The results of these computations will permit more efficient use of the available energy by reducing reliance on safety factors, issuing timely warnings of an impending low battery charge, and accurately assessing any excess energy, which can be translated into more frequent payload programming. Microprocessor technology will make it possible to reduce the energy-management concept to common practice.

Another concept of significance is maximum-power-point tracking. The solar-cell array voltage at which maximum power occurs is constantly varying, particularly in lower-altitude orbits. If the maximum-power-point voltage is tracked, the array-generated energy can be used in the most efficient and economical manner. RCA built and tested a breadboard version of a maximum-power-point tracker under a NASA contract in the late sixties. While a number of spacecraft are already equipped with one of several variations of this technique, bulky circuits, attendant losses, and large voltage excursions present at the solar-array bus have precluded its widespread use. Efficient, reliable voltage regulators and other circuits capable of operating over a large input voltage range, such as 30 to 90 volts, are needed to make this worthy concept more attractive.

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Herb Bilsky joined RCA in 1962 as a member of the advanced power systems group; he worked on photovoltaic, radioisotope-thermionic and radioisotope-thermoelectric power systems producing an early prototype with many advanced features found in present-day design. He has worked on power systems for several RCA satellite programs, including the recent Americom and Anik B communications satellites.

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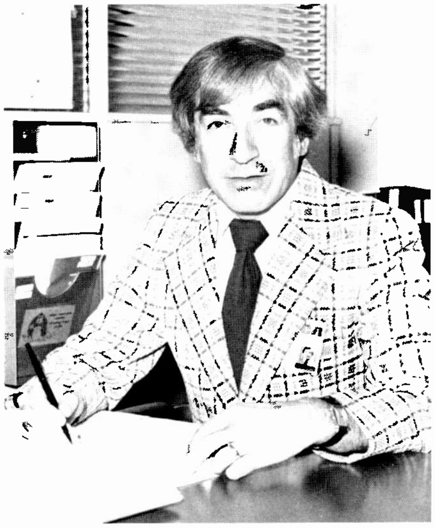

Paul Nekrasov has been engaged in spacecraft power-system analysis on such space programs as TIROS, Relay, Lunar Excursion Module, Nimbus, Ranger, and Atmosphere Explorer. He joined RCA in 1959. Currently he is with the Dynamics Explorer spacecraft program at Astro-Electronics, where he is responsible for defining the interfaces between various scientific instruments and the spacecraft.

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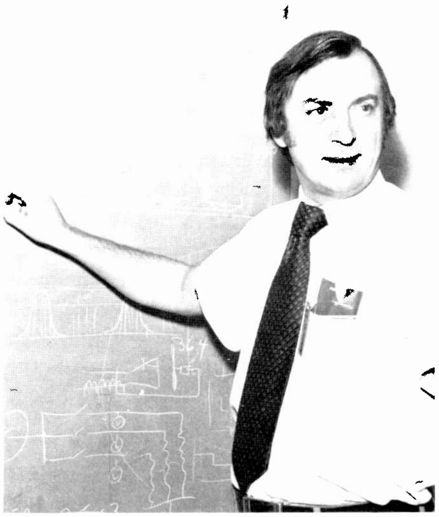
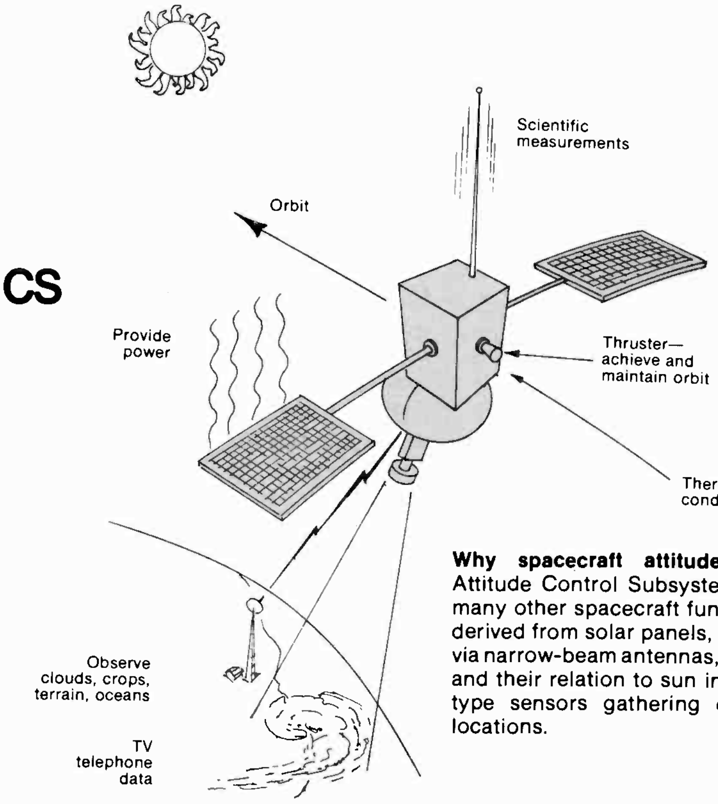


Developments in attitude control systems at Astro-Electronics

All space missions depend on pointing the spacecraft in the right direction.

L. Muhlfelder



Why spacecraft attitude control? The Attitude Control Subsystem (ACS) affects many other spacecraft functions: power as derived from solar panels, communications via narrow-beam antennas, thermal controls and their relation to sun input, observation type sensors gathering data at specific locations.

Since the founding of Astro Electronics in 1958, attitude control system (ACS) developments have helped to keep RCA in the forefront of the unmanned earth satellite business. Therefore, it is of historical technological interest, and not merely parochial motivation, to review the "whats" and "whys" of two decades of our efforts in this area. The accomplishments are the result of the innovation and dedication of numerous RCA engineers, past and present. The record reflects the phenomenal progress attained by the entire aerospace industry and the farsighted support granted by various government agencies. Before proceeding with a chronology of this development, let us briefly review the essential building blocks of the pertinent technology.

Stabilization techniques

When we guide a spacecraft, we control the position and velocity of its center of mass; when we control a spacecraft's attitude, we achieve and maintain the desired orientation about its center of mass. Fig. 1 shows the fundamental attitude control building blocks. As in any typical closed-loop system, control laws respond to sensed parameters and command actuators to acquire or maintain the desired spacecraft pointing with respect to the coordinate reference frame (Fig. 2).

So-called disturbances can often be exploited to advantage in spacecraft attitude control.

Every spacecraft, and particularly satellites in earth orbit, are subjected to most if not all of the following disturbances: gravity gradient torques (differential gravitational attraction caused by variations in distance to the earth's center of mass from various portions of the spacecraft), interactions with the earth's magnetic field, solar radiation pressure, aerodynamic effects, mass expulsion, meteoritic impacts, internal mass shifts, and momentum redistribution. Environmental torques due to gravity gradient, magnetics, and solar pressure are continuous although not constant, whereas

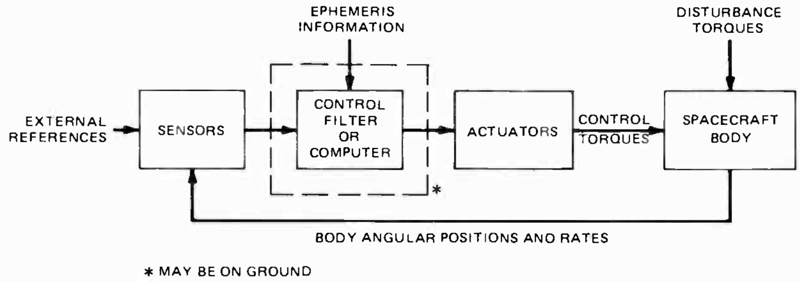


Fig. 1
Basic attitude control system. In this closed-loop system, the spacecraft's angular positions are matched against a reference to determine the control torques to be applied.

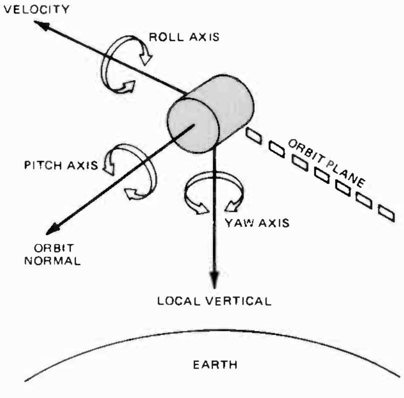
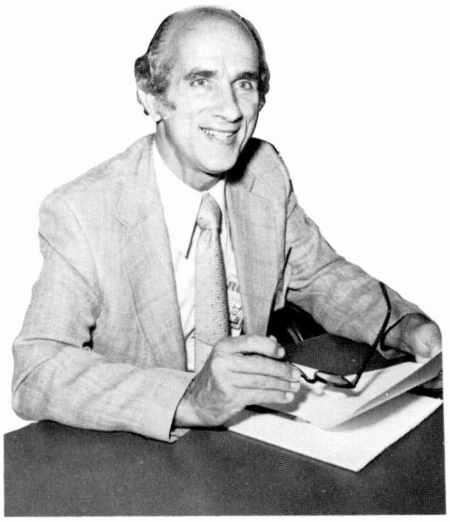


Fig. 2
The satellite's coordinate reference frame, for attitude control purposes involves three axes—although, in passive systems, only two axes are controlled.



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others listed above are often considerably larger and of shorter duration. Any of these disturbances will change the orientation of the satellite; however, several of these "disturbance" torques can also be utilized to acquire and maintain the desirable attitude.

Choosing the stabilization system (Table I)

Probably one of the more controversial aspects of satellite design is the choice of the stabilization system. This should not be surprising since the selected attitude control technique has a substantial influence on the spacecraft's total configuration and its mission capability.

The simplest ACS category is represented by passive systems which require no power, no sensors, no logic.

Typical passive stabilization methods include spin about the maximum moment of inertia axis, gravity-gradient orientation, solar or aerodynamic "sailing", locking to the earth's magnetic field, and combining gravity gradient with magnetic damping. As shown in Table I, the simplicity of these approaches yields relatively coarse two-axis control. Fig. 3 illustrates the basic spin-stabilized spacecraft which, as a gyroscope, maintains an inertially fixed spin-axis orientation in the absence of external disturbance torques.

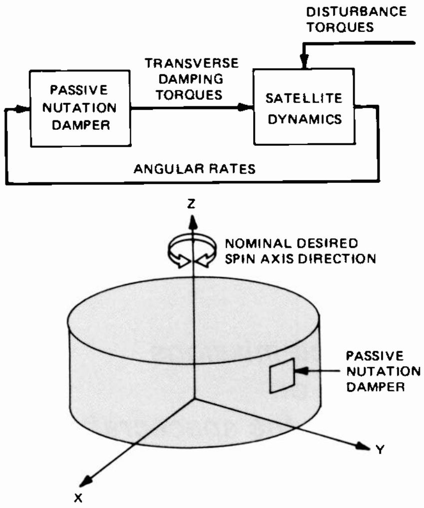
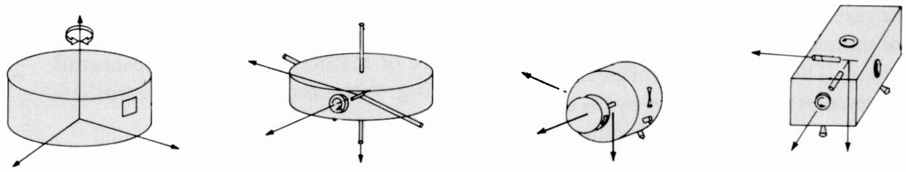


Fig. 3
Spin stabilization is a simple and reliable method of **passive** attitude control. (The earth is spin stabilized in orbit around the sun.)

The semi-passive system can achieve three-axis stabilization with moderate pointing accuracy (1° to 5°).

Typical of semi-passive implementations is the gravity-gradient satellite with passive damping and a constant-pitch momentum wheel. As shown in Fig. 4, the pitch and roll axes are controlled by means of the gravity-gradient booms; yaw control is attained by

Table I
Attitude control systems can range in characteristics depending on the amount and accuracy of control needed for a given mission.



Feature	*Passive*	*Semi-passsive*	*Semi-active*	*Active*
Employs environmental torque	Yes	Yes	Yes	Yes
No. of axes sensed	None	None	Three	Two
Max. no. of axes controlled	Two	Three	Three	Three
Uses control logic	No	No	Yes	Yes
Requires power	No	Yes	Yes	Yes
Uses internal torquing	No	Yes	Yes	Yes
Propulsive torquing option	No	No	Yes	Yes
Attitude accuracy	1° to 10°	1° to 5°	0.001° to 0.2°	0.1° to 1°
Maneuverability	None	Via ground	Flexible	Limited
Acquisition	Single mode	Single mode	Multimode, complex	Unique requirements
Complexity	Simple	Moderate	Considerable	Intermediate

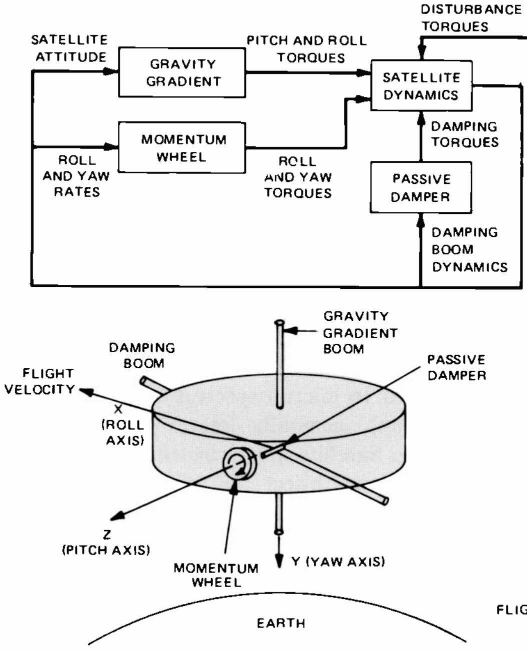


Fig. 4
Gravity gradient stabilization with passive damping and a pitch wheel offers one method of **semi-passive** control.

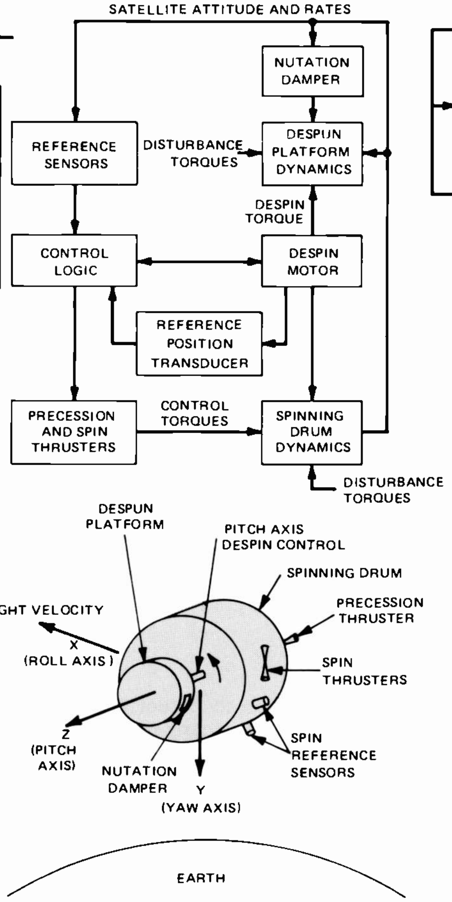


Fig. 5
Dual-spin system with propulsive torquing is one method of **semi-active** control. This sophisticated approach senses about two axes but controls all three.

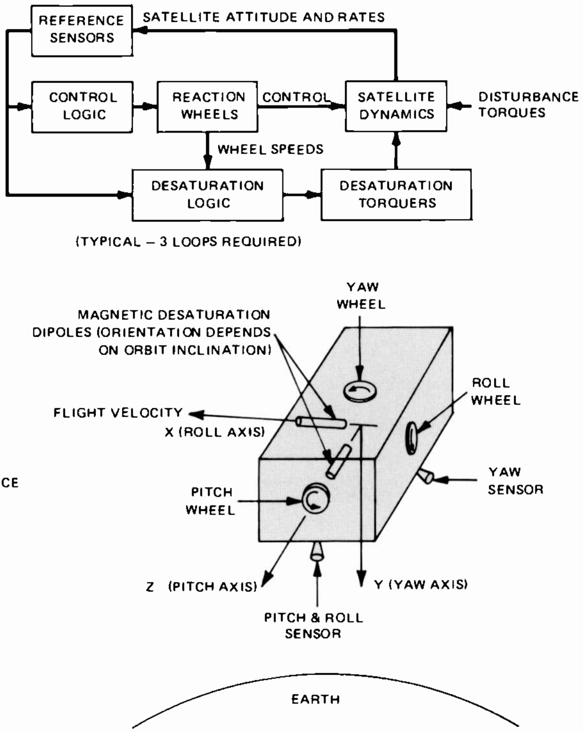


Fig. 6
Three-axis control system with control wheels provides versatile and precise **active** pointing.

gyroscopically coupling the third-axis to roll via a constant-speed pitch wheel. A gyro damper is sometimes used instead of the passive damper and momentum wheel.

Considerable performance improvement can be attained with the semi-active stabilization system.

Semi-active stabilization is different than the prior two classifications because its on-board control logic responds to two-axis attitude sensing while it provides three-axis control. Typical implementations are actively controlled spinners, dual-spinners, and pitch-momentum-wheel-biased spacecraft. Dual-spin satellites employ a spinning drum and a despun (counter-rotating) section, which continuously points to the earth (Fig. 5). Momentum-biased spacecraft derive gyroscopic stiffness of the pitch axis from an internal wheel, which just like the drum, varies its nominal speed by means of a servo loop in order to control pitch attitude of the despun section. The required alignment of the wheel spin axis is maintained by occasional use of thrusters or magnetic torquers. Yaw attitude, generally the most difficult to detect, need not be sensed for this class of attitude control because of the deliberately provided strong gyroscopic coupling between yaw and roll. Thus, sensing and control of roll also results in control of yaw.

The most versatile form of spacecraft stabilization is the completely active implementation.

In active stabilization, each of the three satellite axes is being sensed and controlled directly, and the total angular momentum is maintained near zero. Typical systems use:

1) three orthogonal wheels and momentum desaturation,

2) three-axis control with propulsion torquing,

3) control moment gyro (gimbaled wheels) three-axis control with appropriate momentum unloading, or

4) even a zero-momentum dual-spin implementation with three-axis sensing.

Such systems require significant control logic, not the least of which is devoted to three-axis acquisition. A typical three-reaction-wheel system is shown in Fig. 6. Active or semi-active implementation using momentum storage devices such as wheels will require regular unloading by means of thruster or magnetic torquing in order to prevent wheel saturation due to disturbance torques acting on the satellite.

Device developments

Much effort has been put into developing devices that sense the attitude or angular velocity of space vehicles.

The eyes of our control systems reference themselves to the earth, the sun, prominent stars or entire star patterns, the terrestial magnetic field, and the inertial frame. Basically, a satellite can most easily determine the local vertical direction of the central body about which it orbits. Unique three-axis attitude determination at any one instant requires two non-parallel reference directions. Usually, the sun or higher magnitude stars such as Polaris or Canopus are used for the second reference

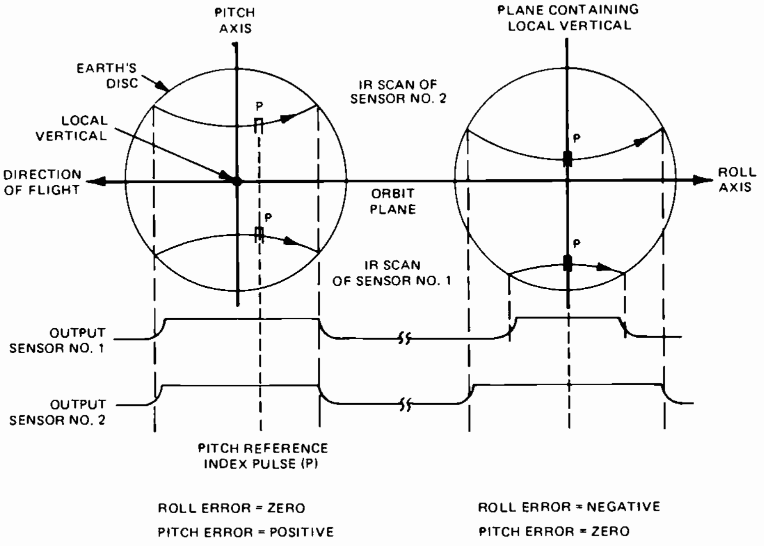


Fig. 7
In two-axis attitude sensing, an infrared sensor is often used to detect the earth-sky transition line (horizon). As shown, the duration of earth and sky scans provides a direct measure of pitch and roll attitude.

Table II
Satellite attitude sensing devices are the "eyes" of the attitude control system—"looking" to the earth, the stars, the sun, or the inertial reference frame.

Reference	*Sensor type*	*Comments*
Earth	Infrared detector (CO_2 spectral band)	Detect earth's horizon Reference for roll, pitch, spin rate and phase Scanning or static types Medium accuracy reference (0.05° to 1.0°)
	RF monopulse	Requires cooperative earth station For geosynchronous orbit
	Magnetometer	Sense earth's magnetic field Requires ephemeris knowledge Coarse accuracy reference (1 to 10°)
Stellar	Sun	For sun tracking Good second reference for earth satellite For single-axis updating (yaw)
	Star	Gimbaled tracker (mechanically complex) Strapped-down mapper (substantial data processing required) Electronic tracker (image dissector) High accuracy reference (<15 arc seconds)
Inertial	Gyroscope	Gyrocompass reference Phase reference for active nutation damping 3-axis determination (position and rate) Requires independent updating to compensate for drift
	Accelerometer	Guidance reference for boost phase Phase reference for active nutation damping

body. Table II summarizes the basic attitude determination means. The pointing accuracy of an attitude control system is primarily bounded by the ability to detect attitude errors.

Most earth satellites use the earth's horizon gradient to determine local vertical and therefore pitch and roll attitude (see Figs. 2 and 7).

Horizon sensors respond to infrared radiation discontinuities or to the earth's albedo. The 14 to 16 micron spectral band (CO_2 absorption) generally serves for this reference. Satellite spin or instrument scan is used: 1) to bisect the angle between opposite horizons, and 2) to compare earth cord lengths generated at various angles from the orbit plane in order to sense pitch and roll attitude, respectively. Static earth sensors intended for non-spinning satellites depend on radiation balance of a circular detector arrangement which circumscribes the earth's horizon line at the null condition. Earth sensor accuracies have reached about 0.05°; unless the infrared CO_2 band can be replaced by a more precise reference, this performance represents a practical limit for this type of attitude determination.

Stars provide more accuracy, but...

Although sun and star sightings offer more accurate references than the earth's horizon, coordinate transformations involving the location of the satellite in orbit (ephemeris) require cumbersome calculations and introduce errors of their own. Even so, the highly predictable motion and extreme angular resolvability make stars the most desirable reference for precision pointing systems of 0.01° or better.

When the inertial frame is used as a reference, gyroscopes are usually selected as the sensing instruments.

One of the more popular applications is a rate-integrating gyroscope for relatively short-term high-bandwidth attitude determination (up to one hour), while using earth, sun, or star updates for the long-term low-bandwidth sensing.

The nerves and muscles make it happen.

As in any feedback implementation (semi-active and active attitude control), the sensed data has to be processed to establish deviations from the desired attitude and to generate the necessary commands to the actuators, i.e., the torquing devices. Such computation, involving logic switching, control law implementation, and dynamic compensation can be accomplished by unique electronic circuitry (analog and digital), a general purpose reprogrammable spacecraft computer, or by dedicated microprocessors.

Table III summarizes the various satellite "muscles" used for torquing purposes. The first four rows represent environmental "disturbances" that can also be exploited in some applications for attitude control or momentum desaturation. Particularly, the torque resulting from the "compass needle type" interaction between an electrically actuated dipole and the earth's magnetic field is an attractive and reliable torquing means. Propellant mass expulsion represents a very versatile control technique with life capacity limited by the available propellant; this is a disadvantage for direct attitude control. By far the most popular and desirable torquers for semi-active and active control are momentum exchange devices, such as wheels, which are either fixed or gimbaled with respect to the satellite structure.

Now that we have gained a brief overview of satellite attitude control techniques, let us look at developments at RCA Astro-Electronics.

In the beginning

In 1958, the U.S. launched its first satellite, Explorer I. The designers chose passive spin stabilization in order to maintain one axis fixed in inertial space and thus satisfy communications requirements. Since a free rigid body (no energy dissipation) can spin stably about either the maximum or minimum principal moment of inertia axis, and since the shape of the last propulsion stage was only 6 inches in diameter, the cognizant JPL team chose minimum axis spin. However, four flexible whip antennas dissipated energy when Explorer I was in orbit; thus the satellite was forced into a catastrophic propeller mode, corresponding to minimum kinetic energy and spin about the axis of the maximum moment of inertia. This mission served as a dramatic lesson for subsequent spacecraft stabilization designs.

In early 1957, a small group of engineers initiated the RCA space efforts at the Laboratories. One of these was Vernon Landon, who in February 1957 had reached the conclusion that could have solved the spin instability problem of Explorer I. In 1958, Landon and others formed the nucleus of the newly founded Astro-Electronics.

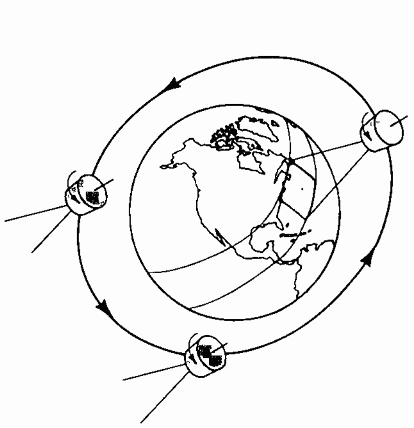
Spin stabilization

TIROS I used yo-yo's, a nutation damper, and spin-up rockets.

The first dramatic product of this new organization was TIROS-I,[1] launched on April 1, 1960. Passively stabilized to spin about its maximum moment of inertia axis, the satellite used a number of interesting attitude control concepts (Fig. 8). To stabilize the orbit-injection maneuvers, the third-stage rocket and spacecraft combination were spun up to 84 r/min. However, to avoid smearing of the meteorological pictures, the spin rate had to be reduced to a 9 to 12 r/min range. This was accomplished by a set of weights at the end of cables (yo-

Table III
Satellite torquing methods. Several kinds of "muscles" are used to control the attitude of an orbiting satellite.

Type of torquing	*Required actuator*	*Comments*
Gravity gradient	Deployable booms (mass distribution)	Pitch and roll for medium altitudes Minimum inertia axis aligns with field gradient Requires damping
Aerodynamic	Movable tabs	Possible for pitch and yaw Low orbit altitude Little practical value
Solar (sailing)	Movable tabs	Possible for pitch and yaw if not eclipsed Also for momentum desaturation
Magnetic	Electromagnets Current carrying coils Hysteresis rods	Simple, reliable for direct control or desaturation Used up to geosynchronous altitude (22,300 miles) Limited to torquing transverse to field
Mass expulsion	Rockets, monopropellant jets, cold gas jets	Versatile, limited by fuel capacity Relatively high torque Used in pulsed mode for direct control or desaturation Possible plume problem
	Cable and weight release (yo-yo)	One time despin
Momentum exchange	Momentum wheels Reaction wheels Control moment gyroscopes (gimbaled wheel)	Requires power Reliable with advanced bearing designs Requires desaturation of secular (uni-directional) torques Good cyclic torque sink Versatile Can provide gyroscopic stiffness



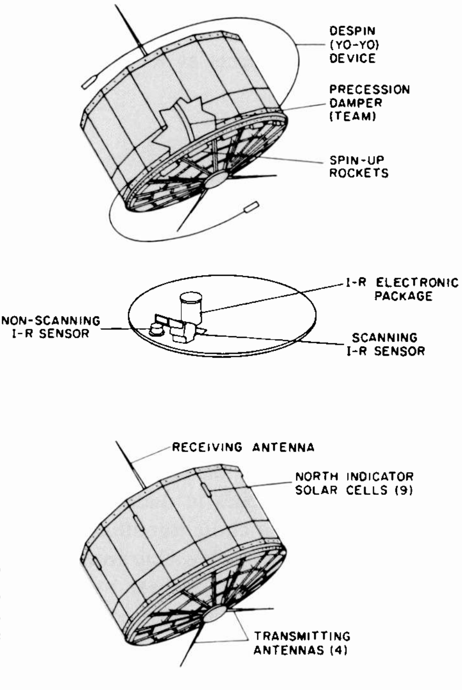


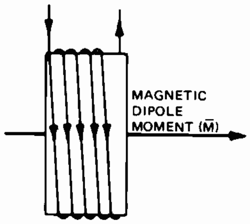
Fig. 8
TIROS-I was passively stabilized to spin about its maximum moment of inertia and applied a number of interesting attitude control concepts (right). However, in its near-polar orbit the satellite's cameras were permitted to point at the earth only 20% of the time (left).

yo's) that had been wound around the satellite structure. When these yo-yo's were released, unwound, and jettisoned (shortly after the satellite separated from the third-stage rocket) they dissipated the spin energy thus slowing the satellite to the desired spin rate. Since nutation of the spin axis could also cause camera smear, a damper, consisting of a mass riding on a monorail section, was installed parallel to and displaced from the spin axis. Within one minute after separation, most residual wobble was removed. Tests and analyses had demonstrated prior to launch, however, that the spacecraft spin would be slowed by magnetic hysteresis losses and eddy current interactions. Small spin-up rockets were installed and actuated by ground command as needed to maintain the desired spin rate. An infrared horizon sensor gathered spin-axis attitude data, which was transmitted over the beacon transmitters. The attitude was ground computed from the ratio of earth-to-sky scan angle. In addition, a set of solar cells served to detect the relative sun angle. Thus, the attitude computation corresponding to each picture could be ascertained.

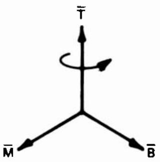
For TIROS II, magnetic "disturbances" were exploited to advantage.

Of course, this weather observation spacecraft relied on the initial spin-axis orientation for prediction of camera coverage area, the camera line-of-sight pointing parallel to the spin. With the spin axis initially lying in the orbit plane, the cameras were directed towards earth about 20% of the orbit period. Instead of remaining inertially fixed, observations revealed that TIROS-I was behaving as a gyroscope subjected to varying, periodic torques. Subsequent analysis conducted by Warren Manger and others conclusively indicated that these torques were produced primarily by interactions between a small magnetic spacecraft dipole and the earth's magnetic field.[2]

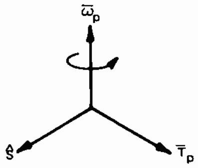
TIROS-I was a pioneering success, and its lessons were quickly applied to TIROS-II and subsequent RCA satellite designs. Transforming magnetic disturbance to magnetic control, the TIROS-II design included a dipole parallel to the spin axis to produce torques to reorient the spin axis (and therefore observation axis) to the desired attitude (Fig. 9). This was accomplished by programming (from the ground) steady-state currents in a coil wrapped around the periphery of the structure.



(a) DIPOLE MOMENT OF CURRENT-CARRYING COIL



(b) TORQUE ($\bar{T}$) DEVELOPED BY INTERACTION OF COIL DIPOLE MOMENT ($\bar{M}$) AND EARTH'S MAGNETIC FIELD ($\bar{B}$)



(c) PRECESSION MOTION ($\bar{\omega}_p$) OF SPIN AXIS ($\hat{S}$) CAUSED BY TORQUE ($\bar{T}_p$)

Fig. 9
Principles of magnetically torquing a spin-stabilized spacecraft. The magnetic dipole moment (a) created by the coil around the periphery of the spacecraft structure interacts (b) with the earth's magnetic field to produce a torque (c) that, if applied perpendicular to the spin axis, could reorient this axis. (If the torque in (c) is applied parallel to the spin vector and commutated every half rotation of the spacecraft, it would increase or decrease the spin rate.)

All subsequent TIROS and a parallel series of classified spin-stabilized satellites, designed and built at RCA, could change magnetic torque via ground command and could determine attitude via infrared horizon sensors. Two refinements of the magnetic torquing principle were introduced on TIROS IX (launched 1965). We magnetically reoriented the spin axis 90° out of the orbit plane and maintained this axis parallel to the orbit normal to permit a camera to be mounted in the radial direction of the satellite (Fig. 10); this provided horizon-sensor-synchronized observation along local vertical once per satellite spin and thus continuously throughout the orbit. To take full advantage of this wheel mode, a sun-synchronous high inclination orbit was selected so that essentially the same illumination would be provided for each orbit. Programmed quarter orbit magnetic torquing[3] reversed the direction of the torquing dipole (coil current) every quarter orbit—the phasing of this switching determining the line in space about which the spin axis reorients. Magnetic torquing was also used in the

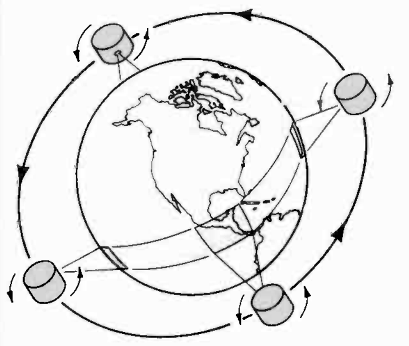


Fig. 10
Wheel-mode spin-stabilized spacecraft has its spin axis perpendicular to the orbit plane, allowing a spin-synchronized radially mounted camera to photograph the earth about 1000 times per orbit.

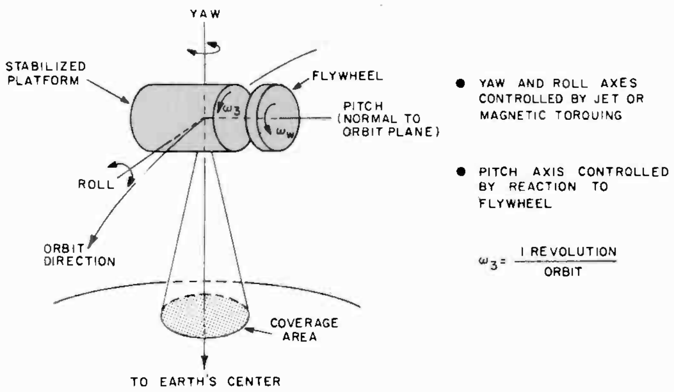


Fig. 11
The Stabilite ® concept is illustrated in this simplified sketch from the June 29, 1964 issue of *Missiles and Rockets.* This three-axis attitude control system provides continuous earth orientation from a stabilized platform.

wheel-mode spacecraft to maintain spin rate at near constant value instead of depending on previously used expendable rockets. By commutating coil current (via the horizon-sensed transitions), a dipole was generated orthogonal to the spin axis twice per spin; the coil thus behaved like a rotor coil of a dc motor, with the earth's field acting as the stator permanent magnet.

Stabilite ® system

RCA unveiled three-axis semi-active attitude control in 1964.

The spinning wheel-mode satellite is limited by 1) the sensitivity and resolution of the radially pointing sensors, or 2) the antenna requirements imposed by shaped narrow beams. To overcome these limitations, continuous and low-jitter earth orientation is necessary. Although a completely active attitude control system (Table I and Fig. 6) would do the job, it would be more complex. The RCA effort of the 1960s therefore concentrated on a semiactive approach as an evolutionary outgrowth of our prior experience. The principal objective was three-axis control while retaining the advantages of gyroscopic stiffness. Rather than being restricted to the maximum inertia spin principle "rediscovered" so painfully on Explorer I in 1958, spacecraft designers had to overcome this restraint to accommodate larger satellites with more complex payloads which had to be launched within the diameter-limited shroud of the boost vehicle.

Vern Landon, in 1962, concluded that the maximum moment of inertia stability limit of spinning satellites can be circumvented if a sufficient portion of the total angular momentum is stored in a rigid rotor. An attempt to publish these unique results[4] in an astronautical journal was unfortunately rejected because their significance was not understood and their mathematical rigor was found wanting.[5] In cooperation with Brian Stewart, also of RCA Astro-Electronics, Landon succeeded in publishing these pioneering results in 1964.[6] This paper states that there is one fairly simple three-axis control technique that is a natural extension of spin stabilization. Control of the third axis (attitude about the spin axis) is achieved by despinning a portion of the spinning spacecraft by means of a motorized despin mechanism. The paper places no constraint on the moment of inertia distribution, provided the nutation damper is placed on the despun portion. Control of the spin axis attitude (the other two axes) could, as for all prior spinners, be accomplished by magnetic or even propulsive type torquing. Thus, semiactive three-axis attitude control had arrived. RCA Astro-Electronics announced and demonstrated this system, dubbed Stabilite ®, publicly for the first time in June 1964 at the AIAA meeting in Washington, D.C. The illustration (Fig. 11) from the June 1964 *Missiles and Rockets* article "unveils" the principle. The despun platform remains phaselocked to the earth by comparing the infrared horizon pulse to the body index pulse.

Meanwhile, on the West Coast,

However, by the fall of 1964, A.J. Iorillo of Hughes Aircraft had initiated an independent investigation of the so-called dual-spin concept, and published his results in November 1965.[7] He concluded that dual-spin stability for realistic mass distribution requires that the despun portion have more energy dissipation than the spinning portion, each with the respect to its own nutation frequency. In other words, he considered the more general case of dissipation in either body. Hughes Aircraft named their dual-spin concept Gyrostat, a spacecraft consisting of a large spinner and a small despun platform.

Subsequent spacecraft, including the important class of geosynchronous communication satellites, were derived from these competitive developments which took place on opposite coasts of our country in the first half of the last decade.

RCA successfully applied the Stabilite ® principle almost simultaneously to TIROS and DMSP missions.

In the Stabilite ® concept, a relatively small and rapidly spinning rotor (momentum wheel) simultaneously provides gyroscopic stiffness, pitch-momentum-exchange capability, and horizon scanning (with infrared sensors), while the platform (i.e., essentially the entire spacecraft) is phaselocked to the earth and thus rotates at one revolution per orbit. Roll and yaw attitude as well as angular momentum magnitude are controlled by magnetic torquing in a manner similar to that used on the wheel-mode spinning spacecraft. Fig. 12 illustrates the basic pitch-attitude control loop. ITOS 1, the first in a series of Improved TIROS Operational Spacecraft, was launched in January 1970 and was successfully three-axis controlled by the Stabilite ® system. Despite its vapor-lubricated brushes, the redundant momentum

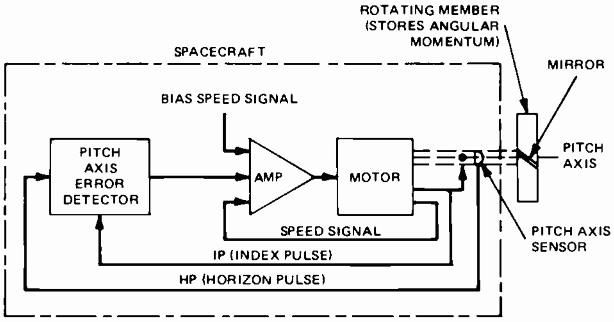


Fig. 12
Basic pitch-axis servo control. The index pulse is phase-locked to the infrared horizon pulse by closed-loop momentum interchange between the wheel and the spacecraft.

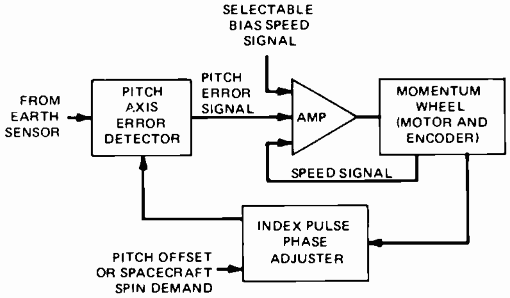


Fig. 13
Atmosphere Explorer provided autonomous pitch-attitude and spin-rate control—an essential feature for scientific observations during perigee passages.

wheel motors failed after 16 months; subsequent designs circumvented this obstacle by using brushless dc motors with Hall-element commutation.[7]

This pitch-momentum-biased control principle was also applied to the three Atmosphere Explorer scientific spacecraft developed by RCA for NASA.

The first Atmosphere Explorer was launched at the end of 1973 and still provides limited operational data four years later. Using a highly eccentric orbit, these spacecraft dip at perigee into the earth's upper atmosphere (≅130 km) for the primary scientific measurements. In the despun mode, the phase-lock momentum interchange servo on Atmosphere Explorer is able to point in any commanded pitch direction with respect to local vertical with a resolution of one degree (Fig. 13). In addition, tachometer-loop operation of the momentum wheel provides a selection of body spin rates up to about 10 r/min. For the 4-r/min case (most important for the science mission), this body rate is maintained with great precision via closed-loop electronic-gear type control. Both attitude and spin-rate control are more important during perigee passages, when the observation of scientific data coincides with maximum aerodynamic disturbances (see the paper by R. deBastos in this issue).

RCA Americom Satellites, placed in geosynchronous orbits, also used Stabilite.®

The first communications satellite developed by RCA was the spin-stabilized Relay I, launched in December 1962 into a low altitude orbit which afforded part-time contacts. Within a few years, it became quite clear that the optimum communications system required a so-called stationary satellite, i.e., a spacecraft orbiting once per day in the equatorial plane at an altitude of 19323 nautical miles. Three-axis body stabilization offers advantages to such a geosynchronous mission in terms of booster constraints, power capability, reliability, payload flexibility, and growth potential.[8] Thus, under contract to RCA Global Communications, Inc. and RCA Alaska Communications, Inc., Astro-Electronics designed and built the two commercial communications satellites which were launched from Kennedy Space Center on December 12, 1975, and March 26, 1976, respectively. These RCA Americom satellites (formerly called Satcom satellites) used the Stabilite® technique, a simple pitch-axis wheel in conjunction with magnetic torquing, for satisfactory and reliable three-axis attitude control.[9] This control system, shown by block diagram in Fig 14, contains a number of innovative features which involve:

1) spin-axis torquing by means of pulsed thrusters during the elliptical transfer orbit,

2) a gyroscopic dual spin turn reorientation (Fig. 15) after final orbit injection,

3) the avoidance of potential wobble during East/West station acquisition,

4) active nutation damping with the pitch wheel via product-of-inertia cross-coupling torque,

5) closed-loop magnetic roll/yaw control at geosynchronous altitude (field strength of one milligauss), and

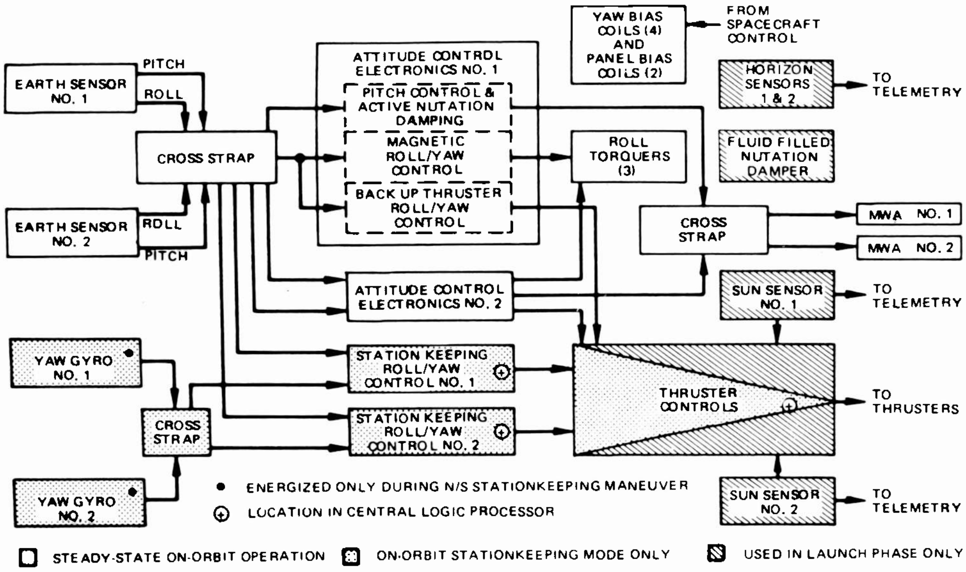


Fig. 14
Attitude control system used on the RCA Americom Satellite (formerly called RCA Satcom). This control system also uses the Stabilite® technique and contains a number of features that resulted in eight RCA patents.

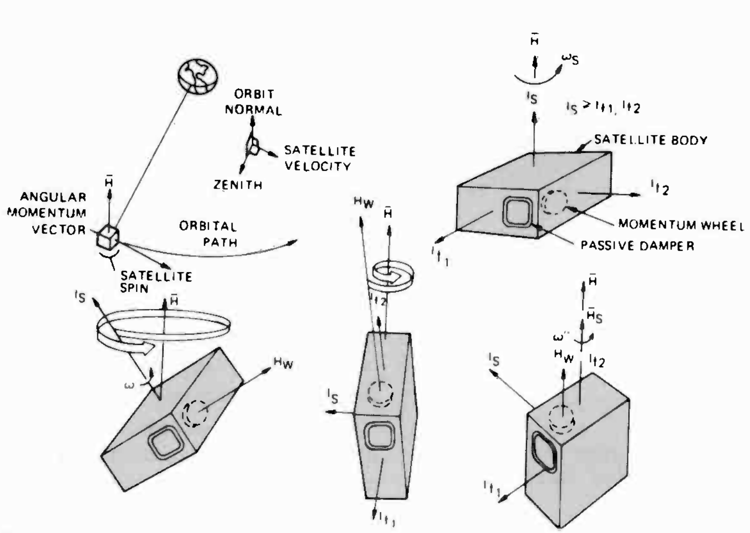


Fig. 15
This gyroscopic dual-spin turn sequence was used to reorient the satellite after final orbit injection.

6) attitude control during North/South stationkeeping (for orbit inclination adjust) by off-pulse modulation of the thrusters.

The attitude control system has a maximum beam-pointing error of 0.16° (3σ) during normal operation and 0.25° (3σ) during stationkeeping, weighs 55 pounds with a redundant standby spare for each active component, and consumes an average power of 15 W. All attitude control modes (spinning in transfer orbit, acquisition, three-axis earth pointing on-orbit) performed their functions for both spacecraft normally and within prescribed limits.

A similar spacecraft (Anik-B) is being readied for Telesat Canada for their domestic communication use. The attitude control system is nominally that of the RCA Americom design, containing some refinements in the magnetic roll/yaw control.

Active three-axis control

High precision pointing was needed for the Defense Meteorological Satellite Program.

At the beginning of this decade, the Air Force defined a need for a 10^{-2} degree-(3σ)-per-axis earth-pointing satellite for the Defense Meteorological Satellite Program. Such a requirement represented a pointing performance improvement of more than one order of magnitude for this type of mission. We have to distinguish here between a body-pointing spacecraft (i.e., line of sight inertially locked to a precise target body such as sun or other star) and the DMSP requirement of pointing to a central body (earth), which is not a sufficiently precise attitude reference for the mission attitude pointing requirements. Inertially fixed body pointing is a nulling operation (often with the primary sensor) and has an accuracy potential of fractional arc-second pointing. Since only stars are suitable references for precision attitude determination, an earth-pointing application has to contend with errors due to component misalignments and due to ephemeris tolerances entering the necessary coordinate transformations, in addition to any inaccuracies of the primary reference. Furthermore, the initial attitude acquisition problem is of considerable complexity.

As a result of a number of studies, the winning Astro-Electronics proposal submitted to the Air Force in 1971 contains a completely active attitude control system (Table I), where each of three axes is independently sensed and controlled. Internal satellite momentum is purposely kept at a practical minimum to avoid undesirable gyroscopic cross-coupling. Fig. 16 shows the primary and back-up orbital attitude control system modes, respectively. The IMU (inertial measurement unit), consisting of accelerometers and gas bearing rate-integrating gyroscopes, furnishes inputs for ascent-phase navigation and provides a short-term attitude reference for the on-orbit phase. A strapped-down silicon detector star mapper is used in conjunction with a stored star catalogue to update the gyro-derived attitude; this technique was developed under prior Air Force sponsorship. Using a satellite ephemeris table that is updated daily, the inertial attitude is transformed to the desired geodetic pointing. Thus, the primary system uses the gyros for high bandwidth information and the star mapper for a low bandwidth reference. Fig. 17 illustrates how the once-per-orbit satellite pitch rotation scans the stars (up to 4.5 magnitude) through six sensor slits. Attitude determination converges to 15 arc-seconds per axis by Kalman filtering techniques, thus permitting overall pointing within $\pm 10^{-2}$ degree per axis. In back-up (also used for acquisition), attitude determination depends on a static infrared earth sensor for pitch and roll and on gyro readings with sun-sensor

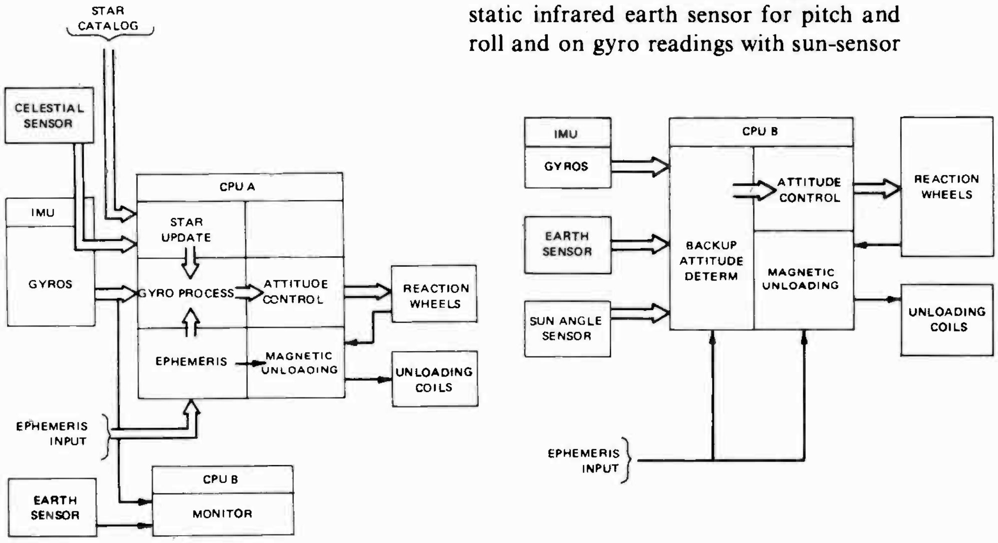


Fig. 16
Primary and backup attitude determination and control for the high precision Defense Meteorological Satellite. The earth-referenced backup system also serves the acquisition function. Wheel momentum is unloaded automatically via magnetics.

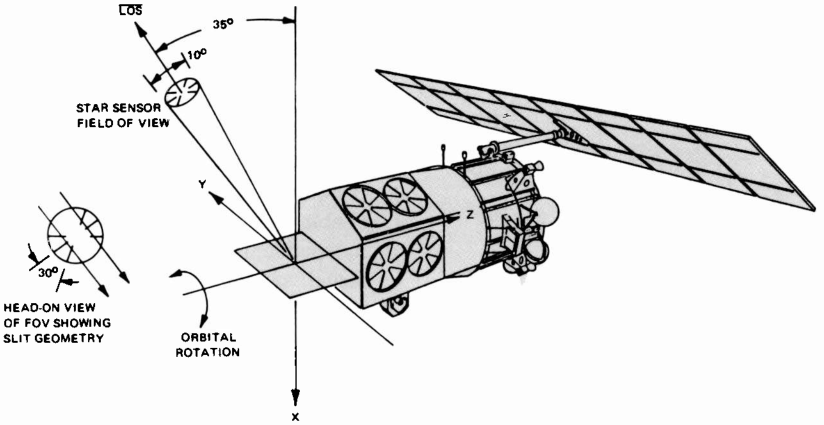


Fig. 17
Star mapper provides very precise reference for the DMSP satellite. Each time an identifiable star passes a particular slit the attitude gyros can be updated; the on-board star catalogue contains up to 80 stars.

updates for yaw. While this back-up system has a pointing accuracy of only 0.12° (3σ) per axis, it requires no initialization and substantially less ground support than the primary implementation.

The attitude control software contains the control laws which, in response to the sensed attitude errors, generate torque commands to the reaction wheels (one per axis) and to the magnetic momentum desaturating coils. The design of these laws was complicated by the coupling between the attitude control loops, the orienting solar array drive servo, and the flexible modes of the solar array and boom (Fig. 17).[10] This design (back-up mode only) has also been applied to the TIROS-N meteorological spacecraft series, which is scheduled to become operational in 1978.

Of particular interest is the RCA-developed reprogrammable general purpose computer,[11] which is used for ascent guidance, command and control, and attitude control. Each unit (two per spacecraft) weighs 8 pounds and draws 5W. Utilizing COS/MOS technology, the read/write memory consists of 16,384 words of 16 bits each, plus 256 words ROM. Arithmetic is binary two's compliment, fixed point. Most operations can be performed in double precision without speed penalty. Software can be written in high-order SPL language.

The launch of the first two new generation meteorological satellites (September 1976 and June 1977) was almost immediately followed on-orbit by an ominous tumble due to inadvertent expulsion of nitrogen gas, which is only required for the ascent phase. Fortunately, the computer could be reprogrammed with newly developed control laws to magnetically desaturate the substantial unwanted angular momentum. Both spacecraft were re-acquired to fully operational status (see the Staniszewski paper in this issue).

IR&D benefits

Since the early 1960s, RCA-Astro-Electronics has conducted an active and beneficial IR&D activity in the area of stabilization and attitude control. IR&D-sponsored programs developed the Stabilite® system and provided the unique demonstrator of this concept in 1964. This approach was incorporated to achieve successful three-axis spacecraft stabilization in the DMSP Block 5A, B, C, in the ITOS, Atmosphere Explorer, and the RCA Americom (formerly Satcom) programs. In recent years, IR&D efforts also resulted in:

1) closed loop roll/yaw control of a momentum biased satellite by magnetic means, including operation at geosynchronous altitude;

2) active nutation damping;

3) development of high-speed reaction wheels to obtain optimum weight/power relationship;

4) pulse-modulated-thruster control during orbit adjust; and

5) optimal stabilization and control techniques in presence of flexible body effects.

Each satellite project, including the high precision pointing DMSP Block 5D spacecraft, substantially benefitted from prior IR&D attitude control studies and developments.

The future

The various attitude control techniques and systems described in this paper and successfully applied to about 80 RCA-designed and -built spacecraft represent a solid basis for our entry in the space shuttle era. No longer will our task begin after injection into final orbit; but we will be on our own after the shuttle doors open.

The guidance and control from the relatively low 160 nautical-mile shuttle orbit to those required by various missions will be our challenge. Current IR&D programs are concentrating on the problems of inertial guidance, thruster utilization and plume impingements, interactions with highly flexible structures, and precision pointing techniques. The experience and success of the last two decades form an excellent springboard for the task ahead.

Acknowledgments

Many present and former employees of Astro-Electronics have contributed to the design and development of our attitude control subsystems. Thus, it is practically impossible to give individual credit. Suffice it to state, that all have helped with creativity and diligence to permit the writing of this technical history.

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Dates and Deadlines

Upcoming meetings

Ed. Note: Meetings are listed chronologically. Listed after the meeting title (in bold type) are the sponsor(s), the location, and the person to contact for more information.

OCT 15-19, 1978—**ISA Intl. Conf. and Exhibit** (ISA) Philadelphia, PA **Prog Info:** Instrument Society of America, 400 Stanwix St., Pittsburgh, PA 15222

OCT 16-17, 1978—**Joint Engineering Management Conf.** (IEEE) Regency, Denver, CO **Prog Info:** Henry Bachman, Hazeltine Corp., Greenlawn, NY 11740

OCT 16-18, 1978—**Electronics Conference and Natl. Communications Forum** Chicago, IL **Prog Info:** National Electronics Conf., Oak Brook Executive Plaza #2, 1211 W. 22 St., Oak Brook, IL 60521

OCT 18-20, 1978—**Joint Automatic Control Conf.,** (IEEE) Civic Center, Philadelphia, PA **Prog Info:** Dr. Harlan J. Perlis, New Jersey Institute of Tech., 323 High Street, Newark, NJ 07102

OCT 18-20, 1978—**Canadian Communications and Power Conf.** (IEEE) Queen Elizabeth Hotel, Montreal, P.Q. **Prog Info:** Jean Jacques Archambault, CP/PO 757, Montreal, Quebec H2L 4L6

OCT 21-25, 1978—**Engineering in Medicine and Biology** (IEEE) Marriott Hotel, Atlanta, GA **Prog Info:** Walter L. Bloom, M.D., Georgia Institute of Tech., Atlanta, GA 30302

OCT 23-25, 1978—**Digital Satellite Communications** (IEEE) Hotel Reine Elizabeth, Montreal, Que. **Prog Info:** Marcel Perras, Teleglobe Canada, 680 Sherbrooke Street W., Montreal, Que. H3A 2S4

OCT 24-26, 1978—**Biennial Display Research Conf.** (IEEE,SID) Cherry Hill Inn, Cherry Hill, NJ **Prog Info:** Lawrence Goodman, RCA Laboratories, Princeton, NJ 08540

OCT 25-27, 1978—**Intelec (Intl. Telephone Energy Conf.)** Sheraton Park, Washington, DC **Prog Info:** J.J. Suizzi, Bell Laboratories, Room 5D-178, Whippany, NJ 07981

OCT 29-NOV 3, 1978—**SMPTE Technical Conf. and Equipment Exhibit,** Americana Hotel, New York, NY **Prog Info:** SMPTE, 862 Scarsdale Ave.., Scarsdale, NY 10583

OCT 30-NOV 1, 1978—**Semiconductor Laser Conference** (IEEE, QEA) Sheraton at Fisherman's Wharf, San Francisco, CA **Prog Info:** T.L. Paoli, Bell Laboratories, 600 Mountain Ave., Murray Hill, NJ 07974

NOV 3-6, 1978—**Audio Engrg. Soc. Conf.** (AES) New York, NY **Prog Info:** Almon H. Clegg, Panasonic Corp., One Panasonic Way, Secaucus, NJ 07094

NOV 6-9, 1978—**Advanced Techniques in Failure Analysis** (IEEE) Marriott Hotel, Los Angeles, CA **Prog Info:** Robert J. Kolb, TRW Defense & Space Systems, 1 Space Park R6/2184, Redondo Beach, CA 90278

NOV 7-9, 1978—**Mini/Micro Conf. and Exposition,** Astrohall, Houston, TX **Prog Info:** Robert D. Rankin, Managing Director, Mini/Micro Conf. and Exposition, 5528 E. La Palma Ave., Suite 1, Anaheim, CA 92807

NOV 27-DEC 1, 1978—**Acoustical Soc. of America 96th Mtg.,** Honolulu, HI **Prog Info:** Acoustical Soc. of America, 335 E. 45 St., New York, NY 10017

DEC 4-6, 1978—**Intl. Electron Devices Meeting** (IEEE) Washington Hilton, Washington, DC **Prog Info:** Susan Henman, Courtesy Associates, 1629 "K" Street, NW, Washington, DC 20006

DEC 4-6, 1978—**National Telecommunications Conf.** (IEEE) Hyatt Hotel, Birmingham, AL **Prog Info:** H.T. Uthlaut, Jr., South Central Bell., P.O. Box 771, Birmingham, AL 35201

DEC 12-14, 1978—**MIDCON** (IEEE) Dallas Convention Ctr., Dallas, TX **Prog Info:** W.C. Weber, Jr., EEEI, 999 N. Sepulveda Blvd., El Segundo, CA 90245

JAN 23-25, 1979—**Automated Testing for Electronics Manufacturing** Los Angeles Marriott, Los Angeles, CA **Prog Info:** ATE Seminar/Exhibit, 1050 Commonwealth Ave., Boston, MA 02215

JAN 23-25, 1979—**Reliability and Maintainability** (IEEE) Shoreham Americana, Washington, DC **Prog Info:** D.F. Barber, POB 1401, Branch PO, Griffiss AFB, NY 13441

FEB 2-3, 1979—**SMPTE Television Conf.** (SMPTE) San Francisco, CA **Prog Info:** SMPTE Headquarters, 862 Scarsdale Ave., Scarsdale, NY 10583

FEB 6-8, 1979—**Aerospace & Electronic Systems Winter Conf. (WINCON)** (IEEE) Los Angeles, CA **Prog Info:** Sheldon Jones, Aerojet Electrosystems, P.O. Box 296, Azuza, CA 91702

FEB 15-17, 1979—**Intl. Solid State Circuits Conf.** (IEEE) Sheraton Hotel, Philadelphia, PA **Prog Info:** Lew Winner, 301 Almeria Ave., P.O. Box 343788, Coral Gables, FL 33134

MAR 6-8, 1979—**Optical Fiber Communication** (IEEE, OSA) Shoreham Americana Hotel, Washington, DC **Prog Info:** Optical Soc. of America, 2000 L Street, N.W., Suite 620, Washington, DC 20036

MAR 13-16, 1979—**Audio Engrg. Soc. 62nd Technical Mtg. and Exhibit, Sheraton, Brussels, Belgium Prog Info:** Donald J. Plunkett, AES, 60 E. 42nd St., New York, NY 10017

MAR 14-16, 1979—**Simulation Symposium** (IEEE) Tampa, FL **Prog Info:** Dr. Joe Clema, Simulation Tech., 4124 Linden Ave., Dayton, OH 45432

MAR 19-21, 1979—**Fourth Annual Control of Power Systems** (IEEE) Texas A&M U., College Sta., TX **Prog Info:** B. Don Russell, Electric Power Institute, Dept. of Elect. Engr., Texas A&M, College Sta., TX 77843

MAR 25-28, 1979—**Natl. Association of Broadcasters Conv.,** Dallas, TX **Prog Info:** NAB, 1771 Broadcaster Conv., Dallas, TX **Prog Info:** NAB, 1771 N St., N.W., Washington, DC 20036

MAR 27-30, 1979—**Vehicular Technology** (IEEE) Arlington Heights, Chicago, IL **Prog Info:** Al Goldstein, Natl. Mgr. Field Engr., Motorola, Inc., 1301 E. Algonquin Road, Schaumburg, IL 60196

APR 2-4, 1979—**Acoustics, Speech & Signal Processing** (IEEE) Intl. Inn, Washington, DC **Prog Info:** Anthony Eller, Naval Research Laboratory, Washington, DC 20375

APR 3-5, 1979—**Space Instrumentation for Atmospheric Observation** (IEEE) El Paso Civic Center, El Paso, TX **Prog Info:** Dr. Joseph H. Pierluissi, Dept. of Elect. Engrg., U. of Texas at El Paso, El Paso, TX 79968

APR 25-27, 1979—**Conf. on Modeling and Simulation,** Univ. of Pittsburgh, Pittsburgh, PA. **Prog Info:** W.G. Vogt, Modeling and Simulation Conf., 348 Benedum Engineering Hall, U. of Pittsburgh, Pittsburgh, PA 15261

Calls for papers

Ed. Note: Calls are listed chronologically by meeting date. Listed after the meeting (in bold type) are the sponsor(s), the location, and deadline information for submittals.

JUN 4-7, 1979—**National Computer Conf.** (AFIPS) New York Colosseum, New York, NY **Deadline Info: 150-word abs. to** Dr. Richard E. Merwin, Box 32222, Washington, DC 20007

Pen and Podium

Recent RCA technical papers and presentations

To obtain copies of papers, check your library or contact the author or his divisional Technical Publications Administrator (listed on back cover) for a reprint. For additional assistance in locating RCA technical literature, contact RCA Technical Communications, Bldg. 204-2, Cherry Hill, N.J., extension 4256.

Broadcast Systems

V.F. Renna|F.D. Galey|H.P. Howard

New product-development quality assurance system approach—ASQC Conf., Houston, TX (5/14/78)

Laboratories

R.C. Alig|S. Bloom

Secondary-electron-escape probabilities—*J. Appl. Phys.* Vol 49 No. 6 (6/78) pp. 3476-3480

M.S. Bae

Effective gettering of silicon devices by oxygen-forming gas boron diffusion technique—153rd Semi-annual Electrochemical Society Mtg., Seattle, WA (5/21/78)

A. Bloom|P.L.K. Hung

Liquid crystalline cholesteryl azo dyes—*Mol. Cryst. Liq. Cryst.*, Vol. 44 (1978) pp. 323-332

A. Bloom|P.L.K. Hung

The effect of dye structure on order parameter in a nematic liquid crystalline host—*Mol. Cryst. Liq. Cryst.*, Vol. 40 (1977) pp. 213-221

W.J. Burke|D.L. Staebler
W. Phillips|G.A. Alphonse

Volume phase holographic storage in ferroelectric crystals—*Optical Engineering*, Vol. 17, No. 4 (Jul/Aug 1978) pp. 308-16

J.K. Butler|H.S. Sommers, Jr.

Asymmetric modes in oxide stripe heterojunction lasers—*IEEE J. Quantum Electronics*, Vol. QE-14, No. 6 (6/78) pp. 413-417

C.R. Carlson

Thresholds for perceived image sharpness—*Photographic Science and Engineering*, Vol. 22, No. 2 (3-4/78) pp. 69-71

R.W. Cohen

Applying psychophysics to display design—*Photographic Science and Engineering*, Vol. 22, No. 2 (3-4/78) pp. 57-58

D.A. deWolf

Coherence of a light beam through an optically dense turbid layer—*Applied Optics*, Vol. 17, No. 8 (4/15/78) p. 1280

D.A. deWolf

Waves in random media: weak scattering reconsidered—*J. Opt. Soc. Am.*, Vol. 68, No. 4 (4/78) pp. 475-479

M. Ettenberg

A new dielectric facet reflector for semiconductor lasers—*Appl. Phys. Lett.*, Vol. 32, No. 11 (6/1/78) pp. 724-25

M.T. Gale|R.S. Engelbrecht
J. Kane|K. Knop

Surface-relief microimages—*J. Micrographics*, Vol. 11, No. 3 (Jan/Feb 1978) pp. 155-162

R.A. Geshner

Microlithography overview—IGC Symp. on Photolithography, Amsterdam, Holland (4/27/78)

J. Goel|H.J. Wolkstein

Microwave field effect transistors—IEEE Intl. Solid State Circuits Conf. (2/16/78) pp. 126-7

J. Goel|J. Wolkstein

A 4-8 GHz dual-gate MESFET amplifier—*Electronics Lett.* (3/16/78) Vol. 14, No. 6 pp. 167-168

B. Goldstein|D.J. Szostak

Characterization of clean and oxidized (100) LaB_6—*Surface Sci.*, Vol. 74 (1978) pp. 461-478

W.J. Gordon

VideoDisc testing philosophy and techniques—*RCA Review*, Vol. 39, No. 1 (3/78) pp. 187-197

I. Gorog

Optical techniques developed for the RCA VideoDisc—*RCA Review*, Vol. 39, No. 1 (3/78) pp. 163-185

A. Guida

On the reciprocal of a fourier series—Proceedings of the IEEE, Vol. 66, No. 3 (3/78)

T.T. Hitch

Adhesion measurements on thick-film conductors—Special Technical Publication 640, American Soc. for Testing and Materials (1978) pp. 211-232

S.A. Keneman

Evaporated films of arsenic tribulfide: dependence of optical properties on light exposure and heat cycling—*J. Optical Soc. of Am.*, Vol. 68, No. 1 (1/78) pp. 32-38

H.P. Kleinknecht|H. Meier

Optical monitoring of the etching of SiO_2 and Si_3N_4 on Si by the use of grating test patterns—*J. Electrochemical Soc.*, Vol. 125, No. 5 (5/78) pp. 798-803

H. Kressel|M. Ettenberg|I. Ladany

Accelerated step-temperature aging of $Al_xGa_{1-x}As$ heterojunction laser diodes—*Appl. Phys. Lett.*, Vol. 32, No. 5 (3/1/78) pp. 305-308

H. Kressel|C.J. Nuese|G.H. Olsen

Red-emitting Ga(As,P)|(In,Ga)P heterojunction lasers—*J. App. Phys.*, Vol. 49, No. 6 (6/78) pp. 3140-3149

H.W. Lehmann|R. Widmer

Fabrication of deep square wave structures with micron dimensions by reactive sputter etching—*App. Phys. Lett.* 32(3) (2/1/78) pp. 163-165

A. Levine

Determination of water content of molded plastics—36th Annual Mtg. of SPE, Washington, DC (4/25/78)

E.R. Levin|I. Ladany

Cathodoluminescence of $Al_xGa_{1-x}as$ grown by liquid-phase epitaxy—*J. App. Phys.*, Vol. 49, No. 6 (6/78) pp. 3025-3029

J.D. Levine

Magnetic modulation of thermionic emission between parallel cathodes—*J. Vac. Sci. Tech.*, Vol. 15, No. 1 (Jan/Feb 1978) p. 129

C.W. Magee|W.L. Harrington|R.E. Honig

Secondary ion quadrupole mass spectrometer for depth profiling—design and performance evaluation—*Rev. Sci. Instrum.* Vol. 49, No. 4 (4/78) pp. 477-485

C.W. Magee|C.P. Wu

Hydrogen ion implantation profiles as determined by sims—*Nuclear Instruments and Methods*, Vol. 149 (1978) pp. 529-533

G.H. Olsen|M. Ettenberg

Growth effects in the heteroepitaxy of III-V compounds—*Crystal Growth*, Vol. 2 (1978) pp. 1-56

J.I. Pankove|M.A. Lampert|M.L. Tarng

Hydrogenation and dehydrogenation of amorphous and crystalline silicon—*Appl. Phys. Lett.*, Vol. 32, No. 7 (4/1/78) pp. 439-441

R. J. Powell|M. Morad

Optical absorption and photoconductivity in thermally grown SiO_2 films—*J. Appl. Phys.* Vol. 49 No. 4 (4/78) pp. 2499-2502

W. Rehwald

Anomalous temperature dependence of the shear modulus c_{44} in nickel-iodine boracite—*J. Phys. C: Solid State Phys.*, Vol. 11 (1978) pp. 157-159

P.M. Russo|C. Wang
P.K. Baltzer|J.A. Weisbecker
Microprocessors in consumer products—*Proc. IEEE,* Vol. 66, No. 2 (2/78) pp. 131-141

R.J. Ryan
Material and process development for VideoDisc replication—*RCA Review,* Vol. 39, No. 1 (3/78) pp. 87-115

H. Schade
Work functions and sublimation entropies of the elements—*Proc.,* Seventh Intl. Vacuum Congress and Third Intl. Conf. on Solid Surfaces, Vienna, Austria (9/12-16/77) pp. 437-440

H. Schade|J.J. Hanak
Electron emission from thin films—*Proc.,* Seventh Intl. Vacuum Congress and Third Intl. Conf. on Solid Surfaces, Vienna, Austria (9/12-16/77) pp. 1833-1836

P. Sheng|E.K. Sichel|J.I. Gittleman
Fluctuation-induced tunneling conduction in carbon-polyvinylchloride composites—*Phys. Rev. Lett.,* Vol. 40, No. 18 (5/1/78) pp. 1197-1200

H. Sommers, Jr.
Algorithm for measuring the internal quantum efficiency of individual injection lasers—*Appl. Phys. Lett.,* Vol. 32, No. 9 (5/1/78) pp. 547-549

D.L. Staebler|S. Mascarenhas
Electrical effects during condensation and phase transitions of ice—*J. Chemical Phys.,* Vol. 68, No. 8 (4/15/78) pp. 3823-3828

M.L. Tarng|D.G. Fisher
Auger depth profiling of thick insulating films by angle lapping—*J. Vacuum Sci. and Tech.,* Vol. 15, No. 1 (Jan/Feb 1978) pp. 50-53

C.E. Weitzel|R.T. Smith
Silicon-on-sapphire crystalline perfection and MOS transistor mobility—*J. Electrochemical Soc.,* Vol. 125, No. 5 (5/78) pp. 792-798

C.C. Wang|D.C. Fisher
Preparation and properties of NEA heteroepitaxial semiconductor thin films—*Proc.,* Seventh Intl. Vacuum Congress and Third Intl. Conf. on Solid Surfaces, Vienna, Austria (9/12-16/77) pp. 1939-42

Missile and Surface Radar

A. Schwarzmann|G.J. Brucker|A. Rosen
Neutron damage in PIN diode phase shifters for radar arrays—IEEE Annual Conf. on Nuclear and Space Radiation Effects, Albuquerque, NM (7/18-21/78), also *IEEE Trans. on Nuclear and Space Radiation Effects*

Patents

Advanced Technology Laboratories

S.E. Ozga
Hardware control for repeating program loops in electronic computers—4097920 (Assigned to U.S. Government)

Broadcast Systems

W.L. Behrend
Amplitude and delay equalization of surface acoustic wave filters in amplitude modulation system—4096454

B.M. Pradal
High signal-to-noise ratio negative resistance crystal oscillator—4096451

Consumer Electronics

B.W. Beyers, Jr.
Timekeeping apparatus with power line dropout provisions—4099372

M.L. Henley
Vertical deflection circuit with retrace switch protection—4096416

J.C. Peer|D.W. Luz
Television raster width regulation circuit—4104567

J.L. Smith
Eccentric convergence apparatus for in-line beam cathode ray tubes—4100518

J.P. Yu
Video record player switching system—4097899

D.H. Willis
Horizontal deflection circuit with high voltage selection capability—4101815

Corporate Staff

G.A. Riley
Electronic wristwatch—4103483

Government Communications Systems

R.A. Dischert|A.J. Banks
R.S. Hopkins, Jr.
Television synchronizing apparatus—4101926

Laboratories

G.A. Alphonse
Variable acoustic wave energy transfer-characteristic control—4096756

Z.M. Andrevski
Flat display device with beam guide—4101802

F. Aschwanden
Phase locked loop tuning system with a preset channel memory—4097810

G.W. Bain, Jr.|A.G. Morris|S.V. Forgue
Infrared sensitive photoconductive pickup tube—4097775 (Assigned to U.S. Government)

A.E. Bell|R.A. Bartolini|A. Bloom
Overcoat structure for optical video disc—4101907 (Assigned to U.S. Government)

S. Berkman|K. Kim
G.W. Cullen|M.T. Duffy
Apparatus improvements for growing single crystalline silicon sheets—4099924

A. Bloom|H. Sorkin
Method to provide homogeneous liquid crystal cells containing a dyestuff—4098030

T.L. Credelle
Flat display device with beam guide—4103204

T.L. Credelle
Flat display device with beam guide—4103205

G. Denes
Memory cells—4013185

J.J. Dipiazza
Nonreflecting photoresist process—4102683

J.G. Endriz|J.A. VanRaalte|J.A. Rajchman
Parallel vane structure for a flat display device—4099085

G. Forster|W. Bohringer
Horizontal deflection circuit with auxiliary power supply—4104569

J.S. Fuhrer|E.O. Keizer
Method for forming a narrowed-electrode pickup stylus for video disc systems—4098030

R.A. Gange
Uniform filament and method of making the same—4100449

P.E. Haferl
Side pincushion distortion correction circuit—4101814

P.E. Haferl
Switched vertical deflection circuit—4096415

S. Hagino
Turntable speed control system—4100465

W.E. Ham
Method for determining whether holes in dielectric layers are opened—4103228

J.M. Hammer|C.C. Neil
Process for forming an optical waveguide—4100313 (Assigned to U.S. Government)

J.M. Hammer
Optical waveguide coupler employing deformed shape fiber-optic core coupling portion—4097118 (Assigned to U.S. Government)

F.Z. Hawrylo|H. Kressel
Metallized device—4097636

W. Hinn
Video amplifier—4096517

R.J. Hollingsworth
Sense circuit for an MNOS array using a pair of CMOS inverters cross-coupled via CMOS gates which are responsive to the input sense signals—4096401

W. Kern|C.E. Tracy
Combination glass/low temperature deposited $Si_w N_x H_y O_z$ passivating overcoat with improved crack and corrosion resistance for a semiconductor device—4097889

M.A. Leedom
Video disc handling system for a video disc player—4098511

A. Miller
Optical coupler—4102560 (Assigned to U.S. Government)

C.C. Neil|R.A. Bartolini|J.M. Hammer
Optical coupler having improved efficiency—4097117 (Assigned to U.S. Government)

K.D. Peters
Guided beam flat display device with focusing guide assembly mounting means—4099087

E.S. Poliniak
Method of transferring a surface relief pattern from a poly(1-methyl-1-cyclopropene sulfone) layer to a non-metallic inorganic layer—4097618

D.H. Pritchard
Electronic signal processing apparatus—4096516

B.D. Rosenthal|A.G. Dingwall
Quasi-static inverter circuit—4013183

W. Rosnowski
Method of fabricating a semiconductor device—4099997

M.D. Ross
Color video signal processing circuits—4096513

K.M. Schlesier|J.M. Shaw
C.W. Benyon, Jr.
Method of making a sapphire gate transistor—4097314 (Assigned to U.S. Government)

F.W. Spong
Multilayer optical record—4097895

A.V. Tuma|L.A. Harwood
W.H. Groeneweg
Average beam current limiter—4096518

A.V. Tuma|W.H. Groeneweg
Standard/nonstandard internal vertical sync producing apparatus—4096528

J.L. Vossen, Jr.|F.R. Nyman|G.F. Nichols
Adherence of metal films to polymeric materials—4101402

C.F. Wheatley, Jr.
Shunt voltage regulator—4103219

J.P. Wittke
Semiconductor laser having fundamental lateral mode selectivity—4100508

Missile and Surface Radar

O.M. Woodward
Dual channel transmission of microwave power through an interface of relative rotation—4103262

Patent Operations

A.L. Limberg
Switchable current amplifier—4103246

Picture Tube Division

F.C. Farmer, Jr.
Method and apparatus for measuring cathode emission slump—4101623

W.D. Masterton
Shadow mask color picture tube having a mosaic color screen with improved tolerances—4099187

RCA Ltd., England

L.R. Avery
Sync separator circuit—4097896

RCA Ltd., Canada

R.H. Buckley
Ultraviolet radiation detector—4096387

SelectaVision Project

L.D. Huff
Automatic disc wiping apparatus—4099724

C.F. Pulse
Record—D248753

Solid State Division

R.L. Baker|J.D. Partilla
C.M. Mahoski|H.R. Ronan, Jr.
Chuck for use in the testing of semiconductor wafers—4104589

S. Berkman|D.B. Irish
Susceptor for heating semiconductor substrates—4099041

M.S. Fisher
SCR trigger circuit—4097770

C.W. Horsting|W.B. Hall
Liquid crystal device and method for preparing same—4095876

H. Khajezadeh|S.C. Ahrens
Monolithic resistor for compensating beta of a lateral transistor—4100565

G.I. Morton
Complementary-symmetry amplifier—4103188

S.A. Ochs
Wafer mounting structure for pickup tube—4103203

J. Ollendorf
Protective circuit for MOS devices—4100561

M.A. Polinsky
Monolithic light detector—4096512

S. Shwartzman
Method and apparatus for detecting ultrasonic energy—4099417

Engineering News and Highlights

Management changes at Missile and Surface Radar

William V. Goodwin was recently appointed Division Vice President and General Manager of RCA Missile and Surface Radar. For the past ten years, Mr. Goodwin has been RCA's chief executive for the AEGIS Program, the U.S. Navy's fleet defense system for the 1980s and beyond, for which RCA is prime contractor. In his new position, Mr. Goodwin reports to **Dr. James Vollmer,** Division Vice President and General Manager, RCA Government Systems Division.

Mr. Goodwin succeeds **Max Lehrer,** who has been appointed to the new position of Division Vice President, Contract Administration, on the Division staff reporting to Dr. Vollmer.

He started working for RCA in 1949 as an engineering trainee and has spent his entire business career with the company except for a four-year period when he was Chief Missile System Engineer for the Bendix Missile Division.

Upon rejoining RCA in 1959, Mr. Goodwin was appointed Manager of Advanced Projects at the Missile and Surface Radar operation. Four years later he was named Manager of its Navy Air Defense Programs, and in 1967 he became Manager of the Marketing Department.

In 1968 Mr. Goodwin was appointed Manager of the Advance Surface Missile System, the former name of AEGIS, and began his tenure as the RCA executive in direct charge of the Navy program. He was promoted to his most recent position, Division Vice President and Program Manager, AEGIS Program, in January 1970.

Lawrence J. Schipper has been named Division Vice President and Program Manager, AEGIS Department, in the RCA Missile and Surface Radar organization. Before his promotion, he had been Deputy Program Manager for AEGIS.

Mr. Schipper joined RCA in 1959 as an engineer in Moorestown. Two years before RCA won the AEGIS Program contract, he was named leader of an engineering group developing and defining features of an Advanced Surface Missile System as the basis for a proposal to the Navy. ASMS became AEGIS after the contract was awarded in 1969. As the AEGIS program progressed, Mr. Schipper became responsible for analysis and control program development of the SPY-1 phased-array radar, heart of the AEGIS system. In 1973 he was promoted to Manager, AEGIS System Engineering, and a year later became Manager, AEGIS Development, with responsibility for systems engineering, computer program development and test of the AEGIS weapon system. He was advanced to Deputy Program Manager in 1976.

Solar Electric Energy organization formed

A new organization dedicated to the development of solar electric energy business has been formed. This organization will be responsible for developing business plans, establishing relationships with potential customers, both domestic and foreign, and developing knowledge and skills required to manufacture a product responsive to electric-energy needs.

Robert L. Weinberg has been appointed Director, Solar Electric Business Development reporting to **Howard Rosenthal,** Secretary of the Corporation's Electronic Business Development Committee. **Louis Napoli** has been named Manager, Engineering, for the organization, which is located at the David Sarnoff Research Center in Princeton.

Laboratories and Picture Tube Div. establish joint Technology Transfer Lab

To enhance the implementation of new techniques and processes into RCA color picture tubes, the RCA Laboratories and Picture Tube Division have jointly formed a Technology Transfer Laboratory. This organization will be responsible for coordinating advanced developments required in electron guns, aperture masks, yoke technology, and manufacturing technology to assure a continuing flow of technological innovations into the Picture Tube Division. This activity will be located in Lancaster under the management of RCA Laboratories. Research on picture tubes will continue at the RCA Laboratories in Princeton and will interface with the Technology Transfer Laboratory and Picture Tube Division Engineering.

The new Laboratory is similar in concept to the New Products Laboratory established at Consumer Electronics in Indianapolis. Both laboratories are part of a continuing program to strengthen RCA product lines by speeding innovation from research to manufacturing.

Licensed engineers

When you receive a professional license, send your name, PE number (and state in which registered), RCA division, location, and telephone number to *RCA Engineer,* Bldg. 204-2, RCA, Cherry Hill, N.J. New listings (and corrections or changes to previous listings) will be published in each issue.

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Broadcast Systems

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Laboratories

Stewart, R.G., Somerville; WA-13533

RCA Ltd.

Byrum, E.J., Prescott; ONT-0732245 (correction)

Obituaries

Harry Kleinberg, Manager of Corporate Standards Engineering, died on August 19, 1978, as the result of a heart attack he had suffered two weeks earlier. He was 54 years old.

Harry had been Manager of Corporate Standards Engineering since 1971, and guided CSE through a wide variety of programs, including the company's position on metrication. He was involved with many standards organizations—he was a member of the Board of Directors of the American National Standards Institute, and also held several offices in the Standards Engineers Society.

Harry joined RCA in 1953 as a logic designer on the Bizmac computer, RCA's first commercial data-processing system. He held a variety of assignments in the Computer Division for the next eighteen years, including seven years as Manager of the Engineering Department at the Palm Beach Gardens, Florida, plant. At Palm Beach he had responsibility for many elements of the Spectra product line.

Although Harry was a knowledgeable "standards man," his first love was the computer. He combined his love of computers and literature, and a year ago Lippincott published his first book, "How You Can Learn To Live With Computers." It gives a clear picture of what computers can and cannot do, and is written with much warmth and humor. Harry was writing a second book on computers at the time of his death.

He had been one of our favorite contributors to the *RCA Engineer;* his recent articles included "Zen, existentialism, and engineering" (Aug|Sep '77) and "Programming in CHIP-8" (Apr|May '78). We will miss Harry's professional guidance, his friendship, and his special sense of humor. We are grateful for many good memories, and will remember him with affection.

Jon F. Baumunk, who had been an engineer at RCA Astro-Electronics, died July 21 at the age of 45.

Mr. Baumunk began his RCA career at RCA Laboratories in 1957, and transferred to Astro-Electronics when it was formed, remaining there for 14 years until he left RCA to work at the Naval Air Development Center at Johnsville, Pa. While at Astro-Electronics, he specialized in communication systems, working on such programs as TIROS, Relay, and the backpack tv camera. He held a succession of engineering positions, becoming Manager, Data Transmission in 1966. He was Program Manager of a classified project when he left RCA.

Baumunk

Dr. Henry N. Kozanowski, died July 27 at the age of 70. "Hank" retired from RCA in 1971 after a long career as an outstanding engineer and scientist.

He joined the engineering department of RCA in Camden in the mid-1930s, and was always in the forefront of new developments in television, including military applications and, in particular, color television studio equipment.

Hank also gave much of his time and energy to SMPTE activities, serving many years on the television committee and a term as Governor of the Society. His contributions to television broadcasting were honored by a number of important awards. He became a Fellow of the SMPTE in 1953 and a Fellow of the IEEE in 1962. He received the David Sarnoff Gold Medal Award in 1963 and the Herbert T. Kalmus Award in 1965.

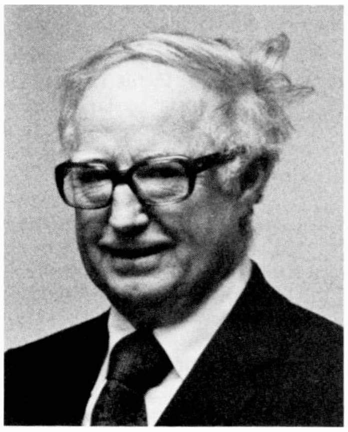
Kozanowski

Edward O. Nester, a Senior Member of the Engineering Staff for Mobile Communications at Somerville, N.J., died July 24 in a mountain-climbing accident in the Canadian Rockies. He was 39. Nester was an experienced climber who had previously received awards for mountain rescue work.

He earned his BSEE from City College of New York, and his MS in electrical engineering from Princeton. Before transferring to the Mobile Communications group at Somerville, he had been at RCA Laboratories at Princeton.

William Stonaker, an electrical with twenty-five years of design experience at RCA, died September 5. He was 58.

He spent most of his career with the Test Instruments activity at Harrison, N.J., where he designed test equipment for tubes and transistors, including automatic testers, oscilloscopes, and meters. He joined Distributor and Special Products Division in 1975; while there he was the principal circuit designer for the Studio II programmable video game.



Stonaker

Coming up

Our next issue (Oct|Nov) continues our space orientation with a **Missile Test Project** theme covering RCA's 25 years of radar tracking and instrumentation at Cape Canaveral. General-interest articles will cover the **finite element method, digital television,** and **RCA's SelectaVision video disc.**

Future issues will cover **manufacturing** (television, solid state, picture tube), RCA's business involvement with **energy,** and the **color television receiver.**

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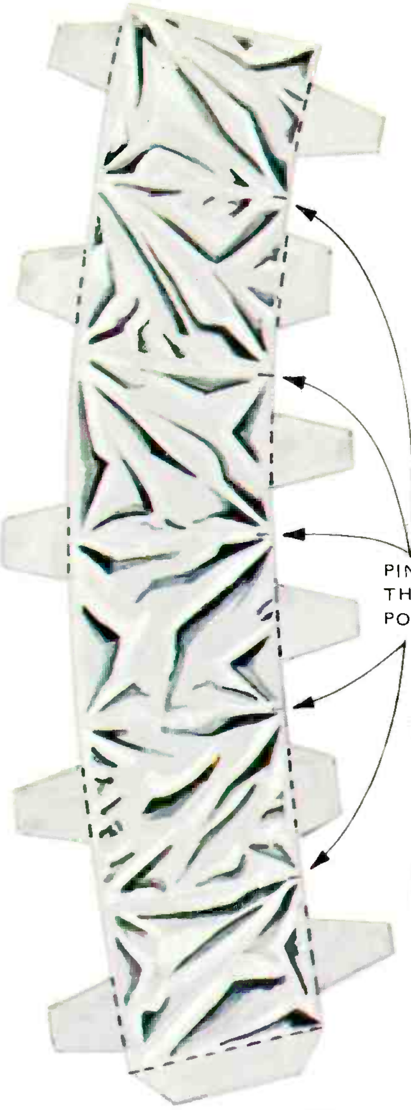

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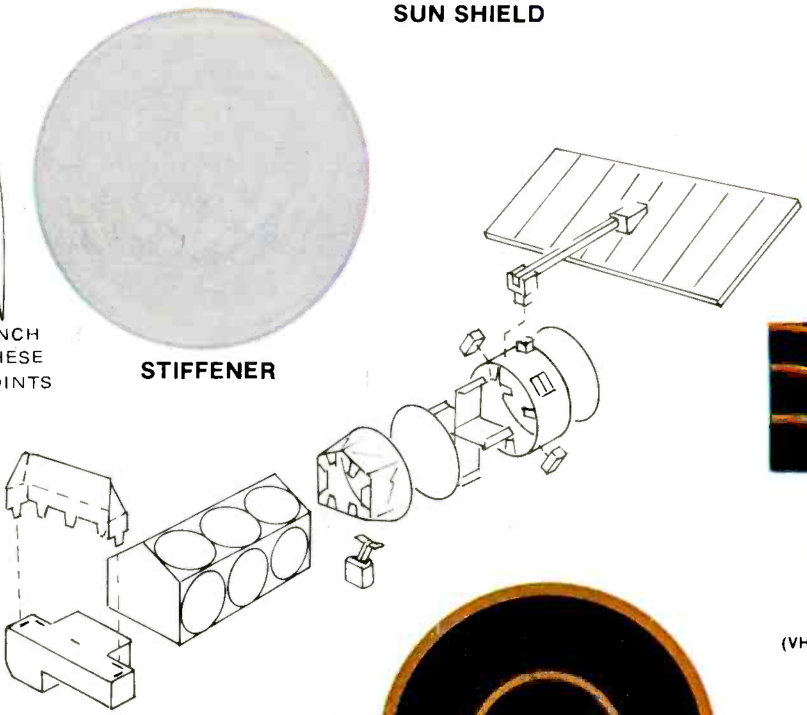

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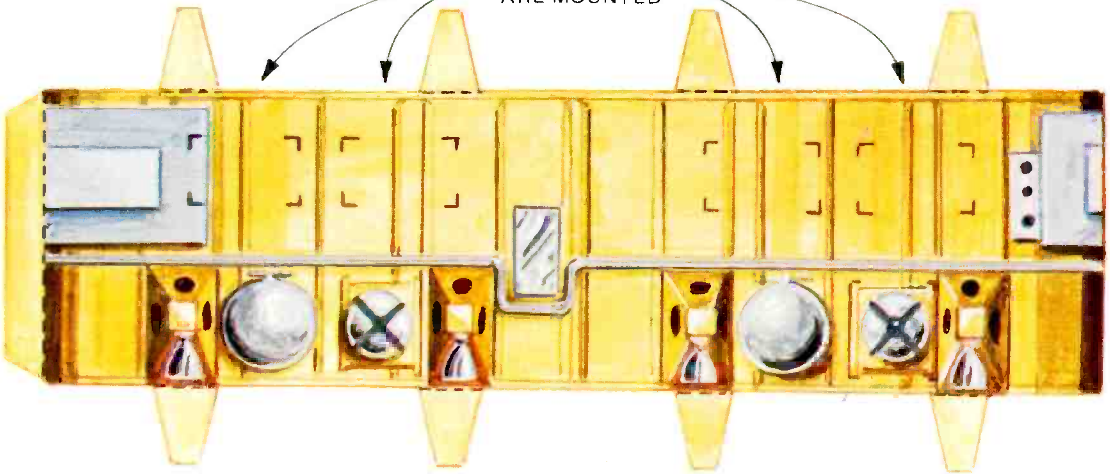
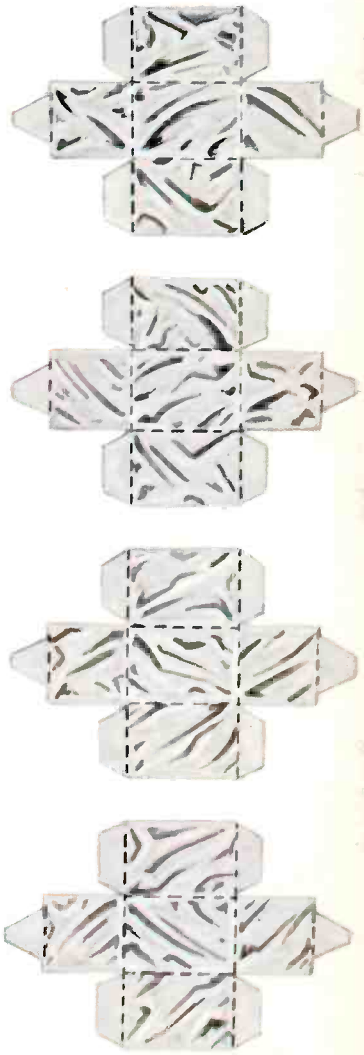
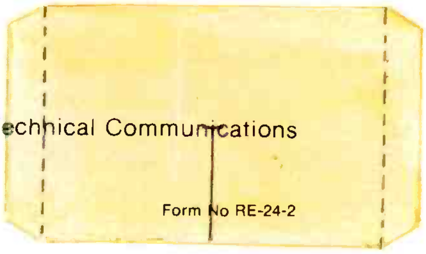
SECOND STAGE MOTOR





BATTERIES



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