RCA Engineer

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ADJUST VOLUME CONTROL
FOR DISPLAYED VALUE
OF 0.9 TO 1.1 VOLTS.
PRESS PROCEED.

TURN BAND SELECTOR SWITCH TO 53 - 75.
PRESS PROCEED.  RCVR SENSITIVITY TEST
                REC-TRANS FREQUENCY 53 MHZ
                VOL CONTROL SETTING 1.0 V
                2000  12.57 DB
                TEST COMPLETE.
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Automatic test systems

ATS technology has matured to the point where it is being used extensively in commercial, industrial, and government/military applications. The range of test system applications is extremely broad—from testing of Army radios to monitoring and controlling environment and service functions in building complexes. Automatic test systems are found in such diverse fields as medical electronics, communications, and factory testing. They are applied to every conceivable form of electronic product and function—from microelectronic to conventional. Additionally, ATS technology has been applied to testing of mechanical components and assemblies, including vehicle engines, jet engine accessories, and hydraulic component and control systems. Of course, operational readiness testing continues to increase in importance for commercial as well as for military customers, whose needs range from "black box" testing all the way up to a total ship status, or a multi-building complex.

The digital computer has been a prime reason for the extensive growth of automatic test systems. Through routine and specialized software, it is used effectively for rapid, faultless test programming and control; for signal processing; and for analysis, reporting and managing of data. Presently, computer applications have been extended to generate stimulus signals and make measurements using high-speed sample-data techniques.

Fourth-generation automatic test systems will see even wider use of the computer via the microprocessor and more sophisticated minicomputers that will increase system usefulness and reduce the cost and size of the test installation. Also, increased versatility and capability will be sought to keep in step with the wide variety and complexity of today's products (including non-electronic) which we wish to test.

RCA is a leading company in developing, using, and supplying automatic test systems technology, software, and systems. The papers in this issue illustrate the breadth and depth of RCA accomplishments and capabilities. It is the high quality of our expanding engineering skills and know-how which maintains our leadership and business growth in this field.

E M Stockton

E. M. Stockton,
Chief Engineer,
Government Communications and
Automated Systems Division,
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Burlington, Mass.

Our cover

...shows two Automatic Test Equipment programs of GCASD in Burlington, Mass. The lower section of the cover shows part of a jeep-engine test sequence using the Automatic Test Equipment for Internal Combustion Engines (ATE/ICE) which is described by R.T. Cowley and R. Hulls in this issue (p.18). The rest of the cover is devoted to EQUATE (see pp. 6 through 27). EQUATE Project Engineer John Haggis is testing and fault-isolating an AN/PRC-77 radio set. The video terminal is the main operator interface of the test system. Operator instructions for manual actions (*e.g.*, setting dials on the radio set) are given via this terminal.

Cover design: Joan Dunn
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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 orestige and professional status.

Contents

Emphasis —Automatic Test Equipment

Twenty years with automatic test equipment

O.T. Carver

In automatic test equipment, as in this *RCA Engineer* special issue, there is something for everyone. There is no product area which cuts so wide a technological swath—from lasers to LSI, from tank engines to TWTs, from software to SSB. It is part of ATE's appeal to the incurably curious engineer that every product his fellow engineers can devise is a potential unit under test, every phenomenon a candidate for test technique application.

O.T. Carver, Mgr., ATE Systems, Government Communications and Automated Systems Division, Burlington, Mass., received the BSEE from West Virginia University in 1949, graduate studies in engineering management at George Washington University and received an M Ed at Northeastern University in 1972. He has participated in ATE programs at RCA since 1956. On the Multi-Purpose Test Equipment programs, he was responsible for test requirements analyses and the configuration of the basic automatic test system for checkout of Army missile systems. He has directed test technique studies aimed at increasing the ability of ATE to perform fault diagnosis and failure prediction. He directed early studies resulting in the specification of functional test assemblies which could be electrically configured by a central programmer. He was responsible for systems design on the MTE program and for test requirement analysis of the advanced Army missile system Mauler, Shillelagh, Lance, and TOW. In the latter task, he performed test system design concurrent with missile system development requiring close coordination and data exchange to ensure compatibility of the end product. An important part of his task responsibility involved the location of test access points and criteria for performance evaluation. He also supervised the study of fault isolation by mathematical approach and studies investingating improved programming procedures for Automatic Test Equipment. The latter studies developed tradeoffs between hardware and software aspects of the total test system. Recent programs under his direction have developed support system simulation models for effectivenss evaluation of alternate support concepts. Current programs include improved inspection procedures for helicopter maintenance, on-board monitoring systems, and advanced maintenance concepts for new ship classes.

ATE IS BIG BUSINESS, accounting for about \$500 million of industry sales to the United States Government in 1974. Within RCA, ATE sales have totaled about \$250 million since 1960. The government market has shaped the industry because the tradeoff of equipment-for-people appealed first to the military customer. The industrial ATE market has, however, expanded rapidly, taking advantage of early R&D costs borne by military/NASA applications.

Today, the DOD finds itself in even greater need of alternatives to maintenance by technician manpower. In the 1975, total DOD budget of the \$86B, "operations and maintenance" accounts for \$26B. The agonies of reprogramming which took place in 1974 were necessary to pay the O&M bill. This was done at the expense of reduced weapon system buys, and delayed or deleted R&D programs. Consider the O&M allocations shown in Table 1. About \$8.5 billion goes to "logistic support" — depot maintenance, supply operations, etc. There is great business opportunity for a product that can reduce the number of technicians needed, increase the operational readiness of weapon systems, and improve confidence that an item labeled "good" is really good and one labeled "bad" is really bad.

A relatively new product area 20 years ago, ATE consisted almost solely of cable continuity checkers. However, 20 years have spawned three rather distinct generations of equipment. The earliest continuity checkers and other externally fixed program systems were the first generation. The second generation was characterized by computer control and the power of an internal random-access memory to modify the test sequence in response to intermediate measurements. The third generation, typified by RCA's EQUATE, trades hardware for software, making the central processor a generator of stimulus waveforms and a participant in measurement analysis.

Twenty years and three generations in a product lifetime are also time enough to have generated a nostalgia — memories of intense personal commitments to projects, some of which were rousing successes and some of which quietly fizzled. This overview will resurrect some of RCA's ATE history that properly belongs in the nostalgia file. Each

Table I — Analysis of FY 1975 DOD operation and maintenance budget by mission/function.

	\$ billion obligations, FY1975
Operating forces:	
Strategic	1.3
General purpose	2.8
Guard & reserve	1.5
Subtotal: Operating forces	5.6
Training, medical, personnel support	3.0
Logistic support:	
Supply operations	2.0
Depot maintenance	4.4
Other logistic support	2.0
Subtotal: Logistic support	8.4
Base operations and facilities maint.	5.2
Other missions	
(Intelligence communications support of other nations)	2.6
Administration	1.3
TOTAL	26.0

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program had an investment of RCA engineering skills plus a lot of 20-hour days and the kind of exhilaration that is shared by a group of people who are focusing all their energies to get a job done.

As with few other products, acronyms are part of ATE lore. How many readers can identify DEE, FATE, or FATAL? How about PEACH? One of the first RCA automatic test systems had the almost unpronounceable acronym of APCHE (Automatic Programmed Checkout Equipment). APCHE was a punched-card-reading ATE for periodic and prelaunch checkout of the ATLAS missile system. Shown in Fig. 1, APCHE generated and measured low frequency analog signals through a bank of DACONS and ADCONS (digital-to-analog and analog-to-digital converters). It also looked at discrete signals, and made timing and resistance measurements. Quantities of blood, sweat, and tears were spilled at Vandenberg Air Force Base in integrating and debugging the first APCHE installation. Prime RCA division on this key program was Missile and Surface Radar in Moorestown, with participation from Burlington and Van Nuys.

Following this big program was NAOME (Nike Ajax Ordance Missile Evaluator), a one-of-a-kind equipment known only to a handful. It was built in 1958 as part of an Army-funded program, to show that the common functions of missile test equipment could be packaged in building blocks and that these building blocks could be put together to make a tester for each different missile. NAOME (Fig. 1) tested the Nike Ajax, and many of her building blocks could be removed and inserted in another rack to make a Lacrosse tester. Both testers were built in the RCA Service Company facility at Alexandria, Virginia where the MPTE (Multi-Purpose Test Equipment) idea was born.

By the end of the 1950s, the focus of RCA's ATE activity was in the Airborne Systems Division in Camden. In 1960, there was a series of presentations and demonstrations involving an ATE which eventually went to Letterkenny Ordnance Depot as the Letterkenny DEE (Digital Evaluation Equipment). The DEE was an outgrowth of the MPTE building-block concept and was configured to meet the test requirements of five different missile systems.

DEE had a number of unique features. It used magnetic tape as external program storage and had a magnetic core memory which was used as a time buffer between the high rate of data coming off the tape and the slower speed of responding to test program instructions within the ATE. Digital logic circuits were encapsulated in color-coded throw-away modules so that a green replaced a green, red replaced red, etc. Fig. 3 illustrates the building-block packaging and the color-coded module idea.

DEE also had a clock that ran backwards, along with an electric typewriter and column printer which were output peripherals for the test system. These are shown in Fig. 4.

Bucking the digital tide, DATS (Dynamic Accuracy Test System) was an innovative and successful analog programmed equipment used to test the MG-10 fire control systems of the F-102. Fig. 5 shows DATS being used at the flight line. Fire-control equations simulating target closing rates in several quadrants were programmed on mechanical cams, and the MG-10 was asked to lock-onto, and solve, simulated targets injected in real time at the directional coupler. Data readout was in armament miss distance and elevation.

The Pre-Flight Test Set (PTS)/Mohawk program was a response to inplace checkout of Army aircraft avionics. Using only an rf interface through aircraft antennas, PTS exercised communications/navigation transmitters, receivers, and associated instrumentation. PTS provided a much more effective evaluation of avionics preflight status than the usual method of talking to the tower. Fig. 6 shows the Mohawk with a PTS remote control unit. The Mohawk adaptation added to the PTS a capability for pre-flight checkout of the side-looking radar on the OV-1 Mohawk airplane.

In testing the PTS/Mohawk equipment at Monmouth County Airport, wet runways were needed to determine the effect of rain on near-field antenna patterns. There was no rainfall in sight and a local radio station was inveigled into broadcasting an appeal for water to wet down the runway. Lakehurst Naval Air Station responded, sending trucks with 25,000 gallon water tanks to do the job — an extraordinary example of inter-service cooperation.

AIDE	Automated Image Device Evaluator
APCHE	Automatic Programmed Checkout Equipment
ATE	Automatic Test Equipment
ATE/ICE	Automatic Test Equipment for Internal Combustion Engines
ATS	Automatic Test System
ATSJEA	Automatic Test System for Jet Engine Accessories
BITE	Built-In Test Equipment
DATS	Dynamic Accuracy Test System
DEE	Digital Evaluation Eqiupment
DIMATE	Depot Installed Maintenance Automatic Test System
DIO	Digital Input/Output
EOC	Elementary Operations Controller
EPC	Electro-Pneumatic Converter
EQUATE	Electronic Quality Assurance Test Equipment
FATAL	Fully Automatic Test Algebraic Language — an early attempt at test program language development
FATE	Factory Automatic Test Equipment — a one-of-a-kind system built for the Camden factory
LCSS	Land Combat Support System
MPTE	Multi-Purpose Test Equipment
MTE	Multi-system Test Equipment
NAOME	Nike Ajax Ordnance Missile Evaluator
PEACH	Personnel Exerciser and Checkout — a Moorestown product in support of the land-based TALOS system
PIU	Programmable Interface Unit
PTS	Pre-Flight Test Set
STE/ICE	Simplified Test Equipment for Internal Combustion Engines
TUT	Tube Under Test
UTP	Universal Test Point
UUT	Unit Under Test
VTM	Vehicle Test Meter

Fig. 5 — DATS (Dynamic Accuracy Test System) being used on an Air Force flight line.

Fig. 7 — Gathered around the old Chevy used for initial engine testing at Burlington are (from left to right) George Chamberas, Robin Hulls, Rick Cowley, Gene Stockton, Newton Teixeira. John McAllister and Harry Woll.

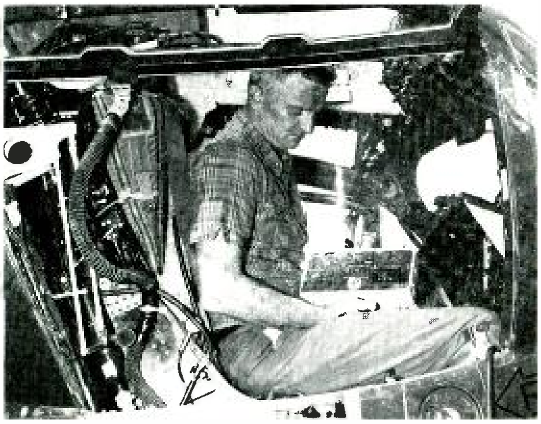
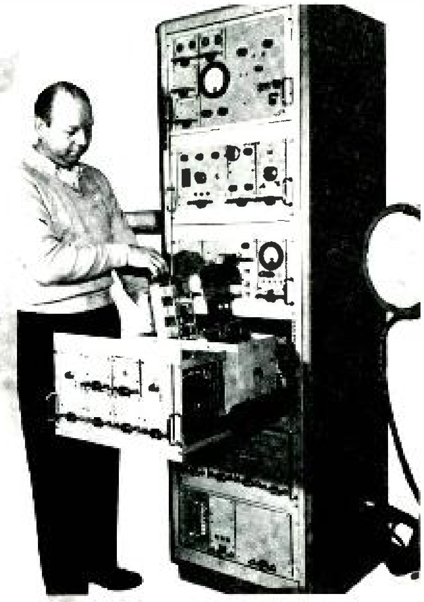


Fig. 6 — In Mohawk airplane cockpit, Ken Johnson is using the PTS remote control unit.

Fig. 2 — The Nike Ajax Ordnance Missile Evaluation (NAOME) was a one-of-a-kind "building-block" equipment.



Recognizing the fact that test equipment exists only to support a prime system, it is obvious that your ATE will flourish with the success of the systems you support, as did the Land Combat Support System (LCSS). LCSS is RCA's largest single ATE program, which supported Shillelagh, Lance, TOW, and Dragon.

Conversely, if your automatic test equipment supports Mauler, Cheyenne, or Dynasoar, your most ingenious designs may gather dust in the corner along with weapon system prototypes after program cancellation.

RCA's Multisystem Test Equipment (MTE) was tied to Mauler. Because Mauler never became operational, neither did MTE. However, this program was responsible for a number of pioneering ATE programs. DIMATE (Depot Installed Maintenance Automatic Test Equipment), which put RCA ATE in three Army depots, was a direct recipient of R&D work done on MTE. Without an MTE, there would never have been an LCSS, which followed and was many times ahead of the equipment it supported through world-wide deployment.

MTE was an extraordinarily ambitious program — a three-station, computer-controlled ATE. The first station was to test digital processors and low frequency analog units under test. The second station was configured for test of rf and microwave assemblies, and the third was to automatically check out hydraulic and electromechanical assemblies. Each station was housed in a shelter and could be operated independently or under control of the computer in Test Station No. 1.

It was at the inception of the MTE Program that automatic test equipment moved from Camden to Burlington, and by the mid-60s, ATE was a viable product line.

Fig. 4 — Fred Everhard in front of the DEE backward clock.

Fig. 3 — Building-block packaging used in DEE (Digital Evaluation Equipment).

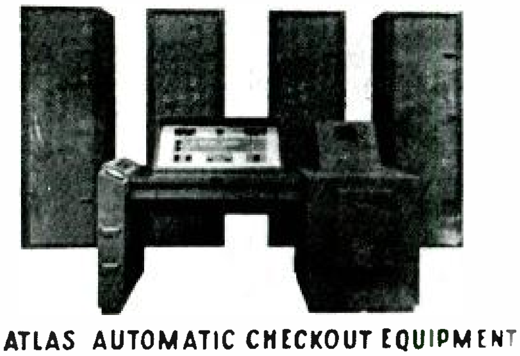


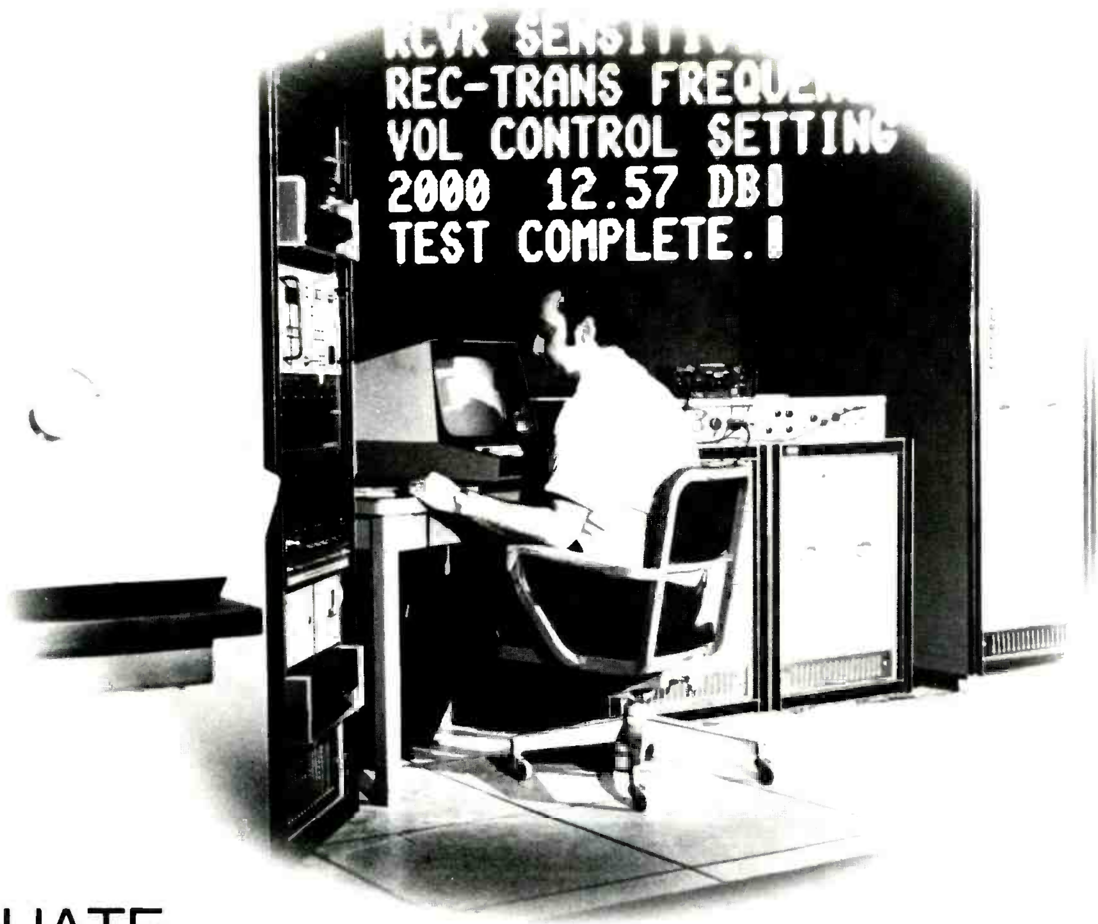
Fig. 1 — APCHE (Automatic Programmed Checkout Equipment) was one of RCA's first automatic test system.

Ed. Note: Over the past two decades, the ATE "family tree" has grown from basic continuity checkers, through three generations, to a group of testers that match almost every imaginable product area from electronics and optics to machinery and industrial systems.

The MTE hydraulic test station was RCA's first effort in nonelectronic test automation. Subsequent work was directed to automotive test, with early IR&D programs using an old Chevy engine for diagnostic instrumenation experiments. The test lab was an old garage at the rear of an abandoned house near the Burlington plant. In the foreground of Fig. 7 is the doughty Chevrolet on which the first test runs were made to verify the wide-open throttle technique for making engine-load tests without requiring a dynamometer. The technique controls the firing sequence so that each cylinder alternately carries the whole load of turning the engine. The Chevy engine didn't blow up or melt down, and such ingenious work as this, followed by a dozen patents, provided an effective answer to the question, "What does RCA know about automobile engines?"

Since the pioneering work in the drafty garage, Burlington has built automated test stands for the jet engine fuel control testing, automated stands for Navy hydraulic pumps, and a family of computer/microprocessor controlled test sets for trucks, tanks, and jeeps. The old garage is gone now, and Burlington has a warm and roomy engine test facility where M60 tanks can be brought inside for test.

Articles that follow in this special issue will describe current programs such as EQUATE, ATE/ICE, ATSJEA, and ORTS— programs impressive in their scope and sophistication. Even so, RCA-Burlington engineers have already embarked on studies for a fourth generation ATE. There is still room for the technologically curious in this product area.



EQUATE — RCA's third-generation test system

R.J. Monis

Today's Automatic Test Equipment (ATE) concepts are the product of an evolutionary development which began in the mid 1950's. Early attempts to automate factory, field, and depot test of electronic assemblies met with all types of obstacles — ranging from general user rejection to very high cost and poor reliability. Persistent efforts by ATE developers, working with vitally interested government agencies and military personnel, have led to the development of ATE systems that provide high speed, extremely accurate performance and diagnostic test capabilities at reasonable cost and greatly enhanced reliability. RCA's most recent development is the Electronic Quality Assurance Test Equipment (EQUATE). This system is one of two systems in the country which have been labeled third-generation automatic test systems.

If one stands back far enough, all ATE systems look alike. Basically, every system contains four subsystems:

- Control
- Stimulus
- Measurement
- Switching

What is third-generation ATE?

Second-generation ATE systems are controlled by general-purpose processors whose main function is to provide set-up data for wideband stimulus and measurement boxes, to direct test sequencing, and to make go/no-go decisions on test data acquired from the Unit Under Test (see Fig. 1). The stimulus subsystem contains wideband synthesizer building blocks, which provide stimulus signals. The measurement subsystem contains multifunction meters which resolve measurement values. The switching subsystem generally consists of a large relay matrix which routes measurements and stimulus capability to a set of system interface connectors.

In third-generation systems (see Fig. 2), the control function is again performed by a general-purpose processor; however, its role in the test process has changed significantly. Instead of merely controlling test sequences and setting up programmable stimulus and measurement building blocks, it is intimately involved in the synthesis of stimulus signals and the resolution of measurement characteristics.

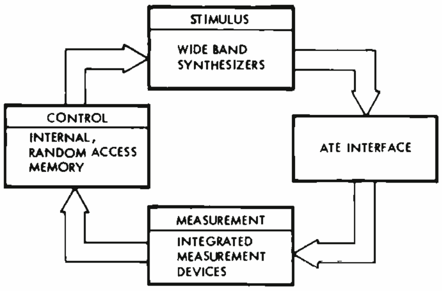


Fig. 1 — Second generation ATE.

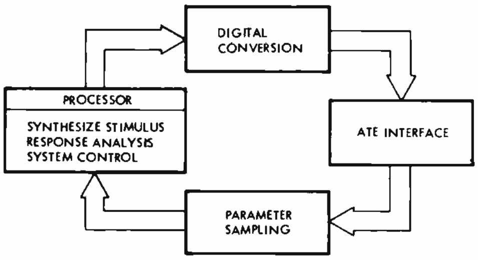


Fig. 2 — Third-generation ATE.

Stimulus

The stimulus subsystem takes on a totally different look, and here we find digital-to-analog converters which generate signals in accordance with computer words which describe in detail the shape and frequency of the desired waveform. The stimulus generator, which includes the digital-to-analog converter, is called an arbitrary waveform generator.

Measurements

Measurements are made in third-generation systems with a sampling system. The analog-to-digital hardware, necessary to resolve voltage samples, is all that is required in the measurements subsystem. Measurements are made by computer control of the samplers, plus arithmetic manipulation of the sample data by the central processor.

The unique approach, the substitution of computer software routines for conventional stimulus and measurement devices, substantially reduces the total cost, size, and complexity of the test system. Pictorially, the stimulus generation and measurement processes are shown in Fig. 3.

Interfaces

The switching subsystem in the third-generation system is called a Programmable Interface Unit (PIU). It is a hardware design that allows any pin on the test system interface connector to be assigned by the test program to be a stimulus or a measurement test point. This versatility reduces the complexity of interface cabling which runs between the unit under test and the test system.

In summary then, third-generation ATE is an integrated system design that makes maximum use of the central processor to eliminate redundant hardware functions in the stimulus measurements and switching subsystem. It should be noted, however, that this minimal hardware design can provide more test capability than most second-generation systems of twice the volume. Higher system reliability is implicit in this reduced hardware approach. One manifestation of this hardware reduction is illustrated in Fig. 4 which shows the third-generation EQUATE and the second-generation DIMATE system.

Development of the third-generation ATE

In automatic test systems, as in all product lines, improvements are always in demand. Some of the more commonly sought after improvements are:

- Simplification of test languages
- Reduction of complex interface adapters
- Greater program generation efficiency
- Extended test system reliability

The specific goals, then, for third-generation ATE designers were clearly to develop a system meeting the following criteria:

1) Easier to program -the machine language must more English oriented.

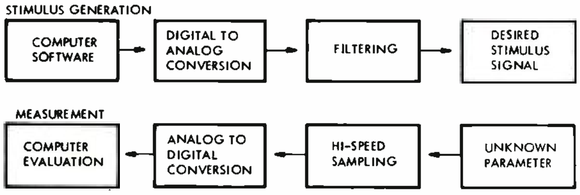


Fig. 3 — Integrated stimulus and measurement.

R.J. Monis, Mgr., Automatic Monitoring and Test, Government Communications and Automated Systems Division, Burlington, Massachusetts received the BSEE from Southeastern Massachusetts University in 1958, and has completed numerous graduate and company-sponsored courses in management and computer technology. Mr. Monis is presently responsible for all engineering activity in the areas of military and industrial automatic test equipment and monitoring systems. Significant among these are electronic ATE (EQUATE) and the AEGIS Operational Readiness Monitoring System. Previously, he directed design, fabrication, and test of NASA Data Bus Systems; supervised related studies on onboard computer configurations; power requirements, cabling characteristics, etc.; had complete management responsibility for Grumman Aircraft study related to conceptual design of information management systems for Space Shuttle application; and had complete responsibility for the company-sponsored R&D programs related to LSI technology and application to remote interface terminals for aircraft and spacecraft modular systems. Previously, he supervised the design and production of automatic test equipment and test programs for the Shillelagh, LANCE, DRAGON, and TOW missile weapon systems. Joining RCA in 1960, Mr. Monis was initially responsible for the complete design of several digital military subsystems. He was also engaged in the design and development of the RCA 110 computer system with principal application in industrial process control. Prior to joining RCA, Mr. Monis was employed by the Laboratory for Electronics, where he was responsible for the design of automatic factory test stations for subsystem test of various doppler navigation equipments.

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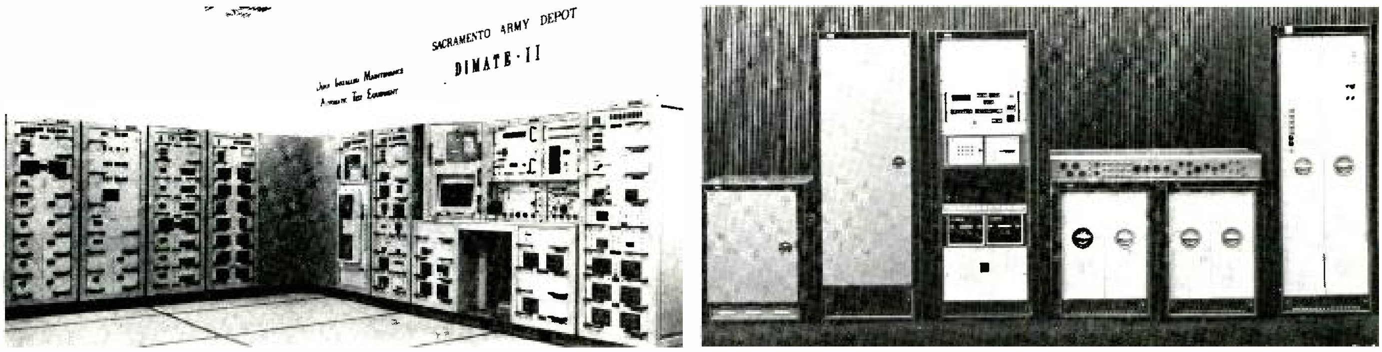

Fig. 4 — Comparison of second-generation and third-generation automatic test systems. a,left) DIMATE — RCA-built second-generation test system for dc to 400-MHz operation. b, right) EQUATE — RCA-built third-generation test system for dc to 18-GHz operation. Note the overall size reduction.

2) More flexible at the interface - measurement and stimulus pin assignments should be programmable.

3) More efficient hardware eliminate redundancy by more versatile software.

4) More reliable should achieve over 500 hours MTBF.

All of these enhancements, however, must not upset previously achieved goals of functional expandability, minimum test time, and minimum operator skill requirements.

Applications

EQUATE (Electronic Quality Assurance Test Equipment) provides performance evaluation, as well as complete diagnostic capability for a broad range of electronic, electro-optical, and microwave assemblies and subassemblies. It is designed in a modular fashion for ease of reconfiguration. Application studies indicate that configurations of most interest will include:

- Digital printed-circuit-card test capability only.
- Low frequency analog (dc 6 MHz) and digital test capability.
- RF (dc 500MHz) test capability.
- Microwave and radar (dc 18GHz) test capability.

The disc operating system, including computer and peripherals and stimulus/measurement subsystem with test capability from dc to 18 GHz, was the original configuration sold off to the Army. Complete system self-test programs and an acceptance test program for the GRC-106 Transceiver were also demonstrated in June of 1973.

System description

The EQUATE system consists of the functional units shown in Fig. 5. This is a digital and low frequency test configuration that will be used to describe the functional operation of the system.

Control and display

The control and display subsystem con-

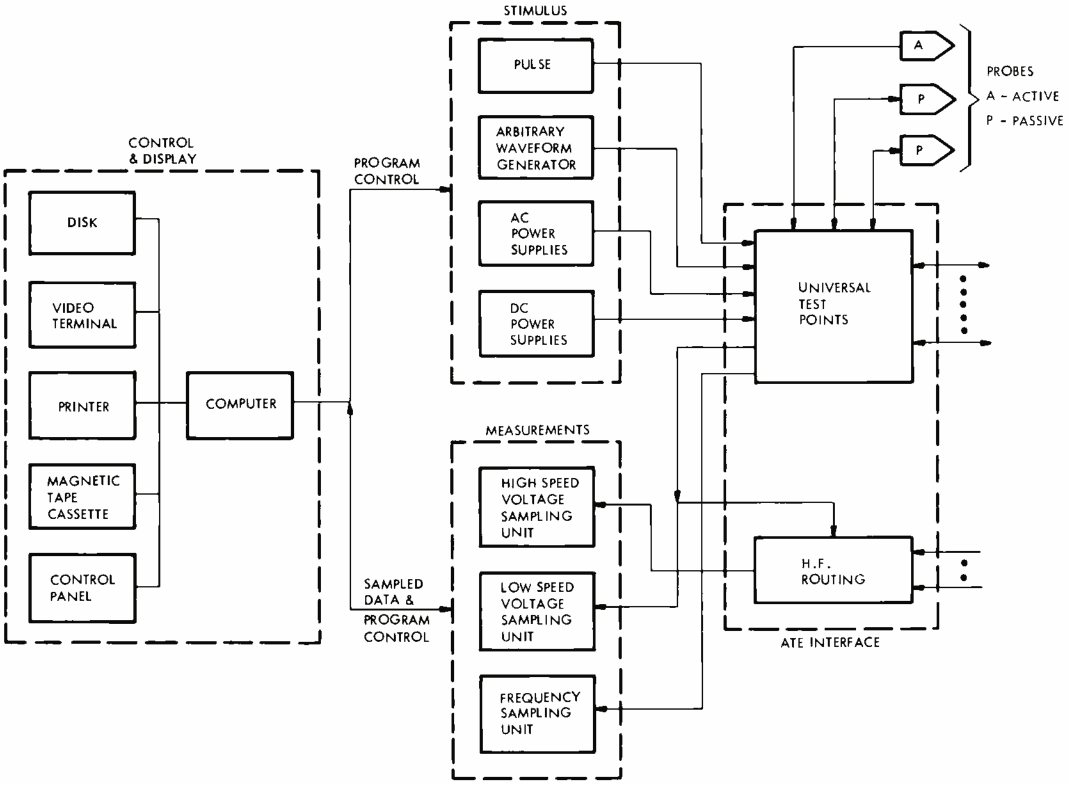

Fig. 5 — EQUATE block diagram (digital and low frequency analog test configuration).

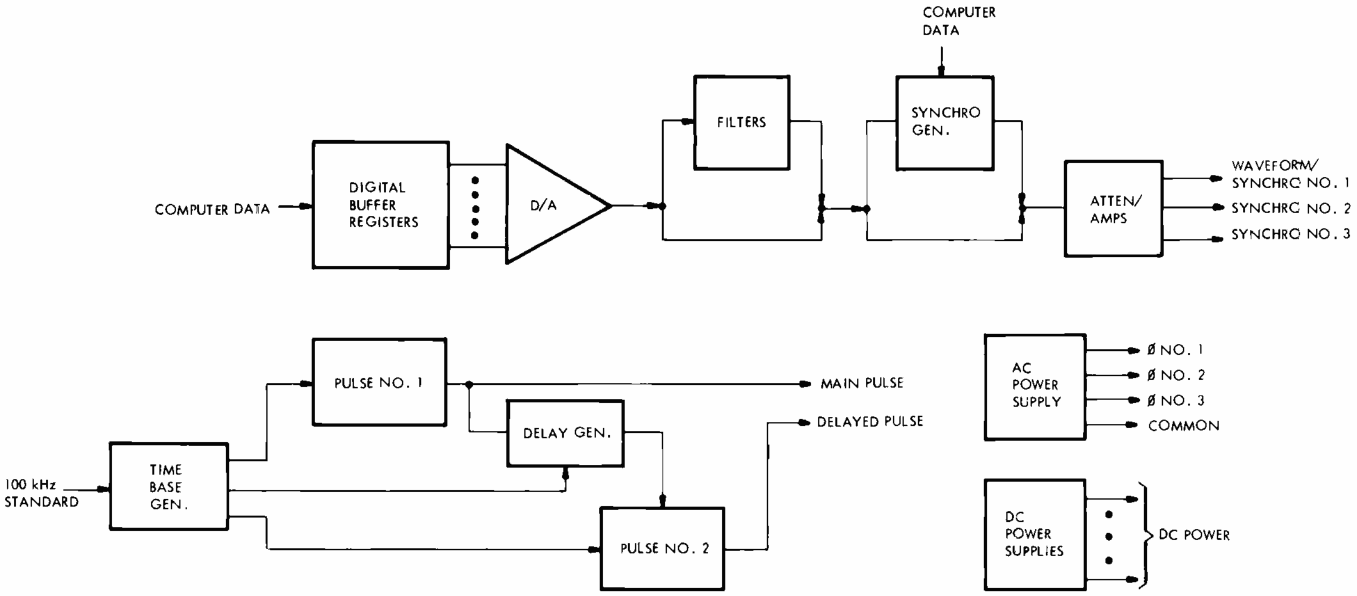

Fig. 6 — Stimulus subsystem.

tains the computer and the following peripheral devices:

- Control panel
- Disk
- Magnetic tape cassette
- Video terminal
- Printer

The computer, a Data General NOVA 800, is a very high-speed processor (800 ns add time) which is in keeping with its expanded role in both test generation and execution. While the architecture of the software system allows operation with only a 16k memory, the test program process is considerably slowed down in order to swap program segments between the computer and the disc. Hence, the computer is supplied with a 32k memory, thereby reducing the need for program swaps and enhancing program execution speed.

The computer is supplied with hardware multiply/divide, power monitor, and autorestart and automatic program load (bootstrap). Control of the peripheral devices is accomplished using a combination of standard and special logic cards located within the computer's main frame.

A user-oreinted Operator Control Panel provides all control functions required for normal operation during UUT testing and debugging test programs. This panel also contains an elapsed time meter, a power-on key-operated switch to prevent unauthroized use, and an emergency power-off switch.

The Video Terminal provides straightforward control of test programs by displaying all operator commands and test results. The Video Terminal is the main man/machine interface in the generation and compilation of test programs. System commands are entered via the terminal keyboard in an "English" like command language.

The Disk provides the permanent storage for the run-time system (stimulus control and measurement analysis), compiler, and temporary storage for test programs that are being compiled or executed.

The Magnetic Tape Cassette Unit provides the medium for inputting the source test program or the executable test program. The Printer provides a permanent record of test results. In addition to these peripherals, appropriate hardware and software are provided to permit hookup of an ASR-35 teletype unit.

Stimulus

A block diagram of the stimulus subsystem is shown in Fig. 6. Three basic types of stimuli are generated:

- Pulse signals
- Waveforms
- AC/DC power

All outputs require the use of the computer, as well as various linkages to the functional elements of the subsystem. Digital stimuli, as well as digital measurements, are produced within the programmable ATE interface to minimize line lengths and signal switching.

Pulse signals

Pulse signals are produced by programmable counters assembled into two pulse generators, one of which may produce signals programmably delayed with respect to the other. The pulse generator timing is provided by a 100-MHz phase-locked loop tied to the frequency standard. In this way, the inherent stability and accuracy of the standard is transferred to both generators. Using this technique, pulse waveforms are "assembled" in 10-ns time increments from 50-ns to 1.3-ms periods. Slower waveforms are obtained by dividing the 100-MHz time base. The signals are then routed to a set of amplifiers which in turn, create rf (to 20 MHz), power, or variable rise/fall time pulses. Note that both pulse outputs may be either continuous or in a burst mode with each burst separately programmable from 1 to 9999 counts.

Waveforms

As shown in Fig. 7, EQUATE generates all waveforms required by means of digital signals, which are then converted to analog form prior to routing to the unit under test (UUT). Since outputs are thus defined mathematically through software, the addition of waveform types

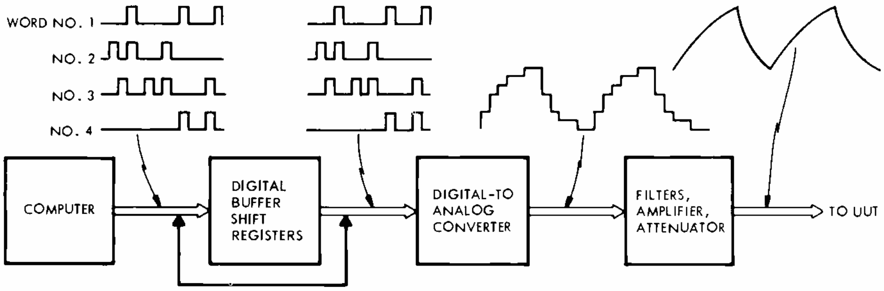

Fig. 7 — Waveform generator.

is accomplished without increasing the size or cost of the hardware itself. Waveforms provided in the basic software package include sine, square, triangle, sawtooth, ramp, and complex functions. Characteristics of the EQUATE waveform generator are described by B. A. Bendel in "Digital waveform synthesis in the EQUATE system" in this issue.

AC/DC power stimulus

Programmable ac/dc power stimulus is provided using off-the-shelf hardware. This part of the test system is usually customized for each application.

Measurements subsystem

Measurements are made in EQUATE by sampling techniques which employ three hardware functions and the system processor. These functions are:

- Low-speed voltage sampler
- High-speed voltage sampler
- Frequency sampler (computing counter)

The low-speed sampler contains a 15-bit analog-to-digital converter. When used to randomly sample an unknown signal under computer control, the low-speed sampler can provide data to the processor for arithmetic manipulation in accordance with measurement algorithms. The system software contains algorithms for estimating most classical measurement parameters such as ac, dc, trms, distortion, phase angle, resistance, etc.

The high-speed sampler includes an analog narrow-aperature sample-and-hold function which is used to provide real-time data and also non-real-time reconstructed data for measurements on ac signals from 50 kHz to 500 MHz.

The frequency sampler is a computing counter function which provides frequency and time-measurements data to 300 MHz. Sample data returned from these three functions are processed in the system computer by one of a number of waveform analysis programs. These programs are derived from various digital signal processing and data reduction techniques for time series and include:

- Fast Fourier transform
- Digital filtering
- Statistical analysis
- Min-max sorting

Both synchronous and nonsynchronous sampling techniques are used. All measured voltages are corrected by an appropriate correction polynomial which corrects for offset, gain, and any nonlinearties that occur in the voltage sampling units. Characteristics of the EQUATE measurements subsystem are more completely discussed by N. B. Wamsley in "EQUATE Measurement System" in this issue.

ATE interface subsystem

The ATE interface subsystem provides the necessary routing and multiplexing circuitry to enable distribution of stimuli and access to measurement at the test system interface connectors. The EQUATE system is designed to provide either a straightforward relay matrix as shown in Fig. 8 or a programmable interface unit as shown in Fig. 9.

Programmable interface unit (PIU)

The functions incorporated in the PIU are:

- Stimulus buffering and routing
- Measurement buffering and routing
- Programmable loads
- High frequency routing
- Digital message generation
- Digital message reception

To provide a completely universal interface pin, one which can be designated a stimulus or a measurement point or a load point, it is necessary that all six of the above functions can be provided for each pin of the test system interface connector. The EQUATE PIU provides this capability through the use of universal test point assemblies, of which there is one per test point.

Fig. 9 shows a simplified block diagram of the PIU, and it depicts three functional groups of hardware: the universal test point (UTP) boards, the control logic and stimulus buffers, and a high-frequency measurement routing matrix. All stimuli and computer control lines are routed to the PIU control logic and distributed within the PIU to each of the UTP cards, via a stimulus buffer. UTP cards are packaged in 16 test-point assemblies. For standardization purposes, systems are therefore configured in 16-point increments up to the total number required.

Typically, hand-held probes are desired, and, in EQUATE, a probe can also be designated by the test programmer to be either a measurement, a stimulus, or a load. The high-frequency routing matrix provides a coaxial measurement multiplex capability so that rf signals can be properly routed via coaxial transmission lines to the measurement subsystem. Characteristics of the EQUATE PIU are more completely described by N. B. Wamsley, entitled in "Automatic Test Equipment Interface" in this issue.

RF subsystem

The EQUATE rf subsystem contains all the hardware necessary to extend the low-frequency stimulus and measurements subsystem capabilities to 18 GHz. This hardware design is the culmination of several years of IR&D techniques development.

RF/microwave measurements

The rf measurements subsystem, as a single unit, serves as a preprocessor of rf measured data. Inputs and outputs of this subsystem are multiplexed at the unit itself, thereby reducing line lengths and line losses as well.

Two rf synthesizers are used as local oscillators and test signal sources as required. All types of high-frequency measurements are made directly by the subsystem. These include peak power, average power, frequency, vswr and phase. In conjunction with the computer and low-frequency measurements subsystems, it is also possible to measure other rf parameters, such as amplitude and frequency modulation, recovery time, pulse width, prf, etc. A separate detector is used for measurements involving pulse and amplitude-modulated signals. Pulsed carrier frequencies are measured by computer-aided automatic spectrum analysis techniques.

RF/microwave stimulus

The two identical rf synthesizers cover the band from 10 kHz to 100 MHz. The output frequencies are derived from a precise standard frequency by using a combination of addition, subtraction, division and multiplication. The synthesizer is programmable in 100-Hz steps from 10 kHz to 99.9999 MHz.

The amplitude modulator and pulse modulator provide the means to modulate the synthesized signal with the low-frequency waveform-generator output signal. The modulated signal is then amplified in the output amplifier and routed to the programmable attenuator for program-controlled leveling. Modulations possible in the first synthesizer are cw, a.m., fm, ssb, fsk, pulse, and fdm to 18 GHz. Modulation in the second synthesizer will be a.m. and fm, with the carrier extended to 500 MHz.

The microwave stimulus provides signals for the 100-MHz to 18-GHz spectral region. It is currently being housed with the rf synthesizer in a single rack. The microwave stimulus receives its initial input from rf stimulus "A" which generates a 10-kHz to 100-MHz signal. This signal is multiplied and filtered a number of times to yield the following groups of outputs:

100MHz to 1GHz
1GHz to 4GHz
4GHz to 12GHz
12GHz to 18GHz

All of these signals may be amplitude or pulse modulated; fm is possible from 80 MHz to 18 GHz. Outputs are switched (after final attenuation) so that the signal may be routed to either one of two UUT

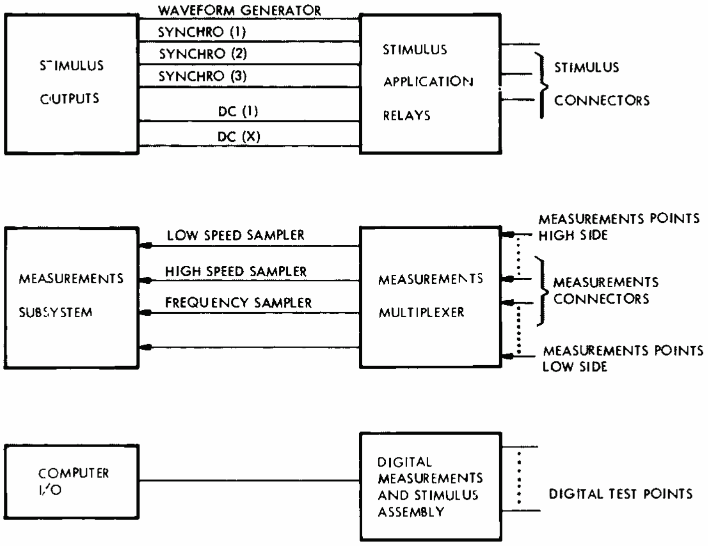

Fig. 8 — Conventional ATE Interface.

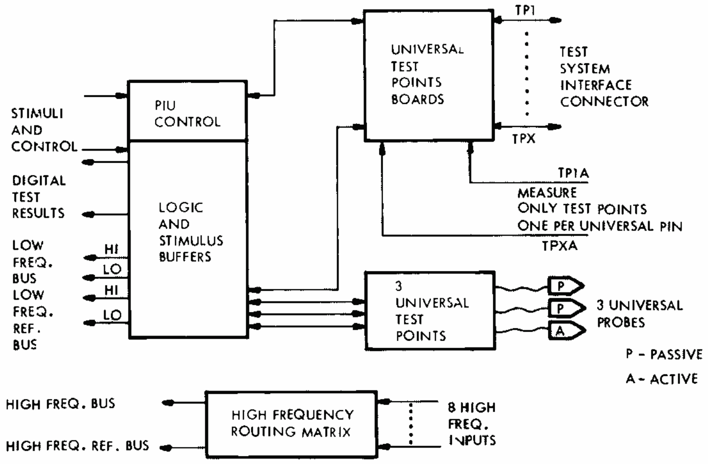

Fig. 9 — Programmable interface unit (PIU).

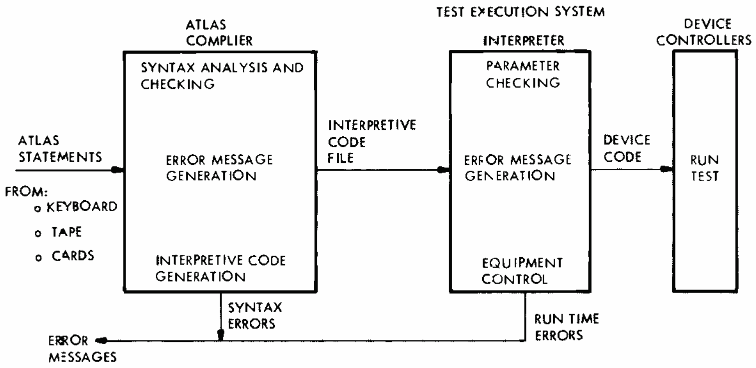

Fig. 10 — EQUATE software system.

ports, or to self test. In addition, the output signal may also be applied as a local oscillator to the Spectrum Analyzer and Impedance Measurement Units.

Programming language

The EQUATE programming language is an extended version of ATLAS, a language originally developed for Airline Avionic Equipment Testing. ATLAS was selected because it is a test-oriented language that allows engineers with no software training to write programs. All that is needed to use this language is a simple reference manual defining the programmable characteristics of each stimulus and measurement device in the system.

System operation

The three basic ways in which EQUATE is used are 1) testing (UUT), 2) program validation, and 3) system software modifications.

High volume testing and limited program validation would normally be done at the deployed locations where UUTs are subjected to final testing. System software modifications would most likely be done at a programming center when major changes or additions are required in the software operating package to improve or extend the automated test system. In all cases implementation is with the "on-line" computer which is integral to the EQUATE system.

Testing (UUT)

In using EQUATE for testing, the operator would go through the following steps:

1) Apply power to system
2) Check that mode select switch is in "automatic"
3) Use the video terminal keyboard to type in the "test" command and the UUT name
4) Press "START TEST" push button
5) Follow instructions given on video terminal

At this point the system will proceed through the test of the UUT.

Program validation

In using EQUATE for program validation, the operator would go through the following steps:

1) Apply power to system
2) Set operating mode to "manual"
3) Type "test" command and identify UUT
4) Connect UUT
5) Run selected tests by using appropriate control switches
6) If necessary to make changes, load the UUT source program, type "text edit" command, and make changes
7) Type "ATLAS" command to compile the edited program
8) Repeat the change cycle until all tests compile and run satisfactorily

System software modifications

EQUATE is provided with the following programs used for systems software development:

ALGOL compiler –A compiler program for the ALGOL-60 language with extension for definition of non-standard operators, and for bit, byte and string data manipulation. (The ATLAS compiler is written in ALGOL).

FORTRAN compiler—A compiler program for FORTRAN IV extended for real-time multitask programming.

Relocatable assembler and linker loader An extended assembler is provided that differs from more basic assemblers in four respects:

1) Relocatability programs are assembled so that they can be loaded anywhere in core memory by the relocating loader.

2) Interprogram linkages—programs can be assembled which reference data, instructions and addresses defined in other programs. All such linkages are resolved by the loader.

3 Number definition simple methods for defining double precision, decimal, and floating point constants are provided.

4) Conditional assembly whole programs or portions of programs can be assembled or bypassed on the basis of a conditional expression.

Text editor

A text-editor program developed by RCA provides an extremely effective means of editing source programs. The video terminal provides hardware for character and line insertion/deletion and also provides extra storage for text exceeding the limits of the visible screen. The editor programs move text to and from the video terminal using the following commands:

SCAN scan forward, page by page over the text stored in a file

PAGE M- locate and display the *Mth* page of textp

LOCATE "word"--locate and display the page containing the designated character string

CURRENT—recover the current page. (When the user has made some mistake, such as erasing the whole page)

RETURN—returns control to the operating system

Utility programs

EQUATE includes a full range of utility programs for debugging, binary file edit, library file edit, and arithmetic functions.

All of the above programs are controlled from the video terminal keyboard via an interactive command line interpreter. At a software development center, all of the above programs would be permanent files on the disc memory which can be brought into execution simply by typing the program name. At deployed installations, these programs would be available on a tape which could be loaded onto the disc as required. After the loading process (which takes only a few minutes) from cassette tape, all of the programs become instantly available, as before, by typing the name of the desired program.

Software description

EQUATE is supplied with an extremely powerful and capable state-of-the-art software system for test program development, debugging, and validation. The EQUATE software system shown in Fig. 10 is a hybrid system incorporating the best features of conventional compilers and interpretive systems. The marriage facilitates faciliates a powerful programming language, excellent program error checking, compact object code, fast execution and efficient program debugging and validation. J. E. Fay provides a complete description of the software in "EQUATE System Software" in this issue.

System status

EQUATE was designed and built over a two-year period, from 1971 to 1973 under contract with the U.S. Army Electronic Command (ECOM). In June of 1973, the first system was fully demonstrated and accepted by the Army. Later in 1973, another full-scale technical evaluation of EQUATE was made by Lockheed and Navy evaluators and found to meet all of the design criteria established for third-generation ATE. Systems are now being built for Army Masters test evaluation at Fort Hood, Texas and the Naval Avionics test facility at Indianapolis, Indiana.

Digital waveform synthesis in EQUATE

B.A. Bendel

Traditionally, low-frequency (<5-MHz) waveform generation within automatic test systems has been via an assemblage of discrete function modules, each capable of creating one or more specific types of waveform. Whenever a particular waveform is required, the ATE computer merely selects the proper module, at the required repetition rate and signal level, for the duration of the test. This simplistic scheme of generation, a standard in so-called "building block" automatic test systems, runs into problems as the system grows in size and complexity. In particular, as the need for additional waveforms to meet the requirements of new equipment becomes significant, additional hardware modules, with their attendant software drivers, must be "tacked on" to the system. These modules, in turn, become larger and more costly as the waveforms required become more complex. Hence, the problem is one of severely limited flexibility and expandability, due to cost and size constraints. The solution to this problem, involving a software, rather than a hardware methodology, was developed as a part of RCA's third generation automatic test system—EQUATE.

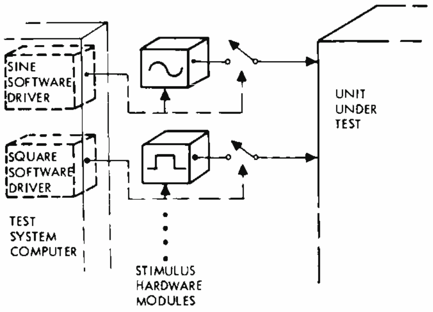

Fig. 1 — Low frequency stimulus approach traditionally used in ATE systems.

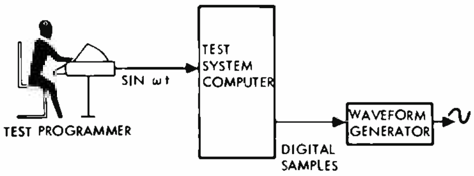

Fig. 2 — Digital waveform synthesis where the test programmer defines the waveform via a manual input.

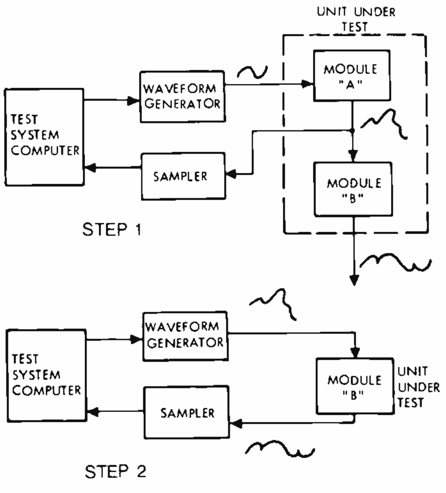

Fig. 3 — Digital waveform synthesis where the unit under test defines the waveform.

In GENERAL, the third generation of automatic test equipment has been based on the more efficient use of the ATE computer in all phases of the testing process. In previous systems, the computer's role in stimulus generation has been nothing more than the applying and removing of discrete waveform outputs, as illustrated in Fig. 1. For EQUATE, however, it was decided that the computer itself would calculate, via software routines, a digital representation of the desired waveform.

The primary mode of operation, shown in Fig. 2, requires a mathematical description of the desired waveform, which is entered by the test programmer via a manual input device. Alternatively, should it not be possible to describe a particular waveform in this fashion, sampling techniques can be used to "copy" the desired shape, as illustrated in Fig. 3. In either case, once the digital representation has been derived it is translated into analog form by means of high-speed digital-to-analog techniques. A simplified example of the translation hardware, employing recirculating shift registers and a D/A converter is shown in Fig. 4. The shift registers act as "buffers", thereby removing any constraint on waveform output frequency due to the computer's I/O speed.

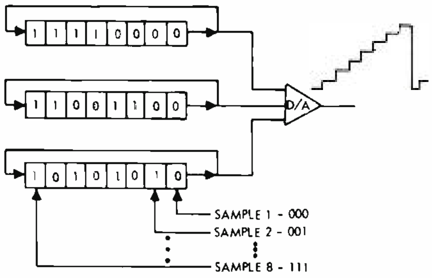

Fig. 4 — Basic operation of the waveform generator used in EQUATE.

Note that this method of waveform generation immediately eliminates the "building block" system restrictions by creating an "all-purpose" hardware block, whose only function is the translation of computer outputs into analog waveforms. The "problem" has been moved back into the ATE computer, where it is effectively "solved" via the use of software techniques. In this way, a requirement for a new waveform may be met by addition of software, rather than hardware.

Design objectives and constraints

With the generation of waveforms now essentially one of mathematical computation, any limitation on waveform complexity is now based solely on the ability of the hardware to reproduce the desired waveshape. Obviously, the capabilities of the D/A converter are a significant factor in this approach. In addition, the number

Barry Bendel, Design Engineering, Government Communications and Automated Systems Division, Burlington, Mass. received the BSEE from Cornell University in June, 1965. The following February he received the MSEE, also from Cornell University. He has been involved in the design and development of automatic test equipment — the DIMATE series and the EQUATE — since joining RCA in 1965. For his work on the DIMATE Computer/Controller Subsystem he shared in a Technical Excellence Team Award. For his work on DIMATE IV, Mr. Bendel was made "Engineer of the Month" for November 1969. On the EQUATE program, Mr. Bendel assumed primary responsibility for the design, factory follow, and test of the Low Frequency Stimulus and Switching Subsystems. He also designed the various computer interfaces and participated in overall system integration and sell-off. For his work on this program he shared in a Technical Excellence Team Award.

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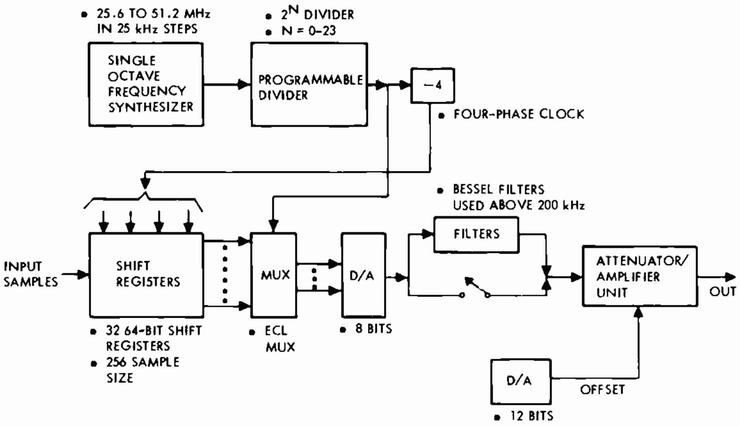


Fig. 5 — Waveform generator.

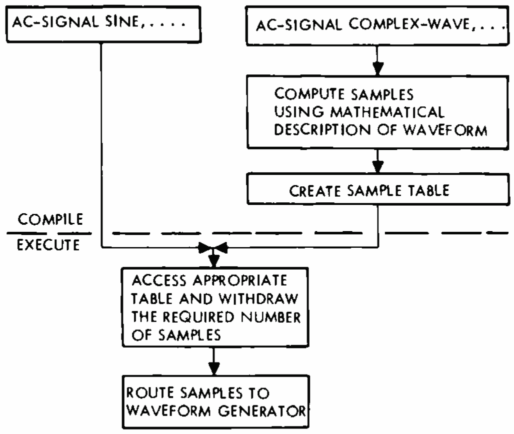


Fig. 7 — Software sequence for waveform generation.

of digital "samples" used to create a particular waveform will influence the quality of the final output. The more samples, the better the waveshape, but this is limited by the equation:

$$\text{Frequency out} = \frac{\text{clock frequency}}{\text{number of samples}}$$

Hence, as the number of samples is increased, the rate at which the samples are clocked through the D/A converter must also increase to maintain the same output frequency. A limit is ultimately reached at which hardware size and cost become prohibitive. Thus, a compromise must be reached, involving hardware operating speed, number of samples, filtering, and allowable output distortion.

The objective of the waveform generator design — to generate arbitrary waveshapes from dc to 3 MHz, with a distortion of less than 1% — was met by the design shown in Fig. 5.

Hardware description

A single-octave frequency synthesizer and programmable divider are used to generate clocking frequencies from 3 Hz to 51.2 MHz, in steps ranging from 0.003Hz to 25 kHz. This clock is, in turn, split into four phases, and used to shift waveform samples, previously loaded by the computer into a shift register unit, through a high-speed D/A converter, filters, attenuators, and amplifiers. Shift register speed, size, and cost led to a selection of a maximum sample size of 256. Using the equation, with a maximum clock frequency of 51.2 MHz, the full set of samples may be used to produce waveforms up to 200 kHz. For a sine wave, with distortion equal to:

$$D = [(\pi^2/3N^2) + (2/3M^2)]^{1/2}$$

where N is the number of samples, $M = 2^K$, and K is the number of D/A inputs.

The use of an 8-bit D/A converter and 256 samples yields $D = 0.78\%$ for frequencies below 200 kHz, with no filtering.

With 51.2 MHz as a maximum clock frequency, the only way to generate waveforms above 200 kHz is to reduce the number of samples. To compensate for this reduction, Bessel filters are used to convert the staircase D/A output into an approximate straight-line (polygonal) waveform. In this case, total distortion becomes,

$$D = [(2.1646/N^4) + (4/9M^2)]^{1/2}$$

The minimum number of samples used by the Waveform Generator is 16 (in the range from 1.6 to 3.2 MHz output). Thus, in this worst case, (N=16, M=256), sinewave distortion becomes, $D = 0.63\%$.

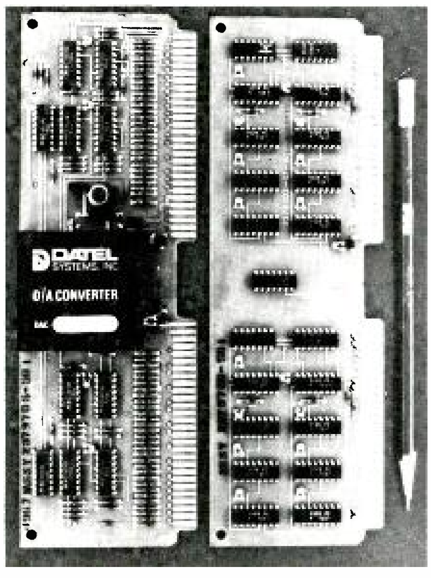


Fig. 6 — Two printed circuit cards used in the waveform generator: Multiplexer — D/A (left) and Shift Register.

As described above, the overall capacity of the shift-register unit was chosen to be 256 bits. This capacity has been split between four sets of 64-bit shift registers. This split, coupled with a four-phase clocking scheme, reduces the shift rate for any one register to only 12.8 MHz. The 8-sets of four registers are combined via high-speed ECL logic before being routed to the 8-bit D/A converter.

The D/A converter is a high-speed device, with an output settling time (to ± 0.1% of full scale) of 25 ns. The output is amplified by a wideband high-slew-rate operational amplifier, with two fixed gains (6.32 and 20). Following the amplifier, a programmable attenuator, consisting of a 10-bit ladder network, is used to drop the signal to between 0.316 and 0.999 of its input value. The output, at this point, leaves the waveform generator chassis. Final attenuation to 40 dB in 10-dB steps, producing a total output range of from 20mV p-p to 20V p-p, occurs elsewhere in the EQUATE system, thereby insuring a minimum of noise pickup at low levels. Note that, as shown in Fig. 5, a separate, programmable D/A converter is used to offset the waveform as required.

Fig. 6 is a photograph of two of the waveform generator printed circuit cards: the Multiplexer — D/A and a portion of the Shift Register Unit.

Software

The software used to generate analog waveforms may be divided into two basic categories. The first of these deals with the generation of so-called "standard" waveforms, such as a sinewave, sawtooth, triangle, *etc.*, while the second permits the derivation of complex waveforms, *i.e.*, those described mathematically by the test designer. A flow chart illustrating the functions performed by the ATE software, both during the compilation phase and at run-time, is presented in Fig. 7. For example, to utilize a "standard" waveform in an ATLAS UUT program the test designer merely calls for:

AC-SIGNAL X, . . .

where X may be sinewave, sawtoothwave, triangular-wave, etc. Tables of 256 samples of these waveforms exist as permanent sections of the EQUATE run-time system. When the program is executed, this run-time software will, based on the desired waveform output frequency, extract the necessary number of samples from the appropriate table, and route them to the Shift Register Unit. Fig. 8 illustrates some of the "standard" waveforms produced by the Waveform Generator.

For complex waveforms, the test designer calls for:

AC-SIGNAL COMPLEX-WAVE, . . .

In addition, he must supply a mathematical equation describing the desired complex function. The computer will then utilize this equation to create a new table of samples. Once this table has been created, it may then be treated as any of the so-called "standard" tables, and accessed, during program execution, to output the appropriate waveform data. Note that once a table has been derived for a new waveform type, it is possible to transform it into a "standard" waveform by incorporating the table permanently within the run-time system.

Example

During the testing of an AN/GRC-106 Transceiver, the EQUATE system was required to measure and evaluate receiver cross-modulation. To perform this test, EQUATE had to stimulate the Unit Under TEST (UUT) with a two-tone waveform, and perform a spectrum analysis of the resulting UUT output.

The two-tone signal required for this test was a summation of two sineways, with $f_1=5X$ Hz and $f_2=3\ X$ Hz. In a "building-block" ATE system, such a stimulus would require two sinewave generators, plus the hardware necessary to combine the outputs into a single signal. To obtain the stimulus using the waveform generator, a simple ATLAS program was written, as shown in Fig. 9. This program mathematically sums two sinewaves, and forms a table containing 256 samples in the range from 0 to 1. In addition, the code is shown for applying the signal, at a 500-Hz rate, to EQUATE interface pin 141. The actual waveform produced by this program is shown in Fig. 10.

Conclusions

The development of a computer-based waveform generation capability for third-generation ATE has resulted in several key advantages over previous systems. First, it represents a flexible, expandable approach to waveform generation. New waveform types, permitting the testing of new UUT's may be created by the addition of software rather than hardware modules. In addition, existing waveforms may be modified to reflect modifications to existing UUT's, again without hardware redesign.

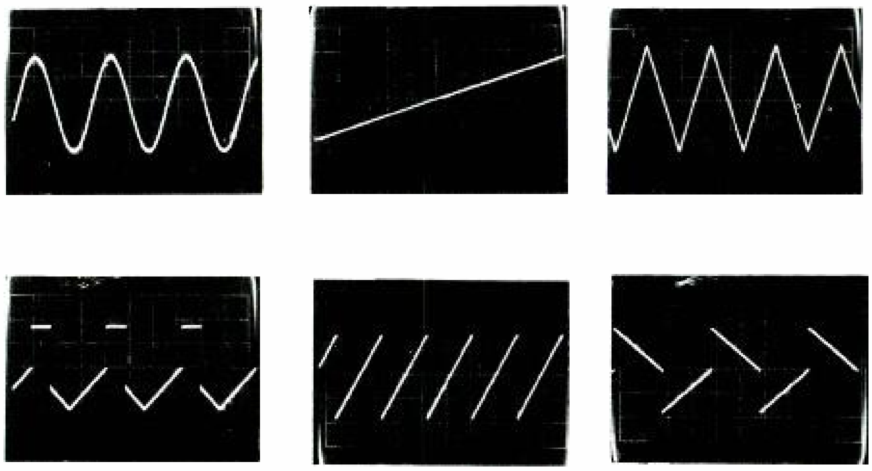
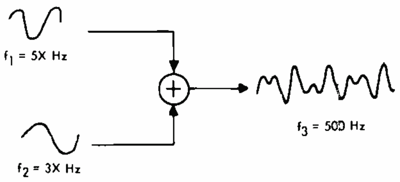


Fig. 8 — Some of the "standard" waveforms produced by the Waveform Generator.



```
   BEGIN, TWO-TONE GENERATOR $
   DECLARE, DECIMAL, LIST, 'SAMPLES' (256) $
   DECLARE, DECIMAL, 'X', 'Y' $
C  COMPUTE TIME SAMPLES OF REQUIRED FUNCTION IN RANGE
          0-1 $
E   1 'X' = 0 $
    2 'X' = 'X' + 1 $
    'Y' = (6.28318530) * ('X' - 1)/256 $
    'SAMPLES' ('X') = 0.25 * SIN (5 * 'Y') + 0.25 * SIN (3 * 'Y')
          + 0.5 $

    COMPARE, 'X', LT 256 $
    GO TO, STEP 2 IF GO $

C   APPLY TWO-TONE TO UUT PIN 141 $
    APPLY AC-SIGNAL COMPLEX-WAVE, VOLTAGE-P 1 V, STIM
          'SAMPLE' (1), FREQ 500 Hz, SAMPLE-COUNT 256,
          CNX HI 141 $
    WAIT-FOR MANUAL-INTERVENTION $
```

Fig. 9 — Example of a two-tone waveform generation.

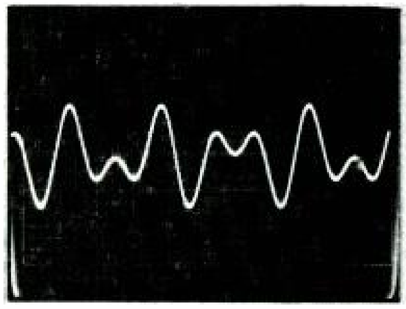


Fig. 10 — Actual waveform produced by the techniques outlined in Fig. 9.

But most importantly, digital waveform synthesis permits the straightforward generation of complex waveforms, where these waveforms may be definable only in mathematical terms, or in terms of an existing hardware output. In either case, the building-block hardware design effort necessary to realize them might prove long, costly and, in the end, totally ineffective. Hence, the technique becomes a time-saving and cost effective tool for the UUT test program designer.

Acknowledgments

The author wishes to acknowledge the help and support of the rest of the Waveform Generator design team: R.J. Bosselaers, A.H. Frim, A.J. Krisciunas, and K. Miller.

EQUATE measurement system

N.B. Wamsley

Traditional Automatic Test Equipment (ATE) measurement systems have required separate building blocks for each major function. Voltages were measured using digital voltmeters, distortion via distortion meters, etc. — all under computer control. The net result was an inefficient system which utilized numerous pieces of hardware and, as a result, were inflexible and very often unreliable. Recognizing the need for a completely flexible integrated measurement system, RCA developed a third generation, sample data, measurement system that uses the full computational capability of a computer as a major system element.

In DEVELOPING the EQUATE measurement system, RCA's approach was not toward full digital conversion of particular parameter such as a phase angle, but rather in generating a time-series approximation of the measured waveform and extracting that parameter through an appropriate algorithm. The algorithms used, which in general perform functional operations on the time series, are the foundation of the EQUATE measurement system.

By submitting the design to the disciplines of both time-series and sampled-data analysis, RCA has developed a measurement system which provides maximum flexibility through the use of elemental hardware building blocks that allow functional expansion through software.

Measurements system

The measurement system pre-processes waveforms for subsequent computer analysis and evaluation. As shown in Fig. 1, the measurement system consists of a low-speed-voltage sampling unit, a high-speed-voltage sampling unit, a frequency sampling unit, and associated routing.

The voltage units sample the input signal and convert it to digital data which is processed in the system computer by one of the several waveform analysis programs. These programs, the measurement algorithms, are derived from various digital signal processing and data reduction techniques for time series and include:

- Fast Fourier transform
- Digital filtering
- Statistical analysis (mean and variance estimation)
- Min max list sorting
- Least squares curve fitting

From these waveform analysis programs, the measured parameter is determined. Measured parameters that are processed through the low-speed and high-speed voltage sampling units include:

- DC voltage
- AC voltage
- Phase magnitude
- Angle position
- Impedance

From these basic parameters, more complex parameters such as transfer function or distortion are derived by the system software.

To generate the proper sampled measurement data, various sampling techniques are used. These are:

- Synchronous real time sampling (ac waveforms up to 50 kHz)
- Synchronous non-real time sampling (ac waveforms up to 500 MHz)
- Random sampling (statistical parameter estimation)

All measured voltages are calibrated using an appropriate correction polynomial derived periodically and permanently sorted on disc. The polynomial corrects for offset, gain and any non-linearities occuring in the voltage sampling units.

The measurement system uses a frequency sampling unit to make frequency, period, and time interval measurements. The following paragraphs explain the operation of the various measurement system units.

Low-speed-voltage sampling unit

The low-speed sampling unit contains a programmable 15-bit analog to digital converter, a 100-ns sample-and-hold circuit, a programmable amplifier/-attenuator and a programmable current source which may be driven by an ac or a dc signal for use as an impedance adapter (see Fig. 2). This floating measurement unit is fully isolated from system ground since the digital inputs and outputs are photon-coupled through light-emitting diodes and photo transistors, while pulse and ac signals are transformer coupled. The unit has its own isolated power supply.

The analog to digital converter has a programmable conversion time of either 0.5 or 1.0 μs/bit. For dc and low-frequency ac, the unit is programmed to 15-bit conversion at 1 μs/bit (total conversion time is 15 μs) while for higher frequencies the unit programmed to a 12-bit conversion at 0.5 μs/bit (total conversion time is 6 μs).

The programmable amplifier/attenuator

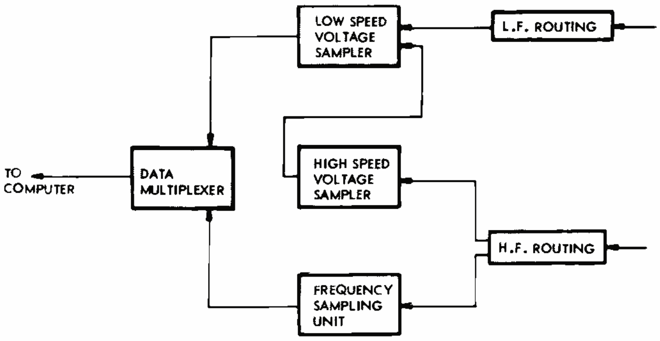


Fig. 1 — Measurement system block diagram.

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Mr. Wamsley's biography and photograph appear with his other paper in this issue.

provides full scale settings of:

- 1 Vdc (0.707 Vac)
- 10 Vdc (7.07 Vac)
- 100 Vdc (70.7 Vac)
- 565 Vdc (400 Vac)

The low-speed-voltage sampling unit is used to make the following measurements:

- DC voltage
- DC ratio
- AC voltage (up to 50 kHz)
- Phase (up to 50 kHz)
- Spectrum analysis (up to 50 kHz)
- Peak (up to 50 kHz)
- AC ratio
- Resistance
- Angle position indication
- Peak-to-peak (up to 50 kHz)
- Pulsed dc (up to 50 kHz)
- Network analysis (up to 50 kHz)
- Waveform analysis (up to 50 kHz)

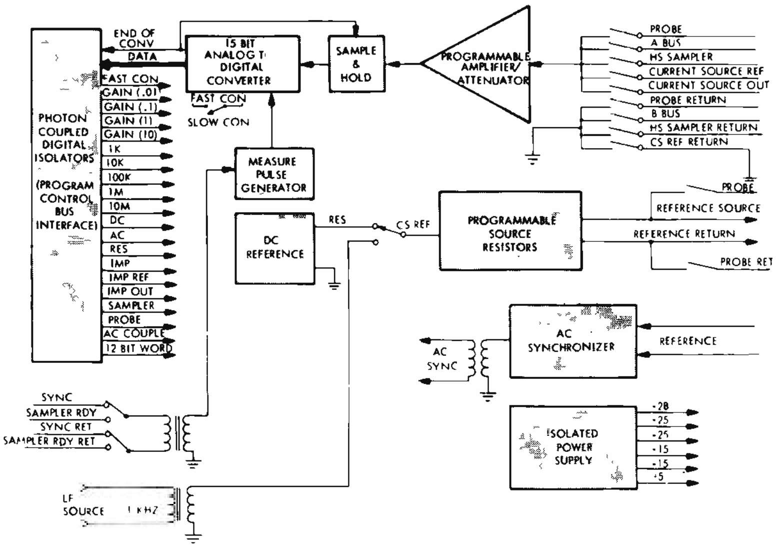

Fig. 2 — Block diagram of the low-speed-voltage sampling unit.

High-speed-voltage sampling unit

The high-speed-voltage sampling unit is used to sample and hold high-frequency signals and then transfer them to the low-speed-voltage sampling unit for conversion to digital data.

All measurements made with the high-speed sampler are non-real time; that is, the measurements either sample the data randomly (true rms, peak voltage, *etc.*) or in a delay mode synchronous with a trigger, as if it were a sampling oscilloscope. The unit is used to make the following measurements above 50 kHz:

- Waveform analysis
- Spectrum analysis
- AC voltage - TRMS
- Peak voltage
- Peak-to-peak voltage
- Pulsed dc
- Distortion
- Phase

A block diagram of the sampler is shown in Fig. 3. RMS, peak, and peak-to-peak measurements are accomplished by eliminating the feedback path from the dc attenuator to the sampler head. The unknown signal is sampled at random intervals by the random sampler, and held by the sample and hold.

Waveform reconstruction in non-real time is somewhat more complicated. The sampling loop is essentially a null-seeking servo, wherein the sampling head, when interrogated, reports the difference between the input and the attenuated output of the sample and hold. A nonzero difference causes the content of the sample-and-hold circuit to change, incrementally, to the new value of the input. The amplifiers and attenuators are ganged to provide ranging from 1 mV full scale to 1 V full scale.

Timing of sampling pulses is accomplished by the trigger, fast ramp, and staircase. The trigger examines the input for some recognizable event (threshold and slope) and commences the fast ramp. One sample of the test signal will be taken when the fast-ramp voltage equals the staircase voltage. Then the staircase is incremented to its next value and the process starts anew. Equivalent time between samples is determined by the millivolts/nanoseconds slope of the fast ramp and the step size (millivolts) of the staircase. Step size and ramp steepness are both programmable, so considerable flexibility is available.

The major needs of the new high-speed sampler are timing accuracy and automatic triggering. Accurate timing has been accomplished by charging precision capacitors with well-controlled current sources in the fast ramp. An accurate staircase is provided by a high grade D/A converter. Reliable triggering is accomplished by using asynchronous logic design techniques and emitter-coupled logic. Triggering is programmable to be ± slope, ac or dc with threshold. Variations in signal amplitude are accounted for with emitter followers. The trigger works directly for frequencies

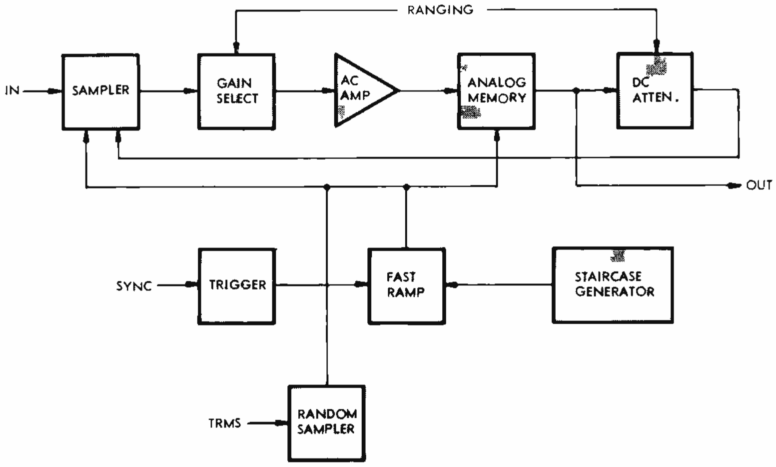

Fig. 3 — High-speed-voltage sampling unit.

up to 150 MHz; from 150 MHz to 500 MHz a divide-by-four is used to prescale the signal down to a usable frequency.

Frequency sampling unit

The frequency sampling unit, a modified commercial counter, provides the capability of making frequency and period measurements on signals up to 320 MHz and single- and dual-channel time interval measurements on signals in the range between 15 ns and 100 s. Each channel has independently programmable thresholds, terminations, and slopes (for START and STOP).

Measurement techniques

No attempt will be made to define or list all of the measurement functions which can be accomplished with such a versatile system. However, some representative techniques will be defined so that the reader better understands the overall system capabilities.

DC measurements

The technique used for performing dc measurements is shown in Fig. 4. For all measurements, 1000 samples are taken. Normally, the sampling interval between measurements is 166.7 μs and thus the 1000 samples are taken over 10 periods of the 60-Hz line frequency. This provides a minimum of 20 dB of line frequency rejection (normal mode noise).

The minimum programmable sample-width is 50 ms, while the maximum is 100 s. The 1000 samples will be made during the sample-width time. In all cases, each measurement is calibrated against the calibration polynomial which, in the particular case of dc, essentially corrects for offset and gain errors in the programmable amplifier, the sample and hold, and the analog-to-digital converter.

AC voltage

There is a logical extension of the measurement system to perform ac measurements based on the techniques used for dc. Fig. 5 and 6 show two types of ac measurements, true rms (trms) and average ac. The trms value is generated by randomly sampling the input waveform a total of 10,000 times, squaring each sample and calculating the square root of the average squared value. The measurement range is from 0.001 Hz to 500 MHz. For frequencies below 50 kHz, the signal is routed directly to the low-speed-voltage sampling unit; while for higher frequencies, the signal is fed through the high speed sampler.

For average ac measurements, the measured value is the average ac scaled to rms. The technique used is to calculate the average value of the absolute value of all samples and scale the results to rms. Thus, this measurement is compatible with "averaging" ac voltage measurements devices. This measurement generates a total of 960 samples of the input waveform over a minimum of 120 periods of the frequency. Thus, normally eight samples are taken each period.

Resistance/complex impedance

The extension of the measurement system to resistance and complex impedance is straightforward. The programmable dc or ac voltage standard is connected to the unknown impedance through a programmable precision resistor, and a voltage measurement (V_x) is made which allows computation of the unknown parameter. The software compensates for the loading effects of the input impedance of the low frequency measurement system (1 Megohm).

Waveform analysis

Due to the general approach to the solution of the various measurement problems, it must be clear that waveform analysis is not significantly different from other ac measurements. Indeed the block

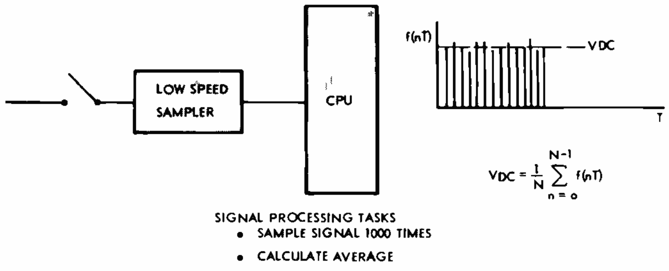

Fig. 4 — DC measurement technique.

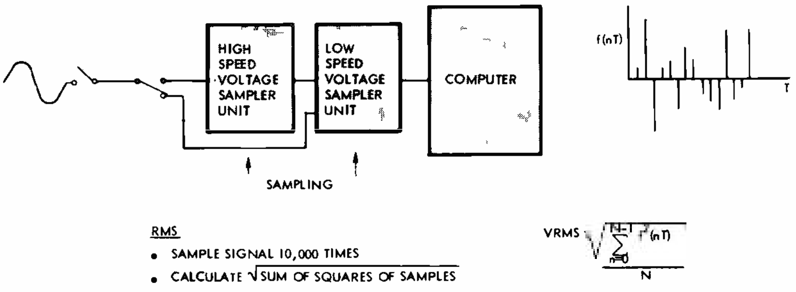

Fig. 5 — TRMS measurement technique.

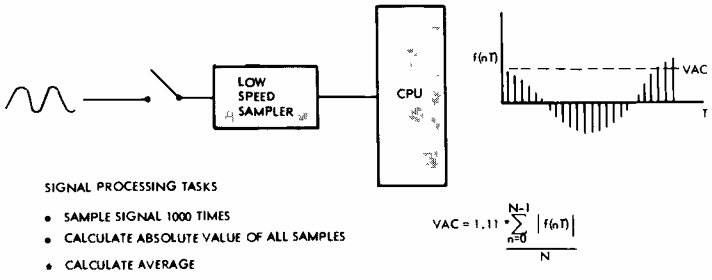

Fig. 6 — Average ac measurement technique.

diagram of the technique for waveform analysis (see Fig. 5) is no different than the technique shown for the trms. As a result a wide assortment of waveform analysis measurements can be performed. Included are:

- Peak voltage
- Peak-to-peak voltage
- Pulse dc
- Risetime
- Falltime
- Pulse width
- Frequency
- Generalized sampling

Frequency and pulse width will be implemented using the standard frequency and time-interval measurements of the frequency-sampling unit.

The peak voltage measurement utilizes random sampling and sorts an array for a weighted maximum (*i.e.*, the average of the four highest samples). The measurement range extends up to 500 MHz. The peak-to-peak voltage measurement is similar except that the array is sorted for both a weighted maximum and minimum. The peak-to-peak value is calculated based on the difference.

Pulsed dc measurements provide the capability of measuring the weighted maximum or weighted minimum peak of pulsed dc signals (low duty cycle).

Fourier analysis techniques

Given the generalized approval to the measurements that have been utilized, it is apparent that a broad class of measurements may be viewed as nothing more than Fourier Analysis of arbitrary waveforms. If we can generalize and say that Waveform Analysis is a time-domain operation on a time series then it also follows that the following measurements are frequency-domain operations in the time series:

Distortion
Transfer function (network analysis)
Spectrum analysis

The key to all these measurements is the Fast Fourier Transform (FFT). The FFT is an algorithm which permits the fast solution of the Discrete Fourier Transform. The Discrete Fourier Transform of the time series $F(nt)$, is represented by

$$F(k\Omega) = \sum_{n=o}^{N-1} f(nt) \exp(-j\Omega nkt)$$

where $\Omega = 2\pi/NT$ and T is the period of the time series; N is the total number of samples taken over T; and k denotes the k^{th} element in the series.

The result of performing an FFT on a time series is a complex array, $F(k\Omega)$, where each element represents the real and imaginary part of the spectrum at harmonic values of Ω.

Since the FFT preserves both phase and magnitude information of the signal, the technique is inherently more powerful than other techniques of spectrum analysis. It also follows that the estimation of the period, T, becomes a most significant parameter in the generation of the time series and transform. In the design of the measurement system, RCA successfully mastered this problem and was able to utilize Fourier Analysis in the testing of complex modulated communication waveforms.

Distortion

Harmonic distortion is calculated from the spectrum using FFT as follows:

$$D^2 = [\sum_{i=2}^{\infty} A_i^2] / A_1$$

where A_i represents the amplitude of each harmonic and A_i is the amplitude of the fundamental.

To insure a high degree of accuracy, the measurement routine first makes a frequency measurement on the signal to determine the fundamental. Sampling intervals are calculated from this frequency measurement.

Transfer function

Network analysis is performed utilizing complex impedance and transfer function measurements. Impedance measurements were explained earlier. Transfer function measurements are derived from the spectrum as follows:

$$G(\Omega) = [|F(\Omega)| / |R(\Omega)|](\cos\theta + i \sin\theta)$$

Where $G(\Omega)$ is magnitude and angle of the transfer function at radian frequency, $F(\Omega)$ is the test signal, $R(\Omega)$ is the reference signal, and θ is the phase shift.

Spectrum analysis

Since all Fourier analysis is spectrum analysis, the measurement technique is obvious.

The measurement sampling rate is calculated based on the bandwidth, frequency and S-line frequency. The output array is a logarithmic power spectrum formed by calculating the sum of the squares of the real and imaginary Fourier coefficients at each spectrum frequency. Each array member is represented in dB, where 0 dB is a full scale reading and −90 dB is the minimum discernible signal. Thus, all array members will be between 0 dB and −90 dB.

Since the signal-to-noise ratio of each sample is proportional to the square root of the number of measurements, increased sensitivity is afforded by what is effectively digital filtering. This technique obviates the need for swept bandpass filters since the filtering is being done by software. In this manner, a sensitivity of −70 dB_m is reached over a 500 MHz bandwidth.

It must be noted that effective use of this technique requires that, for any modulated waveform, the modulating signal and carrier must be phase synchronous.

Conclusion

Although this article has been a brief and somewhat simple description, the reader should, however, be aware of the tremendous potential of so versatile a system. He undoubtedly has thought of solutions for other measurement problems which justifies the "expansion via software algorithm" theme we established as our original goal.

Acknowledgments

The author would like to thank the many dedicated engineers and support personnel for their contributions which developed an idea into reality. I would like to especially acknowledge the efforts of Mr. Fred Schwedner and MR. Eldon Sutphin, without whom a rough road may never have been trod.

Automatic test equipment interface

N.B. Wamsley

The development of the programmable interface unit, which interfaces the automatic test equipment with the unit under test, was a major factor in extending the versatility of third-generation automatic test systems. Previously, complex and costly adapter boxes were required to connect individual units being tested to the automatic test system. System capability and cost considerations highlighted the need for an interface that could handle a wide variety of units to be tested without an inventory of custom adaptors.

N. Bruce Wamsley, Mgr., Design Engineering, Government Communications and Automated Systems Division, Burlington, Mass., received the BSEE from West Virginia University in 1951. He has continued his education by taking courses at: the University of Pennsylvania, MIT, Rutgers, West Virginia University and Northeastern University. His present assignment is Design Manager for EQUATE and EQUATE-related automatic test systems. Mr. Wamsley joined RCA, Camden, N.J., in 1951 where his first assignments were in the design of various circuits for infrared applications. Mr. Wamsley then transferred to RCA's automatic test group where he has become proficient in both the detail and system considerations of modern automatic test equipment. He directed the design of the stimulus portion of the MPTE and integration and installation of the SCDEE at Tobyhanna Army Depot. His assignments in the MTE Program included the technical requirements analysis, black box design, factory follow, integration, and test of all three MTE shelters. Mr. Wamsley then took over the DIMATE Program which culminated in successful installation at Tobyhanna Army Signal Depot in October 1966. He was responsible for DIMATE II which was installed at the Sacramento Army Depot in August of 1967, the DIMATE III which was installed at the Lexington Army Depot in November of 1969, and the DIMATE IV which was installed at Tobyhanna Army Signal Depot in September of 1969.

Since the late 1950's, RCA has designed and built automatic test equipment (ATE) such as the Multi-Purpose Test Equipment (MPTE) and Digital Evaluation Equipment (DEE), Multi-system Test Equipment (MTE) and Depot Installed Maintenance Automatic Test Equipment (DIMATE). Although advanced for their time, they had the stimulus outputs and measurement test points hard wired to dedicated connectors, thereby requiring a test adapter for each unit under test (UUT). Many of these adapters were small and simple; however, some were large and encompassed complicated circuitry, creating an increased maintenance load.

When the Land Combat Support System (LCSS) was designed in the early 1960's, the interface problem was attacked. A significant improvement was realized through the patchboard approach. In this approach, all stimulus outputs and measurement test points were brought out to a patch panel. By judicious slection of UUTs, one patch box adapter could be configured that would interface with up to four or five UUTs.

In the early 1970's, EQUATE — a third-generation ATE — was developed. Fig. 1 shows graphically the basic differences. In the conventional approach, both inputs/outputs are fixed; in the EQUATE appraoch, only the UUT inputs/outputs are fixed. A major improvement in this generation of ATE was the successful, practical implementation of the Programmable Interface Unit. This programmable ATE/UUT interface which is a generalized solution to the problem. Such an interface greatly reduces the cost of external adapters at the cost of increased ATE hardware.

The Programmable Interface Unit (PIU) was configured as a set of universal test points, plus associated buffers and multiplexers to perform three basic tasks:

- Generate and/or route analog and digital stimulus to the appropriate UUT pin or pins.
- Condition and route analog and digital measured data from the appropriate UUT pin or pins to the ATE measurement subsystem.
- Apply programmable loads at the appropriate UUT pin or pins.

In addition, the PIU contains probes and discrete connectors for routing rf signals (above 10MHz) and high current (above 2 A/pin) as required.

Universal test points

This concept is shown in block diagram form in Fig. 2. Each universal test point is identical in design, and consists of a single printed-circuit card (see Fig. 3). Hence, the overall design of the Programmable Interface Unit is flexible, in that numbers of universal test points may be added or deleted as required in order to create ATE systems capable of testing large or small equipments.

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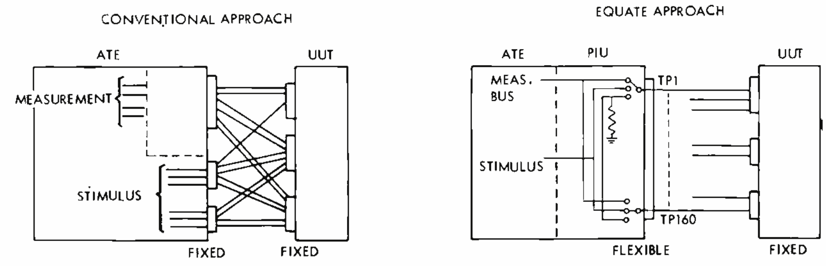

Fig. 1 — Comparison of conventional and third-generation (EQUATE) interfaces. With conventional ATE, inputs and outputs were fixed; with EQUATE, the input and output connections to the unit under test are fixed, but the stimuli, measurement data, and loads are switchable via computer control.

Analog stimulus

For analog stimulus, the Programmable Interface Unit (PIU) acts merely as a routing mechanism, whereby the proper stimuli, generated within the ATE, are routed, either singly or in combinations to the appropriate UUT pin or pins. Based on past experience with the stimulus requirements of hybrid (analog and digital) UUT's as well as on the capabilities of the ATE system, the following analog stimulus buses are routed to all UTP's:

- Five separately programmable dc stimuli (both hi and lo brought out on separate buses).
- Three-phases and neutral of a programmable ac power supply.
- Two-pulse generator stimuli (main and delay pulse).
- One arbitrary waveform generator.
- Three phases of a synchro generator.
- One ac/dc standard.

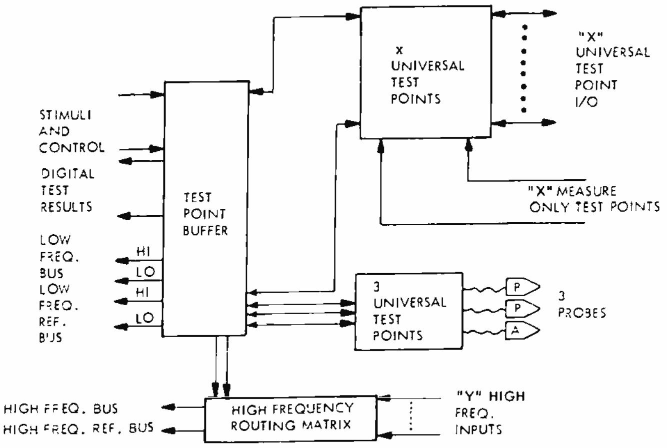

Fig. 2 — Programmable Interface Unit — a set of universal-test-point printed-circuit cards.

Analog measurements

All analog measurements below 10MHz, and at amplitudes up to ±200V, are made through the PIU. A measurement buffer/attenuator on each universal-test-point card will be used to buffer and condition the signal as required before routing it to the measurement subsystem. Each test point is connected via a set of relay multiplexers to any of four measurement buses, as illustrated in Fig. 4. MUX "A" consists of four separate 16-to-1 relay trees, and services up to sixteen universal test points (UTPs). There are four "B" MUX's, each a 16-to-1 relay tree, which multiplex the outputs of all "A" MUXs onto the four measurement buses. Hence, the output of UTP K can be programmably routed to BUS #1, UTP K + N to BUS #2, UTP K + M to BUS #3, *etc.*

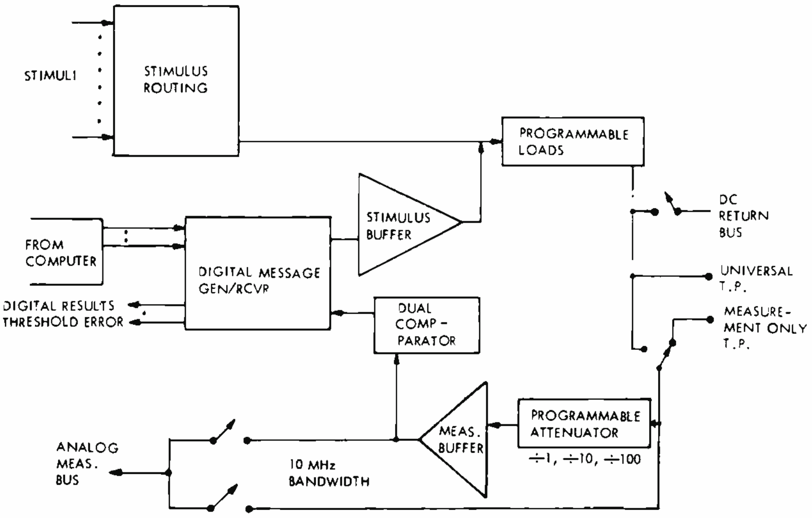

Fig. 3 — Universal test point. Each UTP consists of a relay matrix for stimulus routing, a one-bit slice of a digital message generator/receiver, programmable loads, measurement and stimulus buffers, and a dual voltage comparator (for threshold error detection).

Digital stimulus/response

The concept of a Programmable Interface Unit consisting of a number of identical UTP's presents a unique opportunity to eliminate a discrete digital message generator/receiver. Instead, one slice of the message generator/receiver is placed on each UTP board. This provides an optimum configuration for noise immunity, crosstalk, and skew. Fig. 5 illustrates a typical digital test setup, utilizing three UTP's.

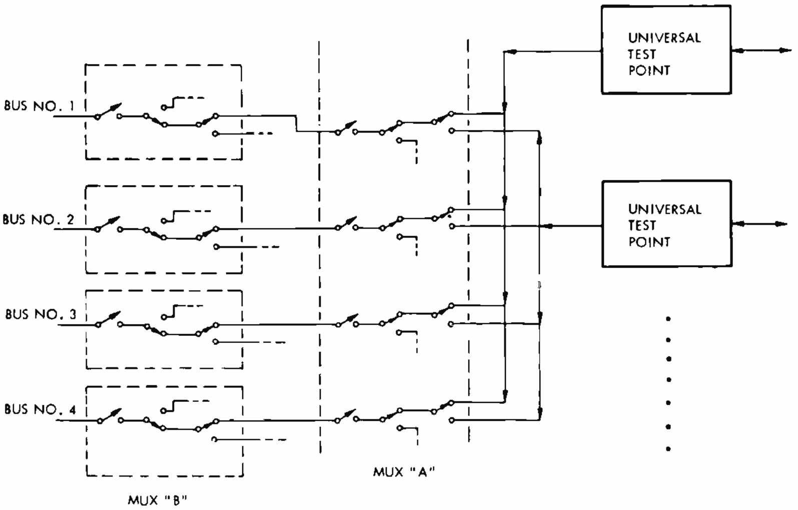

Fig. 4 — Analog measurement routine with the Programmable Interface Unit.

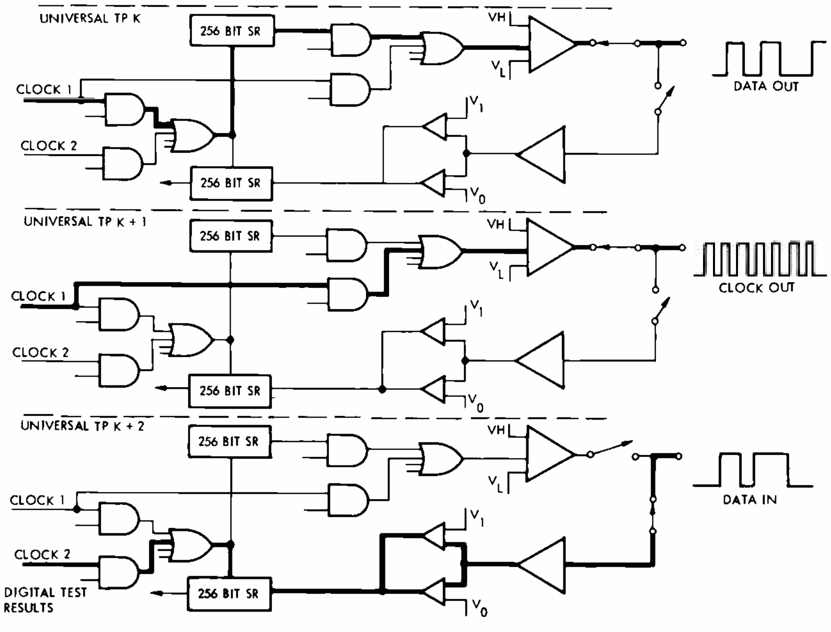

Fig. 5 — Digital stimulus/response with the Programmable Interface Unit.

Digital responses are routed to the computer for evaluation, using a set of 16-to-1 digital multiplexers. In addition, threshold error detection is utilized on each UTP board, and a flag set upon detection. These flags may be examined by the computer, using the same digital multiplexers.

The stimulus buffer is capable of buffering all digital and clock outputs from the 256-bit shift register used as the digital message generator and receiver. This buffer consists of a programmable level shifter, covering the range from −6 to +6Vdc, with a slew rate of 250 V/µs, or covering the range from −30 to +30Vdc, with a slew rate of 100 V/µs.

As a source of sink, the stimulus buffer is capable of up to 100-mA operation. Using the programmable voltage levels V_H and V_L, the stimulus buffer is capable of generating logic levels from −6 to +6Vdc in steps of less than 5 mV, or −30 to +30 Vdc in steps of less than 25 mV. As a source of digital stimuli, the buffer is capable of transmitting data at rates greater than 10 MHz.

The measurement buffer is capable of handling input signals of up to ±150 V in amplitude. The circuit consists of switchable attenuators (÷ 1/ ÷ 10/ ÷ 100) feeding a very high speed (slew rate 1500 V/µs), high-input-impedance unity-gain buffer. Overall loading is greater than 1 megohm, with less than 80-pF capacitance. Bandwidth of this buffer is greater than 10MHz. As shown in Fig. 3, it is possible to programmably bypass the measurement buffer whenever unbuffered measurements must be made.

The output of the measurement buffer may be programmably routed to the shift register when receiving digital data. Before reaching the shift register, however, it is first passed through a dual voltage comparator, whose upper and lower voltage limits are controlled by the V_{min} "1" and V_{max} "0" voltages. Thus, it is impossible to check high and low logic voltage levels in steps of:

1 mV to ± 1 Vdc
5 mV to + 5 Vdc
10 mV to ± 10 Vdc
50 mV to ± 50 Vdc
100 mV to ± 100 Vdc
500 mV to ± 500 Vdc

The 256-bit shift-register chip forms a single slice of an *n*-bit digital message generator/receiver distributed over all *n* UPT's. This device performs the following functions:

1) Output a static parallel signal which, in conjunction with other UTP's, could mean a static parallel output word of up to *n* bits.
2) Output a clocked parallel signal, clocked by either the main pulse, delayed pulse, or external clock, at rates of up to 10 MHz.
3) Output a serial stream of up to *n* bits, either as a burst or continuously recirculated, at a data rate greater than 2.5 MHz, clocked by the main pulse, delayed pulse, or external clock.
4) Input a parallel signal, either static or clocked at up to 10-MHz rate.
5) Input a serial stream of up to *n* bits, clocked by either the main pulse, delayed pulse or external clock, at rates of over 2.5 MHz.

Finally, it should be noted that the switching configuration of the UTP is ideally suited for self-test and calibration, since any of the stimulus outputs can be routed to the measurement inputs without the need for any external connections.

Programmable loads

In addition to its stimulus and measurement capabilities, the Programmable Interface Unit contains the capability of applying a programmable load resistor at any UUT pin, using one or more UTP's. To accomplish this, each UTP board contains five resistors, which permit any one of 31 resistance values to be connected, either in series or shunt at the pin. A shunt-to-dc return (up to 5 A) or open circuit is also possible. Unused stimulus buses may be assigned as common buses to achieve even more versatility.

Test probes

Three probes are available for use by the test operator; these can be connected to UTP's so that the probes themselves become programmable in function. They may accept ac or dc voltages to 200 V, analog waveforms to 10 MHz for frequency or time-interval measurements, or digital data to 10 MHz. In addition, they provide all of the stimulus capabilities of the UTP, so that signals may be injected as well as measured at internal test points. Note that with two probes, dual-channel time-interval measurements, as well as stimulus/response testing, are possible. The third probe is an active device, used when making extremely low voltage measurements (down to 100 µV). This provides the capability of amplifying such low-level signals prior to introducing them into the ATE routing environment.

Acknowledgment

The design and fabrication of the initial PIU required the contributions of many people; however, special thanks should go to Mr. Jack Klein, Mr. Knowlton Miller, Mr. Richard Percoski and Mr. Barry Bendel.

Systems software for automatic test

J.E. Fay

An ATLAS-based software system has been designed by GCASD in Burlington, Mass., for adapatability to a wide range of automated support systems. Advanced software design techniques were employed to achieve reliable and maintainable software. The implementation language was a high-level structured algorithmic language. Structured programming techniques were used and proved to be remarkably effective. All software executes on the test system minicomputer. A translation program and a fault-isolation program are supplied to accept and implement digital tests produced by an automatic test generation system. To date, the system has been successfully used to test communications and radar systems to 18 GHz, ground support and prelaunch checkout of space satellites, and systems with programmable interface units for module and printed-circuit-board testing.

EQUATE was a significant departure from previous ATE architecture, providing only the basic elemental functions in hardware and relying on the software for functional expansion.[1] This is in marked contrast to the conventional ATE design where the computer was essentially no more than an I/O processor for a large collection of hardware building blocks.

As an I/O processor, the computer was often idle waiting for a building block to perform a measurement conversion. For reasonable accuracies, analog circuits in the building blocks had to contain filters characterized by long response time. EQUATE puts this idle processor time to more productive use. Waveshapes are digitized directly by high-speed sampling circuits. Measured values are obtained through software algorithms that use advanced sampled-data parameter estimation and fast-Fourier-transform techniques. Stimulus waveforms are also produced by digital logic circuits and memory driving high-speed D/A converters. The software that performs these functions is an interesting topic in itself, but this paper will be devoted to the design of systems software for ATLAS-based automatic test systems.

The original EQUATE application was Quality Assurance testing of communications equipment. EQUATE was designed, however, to serve as the prototype for a new generation of automatic test systems with much wider applications. Systems software design had to reflect this wider goal.

The test programming language had to be easy to learn, easy to use, and widely accepted. Adapted ATLAS was an obvious candidate language, but others were considered as well. The language translator had to be quick and efficient and yet had to produce test programs that execute rapidly. Diagnostic messages had to be specific and meaningful. The test executive system had to support an interactive debugging environment to handle the special problems associated with validation of test programs.

In addition to these requirements which reflect user needs, we also had to produce systems software that was reliable, maintainable, and which could be readily adapted to widely varying hardware configurations (e.g., single processor/single station, single processor/multistation, and multi-processor configurations). These tasks — adaptation and maintenance — could be assigned to any competent systems programmer who would not necessarily have been a member of the original design team.

All of these requirements have been met by the ATLAS software system which has been successfully applied to EQUATE — also to a multiprocessor system used for factory and prelaunch checkout of space satellites, and to a hybrid module tester with a programmable interface adapter.

Software system

The ATLAS software system consists of

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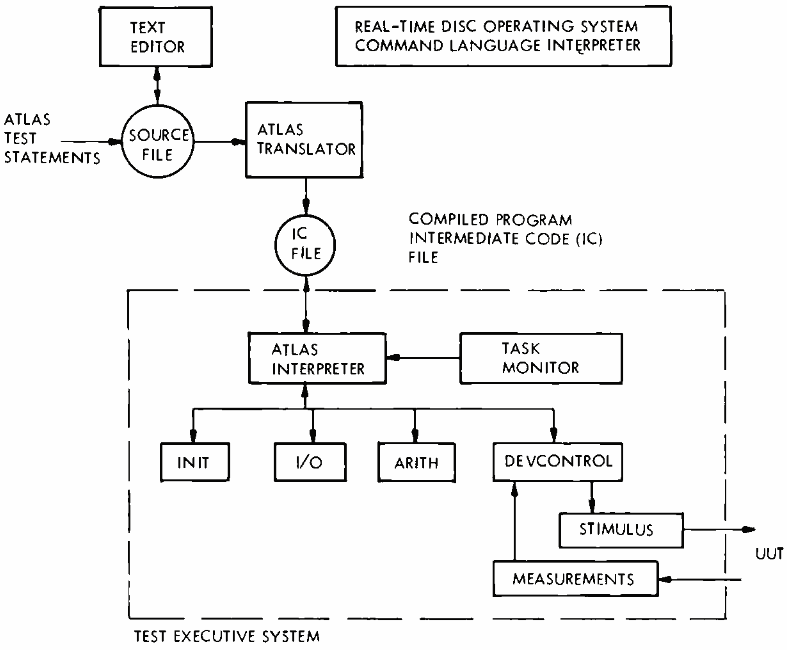

Fig. 1 — Software system organization.

four major components. One is a text editor used to create and modify programs. The second is an ATLAS compiler which accepts as its input, ATLAS source statements and generates code as its output. The third element is the test executive system which takes the code generated by the compiler and goes about the test sequence based upon these instructions. The fourth component is the operating system, under which all of these programs execute. The operating system handles all I/O providing file/device independence at run time. It also manages dics memory, maintains program directories, and provides the scheduling and resource allocations in multitask environments. This software organization is illustrated in Fig. 1.

It sould be realized that this is not the only practical software system organization. Succcessful systems have been based on other architectures using interpreters (ATLAS or BASIC), conventional on-line compilers using a linking loader (FORTRAN), or off-line compilers using an interpretive run-time system (VITAL). There seems to be a growing consensus that the off-line systems which require a support computer are ineffective because they cannot support the interactive environment needed to validate test procedures. In fact, an on-line MINI-VITAL has been developed to overcome the limitations of the original VITAL concept.

The software system is based on many years of experience in the design of automatic test systems, but like most successful software projects, it was the product of a very small dedicated group of systems programmers. Our basic philosophy was to provide a programming system that was easy to use so that test engineers or technicians who had never written a computer program before could write effective test procedures. This had to be accomplished without placing unnecessary restrictions on an experienced user.

Our earlier experience with off-line compilers indicated that systems which attempt to track program flow, and resolve equipment conflicts at compile time, are not suitable for conversion to on-line use. A true interpreter from the ATLAS source language appeared to be the ideal approach for a test system dedicated entirely to test program development. However, totally interpretive systems must perform statement analysis and symbol table searches each time the program is executed and such overhead is extremely wasteful during normal test program use. It was clear, however, that the use of an interpreter greatly simplified the problems of equipment conflicts and parameter range checking since it is a trivial task to maintain the status of the automatic test system while a program is being executed.

The solution to this conflict of requirements was to provide a compiler which performs a rapid conversion of the ATLAS source program to an intermediate code and, at the same time, checks statement syntax. The intermediate code is a machine-independent code suitable for direct execution by an interpreter which controls the test system, maintains its status, and checks for equipment conflicts.

The RCA compiler-interpreter software is a system incorporating the best features of two basic systems: the conventional compiler and the interpreter. This combination results in optimum system performance encompassing the translation speed, diagnostic capability, and debugging aids inherent in an interpretive system and the execution efficiency of a compiler supported system. Features troublesome to the test designer have been eliminated, e.g..

- Limitations on program size through use of a virtual memory.
- Knowledge of file locations.
- Mandatory statement numbering.
- Prefixed branch terminations (the ATLAS B flag).
- The decoding of error messages.
- Designation of statements to be saved for later reference (S flag).

In addition, the system enhances the use of standard user library procedures, allows direct storage of unlimited variables and arrays, and simplifies the formatting of output messages and the use of device statements.

Language adaptation

ATLAS was chosen because it has achieved wide acceptance for preparation of test procedures. ATLAS, as defined by ARINC Specification 416, is more of a publication language than a programming language. It is intended to be a machine-independent language and great pains were taken by the committee that designed it to be sure that no constraints were placed on the implementation of test system.

However, a present limitation of ATLAS is the lack of convenient structrues for expressing algorithms (no loop control, no if-then-else construct, and no block structure). However, RCA and other manufacturers are continuing to work through the ARINC committee to initiate improvements in the language. Also, we expect any forthcoming standard test languages to be significantly influenced by ATLAS concepts.

The principal factor governing selection of an appropriate subset of ARINC ATLAS is the need for efficient translation on a minicomputer. Essentially, this means selecting statements suited to context-free translation in one pass over the source code. Unavoidable context dependencies, such as equipment conflicts, are resolved by the run-time interpreter. For these reasons, such things as the S flag, the ALTER verb, and PREPARE-EXECUTE were not implemented. Other elements of ATLAS (e.g., the SYNC-WHEN statement) were not implemented because there were no plans to introduce hardware capable of performing the intended actions.

After selecting a workable subset of standard ATLAS, it is necessary to add extensions to adapt to the capabilities of the test system and cover shortcomings of the ARINC specification. The RCA-adapted ATLAS provides the following extensions and adaptations:

- Statements are free field.
- Test numbers are optional.
- Arithmetic exressions can be used wherever a variable or constant is allowed.
- All noun-modifiers can be run-time variable.
- All connections can be run-time variable.
- File I/O is provided.
- Device identifiers can be appended to the nouns.
- Measured characteristic includes a storage label and dimension identifier.
- Fifteen digit precision for numbers and math. functions.
- Picture format output (e.g., "loop gain = ###E##").
- Ability to include text from another source file at compile time.
- Linkage to another ATLAS program at run time.
- Input format conversion for run-time variables:

  Engineering notation (1.414E-6)
  Binary (101010)
  Octal (77777)
  Hexidecimal (FFFF)

The compiler program was developed specifically for ATLAS and is not based on adapting an existing compiler (FORTRAN or Dartmouth BASIC for example) to ATLAS syntax. Thus, we are not constrained to a specific language format or structure, and expect to add the elements of structured programming as soon as some reasonable standards are established.

Test system tables

As discussed previously, a primary objective was the support of a broad-based ATE product line. The RCA ATLAS system provides a general purpose programming language base, plus the facility to add test system oriented extensions to the language. This extensibility is in the form of a generalized syntax checking procedure in the compiler, and a disc-resident table which specifies the syntax (within certain constraints) of the test system extensions. Language definition tables are constructed for each distinct test equipment configuration.

A macro-assembler is used to construct these tables from ASCII source using special macro-definitions. Device statements for stimulus and measurements comprise the largest portion of the tables; but, in addition, the table also contains an identifying header to be printed in UUT program listings, a list of testable conditions for GO-TO and WAIT-FOR statements, and a list of acceptable noun-modifier dimensions and dimensional unit conversion factors.

Although tables are disc resident, they are accessed by virtual memory techniques which provide table-searching efficiency approaching that of a core-based table.

Design of the interpretive code

The object code generated by the ATLAS compiler is a machine independent code optimized for automatic testing. It is designed to express test instructions compactly and efficiently while avoiding the usual limitations of a minicomputer instruction set. The object code is loaded into a random access disc file which serves as a virtual memory for the test program. This file provides a byte-addressable memory space for both instructions and data.

Most of the instructions consists of a one-byte operation code with no arguments. These instructions perform operations on the top elements of a push-down stack maintained by the run-time system. Memory reference instructions are followed by a three-byte address field to provide 24 million bytes of directly addressable virtual memory. This is more than sufficient for the largest practical test program.

Other operations require one or more addresses or fields of intermediate data, and are used for literals, branching, procedure calls, and to pass line numbers and test step numbers to the run-time interpreter. This last item was needed to implement validation aids that are keyed to lines and test steps in the original ATLAS program listing. This feature, combined with a fast on-line ATLAS translator, encourages users to think and work in the source language. We do not expect any users to patch the intermediate code, or to even understand its construction or operation.

One of the operation codes specifies data to be passed to routines that control test devices. This formalized linkage to run-time routines can also be used to call routines that perform special functions not related to device control, but which are frequently used or which cannot be conveniently expressed in ATLAS. The format of the call to run-time routines is as follows:

```
OPCODE
BYTECOUNT
DEVCODE
VERBCODE

MIN     }
NOM     }  First noun-modifier
MAX     }
ERRLIM  }

•       }
•       }  Second noun-modifier
•       }
```

The device code and verb codes are one-byte long, supporting up to 256 device routines with up to 256 verb actions. For each noun modifier, one-byte pointers indicate the location of the values on the stack. In addition to instructions and data, the intermediate code files also contain a table of permissible step-number entry points.

ATLAS translator program

The compiler that translates ATLAS statements to intermediate code is organized as shown in Fig. 2. It consists of a main segment, which dispatches control to separate processors for each verb type, and a set of supporting routines. These routines perform basic compiler functions: lexical analysis, arithmetic expression analysis, symbol table manipulations, and virtual memory management.

Lexical analysis

The structured environment for the statement processors contains a number of significant nucleus procedures. Procedure LEXEME is perhaps the most important. LEXEME reads the source program as a sequence of lexical elements consisting of keywords, labels, literals, and miscellaneous characters. Two tables direct the lexical scan: one partitions the ASCII character set into disjoint groups, the second is a finite-state-machine-transition table.

The current state and character group determines a state transition. Each transition has an associated action. Eventually a terminal state is reached and the lexical element and its type is returned to the calling program. Macro expansion is performed by the LEXEME procedure. For each label, the symbol table is checked to determine if the label represents a macro definition. Macro expansion is invisible to the program which called LEXEME.

Arithmetic expression analysis

Expression analysis is performed by procedure AE. The analysis is governed by an operator table and a set of simple evaluation rules. The expression is processed in a single left-to-right scan with intermediate code generated as the analysis proceeds. Each operator has an evaluation precedence and a bounded-context indicator. The context indicator specifies whether everything to the left and the right must evaluate to an expression. Variables, parentheses, and functions are treated as operators and also have a precedence order and context indication.

A literal or variable is simply a trivial arithmetic expression. The ATLAS statement processors call AE whenever the syntax allows a number or a variable. Thus, an exprssion may also be used to define a noun-modifier value or connection value (e.g., VOLTAGE 'Y' * SQRT ('X') V).

Virtual memory management

Fetch and store operations to virtual memory are handled by procedures in the Virtual Memory Management (VMM) program. A large number of core buffers are maintained for efficient operation (usually as many as will fit in available memory). Each buffer is one disc block in length for efficient swapping. VMM keeps track of each buffer access and flags any buffers that were modified by a store operation.

The virtual memory program is designed to support access to any number of disc files at a given time. The compiler program, for example, uses it for accessing both syntax-definition tables and its object-code file. When the I/O channel providing virtual-memory access to a file is closed, the VMM program will flush all modified buffers associated with the channel number to the disc to ensure that the disc-resident copy contains all of the changes that were made to the core-resident segments.

ATLAS test executive system

The executive system provides all run-time functions needed to run test programs in both an interactive mode for debugging and validation, and also in a non-interactive mode for final programs. Like the compiler, the run-time system is modularly structured about a core system that provides the basic programming functions such as input/output and arithmetic expression evaluation.

Multi-station test executive organization

The ATLAS multi-station test executive system is modularly organized, consisting of a task monitor, test station executives, and common re-entrant subroutines. The control of each test station is handled as a task within a multitask program environment. A task is defined as a logically complete asynchronous execution path through the user address space demanding use of system resources. The resources shared by the tasks include peripheral devices for I/O, memory for system and user overlays, or simply CPU control. Only one task may receive CPU control and the desired resource at any single moment. This allocation is awarded to tasks according to their priority and readiness to use the resources. The task monitor governs the transfer of control to each task.

The organization of the multi-station test executive system is illustrated in Fig. 3. The system contains the following major functions:

Task monitor — This function assigns system resources to the test-station control tasks. At any given time, each task may be in one of four states: dormant, suspended, ready, and executing. A *dormant* task is one that has not been activated or one that has terminated. A *suspended* task is one that is

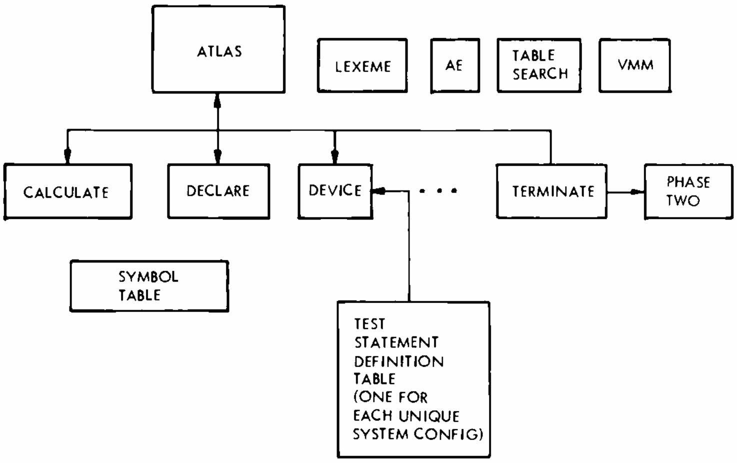

Fig. 2 — ATLAS compiler organization.

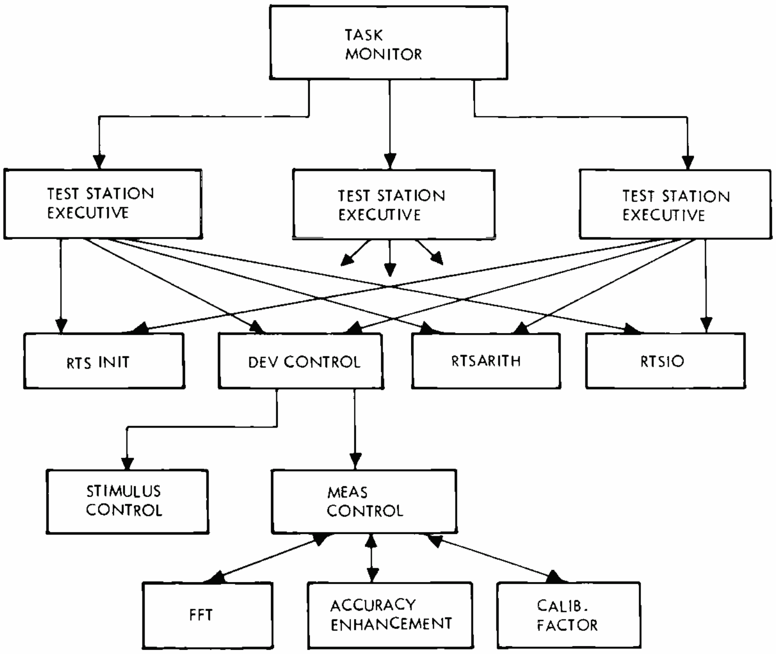

Fig. 3 — Multi-station test executive system.

not ready to proceed because it is waiting for I/O, a time delay or some external event (such as measure complete). A *ready* task is one that can proceed when given control of the processor. The task scheduler gives control to the highest priority ready task. If more than one task has the same priority, control is given to each task consecutively in round-robin fashion. An *executing* task retains control of the processor until it has completed or it relinquishes control by issuing a system call for I/O, overlay load, or programmed delay. The task scheduler receives control at each system call and in turn assigns control to the next ready task. State variables and stack pointers for the task being suspended are saved by the task scheduler.

Test station executive -- This function controls testing operations at the test stations. There is one executive control task for each test station. A command interpreter interacts with the operator to determine the name of the unit under test, program entry point, and operating mode (a program validation mode is available for use at program development centers). The station test executive performs the test procedures by interpreting operation codes and associated parameters from a copy of the intermediate code file generated by the ATLAS language translation. Interpretation of the operation codes results in subroutine calls to the common re-entrant routines,described below:

Initialization (RTSINIT) — This function performs initialization when a test station is activited. It determines the UUT program name, entry point, and test station operating mode. The necessary system files are allocated and opened.

Input/output (RTSIO) -- This function contains the interpreter logic for ATLAS I/O statements. It performs these operations via system calls to the operating system. All I/O to standard peripherals is handled by RDOS routines operating in a priority interrupt environment.

Arithmetic (RTSARITH) — This function performs evaluation of arithmetic expressions. Standard floating point interpreter routines are used in systems that do not include the hardware floating point processor.

Device control (DEVCONTROL) - This function provides a common interface between ATLAS test-device-control statements and the handler routines for each type of test equipment.

Stimulus device control -- The interpreter logic and device control logic are grouped into subsystem-oriented functions to optimize use of common routines. One set of related routines handle, for example, power supply programming for all test stations.

Measurements This module handles the voltage samplers, frequency sampling unit and data processing functions needed to interpret measurement statements. The number and spacing of samples is computed for the data measurements. Special subroutines develop values for dc, ac, rms, peak, etc. The Fast Fourier Transform (FFT) is used for distortion, spectrum analysis and other related measurements. Averaging techniques provide enhanced accuracy. If the optional ac and dc standards are included, calibration factors are applied to remove offset and nonlinearities.

Automatic test program design system -- For digital logic circuits, EQUATE provides a fully automated test program design system. The test programmer enters a model of the circuit that specifies connections between standard elements. (such as NAND gates, FLIP-FLOPS, etc.). Stimulus patterns are developed automatically for an unknown circuit or can be entered directly if already known. A fault simulator determines no-fail response and responses in the presence of logic failures. The stimulus patterns, response patterns, and fault isolation data are written to magnetic tape which is loaded onto EQUATE disc files. The patterns are applied and responses saved and analyzed via a single ATLAS statement. The measured responses are compared to expected responses. If a failure is detected, the ten most likely causes are computed and printed out along with the probability of each being the observed failure. This procedure accounts for multiple failures and non-logical failures such as solder bridges between logically unrelated elements.

Summary and conclusions

The software system described in this paper has been in extensive use for the past two years. It has been extremely reliable with very few program bugs discovered by its users. Throughout this time, the system has gone through a series of evolutionary changes which have added new capabilities and improved performance. The few problems reported by users were typically resolved on a same-day basis. This high degree of reliability and maintainability is largely attributed to the use of advanced software development techniques employing top-down design and structured programming. The current state of development is such that new users can expect to receive error-free software and will not experience the software maintenance problems typical of systems developed with the old techniques.

Acknowledgments

The software system design described in this paper is the end product of the dedicated effort of many people. The author wishes to extend acknowledgments to the principal contributors: Lloyd Dickman for his work on the compiler lexical and arithmetic expression analysers; William Neumann for his work on noun-modifier decision logic in the language-definition tables and for his work on implementation of computer-aided test-program design for digital logic; Fred Schwedner for his work on run-time routines for measurements; and Anthony Vallance for his work on compiler design and run-time routines for the stimulus generators.

Reference

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Automatic testing of engines and machinery—an overview

R.T. Cowley| L.R. Hulls

The sophistication of aircraft, land-based vehicles, and machinery in general has reached the point where it taxes the skill and resources of the personnel available for maintenance. A prequisite of efficient maintenance is the ability to rapidly diagnose and isolate malfunctions. To meet this requirement, the Government Communications and Automated Systems Division at Burlington, Mass., has developed test systems for such non-electronic equipment as gasoline and diesel engines, gas turbine accessories, and hydraulic components. A long and successful history of developing ATE systems for electronic equipment was the original technical base. In considering mechanical ATE, it is not sufficient to draw an oversimplified parallel with ATE systems for electronic equipment. The nature of machinery and its failure modes are sufficiently different from those of electronic equipment that we must examine the problem in some detail before useful conclusions can be drawn.

MACHINERY TESTING falls into three basic categories:

1) Calibration and adjustment
2) Performance
3) Diagnosis

Examples of Category 1 are the testing of fuel controls for turbine engines and carburetors for reciprocating engines. Engine test cells are examples of the performance test, although it is not unusual to find calibration, adjustment, and performance testing combined when the engine is adjusted in the cell prior to the final performance test.

Diagnostic testing is associated with the maintenance function where fault diagnosis and isolation are prerequisites to establishing the appropriate maintenance action. Often, a performance test is a preliminary to diagnostic testing. Maintenance may also involve calibration and adjustment testing as, for example, in the spark-timing adjustment required in the servicing of a gasoline engine. Thus, it will be noted that although there are clear functional differences between the three categories of testing, many practical test situations involve more than one kind.

Automatic testing techniques will normally be applicable if there already exists a manual test precedure involving extensive instrumentation and an involved but well-defined test sequence. These are the applications where we can logically predict a significant improvement in product quality, as well as a dollar savings. Gas-turbine fuel controls, variable-displacement hydraulic pumps, and carburetors for gasoline eninges are typical examples. The existing manual test procedures have provided the basic data for a functional specification of these automatic test systems. The designers do not have to possess detailed knowledge of all the internal operating characteristics of the equipment that is being tested.

The ATE system can thus be defined in terms of stimulus, measurements, and control. This involves pressure, flow, temperature, velocity, position, and other mechanical phenomena. However, a word of caution is appropriate. Experience has taught us that a man performing a complex manual test procedure does not always follow the test procedure laid down in the technical manuals. Failure to recognize this has led to difficulties in producing the final application test programs. This can be avoided only by careful validation of the manual test procedure prior to proceeding with coding.

In comparison with calibration and performance test systems, development of a diagnostic test system is significantly more difficult. Few, if any, machine designers consider ease of fault diagnosis or test measurement accessiblity to be important design criteria. Frequently, there is no established test method or technique available, and success has been a function of the individual skill and experience of the mechanic. The ATE designer is faced with developing the basic test procedure, as well as designing the test system hardware and software. This, in turn, requires that he possess a detailed knowledge of the unit to be tested — unlike his counterpart, who is designing calibration, adjustment, and performance test systems, where detailed manual procedures are already established.

It is generally agreed by those responsible for maintenance that inability to diagnose a malfunction correctly results in time and money wasted by trial-and-error replacement of component parts. However, when trading off the cost of using automated diagnostic equipment against a manual system, it is often difficult to establish an accurate estimate of the savings. It is often impracticable to determine the diagnostic accuracy (or the cost of inaccuracy) currently being achieved.

The progress by RCA-Burlington in non-electronic ATE covers both the automation of existing test procedures and the development and automation of diagnostic tests to aid in the maintenance process.

The initial Automatic Test System for Jet Engine Accessories (ATSJEA), installed at Tinker Air Force base in Oklahoma, is a system which automates the existing calibration and performance testing of the main and afterburner fuel controls for the J-79 engine. The system, which went into production test in December of 1971, achieved the design goal of cost savings due to reduced test time. To date, the system has an almost perfect record of quality, and test system availability has exceeded 95%. Largely due to the success of this system, the customer has ordered expansion of the original system and an additional ATSJEA for installation at Kelly Air Force Base in San Antonio. A two-test-stand expandable ATSJEA system will be delivered to a Japanese firm, IHI, in mid-1975. The ATSJEA technologies are being applied to produce a ten-stand system for the U.S. Navy which will be used to calibrate and test a variety of hydraulic components.

Our current inventory of hardware designs and computer programs can solve most mechanical measurement and con-

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trol problems. Both hardware and software are available in modular form to permit RCA to offer a quick response to a potential customer's needs. Growth in the automation of existing test methods will closely track improvements in the new technologies which reduce the cost of ATE systems. The potential market will grow as the cost of ATE systems brings it within the range of favorable cost tradeoffs against exisitng manual systems.

A diagnostic test equipment for machines presents an entirely different picture from automating existing procedures. Neither the diagnostic procedure nor the technology for its practical implementation is usually available.

Inefficient diagnosis by parts replacement is often the mechanic's only alternative. The time-honored procedure of disassembly, inspection and test, piece-by-piece, is today still an unavoidable part of the maintenance procedure.

At RCA-Burlington, we have concentrated on developing diagnostic techniques for gasoline- and diesel-fueled reciprocating internal combustion engines. Initial success was obtained largely by applying recent developments in transducers, electronic signal processing, and computer software to in-vehicle diagnosis of accessory items. It was recognized in the early development programs that practical test techniques for the basic engine power-producing components would require an alternative to the conventional large and expensive dynamometer. In addition, the proper performance of the fuel, air, and ignition subystems can only be verified under load. This led to the development of electronic techniques to measure the horsepower of a gasoline or diesel enginer.

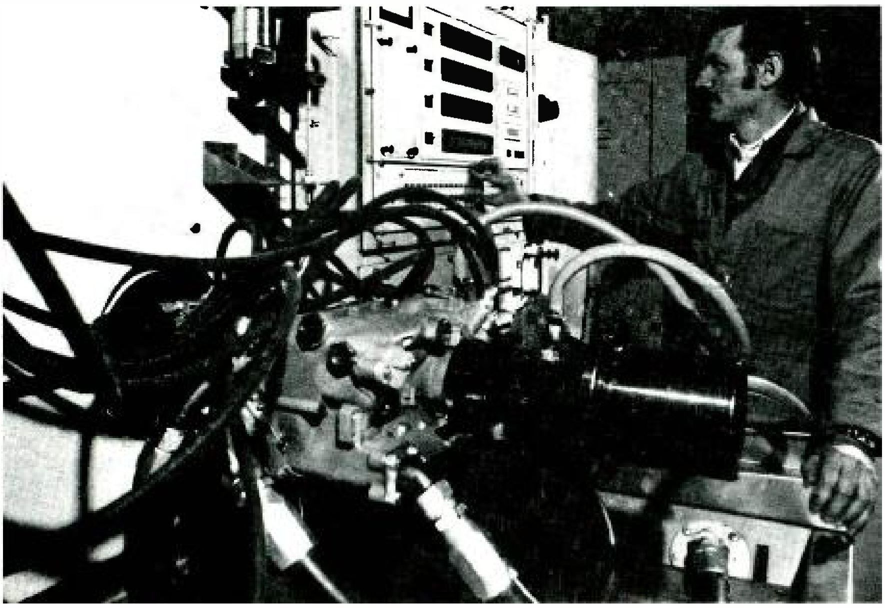
These techniques have been incorporated in two systems delivered to the U.S. Army. STE/ICE (Simplified Test Equipment for Internal Combustion Engines) is currently undergoing development tests at the Aberdeen Proving Grounds in Maryland. This system puts a modern measurement tool in the hands of the mechanic to run power tests and make the measurements needed for diagnosis of the most common failures on four different engine designs. This hand-held unit incorporates a programmable microprocessor which provides the flexibility for application to many different engines and vehicles. ATE/ICE (Automatic Test Equipment for Internal Combustion Engines) is a fully automatic diagnostic system programmed to diagnose most failures which prevent starting or affect performance of a 1/4-ton truck (Jeep) engine. In addition, it provides instructions and monitors the mechanic for proper visual inspections and tune-up adjustments. This system will undergo initial evaluation tests by the U.S. Army in mid-1975.

The R&D performed at RCA-Burlington on diagnosis of gasoline and diesel engines has resulted in 49 disclosures to date, for which 15 patents have been granted. Our techniques have been reduced to practice on a number of engine types and have provided solutions to a number of diagnostic problems which are of vital importance to efficient maintenance.

The key to the future growth of ATE for diagnosis of engines and machinery is the development of techniques which consistently and accurately perform fault identification and isolation. This will be achieved by engineers who combine a detailed knowledge and analytical understanding of modern machinery with skill in the design of electronic hardware and software. Providing an environment in which the engineer can acquire experience in these two disciplines — machinery and electronic systems — is essential to a profitable future in non-electronic test.

R.T. Cowley, Mgr., Government Communications and Automated Systems Division, Burlington, Mass., received the BSME from Iowa State University in 1950. Mr. Cowley joined RCA in 1961. From that time to the present, he has worked in ATE Engineering in a supervisory capacity. He was responsible for the design and development of various Apollo prelaunch test systems in addition to various ATE technique studies and contracts. Currently, Mr. Cowley is manager of non-electronic test engineering, which includes RCA's investment programs and contracts relative to the application of the ATE technology to the test and process control of mechanical systems. He has spearheaded the drive to make RCA a leading firm in the areas of turbine and internal combustion engine test and diagnosis.

L.R. Hulls, Government Communications and Automated Systems Division, Burlington, Mass., received the BS in Physics and Electrical Engineering from Manchester University, England, in 1944. His education includes post-graduate courses in servomechanisms from Manchester College of Technology; servomechanisms from Massachusetts Institute of Technology; Mathematics from Chelsea Polytechnic; Electrical Engineering from Southampton University; Physics from Stafford Technical College; Control Systems from Birmingham University, and, more recently, automation equipment at New York University. Mr. Hulls worked in England and Canada in the field of electronic instrumentation and control for over ten years. During his tenure as Section Chief in English Electric Company's Industrial Electronics Department, he was responsible for a variety of instrumentation and control projects including the development of electronic ignition analyzers for internal combustion engines. At Philco-Ford Corporation, he was section manager for vehicle engine diagnostic and checkout activity. He was responsible for performance on the Phase I contract for Army Tank Automotive Center (ATAC) diagnostic program. He also led research teams on diagnostic techniques. Mr. Hulls acted as consultant to the Ford Motor Company for the special dynamometer in their new Service Research Center at Dearborn. His other work includes the design of a computerized electro-hydraulic test stand for automatic transmissions. He joined RCA in January 1968. Mr. Hulls' projects at RCA include the demonstration of an automatic engine ignition analysis using the Army's LCSS equipment, the testing of diesel engines and high-speed gear trains using an RCA-developed accelerometer, and a pattern recognition analysis for inspection and life prediction of turbine engine bearings. He has also performed the major instrumentation systems design on an automatic test system for Jet Engine Fuel Controls for the J-79 Jet Engines — an Air Force project named ATSJEA currently under contract.



Automatic test system for jet engine accessories

R. Hartwell

The Automatic Test System for Jet Engine Accessories. (ATSJEA) provides a fully automated test facility for a wide range of jet aircraft fuel controls, pumps, and similar accessories. Computer-directed programs control, measure, record, sequence, and evaluate individual tests. In ATSJEA, RCA has applied highly advanced automatic test concepts to a non-electronic test environment, in which hydraulic and pneumatic flows and pressures, mechanical rotations, and physical linkages, are the principal elements to be exercised. Automation provides accuracy, repeatability, and reliability in testing not normally realized in manual systems, plus a four-fold increase in testing speed.

The original Automatic Test System for Jet Engine Accessories (ATSJEA I), installed at Tinker Air Force Base, Oklahoma City, in 1971, is dedicated to the production testing of J-79 main fuel and after-burner fuel controls on four hydraulic test stands which are connected to the central processor.

This article describes the design concepts of the ATSJEA II system now under contract for delivery to Tinker Air Force Base in Oklahoma City and Kelly Air Force Base in San Antonio, Texas. At Tinker Air Force Base, six test stands will be added to the existing ATSJEA facility. Although software improvements have been made, the programming at the unit under test program level remains unaltered. At Kelly Air Force Base, six test stands will be installed, along with a central processing unit identical in hardware and operational software to that at Oklahoma.

Significance of ATSJEA technology

As an automatic test system, ATSJEA uses a number of advanced programming concepts. The test programs are written in higher order language (FORTRAN IV). Since these programs are quite complex, it is efficient to use a programming language which is easy to change and easy to edit by those who did not originate the programs. The test programmer must be skilled in the test functions of the fuel control and will not normally be a highly experienced computer programmer. The central processor serves a dual function. It stores and executes the test programs for each test stand in the system, and it provides the programming capability to develop new or modified test programs, plus any number of support programs which may be desired. The central processor has the necessary software to support the time-shared operations for a mulitple number of test stands, as well as the capability to compile FORTRAN programs for new tests.

The software and hardware technology of the ATSJEA sysems is typical of current automatic test equipment projects at RCA Burlington, but it represents a rather unique extension of that technology into non-electronic test

R.E. Hartwell, Senior Engineering Scientist, Technical Staff, Government Communications and Automated Systems Division, Burlington, Mass. received the BS in Physics from the University of Massachusetts in 1954 and the MS in Electrical Engineering from the University of Pennsylvania in 1964. In 1957 he joined RCA Airborne Systems Development group in Camden, N.J., and worked in the design of control and timing for an airborne radar inteceptor. In 1958, work assignments included design on a digital switching system for the SAGE data link equipment, design and systems integration on a semi-automated test shelter for the HAWK missile electronics, design and integration on a ground support complex for the DynaSoar aerospace vehicle, and design of a programmable audio oscillator for a prototype automated depot test system. Since 1961, Mr. Hartwell has worked in the Automatic Test Equipment group at RCA in Burlington, Mass. In 1966, he became an engineering group leader, with responsibility for the design, test, and delivery of a portable air traffic control tower (AN/TSW-7), an automatic test set for the IGLOO WHITE communications sensor, and an automated hydraulics test system (ATSJEA). Since 1972 he has been involved in the systems design of a number of automatic test systems, including fuel control testing (ATSJEA-II), aircraft hydraulics, and other aircraft accessories.

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applications. From a physical point of view, control or measurement is the same after the parameters (flows, pressures, speed of rotation, etc.) have been converted into electrical signals. From the total project viewpoint, these systems require a separate dimension of technical competence, in the understanding of the test requirements of the devices to be tested and the design requirements of the hydraulic/mechanical test stands. A key to the success of the ATSJEA projects is the melding of a team able to span the diverse problems of the mechanical, electrical, and computer software aspects of the system.

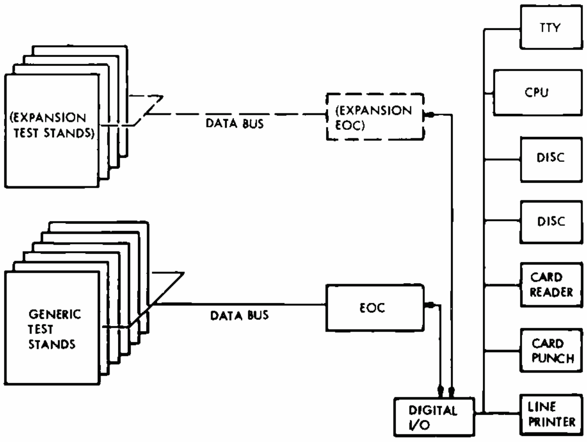

Fig. 1 — ATSJEA fuel control test installation.

Jet engine fuel control

ATSJEA tests a complex mechanical assembly which meters the fuel to the jet engine. The device consists of hydraulic and pneumatic servo mechanisms, bellows, rack and pinions, three-dimensional cams, and the like, which constitute a mechanical analog computer to sense a number of engine parameters and meter the proper amount of fuel for introduction into the engine burner compartment. Air is ingested at the engine input, compressed by the rotating blades of the compressor section, and jet fuel is sprayed into the compressed air in the burner chamber. The exhaust gasses rushing through the turbine section cause turbine blades, and hence the main engine shaft, to rotate, providing power for the compressor. The engine thrust is produced by the outrushing gasses and, in more recent designs, the main engine shaft also rotates a fan which bypasses air over the engine and provides both cooling and some degree of thrust.

The main fuel control senses the engine speed and compares this to the power lever angle (the pilot's control thottle), and a metering valve in the control is positioned to deliver the proper amount of fuel to the engine nozzles. Fuel is delivered to the control from the fuel pump which is geared from the main engine shaft. Fuel pressures up to 1000 psig are developed, since the fuel must be sprayed through the nozzles into the pressurized burner chamber. The fuel control also monitors the temperature of the input air and burner pressure, in order to deliver the proper air-to-fuel ratio. The fuel control schedules a controlled slope for the change in fuel delivery during acceleration and deceleration, so that the temperature in the burner chamber will never exceed safe limits and burn the turbine blades or, at the other extreme, cause a flame-out because of inadequate fuel. Pressurized fuel is also used in the aircraft to position inlet guide vanes which deflect a portion of the air over the engine, turn on after burner controls, and similar functions. The fuel control will normally house the mechanisms which control these auxiliary functions, and these must also be tested along with the fuel metering performance.

Many military aircraft use an afterburner section to produce added thrust by "brute-force" burning of fuel in the exhaust trail from the main burner chamber. The afterburner fuel control meters the amount of fuel delivered to the afterburner section. There are usually multiple spray nozzles or rings in the afterburner section, and the control must meter the build-up of fuel flow to each nozzle in a prescribed time profile.

ATSJEA II system hardware description

Fig. 1 is a view of the overall ATSJEA system. Included are the central processing unit (CPU) and its peripherals, one or more elementary operations controller (EOC), the data bus interface to the test stands, and a number of automatic test stands. The CPU obtains test programs from the unit under test (UUT) program library on the random access discs. The discs provide a mass storage media for computer programs, which are introduced into the core memory of the computer for execution. Test program execution at the CPU level consists largely of interpreting the UUT program coding and passing commands down to the EOC. Typical commands to the EOC include requests for measurements, values of pressures and flows to be adjusted, and lamps and relays to be energized. Once a command is forwarded to the EOC, the CPU is free to pursue other calculating tasks, and it is the EOC's function to execute the commanded task. When parameters are to be controlled to set limits, such as pressures, flows, speed, etc., the EOC will constantly monitor these values and send control signals to the test stand to adjust the controls. It is a feature of the automatic test system that measurements are not recorded, and new test sequences are not entered, until the exact conditions commanded by the test program have been established for all controlled conditions.

Description of the test stands

The modular arrangement of the ATSJEA test stands is shown in Fig. 2. Fig. 3 shows the front view of the stand. Four basic modules make up the stand. The electronics/pneumatics and variable speed drive modules house the speed drive, display and control panel, pneumatic controls, and an air-purged chamber to enclose the electronics from the fuel testing environment. The fuel supply module houses a fuel reservoir, boost and high-pressure pumps, electric drive motors, filters, and water cooled heat exchangers. Fuel from the reservoir is pumped to pressures up to 1200 psig. This module is sized for low, medium, and high flow capacities, with different sizes of reservoir, pumps, pump motors, and heat exchangers. The back pressure module contains flow and pressure regulating valves necessary to support all hydraulic interfaces to the fuel control including the input flow, metered output,

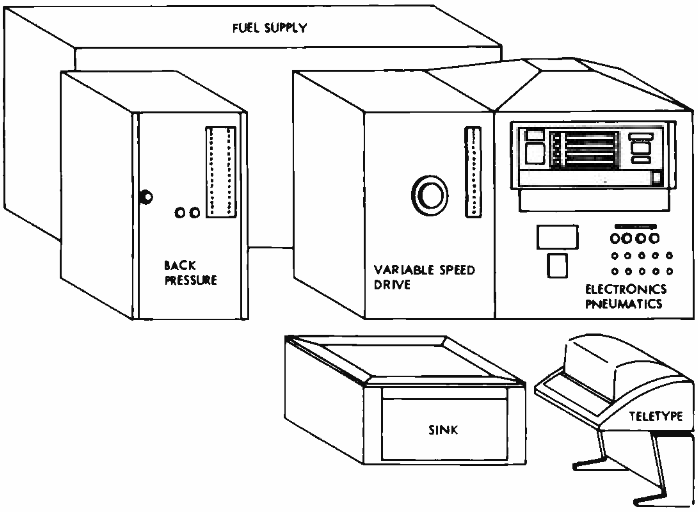

Fig. 2 — ATSJEA modular construction.

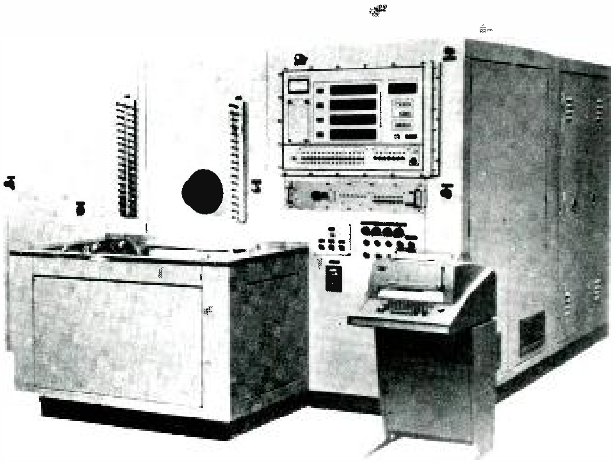

Fig. 3 — ATSJEA hydraulic test stand.

and fuel bypass connections. The sink module mounts the fuel control during testing and contains flow measuring devices.

The physical appearance of these stands compared to conventional manual test stands is quite impressive. Fig. 4 shows a conventional stand, with pressure gauges, glass-tube flow meters, and valve control handles and knobs dispersed over a vast frontage of the equipment. The ATSJEA stands have centralized displays and controls, electrically operated by means of switches, lamps, and illuminated displays (see Fig. 5). During fully automated testing, the displays are necessary only to inform the operator of the status of the test. When operator intervention is required, the displays and controls may be needed to guide the manual adjustments. The presentation of displays and the labelling of switches and lamps has been carefully designed so that test operators will be able to follow the course of the tests and detect any abnormal test conditions. Unlike the previous manual stands, the automatic test stands have a uniform arrangement that permits an operator trained on the system to be able to operate any other ATSJEA test stand without special familiarization.

The ATSJEA operator control/display panel (Fig. 5) groups all of the measurement and control functions in one location. The general measurement displays, which are four independent projection type readouts, occupy the central area of the panel. Each display has a two-digit selector switch (digi-switch) for dialing any of the measurement parameters in the test stand. The complete list of such devices by name is listed on the parameters table at the left of the displays. In addition, when the operator selects a parameter number and dials it into the digi-switches, a mnemonic caption (such as P OUT, Pb etc.) is displayed to the immediate left of the four-digit numerical value of the parameter. Decimal points are automatically placed, and the measurement unit (PSIG, PSIA, DEG) is projected to the right of the numerical value.

Organization of the automatic test system

The (CPU) consists of the SEL 810B Computer, an ASR 35 Console Teletype, two random access discs, the digital input/output (DIO), and card reader, card punch, and line printer. The computer, teletype, and disc perform the automatic mode test control. The card reader, card punch, and line printer serve principally for program generation facilities.

Fuel control test programs, known as UUT programs, are stored on one

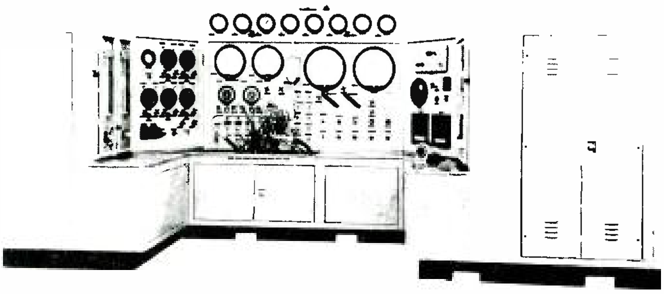

Fig. 4 — Conventional fuel control test stand.

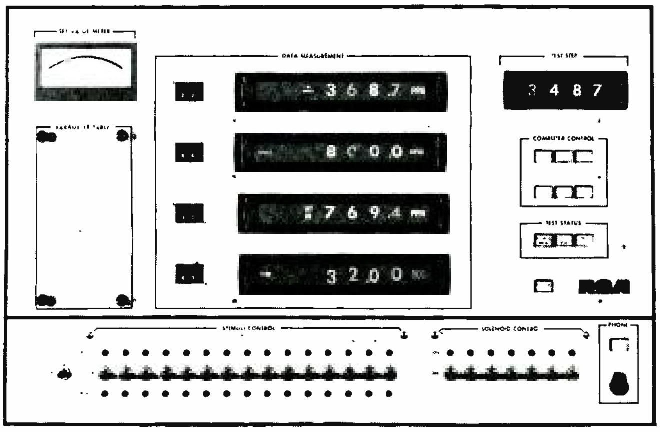

Fig. 5 — ATSJEA control and display panel.

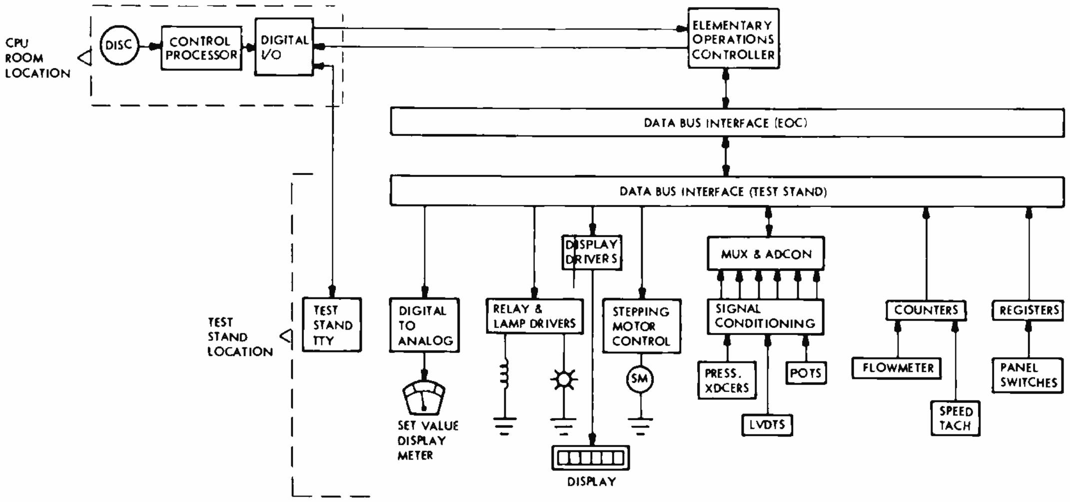

Fig. 6 — Measurement/control organization.

operational disc. The computer runs under the real time executive (RTX) which time shares program segments for all active test stands, bringing test program segments into the core overlay area for execution, and storing partially executed test segments with their activation record back on the disc (checkpointed) during periods of suspended activity.

The CPU communicates directly to the stand teletypes via the DIO. Test stand operators receive instructions, test information, and "logging" information via the teletype printer. Stand operators enter test number requests, test model numbers, and serial number information, via the teletype keyboard. Fig. 6 shows the basic automatic provisions of the system.

The CPU communicates all automatic mode commands to the test stand via the EOC. The CPU issues commands, on a one-time basis, for stepping motor control loops, lamps, solenoids, displays, and measurement requests. The EOC executes these commands and returns pertinent information to the CPU. In the case of control loops, the command sent to the EOC includes the number of a stepping motor, the number of a gauge, and a group of control loop constants. The EOC will subsequently monitor the assigned gauge, calculate the number and direction of pulses to drive the parameter into the programmed limits, and issue the command to the test stand to commence pulsing. The EOC will continue to monitor the gauge until the limits have been acquired, and will periodially recheck the acquisition and send additional pulses if the controlled parameter drifts or changes because of interactive conditions.

The EOC also measures test stand gauges and converts the raw data into engineering units, using calibration constants stored in the EOC. Measurements are available to the CPU on command, providing that the stepping motor control loops are all within their acquisition limits. Measurements are available at any time to the test stand operator at his display panel, regardless of the mode of operation of the CPU.

Test stand control loops are implemented with stepping motor circuits which are based upon the application of pulses to the controlling circuit, at a specified pulsing rate, in order to adjust the designated parameter. Figs. 7 and 8 show two types of controls used in ATSJEA. Where actual rotational placement is

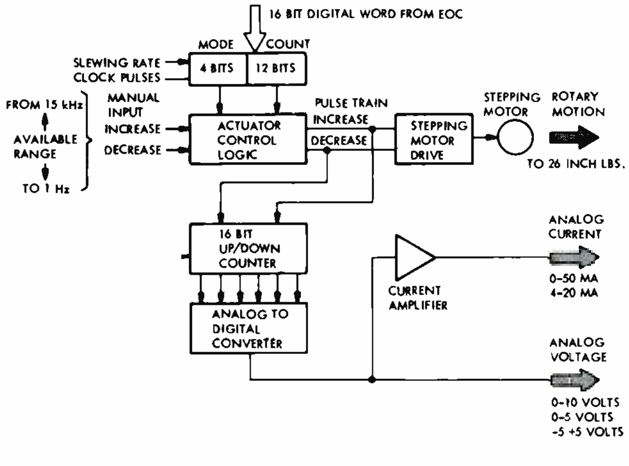

Fig. 7 — Actuator control scheme.

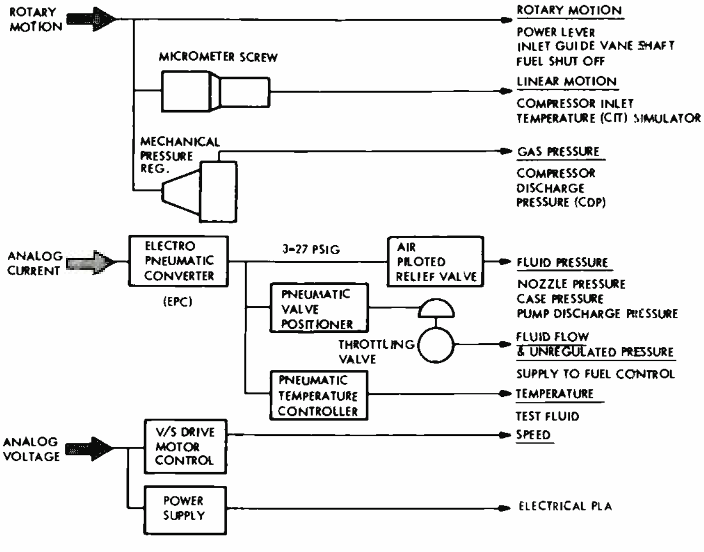

Fig. 8 — Actuator types.

needed, stepping motors make the adjustment. A potentiometer on the shaft of the stepping motor can be measured to determine the motor position, and any other affected parameter (pressure, flow, etc.) may likewise be assigned for control loop operation. An electro-pneumatic converter (EPC), a variation of the control circuit, is also shown in Figs. 7 and 8.

To maintain uniform control characteristics for all loops, the EPC is also controlled with pulses. The pulses are accumulated in an up-down counter in the EPC driver circuit, which generates a voltage in proportion to the accumulated number of (forward) pulses. The analog voltage is used to generate a current, which drives the EPC. The EPC, in turn, produces a proportional pneumatic signal (3 to 27 psig), which is the basis for the control of some working pressure or flow in the test stand.

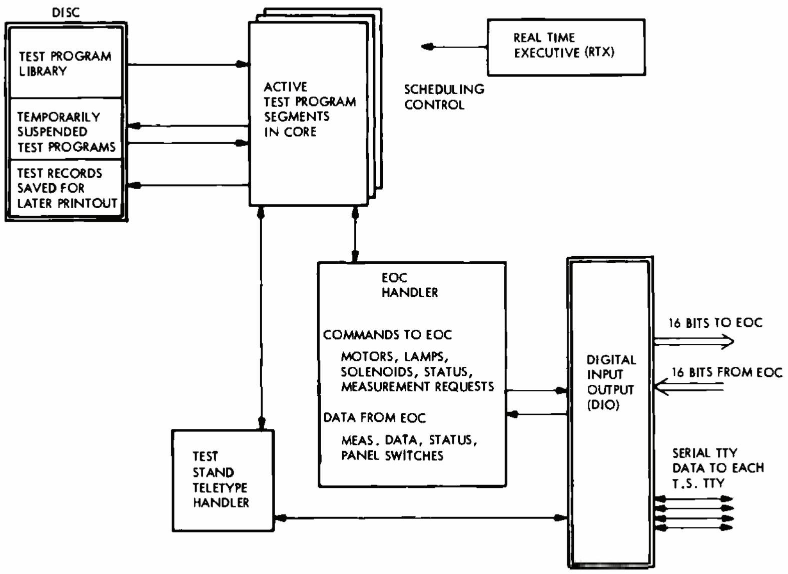

Fig. 10 — CPU processing functions.

Functions performed by the test stand electronics are shown in Fig. 9. The test stands receive all communications from the EOC via the single-cable data bus. Commands to the test stand are sent in a two-word transmission, one command word followed by one data word. These commands result in an input to one of the devices shown in Fig. 9 on the write bus, within the test stand. Data is requested from the test stand by the EOC in a single command word request, and the test stand responds by sending the data back via the data bus. Such data will be obtained at the test stand from the "read bus".

Computer software and programming description

The basic processing functions of the CPU are shown in Fig. 10. The RTX provides scheduling control to time-share the CPU resources with each test stand in the system, such that test execution at each stand appears to have exclusive use of the CPU. Test programs are brought from disc to CPU core memory for activation, in program segments of about 4-k (16 bit) words. Each segment is active until it becomes bound by input/output processing or test stand delays, or until the time-shared time-slice expires. Because of the relatively slow operations in real time at the test stand, test segments usually relinquish their active status before being suspended by the time-slice. A real-time clock in the CPU establishes a time-slice to prevent any one activity

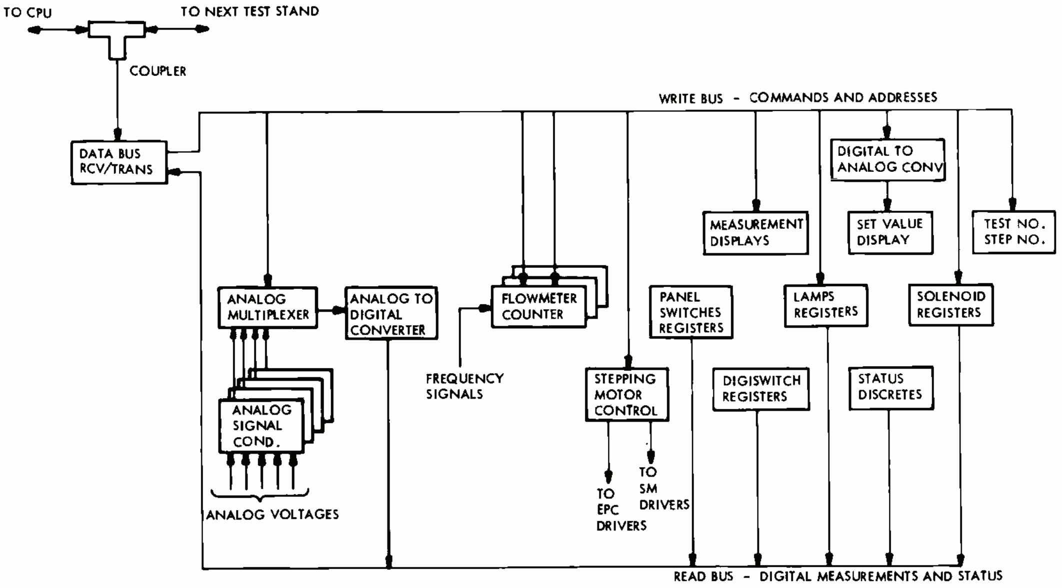

Fig. 9 — Test stand electronics control and measurements circuits.

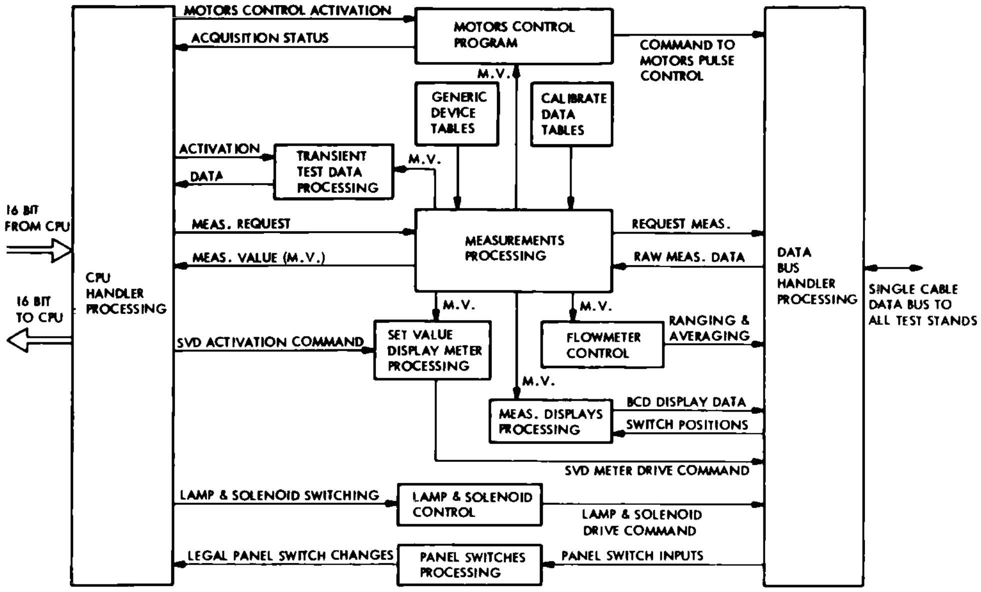

Fig. 11 — EOC processing functions.

from blocking the test system. Suspended test segments are checkpointed back onto the disc, along with their test records and data. The current status of each active test program is maintained in core by the CPU.

The basic test program library is stored on disc. The disc also contains checkpointed test programs which have been temporarily suspended and test records which have been saved for subsequent printout. Because this information is saved on the disc, it is possible to end testing at all stands for the end of day and resume testing the next day without the loss of interim test records.

Test program execution consists mainly of communicating commands to the EOC and receiving data back from the EOC, and making program decisions based on the data obtained. Communications to the test stand operator are made via a teletype at the stand, with direct communications to the CPU. All data to and from the CPU concerning the test stand is routed through the DIO.

Test program structure

FORTRAN test programs are augmented by 30 common test subroutines (CTS) specially developed for hydraulics test stand control applications. This test language gives the test programmer considerable flexibility in the configuration of test procedures, the formatting of test reports, and communciations between the test program and the test stand operator. It can be used effectively by technical people without the need for full time services of a computer programming specialist.

The test program can command each of the stand's stepping motors in a number of optional controls modes. By use of the ADJUST CTS, a selected stepping motor can be commanded to close a control loop involving the control actuator and any desired measurement device associated with the controlled parameter. Also at the programmer's option are the maximum stepping rates to be permitted, the upper and lower limits to which control shall be established, and selectable delays to allow for hydraulic settling time before the program is permitted to advance.

EOC processing functions

The elementary operations controller is the heart of the control and measurements processing for the ATS-JEA system. The EOC in ATSJEA II is a NOVA Model 800 miniprocessor. Fig. 11 shows the EOC processing functions. Measurements processing is the central activity, providing current measurements values for the motors control, flowmeter control, operator displays, and measurement values to be returned to the CPU. Measurements processing relies on two table structures in the EOC memory. The generic devices table defines for the EOC the exact disposition of gauges, motors, and solenoids at each test stand. Since the type of UUT to be tested at the stand can be changed, these tables can be reloaded to change the device assignments at the software level. This permits the changes to be made in the stands without significant rerouting of wires and hydraulic piping in the test stands. The calibration data tables contain the current calibration data for each transducer in the test stands. These tables are reloaded when periodic recalibration is required. By storing the calibration factors in software tables, calibration adjustments are not needed in the hardware, calibration records can be maintained in a data-processing format, and better calibration standards can be realized.

The motor control program obtains target values of flow, pressure, etc., for which the stepping motors (or EPC drivers) are to be adjusted. The motors program uses the measurement processing to find the actual value of the parameter to be controlled, and causes a train of pulses to be issued to the motor if the target limits are not satisfied. After initial acquisition, the EOC periodically rechecks these parameters and issues correcting pulse commands.

The set value display (SVD) meter is an analog dial meter driven by a digital to analog converter at each display panel. Under UUT program control, the SVD may be assigned to display in analog form the value of any parameter in the test stand. The meter has a redband at the right and left and a green band in the center, and its purpose is to indicate to the operator when the adjusted value is No-Go (in the red) or Go (in the green).

Automated test facility for aircraft hydraulic pumps and motors

R. Blanchard | L. R. Hulls

Aircraft hydraulic systems use three basic configurations of hydraulic pumps and motors. A multi-stand test facility has been designed which automatically tests these three types of aircraft pumps and motors. This integrated facility has many advantages over individual test stands, including cost savings and energy conservation.

THE PRIME FUNCTION of the aircraft hydraulic pump is to supply high-pressure fluid to the aircraft hydraulic systems which position the control surfaces, raise and lower the landing gear, and perform other auxiliary functions. Since the demand for hydraulic fluid fluctuates, most of the pumps used are of the variable displacement type and are pressure compensated to provide a constant supply pressure regardless of the flow demand. The pumps are driven at high speed via an auxiliary power takeoff from the aircraft engines. These pumps use a multicylinder arrangement in conjunction with a wobble plate to control the displacement.

Hydraulic starter motors are used to bring the aircraft engines up to starting speed. In some cases, the pump and starter motor functions are combined in a single pump/motor package where the pump/motor changes to a pumping mode once the engine has been started. The automated ten-test-stand facility described in this paper is designed to test a range of sizes of all three kinds of units:

Functional test stand characteristics

Pump test stands

There are six of this type stand in the Hydraulic Test Facility. The stands cover the ranges listed in Table I.

Starter test stands

There are two of this type stand in the Hydraulic Test Facility. The stands cover the ranges listed in Table II.

The starters for which these stands are designed are essentially high-speed hydraulic motors. They generate substantial shaft horsepower that is absorbed regeneratively by returning electrical power to the main bus, either in their speed/braking mode or in their selectable inertia-simulation mode.

The simulated inertia mode utilizes a torque-control circuit commanded by an electrically differentiated tachometer signal. Thus, it is possible, by simply varying the gain of this angular acceleration signal, to simulate inertia values from near zero to the values listed above and even higher.

Fluid temperature control is achieved in these stands by the appropriate mixing of two sources of 5000-lbf/in.^{2} oil, one at 120° F, the other at 300° F. This scheme permits fluid at various temperatures to be supplied simultaneously at all four motor-type stands.

Table I — Ratings of pump test stands.

Function	*Range*
Variable speed resersible drive pad:	
Shaft power	25 to 200 hp
Speed	7500 to 10,000 r/min
Low-pressure oil supply	15 to 90 gal/min @ 120 lbf/in^2
Re-circulating oil temperature	120 to 300° F
Back-pressure control	200 to 5000 lbf/in^2
Drain service connection	5 to 15 gal/min

Table II — Ratings of starter test stands.

Function	Range
Variable speed reversible regenerative (braking) drive:	
Shaft power	50 and 150 hp
Low-speed pad	15,000 r/min
Over-speed pad	30,000 r/min
High-pressure oil supply:	
Oil pressure	100 to 5000 lbf/in^2
Oil temperature	120 to 300° F
Oil flow rate	20 to 50 gal/min
Simulated inertia mode:	
Max. inertia ratings	4 and 8 slug-ft^2

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Mr. Hulls' biography and photograph appear with his other paper in this issue.

Table III — Ratings of pump/motor test stands.

Function	*Range*
Variable speed reversible drive pad:	
Shaft power	50 and 100 hp
Speed	15,000 r/min
Hydraulic supplies:	
Low pressure (120 lbf/in.^{2} max.)	40 and 60 gal/min
High pressure (to 5000 lbf/in.^{2} max.)	40 and 60 gal/min
Oil temperature	120 to 300° F

Pump/motor test stands

There are two of this type stand in the Hydraulic Test Facility. The stands cover the ranges shown in Table III.

These two stands are the most complex of the ten, combining most of the components and circuits used in the pump and starter stands. Consequently the variable speed drives are capable of delivering shaft horsepower to the unit under test (UUT) when operating in the motor mode. They do not, however, contain an inertia mode. Unlike the starter stands, these stands are not equipped to simulate inertia.

Two kinds of fluid temperature control are used: recirculation for pump operation and fluid mixing of high-pressure sources for motor operation.

The multi-stand test facility

The Hydraulic Test Facility consists of the ten test stands whose basic capabilities are outlined above, a central-hydraulics complex, an enclosure acoustically separating test stand faces from all rotating machinery, and a central computer enclosure (CPU/EOC Complex). Fig. 1 is an artist's rendering of a typical pump test stand.

The entire facility is air conditioned with the machinery area serviced by a single 10-ton unit. The central computer enclosure and stand face areas are serviced by two smaller (5-ton and 3-ton) units.

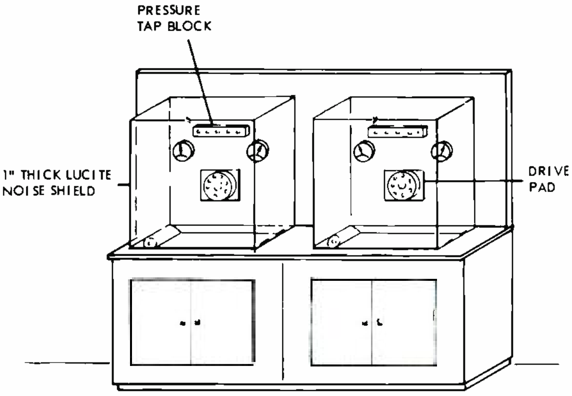

Fig. 1 — Typical double stand at operators station.

The central hydraulics concept

The term "central hydraulics" implies an assembly of pumps, possibly but not necessarily remotely located relative to the test stands, which share the load in delivering fluid under pressure to a common supply manifold.

Typical hydraulic configurations within the facility

Central hydraulics

The central hydraulics configuration is shown in Fig. 2 and includes the one low-pressure manifold. The 15-hp boost pumps provide both the 120-lbf/in.^{2} oil to the six pump stands and the boost pressure to the low-temperature, high-pressure pumps. The high-pressure supply comprises one variable and two fixed displacement pumps that together provide low temperature fluid according to the flow deamands.

In the high-temperature, high-pressure circuit (upper portion of Fig. 2), two fixed displacement pumps are provided in a recirculating loop using a steam heat exchanger to achieve the 300°F temperature required.

A central oil-to-water heat exchanger is located immediately in front of the reservoir.

Pump stand

A typical pump stand, somewhat simplified, is shown in Fig. 3. The pump inlet circuit consists of a 120-lbf/in.^{2} supply of oil at 120°F, a solenoid valve, and a computer-controlled inlet pressure-regulating valve.

The outlet circuit includes a computer-controlled throttling valve for back-pressure control and a series solenoid valve for flow cycling the UUT's pressure compensator. A remotely set output safety relief valve is also provided in parallel.

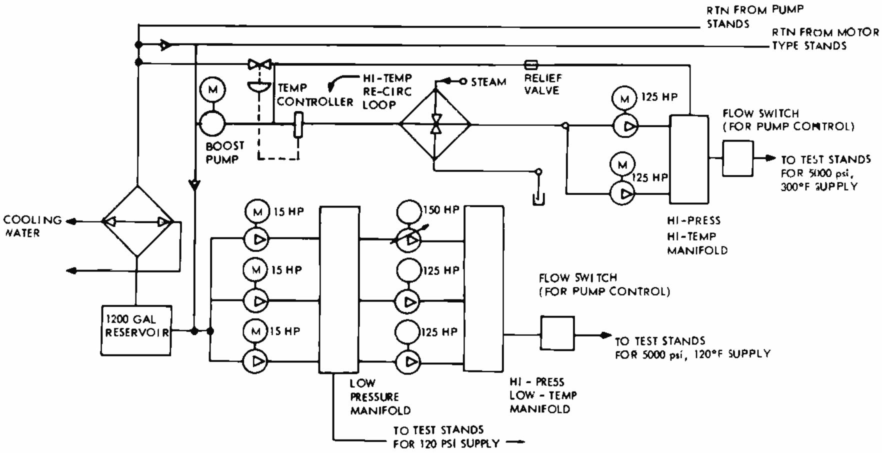

Fig. 2 — Central hydraulics, basic configuration.

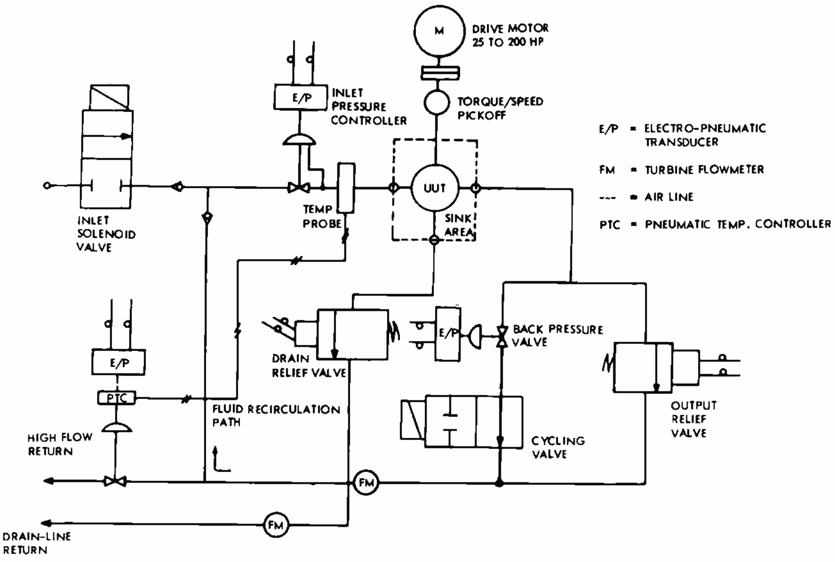

Fig. 3 — Typical pump stand configuration.

The drain connection is back-pressured by a computer-controlled low-flow relief valve.

A temperature control valve is used to block the normal return line when oil temperature is lower than desired, thus, recirculating fluid until high-pressure throttling heats it to the desired level.

Measurements of flow are made for both drain and outlet lines (from which the inlet flow may be deduced). Pressure and temperature measurements are made at all three UUT ports.

Motor/starter stand

A simplified motor/starter stand configuration is shown in Fig. 4. The inlet solenoid in this case is preceded by a fluid mixing valve for purposes of temperature control in which the hot and cool high-pressure oil supplies are combined to achieve the desired inlet oil temperature.

Because of the requirement to provide oil to the UUT during transient acceleration tests, the pressure control scheme on the inlet circuit is designed to provide transient flow to the UUT while maintaining a nearly steady state flow rate at the inlet. This is accomplished by using the "inlet pressure controller" and "inlet flow controller" to pass the maximum flow that will be required by the UUT during the transient test before the "start solenoid" is opened. In this way, inlet fluid temperature may be stabilized before and during the transient test, the flow being largely bypassed through the inlet pressure controller early in the acceleration test, and flowing largely through the UUT later as the UUT reaches high speed.

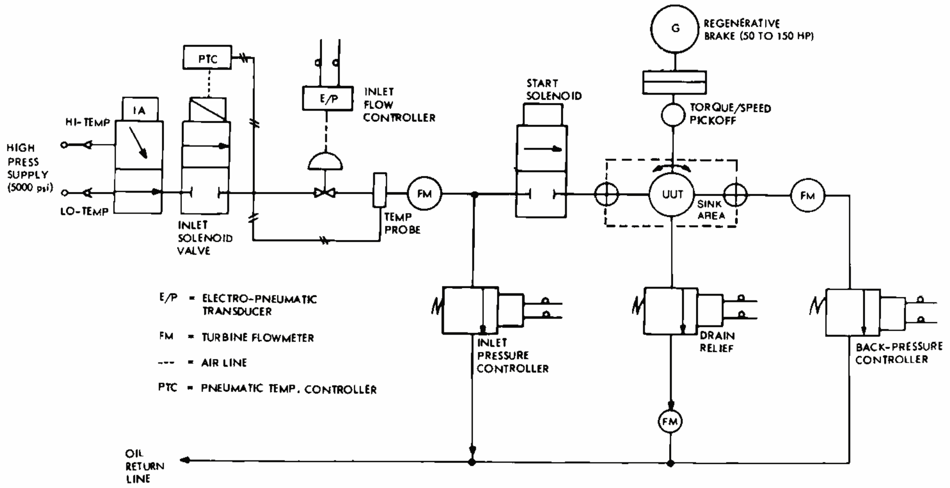

Fig. 4 — Typical motor/starter stand configuration.

For tests at stable speeds, the computer simply adjusts the inlet controllers such that a small amount of fluid is bypassed to insure a stable inlet pressure. The back-pressure controller and drain relief valve are similar to those in the pump stand.

Pump/motor stand

The pump/motor stand is the most complex of the three because it embodies the basic configurations of both the pump and starter in the same stand.

The main deviation from this dual configuration is in the motor inlet circuit which uses a pressure regulating value in series with the temperature-mixer. This suffices because no transient tests are required of the pump/motor stand.

On-line particulate monitoring system

The particulate monitoring system is expected to replace the present tedious procedure in which particle counts are accomplished manually after extended flow tests on the UUT with subsequent dismantling and flushing of the filter element. The on-line monitoring system will be able to alert the operator to a malfunctioning pump by indicating an abnormal rise in the count early in the run-in period.

Energy conservation considerations

The operation of a ten-stand test facility requires the expenditure of a significant amount of energy in the form of electric power and steam. In this particular design, operation of all ten stands at maximum capability would require 900 hp to operate the UUTs. Additional energy would be required to raise the temperature of the hydraulic fluid to meet the specific test requirements. In the absence of any mechanism for regenerating electric power and returning it to the supply, all the energy added appears as heat. A cooling system is, therefore, required to keep the operating temperature of the facility within acceptable limits. The operation of this cooling system requires an additional energy input into the system.

The following methods are used to minimize the energy required to operate the test facility:

1) Recirculation of hydraulic fluid around pumps to enable a fraction of the energy supplied to the pump to be used to heat the fluid to the required test temperature.

2) Use of regenerative drives on motor and starter stands so that a portion (dependent upon drive efficiency) of the mechanical power generated by the UUT can be returned to the electric power system.

3) Utilization of a combination of fixed displacement and variable displacement pumps in the central high-pressure hydraulic supply so that the flow can be closely matched to the actual demand. This eliminates wastage of power through pumping an excess volume of high-pressure fluid.

4) Temperature-controlling of high-pressure fluid by proportioned mixing of separate high-temperature and low-temperature supplies which permits recirculation of high-temperature fluid around pumps and motors with an appreciable energy savings.

Methods 1 through 3 are conventional techniques which are generally applicable to hydraulic testing of pumps and motors. Method 4 was specially designed for the ten-stand complex to avoid the excessive energy wastage which would occur if all the fluid passing through a motor or starter had to be heated to test temperature and subsequently cooled before returning to the reservoir. The hydraulic schematic diagram of Fig. 2 shows how heat is conserved by recirculating the hot fluid through a steam-heated exchanger and high-pressure pump to provide the high-pressure, high-temperature supply.

Table IV shows the comparative energy savings which result from the implementation of this recirculation system. For the purpose of computing the energy savings, the four-test-stand model used assumed that the two largest pump stands were running at maximum output and temperature (300° F), the largest pump/motor stand was running at maximum input and temperature, and the largest motor starter test stand was operating at maximum power and low temperature.

Computer system

The computer system is shown in simplified form in Fig. 5. A computer identified as an elememtary operations controller (EOC) interfaces the central processor unit (CPU) to a group of ten test stands.

The system can be expanded by adding EOC's with each one having the potential capacity for interfacing a further ten test stands to the CPU.

The EOC program functions independently from the test programs and, therefore, does not have to be changed when different kinds of units are being tested. The EOC program is responsible for supervising the primitive operations associated with the test stand measurement and control functions and the displaying of data to the test stand operator.

Test programs are stored on a disc memory which is accessed by the CPU. The CPU and its programs are responsible for the time sharing functions as well as the sequencing of the test procedure and the collection and processing of test data. The time sharing system services the test stand so rapidly that an individual test stand operator has the illusion of exclusive use of the CPU.

Conclusions

Many savings and advantages can be achieved in the design of an integrated automated test facility as opposed to designing individual test stands. The use of a central hydraulic supply reduces the number of motors, pumps, and heat exchangers. There are many examples where the integrated facility achieves economies by sharing amongst many test stands some of the more costly components of the automated system.

The flow capability of the central supply does not necessarily have to equal the summation of the maximum rated flow of every test stand in the facility. In a practical testing situation not every stand will demand maximum flow simultaneously and, therefore, it is realistic to use a diversity factor in sizing the hydraulic supply.

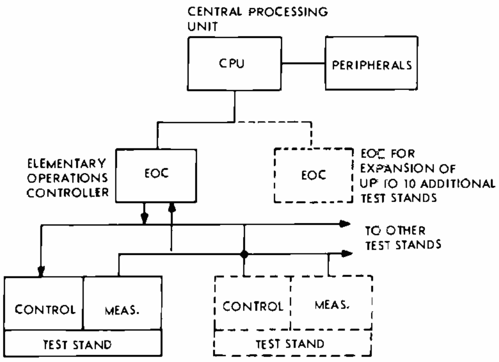

Fig. 5 — Computer system, simplified.

The removal of heat from the system can be achieved at less cost by using fewer larger components as compared to supplying a large number of smaller components on a per test stand basis.

The integrated facility includes the structure that encloses the hydraulic and electrical equipment. This is important in this case because it facilitates the design of the sound proofing arrangements required to protect personnel from exposure to a high noise level enviornment.

Operation of a test facility of this kind requires an appreciable expenditure of energy in the form of electric power to operate the drive motors and steam to heat the hydraulic fluid. Particular consideration has been given to energy conservation in the design of the system described in this paper. This has resulted in both a reduction in the cost of the facility as well as offering the prospect of reduced operating costs.

Table IV — Comparison of heating and cooling requirements.

	Cooling requirement (hp)	*Cooling water (gal/min)*	*Steam @ 80 lbf/in.*^{2}*(g) (lb/hr)*	*Fuel oil required (gal/hr @ 80% eff.)*
Straight-through heating/ cooling (4-test-stand model)	1388	118 @ 70° F*	2666	23.3
Re-circulation scheme	810	69 @ 70° F*	1081	9.5

*To avoid excessive fouling of heat exchangers, outgoing water temperature is limited to 130° F maximum.

Simplifying automotive testing with advanced electronics

H.E. Fineman | T.E. Fitzpatrick | A.H. Fortin

The need to develop automatic test equipment for simplifying diagnostic tests on automotive engine and accessory systems has resulted in new techniques using complex electronics. One of these techniques has been incorporated in a system delivered to the U.S. Army — a Simplified Test Equipment for Internal Combustion Engines (STE/ICE). The STE/ICE system is a hand-held measurement tool that incorporates a programmable microprocessor. This microprocessor provides the flexibility needed for application of the tester to many different engines and vehicles.

> "...Experience has shown that, in the maintenance of complex electronic, electrical and mechanical equipment, from 60 to 90% of the mean time to repair is spent in determining the cause and location of the malfunction. In the automotive areas, the practice has been to replace components, generally on a hit-or-miss basis, until the symptoms have been alleviated. As an example, data from the field shows that as high as 50% of the automotive components returned for direct exchange were either serviceable or required only minor repair. All of these difficulties can be traced to lack of sophisticated test equipment and lack of personnel skilled in the art of troubleshooting...." (Ref. 1)

RECOGNIZING THIS as a major logistics and support problem, the U.S. Army Tank-Automotive Command commissioned Burlington Operations of GC&ASD to develop a Simplified Test Equipment for Internal Combustion Engines (STE/ICE) which would be responsive to the following requirements:[2]

Functional

— The system must provide a summary measurement of overall vehicle readiness.

— The system must be capable of performing a broad spectrum of vehicle troubleshooting tests rapidly and accurately.

— The system must initially support four types of Army vehicles and must be future compatible with most of the Army's fleet.

Human factors

— The system must be simple to install, operate, and interpret.

— The system must be portable.

Environmental

— The system must operate reliably in the U.S. Army tactical/automotive environment.

Cost

— System cost must be minimized to the extent that deployment at the organizational (Motor Pool) level is practical.

The need to simplify operation burdened the system design with substantial control logic and conversion circuitry requirements. These requirements compounded the difficulty in attaining the size, weight, environmental and cost goals. All goals were achieved, however, because of timely developments in electronics, transducer, and computer technology. In the system design, maximum use was made of solid-state sensing elements, MSI, LSI, and hybrid analog and digital circuits.

System description

The STE/ICE system was designed to perform more than 70 tests and measurements on engine and accessory systems. In addition to measuring pressure, temperature, speed, voltage, and current, the system electronically performs a power test on gasoline and diesel engines without the need for an external dynamometer.

The STE/ICE system includes three major items of equipment: 1) the vehicle test meter (VTM), 2) a transducer kit, and 3) a diagnostic connector assembly. The first two items are shown in Fig. 1, along with the system transit case. The third item, built into the vehicles to be tested, includes pressure, temperature, and vacuum transducers, current shunts, and electrical connections. These are tied together by a system harness which brings all the test points to a conveniently mounted diagnostic connector. The VTM can make measurements using either the transducer kit or the diagnostic connector assembly. The pressure sensors used in the STE/ICE system have solid-state sensing elements and have all the advantages of microcircuitry including small size, excellent repeatability and reliability, high output, low power, and high resistance to acceleration, vibration, and shock.

When the VTM is connected to a vehicle equipped with a diagnostic connector assembly, a mechanic can perform tests of engine power and compression, fuel/air, lubrication, cooling, ignition, starting, and charging systems in just a few minutes. Using conventional test equipment these same tests would take several hours and would not include a power test. The transducer kit is used on

Fig. 1 — Vehicle test meter and transducer kit.

those vehicles which do not have a built-in diagnostic connector. The transducer kit's flexibility also allows it to be used as a supplement to the diagnostic connector tests by providing measurement capability for those parameters not implemented through the diagnostic connector transducers and test points.

A list of the tests which can be performed by STE/ICE is shown in Table I.

The block diagram in Fig. 2 shows vehicle-mounted portions of the STE/ICE system to the left of the dotted line. The VTM connects to either the diagnostic connector or the transducer kit. These items are both interfaced to the VTM through the same connector. The mechanic selects the desired test or measurement by means of the measure-

Table I — STE/ICE test and measurement capability.

Engine
Spark ignition (gasoline) power test
Compression ignition (diesel) power test
Compression balance
Engine r/min

Fuel/air
Fuel supply pressure
Fuel return pressure
Fuel filter pressure drop
Air cleaner pressure drop
Turbocharger outlet pressure
Airbox pressure
Intake manifold vacuum
Intake manifold vacuum variation

Lubrication and cooling
Oil pressure
Oil temperature
Coolant temperature

Starting/charging
Battery voltage and current
Battery electrolyte level
Starter voltage and current
Starter current, first peak
Starter ground cable voltage drop
Alternator/generator output voltage and current
Alternator/generator field voltage and current

Ignition
Dwell angle
Points voltage
Coil primary voltage/resistance
Timing

Howard E. Fineman, Manager, Product Design, Non-Electronic Test Engineering, Government Communications & Automated Systems Division, Burlington, Massachusetts received the BSME from the Massachusetts Institute of Technology in 1962, has taken additional technical courses at Johns Hopkins University, and will receive an MBA degree from Northeastern University in 1975. He worked at AAI Corporation, Cockeysville, Maryland, from 1962 to 1969. Mr. Fineman joined RCA in 1969 and has been developing automatic test equipment (ATE) for automotive engines and turbine engine fuel controls. He was responsible for the development of a built-in go/no go indicator and memory system for U.S. Army vehicles and for a study to define system requirements and equipment concepts for an automotive test set for direct support maintenance in the Army. He also designed an integrated instrumentation system for the RCA Vehicle Test Facility and has directed use of this facility for diagnostic test development. His present responsibility is the engineering management and systems engineering of STE/ICE. Mr. Fineman is a Registered Professional Engineer in Massachusetts and Maryland and a Member of the Instrument Society of America and Sigma Xi. He has been granted two patents relating to automotive test systems, and other applications are pending.

Thomas E. Fitzpatrick, Senior Project Member, Technical Staff, Government Communications and Automated Systems Division, Burlington, Massachusetts, received the BSME from Worcester Polytechnic Institute in 1968. Since joining RCA in 1970, Mr. Fitzpatrick has held project engineering responsibilities in the automatic test equipment program management office on the U.S. Navy AEGIS program and the U.S. Army internal combustion engine powered material test equipment programs. On the AEGIS program his responsibilities encompassed cost, schedule, and technical control of the design and manufacture of the operational readiness test system (ORTSO. He was involved with data management, system assurance, qualification testing, and hybrid microelectronic developments. Since the latter part of 1973, Mr. Fitzpatrick has been acting as the project engineer on both the ATE/ICE (automatic test equipment/internal combustion engine) and STE/ICE contracts with the U.S. Army TACOM. On these contracts he has been responsible for the successful achievement of TACOM's goals. He was also responsible for the application of management and engineering personnel, experienced in both ATE and automotive diagnostics, to the evaluation of a cost-effective product.

Auguste H. Fortin, Senior Engineering Scientist, Technical Staff, Government Communications and Automated System Division, Burlington, Massachusetts, received the BS in Electrical Engineering from the University of Massachusetts in 1958. He joined RCA immediately after graduation. Mr. Fortin has done circuit design on the BMEWS project, programming of self-check on the APCHE and MAPCHE systems, and logic design on the AM 3100 and AM 3200 computers. He was the responsible engineer for the logic design and checkout of the control programmer and camera sequencer subsystem for the RANGER VI program. He has also done system and logic design work on the computer/controller subsystem of the MTE and DIMATE programs. Mr. Fortin was the responsible engineer for the logic design fabrication and checkout of the controller subsystem on the LCSS program. He has also been involved in the LCSS system checkout and sell off. Most recently, Mr. Fortin has been responsible for the implementation of a microcomputer into STE/ICE. Mr. Fortin is a member of Tau Beta Pi.

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ment select and test switches which are shown in the upper right of the diagram. With this information, the microprocessor causes the six measurement blocks, shown to the left of the input/output (I/O) logic, to acquire the signals needed for the selected test or measurement. These signals are converted to digital format by the measurement blocks and are then routed to the central processor unit (CPU) logic through the I/O logic. Here the necessary arithmetic logic scales the resulting answer in engineering units consistent with the selected test. The scaled value is then routed to the seven-segment display decoder/drivers which cause the four-digit numeric display to show the digital value in scaled engineering (or mechanics') units.

The individual measurement blocks shown at the input of the VTM can accommodate a variety of signals from the vehicle. Most of the signals go through the analog input multiplexer and signal conditioner. These include vehicle voltages and currents and signals from pressure and temperature transducers.

A number of tests and measurements require special-purpose analog signal processing. These include the extraction of engine compression information from starter current waveforms; intake manifold vacuum variations; and initial peak starter current.

The analog sub-multiplexer can select signal paths 1) to permit measurement of vehicle voltages with respect to a number of different vehicle ground points, or 2) to permit measurement of differential signals. This switching flexibility is needed because the same signal may be used differently to satisfy the needs of variant tests and measurements. The analog sub-multiplexer switches the desired signals into the amplifier which provides isolation and scaling to a level compatible with the analog to digital (A/D) converter. The A/D converter changes the analog signal into a digital format which is compatible with the I/O logic.

The ignition signal conditioning and interrupter circuit serves two functions. First, it provides filtering and squaring for the ignition points signal which is used for speed and dwell measurements on spark ignition engines. The second function of this block is to provide the necessary control logic to operate the vehicle in the ignition interrupt mode. This mode permits operating the vehicle at wide open throttle with full air/fuel flow without over-speeding the engine. It is used to provide a power check on spark ignition engines (U.S. patents no. 3,757,370 and 3,839,907).

The speed and acceleration burst logic is used to acquire engine speed information from the magnetic pulse tachometers which are used on the compression ignition engines. The acceleration burst logic together with the microprocessor is used to measure the precise time interval for a compression ignition engine to accelerate from a known low speed to a known high speed at wide open throttle conditions with no external load. This information is used as the basis for the power check on the compression ignition engines.

The operation of all of the measurement blocks described above is controlled in accordance with pre-programmed instructions contained in the microprocessor. When the VTM is connected either to the diagnostic connector or to the transducer kit, an identification code is read and translated to determine the type of vehicle to be tested. (When the transducer kit is ued, the code signifies

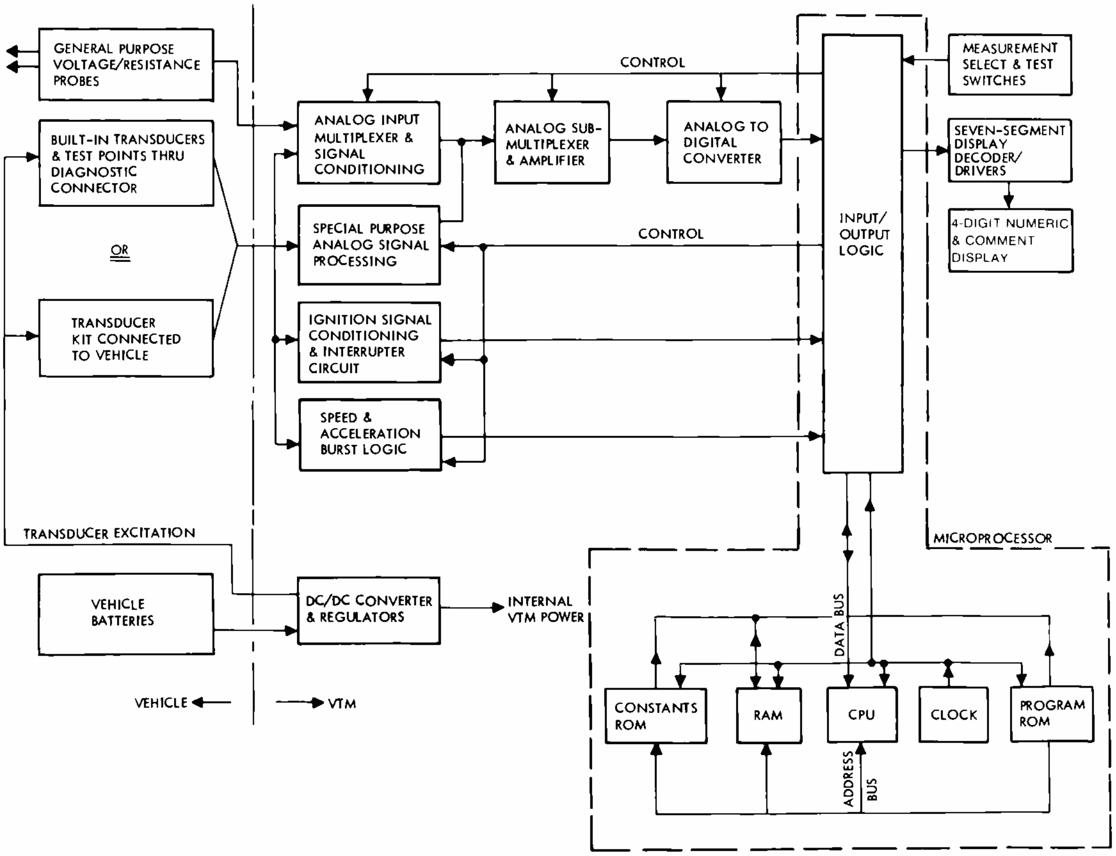

Fig. 2 — STE/ICE block diagram.

Fig. 3 — Vehicle test meter (closeup of top panel).

which transducers are connected to the VTM.) The vehicle code is used to select the pertinent logic sequences and scale factors for that type of vehicle or transducer.

Operating power for the VTM is drawn from the vehicle batteries or an equivalent battery source. This power is routed to the VTM through the diagnostic connector when used in that mode or via battery clips or other adapters when used with the transducer kit. The batteries used do not have to be in the vehicle-under-test so that it is feasible for the mechanic to connect the VTM to his own vehicle batteries, if he happens to be testing a completely dead vehicle-under-test. The dc-to-dc converter and regulators permit the VTM to operate from an input voltage range between 8 and 32 V dc. This will permit working not only with conventional 24-V electrical systems presently in military vehicles, but also with the 12-V systems in staff cars and in future commercial transport vehicles which are likely to be used by the Army. It will also permit operation with heavily discharged batteries in either a 12- or 24-V system.

The VTM shown in Fig. 3 is a completely enclosed, environmentally sealed chassis. This sealing was necessary to satisfy the fundamental objective of operation in the relatively dirty environment (oil, gas, sand, rain, etc.) of Army field maintenance. Since the chassis is sealed, particular attention was given to minimizing the power required to perform the necessary functions. This factor along with the portability requirement resulted in a decision to maximize packaging density and minimize special purpose electronics circuitry through the use of the Rockwell International PPS-4 microprocessor.

The developmental model of the VTM uses INTEL's 1702A programmable read only memories (PROMS) for its program memory and look-up tables, because the low initial production volume could not justify mask-programmed read only memories. The use of PROMS gives the advantage of easy program and test modifications; however, a severe penalty could be paid in power requirements. To minimize this penalty, power switching of the PROMS via COS/MOS analog switches was used with a resultant 5 to 1 reduction in memory power.

The VTM uses the microprocessor to perform control and computational tasks for each measurement. The microprocessor performs the following functions pertinent to the test number selected by the mechanic:

- Valid test number check for vehicle type being tested
- Correction for VTM and transducer offset voltages and for transducer excitation drift
- Measurement path routing (multiplexers, rectifier, peak detector, filters, ADCON, counters)
- Repetitive versus single-shot measurements
- Range control for current probe
- Time interval measurements
- Averaging of dynamic signals for stable display
- Autoranging
- Comparison against limits
- Conversion of measured values to engineering units

The PPS-4 microprocessor system used to accomplish these tasks includes a 4-bit CPU, 512×4 words of scratch pad memory, 1536×8 words of constants memory (PROMS) and 4096×8 words of program memory (PROMS). It also includes a 4-phase clock and I/O data/control lines (68 in/64 out).

The VTM measures 11.5×8.5×7 in. and weighs 11 lb in its prototype configuration as shown in Fig. 3. Below the top panel, and tied to it for thermal and EMI considerations, is a nest of seven circuit boards.

To minimize training requirements, the instruction cards integral to the meter were carefully structured into test categories with the appropriate test numbers for input to the measurement select and test switches.

Our goal was to have the unit operate with minimal inputs and to have the outputs easily read, without interpretive conversions, by the mechanic. RCA NUMITRON digital display devices were chosen for the display because of the military need for visibility in direct sunlight. In addition to numerics, the display is capable of displaying PASS/FAIL, HI/LO, and simple key instruction or error messages to the mechanic.

Conclusion

At the time of this writing, the STE/ICE system has successfully completed the performance and environmental test and demonstration conducted by RCA. The Army has programmed the field testing of six prototype systems which will lead to type classification and subsequent production.

For the Army, the STE/ICE system complements another diagnostic system (Automatic Test Equipment for Internal Combustion Engines) to form a comprehensive approach to diagnostics and support of the military vehicle fleet. The applicability to non-military fleets is obvious but such uses need related essential concurrent developments.

Full potential use of these techniques awaits significant improvements in the design construction and economics of transducers and the development of microprocessors oriented to vehicle use, whether for engine control, emission control, safety management, or diagnostics.

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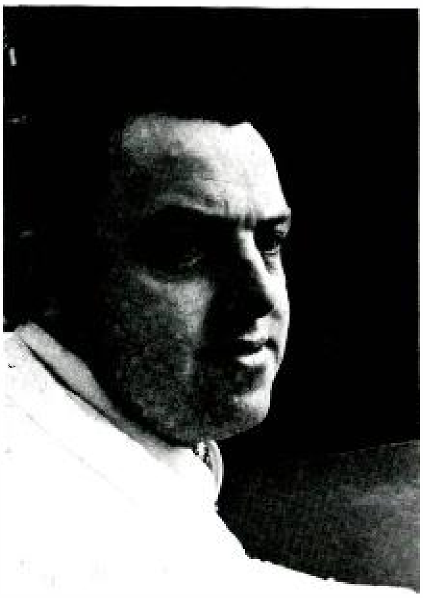
Holographic document viewer for the automated support system, man-machine interface

R. C. Plaisted| V. J. Stakun

The man-machine interface of an automated support system can be significantly improved with a document viewer using holographics. The document viewer employing digital holograms provides lower operating cost, space savings, speed and convenience of retrieval, low-cost reproduction and distribution, and versatility.

R. C. Plaisted, Automatic Test & Monitoring Engineering, GCASD-Burlington, Mass., received his B.S. degree in Electrical Engineering from the University of Maine in 1960, and has continued his education by taking state-of-the-art courses; receiving credits towards his M.S. degree from Northeastern University Mr. Plaisted joined RCA as an Engineering Trainee in the Design and Development program in 1960, and worked on engineering assignments at RCA plants in New York, N.Y., Lancaster, Pa., Camden, N.J., Burlington, Mass., and was permanently assigned to the RCA Plant in Burlington, Mass. Recently Mr. Plaisted provided the preliminary investigation and accumulation of background material for proposing application of holographic techniques to ATE systems, including presentations to potential customers. He was the principal investigator and engineer responsible for generation of a report considering the application of holographic techniques for documentation and tape storage to enhance the LCSS Test Station. He also has been involved in the design reviews of both analog and digital modules and has participated in proposal efforts throughout the year. He submitted a patent disclosure on a unique method of creating objects for holograms in June of 1973. He is a member of the IEEE and a registered professional engineer in Massachusetts.



V. J. Stakun, Automatic Test & Monitoring Engineering, GCASD-Burlington, Mass., received the BS in Physics from the University of Massachusetts in 1951. He is presently pursuing work in the Engineering graduate school at Northeastern University. He also pursues courses in state-of-the-art in Laser Technology and Optics. Since joining RCA in 1958 he has been engaged in diverse electro-optic activities including automatic test equipment and techniques for advanced missile system electro-optical components; analyses of field failures of the Specialized Electro-Optical Equipment with a view to improving state-of-the-art; developing computerized programs for automatic checkout of Electro-Optical Assemblies of such complexity as missile trackers, using coherent and incoherent sources; developed telemicroscope and associated reticle patterns for test and evaluation of optical sight for operational weapon systems. He also developed special tooling for alignment of these systems; developed radiometric tests for calibration of IR narrow band radiometers; and designed cost effective solutions to costly fielded radiometers through use of off-the-shelf electro-optical products. Mr. Stakun holds two patents; one for a rapid start-stop tape recorder mechanism, another for a vidicon rotary scanning tracker.

A MAJOR PROBLEM facing the user of automated support systems is to handle the documentation for the system and associated equipments to be tested and repaired by automated support. Documentation must be reproduced, stored, filed, sorted, distributed, updated, and manipulated or searched as the need for the required information occurs. It is an essential part of the man-machine interface of any automatic support system. Such software support necessarily consumes much valuable space in Automated Test System (ATS) stations.

Techniques examined

RCA undertook to examine basic techniques for reduction, consolidation and automatic retrieval of documented information. Study showed that, by using holographic techniques, a volume reduction of 400 times over present documentation handling methods in ATS stations could be achieved.

Developmental effort involved breadboarding and establishing a cost effective interface between the digital format employed by ATS stations and an object from which holograms could be generated.

Overall holographic concepts, duplication technique, RCA's recording configuration, alternative holographic storage and retrieval systems, and a playback system are described.

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Holographic considerations

Holography is a technique for recording and later on reconstructing optical wavefront information. High volumes of data can be embossed on tape (similar to audio grooves on a record). The phase hologram derives its phase characteristics by surface relief created on a 3 to 4 micron photoresist layer after exposure and development. Prime reasons for initially using the holographic approach are:

- The exceptionally low cost of replicating a relief record by heat embossing on thermal plastic. The process is mechanical and involves no intermediate electro-optical processing as, for example, in reproduction of microfiche. Attendant loss in resolution due to lens MTF, and setup and processing losses are not present in the hot embossing replications.
- A class of hologram recorded in the Fraunhofer or far field plane will display a high degree of "redundancy". This feature makes the records quite tolerant of handling, dust, scratches and digs.
- The Fraunhofer hologram displays a high degree of image immobility since playback of the hologram is accomplished by an imaging lens set at infinity.

Duplication technique: A major advantage of holographic storage of digital data is that the recorded information can be rapidly duplicated on a durable but inexpensive medium.

The ability to duplicate holograms rapidly and inexpensively leads to a concept in which holograms containing image information are produced as relief image holograms on photoresist. The replication process is based on the HoloTape® process developed at RCA for holographic video storage.[1] Such holograms form metallic duplication masters; the metallic holographic masters transfer the image information to a polycarbonate storage tape strip by a pressing process.

The surface-relief hologram is gold or silver plated in either a chemical or vacuum deposition process to a thickness of several micrometers (both processes have been used successfully). The gold-plated photo-resist hologram is the cathode in a standard nickel electrolytic-plating process in which nickel is deposited on the silvered surface to a depth of several mils.

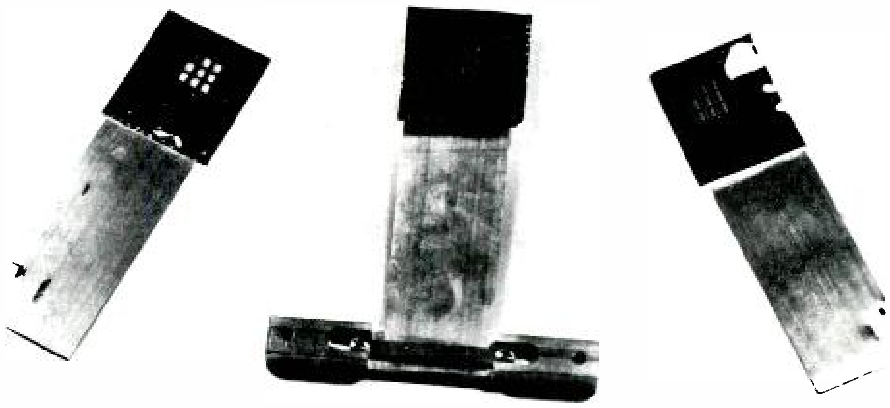

Fig. 1 — Sample hologram master.

The process (similar to that used to stamp phonograph records) transfers the hologram from the metallic master to the storage material used in the display. Duplication involves pressing the heated hologram metallic master die against the thermoplastic surface. Proper control of the pressure, temperature, and time dictate the success of the transfer operation in which the surface of the thermoplastic material is deformed to the relief of the die face. The photograph of Fig. 1 shows the dies used to produce the data cards generated for a digital-data playback system.

Preliminary design and development

Digital Recording System: The recording configuration is shown in Fig. 2. For the system utilized during this program and recommended for extended development, the hologram configuration selected was a Fraunhofer, or more descriptively, a displaced Fourier transform hologram technique.

To form a true Fourier transform hologram employing a transparent object, a collimated beam derived from a coherent source is intensity modulated by the information to be recorded. Zero-order information is transmitted directly through the transparency while diffraction terms are produced by information appearing in the object plane as density variations. The zero-order and higher-order diffracted terms are collected by a lens system to form the Fourier transform of the object information at a plane located a focal length away from the back principal plane of the recording lens.

To eliminate high energy concentrations in the recording medium, the recording plane is moved out of the Fourier plane. The wavefront at this plane has the energy distribution shown in Fig. 3. During recording, using this displaced technique, the energy is more uniformly distributed over the hologram recording area causing a significant reduction in the dynamic range requirements of the storage medium while introducing a high order of redundancy. The distribution is achieved by adjusting: 1) the focal length

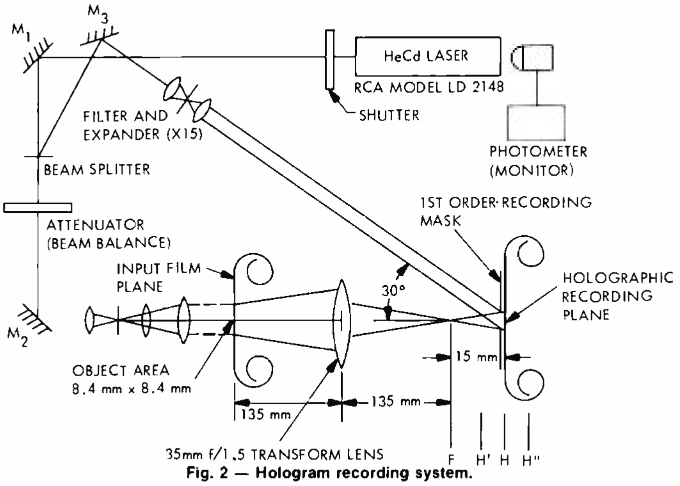

Fig. 2 — Hologram recording system.

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*Registered RCA trademark

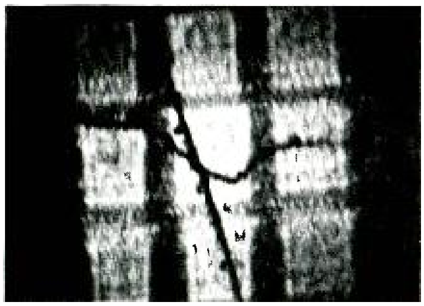

Fig. 3 — Transform plane of circular bit pattern.

of the transform lens, 2) the size of the object bit array, 3) diameter of the bits comprising the object array, and 4) the geometry of the bit pattern.

A computer with a CRT-to-film printout was programmed to transcribe information from paper or magnetic tape to a transparent object format suitable for use with the recording system of Fig. 2.

Two configurations achieving most attention are shown in Figs. 4 and 5. The object data array of Fig. 4 was empirically found to produce a reconstructed image having a minimum of intermodulation products and a high signal-to-noise ratio when read out using vidicon reconstruction. The object data array of Fig. 5, when stored as a displaced Fourier transform hologram (although ideal from the viewpoint that data can be easily reconstructed in a self-synchronizing vidicon scanning system), was found to produce high spurious signal components in the reconstructed data plane. The coding employed in the latter case is a Manchester technique where data is stored along horizontal raster lines. In this case, a *one* is represented by a black bar followed by a white bar; a *zero* is represented by a white bar followed by a black bar.

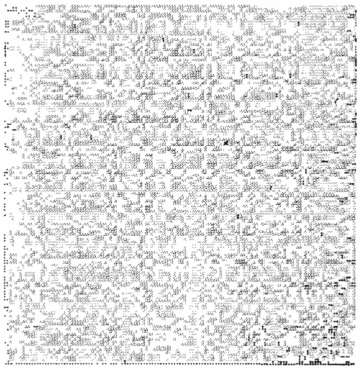

Fig. 4 — Object array—dot pattern.

As a result of the conclusions indicated above, the finalized recording system was set up as shown in Fig. 2. A 130 x 130 element object data array was employed which was 8.4 mm x 8.4 mm on a side. The array was produced using the computer controlled CRT printing system with original copy at 100 x 100 mm reduced to the 8.4 x 8.4 mm format. The 8.4 x 8.4 mm object arrays were produced as transparencies on a 35-mm film strip. The spot separation was 0.065 mm with the spots representing *ones* having a diameter of 0.0325 mm and a cylindrical transmission distribution.

The object was illuminated from the rear using a collimated beam drived from a *HeCd* laser. A laser having a 40 mW output at 441.6 millimicron was used for this purpose. The output from the laser was split into two components. One component, the object beam, was passed through a beam expander-collimater containing a pinhole filter to form the collimated reference beam which was directed through the object transparency. The beam was enlarged sufficiently to ensure that the object was uniformly illuminated (less than a 5-percent energy variation across the active object).

The second component of the source beam formed by the beam splitter (BS) of Fig. 2 was expanded and collimated to uniformly fill the recording area at the holographic recording plane. A 10:1 reference beam-to-object beam ratio was maintained as measured at the hologram recording plane with 50 percent populated object array in plane in the object plane. The optical efficiency of the recording system was approximately 10 percent; exposure times were of the order of 10 seconds.

A lens (transform lens) having a 135-mm focal length was used during recording. The recording system was established so that the object was located at a distance of 135 mm from the front principal plane of the lens causing the formation of a Fourier plane 135 mm in back of the back principal plane of the lens.

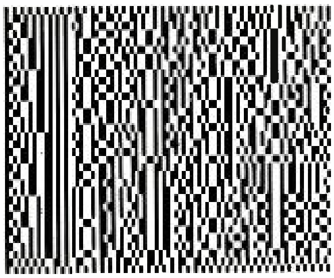

Fig. 5 — Object array—manchester code bar pattern.

Using the lens in this fashion a dc or zero-order term, the unmodulated portion of the energy passing through the object transparency is focussed to a point on the axis of the optical system in the transform plane. Energy radiation from a point in the object plane is converted to a parallel wavefront in the Fourier plane.

As indicated above, the interference pattern forming the hologram is produced at a plane removed from the Fourier plane of the lens system to produce the energy distribution shown previously. For the geometry employed for this program, the recording plane is removed a distance of 15 mm beyond the Fourier plane. For, this geometry, the first-order terms are displaced at the Fourier plane a distance equal to

$$f_1 \sin^{-1}\left(\frac{\lambda}{d}\right)$$

where f_1 equals the focal length of the lens, λ is equal to the wavelength of the optical recording source, and d equals the separation of the object array elements. For the final recording configuration

$f_1 = 135$ mm

$\lambda = 0.4416 \times 10^{-3}$ mm

$d = 0.065$ mm

Indicating an order separation in the Fourier plane of 0.92 mm this implies an order separation in the displaced plane of 1.1 mm [(150/135) × 0.92] resulting in a hologram which includes the zero and the lst order terms in a 3 mm x 3 mm area. A 3 mm x 3 mm mask was placed in the holographic recording plane to limit the area exposure to the extent of the first terms. This mask acted on both the reference and object wavefronts. The recording on an array of holograms was accomplished by moving the photoresist plate behind the mask between successive exposures.

The recording on the photoresist master consists of the interference pattern

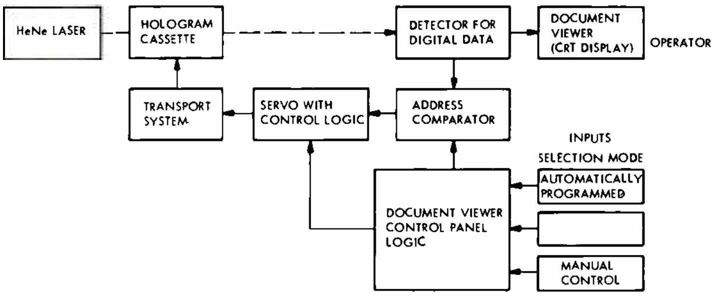

Fig. 6 — Block diagram of proposed digital data holographic documentation storage and retrieval system.

produced between the object wavefront and a 3 mm x 3 mm plane wavefront, reference wavefront, derived from the common *HeCd* laser.

The object beam to reference beam angle was set at 30° producing a fundamental grating frequency on the hologram of 1132 line pairs/mm as follows:

$$f_g = \frac{\sin\theta}{\lambda} = \frac{\sin 30^\circ}{0.4416\times10^{-3}}$$

$$=1132 \text{ lp/mm}$$

This grating frequency effectively acts as a sampling system. It can be shown that to reconstruct accurately the recorded information, grating frequency must be at least three times the number of information lines. This implies that (at the selected recording frequency) the total 130 x 130 raster array, as limited by the sampling theory, could be recorded in approximately a 1/2 mm x 1/2 mm area. Based on this consideration, the grating is not a limiting system since each recorded order occupies a 1 mm x 1 mm area of the total hologram area.

Recording in the configuration indicated above provides a system which in theory allows playback of the recording information with eight of the nine recorded orders obscured or destroyed. In practice, obstruction of this much of the hologram reduces the signal strength by a factor of nine while increasing the intermodulation components which are suppressed when the full hologram is read out. Information distortion is also introduced. It has been determined empirically, however, that as much as 50 percent of the hologram area can be obstructed without producing a significant degradation of the reconstructed image information. Random scratch and abrasion will not affect the quality of the information during readout until a major portion nearing half of the hologram area, is abraided.

RCA has designed a stable, inexpensive table configuration for this recording system, but it does require a permanent depot-type installation.

Design concept for holographic documentation storage and retrieval system

The approach considered most feasible for holographic documentation viewing is a completely digital data storage system illustrated in Fig. 6. In this approach all documentation is converted to binary information and is stored as digital data. A redundantly recorded Fraunhofer hologram would contain both the indexing address code and the document information coded digitally in the proper format for communication to an ordinary CRT display terminal or any output device utilized in the automatic support system.

Various select modes for retrieving the holographically stored documentation are provided. The transport system positions the desired hologram in the readout area under automatic, semi-automatic, or manual control. The utilization of the Fraunhofer hologram for address coding procuces an image which does not move with translation of the hologram. Thus, without image motion, the address code can be detected while the tape is moving continuously or at various rates of speed. Therefore, the control of the tape motion is simplified, and the mechanical mechanism resembles a simple audio tape transport.

Playback system description

To demonstrate the advantages of this holographic digital data storage system, a feasibility model was designed and constructed utilizing a *X-Y* positioning system. An array of 3 x 3 holograms at different locations on a 4 by 6 inch card was embossed from a gold metal master. Retrieval of these holograms is accomplished by moving the card such that an addressed hologram is placed in the readout beam. The resulting reconstructed image is formed on a vidicon where it is converted to an analog video signal. The analog signal may subsequently be interpreted as a serial digital bit stream.

A 3 mm x 3 mm hologram was used for storing 130 x 130 bits with redundancy. To allow separation of holograms on readout, a 1-mm spacing between holograms is allowed. Thus, the total area occupied by each hologram is 4 mm x 4 mm; the 4 by 6 inch storage card contains 24 x 36 holograms or a total of 864 holograms with a storage capacity of 16,900 x 864 = 1. 42 x 10^7 bits.

The formatting of the holograms on the data card for the base line system is indicated in Fig. 7. During the course of this program, a sufficient number of holograms were stored to demonstrate the ability to produce a fully populated hologram array. Four 3 x 3 hologram arrays were placed in the corners while a fifth hologram was placed in the center of the card. Each hologram contained the full 130 x 130 data bits and was recorded with redundancy.

Fig. 8 shows the configuration used. The system consists of a *NeNe* Laser (RCA Model No. LD-2174), an RCA assembled stepping motor card transport mechanism with its associated drive electronics, beam collimation optics, a reconstruction lens, and a vidicon

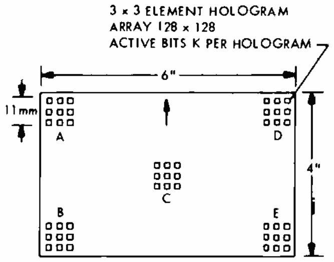

Fig. 7 — Data card format.

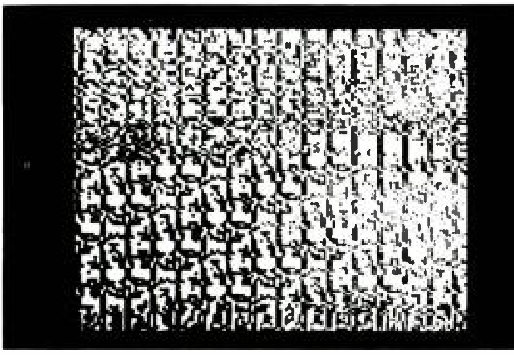

Fig. 9 — Reconstructed data plane.

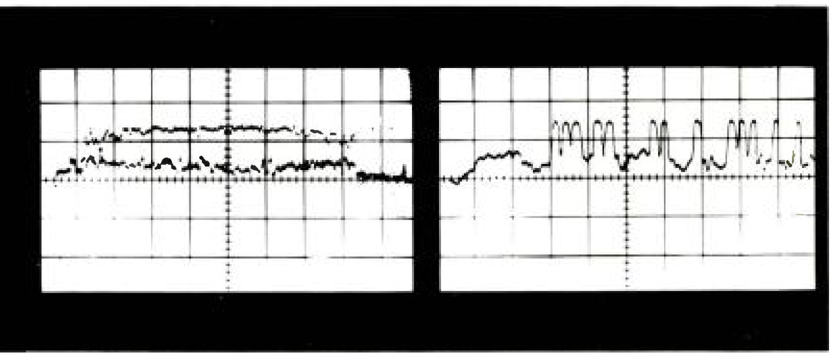

Fig. 10 — Video data output-data stream.

camera. The camera output was displayed on a video monitor and as an A-scope presentation for image quality evaluation.

For data readout, the output from the laser is collimated and filtered by a beam enlarger pinhole combination. The enlarged beam is directed to the holographic storage card. The beam passes through the storage card to interrogate the hologram which is on the face of the card nearest to the readout camera.

Fig. 9 is a photograph of the reconstructed information as displayed on the monitor. The nonuniformity of the information is not a defect in the holographic recording system, but of the CRT printer used to generate the source material. The same nonuniformity present in the monitor photograph can be seen in the object array of Fig. 4, which served as the input to the system. Alignment of the computer of CRT converter is called for.

An oscilloscope with its delay sweep triggered to the vertical synchronization pulse of the vidicon frame and the line sweep triggered to the horizontal sync pulse was used to obtain A traces of the video signal as a signal data line of the reconstructed array. Typical tracings are present in Figs. 10a and b. These traces which were taken at standard video rates show a high signal-to-noise ratio and low spurious signal responses.

The design of a roller pressing system of the type shown schematically in Fig. 11 for a tape system provides a distorition free copy of the nickel plated master.

Conclusions

The advantages associated with a man/machine interface device utilizing holographically stored documentation have been verified. A holographic document viewer incorporates a new technology which can reduce the user problems caused by the creation of large amounts of documentation in association with automatic support systems. The major reasons for utilizing holographic techniques for memory applications are: a compact high-density data storage, a redundant storage media, and a rapid and inexpensive duplication process. The characteristic of precise registration of holographically stored images independent of the position of the storage medium allows utilization of well known mechanisms to manipulate the stored data. Holography has enabled the use of a single medium which is capable of replacing the three media (paper, magnetic tape, and microfilm) currently used.

Acknowledgement

Some of the work reported in this paper was supported under government contract. Under Contract No. DAAA-25-74-C-0301 for Frankford Arsenal, work was performed on a holographic digital data storage system. Under Contract No. DAAH01-72-C-0567 for MICOM, holographic techniques were applied to test station design for the Land Combat Support System.

Reference

1. Hannan, W.J., et al, "HoloTape A Low Cost Prerecorded Television System Using Holographic Storage", *Journal of the Society of Motion picture and Television Engineers*, Volume 88, Number 11, November 1973.

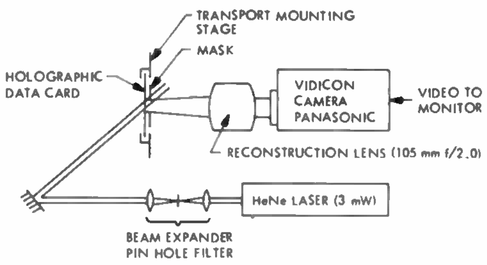

Fig. 8 — Feasibility readout system schematic.

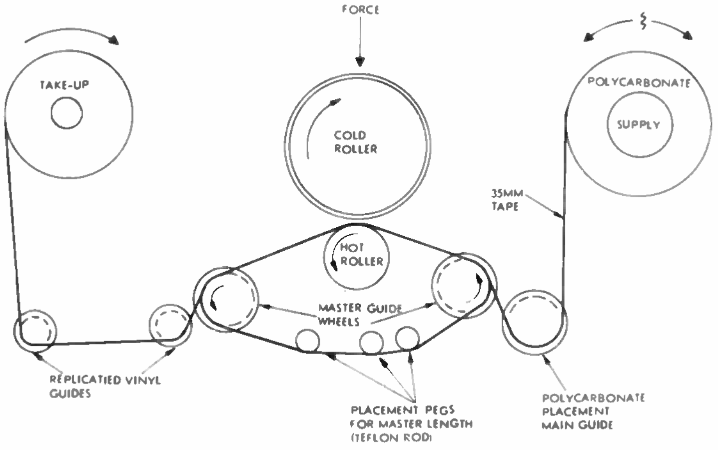

Fig. 11 — Roller press-tape system.

Infrared testing for an enhanced ATE system

R.B. Merrill| D.R. Bartlett

A new approach for fault isolation of printed circuits boards using infrared testing is under development. Both infrared and conventional test methods are being considered to improve ATE system performance. Fault isolation by infrared testing can eliminate the need to probe components, reduce the number of fault isolation tests, and reduce the time to isolate a fault. This paper proposes a truth table approach to fault isolation of analog printed circuit boards. The approach predicts circuit board temperture from the electrical powers dissipated in the components. Computer-aided test program generation and the configuration and usage of an infrared enhanced ATE system are also discussed.

THE FIRST requirement of a printed-circuit-board automatic test equipment (ATE) system is to determine that a unit is functioning within its performance requirements. To do this, involves the application of stimuli and loads and the evaluation of circuit response under specified conditions. The response characteristics of almost all printed circuit assemblies are specified in terms of conventional electrical parameters, *e.g.*, voltage, current, phase, resistance, etc.

The second requirement of a printed-circuit-board ATE system is that, once a functional failure has been detected, a diagnostic routine be entered to isolate the fault to the lowest replaceable piece part.

Automatic testing considerations

Third generation ATE systems have proven to be effective in determining functional performance of printed circuit boards through state-of-the-art electronic test techniques. Fully automatic functional go-chain testing can be accomplished cost-effectively using these computer organized ATE systems. Conventional electronic test methods therefore satisfy the first requirement of determining that a printed circuit board is functioning as specified.

Conventional electronic fault isolation routines, however, are not always fully automatic. Even some of those conventional routines which are fully automatic take significant time to execute depending on the number and types of faults to be isolated. Test techniques that improve conventional electronic fault-isolation methods would minimize the following factors:

- Dependence on manual action such as the probing of components with power applied; disconnecting (unsoldering) components; and use of manual test equipment such as oscilloscopes.
- Test time required to isolate faulty components. This time will vary considerably depending on the board complexity and the failure mode. For discrete component analog boards of moderate complexity (less than 100 components), the time is estimated to be as much as thirty minutes.
- Dependence on well trained and skilled operators to make decisions; the possibility of human error can lead to incorrect fault isolation.
- Amount of technical documentation to supplement ATE directed routines.

IR testing improves ATE fault isolation

There are two types of responses that can be obtained when a printed circuit board is electrically energized. There is the well known electronic response, and there is also a thermal response. Conventional ATE methods have been concerned with evaluating only the electronic response. The thermal response can be determined by measurement of the emitted infrared radiation. This response can supply additional information about the electrical performance of a board. This is based on the fact that the infrared radiation is proportional to the electrical power (I^2R) dissipated as heat by the board. The Stefan-Boltzmann Law defines the relationship between the absolute temperature T (in °K) of a body to the infrared radiation W (radiant flux in

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R.B. Merrill, Senior Engineering Scientist, Government Communications and Automated Systems Division, Burlington, Mass received the BA in Physics from Harvard before joining RCA in 1950. From 1964 to 1973, he managed several groups working on electro-optical research, design, development and field test projects including: low light level television cameras; infrared solid state mosaic camera and area flash detector; systems involving laser illuminators and electronically gated television cameras; high resolution return beam vidicon and scan converter tube development; high resolution television systems for real-time reconnaissance; and electro-optical space surveillance sensor performance analysis. Subsequent responsibilities have included study and preliminary design of advanced electro-optical systems. Mr. Merrill, a member of IEEE, SPIE, and RESA, is the author of "IR Vidicon Measurements of Missile Plumes," *Proceedings of IRIS*, Vol. 6, No. 1 January 1961, and the chapter, "Radar and Infrared Homing Guidance," in *Handbook of Astronautical Engineering*, McGraw-Hill, 1961.

mW/cm^2) emitted per unit area, by the expression:

$$W = \epsilon\sigma T^4$$

where ϵ is the emissivity (a surface characteristic) of the body, and σ is the Stefan-Boltzmann constant. It is empirically obvious that the temperature of a component is dependent on the power dissipated in the component. An analytic relationship between the power dissipated by a device and the temperature of that device involves the physical characteristics of the device (mass, specific heat, etc.), and the physical characteristics of its environment (mounting configuration, mass of the assembly, thermal conductance, heat transfer by convection to the ambient, etc.), as well as the electrical power dissipated as heat in the device.

An infrared scanner can measure the temperature of components and/or thermal nodes on a board without the need to physically contact the board. Additional data to aid fault isolation can be measured for components and circuit nodes that are otherwise not accessible without probing. An infrared scanner, such as that made by Vanzetti Infrared and Computer Systems, Inc., can be computer controlled to measure the infrared radiation at a number of preselected points on a board. All circuitry and components that could cause functional failures can be measured with one infrared scan. Thus all data necessary to perform fault isolation can be obtained in one test, instead of conventional electronic test methods where data acquired by serial tests can become a length procedure.

Certain criteria must be met for infrared testing to be effective. One requirement is that the IR procedure take less time to isolate a fault; others are that procedures be fully automatic, generation of tests be simple, and that the test design be cost effective. To be simple and cost effective, the test programming should lend itself to computer-aided test-design techniques.

When to use IR testing for fault isolation

There are three general classes of printed circuit boards which ATE systems must test. Fault isolation of the different classes is necessarily done in different ways. IR test techniques are more effective for fault isolation of analog and hybrid boards than for digital boards. Digital boards require a large number of stimulus patterns (combinations of *ones* and *zeros* at the circuit inputs) to fully exercise the circuit to determine the presence of a fault. IR measurements for each input pattern would be necessary for isolation of the fault. Such isolation methods take time and since most digital devices are low-mass items, thermal interaction between components can *mask* the presence of a faulty device. This "thermal masking" (*i.e.*, the increase in the temperature of a device due to heat transferred to it from nearby devices rather than from heat internally generated by electrical power dissipation) is of particular concern in densely packed circuits — a typical configuration for today's digital printed circuit boards. It is not the intent to imply that there is no future for IR fault isolation of digital boards. It is considered that digital-board diagnostic test programming is adequately covered by existing computer-aided test design.

Fault isolation of analog and hybrid boards has typically been a more difficult task for conventional ATE systems. Analog components can fail in essentially an infinite number of ways. For instance, a carbon composition 1 kilohm (± 10%) resistor can fail high at an infinite number of values between 1.10 kilohms and infinity. Such a large number of failure modes can make for very involved and time consuming conventional isolation routines. A functional failure can be caused by many individual component faults. Often, components are not hardwired to test points accessible to conventional electronic test equipment. However, infrared testing can measure such inaccessible components since IR testing is a non-contact technique. Infrared testing of analog and hybrid boards, therefore, provides valuable supplementary data for fault isolation. Infrared testing can be used effectively in view of the following considerations:

a) Analog boards typically dissipate (or can be made to dissipate) significant amounts of power; therefore they radiate in the IR region at readily measureable levels.

b) The power dissipated in an analog component is directly related to the signal being processed (stimulus), therefore within some limits, the power can be controlled.

c) The power dissipated in an analog component for normal and faulted conditions is calculable by the use of computer programs designed for circuit analysis.

Current infrared testing techniques

The current approach involves comparison of the infrared signature of a *board under test* to a standard infrared signature for that board type. The standard infrared signature is established by IR measurement of a statistically valid sample of boards known to be good. Existing infrared printed-circuit-board testers display the IR deviations of the test board from the standard. The deviations are analyzed by a manual procedure requiring a skilled operator. This involves referring to the board schematic to determine subjectively what component has most likely failed — from knowledge of which components are hotter and colder than the standard.

Therefore, a new approach discussed here is aimed at providing fully automatic fault isolation; it is compatible with the concept of an ATE system.

Truth-table technique for fault isolation by infrared

Infrared measurements provide a means to determine the temperature of particular locations on a printed circuit board. It has been determined that the most desirable points to examine to

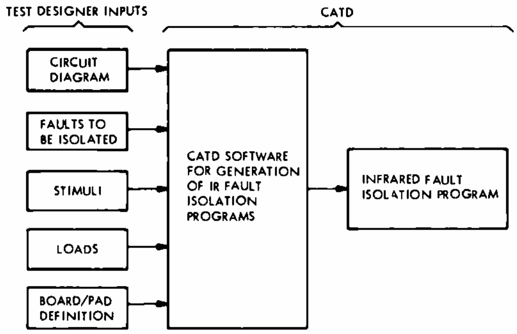

Fig. 1 — Infrared fault-isolation program design.

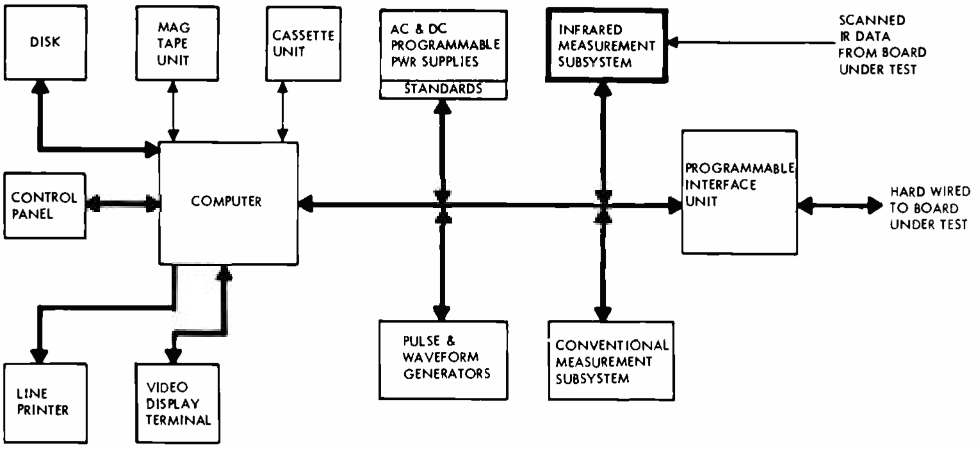

Fig. 2 — IR enhanced ATE system block diagram.

evaluate circuit performance are the component pads on the back side of a circuit board. This is more advantageous than front-side scanning since: different components have different emissivities; component locations vary from board-to-board of the same type; and components (even from the same vendor) are often different. Also, the temperatures of component pads depend primarily on the heat input to the pads conducted by the component leads. The heat input is proportional to the powers dissipated in the components.

The fault-isolation approach under development is based on the premise that the temperature of a particular pad can be predicted by the power fed into that pad. Fault isolation is accomplished by comparison of power-and temperature-truth tables. The test designer using computer-aided techniques, creates truth tables which predict temperatures based on powers for each fault. An infrared scanner can measure the temperatures of a faulty board and an ATE system can create a truth table based on these temperatures. The fault can be uniquely identified by comparing the temperature-truth table to the power-truth table. There are significant advantages to such a fault isolation approach:

a) The test designer does not have to rely on a "standard" signature. A "standard" signature would be difficult, at best, to obtain, either analytically or empirically.

b) The creation of the power truth table can be accomplished by computer-aided test design (CATD)

Computer-aided test design (CATD)

Fig. 1 shows the infrared fault isolation program design process. The test designer determines stimuli and loads for the board to be tested. The stimuli and loads are chosen to cause power dissipation in the components to be isolated. This information along with the electrical model of the circuit, are inputted to the circuit analysis portion of the CATD program to compute the powers dissipated in the components for the nominal and faulted cases. The program assigns designations to the pads of the components. The power in each component pad for each fault case is then computed.

These values are determined from knowledge of the total component power dissipation and the percentage of the total power dissipated as heat in each pad. The CATD program then compiles this information in the form of a truth table which uniquely identifies each fault. The truth table forms the basis of an infrared fault-isolation program.

An infrared enhanced ATE system

Addition of infrared test capability to a third-generation ATE system such as the RCA developed EQUATE is relatively straightforward. Fig. 2 shows a functional block diagram of an infrared enhanced ATE system. All the hardware elements of the conventional EQUATE system are shown in the diagram. The infrared measurement subsystem hardware is interfaced to a computer I/O channel similar to the other EQUATE system elements.

The infrared measurement subsystem contains the infrared detector, an x-y scanner, detector processing electronics, and an analog-to-digital converter. This subsystem measures the IR radiation from preprogrammed points on a printed circuit board. The radiation data is converted to temperature data in digital form. The computer acquires this digital data directly to create a temperature truth table for use in fault isolation. An appropriate subroutine for handling the infrared subsystem is added to the ATE operating software. Fig. 3 shows a standard rack configuration of the infrared enhanced ATE system.

Acknowledgment

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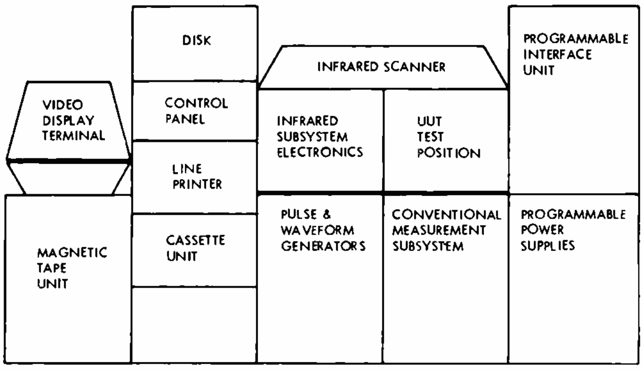

Fig. 3 — IR enhanced ATE system configuration.

AIDE
automated image device evaluator

E. W. Ketler

Presently the Automated Image Device Evaluator (AIDE) System is being implemented at the Burlington Operation. It will demonstrate automatic testing techniques for imaging tubes — in particular, second-generation image intensifiers. The AIDE system takes full advantage of hardware and software elements of the Army's EQUATE system in combination with a return-beam vidicon as the primary imagery measurement sensor. This high-resolution sensor, when merged with EQUATE not only measures the modulation transfer function (MTF) of the image tube, but also determines the overall quality of the tube.

E.W. Ketler, Senior Member, Technical Staff, Government Communications and Automated Systems Division, Burlington, Mass., received the BS and MSEE in 1965 respectively from Cornell University. After graduation Mr. Ketler joined RCA and was assigned tasks in circuit design for Ground Support Equipment and Analysis in Stabilization Control Systems. From 1967 to 1971, he was engaged in low-light-level television (LLLTV) design which has included the design of video processing, synchronization, and control circuits for Project Red Flame, TRIM, and COBRA. During this period, Mr. Ketler also conducted studies on Video Tracking, Automatic Light Control, and Image Motion Stabilization. In 1971, Mr. Ketler joined the Automatic Test and Monitoring Systems group at Burlington, where he was responsible for product improvement of LCSS Automatic Test Equipment. Mr. Ketler's most recent assignment has been project engineer responsible for the Automated Image Device Evaluator (AIDE) electrical design. Mr. Ketler is a member of IEEE, Eta Kappa Nu, Tau Beta Pi, and Phi Kappa Phi.

A NEW GENERATION of image intensifier tubes incorporating the micro-channel plate amplifier have higher gains, but are one-fifth the size and one-half the cost of earlier first-generation tubes. For the military, traditionally the largest user of image intensifiers, these tubes offer new and widespread applications such as pocketscopes and helmet-mounted binoculars. Increased use of these devices will definitely lead to logistics problems, especially in the area of testing a sophisticated electro-optical device. The Army Electronics Command (ECOM) realizing the potential quantities of second-generation image intensifiers in the Army inventory, has sponsored the AIDE program to find a rapid, accurate way of evaluating these tubes.

Because of the increasing complexity and rigid performance requirements of image tubes, present manual test methods are time consuming and require highly specialized test personnel. In addition, and perhaps most significantly, the visual nature of interpreting image-device test results, such as resolution and image quality, is extremely subjective. This allows a considerable margin for error in the acceptance or rejection of a tube under test (TUT).

AIDE has been designed to perform meaningful objective testing accurately and quickly with minimal operator intervention. Subjective measurements which have been made visually in the past will be performed by sophisticated software algorithms using the RCA-developed return-beam vidicon (RBV) camera as the high-resolution substitute for the eye.

This paper describes the AIDE system with particular emphasis on the RBV sensor. Also, measurement techniques are described which illustrate the inseparable software/hardware relationship.

Tube under test

A basic understanding of Tube Under Test (TUT) with its unique properties will provide insight into the test techniques and physical hardware of the AIDE system. The particular device for which AIDE is designed is a second-generation image intensifier. A conventional first-generation intensifier tube consists of a photocathode input surface, electron lens, and a phosphor viewing screen. The light image that falls on the photocathode triggers the emission of electrons. The electrons are accelerated across a potential of several thousand volts towards the phosphor screen where they are focused and converted back to a light image higher in intensity than the input image. Such a device can achieve light image gains of 100. Recent developments make it possible to increase the gain of the intensifier by the addition of an electron multiplier in front of the phosphor screen. This "micro-channel plate" increases the gain of the intensifier to above

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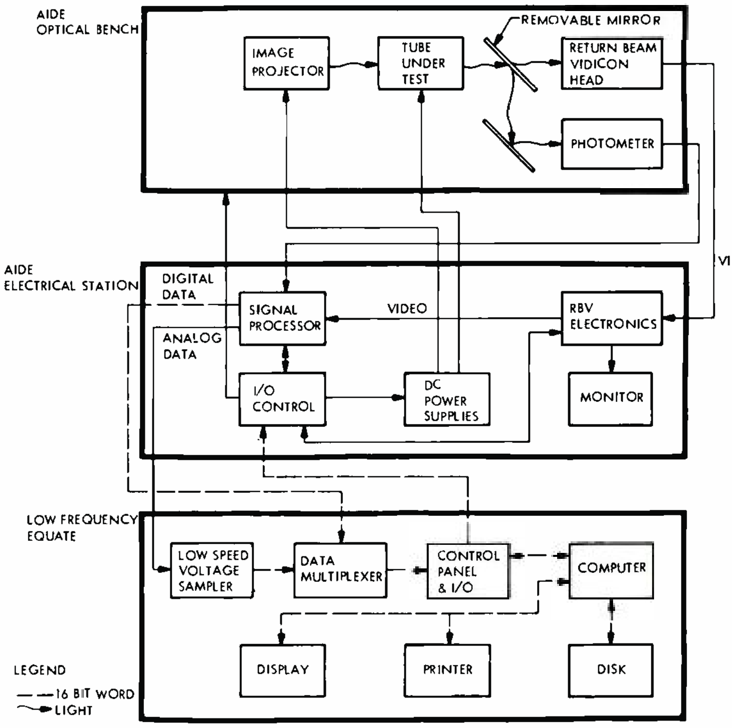

Fig. 1 — Simplified diagram of the AIDE system showing the functional interrelationships among the three major subsystems: the optical bench, the electrical station, and EQUATE.

10,000, thus characterizing the second-generation intensifier.

Production tests on the intensifier can be categorized into imaging and non-imaging tests. Non-imaging tests include luminous gain, equivalent background input (EBI) and signal-to-noise (*S*/*N*) ratio of the phosphor output. As mentioned previously, the light gain can well be over 10,000 times. EBI is a measurement of output light with no input illumination. Temporal signal-to-noise of the light output is a particularly important parameter because it relates to the detection capability of the intensifier at low light level.

Imaging tests are more difficult to measure because they are often subjective in nature. Cathode and screen quality is a test which refers to blemishes that exist on the phosphor screen, fiber-optics or photocathode surface which distract the observer. Modulation transfer function (MTF), which is the spatial frequency response of the tube, describes the ability of the tube to pass image detail. Limiting resolution, which can be related to MTF and *S*/*N* as discussed herein, is the best known of the intensifier parameters.

Test system approach

Several system guidelines were established at the onset of the AIDE design and development. First, it was imperative to reduce subjective tests to objective tests to the maximum extent. An early decision was made to use a return-beam vidicon as the sensor to replace the eye to accomplish this task.

To minimize test equipment complexity, only tests associated with low yield are to be performed. So-called "design" parameters are not tested on this test set.

A further simplification in equipment implementation is to have only *one* test station for testing the TUT. At this station, multiple tests are to be performed by each of the two measurement sensors, the RBV and the photometer.

Maximum usage of the EQUATE technology and hardware described elsewhere is used to reduce developmental costs. The computational and storage capabilities of the EQUATE computer are particularly useful for the image processing needed in performing TUT imaging tests.

Automation is used where it is cost effective. Certain tasks are left to the operator, such as focusing the TUT within the test system. However, exact up-to-date manual instructions are provided to the operator by the computer display.

System description

The Automated Image Device Evaluator System (Fig. 1) was largely developed by integrating existing hardware designs (thus minimizing the development) into a test system for image-intensifier tubes.

Optical bench

The optical bench assembly contains all the electro-optical stimulus, measurement detectors, and mounting hardware necessary to directly interface with the tube under test (TUT). Major assemblies are the calibration projection unit, the return-beam-vidicon head, and the photometer.

The calibration projection unit supplies all the light stimuli required for the eight non-imaging and imaging tests mentioned herein. Major functions of the unit are:

1) Provide a diffused, but uniform, illumination field sufficient to cover the entire photocathode area of the tube under test.
2) Provide light flux levels which are calibrated over a range of 2 x 10^{-} to 10 footcandles (approximately eight orders of magnitude). The source color temperature is 2854 ± 50° K.
3) Provide the necessary projection optics and focusing geometry to project accurate undistorted images of MTF and resolution patterns onto the TUT photocathode.

Because of the stringent color temperature and uniformity requirements of illumination, the projector consists of a tungsten-halogen lamp within an integrating shpere. To obtain the dynamic range of light levels without affecting color temperature, eight selectable apertures of different areas are situated at the exit port of the integrating sphere to attenuate the light in decade steps. Both the light level (aperture selection) and the pattern selection are under computer control by the use of stepper motors.

Sensor selection

Non-imaging and imaging properties of

the TUT output need to be sensed. The basic function of the two sensors in the system is to convert optical patterns at the output of the image-tube test specimen into electrical signals suitable for detection of performance characteristics. Of course, a sensor of two-dimensional imaging capability is the most versatile type for imaging tests and, therefore, most amenable to use in an automatic test configuration. Mechanical set-up is minimized. A serial readout allows efficient and unambiguous conversion of high resolution two-dimensional patterns into a serial stream of data which can readily be accepted by data processing hardware.

Of all the two-dimensional sensors considered, the 4-½-inch return beam vidicon has been chosen as the most appropriate sensor because of its outstanding qualities of high spatial frequency response, high signal sensitivity, wide dynamic range, large image format, and an integrating photosurface. The performance of the RBV has been covered in the literature by Dr. O. H. Schade, Sr.,[1] RCA Consultant, and by M. J. Cantella[2], of RCA Burlington.

These qualities of the RBV are important to the successful testing of second-generation image intensifiers as can be cited below:

1) The RBV has a very high modulation transfer function characteristic, typically 50% MTF at 30 line pairs/mm. Overall resolving power of up to 100 lp/mm has been demonstrated. The test system, especially the sensor, must have substantially higher MTF than the TUT, if the MTF of the image intensifier is to be measured accurately.

2) Its format allows coverage of the entire TUT image format without any mechanical positioning, thus minimizing test time and mechanical complexity. Also, the large format capability of the RBV greatly facilitates the determination of the low frequency normalization of the MTF measurement.

4) The effective storage and integration capability of the RBV target provides a significant improvement in S/N of the image intensifier whose screen brightness generally fluctuates in accordance with the photoelection statistics associated with low level input illumination levels.

When non-imaging tests are being performed, a mirror is positioned in the optical path to redirect the TUT light output to the photometer which is off-axis. A low-noise photomultiplier tube (PMT) with an extended red (S20) response is the photometer sensor. Because of the PMT's high-sensitivity and low-noise characteristics, it is ideal for low-light-level measurements typical in image intensifier testing. This photometer is also used for the periodic calibration of the image projector unit. With the TUT removed, the photometer can measure the luminous light level and color temperature of the projector which can be adjusted if necessary.

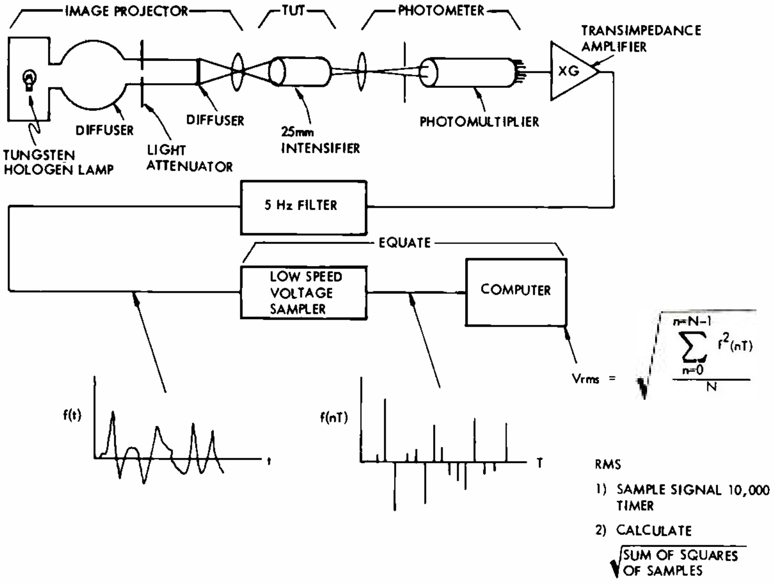

Fig. 2 — Signal-to-noise ratio (S/N) measurement setup and technique.

AIDE electronic station

The AIDE electronic station houses power supplies, signal processor, photometer electronics, RBV electronics, I/O controls, and normal housekeeping controls necessary to operate the AIDE optical bench and to interface with the low-frequency EQUATE system. All electronic assemblies are under computer control to minimize operator intervention.

Within the electronic station, the signal processor is a key device. It preconditions signals from the optical bench sensor output so that they are suitable for processing by the EQUATE low-frequency automatic test system. Specifically, it compresses the sensor output data rate so that the EQUATE computer can process the data efficiently. MTF and blemish test techniques discussed herein indicate how the 10-MHz analog data rate of the RBV is transformed to rates acceptable to the EQUATE subsystem.

The I/O control assembly not only provides control to the AIDE system, but also serves as a data buffer between the AIDE system and low-frequency EQUATE. An RBV electronics assembly contains electronic camera functions such as a video amplifier target control, synchronizer, deflection drivers, and power supplies.

EQUATE

The Army's EQUATE system can be tailored to accommodate a wide range of testing requirements through the utilization of fully integrated modular hardware and software. A minimum configuration of the control and measurement elements of EQUATE to support AIDE is an excellent example of the EQUATE system flexibility. This minimal system is provided with a dedicated NOVA 800 mini-computer with 32,000-word core memory together with its peripherals. The control panel and video terminal provide the primary interface between the operator and the AIDE system. A low-speed voltage sampling unit is the main measurement "building block" that is used by AIDE. It samples the incoming signal from the signal processor and converts these samples to digital data; this sampled data is processed in the NOVA computer by one of a number of waveform analysis programs. A digital input port is also provided by the data multiplexer to accept parallel digital words from the AIDE station electronics at speeds up to 1 MHz.

Non-imaging measurements

Measurement of luminance gain and EBI of the TUT is analogous to measuring the voltage gain and dc voltage offset of an amplifier. Given the light input to the tube, and measuring the light output of the TUT, gain and equivalent background input (EBI) parameters are derived by simple arithmetic techniques quickly and correctly by the EQUATE computer.

Signal-to-noise ratio of the image intensifier is one of the more important non-imaging tests for it is used to determine limiting resolution as will be seen herein. Fig. 2 shows the test flow from stimulus to computer processing.

A uniform illumination from the image projector is placed at the TUT input. Output energy from TUT phosphor screen is sensed by the photometer in a 0.2-mm diameter field. The photometer output, once it is filtered, (5-Hz bandwidth) is sampled and processed by the low frequency measurement system of EQUATE. First, the true rms value of the ac-coupled waveform is determined by randomly sampling the input waveform a total of 10,000 times, squaring each sample and calculating the square root of the average squared value. Likewise, the dc value is determined by averaging 1000 samples — S/N is then determined by the ratio of dc signal to the rms value. However, the rms noise and dc offset of the photometer, attributable to photomultiplier dark current, must be removed from the measured S/N to obtain the actual S/N of the TUT.

More sophisticated methods are available to measure S/N which utilizes the fast Fourier Transform (FFT) algorithms implemented in the EQUATE software. However, the method previously described is more than adequate for S/N measurements. FFT techniques are more useful in power spectral density measurments of TUT phosphor output.

Imaging techniques

Among the functional tests which are performed on the second-generation intensifier tube, the four imaging tests use the 4½-in. return-beam vidicon as the primary sensor for test automation. The methods of implementing these tests are described below:

The image scanning properties of the 4½-in. RBV are fully utilized in performing the photocathode, micro-channel plate, and screen-quality test. A test implementation is illustrated in Fig. 3. Again, the TUT photocathode is uniformly illuminated (bar pattern is removed) with the illumination adjusted to give the best blemish contrast. Next, the RBV senses the entire TUT phosphor output with a square raster format consisting of 1500 tv lines. Each line is further divided into 750 elements. This means that the RBV camera is sensing a 750 × 1500 array of information.

The input video from the scanned RBV is routed to the signal processor blemish channel where it is buffered and split into two channels. In channel 2, the video signal drives the finite time integrator, the output of which is the integral over the T most recent seconds of the input video. The output V_B, therefore, represents the background against which video in channel 1 is compared in a voltage comparator.

Its output is a logic level "1" pulse whenever the RBV raster is scanning a TUT blemish. A pulse-width discriminator eliminates small pulses so that the computer memory is not needlessly filled with blemishes smaller than those of interest. A serial pulse train with an information rate of 8 MHz is then con-

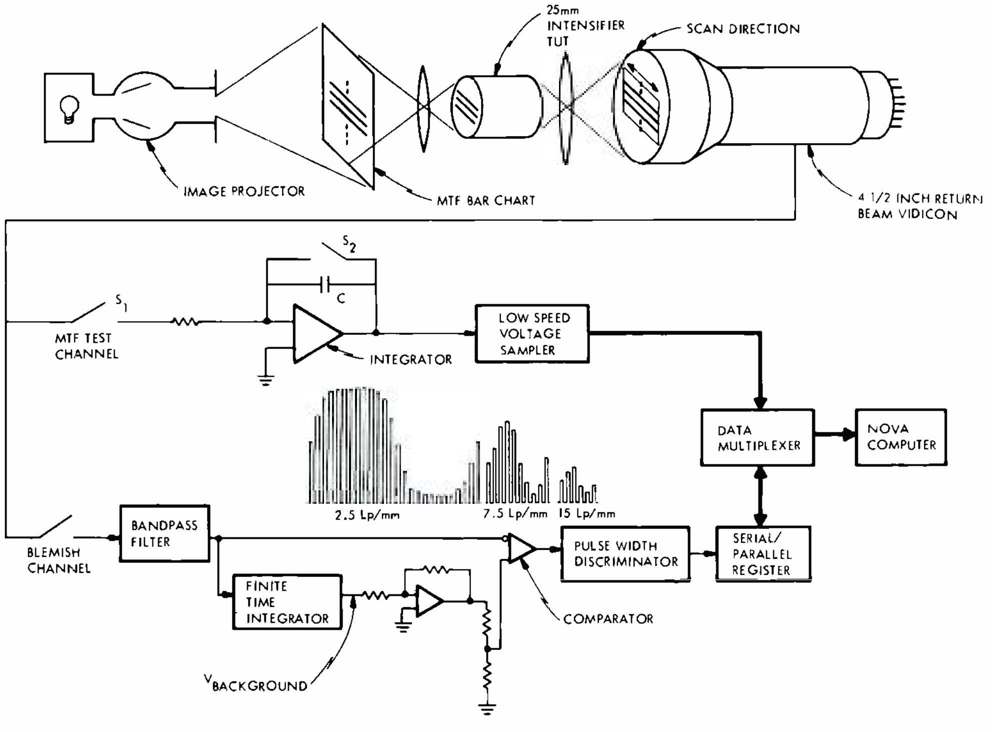

Fig. 3 — Modulation transfer function and blemish testing technique.

verted to 16-bit parallel words which are in turn transferred to the NOVA computer at a 500-kHz rate, well within its 1.25-MHz capability.

Since the RBV scans 1.125 million elements (750 × 1500), a total of 75,000 16-bit words need to be transferred to the computer. However, only blocks of 1500 words are transferred at one time and are partially processed before the next block is accepted. Once in core memory, these words are scanned for "one" bits which represent parts of blemishes. The x-y coordinates of each one-bit is calculated knowing the time sequence of the incoming data. Once all the data has been received and all the *x-y* coordinates of the "ones" have been established, a blemish is built by counting the number of contiguous *x-y* cells. This count represents the size of a blemish. Finally, the software algorithm sorts the blemishes in accordance with size and location to see if the pass criterion is met.

Modulation transfer function

Modulation Transfer Function (MTF) measurement of the second-generation image intensifier at low light levels (5×10^{-4} footcandles) is not a trival problem. At these light levels, the MTF is difficult to measure because of the high noise content of the image intensifier output.

Before the amplitude response of the TUT to a particular spatial frequency can be accurately determined, many samples of the amplitude response must be averaged in order to reduce the corrupting noise to a level consistent with the desired measurement accuracy. The S/N of the measurement improves by the square root of the number of samples averaged. The novel measurement technique illustrated in Fig. 3 does this averaging by utilizing both the storage capabilities of the RBV and the computational capability of the EQUATE system.

For this test, bar patterns of appropriate spatial frequencies (2.5, 7.5, 15 lp/mm) are sequentially projected onto the TUT, the output of which is re-imaged onto the photocathode of the RBV such that the bar patterns are parallel to the scan direction. These bars are elongated to permit large sample averaging along a scan line. The necessary sample averaging for accurate low-light-level MTF measurement is accomplished in the photocathode of the RBV (1 second) and by integrating the video signal along the bar pattern.

Referring to Fig. 3, S1 is closed and switch S2 is opened whenever the scanning beam is on the MTF bar pattern so that the camera video is integrated during this time. As the RBV scanning beam leaves the MTF bar pattern along a horizontal scan line, switch S1 is opened — holding the integrated MTF sample until the end of the scan line. A/D conversion by the EQUATE occurs at this time. At the end of the scan line, S2 closes — dumping the integrating capacitor C. The cycle repeats, and a new MTF sample is taken on each scan line on the MTF pattern.

Video MTF samples presented to the EQUATE appear as shown in Fig. 3. These are samples of the system squarewave response and must be converted to a normalized sinewave response before the measuring system MTF response can be removed to yield the image intensifier MTF. A graphical Fourier analysis on the data array is performed by the EQUATE software to extract the fundamental sinewave response. Since many bars are scanned at each spatial frequency, sufficient data is provided to cause additional averaging in the computer thus enhancing the accuracy of the measurement.

Resolution

Of particular interest is the limiting resolution measurement which has been a very subjective measurement in the past. Dr. O.H. Schade, Sr. has shown in the literature[3] that limiting resolution can be calculated by knowing the MTF and S/N of the device. In particular, the image must have a detailed signal-to-noise ratio (S/N_d) of a certain threshold value for the detection of a resolution test pattern (3-bar Air Force pattern). This S/N threshold value is two for a 50% probability of resolving the 3-bar pattern.

S/N_d can be calculated by the following expression:

$$S/N_d = S/N_m \, (A_o/A_m)^{1/2} \, F_a$$

where S/N_m is the measured signal-to-noise; A_m is the area of measured aperture; A_o is the area of 1 bar of Air Force, 3-bar test pattern; and F_a is a MTF-dependent factor. F_a can be calculated knowing the MTF of the device along with other physical characteristics. The detailed relationship is discussed elsewhere.[3]

Conclusions

The techniques developed for the AIDE program will allow practical production testing of imaging devices. In particular, subjective measurements usually performed by the eye, such as limiting resolution and image quality, have been reduced to quantitative automatic-test-equipment measurements. These measurements are well within the capability of the return-beam vidicon and photomultiplier sensors, along with the computational capability of the EQUATE low frequency automatic test system. Although the AIDE is not completely automatic, sufficient computer control and operator instructions have been included to provide uniform, standardized, and repeatable measurements, along with a test-time reduction so necessary in production testing. The AIDE hardware is specifically configured to test second-generation image intensifiers; however, it employs techniques which can be used for testing other high-performance imaging devices.

Acknowledgments

The author acknowledges his co-workers at Burlington who have made many contributions to this effort. Credit is due to D. Dion and M. Cantella, of the Radiation Systems Group, for their many valuable contributions in the AIDE Program, especially in the area of video processing and RBV applications. A special appreciation is extended to Dr. Otto H. Schade, Sr., RCA Consultant, for his many ideas on MTF and Resolution Measurements on Imaging Devices.

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User-oriented data cartridge recording system

C. R. Horton | L. W. Dobbins

New generation satellites such as ERTS present a new challenge to the data recording industry. Continuous wideband data creates an enormous storage/retrieval problem. Recently developed high density tape storage solves the volume problem but does not provide fast access. Clearly, some cartridge-type device is required. A similar problem faced the broadcast tv industry. Cartridge equipment was developed to allow automatic programming of short segments. This paper describes application of this technology to present and future data storage requirements. With the technique described, ERTS data can be segmented into groups of ten frames each and stored in easily accessed tape cartridges. Access to 100 Terabits in a few seconds is provided by one TCR-100 with its data file. Many mass data system applications can be imagined!

IMAGE DATA sensor systems have caused a quantum jump in telemetered data throughput. A typical multispectral sensor (MSS) from an Earth Resources Technology Satellite (ERTS), such as in Fig. 1, creates approximately 180 million data bits every 25 seconds. The return-beam vidicon (RBV) sensor, after it is turned on, will create an equal burden. Other system applications such as those in the insurance industry are experiencing similar data flow. Transmission and data recording subsystems grew to meet the challenge. A challenge remains. This voluminous data source must be made quickly and automatically available to the user via efficient data processing/distribution centers. The objective is data transfer to user as useful and timely information.

Fig. 1 — This ERTS MSS frame over Greece contains approximately 180 million bits of data. One 4-band frame is sensed and recorded every 25 seconds, telemetered to ground stations and re-recorded on high density magnetic tape. RCA 15-Mb/s digital tape recorders are employed in both spaceborne and ground station applications.

This paper describes the need for high-density cartridge-stored data, and a proved technique for filling the need. First, the applicability of wideband, broadcast tv recorders to high-density *digital* storage requirements is established. Second, a fully automatic cartridge type system is described [A modified version of the RCA TCR-100 broadcast tv cartridge system, tailored to random access, mass memory system requirements]. Its capabilities are then stated and compared to two other systems. A system "fit" is then suggested.

The need

Table I points out major reasons for high density data storage. Four, RCA high-

Definitions

CVR	Continuous video recorder, which implies that any continuous data stream within the equipment band pass may be recorded, regardless of format.
ERTS	Earth Resources Technology Satellite.
RBV	Return-beam vidicon, a high resolution tv sensor built by RCA Astro-Electronics Division for ERTS.
MSS	Multispectral scanner, a 4-band sensor for ERTS by Hughes. Fifth band may be added to later systems.
S/N	Signal to noise ratio, pp/rms.
Mb/s	Megabits per second.
Frame	2340 lines of ERTS MSS data or 25 seconds of RBV data.
HDMR	High density multitrack recorder, see Refs. 3, 4 and 6.
CCT	Computer compatible tape, one of the ERTS products. One CCT contains one-fourth of a frame, sliced vertically.

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Table I — Tape storage comparison.

System	*Tape volume* 1000 *frames* (*ft*^{3})	*Tape cost* 1000 *frames* ($)	***ERTS MSS frame storage/reel*** (*cartridge*)	*Storage format*
HDMR "CCT"*	0.7	1,000	50 frames	1/2", 2400 ft reel
HDMR cassette	9.2	12,000	1 frame	3M cassette
TCR-100	2.5	2,000	10 frames	2.5x5.0x3.5 in. cartridge
TR-70 ERTS	0.6	1,000	360 frames	2 in. x 7200 ft (14 in. dia.)
Computer tape deck	140	24,000	1/4 frame	NASA/ERTS CCT

* 1/2 inch. 30 track

density tape approaches are compared to standard computer tape. Tape cost and storage volume tell the story. At $3,400/h of MSS, CCT (Computer Compatible Tape) is a luxury, regardless of initial equipment cost. Twenty cubic feet of tape/hour is a tremendous storage and distribution burden.

High-density storage does not completely solve the problem. Data must be transformed into useful information in a timely manner. The "several minutes" average time required to address data on a reel-to-reel machine does not "fit" an on-line production system. To be optimum, data library average access time must be less than the "frame" time. The data processing system must not starve for data. Therefore, on-line cartridge equipment is required. Fig. 2 demonstrates the improvement made possible by one approach, described later.

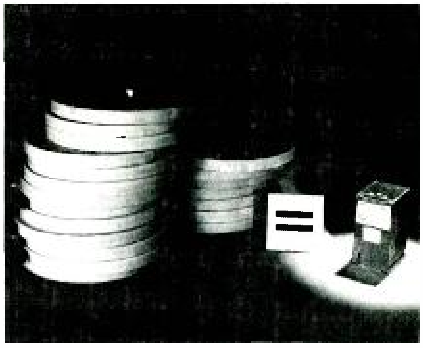

Fig. 2 — Data file comparison. This photograph shows volume and handling advantages made possible by high density cartridges. Comparison is made between high density computer tape and the equivalent tape cartridge.

Smaller scale users do not need this production capability. They should, however, enjoy the advantages of HDMR (High Density Multitrack Recording). For these users, HDMR provides capability to store one full ERTS MSS frame on one standard cassette. Ref. 3 describes the technique in detail. Basically a revolutionary RCA-developed magnetic head technique allows high density recording on standard tape decks, including cassette machines.

TCR-100 cartridge recorder — tv technology again

The use of wideband *serial* recording

Authors Horton (left) and Dobbins at the TCR-100.

Lawrence W. Dobbins. Recording Systems, Government Communications and Automated Systems Division, Camden, N.J., received the BSEE from Auburn University and has completed course work for the Master's Degree at Drexel Institute of Technology. Mr. Dobbins joined RCA in 1955 and has done design work on transverse scan magnetic recorders, optical correlators, and spectrum analysis devices. He also took an active role in the design of optical and electronic systems in the LR70. Mr. Dobbins is presently a Senior Member of the Engineering Staff. He is a member of the IEEE, the Society for Information Display, and the Society of Photo-optical Instrumentation Engineers.

Charles R. Horton, Ldr., Recording Systems Government Communications and Automated Systems Division, Camden, N.J. graduated from the University of Maryland in 1956, and joined the Recording and TV Equipment Section (now Recording Systems) in Camden. He participated in RCA's Graduate Study Program at the University of Pennsylvania where his studies led to the masters degree. In his initial assignment, he participated in the design and development of a miniature spaceborne television recorder delivered to NASA in Houston. In 1969, he was assigned to laser recorder development and became responsible for the LR70 and LR71 high resolution laser scanner/recorders. In 1971, Mr. Horton was promoted to Group Leader with responsibility for laser programs where he became program director for PAR5 development program. Mr. Horton holds one United States patent.

Fig. 3a — TR70-CVR-3E Recorder/Reproducer. This modified tv broadcast recorder allows either 15-Mb/s digital or 7.5-MHz analog instrumentation recording. Either multispectral-scanner (MSS) or return-beam-vidicon (REV) data from ERTS may be stored. The TR70 combines broadcast equipment production base with its inherent standardization, and advanced digital-analog processing techniques.

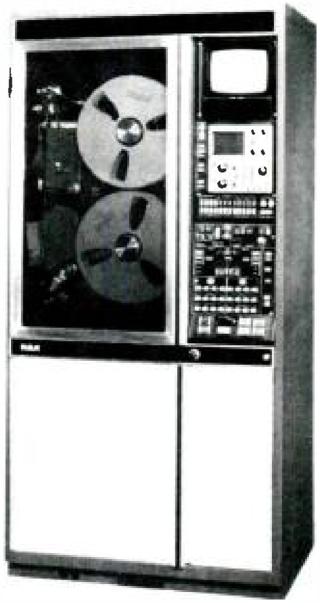

Fig. 3b — The CVR62 Instrumentation Recorder/Reproducer. This recent product in the CVR series allows simultaneous recording of two 6-MHz analog or two 15-Mb/s digital data channels. Modular design allows this recording system to be tailored to a wide range of applications with low non-recurring engineering costs. The latest example is the 15-MHz, 2-channel CVR152.

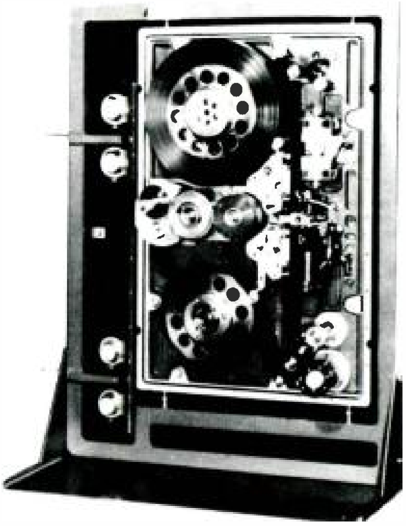

Fig. 3c — ERTS wideband VTR. This spaceborne video tape recorder/reproducer, developed by NASA Goddard, allows recording of 15 Mb/s MSS or analog RBV data, switchable by remote control from the ground.

systems eliminates the entire deskew/inter-channel flutter problem from telemetry data processing systems. One-channel reliability established by the tv industry also eliminates MUX-/DEMUX systems.

The TR70CVR-3E (Fig. 3a) is a modified version of the RCA TR70 broadcast tv color recorder/reproducer, originally designed for high-band television studio record/playback. As a CVR (continuous video recorder), it is capable of recording/reproducing a 15-MB/s digital data stream such as provided by the Multispectral Scanner (MSS) in the ERTS satellite. [CVR instrumentation reorders employ rotary head techniques for continuous, wideband applications via unique playback electronics with closed-loop, electronic timebase correction]. Alternatively, it can record analog signals such as those provided by the ERTS Return Beam Vidicon, with bandwidths to 7.5 MHz. Other uses include recording signals from radar, telemetry, spectrum, i.f., rf, and non-standard tv sources. Approximately seventy units have been modified for instrumentation applications.

The TR70 recorder is in operation at all ERTS ground stations and operates with a bit error rate of 1 in 10^{-7} in the MSS application. The TR70 can operate with tape reels holding up to 7200 ft of tape, providing 72 min. of continuous operation, with a capability of storing 6.6×10^{10} bits. The recently developed CVR62 (Fig. 3b) allows 2-channel recording with similar performance.

Instrumentation recorders in space

The video recorder technology has been successfully employed in space in both digital and analog applications.

The most appropriate example of a spacecraft video recorder is the Earth Resources Technology Satellite video tape recorder shown in Fig. 3c. This device stores image data from the return beam vidicon (RBV) or the multi-spectral scanner (MSS) for 30 min. The two recorder systems aboard each spacecraft allow simultaneous operation of both. The RBV signal is analog video data with a spectrum from dc to 3.5 MHz and is reproduced with a recorder S/N of better than 42 dB. The MSS data is in the form of 15 MBs, NRZ. This is reproduced with a recorder bit error rate of less than 1×10^{6}.

TR70 instrumentation recorder — tv technology for instrumentation

The TCR-100 can be applied to instrumentation requirements (digital and analog) in a manner identical to the TR70 and ERTS spacecraft recorders. The TCR-100 (see Fig. 4) is in production and field proven by more than 100 tv stations.

This unit can be applied to automatic, hands-off programming of high-density data. It is useful in any on-line production situation where sequences of short, back-to-back segments are programmed. It programs, in advance, from one to nine sequences with one to eight events in each sequence. For ERTS MSS, each "event" holds 10 frames (all 4 bands).

Fig. 4 — TCR-100 wideband mass data storage system. Each fully automatic cartridge equipment stores 8.8×10^{12} bits of digital data (or an equivalent amount of analog data). Maximum access time is 25 seconds. These equipments can be "stacked" to provide an even larger data storage/retrieval capability.

Fig. 5 — This cartridge stores ten complete ERTS frames with zero data reformating. It stores easily and protects the tape from dust, dirt, handling abuses and other physical camage. Tape is good for several hundred passes due to *rear side* tape handling.

The TCR-100 uses standard tv, quadruplex tape format. Tape recorded on TR70's or CVR62's can be loaded into cartridges (Fig. 5) and played on the TCR-100. Or, TCR-100 can be used as the primary recording device.

A two-transport system is employed. While one of the transports is playing, the other is preparing itself for the next program event. At the end of each event, in a multiple-event sequence, the machine automatically makes the changeover, complete to the video switch. Then the machine rewinds the played cartridge and returns it to the magazine, clearing the transport for the next cartridge which is automatically loaded and "cued" for the next *play* command. This operation takes less than 25 seconds. ERTS frame time equals approximately 25 seconds; therefore, 100% production factor is achieved.

The magazine holds 22 cartridges with all but the cued cartridges accessible for checking and/or changing.

How it works

Behind the cartridge magazine are two tape transports. The cartridges are automatically transferred to the transport and the tape is threaded. Once threaded, the tape is cued at a point 2 seconds ahead of frame start.

While one transport plays tape, the machine threads and cues the other transport. When the cartridge in transport A reaches a point 2 seconds prior to the frame end, the machine automatically pre-rolls the tape cued in transport B. Two seconds later, the TCR-100 performs the video switch to deliver a fully synchronized data stream to the production system. It then rewinds the tape on transport A and sets up the next cartridge. All this takes place in a few seconds.

TCR-100 flexibility and growth

TCR-100 can store both 15-Mb/s digital and/or 7.5-MHz analog data. This capability is field-proven by hundreds of modified tv instrumentation recorders. Near term growth to 30 Mb/s and 15 MHz has been deonstrated on the latest equipment. Significantly higher rates should probably use HDMR.

Twenty ERTS MSS frames per cartridge could be easily stored on a cartridge by simply pre-processing the data to obtain 100% duty cycle. The 10-frame figure is based on zero modification to the present MSS data stream, which has less than 50% useful data. Preprocessing and recording at half-speed thus doubles density.

Comparison of approaches to 10^{12}-bit storage

Alternative techniques for modular Terabit storage include the RCA TRC-100, Ampex Terabit, and Unicon of Precision Instruments, Inc. (see Table II). The first two approaches employ video magnetic tape recorders, while the Unicon employs an Argonion laser to record on thin metallic film strips.

The RCA TCR-100 offers considerable flexibility in re-arranging data and in gaining access to particular segments due to storage in relatively small cartridges. For example, in ERTS applications, images are produced upon customer request. The cartridge with the desired frame is found and placed in the transport. Threading and cueing are handled automatically. Back-side tape handling reduces wear.

In the Ampex Terabit system, data is stored on large reels of 2-inch magnetic tape. Particular data segments are located by searching along the tape at speeds up to 1000 in./s. Tape and equipment wear are significant. Sequential organization of data is performed by cueing the date on several transports under minicomputer control. Segments are then played in the

Table II — Mass data storage device comparisons.

Comparison basis	*RCA TCR-100*	*Ampex Terabit*	*Unicon Model 192-60*
Technology	Video tape	Video tape	Laser on metallic film
Storage units	Cartridge*	Reel-to-reel	Strip-medium data packs
Data transfer rate (bit/sec)	15×10^6	6×10^6	3.2×10^6
Number of machines per terabit	11	11	8
Comments	Mass produced technology >160 machines	High-speed shuttling causes wear	1 sold nonerasable medium

*Cartridge storage of data allows convenient storage of off-line data. An efficient library layout combined with a *single* TCR-100 allows fast access to hundreds of Terabits.

desired sequence. Each transport system holds two reels of data tape.

In the Unicon, the data packs contain approximately five times as much data as a single TCR-100 cartridge. However, the total storage density is not significantly different on an equipment volume basis. The Unicon is suited only to archival storage since the recordings cannot be erased. Updating is performed by recording in an unused portion of the storage media.

The TCR-100 was first operated in the field in 1970. Since that time, 160 machines have been sold. In addition, the 15-Mb/s digital storage with video tape recorders has been in operation more than a year on the ERTS program. In the TCR-100, read-write heads have an average life of 500 read-write hours. No wear is caused by search/rewind operations. Worn heads are rebuilt inexpensively on a mass-production basis along with standard television recording heads. The Ampex Terabit system is similarly based upon broadcast tv recording technology. However, cartridges are not employed. Therefore, longer access time and high tape wear result.

Production facility

The problem facing an image processing facility is that the image data tapes are produced and stored chronologically while the users want images from any point in time. Since the bulk data is stored on magnetic tape, the correct reel or cartridge must be located, loaded in the tape player, and the tape searched and cued to the proper frame. This operation is considerably facilitated when the data is stored in cartridges. The cartridges are easily handled and loaded. Sequence programming, threading, search, cue, and play operations are all automated, including automatic annotation.

Fig. 6 shows how on-line cartridge equipments could be utilized. Of paramount importance, the data is initally electronically indexed and pre-annotated on the high-density tape so that synchronization of multiple data sources does not become an operational bottleneck. In fact, initial one-time geometry and radiometry correction is feasible for most errors. The sequence of events listed below suggests a possible operations plan.

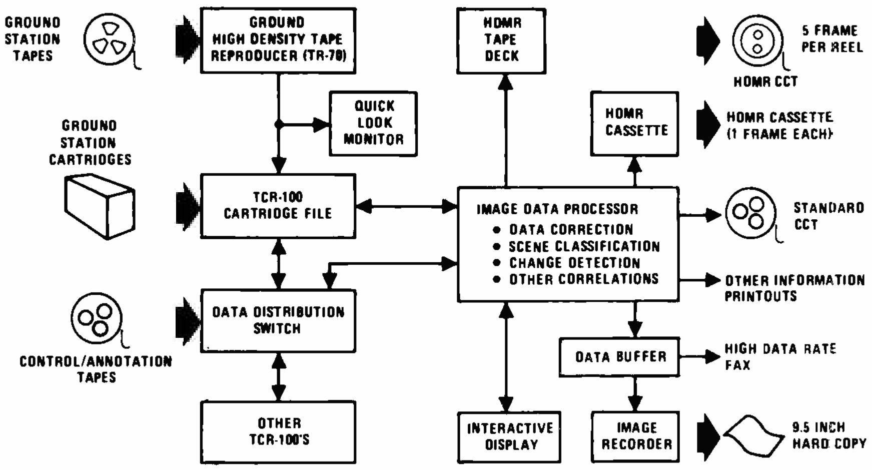

Fig. 6 — Data processing facility. This block diagram shows how high density cartridge equipment could be employed. Huge stores of pre-annotated data can be on-line with access time less than ERTS frame time. This means that 100% production facility utilization is possible. Many errors in the data can be precorrected on a one-time basis.

Axioms

- Library chronologically ordered.
- Cassettes electronically indexed (on-tape).
- Location of on-line data in memory (available as management information output).

Days work setup

- Establishment of user priorities.
- CRT display/edit formulation of program.
- Final program input to system.

Operation

- Operator provides required cartridge interchange.
- Exact frames automatically sequenced.
- Operation can be interrupted for sequence change, dubbing, etc.

This plan assumes that much of the useful (most called for) data is stored on-line, but that an operator-controlled "conventional" library is established for cartridge archive. A suitable floor plan will insure that off-line cartridges are not "lost". Cartridge interchange is established primarily on a user demand basis and computer controlled. Printout of management information is of course available in many forms.

Summary

High-density data storage has been established as a firm requirement. Cartridge storage is seen to offer a distinct advantage. The time savings can be great. Techniques which allow proper image data preparation (pre-annotation and error correction where feasible), automatic production sequence control, and "real-time" 100% duty, image data processing/distribution have been suggested. For earth resource systems to be fully utilized, these techniques (in some combination) should be employed.

Although the emphasis in this paper was on image data systems, it must be recognized that similar problems face other mass data systems. TCR-100 technology, tailored to fit mass-data-user requirements, should offer solution to many seemingly impossible problems.

Acknowledgment

The authors thank the entire Broadcast Systems team for development of the TCR-100. The TCR-100 provides a powerful baseline for a wide range of mass data systems — analog and digital.

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Characterization of materials at RCA Laboratories

Dr. R. E. Honig

Materials characterization continues to be of prime importance to the ever-expanding field of materials research. It provides vital information on structure, defects, and composition of conductors, semiconductors, and insulators, making it possible to control their quality in an unambiguous fashion. Recently, there has been a marked shift of interest from elements to compounds; from bulk materials to surface and thin films; and from average composition to inhomogeneous distribution of impurities. To keep pace with these changes in emphasis, the roster of sophisticated instrumentation is constantly being expanded to include the latest equipment needed to solve problems in this area. The present paper reviews significant developments made in the established areas discussed in an earlier paper, and the methods used illustrated by various examples of problems recently solved. Attention is focused on the difficult subject of surface and thin film analysis, discussing in some detail the complex instrumentation and methods employed for this purpose—and some typical problems are presented. Finally, there is a brief discussion of recent developments in data processing as applied to analytical problems.

THE MATERIALS Characterization Group at David Sarnoff Research Center provides RCA Laboratories with a centralization of specialized professional skills and sophisticated instrumentation — organized to solve complex problems in physical characterization and chemical analysis. Such problems originate not only at RCA Laboratories, but also in many other activities of RCA, such as those located in Hightstown, Somerville, Harrison, Lancaster, Indianapolis, Circleville, and Findlay. Furthermore, some self-generated work is being carried out to expand the fields of application of existing techniques, to improve their accuracy and sensitivity, and especially to develop novel methods applicable to surface and thin-film problems.

Shift in emphasis

An earlier report on Materials Characterization,[1] published in 1969, dealt with the various areas and major functions of physical characterization and chemical analysis at RCA Laboratories. At that time, emphasis was placed largely on the complete characterization—structure, defects, and composition —of electronically active *bulk* materials, and the major areas investigated included: Microscopy, X-Ray Studies, Mass Spectrometry, Optical Spectroscopy, Chemical Analysis, Nuclear Radiation, and Data Processing (see Table I of Ref. 1). At present, work continues in all of these areas except Nuclear Radiation; meanwhile, significant shifts in Company interest occurred:

From	*To*
bulk solids	surfaces and thin films
average composition	three-dimensional composition profiles
elements	compounds and alloys

Shifts in emphasis are clearly seen in the *current* listing of major functions presented in Table I. The major new items include: Electron-Probe Microanalysis (EPM); Ion Scattering Spectrometry (ISS); Ion-Probe Microanalysis (IPM); Secondary Ion Mass Spectrometry (SIMS); Auger Electron Spectroscopy (AES); and Electron Spectroscopy for Chemical Analysis (ESCA). These methods (which serve in the analysis of surfaces and thin films) require complex, expensive instrumentation either set up recently at RCA Laboratories, or available on a rented-time basis. Because such a bewildering array of modern instrumentation exists, it seems desirable to present the physical basis of each method. This is done succintly in matrix form in Table II; here, rows represent the different types of primary excitation, columns the detected emission. The methods available to RCA and discussed

Table I — Materials characterization: areas and major functions

Area	*Major function*
Microscopy	Electron microscopy & diffraction Scanning electron microscopy
X-rays	Topography Electron-probe microanalysis Single crystal diffraction Powder diffraction, Fluorescence Instrumentation Consulting
Mass spectrometry	Solids analysis Gas analysis Ion scattering spectrometry Ion microprobe (rented time) Secondary ion MS
Electron Spectroscopy	Auger electron spectroscopy ESCA (rented time)
Optical Spectroscopy	IR, visible, and UV spectroscopy Instrumental development Atomic absorption, Emission spectroscopy
Chemical analysis	Wet Chemistry Consulting
Data processing	MS, X-rays, electron probe, etc.
General	Administration, Special problems

in this paper are shown in capital letters, while all others are placed in parentheses.

The present paper will not repeat the basic information contained in the earlier paper[1] which is still available in reprint form. Instead, the following reviews significant developments in established areas — and then concentrates on the subject of surface and thin-film analysis.

Structure and defects — microscopy

Transmission electron microscopy (TEM)

A new Philips Transmission Electron Microscope, Model 300, recently installed for another group, is available for materials characterization on a part-time basis. Its resolution capability is better than 2.5 Å (direct imaging of gold), and routinely 3.8 Å (lattice imaging of graphite), at 500,000 x magnification. A goniometric stage for the analysis of crystalline imperfections is available. This TEM has been applied to a number of problems including intergranular metals (metal films interspersed with insulators) and video-disk coatings.

Scanning electron microscopy (SEM)

Our capabilities in this area[2] have increased significantly by exchanging in 1972 our 1966-vintage SEM for the latest model Kent Cambridge Model S4, providing improved resolution capability, stability, and versatility of operation. A second smaller SEM, Kent Cambridge Model S600 (purchased and installed in 1974) helps to cope with the large volume of routine problems submitted.

Filling the magnification gap existing between light microscopes and TEM's, the SEM, with its large depth of focus, has been remarkably successful in resolv-

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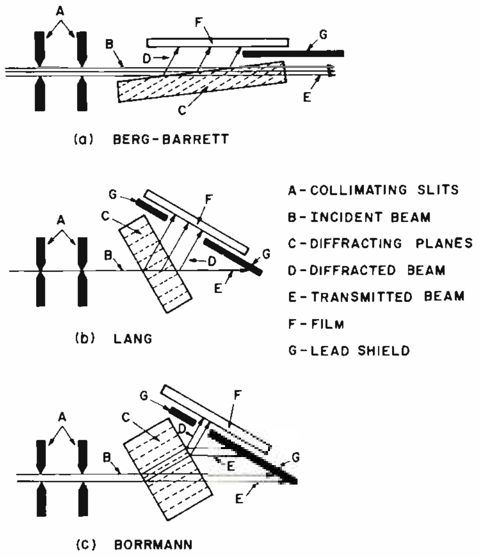

Fig. 1 — The three major geometries used in x-ray topography.

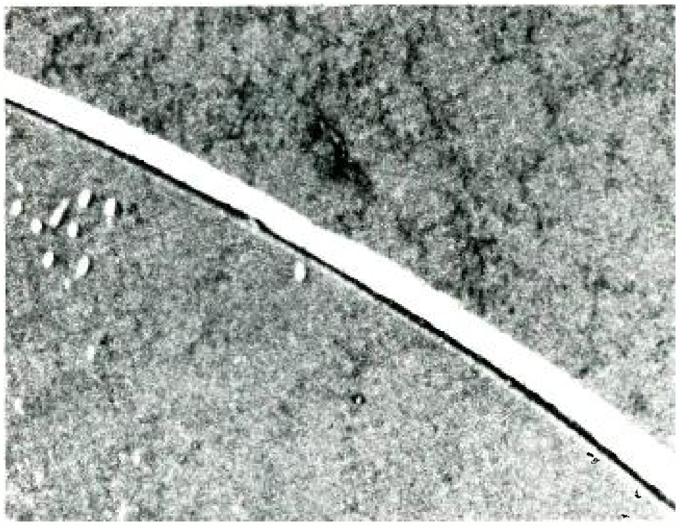

Fig. 2 — Reflection topograph of liquid phase epitaxial GaAs layer and GaAs substrate. Dislocations visible near the substrate surface (above the white band) are greatly reduced in the epitaxial layer (below the band).

ing a wide variety of structural problems, particularly in the area of semiconductor devices. Recent SEM work includes: measuring diffusion lengths of minority carriers in semiconductors[5-6] -extended to allow measurements in multiple junction structures, at isolated junctions, and on silicon active elements, all with favorable results; and a new contrast theory[7] which relates the angular dependence of secondary emission for several commonly observed elements; the latter enables prediction and optimum utilization of contrast changes. There has been a wide range of materials studies[8-10] proving very valuable where surface or textural characteristics are important. Simplicity of specimen preparation and versatility of observational modes[11] have produced significant SEM contributions to research in many areas. With rapid feedback of results, SEM data contributed directly and effectively to the evolution of novel processes and procedures. The number of successful applications to semiconductor devices increased. Thus, SEM techniques are uniquely suited to problems in device fabrication, and the augmented capability for dynamic electrical studies in SEM enhances the evaluation of devices and failure-mode analysis.[12]

Light microscopy

Our optical microscopy capabilities have recently been enlarged by the acquisition of a Normarski microscope. This incident-light interference contrast microscope shows up, in a clear and striking manner, small imperfections in nearly smooth surfaces, often undetectable by SEM and other microscopy techniques. This microscope completes our present optical facility which includes the finest available metallographic microscopes.

Table II — Survey of major methods of material characterization.

DETECTED EMISSION / PRIMARY EXCITATION		OPTICAL	X-RAYS	ELECTRONS		IONS (+ AND –)
PHOTONS	OPTICAL	"AA": ATOMIC ABSORPTION "IR": INFRARED, VISIBLE, "UV" ULTRAVIOLET } SPECTROSCOPY		"ESCA": ELECTRON SPECTR. F. CHEMICAL ANALYSIS	"PESOS" PHOTOELECTRON SPECTROSCOPY - OUTER SHELL	
	X-RAYS		X-RAY FLUORESCENCE SPECTROMETRY X-RAY DIFFRACTION		"PESIS": PHOTOELECTRON SPECTROSCOPY - INNER SHELL	
ELECTRONS			"EPM": ELECTRON-PROBE MICROANALYSIS	"AES" AUGER ELECTRON SPECTROSCOPY "SAM": SCANNING AUGER MICROANALYSIS "SEM" SCANNING ELECTRON MICROSCOPY "TEM" TRANSMISSION ELECTRON MICROSCOPY		
IONS (+ AND –)		["SCANIIR": Surf. Comp. by Anal. of Neutral and Ion Impact Radiation]	[Ion-Induced X-Rays]			"SIMS": SECONDARY ION MASS SPECTROMETRY "IPM": ION-PROBE MICROANALYSIS "ISS". ION SCATTERING SPECTROMETRY ["RBS": Rutherford Backscattering Spectrometry]
RADIATION		"ES": EMISSION SPECTROSCOPY				"SSMS": SPARK SOURCE MASS SPECTROMETRY

Structure and defects — x-ray techniques

Topography

Since its establishment in 1967, x-ray topography has been used extensively for the study and characterization of the crystallinity of nearly perfect single crystals (containing less than 10 defect lines/cm).[13-19] Fig. 1 is a schematic diagram of the three major arrangements used:

1) *Berg-Barrett surface reflection* topography reveals surface defects, such as misfit dislocations, provided they lie within a few microns of the surface to be imaged.

2) *Lang transmission* is used for crystals that are relatively transparent to x-rays, with defects appearing as enhanced intensity. A *projection* topograph is obtained if crystal and film are translated in the beam during

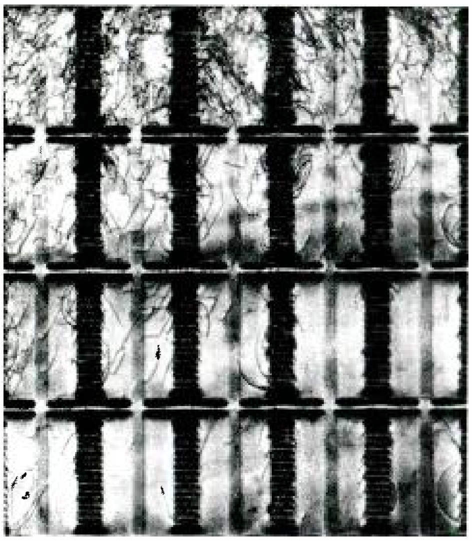

Fig. 3 — Projection topograph of silicon wafer showing dislocations introduced around the devices by the diffusion process.

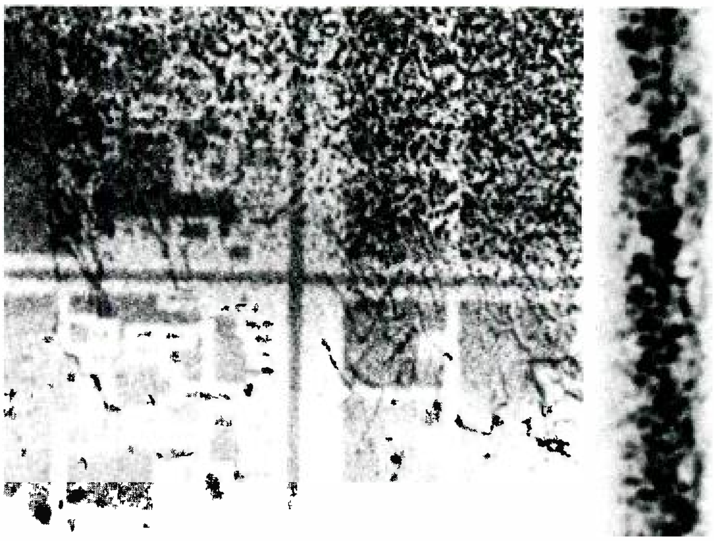

Fig. 4 (left) — Projection topograph of silicon wafer showing dislocations and spot defects (probably precipitates) introduced in the wafer by processing steps. Fig. 5 (right) — Section topograph of the wafer of Fig. 4, showing that spot defects are distributed throughout the entire wafer.

the exposure and all the defects in the crystal are imaged. A *section* topograph is obtained if crystal and film are stationary, in which case only defects along the plane of intersection of the x-ray beam and the crystal are imaged.

3) *Borrmann anomalous transmission* is used for crystals relatively opaque to x-rays, with imperfections appearing as reduced intensity.

There is no magnification inherent in any of these methods, but details can be brought out by enlarging the fine-grained emulsion used to record the image. Fig. 2 shows a reflection topograph of a liquid phase epitaxial GaAs layer grown on GaAs. The dislocations in the substrate (above the white band) are substantially reduced in the layer (below the band). The white band is the *shadow* of the edge of the layer while the white spots below it are shallow pits. Figs. 3 and 4 are projection topographs taken to characterize silicon wafers in early stages of processing. Fig. 3 shows dislocation loops introduced around the devices due to the strain of the diffusion process. Part of an IC wafer is shown in Fig. 4, where dislocations and spot defects (probably precipitates) are evident as well as the pattern of the first diffusion step. Fig. 5 is a section topograph of the IC wafer shown in Fig. 4, indicating that the spot defects are distributed throughout the entire wafer and are not confined to the processed surface.

Fluorescence spectrometry

X-ray secondary emission (fluorescence) spectrometry is used to determine nondestructively the elemental composition of various samples and films within about 100μm of the surface, with an optimum detection sensitivity of about 100 parts-per-million atomic (ppma). The equipment produces a primary x-ray beam that excites in the sample secondary x-rays characteristic of the elements present. Recently, a new Siemens X-Ray Vacuum Spectrograph type "VRS" was added to our equipment, extending analyses to the lighter elements including fluorine ($Z>9$). Analyses carried out with this equipment will be discussed below, under *Surface and Thin Film Analyses*.

Diffractometry

X-ray diffractometry continues to be applied to a wide variety of single-crystal problems, such as: line broadening studies relating Si layer quality to Al_2O_3 substrate misorientation; crystalline quality and orientation of Al_2O_3 substrate materials from different suppliers; graded solid solutions of various ternary and quaternary systems; crystallinity of AlN layers on Al_2O_3 substrates; and, most recently, an effort to relate ultra-high precision (± 1 ppm) determinations of interatomic distances with stoichiometric changes in binary compounds.

Bulk analyses

Mass spectrometry

Solids—The analytical precision of our vintage, AEL-MS7 solids mass spectrograph,[20] has been substantially improved by the design and installation of an automatic spark gap control and surface scanner. This modification uses stepping motors to maintain a constant spark gap, which stabilizes sparking conditions and improves instrumental precision, and at the same time permits automatic scanning for surface analyses. The spectrograph has been used successfully for a number of years in an extensive program of Si product line evaluation for RCA Somerville. It remains unsurpassed as a relatively fast, high-sensitivity survey tool capable of determining trace impurities at the parts-per-million (ppm) level in semi-quantitative fashion.

Gases—Our capabilities for analyzing gas samples by mass spectrometry significantly improved by replacing the old MS-10 magnetic analyzer by a UTI model-100C quadrupole MS of improved sensitivity, speed, mass range, and mass resolution. In addition, a special gas-inlet system was designed and built to permit the handling of very small gas samples; typical samples include: gas bubbles occluded in glass and liquid crystals; residual gases contained in $CdSe$ and PbO vidicon tubes, and in hermetic devices; and gases evolved from heated faceplates. However, the problem of determining trace amounts of chemically active gases, such as O_2, SiH_4, and PH_3, has yet to be satisfactorily resolved.

Optical spectroscopy

Instrumentation is available for optical measurements from ultraviolet to far-infrared, over the entire wavelength region extending from 0.25 to 200 μm. Within this region, optical measurements of vibrational or rotational and electronic absorption processes readily yield information concerning the quantity, composition, and chemical structure (bonding) of inorganic and organic materials. For example, the infrared absorption by silicon dioxide permits this material to be detected in microgram amounts.

Infrared spectroscopy—Three Perkin-Elmer spectrometers (PE 457, PE 221, and PE 301) cover the entire infrared range and provide, in a non-destructive manner, basic information about the molecular composition of either crystalline or amorphous materials, as well as their electronic and physical properties.[21-25] For surface analyses, especially the composition of surfaces coated with 1-10 μm layers, the spectrometers are used in conjunction with a Wilks attenuator total-internal-reflection device or a Harrick specular reflection accessory. The molecular composition of 400-Å thick organic films used to coat video disks has been determined by this method. Thickness measurements have been made for many epitaxial films, including AlN on sapphire, As_2S_3 on KBr, GaP on metal substrates, and $GaAs$ on Ge.

Visible—ultraviolet spectroscopy—Visible-ultraviolet measurements, made on our Cary 14 instrument, also serve to determine composition as well as electronic and physical properties of many materials, similar to infrared measurements, but at higher photon energies. Typical studies include: the dependence on composition of electronic and optical properties of ternary compounds, such as $In_xGa_{1-x}As$[26]; the film thickness of *Au-In* composites on thin organic substrates; and the reflectivity of triglycine sulfate thin films.

Special equipment—A specially designed, mercury-pumped, high-vacuum system permits the characterization of oxide films in vacuum tubes by simultaneous optical, electrical, and mass measurements. Reflection measurements yield bandgap data for the film while at the same time mass spectrometry determines the composition of residual gases found in the vacuum envelope. Measurements of this type correlate in a meaningful manner tube performance with optical and mass data, indicating those factors that are critical in the preparation of the oxide layers. A second vacuum system is used in conjunction with optical devices for a variety of infrared transmittance measurements, such as the study of atomic-molecular reactions.[27]

Gas chromatography—A Model 74 Pye Unicam Gas Chromatograph with electron capture and flame ionization detectors is available for the physical separation of components of gaseous, liquid, or solid mixtures, and subsequent analysis of each constituent. For this type of work, detectors with very high sensitivity are essential. The electron capture and thermionic flame ionization detectors respond to selective groups of materials when at least 10^{-12} to 10^{-14} gram/sec of material is present. Each detector is characteristically selective in its response. The electron capture detector responds to halide and oxygen compounds, while the thermionic flame ionization detector responds to all organic and phosphorus-containing materials. The equipment has been applied to the separation and identification of impurities at the ppm level in vapor deposition gases, in doping mixtures, in H_2 gas used in *Pd-Ag* diffusers, and in many other samples. A problem of special interest is the detection of ppm amounts of water in gas streams. This is achieved by converting, via the carbide reaction, water to acetylene for which exceptionally sensitive and selective ionization detectors are available.

Atomic absorption–flame emission spectroscopy—The Jarrell-Ash combination atomic absorption and flame emission spectrophotometer, Model 82-500, is used for chemical composition problems when the concentration of a specific, known constituent is to be determined with good accuracy, sensitivity, and speed. Recently developed *flameless* sources markedly improved the detection sensitivity of atomic absorption measurements to well below the parts-per-million (ppm) level. The flameless source in our present atomic absorption instrumentation is a heated carbon rod device, permitting impurity analyses at the parts-per-billion level, and its general versatility improved by the addition of a direct digital readout and printer system. This instrumentation fills the gap between wet chemistry and mass spectrometry.

Emission spectrography—The Jarrell-Ash 3.4 meter Ebert Spectrograph continues to be used for qualitative and semi-quantitative problems, providing quick survey answers with a minimal outlay in time and expense.

Wet chemistry

Chemical analyses previously made by conventional methods are now complemented by the Orion Model 801 Ionanalyzer which uses specific ion electrodes (solid-state membrane electrodes) to determine a particular element. Each electrode responds selectively to a given cation or anion, regardless of sample ionic composition or total ion strength, and develops a potential proportional to log (activity) of the specific ion.

Surface and thin-film analyses

During the past few decades, a variety of sophisticated methods have been developed to determine the elemental composition of surfaces and thin films—and to obtain three-dimensional concentration profiles. Some methods are essentially "non-destructive", such as x-ray fluorescence spectrometry (XRFS), electron-probe microanalysis (EPM), Auger electron spectrometry (AES), and electron spectroscopy for chemical analysis (ESCA), although the primary x-ray or electron beam may in certain instances produce significant chemical changes in the sample.

On the other hand, all methods utilizing ions either for the primary beam, or for the purpose of surface removal by sputtering, are "destructive". These include spark-source mass spectrography (SSMS), secondary ion mass spectrometry (SIMS), ion-probe microanalysis (IPM), ion-scattering spectrometry (ISS), and also AES and ESCA when used in conjunction with sputtering for in-depth profiling.

There are a number of major analytical parameters that have to be considered for the analysis of surfaces and thin films. Such parameters include: detection sensitivity and reproducibility; matrix effects, i.e. the dependence of a given elemental sensitivity on its chemical environment, in particular the matrix; mass or energy resolution for positive identification of an unknown constituent;

spatial resolution, both planar and in-depth; sampling or information depth; elemental coverage, defined as the ability to detect *all* impurities in a given matrix; sample and time consumed per complete analysis; rate of material removal for in-depth profiling; and, last but not least, equipment cost.

It is clearly impossible to discuss all these parameters in detail for each of the methods employed at RCA Laboratories. Instead, Table III compares, in concise fashion, the most important aspects; the methods are arranged in descending order of sampling depth. For an inclusive review of mass spectrometric methods, including ISS, consult a recent publication by this author.[28] In the following, each method will be briefly discussed, with emphasis on its advantages and limitations.

Table III — Survey of methods for thin-film and surface analysis.

METHOD	PROBE DIAMETER µm	SAMPLING DEPTH		OPTIMUM DETECTION SENSITIVITY (ppm atomic)	REPRODUCIBILITY (%)	COVERAGE OF ELEMENTS	SPECIAL FEATURES	APPROX. PRICE (K$)
		µm	ATOMIC LAYERS					
X-RAY FLUORESCENCE SPECTROMETRY	10^4	3-100	10^4-$3\cdot10^5$	1-100	±1	NEARLY COMPLETE (Z > 9)	QUANTITATIVE; NONDESTRUCTIVE; INSULATORS	25
ELECTRON-PROBE MICROANALYSIS	1	0.03-1	10^2-$3\cdot10^3$	100-1000	± 2	COMPLETE (Z > 4)	QUANTITATIVE; "NONDESTRUCTIVE"	100
SOLIDS MASS SPECTROGRAPHY	1-10	0.3-10	10^3-$3\cdot10^4$	0.01-10	± 20 ± 2	NEARLY COMPLETE	SEMI-QUANTITATIVE; ION-SENSITIVE PLATES ELECTRICAL READOUT	100 150
ION SCATTERING SPECTROMETRY	10^3		1	0.1-1%	± 20	NEARLY COMPLETE NO H, He	SEMI-QUANTITATIVE; IN-DEPTH CONC. PROF. INSULATORS	40
SECONDARY ION MASS SPECTROMETRY	10^3		3	0.1-100	± 2	NEARLY COMPLETE	SEMI-QUANTITATIVE; IN-DEPTH CONCENTRATION PROFILE	25-100
ION-PROBE MICROANALYSIS	1-300		10-1000	0.1-100	± 2	NEARLY COMPLETE NO H, He	SEMI-QUANTITATIVE; THREE-DIMENSIONAL CONC. PROFILE	300
AUGER ELECTRON SPECTROMETRY	25-100		2-10	0.1-1%	± 20	NEARLY COMPLETE	SEMI-QUANTITATIVE; THREE-DIMENSIONAL CONC. PROFILE	55
"SAM": SCANNING AUGER MICROANALYSIS	3-25		2-10	0.1-1%	± 20	NEARLY COMPLETE NO H, He	SEMI-QUANTITATIVE; THREE-DIMENSIONAL CONC. PROFILE; TWO DIM'L. AUGER IMAGES	100
"ESCA": ELECTRON SPECTR. CHEM. ANALYSIS	10^4		2-10	1%	± 20	COMPLETE	SEMI-QUANTITATIVE. VALENCE STATES	150

X-ray fluorescence spectrometry (XRFS)

X-ray Fluorescence spectrometry (XRFS), or X-ray secondary emission spectrometry, is a non-destructive, fast and quantitative method capable of determining impurities in large samples (area 1-10 cm^2) down to about 100 ppm. Sampling depth ranges from 3-100 µm. The recently acquired Siemens X-Ray Vacuum Spectrograph, Type VRS, has solved many important film problems (semiconductors, phosphors, transparent resistors, glasses, permalloys, and oxides). The method is especially advantageous in the case of insulators which charge up when analyzed by methods involving charged particles.

Electron-probe microanalysis (EPM)

The electron-probe microanalyzer employs a primary electron beam of micrometer dimensions to excite x-ray spectra characteristics of the elements contained in a microvolume (~ 1 µm^3) of a solid sample. It is essentially non-destructive, and may be used to map variations of elemental concentrations with a planar resolution of about one µm. Operation and application are discussed in detail in two reports.[29,30] Important problems recently resolved include: many different films (conducting, semiconducting, and insulating) on various substrates; surface-to-substrate concentration gradient profiles on angle-lapped specimens; and characterization of foreign particles in glass.

Spark source mass spectrography (SMSS)

The automatic surface scanner mentioned earlier has greatly facilitated the analysis in the MS7 solids mass spectrograph of films of micrometer thickness.[31] Since scan rate and gap width are closely controlled, extended areas (1-2 cm^2) can be analyzed under constant spark conditions much faster, more reproducibly, and more conveniently than was previously possible. This system has been successfully applied to many problems, in particular silicon wafer analysis. Tracks of spark craters obtained with the automatic surface scanner are shown in Fig. 6.

Ion scattering spectrometry (ISS)

Ion scattering spectrometry (ISS) is a recently developed analytical technique yielding information concerning the top atomic layer of a solid specimen.[32] The method uses a primary beam of rare gas ions which are in part elastically scattered

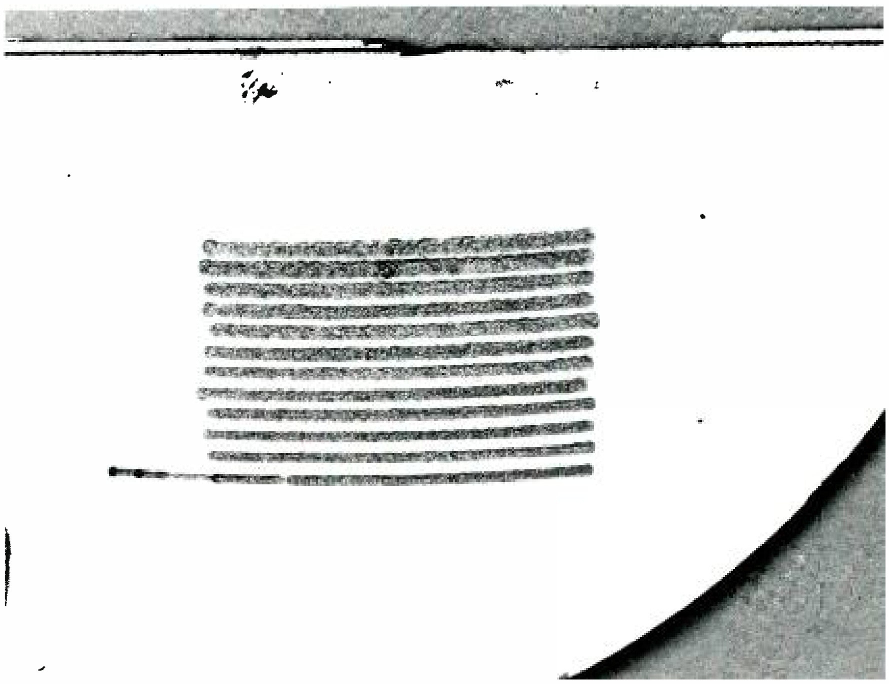

Fig. 6 — Photograph of a SMSS surface-scan, showing tracks of sparked craters on Si sample. Track width varies from about 350 to 550 micrometers; crater depth is about 5 micrometers.

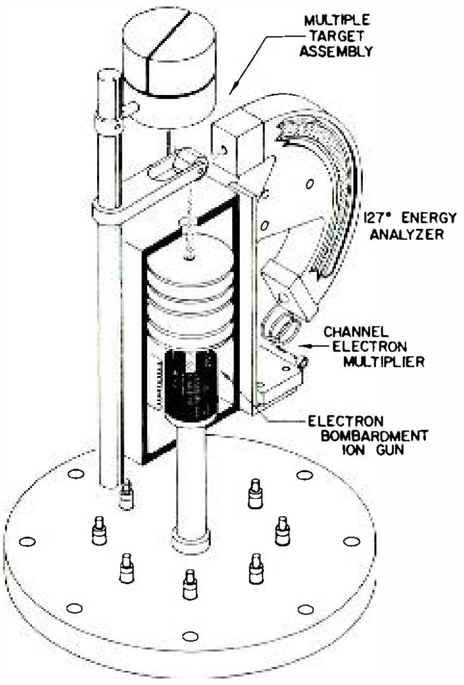

Fig. 7 — Schematic of the 3M ion scattering spectrometer.

by the surface atoms; at the same time, the remaining ions remove the surface atoms by sputtering. From the energy of the scattered ions, the mass of the scattering centers is readily deduced—and surface composition of the sample established. The simultaneous sputtering action of the ions makes it possible to determine in-depth composition profiles which are of great importance in most problems encountered today. Fig. 7 is a schematic of the 3M ion-scattering spectrometer installed at RCA Laboratories in December 1971. It has been applied to a wide variety of problems including conductors, semiconductors, and in particular insulators that cannot be handled by other surface-analytical techniques. An important example is the diffusion of alkali elements in specially treated glasses. Also of interest are results obtained for polar semiconductors, such as *CdSe*. As shown in Fig. 8, ISS clearly differentiates between the two opposite faces of such compounds.

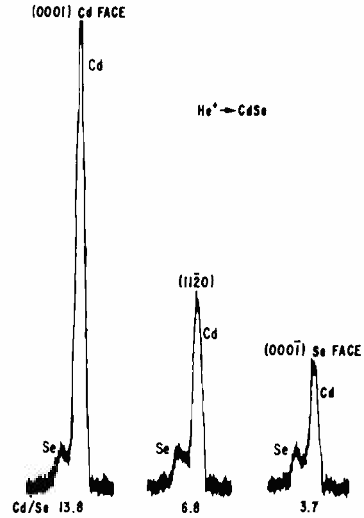

Fig. 8 — Effect of *CdSe* crystal orientation on ion intensities scattered from *Cd* and *Se* atoms.

Ion-probe microanalysis (IPM)

In the ion-probe microanalyzer, a beam of medium-energy (5-15 keV) positive or negative ions bombards the sample surface to be studied, producing secondary sputtered ions that are imaged and identified in a mass analyzer. The instrument is capable of three-dimensional profiling of impurities down to the ppm level: the rastered primary beam of micrometer dimensions produces planar concentration profiles, while its sputtering action yields in-depth information. Although there is no ion microanalyzer available at RCA Laboratories, we have access to a "Cameca" instrument on a rented basis. Selected problems solved by this method include concentration profiles of; impurities in *Si* and *GaAs* wafers; impurities in various epitaxial layers; and various metal alloys, compounds, and multilayered structures.

Secondary ion mass spectrometry (SIMS)

Secondary ion mass spectrometry (SIMS) employs the same operating principle as the ion-probe microanalyzer, except that it uses a larger primary ion beam (typically of mm dimensions). While SIMS cannot perform planar profiling, its in-depth profiling capabilities can be equivalent to IPM. Since the cost involved in setting up this instrumentation is within reach of RCA Laboratories, we are in the process of designing and building SIMS equipment. This includes a primary ion gun, a sample-manipulator, and a quadrupole mass filter for the analysis and detection of the secondary ions, all placed in a bakeable ultrahigh vacuum system.

Auger electron spectrometry (AES)

Auger electron spectrometry (AES) is a recently developed surface-analytical technique based on bombarding the sample with a primary beam of keV electrons, and analyzing the secondary "Auger" electrons emitted when the excited sample atoms return to their equilibrium state. These Auger electrons have energies characteristic of those atoms that are contained within a few atomic layers of the sample surface. The method is particularly sensitive for light (low-Z) elements, such as *C*, *N*, and *O*, which is of considerable practical importance. Recent technical improvements reduced the primary electron beam diameter to about 3 μm, permitting this instrument to be used as a Scanning Auger Microprobe ("SAM") that presents two-dimensional images of impurity distributions. When used in conjunction with an ion sputtering gun, AES yields in-depth profiles of impurity concentrations quickly and accurately.

While up-to-date Auger equipment, including "SAM", was being installed at RCA Laboratories, in the Fall of 1974, analyses in many areas have been carried out for us during the past at Physical Electronics Industries, on a paying basis. These analyses include depth profiles of: *Hf* and *Ta* on Al_2O_3; silicon on polystyrene, *S* in metal oxides; and oxide coatings on various glasses. A representative in-depth composition profile of a 1000-Å thick *Ta* film on Al_2O_3 sample is shown in Fig. 9. In this instance, the apparent depth resolution is about 150Å at the interface, 1000Å below the surface. The installation of this instrumentation at RCA Laboratories represents a great leap forward for surface analysis.

Electron spectroscopy for chemical analysis (ESCA)

Electron spectroscopy for chemical analysis (ESCA), sometimes called Photo-Electron Spectroscopy (PES), is a powerful surface method which provides information concerning chemical composition as well as valence states of major and minor components. It utilizes a primary beam of monochromatic x-rays, frequently the *Al Kα* line at 1486.6 eV, which ejects from surface atoms both inner shell electrons with binding energies characteristic of the elements, and outer shell (valence) electrons providing information on the molecular state. The equipment consists of an x-ray source and monochromator, sample manipulator, electron energy spectrometer, and a sensitive detection and display system, all components being mounted in an ultrahigh vacuum system. For some applications, the x-ray source is replaced by an ultraviolet light source.

While there is no ESCA equipment

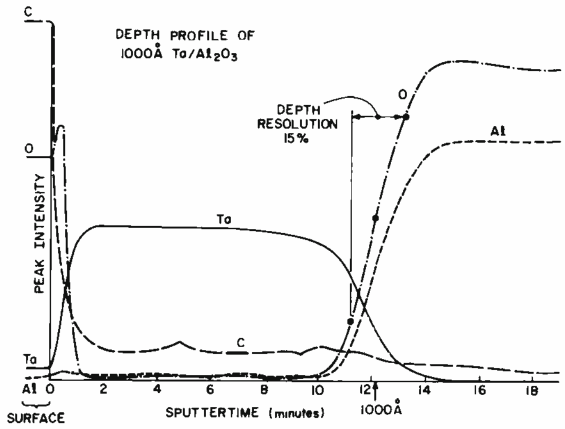

Fig. 9 — In-depth composition profile of a 1000-angstron-thick Tantalum layer on Aluminum-Oxide substrate, obtained by Auger electron spectroscopy. It indicates a depth resolution of about 150 angstroms at the Tantalum/Aluminum-Oxide interface.

available at RCA Laboratories, analyses have been carried out for us at the Chemistry Department of Purdue University, on a paying basis. The method is complex and time-consuming but has been applied successfully to a series of oxide samples, establishing oxidation states and crystal forms. Because the equipment is expensive and applicable only to certain types of problems, its acquisition is not being considered at this moment.

Data processing: computer interaction with analytical instruments

The use of computers via time-sharing as a direct aid in collecting data and performing complex calculations in a man-machine interactive loop is under investigation, and several specialized digital data interfaces have been constructed. One such system, applied to densitometric data from the solids mass spectrograph, effectively couples the judgment and analytical experience of an analyst to the speed and memory capability of a computer to improve significantly the quantitative accuracy of mass spectrographic analyses. This system provides the analyst instantly with any information or calculations needed to interpret the mass spectrum and, at the same time, takes care of all the clerical work of report writing and record-keeping. Another system, used for processing x-ray powder camera films and electron diffraction plates, now permits the analyst to collect semi-automatically in a few minutes all the data needed to index crystallographic lines and to determine lattice parameters and other data. This system, built around a densitometer, is based on a linear optical encoder that was designed and fabricated in RCA Laboratories. In addition to these systems, many time-sharing programs have been written for processing data obtained by ellipsometry, x-ray diffractometry, gas mass spectrometry, and ion scattering spectrometry. A fully interactive, time-sharing program for the evaluation of results from electron-probe microanalysis has been developed. Recently, a data acquisition system was designed and built which automatically records the number of video signal "drop-outs" per one-second interval detected during repeated playings of test records on a VideoDisc player.

Acknowledgment

It is a real pleasure to acknowledge the cooperation and contributions of, and discussions with, members of the Materials Characterization Group, on whose work this report is largely based.

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Miniature TWTs for phased arrays

M. Milden | M. Schindler | H.J. Wolkstein

High-efficiency traveling-wave tubes (TWT's) have been designed that lend themselves for use in phased-array transmitter systems. Several design considerations are described herein, as are TWT characteristic and performance test results. Two minature TWT types (A-1480 and A-1487) possess gain and phase characteristics that can be properly controlled for phased-array systems to a degree not readily matched by other devices.

MICROWAVE PHASED-ARRAY transmitter systems have long been conceived with extremely versatile and flexible performance capability. Indeed, the capacity for electronically steerable arrays to deliver large doses of effective radiated power (ERP) to multiple and precisely located targets within the antenna scan pattern has been demonstrated. However, progress on broadband, octave, CW, phased-array systems has been grossly inhibited by the lack of the proper microwave amplifier vehicle to augment the system.

Current approaches

Historically, several widely different basic approaches have been utilized for the phased-array concept depending on the power level of the rf amplifier and hence the phase steering mechanism to implement the system. Critical selection of components for optimizing the power delivered, maintaining operational reliability, achieving long life, and potentially low cost in volume production have influenced the conceptual design approach.

One of the classical approaches — the use of a single high-powered microwave tube source — makes use of corporate feed techniques to excite individual high-power phase shifters for each of the antenna elements in the array. This approach lacks rf source redundancy and must sustain distribution line and ferrite phase shifter losses before each of the antenna elements is excited. Furthermore, high-power phase shifters are difficult to produce with more than octave bandwidth capability.

The other basic approach for powering a

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Morton Milden, Engineer, TWT Product Design, Electronic Components, Harrison, N. J., received his BS in mathematics and physics from the City College of New York in 1951. He also attended the U.S. Signal Corps Radar School at Fort Monmouth, took graduate courses in the City College of New York School of Education and electrical engineering courses at CCNY. In 1955, Mr. Milden was employed by the ITT Federal Laboratories as a design engineer on Traveling-Wave Tubes (TWT's). Milden joined RCA's Microwave Tube Operations Department in 1964 as a design and development engineer on TWT's. One of his early assignments was to develop a metal ceramic TWT for a communications satellite. One of his recent achievements was to extend the state-of-the art overdrive capability of a C-band tube for an ECM system. He is now working on the design of 30-watt Metal Ceramic TWT for a communication system and two Metal Ceramic, X-Ku Band Tubes - a low-noise, 2-watt tube and memory storage tube, both for airborne ECM systems.

Dr. Max Schindler, Senior Engineer, Microwave Devices Operations Department, Electronic Components, Harrison, N.J. received his MS in Electronic Engineering in 1951, and the degree of Doctor of Technical Sciences in Solid State Physics in 1953, both from the Technische Hochschule in Vienna, Austria. He joined the RCA Microwave Tube Operations in 1958, and has since worked on a number of basic technical problems related to the design of traveling-wave tubes, magnetrons, crossed-field devices and solid state devices. Prior experience included an assignment as acting group leader of the Magnetron Design Group, where he directed the development of a hydraulically-tuned magnetron. From 1963 to 1967, he has led groups working on the design and development of high-efficiency traveling-wave tubes for communication satellites, and recirculating TWT's for ECM systems. Dr. Schindler joined the Microwave Applied Research Laboratory of the David Sarnoff Research Center in Princeton, New Jersey in September 1967, where he worked for 2 years on crossed-field delay devices and computer techniques for Microwave R&D. After his return to Harrison, he worked in Solid State Engineering on integrated components and on transferred-electron amplifiers. For the last year, he has been instrumental in the development of minature traveling-wave tubes with the highest power-frequency product in the industry. Dr. Schindler has published many articles pertaining to magnetics, microwave tubes and computer-aided design. He has also presented a number of papers and holds three patents in the magnetic field. He is a Senior Member of IEEE, and is Chairman in the North Jersey Section. He is listed in American Men of Science.

Wolkstein

Milden

Schindler

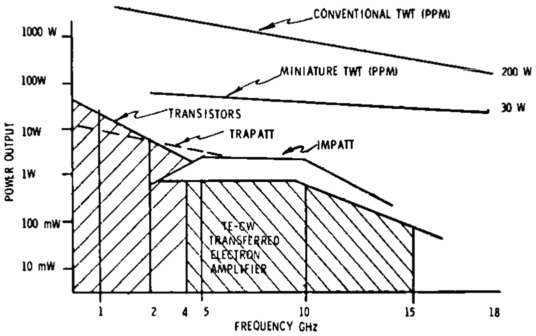

Fig. 1 — Demonstrated CW performance capability, conduction-cooled amplifiers.

phased array — the use of a medium-power rf driver directly at each antenna element — inherently lends itself to high reliability with many parallel active transmission paths for graceful system degradation.

Obviously, the overall design philosophy forthe broadband phased array is completely dependent on the choice of the basic amplifier to drive the system. The selection of a single high-power amplifier, or multiple small-powered devices — the use of solid state devices or vacuum tubes — is a basic consideration that determines the overall system concept.

New miniature TWT's

More recently, miniature broadband, CW traveling-wave tubes capable of fitting between the 1/2-wave antenna-to-antenna separation of the phased-array system have been developed. These octave (or higher) bandwidth, high-efficiency TWT's uniquely lend themselves to the phased-array transmitter system. Moreover, the tubes have demonstrated gain-bandwidth and power capability which greatly surpasses that of other solid-state CW amplifying devices available (Fig. 1)[1] These miniature tubes located at each antenna port provide the characteristics necessary to power a wideband phased-array system.

Reproducibility and yield

Obviously, the degree of precision achieved in setting the angular position of the radiated beam pattern in a phased-array system is of extreme importance. Assuming that all TWT's at each antenna are driven in the proper phase sequence, the overall system phase-error deviation is dependent on the reproducibility of both gain and phase characteristics on a tube-to-tube basis.

Each tube in the system must provide closely controlled characteristics as a function of frequency, over extremes in rf drive, voltage variation, load, and environmental conditions.

Establishment of standardized characteristics unique to the tube type utilized for the antenna drive is an essential criteria. Moreover, all tubes must meet this criteria within tolerable limits. This must be accomplished with reasonable tube building yields, good reliability, and at potentially low cost for a viable phased-array system.

Recently, a number of miniature tubes have been designed, built and tested expressly for airborne phased-array systems applications. Accumulated data obtained from two such tube types intended for separate phased-array systems applications are reviewed in this paper.

RCA A-1480 miniature TWT

One of the miniature TWTs developed expressly for a phased-array application is the RCA type A-1480, a 20W, J-band tube whose major specifications are summarized in Table I. The tube has also been operated at power levels up to 40 W at center band, and one variant (Type A-1494) was built with a 50 dB minimum gain over the 8- to 18- GHz band, with an output power of 50 W at midband, 25 W minimum.

Fig. 2 shows the external appearance of the type A-1480 with outline dimensions of 0.5 × 1.375 × 7.7 inches together with its power supply. Construction of the tube emphasizes ruggedness, thermal capability, and ease of assembly. The gun is of conventional stacked design, but because of the 0.5 inch width of the tube, it incorporates some novel techniques to prevent voltage breakdown at high altitude and improved mechanical reliability. The helix assemblies are of a

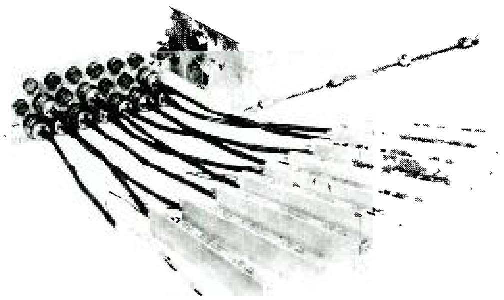

Fig. 2 — Miniature TWTs; power supply and distribution box.

Table I — Electrical performance — tube type A-1480.

Parameter	14-15 *GHz*	11-18 *GHz*
Min. power output	20W	16 W
Small signal gain	38-43 dB	37-41 dB
Total dc power	150W	
Gain compression	2-6 dB	
Gain tracking	±1.5 dB	
Fine grain gain	1.5 dB peak-to-peak	
Phase tracking	±18 deg.	
Noise figure	35 dB	
Am/Pm	5 deg./dB	
Hot input VSWR	1.5:1	
Hot output VSWR	3.5:1	

wrapped construction, using gold-plated tungsten tape. The thermal capability of this design is usually high. A dissipation of 80 W/in only raises the helix temperature 300°C above the barrel temperature. The collector is of the same diameter as the helix assembly, permitting the magnet assembly to be slipped over it. The collector is heatsunk through a beryllia sleeve to a copper cooler, which is bolted to the tube base. The tube is mounted to the heatsink with only one screw at each end; no other cooling is necessary as long as the heatsink stays below 90°C.

The magnet assembly of the A-1480 incorporates several novel design features which improve both thermal capability and ease of assembly. The magnets and pole pieces are made into two assemblies which can be adjusted and tested independently of the tube. They are then slipped over the helix envelope, and each half is aligned accurately with respect to the rf feedthroughs. The tube and magnet tolerances are accommodated by the small gap remaining between the two assemblies, without affecting the focusing. The ID of the magnet assembly is a close fit to the helix envelope, and the pole pieces are pressed down into the base, establishing an excellent thermal path from the helix envelope to the base.

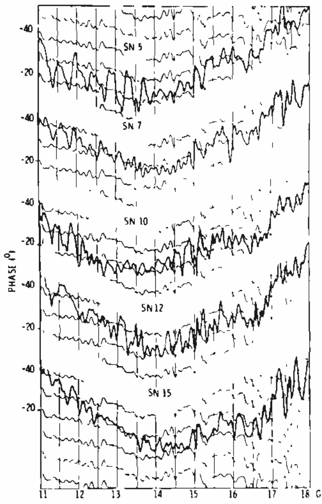

Fig. 3 — Swept phase versus frequency, RCA, tube type A1480.

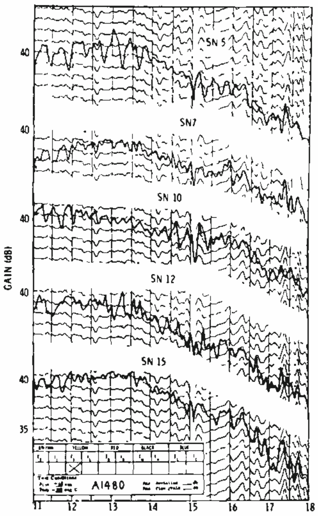

Fig. 4 — Swept SS gain versus frequency, RCA tube type A1480.

Phased array application

In a phased-array application, both the gain and the phase of the tubes must be matched within close tolerances over a wide range of temperature and drive levels. With a gain in the 40 to 70 dB range, and an electrical length of 20 to 30,000 degrees, some means for gain and phase adjustment must be provided. Both tubes discussed in this paper accomplish the gain matching by adjusting the beam current by means of droppping resistors. Because the electrical length of a TWT is very sensitive to the helix voltage, all tubes in one array are usually driven from a single common power supply. The resistor chain is, therefore, also used to make up for tube-to-tube variations in helix and anode voltage.

The phase adjustment is accomplished by choosing the proper length for the input cable. It is then bent in a special fixture to the correct mechanical length. Both input and output cables are .085-inch diameter, and are pressed against the rf feedthroughs by conical springs.

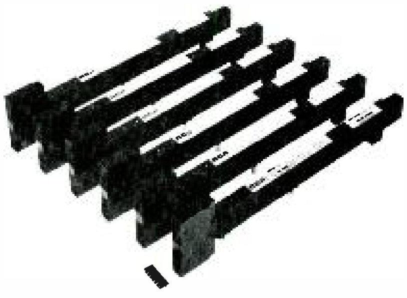

Fig. 5 — An array of six A1487 tubes.

Table II — Twenty-two flight models, summary of characteristics.

Test	*Min*	*Max*	*Avg*	*Units*
Emission change	0.8	10.0	4.3	mA
IW. overdrive	2.6	11.0	5.7	mA
Po mid-band	20.0	28.2	23.6	W
Po band edge	17.0	29.5	21	W
Po dc total	113	136	125	W
Gain comp. min	1.0	3.9	2.4	dB
Gain comp. max	2.0	6.0	3.6	dB
Noise figure	26	31	29	dB
Fine-grain gain	1.5	5.3	3.3	dB
(12 - 16 GHz)	(1.0)	(3.3)	(2.0)	dB
Gain tracking	1.5	4.5	2.8	dB
(12 - 16 GHz)	(1.0)	(2.5)	(1.7)	dB
Phase tracking	14	48	23	deg.
(12 - 16 GHz)	(10)	(23)	(15)	deg.
Am Pm conv	1.3	5.0	3.0	deg./dB
Hot VSWR, in	1.5	2.3	1.9	–
Hot VSWR, out	3.0	12	7.2	
(12 - 16 GHz)	(2.5)	(4.9)	(3.6)	–

Approximately 30 of the subject tubes were assembled and packaged. Figs. 3 and 4 are a sampling of phase and gain characteristics from the beginning of this prototype run. The electrical characteristics of the last two thirds of the run are summarized in Table II. The following comments apply to the listed parameters:

1) "Emission" is the change in cathode current when the heater voltage is lowered 10%.
2) "I_w overdrive" is the maximum helix current, which normally occurs at the lowest frequency, when the tube is driven beyond saturation.
3) "P_o midband and P_o band edge" are self-explanatory.
4) "P_{dc} Total" is the total power consumed by the tube, including the heater which was operated by square wave ac.
5) "Gain Compression" is the difference between small-signal gain and the gain at rated power.
6) "Noise Figure" was measured with automatic NF test equipment.
7) "Fine Grain Gain" is defined as the worst peak-to-peak variation within the 11- to 18-GHz band. When the band edges are excluded, the lower parenthetical figures apply.

As given in the table, *gain tracking* and *phase tracking* are the deviations from a mean curve which was established from the performance of the first five tubes. In the case of the *phase tracking*, it includes the fine structure. Listed are the worst cases under three conditions — small signal, rated power and overdrive.

Am/Pm Conversion was taken at rated power output, which is usually the worst condition.

Hot VSWR indicates the highest voltage reflection at the input and output port respectively over the full (and reduced) frequency range, while the tube is operating. The hot output VSWR can go beyond infinity, because the reflection coefficient can exceed unity when the reflected signal is amplifed in the output section of the tube.

Even though Table II shows only the averages and the extremes, it indicates adequate uniformity within the prototype run. Distribution curves of some of these parameters are given below for RCA type A-1487, which is of very similar construction and consequently exhibits similar tolerances.

RCA tube type A-1487 miniature TWT

RCA tube type A-1487 differs from the previously described miniature TWT. Mechanically it was designed for air cooled operation with *quick disconnect*, rf and dc fittings. Electrically, it was designed to provide relatively higher rf gain (65 dB at band center rather than 40 dB) for the 7- to 17-GHz band. The tube-to-tube reproducibility experience of the pre-production run for this type compares extremely well with the experience previously described on tube type A-1480.

Tube type-A1487, which provides a power output greater than 20 W at midband, must gain and phase track over the 7-to 17-GHz region at all input signal levels from small signal to saturation drive. Moreover, the tracking requirements similar to the A-1480 were accomplished over an airborne operating environment. A photograph of several of these tubes is shown in Fig. 5. As illustrated, the tubes are one-half inch wide by 10.9 inches. long. The finned radiator of the device (designed to dissipate 150 watts with an input cooling flow of 11 cubic feet per minute at sea level and air input temperature of 55°C) is 1.5 inches long by 2.5 inches high by 1/2-inch wide.

RF performance characteristics - tube type A-1487

Gain

The gain characteristics versus frequency of two tubes are depicted in Figs. 6 and 7. These swept curves are representative of the production tubes. The curves are made using a very slow sweep writing

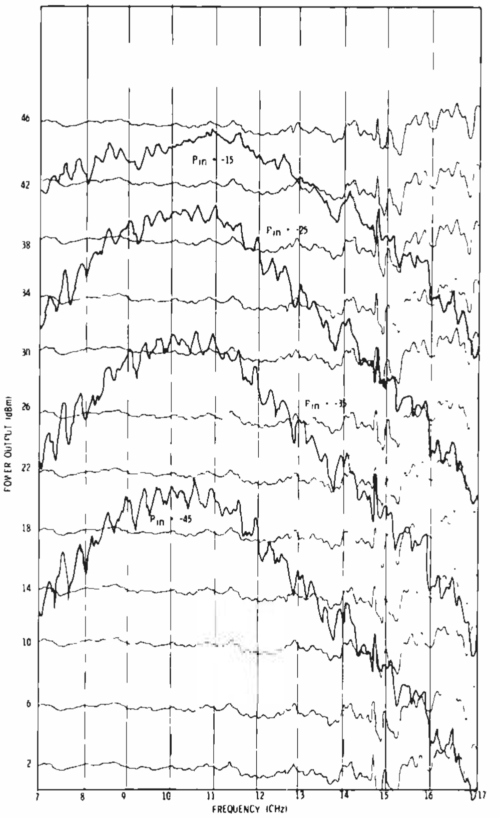

Fig. 6 — Power output characteristics with respect to power input for type A-1487, tube "A".

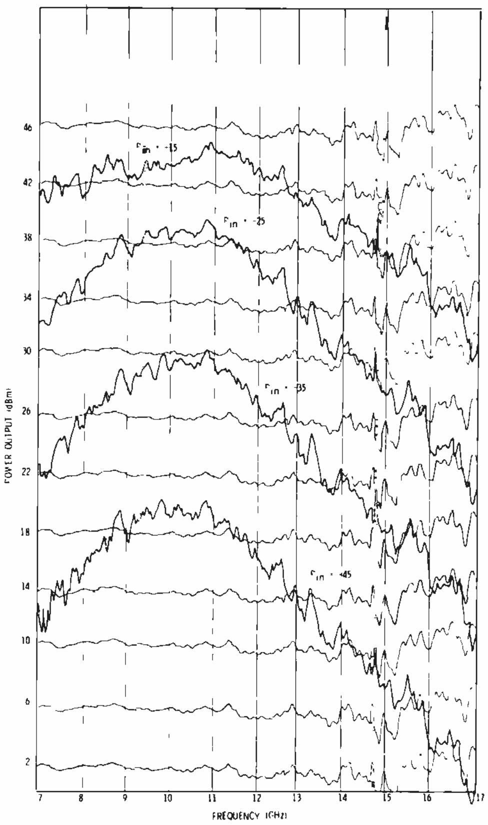

Fig. 7 — Power output characteristics with respect to power input for type A-1487, tube "B".

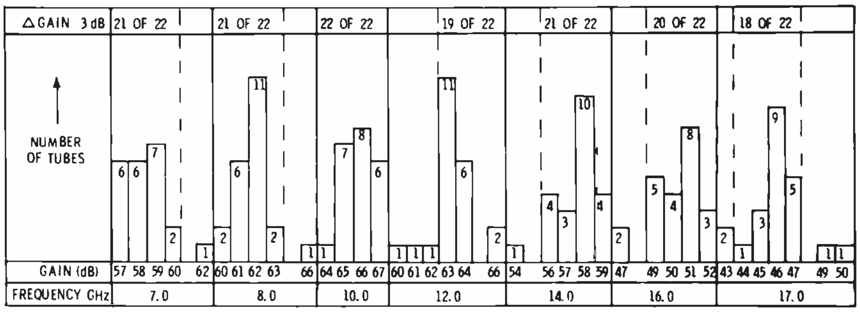

Fig. 8 — Distribution of small-signal gain of 22 tubes.

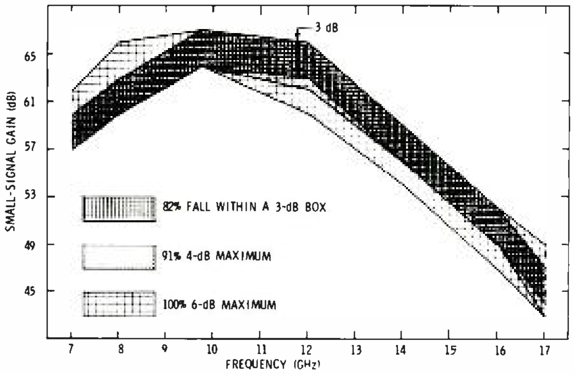

Fig. 9 — Small-signal gain limits of 22 tubes.

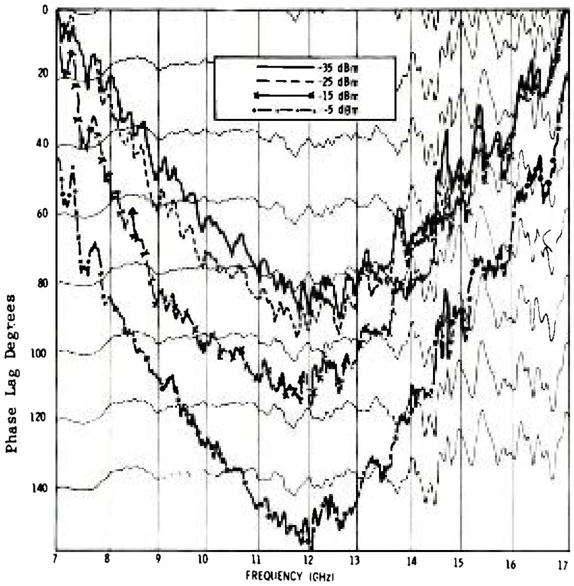

Fig. 10 — Phase characteristics with respect to power input.

speed to allow all the gain fine-structure to be recorded. The gain fine-structure is nominally 2 dB, peak-to-peak, even though the gain level is high.

The tubes must track at all levels of input power from small signal to saturation. Therefore, Figs. 6 and 7 depict power output versus frequency with fixed power input as a parameter. The tubes are in the small-signal gain region at $P_i = -45$ and -35 dBm. With $P_i = -25$ dBm the tubes are in saturation or approaching saturation in the 9 to 12 GHz region; as P_i is further increased, saturation is reached over a wider band of frequencies.

Upon careful examination of Figs. 6 and 7 one can see that the tubes track each other within 1.5 dB. A comparison of gain tracking, shown in Fig. 8 depicts the small-signal gain distribution of the 22 production tubes. The narrow spread in gain at 10 GHz is due to the fact that all tubes were set up to provide the prerequisite gain at that frequency. The same small gain tracking spread can more typically be shown as indicated in Fig. 9. In this figure, a three-dB peak-to-peak gain area and contour versus frequency shows that 82% of the production tubes fall within a three-dB limit. An additionally expanded limit box is shown which includes 91% of the tubes; and finally, an all encompassing area which includes all of the tubes produced.

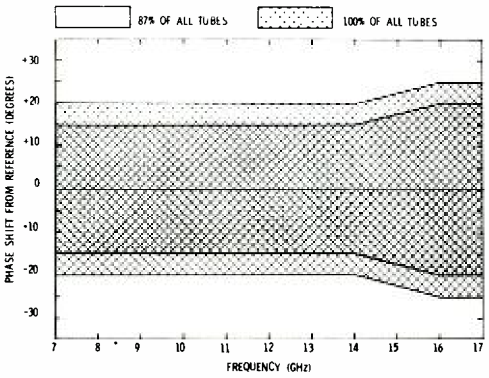

Fig. 11 — Phase shift limits (including fine structure) for 22 tubes.

Phase

The phase dispersion characteristics versus frequency of a representative tube are shown in Fig. 10. Once again, the tubes are required to track at all levels of input power from small signal to saturation. The curves show the phase dispersion at various levels of input power. Fig. 11 shows the normalized phase tracking limits into which fall 87% of the 22 tubes and the extreme limit met by all of the tubes.

Fig. 11 indicates that 87% of all tubes phase track within ±15° over an octave bandwidth (7- to 14-GHz). This is excellent performance when one includes the fine-grain phase variations. The total phase deviation for inclusion of 87% of the tubes requires limits of ± 20° over the last 3 GHz in the band.

Additional phase characteristic sensitivities of the production tubes are as follows:

- Phase change when load VSWR is 2.0:1 and rotated 36° .... 20°
- Am/Pm @ 7 GHz .... 4.3°/dB
- Helix modulation sensitivity;
  - @ 7 GHz .... 1.3°/V
  - @ 12 GHz .... 2.0°/V
  - @ 17 GHz .... 2.3°/V
- Thermal modulation .... .02°/C

Overall results: tube type A-1487

The aforementioned limited production results for tube type A-1487 have led to a traveling-wave tube capable of the following performance:

- Frequency .... 7 - 17 GHz
- Power output .... 20 W at midband
- Small signal gain .... 65 dB at midband
- Gain fine structure ..... 2 dB, peak-to-peak
- Gain tracking .... ±2 dB
- Phase tracking .... .15° including fine structure over an octave
- Harmonic power: 5 dB below fundamental

Conclusions

In summary, the prototype runs discussed for both of the tube types discussed have shown that the phase and gain of miniature TWTs can indeed be controlled to the degree required for phased-array systems. Moreover, such tubes can deliver power-bandwidth products not readily matched by other active devices. Work was undertaken to increase the minimum power level by another factor of two, with nearly the same tube volume, and to further extend the bandwidth, approaching two octaves. It is ironic that the biggest hurdle in the direction of higher power and higher frequencies is the unavailability and deficiency in the state-of-the-art of suitable test components.

Acknowledgments

The contributions on the part of G. Novak, P. Puri, R. Rodrick, R. Sikora and others at RCA Electronic Components relating to the limited preproduction run herein described are acknowledged. In addition, the contributions of cognizant Raytheon, Electromagnetic Systems Division personnel are acknowledged.

Reference

Wolkstein, H.J., Schindler, M.J., and Puri, P., "Miniature Broadband CW Traveling-Wave Tubes" *Microwave Journal*, Oct. 1973.

Operational laser systems used on the MADOS project

F.H. Aron | D.V. Carney

RCA Service Company engineers at Goddard Space Flight Center, Greenbelt, Md., describe satellite observation experiments performed with various operational laser ranging systems. Several systems involve the use of 24-inch, 30-inch and 48-inch telescopes, laser beacons for navigation and spacecraft control, balloon-borne lasers, and mobile argon-laser ranging systems. Orbital techniques, test comparison methods, and major collocation tests are described.

RCA SERVICE COMPANY began providing support to NASA on the Mission and Data Operations Support Project (MADOS) in January, 1973. Located at the Goddard Space Flight Center in Greenbelt, Maryland, the project has among its responsibilities the operation and maintenance of several laser systems.

The present systems, located at the Goddard Optical Research Facility (GORF), include the 30-inch telescope, the Coelostat system, the 48-inch telescope, the 24-inch stationary laser ranging system (STALAS), and two mobile laser ranging systems (MOBLAS-I and MOBLAS-II), with a third mobile system (MOBLAS-III) under construction (see photos of Figs. 1, 2, and 3).

The 30-inch telescope is presently being modified for an experiment designed to measure the deterioration of the corner reflectors on satellites in orbit for several years.

The recently installed 48-inch telescope will be used for a laser communications experiment consisting of ground-to-satellite and satellite-to-satellite laser data links. The various current and planned future activities of GORF personnel are described below.

Skylab earth laser beacon experiment (SELBE)

The main objective of SELBE was to demonstrate the feasibility of using laser beacons as terrestrial *artificial stars* for visual navigation and manned spacecraft control—and as a tracking reference for scientific instruments.

An optical mount having a coelostat mirror system and a DDP-516 computer combined to direct the laser beam to keep the spacecraft illuminated throughout the pass (Fig. 4). This experiment used a 100-watt argon laser and a 10-watt dye laser whose beam divergence was adjusted to 8 arc-minutes and whose frequency could be controlled over a wide range.

Experiments ascertained the output energy required at specific frequencies to allow the astronauts to locate and photograph the laser beam; approximately 2 watts output was found necessary during daytime and only fractions of a watt at nighttime, depending on the laser frequency and earth's albedo. The experiment was highly successful; most of the objectives were accomplished.

Glossary of terms

Albedo — electromagnetic radiation reflected by earth.

Coelostat — a rotating mirror system permitting tracking at any angle reflecting the same part of the sky continuously into a fixed telescope.

Coude focus — any alternate or intermediate focus point of a reflecting or telescope system other than the prime focus point.

Collocation — an arrangement of satellite tracking systems near one-another (without 400 meters) for purposes of making relative comparisons of their tracking data.

Crustal motion — variances in earths motion & crustacean effects.

Geoid — a mathematical model of the earth's irregular shape, a potential surface along which the gravity potential is everywhere equal and to which the direction of gravity is always perpendicular.

Gravity field — a mathematical model of the intensity of the earth's gravatational force near the earth's surface.

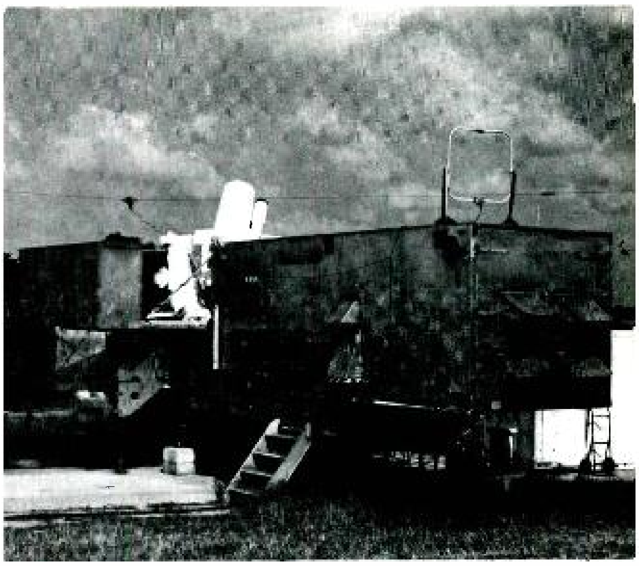

Fig 1 — MOBLAS-II laser tracking systems van.

Fig 2 — Charles Grames and Bill Crawford during MOBLAS-II tracking operation.

Fig. 3 — Rudy Granuert operating the MOBLAS-II control console.

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Kohoutek comet experiment

This experiment was carried out as a crash program beginning in June 1973, with the goal of detecting parent molecules in the comet Kohoutek.

A 30-inch telescope located at the Goddard Optical Research Facility (interfaced to a DDP-516 computer) fulfilled the energy gathering and pointing requirements (Fig. 5). The first successful infrared heterodyne spectrometer featuring semituneable semiconductor diode lasers was constructed for near 8.5 μm to make laboratory measurements of line profiles in N_2O— and to detect thermal emissions from Mars and the Moon. The spectrometer was located at the coude focus of the telescope. The goal of detecting parent molecules in the comet Kohoutek was not achieved because of the comet's faintness; however, the results demonstrated the feasibility of spectroscopic observations of astronomical sources with an infrared heterodyne spectrometer.

Balloon atmospheric propagation experiment (BAPE)

The objective of BAPE was to simulate a space-to-earth laser data transmission link by directing a balloon borne laser transmitter from an altitude well above all significant turbulence to an instrumented ground receiving station. Specific objectives were as follows:

1) Measure scintillation statistics as a function of receiver aperture.

2) Compare statistics of the laser scintillation to available data on stellar scintillation.

3) Compare statistics of daytime scintillation with existing data on nighttime scintillation.

To simulate a space-to-earth laser propagation link, a helium-neon laser transmitter was installed in a gimballed platform aboard the gondola of a high-altitude research balloon. The balloon was launched at White Sands Missile Range and tracked by an optical theodolite of 76-cm aperture. An argon-laser beacon directed at the balloon from the theodolite allowed a star tracker mounted on the gimballed pptics (Fig. 6). A variable-aperture stop system allowed the effective collecting diameter of the theodolite aperture to be changed from 8 cm to the full 76 cm. The signal received was detected by a photomultiplier and recorded for later processing.

Major conclusions drawn from the experiment are that the scintillation of a space-to-ground laser link is similar to that of stellar scintillation and that there are only minor differences between day and night. Nothing was found to indicate that the statistics of laser scintillations are in any way different from those of an inchoherent stellar source.

Mobile laser ranging systems

The mobile laser-ranging system employs a pulsed-laser optical arrangement capable of performing ranging to spacecraft equipped with an array of cube-corner reflectors.

The system consists of a Nike-Ajax radar mount modified for laser ranging; it contains the transmitter and receiver optics, laser transmitter subsystem, receive subsystem, control console, data ranging subsystem, DDP-516 computer, and a timing subsystem. All are mounted in a self-contained environment-controlled trailer. During an operation, the computer points the mount, using *predicts* prepared and transmitted from GSFC. The console operator has the capability of adding angle, range, and time bias during an operation to compensate for errors in the *predicts*. The receiver consists of a 20-inch telescope and gated photomultiplier whose output signal is sent to a 20-channel waveform digitizer. The waveform digitizer generates 20 digital words representing the signal amplitude of 1-nanosecond increments read by the computer and stored on tape.

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Frank H. Aaron, RCA Service Company, Government Service Division, Goddard Optical Research Facility, Greenbelt, Md., joined RCA in 1957 at Patrick Air Force Base Florida, Missile-Test Project. His initial assignments were with Range Safety and Cape Radar at Cape Canaveral. In 1965 he was assigned to Radar Engineering at P.A.F.B., whose function is to provide engineering support for the radars operated by RCA on the Eastern Test Range, which includes developing modifications to improve the performance of the radars, particularly, target acquisition and calibration techniques. From 1968 to 1972 he was assigned to the Range Measurements Laboratory, Engineering Support Group as Project Engineer for the Malabar Laser Facility. During a portion of this period he was also Project Engineer for the On-axis Radar located at P.A.F.B. In 1972 he transferred to the MADOS contract at the Goddard Space Flight Center as manager of the Goddard Optical Research Facility.

Authors Carney (left) and Aaron

The transmitter consists of a Q-switched pulsed ruby laser whose output energy is 1 joule with a pulsewidth of 25 ns. The output pulse passes through a pulse slicer which acts as a high-speed optical switch that is turned on for 5 ns during the peak energy of the pulse. The 5 ns pulse leaves the pulse slicer, passes through a 4-power upcollimater, then up through a coelostat, and out through a 5-power upcollimater mounted on the elevation axis. The resultant beam divergence is one arc-minute.

A sample of the transmitter output pulse is used to start a range time-interval counter which is stopped by the receive pulse. The transmitter pulse width is also measured and recorded on tape. The simplified block diagram (Fig. 7) shows the main signal path. During postflight data processing, the transmitter pulsewidth measurement and the waveform digitizer data are used to correct the range time-interval unit so that a measurement of time is made from the center of the transmitter pulse to the center of the receive pulse. By using this technique a range accuracy of 10 cm and better is obtained on ground targets and various spacecraft.

The mobile system now under construction will be equipped with a 0.2 ns, 0.25-Joule laser, which will improve the range accuracy to 3 to 5 cm. The remaining ranging systems are scheduled for the same type laser as they become available from the manufacturer.

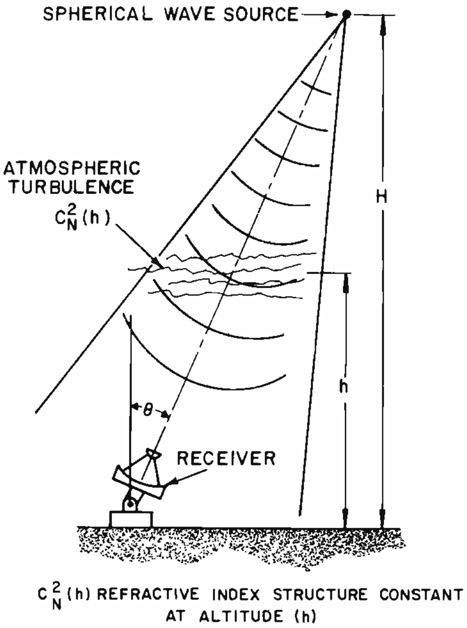

Fig. 6 — Propagation path of space-to-earth argon laser link; star tracker is on a gimballed platform to direct beam.

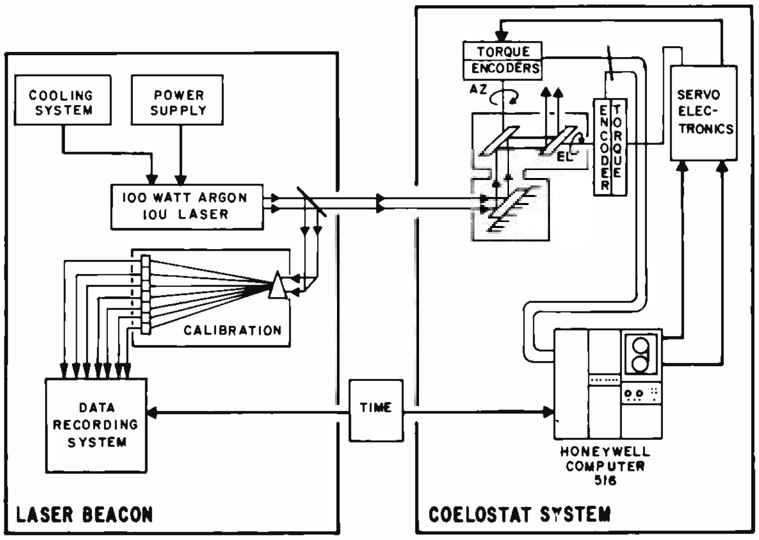

Fig. 4 — Earth laser beacon station.

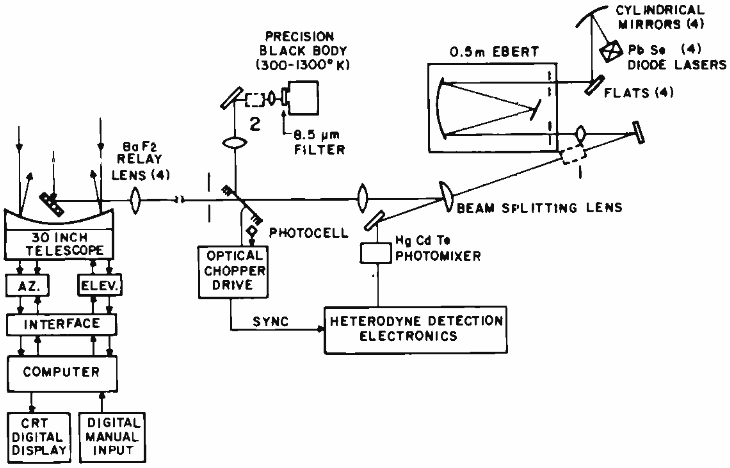

Fig. 5 — Diagram of a 30-inch telescope interfaced with a DDP-516 computer.

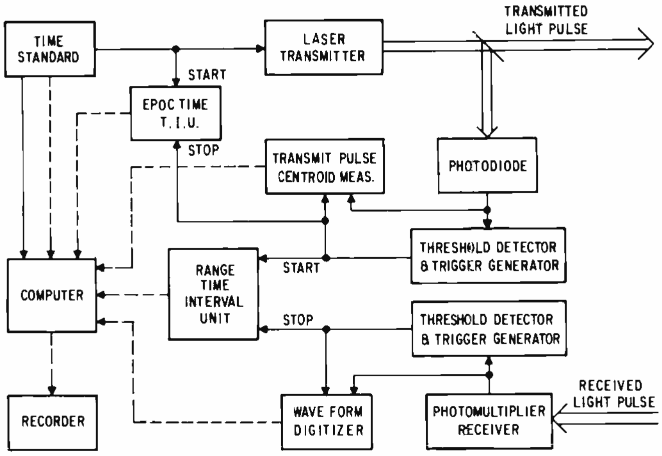

Fig. 7 — Block diagram of the signal path for mobile laser ranging system.

Scientific applications of laser ranging systems

The National Geodetic Satellite Program (NGSP) requirements dictated the use of accurate tracking systems to determine precise satellite orbits. These orbits are then used for geodetic studies to help determine such unknowns as the shape of the earth, the geopotential, and to improve earth survey maps. Thus, the satellite age has produced promising new techniques for improving and expanding our physical knowledge of the geoid.

Of the many tracking systems available for observing a satellite, astrodynamic cameras were the most widely accepted for precision tracking. Using existing techniques of astronomy, an object, providing that it could be seen, could be photographed against the celestial background — and its position determined relative to cataloged stars. If a series of photographs were made at well defined intervals of time, an orbital arc could be defined for a vehicle in terms of its position and directional velocity. The optical systems produce right ascension and declination angles with accuracies on the order of a few seconds of arc from which satellite ranges (accurate to approximately 5-10 meters) can be simply determined. However, the preprocessing procedures necessary are time consuming, often delaying the reduction of satellite data for geodetic purposes by several months, and tracking is generally limited to nighttime. Improvements in other systems in terms of more timely data availability and accuracy were desirable.

Orbital technique

An obvious objective of the NGSP has been to compare the various geodetic observation systems in use and select the most accurate. Originally, well-known optical systems formed reference orbits by linearly fitting a curve (orbit) to their data and minimizing the measurement residuals in a weighted least-squares, differential correction scheme. Once a curve was fit to the data of a particular reference system, data from other comparison systems could be evaluated with respect to that curve and the deviations analyzed.

If points C_i along the calculated best-fit curve C are defined at the time of each tracking system observation, O_i, residual differences, R_i can be obtained such that $R_i = (O_i - C_i)$. A simple linear error-model equation, below, is then used to fit the residual regression curve:

$$R_i = B - TC_i + \xi_i$$

where B represents a constant offset error from the residual curve (*i.e.*, a measurement bias)

T represents the constant slope of the residual curve relative to the reference curve (*i.e.*, a measurement timing bias)

T represents the constant slope of the residual curve relative to the reference curve (*i.e.*, a measurement timing bias)

C_i is the time rate of change of C_i

ξ_i is the remaining randomly distributed error of the estimate (the measurement noise component)

Comparison method

To minimize uncertainties in the system comparisons, a collocation technique was used. By collocating the participating trackers as near to one another as feasible, their relative surveys could be determined to about 10 cm, and their independent clocks could be synchronized with a local standard to within ± 0.1 ms. This approach, coupled with the subsequent determination of only short arcs would also reduce the effects of unknowns in the earth's gravity field model employed in the Orbit Determination Program (ODP) GEODYN.[1]

The ODP corrects the collected and preprocessed data for known time-reference systems differences between the reference system and the comparison systems for parallax, and applies other specified corrections (*e.g.*, refraction). Within the limitations of the ODP, the derived reference orbit will be as accurate as the reference data is over its tracking interval.

The laser range, azimuth, and elevation (RAE) data were used to form the laser RAE reference orbits to compare other tracking systems with the laser. For those tests where simultaneous collocated camera data were available, a combined laser/camera solution was performed by fitting the orbit to the laser range and camera right ascension and declination (RRD) data. The RRD reference orbit resulting from this combined solution was then used to check the laser azimuth and elevation angle statistics, and the measurement error-estimates for the other systems were compared to those derived with the RAE orbits.

After fitting the comparison system residuals to the measurement bias B and timing bias TC_i error-model terms in Eq. 1, the residual means for the systems are reduced to zero. Since the residual RMS remainders (ξ_i) then appear randomly distributed and the points are serially uncorrelated, the per-pass mean (ξ_i) may be interpreted as the RMS error of the estimated (noise) in the system's observations. This noise is composed of relatively small, independent uncertainties in the data itself (*e.g.*, refraction and system timing), perturbations in the orbit, and unknowns in the mathematical models used in the ODP.

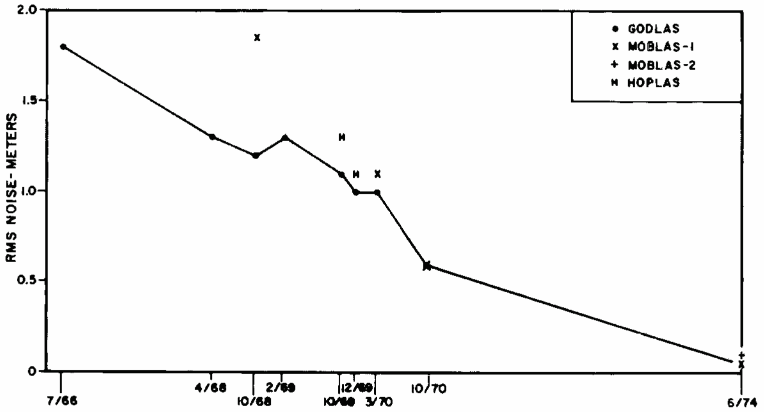

Fig. 8 — Laser range average RMS noise versus date of test.

					Data RMS error of the estimates				*Data biases*				
Test	*Date*	*System*	*No. passes*	*Ref. orbit*	*Range (m)*	*Azimuth (arc-s)*	*Elevation (arc-s)*	*R. Rate (cm/s)*	*Range (m)*	*Azimuth (arc-s)*	*Elevation (arc-s)*	*R. rate (cm/s)*	*Time (msec)*
ROLACO	7/66	GODLAS	15	RAE	1.8 ± 0.8	91 ± 62	37 ± 25	—	—	—	—	—	—
		GRARR	10	RAE	6.8 ± 2.1	—	—	6.9 ± 5.8	−5.3 ± 12.4	—	—	—	−2.1 ± 1.2
WICE	4/68	GODLAS	35	RAE	1.3 ± 0.2	53 ± 53	27 ± 9	—	—	0 ± 0	−6 ± 13	—	—
		GODLAS	21	RRD	1.5 ± 0.2	57 ± 42	27 ± 9	—	—	5 ± 21	0 ± 15	—	—
		Camera	21	RRD	-	1.6 ± 0.8**	1.7 ± 1.1†	—	—	—	—	—	—
		FPQ-6	34	RAE	1.0 ± 0.3	21 ± 18	11 + 4	9.8 ± 4.2	−2.2 ± 2.6	38 ± 37	23 ± 15	2.4 ± 2.9	0.3 ± 0.3
		FPS-16	27	RAE	1.4 ± 0.4	41 ± 33	19 ± 7	—	−2.2 ± 4.1	−51 ± 56	24 ± 23	—	0.3 ± 0.3
		SECOR	32	RAE	1.8 ± 0.4	—	—	—	−17.5 ± 4.0	—	—	—	−0.6 ± 0.5
		TRANET$_l$	26	RAE	—	—	—	4.5 ± 2.0	—	—	—	1.4 ± 3.5	0.0 ± 0.1
		TRANET$_H$	16	RAE	—	—	—	6.1 ± 7.0	—	—	—	−3.2 ± 7.5	0.0 ± 0.0
GORF-1	10/68	MOBLAS-1	5	RAE	1.2 ± 0.2	110 ± 39	69 ± 19		−0.5 ± 0.6	34 ± 81	−40 ± 33	—	—
		GODLAS	5	RAE	1.9 ± 0.2	53 ± 8	26 ± 10	—	—	0 ± 0	−3 ± 13	—	—
CALACO	2/69	MOBLAS-1	92	RAE	1.3 ± 0.2	30 ± 17	22 ± 13	—	—	0 ± 0	−8 ± 4	—	—
		MOBLAS-1	14	RRD	1.3 ± 0.2	35 ± 23	31 ± 9	—	—	10 ± 24	−26 ± 11	—	—
		Camera	14	RRD	—	0.9 ± 0.3**	1.4 ± 0.7†	—	—	—	—	—	—
		FPQ-6	23	RAE	1.1 ± 0.4	42 ± 55	15 ± 18	—	5.0 ± 6.7	−17 ± 32	22 ± 28	—	0.4 ± 1.1
		GRARR	64	RAE	3.0 ± 0.2	—	—	1.4 ± 0.7	−4.0 ± 6.7	—	—	0.5 ± 2.4	0.0 ± 1.2
ARLACO-1	10/69	MOBLAS-1	14	RAE	1.1 ± 0.1	40 ± 15	33 ± 12	-	—	0 ± 0	−19 ± 16	—	—
		HOPLAS	14	RAE	1.3 ± 0.8		—	—	−1.6 ± 1.5	NA	NA	—	—
ARLACO-2	12/69	MOBLAS-1	11	RAE	1.0 ± 0.1	40 ± 12	42 ± 24	-	—	0 ± 0	29 ± 29	—	—
		HOPLAS	11	RAE	1.1 ± 0.4		—	—	1.3 ± 1.7	NA	NA	—	—
GORF-2	3/70	GODLAS	21	RAE	1.0 ± 0.2	182 ± 107	48 ± 16	—	−1.2 ± 1.3	−72 ± 131	7 ± 34	—	—
		MOBLAS-1	21	RAE	1.1 ± 0.1	43 ± 22	30 ± 14	-	—	0 ± 0	19 ± 18	—	—
GORF-3	10/70	GODLAS	4	RAE	0.6 ± 0.2	99 ± 72	41 ± 20	-	0.9 ± 0.3	73 ± 81	30 ± 32	—	—
		MOBLAS-1	4	RAE	0.6 ± 0.1	42 ± 12	33 ± 11	—	—	0 ± 0	−20 ± 13	—	—
GORF-5	6/74	MOBLAS-1	5	RAE	7.9 ± 1.3*	39 ± 34	22 ± 9		1.3 ± 10.6*	22 ± 88	7 . 43	—	—
		MOBLAS-2	5	RAE	9.1 ± 1.2*	131 ± 91	19 ± 11	—	—	19 ± 32	−9 ± 10	—	—

* *Range residual statistics units are centimeters for this test.*
**Right ascension
†Declination

Table I — RMS noise and bias term results.

				Range		*Azimuth*		*Elevation*	
Test	*Date*	*System*	*Ref Orbit*	*RMS (m)*	*Bias (m)*	*RMS (arc-s)*	*Bias (arc-s)*	*RMS (arc-s)*	*Bias (arc-s)*
ROLACO	7/66	GODLAS	RAE	1.8 ± 0.8	—	91 ± 62	NA	37 ± 25	NA
WICE	4/68	GODLAS	RAE	1.3 ± 0.2	—	53 ± 53	0 ± 0	27 ± 9	−6 ± 13
		GODLAS	RRD	1.5 ± 0.2	—	57 ± 42	5 ± 21	27 ± 9	0 ± 15
GORF-1	10/68	GODLAS	RAE	1.9 ± 0.2	—	53 ± 8	0 ± 0	26 ± 10	−3 ± 13
		MOBLAS-1	RAE	1.2 ± 0.2	−0.5 ± 0.6	110 ± 39	34 ± 81	69 ± 19	−40 ± 33
CALACO	2/69	GODLAS	RAE	1.3 ± 0.2	—	30 ± 17	0 ± 0	22 ± 13	−8 ± 14
		GODLAS	RRD	1.3 ± 0.2	—	35 ± 23	10 ± 24	31 ± 9	−26 ± 11
ARLACO-1	10/69	MOBLAS-1	RAE	1.1 ± 0.1	—	40 ± 15	0 ± 0	33 ± 12	−19 ± 16
		HOPLAS	RAE	1.3 ± 0.8	−1.6 ± 1.5	NA	NA	NA	NA
ARLACO-2	12/69	MOBLAS-1	RAE	1.0 ± 0.1	—	40 ± 12	0 ± 0	42 ± 24	29 ± 29
		HOPLAS	RAE	1.1 ± 0.4	1.3 ± 1.7	NA	NA	NA	NA
GORF-2	3/70	GODLAS	RAE	1.0 ± 0.2	−1.2 ± 1.3	182 ± 107	−72 ± 131	48 ± 16	7 ± 34
		MOBLAS-1	RAE	1.1 ± 0.1	—	43 ± 22	0 ± 0	30 ± 14	19 ± 18
GORF-3	10/70	GODLAS	RAE	0.6 ± 0.2	0.9 ± 0.3	99 ± 72	73 ± 81	41 ± 20	30 ± 32
		MOBLAS-1	RAE	0.6 ± 0.1	—	42 ± 12	0 ± 0	33 ± 11	−20 ± 13
GORF-5	6/74	MOBLAS-1	RAE	7.9 ± 1.3 (cm)	−1.3 ± 10.6*	39 ± 34	22 ± 88	22 ± 9	7 ± 43
		MOBLAS-2	RAE	9.1 ± 1.2 (cm)	—	131 ± 91	19 ± 32	19 ± 11	−9 ± 10

* *(cm)*

Table II — Laser residual statistic averages for each test.

Comparison tests

In support of NGSP objectives, the Goedetic Earth Orbiting Satellite (GEOS) Observation Systems Intercomparison investigations were performed to evaluate the relative accuracies of several available geodetic tracking systems in use at that time. These collocation tests were performed during the active lifetime of both GEOS-1 and -2 by the GEOS Principal Investigator at NASA's Goddard Space Flight Center (GSFC), with the support of the RCA Mission Support Group's Mission Analysis Section at Lanham. Of particular interest to the investigation were the NASA/GSFC developmental lasers.

The Goddard mobile laser system (designated GODLAS or MOBLAS or MOBLAS-1 depending upon the test period) and camera systems were shipped into the field several times to be collocated with other tracking systems at various sites in the U.S. and Australia. Other laser-only intercomparisons were conducted both at GSFC and at the Smithsonian Astrophysical Observatory (SAO) laser site in Arizona. A second GSFC mobile laser (MOBLAS-2) was compared against the first (MOBLAS-1) at GORF.

Three major collocation tests, conducted with other tracking systems, and four laser-only collocation tests, were performed as summarized below. The comparison results are given in Table I by test and by reference orbit, outlined in Table II for the lasers and plotted in Fig. 8 for the laser ranges. The azimuth and elevation RMS error estimates shown are about the non-zero residual means and should not be considered valid estimates of the angle noise.

ROLACO

The Rosman Laser Collocation (ROLACO) test[2] was conducted at the NASA tracking station at Rosman, North Carolina, during the period of July through December 1966. A Goddard Range and Range Rate (GRARR) system was compared against the mobile GODLAS reference laser system on GEOS-1 tracks. The 15-pass laser average range RMS noise was 1.8 meters for this test.

WICE

The Wallops Island Collocation Experiment (WICE)[3] took place at NASA's Wallops Island, Virginia, station during the period April through June 1968. Two C-band radars (an AN/FPQ-6 and an AN/FPS-16), an Army SECOR ranging system, a Navy TRANET Doppler (range rate) system, and a NASA PTH-100 camera were compared to the mobile GODLAS reference laser system.

In this test, both laser RAE reference orbits and laser/camera RRD reference orbits were used to evaluate the comparison systems. The GODLAS average range RMS noise showed a 0.5 meter improvement to 1.3 ± 0.2 meters for the 35 RAE orbits and 0.3 meter to 1.5 ± 0.2 meters for the 21 RRD orbits. The average laser azimuth and elevation biases as derived by the RRD orbits differed from the RAE-derived values by less than 6 arc-seconds. The average angle RMS noises derived by the two reference orbits differed by less than 11 arc-seconds.

The RRD results tend to confirm confidence in the laser-only solutions for both ranges, and angles.

GORF-1

the first laser-laser comparison[4] was performed at GORF during October and November 1968. The GODLAS reference system was compared with the newly assembled GSFC MOBLAS (MOBLAS-1) laser system and included some of the first passes taken by the MOBLAS-1. The five simultaneous passes indicated average range RMS noises of 1.86 and 1.23 meters respectively for GODLAS and MOBLAS, relative to the MOBLAS RAE reference orbits. The average range bias for MOBLAS with respect to GODLAS was −0.5 ± 0.6 meters. Again, the laser noise was improved over previous tests.

CALCAO

The Carnarvon Laser Collocation (CALACO) test[5] was carried out during the period February through April 1969 at Carnarvon, Australia. MOBLAS-1 was collocated with another AN/FPQ-6 C-band radar, a GRARR, and PTH-100 camera and tracked a total of 92 GEOS-2 passes. Wherever simultaneous tracks occurred, the systems were compared with the MOBLAS.

As with the WICE test, both laser RAE and laser/camera RRD reference orbits were formed to evaluate the comparison systems. The MOBLAS-1 average range RMS noise for both the 92 RAE orbits and the 14 RRD orbits was agains 1.3 ± 0.2 meters, identical to the WICE and similar to the GORF-1. The average laser azimuth and elevation biases relative to the RRD orbits differed from the RAE values by 5 and 9 arc-seconds, respectively. The average RMS noise for the angles differed by less than 10 arc-seconds, as in the WICE.

During the analysis of the laser passes in this test, an attempt was made to determine if there was any significant difference in the laser residual mean and RMS noise values derived as a function of the time of day (*i.e.*, night or day) of the passes. It was thought that the laser would enjoy a better signal-to-noise ratio for a nighttime pass relative to a daytime pass; however, separating the passes and deriving the statistics for the two groups did not confirm this assumption.

ARLACO

The Arizona Laser Collocation (ARLACO) test[4] was run from October 1969 through January 1970 at the SAO Mount Hopkins Observatory in Arizona. The MOBLAS-1 was laboriously collocated with the SAO laser (HOPLAS) and tracked GEOS-2. The test is broken into two segments (ARLACO-1 and ARLACO-2), since MOBLAS-1 was moved precisely 10 meters to the west of its original position in late November.

For the 14 simultaneous passes of ARLACO-1, the MOBLAS-1 had an average range RMS noise of 1.06 meters, while the average HOPLAS range noise was 1.34 meters with respect to the MOBLAS-1 reference orbit. The average relative HOPLAS range bias was −1.6 ± 1.5 meters. The 11 passes of ARLACO-2 indicated an average MOBLAS-1 range RMS noise of 1.00 meters and an average HOPLAS relative range RMS noise of 1.09 meters. The second average relative range bias for HOPLAS was 1.3 ± 1.7 meters.

GORF-2

The second GORF laser-laser comparison[4] was conducted at Goddard during March through May 1970. Simultaneous data were taken on 21 passes and orbits were fit to the MOBLAS-1 reference system. The MOBLAS-1 and GODLAS average range RMS noises were 1.06 meters and 1.00 meters respectively. The GODLAS showed an average range bias of −1.2 ± 1.3 meters relative to the MOBLAS-1 RAE orbits.

GORF-3

The third GORF laser-laser comparison[4] was conducted at GSFC in 1970. Four simultaneous tracks were taken during October by the GODLAS and MOBLAS-1 systems. Prior to the comparison, both systems had been modified in their pulse-detection schemes. An average range RMS noise of 0.59 meter was shown for both systems, while the average range bias of the GODLAS with respect to the MOBLAS-1 reference orbits was reduced to 0.9 ± 0.3 meters. These results were indicative of the improvements produced by the modifications.

GORF-5

The most recent GORF laser-laser comparison, between MOBLAS-1 and the recently developed MOBLAS-2 systems, includes five simultaneous passes during June 1974. Reference RAE orbits were fitted to the MOBLAS-1 data and MOBLAS-2 was compared to those orbits. Prior to this test, the laser systems had been extensively modified both in the hardware and in the supporting software components. Preliminary results indicate that the average range RMS noise values were 7.94 centimeters and 9.08 centimeters for MOBAS-1 and MOBLAS-2, respectively. The MOBLAS-2 average bias, derived relative to MOBLAS-1, is −1.25 ± 10.57 centimeters. If these results are reliable, as they appear to be, they represent almost an order of magnitude improvement in laser ranging. Further analysis of these data is presently underway.

San Andreas fault experiment

The mobile Goddard lasers (MOBLAS-1 and MOBLAS-2) are currently participating in the San Andreas Fault Experiment (SAFE) in California.

The primary purpose of this experiment is to measure the drift of the Pacific and North American tectonic plates with respect to each other and provide the resulting data to NASA Geodynamics Branch and other Agencies for earthquake prediction.

To accomplish this task, one mobile laser system is located on top of Otay Mountain near San Diego, California, and another mobile system will rotate every 3 months between sites at Quincy, California; LaPaz, Mexico; Mazatlan, Mexico; and Bear Lake, Utah. The two systems simultaneously track a satellite and the data obtained by each site is used to calculate the baseline distance between the two respective sites. By measuring each baseline once each year, a yearly rate of drift can be obtained for each baseline. As can be seen from Fig. 9 each baseline has a different estimated drift rate based on previous data from other sources. The SAFE data will have a greater accuracy than was previously available using other techniques. At present, the ranging accuracy is 10 cm or better, and during 1975 the accuracy will be improved to 5 cm by the installation a 0.2 ns laser and a new receive signal processor.

A follow-on program which is an enlargement of SAFE, is the LAGEOS Laser Network, which will consist of a minimum of two laser sites on each of the earth's six major tectonic plates. The Laser Geodetic Satellite (LAGEOS) is scheduled to be launched in January of 1976. It will be the first satellite launched by NASA specifically for laser tracking and geodetic studies; it will contain no instrumentation. The satellite will be a 24-inch sphere weighing 905 pounds completely covered with 426 retroreflectors, each 3.65 cm in diameter. It is expected to be launched into a 5900 km circular orbit at 110 degrees inclination with a period of 3 hours and 40 minutes.

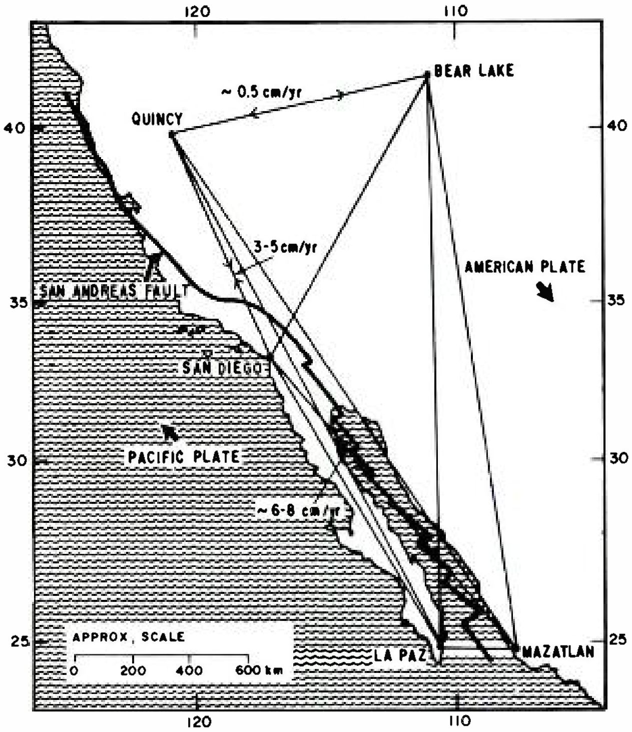

Fig. 9 — (SAFE) laser locations.

In 1977, five additional mobile systems will be added to GORF which will be used to form the LAGEOS Laser Network. The LAGEOS Laser Network Stations will be used for tectonic and fault motion studies and earth rotation investigations. In addition, it is expected that the LAGEOS satellite will be useful for a host of experiments to be conducted over several years as part of the Earth and Oceans Physics Application Program (EOPAP).

The measurement requirements for the future laser systems in conjunction with other experiments are:

Crustal motion	1 cm./year
Polar motion, earth rotation	2 cm./0.5 day
Satellite orbits	10 cm.
Gravity field/geoid	10 cm.
Sea surface topography	10 cm.
Sea state/wave height	1 ÷ 3 m
Surface winds	2 ÷ 5 m/s, <20°
Magnetic field	2 gamma, 0.5 arc-min.

Tracking systems calibration

The mobile lasers are to be deployed to Bermuda and Grand Turk Islands and used in conjunction with the stationary system at Goddard Space Flight Center in Greenbelt, Md., and another at Patrick Air Force Base in Florida to define a tracking systems calibration network for the pending GEOS-C satellite. With the acceptance of the laser as a precise ranging system, has come a need to use it not only for precision satellite tracking, but to evaluate new systems, and to calibrate both new and existing trackers. Among the relatively new systems to be evaluated and calibrated are a satellite-borne x-band altimeter and a satellite-to-satellite tracking technique.

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Evaluating computer programs for control of multifunction sensors

S. Batterman

The design and implementation of large-scale and complex computer programs for radar control require a concurrently developed test program to verify the performance of the operational programs and their compatibility with the driven sensor. Performance is verified at various stages of the computer program development, and each stage usually requires a different test bed. Tests of the radar sensor, on the other hand, start generally before the ultimate operational program is available and use special routines, necessitating the development of a flexible driving program. The driving program need not resemble the operational configuration nor function in real time, except for the communications channel between the radar sensor and its controlling computer and the attendant message formats which should be replicas of the operational program implementation. Test sequences and test beds are discussed, along with the interrelationships between the two programs for design verification and techniques for their integration. Special emphasis is placed on software testing.

MASSIVE, complex computer programs operating in real time are the basis for many of the important advances made in recent years in major command and control systems and critical process control applications. Indeed, application of computer control to major hardware systems has made it possible for system developers to make a quantum jump in system capability at a fraction of the cost of equivalent hardware implementation.

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The price paid for these advances, of course, lies in the scope and complexity of the programs themselves, and perhaps even more so in the attendant problems of software verification. This paper addresses the subject of verifying and testing major real-time computer programs, using the AEGIS AN/SPY-1 radar control program as a representative case.

The AN/SPY-1 multi-function radar is a major component of the AEGIS Weapon System MK 7 designed for shipboard AAW application; the radar control program, in turn, is the critical driving element of the radar system. A brief functional description of the AN/SPY-1 sensor is provided, with emphasis on software architecture. With the context thus established, the overall test program is outlined, including the types of tests and demonstrations conducted and the test progession, from verification of software module loops to full computer-driven hardware demonstrations. The focus is on both the techniques employed and the test methodology for software-hardware integration.

Radar system design

Overview

Fig. 1 is a functional block diagram of the AN/SPY-1 radar system. The input-output buffer/synchronizer partitions the system elements into special-purpose radar components and general-purpose stored-program computers. The radar equipment monitors each beam position, delivering single-point spatial estimates on any targets illuminated in that space angle. This action, termed dwell execution, requires only short-term computer memory. The control programs maintain a longer-term "history" of past target positions and use the data gathered by the radar equipment to schedule subsequent dwell-by-dwell actions.

In the track process, the control programs screen and calibrate each single-point estimate and update the track history to the time of the last sample point. Future target position is then estimated and additional data points are requested to maintain an accurate estimate of the target flight path.

For the search process, the allocation of tasks between the radar equipment and general-purpose computers closely parallels that of the track process. Algorithms define the search beam lattice and periodically generate a queue of beam positions to be monitored. These beam requests, dictated by operational and doctrinal priorities, are transferred to the radar equipment as search commands, one command at a time. Each command sets up a dwell, and not until the dwell is executed is another command transferred. Detections sensed by the radar equipment are returned to the control computers for track initiation. Returns for a complete dwell are also transferred one at a time, starting at an early point in the succeeding dwell.

Architectural considerations

Batch processing is used over intervals of several dwells for generating radar commands and handling return data. Data exchanges between the general-purpose computers and the radar sensors are, as noted, dwell-by-dwell. This approach offers processing efficiencies as a result of fewer interrupts and the application of simple and effective error recovery techniques. In addition, the dwell-by-dwell data exchange in fixed data block formats also simplifies the definition of interface.

The radar control program architecture consists of three primary elements: task

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subprograms, an executive, and a data base. The subprograms and sections of the data base most instrumental in radar control are shown in Fig. 2. The four key subprograms (radar scheduling, radar output control, radar return processing, and track processing) and four data-base tables (output buffer, return buffer, track file, and time table), form the radar control loop. Standard doctrine for control of the overall operation is stored in the doctrine control table, but is modifiable by the radar operator via the switch action subprogram. This doctrine is then employed by the search management, radar scheduling, and track processing subprograms during their normal operation.

The radar control loop is initialized by a call to the search management subprogram. This program element steps through a fraction of the desired search lattice with each call, generating a queue of search beam requests. The radar scheduling subprogram is then activated by executive call and utilizes the contents of the beam request queue and the track time table to schedule an interval of radar time according to predetermined priority rules.

Upon completion of the scheduling, a radar events list is routed to the radar output control subprogram; this subprogram performs coordinate conversions necessary to stabilize the beam and generates the appropriate phase tapers (steering commands), thresholds, blanking gates, and other control information required by the radar equipment for each individual dwell execution. All transfers of dwell control data are initiated by the radar equipment, one dwell at a time.

After the radar equipment has executed all dwells contained within a single radar scheduling interval, an interrupt is generated in Computer 2 which activates the radar return subprogram via the executive. This subprogram examines the dwell return data one dwell at a time. Each set of dwell return data contains an index which provides a reference to the radar events table. This table provides all data (type of beam, stable space pointing position, etc.) necessary to evaluate the individual returns. For search beams, the return data are checked for threshold crossings. If no threshold crossings are found, processing of that particular dwell is terminated, and the next dwell returned is examined.

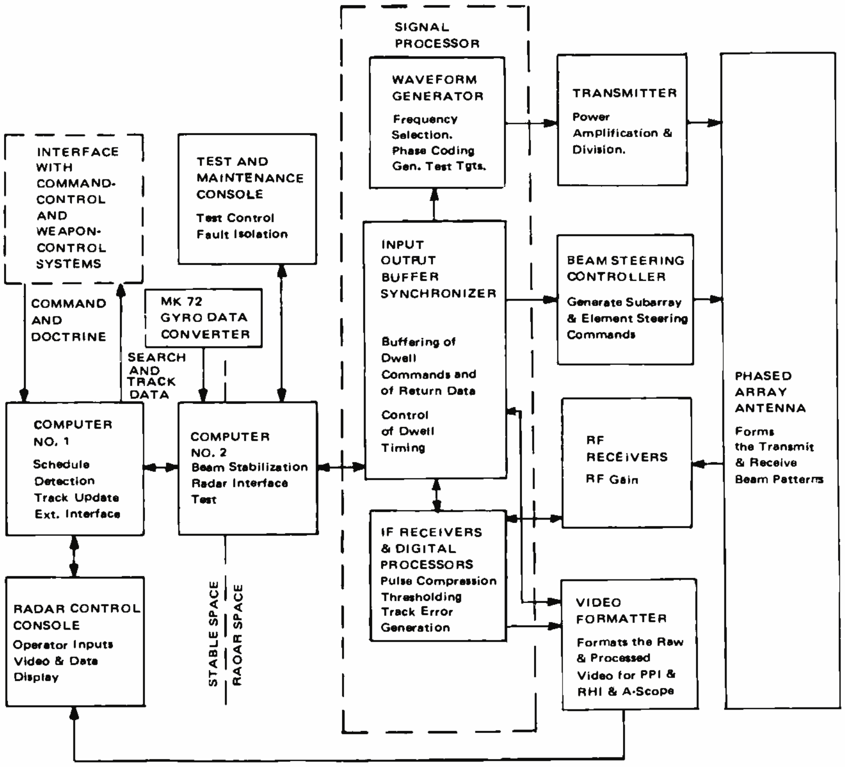


Fig. 1 — Radar functional block diagram.

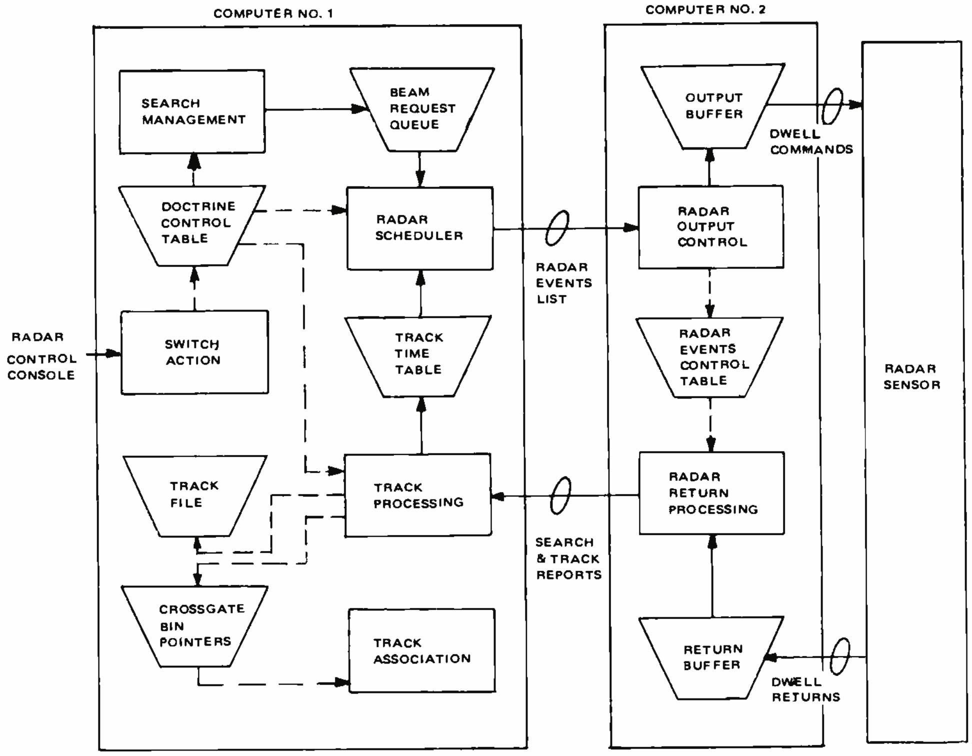


Fig. 2 — Computer program, radar control loop.

If one or more threshold crossings are found, the ranges are corrected for scaling and bias errors, and the report is annotated with the mode employed, time of day, and stable space beam position, for subsequent transfer to Computer 1. For track returns, the data are scaled, corrected for bias terms (range errors, monopulse slopes), and the monopulse errors are rotated to stable space coordinates. As with the search returns, each track return is annotated with administrative data and readied for transfer to Computer 1. When Computer 2 has thus assembled all of the dwell return data for a single scheduling interval, the resulting data are transferred to Computer 1 as a block.

Upon receipt of the detection and track returns in Computer 1, the track processing subprogram is applied for correlation of threshold crossings from search beams with established tracks (a process referred to in the AEGIS System as "crossgating"). Detections which correlate are discarded, while those not correlating are entered into a process referred to as transition-to-track.

This transition-to-track process is initiated by establishing a track file entry for the object and requesting that a track dwell be assigned to the object via the track time table. Transition-to-track data rates are initially high, gradually stepping down to steady-state rates. When this stable track rate is achieved, tracking continues at a constant rate unless increased for tactical reasons.

An individual return from a steady-state track is smoothed using an α-β filter and then handled much in the same way as the first transition-to-track request. The transition-to-track sequence has been designed to employ the same α-β filter used for steady-state track without a change in the smoothing constants.

The track association subprogram (also shown in Fig. 2) sets up the cross-correlation of all steady-state tracks in the track file for the purpose of discarding redundant tracks.

Testing approach

The modular program structure and functionally dedicated equipment chains served to simplify testing and at the same time dictated the test approach. The structure of the radar system made it possible to use simulators for independent but concurrent testing of the radar control programs and the radar equipment. Two simulators were applied to radar equipment tests, with a third simulator representing the control programs; all three were invaluable as pre-integration tools. A fourth simulator, embedded in the tactical control program, was used for operability assessments of the integrated system; it also provided qualification testing with specially programmed kinematics. All simulations were conducted in real time. The following paragraphs outline the general sequence of the test program and describe the simulators and test configurations used.

The test sequences related to integration began with exclusive software tests of the search and track loop program modules, using a radar simulator target generator (RSTG) co-resident in Computer 2. This initial test configuration demonstrated overall control program functioning with the operating system (simulated in an executive program developed to support the three computer-instrumented segments of the AEGIS weapon system).

The software was then exhaustively tested by means of the Multifunction Array Radar (MFAR) interface simulator (MIFS) – a simulator contained in a separate, dedicated computer. A virtually full range of sensor responses was programmed, imparting a high degree of authenticity to the simulator. Authenticity was further reinforced by the fact that its designers functioned completely independently of the control program designers.

Qualification testing of the radar hardware proceeded in parallel, but independently. The hardware was driven by a simplified version of the control program, termed the signal processor checkout (SIPCO) simulator. The simulator exercised the hardware with repeated dwells of the same type, recording the hardware responses but not operating on them.

Upon completion of those tests the integration process was begun, utilizing a simulated dynamic target (SDT) subroutine which is an integral element of the tactical program. SDT, in effect, calls on the waveform generator (See Fig. 1) to furnish excitation for signal injection either internally via the rf receiver, or externally by routing the simulated return to a tower and then radiating it by means of a horn. All modes of the system were exercised in this manner.

The final system tests were operational in nature, using targets of opportunity, balloon-borne spheres, and controlled aircraft.

Configuration No. 1 — radar simulator target generator

This test configuration, shown in Fig. 3, provided early design verification of the critical program modules making up the track loop, including the seeding of the loop through the normal means of searching. Occupying core space in Computer 2, the RSTG time shares resources with the two radar interface modules — radar output control and radar return processing — and is capable of handling several targets simultaneously. Both accelerating and stationary targets are programmable; noise can also be added to the monopulse errors.

RSTG faithfully simulates the interface from the radar sensor to Computer 2. Commands to the radar sensor, however, are intercepted in the radar events control table (where dwell orders for several scheduling intervals are stored) rather than extracted from the computer output buffer. The problem, then, is carried out in inertial space, conserving sufficient time in Computer 2 for proper execution of RSTG. In other words, the ship's motion problem and the normal communications cycle were not entirely modeled. Nonetheless, the configuraiton provided a test vehicle for integration of the subprograms with the executive and common data base and also enabled functional tests and demonstrations of the software instrumented tracking servo.

The operations performed by RSTG are divided into four parts, as shown in Fig. 3. Kinematical equations are solved in the target generator section and the updated target positions are saved for display, correlation with dwell commands, and for computing track errors. Candidate beams for target insertion are determined in the correlator/detector, where either initial detections or redetections are declared and/or track beams are selected for the track error computation. The track error generator computes the differences between the updated target position and the designated position as extracted from the appropriate dwell command. Monopulse error estimation is simply a conversion process as indicated, loading the input buffer with reports intelligible to the radar return processing module. The background or instrumenation noise for these tests depends on the granularity of the monopulse errors in the return message.

Configuration No. 2 — MFAR interface simulator

The second set of exclusively software tests encompassed the full complement of tactical subprograms loaded in the anticipated standard shipboard configuration. (An exception is the program module subset devoted to monitoring and operability testing of the radar system which is normally resident in Computer 2. These subprograms were subsequently verified by means of yet another simulator.) The test configuration is shown in Fig. 4 and points up that the simulator, occupying the third computer, represented the external world to the control program. It provided stimuli, responses, and in some cases merely a sink for recording commands when the physical actions sought could not be realized without the radar hardware. Synthetic video, however, as in the RSTG configuration, was displayed and was of great value in monitoring the progression of the scenario.

The MIFS program enabled realistic realtime exercising of the control program and served as a test bed for the principal software qualification tests. Limitations of the earlier simulation were entirely precluded in this test setup. The MIFS subprograms are outlined in Fig. 4.

The radar/signal processor simulator subprogram can generate more targets than the multifunction sensor can handle. Target distributions and insertion rates are specifiable; each target may be designated as visible in clutter, visible in jamming, or as a jammer. A clutter volume can also be specified over any arbitrary extent. Targets move with constant velocity, but any number of maneuvers can be specified. This subprogram operates on one dwell at a time, validity-checking the radar command. It then extracts such parameters as mode and dwell length, and computes the beam pointing angle from the commanded phase tapers. The target selection process resembles that of candidate beam determination in the RSTG's correlator/detector; the search is speeded by sorting the target population in cosine

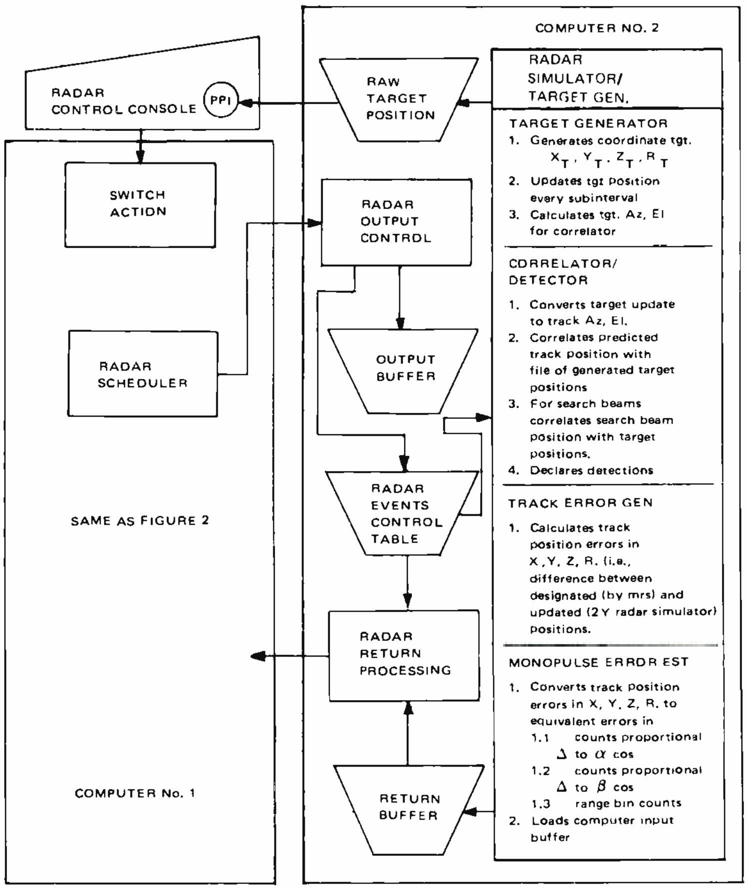


Fig. 3 — Configuration no 1: radar simulator/target generator.

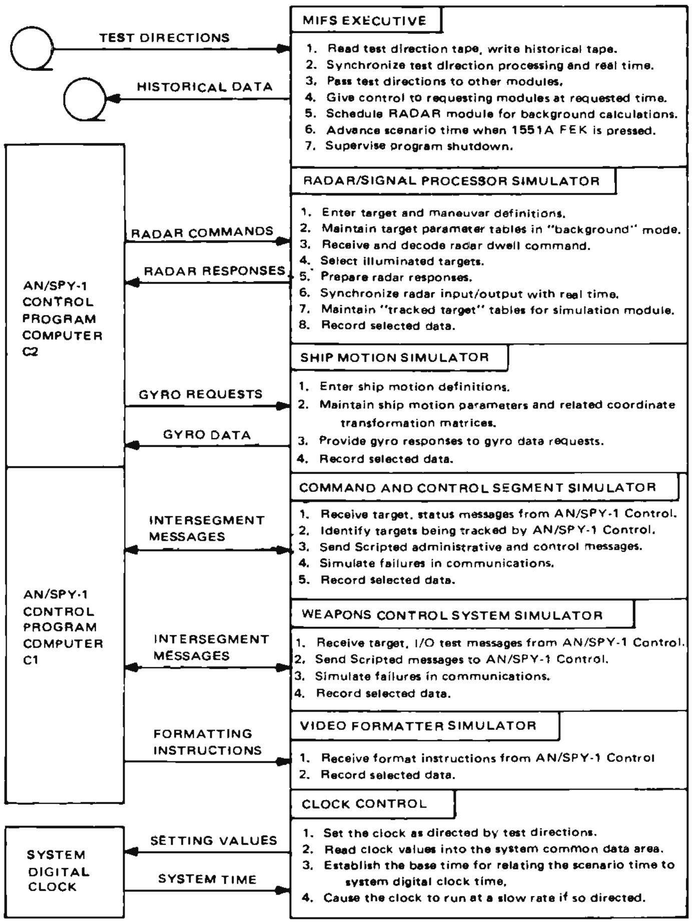


Fig. 4 — Configuration no. 2: MFAR interface simulator.

space. Simulations of responses can exceed real dwell periods, especially when multiple targets are illuminated at the same space angle. Each target requires a positional update necessitating inexact synchronization between command and return data transfers and real time. Strict synchronization, however, is maintained with the start of the radar scheduling subinterval (the period, as noted earlier, spanning several dwells wherein reports are collected for batch processing).

Test scenarios were defined using a language termed MIFS Script. This language afforded unusual flexibility, enabling the experimenter to specify the individual kinematics for every target in the distribution as well as the type and initiation time of communications to the radar control program. A script translator converted the test control language to a binary test direction tape off-line; this tape was then read by the MIFS program during its initializiation.

Fig. 4 illustrates the other interfaces required for total exercising of the radar control programs. The interfaces between AN/SPY-1 control, weapon control, and command and control concern primarily the exchange of tracking assignment priorities and radar metric data.

Configuration No. 3 — signal processor checkout

Qualification testing of the radar equipment employed the configuration shown in Fig. 5. The simulator of the control program, termed the signal processor checkout (SIPCO) routine, enables dynamic monitoring of equipment chains and functional testing of the major signal processor components. The SIPCO program is contained in a single computer, driving the radar sensor in purely deterministic fashion.

SIPCO demonstrations covered input-output channel operations and the radar responses to (in effect) actual commands. The importance of these tests cannot be overemphasized for they were the first level of software-hardware integration, partially verifying the communications cycle and totally confirming command formats. Essentially, the mode, stimulus, and evaluation and reduction routines are preset; all modes were supported. Command formats are identical to those of the tactical program, and the standard communciations cycle applies. Manual or automatic operation is specifiable. In principle, SIPCO exercises the equipment in a manner analogous to that of the operational readiness test system (embedded in the tactical control program). An interesting aspect of SIPCO is a specially developed language (signal processor test oriented language — SIPTOL) which allowed equipment designers to program the checkout procedures effectively and efficiently.

Configuration No. 4 — simulated dynamic target

Operation in the simulated dynamic target (SDT) configuration represents the first major integration of tactical software with the radar sensor. The SDT routine resides permanently in the output control module of Computer 2, timesharing its function with the full set of radar control subprograms. SDT requests are packed into standard radar command formats and transferred to the waveform generator via the input-output buffer (Fig. 1), where a specifiable replica of the transmitted pulse is injected into the receiver or routed to a boresight tower and radiated. The signal processor and at least a section of the receiver (or the entire front end) is presented with a radar return in the same manner as for a real report. And although the origin of this return is differentiable in the software, it is treated virtually the same way as a bona fide detection.

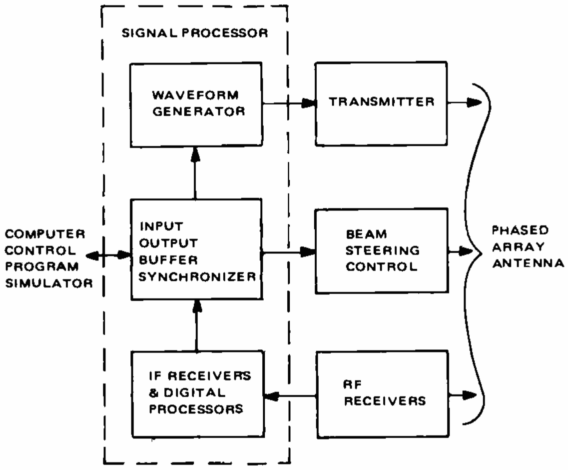


Fig. 5 — Configuration no. 3: radar hardware test setup.

SDT-generated targets can cover a wide range of trajectories and environmental backgrounds. Three acceleration changes per target are accommodated, and mainlobe and sidelobe signal levels, noise, clutter, and doppler frequency are all controllable. Ordinarily, one set of SDT-defining parameters resides in core, although the program can handle two simultaneously. An SDT library of approximately 50 targets resides in a mass memory. Targets are conveniently selectable from a console with their data bases overlaying the current choices.

The radar control program continually inserts SDT's into tactical search dwells whenever a temporal intersection of the illuminated space angle and trajectory occurs. Redetections of these targets, as in all search reports, are crossgated. Track dwells for simulated targets, on the other hand, are dedicated; ordinarily, live transmission does not occur.

Procedural aspects

Test designs and designs of the simulators proceeded hand-in-hand. As detailed procedures were written, constraints forced by the test configurations were removed by expanding the capabilities of the simulators.

Qualification tests of radar set AN/SPY-1 — whether of the radar controller programs exclusively, radar sensor exclusively, or post-integration tests — were generally divided along functional lines into search, detection, track, and user services. Integration tests (which were informal) were patterned similarly, extending program control in stages to encompass all functional loops and modes. Another set of informal tests, termed the Engineering Test and Evaluation program, used the various test configurations to tax system capabilities and to further investigate performance levels.

Some test parameters

Search and track performance were systematically and rigorously tested. Criteria for search performance included coverage (especially with ship's motion), scan rates (especially as a function of track load), mode mixes (*i.e.*, responsiveness to doctrine), and detection sensitivity. Track performance was largely concerned with precision, transition-to-track and track maintenance (both in the face of noisy data and for high-performance targets), and track capacity.

Search performance

Coverage is defined by the lattice of search beams throughout the volume. This grid is specified by the spacing between adjacent beams in azimuth and elevation; non-uniform spacing is employed as a function of elevation angle. Coverage tests could be conducted without simulation (except for ship's motion) because only those factors internal to the radar set are involved. Simulated targets were injected, however, first using the limited resources of RSTG (configuration No. 1) and then later with MIFS (configuration No. 2), allowing simultaneous assessment of coverage and scan rate. Data were recorded in inertial and deck space, with the latter obtained from the actual radar commands so that the beam pointing angles and search modes could be determined as well as the rate of placement for these beams. Detection sensitivity measurements were facilitated by SDT (configuration No. 4). The entire rf loop and the signal processor were tested by channeling the SDT pulse to a boresight tower radiation horn.

Track performance

Track precision can be considered as the combined effect of instrumentation noise and thermal noise. Instrumentation noise, considering a very high S/N target and no thermal noise effects, has the following major components: (1) angle error granularity, (2) beam steering granularity, (3) computer roundoff, (4) beam stabilization residual noise, (5) signal processor random angle noise, (6) rf receiver random angle noise, and (7) antenna random angle noise.

Angle error granularity is a function of the weighting of the least significant bit (LSB) in the monopulse error fields reported to the computer. A complementary error source is the beam steering granularity, determined by the LSB weighting of the phase taper command generated in the computer. Both error sources were manifest in RSTG tests.

Beam stabilization residual noise is the error in the track data following its coordinate transformation to inertial space. The error results in part from the gyro data sampling process. Another contributor is the imperfect modeling of ship's motion within the computer when extrapolating the gyro data to the time of transmission for a dwell. Just as in beam steering granularity, the error contaminates the results of the simulation when ship's motion is considered.

Random angle noise in the signal processor and rf receiver stem primarily from various i.f. and rf gain tracking and phase tracking errors. Antenna random angle noise is the result of many sources, including element-to-element independent errors (such as horn locations), receive subarray correlated errors, array column correlated errors, and errors in the monopulse tracking channels. SDT simulation test results with target injections using a boresight tower and, of course, actual tracks include all of the aforementioned instrumentation noise sources. Computer roundoff errors were precluded by extending the granularity of all track loop calculations such that the overall precision was greater than the range error and angle error granularities.

Experiments involving transition-to-track (including lock-on response) and track maintenance with MIFS were carried out with simulated noise added to the monopulse errors. Performance was measured at various expected noise levels and the probability of hanging on to tenuous tracks established. Accelerating target tests for these same track loop processes were run with MIFS, wherein crossing and radial courses were simulated. These established confidence limits for the range of system data rates employed long in advance of the radar contoller-radar integration.

Conclusion

The validity of the test approach and implementation procedures have been demonstrated in the high degree of success achieved in this test and integration program — particularly in the smooth joining of the radar-control computer programs and the radar sensor. Automatic track initiation and sustained track maintenance on multiple targets was demonstrated in less than two months following equipment emplacement Both the testing and the program architecture itself, principally its modularity and clear cut interfaces, were significant contributors to this achievement.

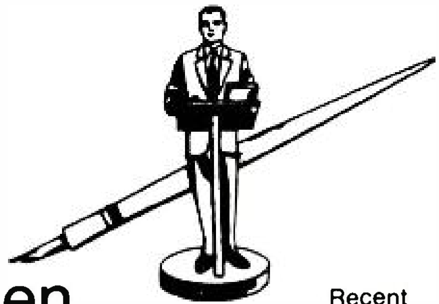
The test configurations continue to serve the needs of this developmental program. MIFS, for example, provides a good test bed for proving out software modifications. SIPCO enables the collection of specialized test data and the observance of effects as computer-driven parameters are manually adjusted. Operator training and exercising are afforded by the RSTG, MIFS, and SDT configurations; the first two do not even require the radar sensor. Both RSTG and MIFS have been useful in integration tests of the three computer-instrumented segments of AEGIS. SDT is an important tool for assessing the operability of the radar set, and its use was extended for operability verification testing of the weapon system. SDT has also served for the dry runs of system-wide (Category II) tests, obviating the need for controlled aircraft until operational readiness was confirmed.

Acknowledgments

This article is based on a presentation by R. A. Baugh and R. W. Ottinger at the 19th Annual Tri-Service Radar Symposium at Colorado Springs in July 1973. Mr. Baugh's tutelage in the field of computer-controlled radar and his review of this paper are gratefully acknowledged.

Bibliography

1. Nessmith, Jr., Dr. J.T.; "AEGIS Weapon System Engineering Management Tools," RCA Reprint RE-18-1-13. An excellent overview of the AEGIS weapon system is included in addition to a treatise on the subject management tools.
2. Weinstock, Dr. W.; "Computer Control of a Multifunction Radar," RCA Reprint RE-18-1-5. This article presents a comprehensive discussion of hardware-software interrelationships of an AEGIS-like multifunction sensor.
3. Baugh, R.A.; *Computer Control of Modern Radar* (1973). This text is notable for its depth and breadth of coverage, presenting the considerations and methodology of software systems engineering as it relates to the radar control problem.
4. Mehling, I.H., "Computer Program Architectural Designs for Weapon System Radar Control," RCA Reprint RE-20-1-14. This excellent paper presents techniques used in developing the structure of large-scale programs for the control of multifunction array radars and describes the tools of the software architect and their application.



Pen and Podium

Recent RCA technical papers and presentations

Both published papers and verbal presentations are indexed. To obtain a published paper borrow the journal in which it appears from your library or write or call the author for a reprint. For information on unpublished verbal presentations write or call the author. (The author's RCA Division appears parenthetically after his name in the subject-index entry.) For additional assistance in locating RCA technical literature contact **RCA Technical Communications, Bldg. 204-2, Cherry Hill, N.J. (Ext. PC-4256).**

This index is prepared from listings provided bimonthly by RCA Division Technical Publications Administrators and Editorial Representatives—who should be contacted concerning errors or omissions (see inside back cover)

Subject index categories are based upon standard announcement categories used by Technical Information Systems. Bldg. 204-2, Cherry Hill, N.J.

Subject Index

Titles of papers are permitted where necessary to bring significant keywords(s) to the left to easier scanning. Author's division appears parenthetically after his name.

SERIES 100 BASIC THEORY & METHODOLOGY

175 Reliability, Quality Control and Standardization

value analysis, reliability analysis, standards for design and production.

SPARES ALLOCATION for cost effective availability achievement — H. R. Barton (GCASD. Cam) Philadelphia Society of Logistics Engineers: 2/26/75.

MTBF, field vs. predicted — M. L. Johnson (GCASD, Burl) Boston IEEE Reliability Group meeting; 2/1875.

180 Management and Business Operations

organization, scheduling, marketing, personnel.

PROJECT MANAGEMENT — future developments — M. W. Buckley (Co-Chairman) (MSRD, Mrstn) AMA Management Center, Chicago, Ill.; 2/26/75.

SERIES 200 MATERIALS, DEVICES, & COMPONENTS

210 Circuit Devices and Microcircuits

electron tubes and solid-state devices (active and passive); integrated, array and hybrid microcircuits, field-effect devices, resistors and capacitors, modular and printed circuits, circuit interconnection, waveguides and transmission lines.

CMOS circuits, EMP hardened — D. Hampel, R. G. Stewart (GCASD, Cam) *IEEE Transactions on Nuclear Science*, Volume NS-21, pp. 332-339; 12/74.

215 Circuit and Network Designs

analog and digital functions in electronic equipment; amplifiers, filters, modulators, microwave circuits, A-D converters, encoders, oscillators, switches, masers, logic networks, timing and control functions, fluidic circuits.

DIGITAL INTERPOLATION FILTERS for increasing the sampling rate, Parallel realizations of — H. Urkowitz (MSRD, Mrstn) *IEEE Transactions on Circuits and Systems*, Vol. CAS-22, pp. 146-154; 2/75.

PARAMETRIC AMPLIFIER, Microwave Metal-Insulator-Semiconductor (MIS) Varactor — R. Camisa, B. Hitch, S. Yuan (GCASD, Cam) 1975 IEEE International Solid State Circuits Conference, Phila., Pa.; *IEEE ISSCC Digest, Volume 18, pp. 94-95.*

240 Lasers, Electro-Optical and Optical Devices

design and characteristics of lasers, components used with lasers, electro-optical systems, lenses, etc. (excludes: masers).

GaAlAs LASERS with carrier injection triggered trapatt (CARITT) device, Nanosecond pulsing of — D. Miller, III, H. Kawamoto (ATL, Cam) ISSCC - Phila., Pa.; 2/12-14/75.

SERIES 300 SYSTEMS, EQUIPMENT, & APPLICATIONS

310 Spacecraft and Ground Support

spacecraft and satellite design, launch vehicles, payloads, space missions, space navigation.

SATELLITE, A body-stabilized, 24-transponder domestic — C.R. Hume, J.E. Keigler (AED, Pr) AIAA 11th Annual Meeting, Washington, D.C.; 2/25/75.

325 Checkout, Maintenance, and User Support

automatic test equipment, (ATE), maintenance and repair methods.

AUTOMOTIVE test equipment through use of advanced electronics, Simplifying — A. H. Fortin, T. E. Fitzpatrick, H. E. Fineman (GCASD, Burl) SAE, Ft. Washington, Pa.; 2/12/75.

340 Communications

industrial, military, commercial systems, telephony, telegraphy and telemetry, (excludes: television, and broadcast radio).

PABX using low-power LSI devices, An advanced technology — P. H. Bennett (GCASD, Cam) *Telephone Interconnect Journal*, p. 14; 11/74

360 Computer Equipment

processors, memories, and peripherals.

MINICOMPUTER monitoring and contro systems — J. H. O'Connell (GCASD, Burl, COMPCON, Spring-1975; 2/26/75.

Author Index

Subject listed opposite each author's name indicates where complete citation to his paper may be found in the subject index. An author may have more than one paper for each subject category.

Dates and Deadlines

As an industry leader, RCA must be well represented in major professional conferences . . . to display its skills and abilities to both commercial and government interests.

How can you and your manager, leader, or chief-engineer do this for RCA?

Plan ahead! Watch these columns every issue for advance notices of upcoming meetings and "calls for papers". Formulate plans at staff meetings—and select pertinent topics to represent you and your group professionally. Every engineer and scientist is urged to scan these columns; call attention of important meetings to your Technical Publications Administrator (TPA) or your manager. Always work closely with your TPA who can help with scheduling and supplement contacts between engineers and professional societies. Inform your TPA whenever you present or publish a paper. These professional accomplishments will be cited in the "Pen and Podium" section of the *RCA Engineer*, as reported by your TPA.

Calls for papers
—be sure deadlines are met

Ed. Note: Calls are listed chronclogically by meeting date. Listed after the meeting title (in bold type) are the sponsor(s), the location, and deadline information for submittals.

SEPT. 2-5, 1975 — **European Solid State Circuits Conference** (IEE, IEEE UKRI Section et al) Univ. of Kent, Canterbury, UK **Deadline info:** (abst) 5-12-75 **to** IEE, Conference Dept., Savoy Pl.. London W.C. 2 R OBL England.

SEPT. 14-19, 1975 — **Environmental Sensing & Assessment Int'l Conf.** (EQC, Univ. of Nev., et al) Stardust, Las Vegas, Nevada **Deadline info:** abst & ms) 4-30-75 **to** J. L. Moyers, Univ. of Arizona, Dept. of Chemistry, Tucson, Ariz. 8572l.

SEPT. 16-19, 1975 — **Optical Fiber Communication Int'l Conference** (IEE, IEEE UKRI Section, Inst. of Physics, IERE) IEE, London, England **Deadline info:** (abst) 5-19-75 **to** IEE, Savoy Place, London WC2R OBL England.

SEPT. 22-24, 1975 — **Int'l Congress on Instrumentation in Aerospace Simulation** (AES) Canadian Gov't Conf. Ctr, **Deadline info:** (abst) 4-25-75 **to** E. S. Hanff, Nat'l Research Council of Canada, Montreal Rd., Ottawa, Ontario, Canada K1A OR6.

SEPT. 28 - Oct. 2, 1975 — **Industry Applications Society Annual Meeting** (IA, Atlanta Section) Regency Hyatt House, Atlanta, Georgia **Deadline info:** (ms) 5-23-75 **to** F. A. Furfari, Westinghouse Elec. Corp., Gateway Ctr., Pittsburgh, Penna. 15222.

OCT. 20-23, 1975 — **U. S. National Meeting of International Union of Radio Science** (URSI) University of Colorado, Boulder, Colorado **Deadline info:** (abst) 7-14-75 **to** Prof. James R. Wait, Chairman, USNC/URSI Technical Program, Room 242, RB 1, C.I.R.E.S., Unversity of Colorado, Boulder, Colorado 80302.

OCT 29-31, 1975 — **Nuclear Division of the American Ceramic Society** (ACS) Olympic Hotel, Seattle, Washington **Deadline info:** (title & authors cards) 5-15-75 (abst) 6-1-75 (notification of acceptance) 7-1-75 **to** P. L. Farnsworth, Program Chairman, Nuclear Division, Exxon Nuclear Company, 2101 Horn Rapids Road, Richland, Washington 99352.

DEC. 1-3, 1975 — **National Tele-Communications Conf.** (AES, COMM., GE, New Orleans Section) Fairmont Roosevelt Hotel, New Orleans, La. **Deadline info:** (S & ms) 5-1-75 **to** I N Howell, Jr., S. Central Bell Tel. Co., POB 771, Birmingham, Ala. 35201.

DEC. 9-12, 1973 — **Magnetism & Magnetic Materials Conference** (MAG, AIP et al) Benjamin Franklin Hotel, Phila., Penna. **Deadline info:** (abst) 8-15-75 **to** B. Stein, Univac Div., Sperry Rand, POB 500, Blue Bell, Penna. 19422.

JAN. 20-22, 1976 — **Reliability and Maintainability Symposium** (MGM Grand Hotel, Las Vegas, Nevada **Deadline info:** abst) 5-1-75 **to** H. L. Wuerffel, RCA Astro-Elec., POB 800, MS 55, Princeton, N.J. 08540.

JAN. 25-30, 1976 — **Power Engineering Society Winter Meeting** (PE) Statler Hilton Hotel, New York, N.Y. **Deadline info:** 9-1-75 **to** IEEE, 345 East 47th Street, New York, N.Y. 10017.

FEB. 4-5, 1976 — **Twelfth Modulator Symposium** (The Advisory Group on Electron Devices — In conjunction with Palisades Institute for Research Services, Inc. & IEEE) Statler Hilton Hotel, Seventh Avenue at 33rd Street, New York City **Deadline info:** (abst-200 words) 10-17-75 **to** Program Chairman, Sol Schneider, Electronics Technology and Devices Laboratory (ECOM), Ft. Monmouth, N.J. 07703.

MARCH 22-25, 1976 — **1976 Symposium on Three-Dimensional Flow in Turbo-machines** ASME, The Rivergate, New Orleans, Louisiana **Deadline info:** (abst) 7-1-75 **to** Dr. William E. Thompson, Turbo Research, Inc., 210 Harvard Avenue, Swarthmore, PA 19081 (ms) 9-1-75 **to** Dr. Robert C. Dean, Technical Editor, JFE, P.O. Box 69, Hanover, NH 03755.

APRIL 12-14, 1975 — **Acoustics, Speech and Signal Processing Int'l Conference** (ASSP, Phila. Section) Marriott Hotel, Phila., Penna. **Deadline info:** (abst) 10-1-75 **to** Thomas Martin, Threshold Tech. Inc., Rt. 130 Union Landing Rd., Cinnaminson, N.J. 08077.

APRIL 27-29, 1976 — **Circuits and Systems Int'l Symposium** (CAS, VDE, (NTG) Tech. Univ., Munich, Germany **Prog info:** (ms) 10-15-75 **to** Alfred Fettweis, Lehrstuhl fur Nachrichtentechnik, Univ. of Bochum, Postfach 2148, D-4630 Bochum, F. R. Germany.

JUNE 14-16, 1976 — **International Conference on Communications** (COMM) Marriott Motor Hotel, Phila., Penna. **Deadline info:** 2-1-76 **to** Ralph Wyndrum, Bell Labs., Whippany Rd., 1B306, Whippany, N.J. 07981.

JULY 18-23, 1976 — **Power Engineering Society Summer Meeting** PE) Portland Hilton Hotel, Portland, Oregon **Deadline info:** W. S. Greer, Westinghouse Elec. Corp., 1414 N.E. Grand Ave., Portland, Ore. 97212.

AUG. 25-27, 1976 — **Product Liability Prevention Conference** (R et al) Newark College of Engineering, Newark, N.J. **Deadline info:** 11-1-75 **to** John Mihalasky, Newark College of Engrg., 323 High St., Newark, N.J. 07102.

SEPT. 27 - OCT. 1, 1976 — **Underground Transmission & Distribution** (PE) Convention Hall, Atlantic City, N.J. **Deadline info:** (abst) 7-1-75 **to** E. K. Duffy, Essex Int'l Inc., POB 1000, Lafayette, Ind. 47907.

DEC. 6-10, 1976 — **Submillimeter Waves and Their Applications** (MTT, OSA et al) San Juan, Puerto Rico **Deadline info:** (ms) 8-1-76 K. J. Button, MIT, National Magnet Lab., Cambridge, Mass. 02139.

Dates of upcoming meetings
—plan ahead

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.

MAY 18-19, 1975 — **Intersociety Engineering Ethics Conference** (IEEE-CSIT, ASME, ASCE, AIChE, NPSE) Baltimore Hilton Hotel, Baltimore, Maryland **Prog info:** Victor Paschkis, Fellowship House Farm, RD #, Pottstown, Penna. 19464.

MAY 19-20, 1975 — **1975 Industrial Power Conference** (ASME) Chatham Center, Pittsburgh, PA **Prog info:** Marion Churchill, Meetings, ASME, 345 E. 47th Street, New York, N Y. 10017.

MAY 19-22, 1975 — **National Computer Conference** (C, AFIPS) Anaheim, Calif. **Prog info:** S. W. Miller, Stanford Res. Inst., Bldg. 30-L109Z, Menlo Park, Calif. 94025.

MAY 19-21, 1975 — **Joint Engineering Applications Conference** (ASME) Hilton Hotel, Baltimore, MD **Prog info:** Paul Drummond, Manager, General Engineering Divisions, ASME, 345 E. 47th Street, New York, N.Y. 10017.

MAY 21, 1975 — **Films for Solar Energy** (The Greater New York Chapter American Vacuum Society) **Prog info:** Dr. W. E. Loeb, Union Carbide Corporation, 270 Park Avenue, New York, New York 10017.

MAY 20-22, 1975 — **EMC Symposium and Exhibition** (EMC, SAE, Region 8 et al) Montreux, Switzerland **Prog info:** F. L. Stumpers, N. V. Philips' Gloeilampenfabrieken, Philips Res. Lab., Eindhoven, Nederland.

MAY 20-23, 1975 — **Ispra Nuclear Elec. Symposium** (North Italy Section, NPS) Palazzo dei Congressi, Strese, Italy **Prog info:** Luciano Stanchi, CCR EURATOM 21020, Ispra, Italy.

MAY 28-30, 1975 — **Laser Engineering & Applications Conference** (Quantum Elec. Council, OSA, Washington DC Section) Washington, D.C **Prog info:** A. S. Halsted, Hughes Aircraft Co., Electron Dynamics Div., 3100 W. Lomita Blvd., Torrance, Calif. 90509.

JUNE 1-4, 1975 — **Power Industry Computer Applications** (PE) Marriott Hotel, New Orleans, La. **Prog info:** C. D. Galloway, Gen'l Electric Co., One River Road, Schenectady, N.Y. 12345.

JUNE 2-5, 1975 — **Int'l IEEE/AP-S Symposium and USNC/ URSI Meeting** (APS, USNC/URSI) Univ. of Illinois, Urbana, Illinois **Prog info:** R. Mittra & S. W. Lee, Univ. of Illinois, Urbana, Ill. 61801.

JUNE 3-5, 1975 — **MH Intersociety Material Handling Symp.** (IA, MHI) Cincinnati Conv. & Expos. Ctr., Cincinnati, Ohio **Prog info:** G. S. Raymond, Jr., The Raymond Corp., Greene, N.Y. 13778.

JUNE 3-5, 1975 — **Machine Processing of Remotely Sensed Data** (C, Purdue Univ.) Purdue Univ., W. Lafayette, Ind. **Prog info:** C. D. McGillem, LARS, Purdue Univ., W. Lafayette, Indiana 47906.

JUNE 3-6, 1075 — **Antennas for Aircraft and Spacecraft Int'l Conference** (IEE, IEEE UKRI Section, et al) IEE, London, England **Prog info:** IEE, Savoy Place, London, W.C. 2R OBL England.

JUNE 5-6, 1975 — **Applied Magnetics Workshop** (MAG, Marquette Univ.) Marquette Univ., Milwaukee, Wisc. **Prog info:** T. Bernstein, Univ. of Wisc., Dept. of EE, Madison, Wisc.

JUNE 9-10, 1975 — **Chicago Spring Conf. on Broadcast & Television Receivers** (CE) Mariott Hotel, Chicago, Illinois **Prog info:** Anthony Troiano, Zenith Radio Corp., 6101 W. Dickens Ave., Chicago, Illinois 60639.

JUNE 9-11, 1975 — **Power Electronics Specialists Conference** (AES, ias, ieci) Americana Hotel, Los Angeles, Calif. **Prog info:** F. F. Oettinger, Nat'l Bureau of Standards, Electron Device Station, Washington, D.C.

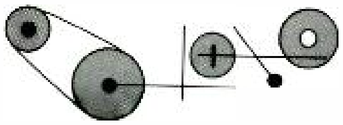
JUNE 9-11, 1975 — **Applications of Ferro-electrics** (SU, USARO, Sandia Labs., Albuquerque Section) Hilton Inn, Albuquerque, New Mexico **Prog info:** Eric Cross, 251A, Engrg. Sci. Bldg., Penn State Univ., State College, Penna. 16802.

JUNE 10-12, 1975 — **Aerospace and Electronics Conference (NAECON)** (AES, em, AIAA, AOC, ION, AFCEA) Dayton Conv. Ctr., Dayton, Ohio **Prog info:** G. G. Rabanus, Air Force Avionics Lab., AFAL/TEA, WPAFB, Ohio 45433.

JUNE 16-19, 1975 — **Int'l Conference on Communications** (COMM, AES, GE) Fairmont Hotel, San Francisco, Calif. **Prog info:** Philip Fire, GTE-Sylvania, POB 205, Mountain View, Calif. 94042.

Patents Granted

to RCA Engineers



RCA Records

Triangular Piezoelectric Transducer for Recording Video Information — J. B. Halter (REC, Indpls.) U.S. Pat. 3865997, February 11, 1975

Government Communications and Automated Systems Division (Burlington Operations)

Multiple Transistor Microwave Amplifier — D. E. Mahoney (GCASD, Burl.) U.S. Pat. 3869678, March 4, 1975

Advanced Technology Laboratories

Electronic Technique for Making Multichannel, Spatial-Carrier-Encoded Recordings — D. J. Woywood and S. L. Corsover (ATL, Cam.) U.S. Pat. 3869705, March 4, 1975

Electromagnetic & Aviation Equipment Division

Four-Port Junction Circulator Having Larger Diameter Conductive Post Contacting Gyromagnetic Post — G. C. Jung (EASD, Van Nuys) U.S. Pat. 3866149, February 11, 1975

Recovery of Normally Illegible, Magnetically Recorded Information — P. B. Korda (EASD, Van Nuys) U.S. Pat. 3869721, March 4, 1975

RCA Limited

Microwave Spectrometer — A. K. Ghosh and H. J. Moody (Ltd. Montreal, Canada) U.S. Pat. 3866118, February 11, 1975

Astro-Electronics Division

Spacecraft Attitude Control System — J. D. Cavanagh (AED, Pr.) U.S. Pat. 3866025, February 11, 1975

Solid State Division

Matching of Semiconductor Device Characteristics — O.H. Schade, Jr. (SSD, Som.) U.S. Pat. 3863331, February 4, 1975

High-Input-Impedance Amplifier — A.A.A. Ahmed (SSD, Som.) U.S. Pat. 3864641, February 4, 1975

Current Amplifier — A.A.A. Ahmed (SSD, Som.) U.S. Pat. 3868581, February 25, 1975

Monostable Switching Circuit — J. E. Wojslawowicz (SSD, Som.) U.S. Pat. 3867651, February 18, 1975

Fractional Current Supply — A.A.A. Ahmed (SSD, Som.) U.S. Pat. 3867685, February 18, 1975

Commercial Communications Systems Division

Battery Connecting Assembly — R. E. Marks (CCSD, Mdwlds.) U.S. Pat. 3864172, February 4, 1975

Trunk Formatter — B. E. Patrusky and A. Mack (CCSD, Cam.) U.S. Pat. 3868481, February 25, 1975

Laboratories

Machine for Reading Article Carrying Coded Indicia — J. T. Oneil, Jr., A. Pelios, A. H. Simon, and F. G. Nickl (LABS, Pr.) U.S. Pat. 3864548, February 4, 1975

Electroluminescent Semiconductor Display — J. I. Pankove (LABS, Pr.) U.S. Pat. 3864592, February 4, 1975

Replaceable Fluid Cartridge Including Magnetically Operable Fluid Jet Devices — K. H. Fischbeck (LABS, Pr.) U.S. Pat. 3864685, February 4, 1975

Printing Apparatus — K. H. Fischbeck (LABS, Pr.) U.S. Pat. 3864696, February 4, 1975

Radiation Sensing Arrays — J. E. Carnes (LABS, Pr.) U.S Pat. 3864722, February 4, 1975

Microwave Transistor Carrier for Common Base Class A Operation — E. F. Belohoubek and A. Presser (LABS, Pr.) U.S. Pat. 3869677, March 4, 1975

Novel Lithium Niobate Single Crystal Film Structure — W. Phillips (LABS, Pr.) U.S. Pat. 3867012, February 18, 1975

Acousto-Optic Devices and Process for Making Same — G. A. Alphonse and G. E. Bodeep (LABS, Pr.) U S. Pat. 3867108, February 18, 1975

Spectrally Sensitized Electrophotographic Materials — W. M. Lee (LABS, Pr.) U.S. Pat. 3867144, February 18, 1975

Method for Recording Fingerprints — R. Williams and A. H. Willis (LABS, Pr.) U.S. Pat. 3867165, February 18, 1975

Circuit for Amplifying Charge — P. K. Weimer (LABS, Pr.) U.S. Pat. 3867645, February 18, 1975

Grating Tuned Photoemitter — J. G. Endriz (LABS, Pr.) U.S. Pat. 3867662, February 18, 1975

Amplifier which Consumes a Substantially Constant Current — P. E. Haferl (LABS, Switzerland) U.S. Pat. 3868537, February 25, 1975

Charge-Transfer Display System — P. K. Weimer (LABS, Pr.) U.S. Pat. 3866209, February 11, 1975

AF Amplifier Having Constant Current Consumption — P. E. Haferl (LABS, Switzerland) U.S. Pat. 3868582, February 25, 1975

Method for Diffusing Impurities into Nitride Semiconductor Crystals — J. I. Pankove (LABS, Pr.) U.S. Pat. 3865655, February 11, 1975

Electronic Components

Electron Discharge Device Having a Hollow Conductor Integral with the Envelope Thereof — R. W. Young (EC, Woodbridge) U.S. Pat. 3864590, February 4, 1975

Inline Electron Gun Having Magnetically Permeable Plates for Enhancing Convergence of Electron Beams — W. H. Barkow (EC, Pr.) U.S. Pat. 3866080, February 11, 1975

High Density Light Emitting Diode Array — P. Nyul (EC, Lanc.) U.S. Pat. 3867666, February 18, 1975

Infrared Vidicon with Off-Axis Electron Gun — L. D. Miller (EC, Lanc.) U.S. Pat. 3857035, December 24, 1974; Assigned to U.S. Government

Consumer Electronics

Control Signal Apparatus for Video Disc Player — C. D. Boltz, Jr. (CE, Indpls.) U.S. Pat. 3864733, February 4, 1975

Palm Beach Division

Fingerprint Display System Utilizing a Stored Fingerprint — E. H. Del Rio (PBD, Palm Beach Gardens) U.S. Pat. 3865488, February 11, 1975

Engineering News and Highlights

Albert Rose

Rose elected to National Academy of Engineering

Dr. Albert Rose, a Fellow of the Technical Staff of RCA Laboratories, was recently elected to the National Academy of Engineering in recognition of his "contributions in the fields of photo conductivity, photosensitivity, and television camera tubes."

Dr. Rose is credited with a series of important discoveries and applications in the fields of photoconductivity and photosensitivity, including basic contributions to the development of the Orthicon, the Image Orthicon and the Vidicon television camera tubes.

In 1931 he received the AB and in 1935 the PhD in Physics from Cornell University. Dr. Rose joined RCA in 1935 in Harrison, N.J., as a member of the tube research group which was then engaged in an effort to improve the sensitivity of the Iconoscope. This research effort culminated in the initial development by Dr. Rose in 1937 of the Orthicon. When RCA Laboratories was established in 1942, Dr. Rose transferred to Princeton, bringing with him an already completed model of what later became the Image Orthicon.

In 1942 Dr. Rose became interested in the relative limitations in the light sensitivity of photographic film, television pickup tubes, and the human eye. This work resulted in development of a theory of visual sensitivity based on the absolute scale of the noise limitations due to the quantum nature of light.

His studies in the field of solids led to his widely recognized work on the theory and analysis of photoconductivity and related phenomena in insulators and semiconductors. His current work is in the areas of space-charge-limited current flow, injected plasmas in solids and electron-phonon interactions in solids.

From May 1955 to July 1957, Dr. Rose headed the research activity of the then newly-established Laboratories RCA, Ltd., Zurich, Switzerland. On his return to Princeton he resumed research relating to the study and application of photoelectric phenomena. In 1959 Dr. Rose was named a Fellow of the Technical Staff.

The recipient of two RCA Laboratories Achievement Awards in 1947 and 1951, Dr. Rose has had about 35 U.S. patents issued in his name. He has published 45 technical papers and articles. He is the author of a book, *Concepts in Photoconductivity and Allied Problems*, published by John Wiley & Sons in 1963.

In 1945 Dr. Rose received the Television Broadcasters Association Award and the Morris Liebmann Award of the Institute of Radio Engineers (now IEEE). The next year he received the Journal Award of the Society of Motion Picture Engineers. In March 1958 he was one of two recipients of the first David Sarnoff Outstanding Achievement Awards in Science and Engineering. He was cited on this occasion "for basic contributions to the understanding and utilization of photoelectric phenomena." In October 1958 he received the David Sarnoff Gold Medal Award of the Society of Motion Picture and Television Engineers for basic contributions to the development of the Orthicon, Image Orthicon, and Vidicon television pickup tubes.

A Fellow of the American Physical Society and the IEEE, Dr. Rose is a member of Phi Beta Kappa and the *Societe Suisse de Physique* and is listed in *Who's Who in Engineering*. He has been an Associate Editor of *Advances in Electronics* since 1949 and has served as an Associate Editor of the *Physical Review*. Since 1959 he has been a member of the Advisory Committee for the Institute of Optics at the University of Rochester. He is currently on the Editorial Advisory Board of the *International Journal of the Physics and Chemistry of Solids.*

George Mackiw (center) reviews the engineering work that earned him the Technical Excellence Award for Leader Glen Wild (left) and Bob Lawton, Manager, Transmission Equipment Engineering.

Murlan Corrington (right) receives IEEE distinguished service award from James H. Mulligan.

Awards

Advanced Technology Laboratories

Murlan S. Corrington, Principal Member of the Engineering Staff, Advanced Technology Laboratories, was presented an IEEE award for distinguished service to the IEEE International Solid State Circuits Conference. The award, from the Solid State Circuits Council, was presented by **James H. Mulligan, Jr.,** Past President of the Institute of Electrical and Electronics Engineers.

Mr. Corrington was one of the founders of this conference in 1953 and served as Chairman of the Sponsors Committee for 19 years. He is now chairman of the Executive Committee for the Conference. The Solid State Circuits Council is a cooperative effort of six groups within IEEE and this award is the first of its kind.

Government Communications and Automated Systems Division

George Mackiw received a Technical Excellence Award for his contributions to the Small Terminal program. Under this program, RCA is delivering satellite communications equipments to the U.S. Army Satellite Communications Agency.

Professional Activities

Missile and Surface Radar Division

Don Higgs, Manager, Technical Communication, has been invited to participate in the Technical Writers' Institute (June 9-13, 1975) sponsored by Rensselaer Polytechnic Institute. Mr. Higgs will lead a workshop discussion in report writing.

Henry Zieper

Henry S. Zieper

H.S. Zieper, of the Advanced Technology Laboratories, Camden, N.J. died March 5. Mr. Zieper had been on medical leave since May of last year. In his most recent position, Mr. Zieper was Staff Engineer to P.E. Wright, Director of ATL. Prior to this appointment he was manager of the ATL Applied Computer Systems Laboratory where he was responsible for the enhancement of the CMOS D/A system, the development of hybrid techniques, and the implementation of SUMC/DV hardware. Mr. Zieper, who was often an author in the *RCA Engineer,* joined RCA in 1959, being initially assigned to the BMEWS project to develop a digital checkout system for the display information processor. Subsequent assignments involved system and preliminary logic design for a number of general-purpose processors. He was a key member of the group that conceived and developed the RCA 4100 series of central processors. In 1965 Mr. Zieper was promoted to Group Leader, with responsibility to direct research programs in areas such as the use of large-scale bipolar arrays in high-speed machine organization. Mr. Zieper received the BSEE in 1955 and the MSEE in 1959 from Worcester Polytechnic Institute.

Staff Announcements

Government Communications and Automated Systems Division

James M. Osborne, Division Vice President and General Manager, Government Communications and Automated Systems Division, has appointed **Fred E. Sashoua** as Manager, Electro-Optical Systems, RCA Burlington Operations.

Donald J. Parker, Chief Engineer, Engineering has announced the appointment of **Daniel Hampel** as Manager, Advanced Communications Laboratory.

Commercial Communications Systems Division

Jack F. Underwood, Division Vice President, Mobile Communications Systems has announced the appointment of **Karl L. Neumann** as Chief Engineer, Mobile Communications Systems.

Astro-Electronics Division

P. J. Martin, Director of Marketing and Advanced Planning has announced the appointment of **Myles V. Barasch** as Manager, Advanced Systems.

Service Company

Julius Koppelman, President of the RCA Service Company, has announced the appointment of **James J. Brant** as Division Vice President, Industrial Relations.

Solid State Division

Bernard V. Vonderschmitt, Vice President and General Manager, Solid State Division has announced the appointment of **Philip R. Thomas** as Division Vice President, Solid State MOS Integrated Circuits.

D. Joseph Donahue, Division Vice President, Solid State International Operations has announced the appointment of **Harry Weisberg** as Division Vice President, Solid State—Europe.

Carl R. Turner, Division Vice President, Solid State Power Devices has announced the organization as follows:

John E. Mainzer, Manager, Power Manufacturing Operations; **James A. Amick,** Manager, Materials & Process Development; **Edward A. Czeck,** Manager, Wafer Fabrication; **Henry A. Kellar,** Manager, Material & Production Control; **Thomas J. Lally,** Manager, Silicon Materials Manufacturing; **Archer E. Moore,** Manager, Manufacturing—High Reliability & RF; **David A. Riggs,** Manager, Manufacturing—Thyristors & Rectifiers; **Louis V. Zampetti,** Manager, Manufacturing—Power Transistors.

Richard A. Santilli, Division Vice President, Solid State Bipolar Integrated Circuits and Special Products, has announced the organization of Solid State Bipolar Integrated Circuits and Special Products as follows: **Marvin B. Alexander,** Manager, Operations Control and Planning—Bipolar IC and Special Products; **William F. Allen, Jr.,** Manager, High-Speed Bipolar IC Operations; **Robert A. Donnelly,** Manager, Findlay Operations Support; **Patrick L. Farina,** Director, Liquid Crystal Operations; and **Richard L. Sanquini,** Director, Bipolar IC Operations.

Marvin B. Alexander, Manager, Operations Control and Planning—Bipolar IC and Special Products, has announced the organization of Operations Control and Planning—Bipolar IC and Special Products as follows: **Stephen J. Schelb,** Manager, Production and Material Control—Bipolar IC and Special Products; **Jurgen W. Scherer,** Manager, Product Control—Bipolar IC and Special Products, and **John R. Steiner,** Administrator, Operations Planning—Bipolar IC and Special Products.

Philip R. Thomas, Division Vice President Solid State MOS Integrated Circuits, has announced the organization of Solid State MOS Integrated Circuits as follows: **Donald R. Carley,** Manager, Microprocessors; **John P. McCarthy,** Director, MOS High Reliability Products; **Henry S. Miiller,** Director, MOS Memory Products; **Philip R. Thomas,** Acting Manager, MOS Manufacturing Operations; and **Norman C. Turner,** Director, COS/MOS Products.

Philip R. Thomas, Acting Manager, MOS Manufacturing Operations, has announced the organization of MOS Manufacturing Operations as follows: **Robert P. Jones,** Manager, Manufacturing—COS/MOS; **Philip R. Thomas,** Acting Manager, Palm Beach Gardens Start-up Operations; **Michael Zanakos,** Manager, Operations Control and Planning—MOS; and **Evan P. Zlock,** Manager, Photomask.

Ralph E. Simon, Division Vice President, Electro-Optics and Devices has announced the organization as follows:

Charles W. Bizal, Director, Power Tube Operations; **William E. Bradley,** Manager, Quality & Reliability Assurance; **William E. Circe,** Manager, Industrial Relations; **Harold R. Krall,** Manager, Electro-Optics Equipment Operations; **Thomas T. Lewis,** Director, Electro-Optics Devices Operations; **Robert L. Rodgers,** Manager, Charge-Coupled Device Operations; and **C. Price Smith,** Manager, Operations Support—Lancaster.

Missile & Surface Radar Division

Max Lehrer, Division Vice President and General Manager has announced the appointment of **Jerry J. Mayman** as Director, Marketing.

Consumer Electronics

Roy H. Pollack, Vice President and General Manager, Consumer Electronics has announced the following appointments:

William E. Boss, Division Vice President, Distributor and Commercial Relations; **Jack K. Sauter,** Division Vice President, Marketing; and **Levon M. Berberian,** Division Vice President, International and "SelectaVision" Video Tape Products.

Distributor and Special Products Division

Paul B. Garver, Division Vice President and General Manager, Distributor and

Special Products Division has announced the organization as follows:

Edward A. Boschetti, Division Vice President, Materials; **Gene W. Duckworth,** Division Vice President, Manufacturing Operations; **Ray M. Easter,** Director, Finance; **Joseph A. Haimes,** Division Vice President, Merchandising and Advertising; **Jesse Lippincott, Jr.,** Division Vice President, Industrial Relations, **Paul R. Slaninka,** Division Vice President, Sales; **Walter A. Smith,** Division Vice President, Product Distribution; and **Fred G. Wenger,** Director, Business Development.

Picture Tube Division

Joseph H. Colgrove, Division Vice President and General Manager, Picture Tube Division announced the organization as follows:

Robert F. Dunn, Director, Domestic Market Planning; **Arnold M. Durham,** Manager, News and Information; **William G. Hartzell,** Division Vice President, International Operations; **Lawrence A. Kameen,** Division Vice President, Industrial Relations; **Clifford H. Lane,** Division Vice President, Technical Planning; **Joseph H. Colgrove,** Acting, Engineering; **Robert B. Means,** Division Vice President, Domestic Sales; **Stanley N. Roseberry,** Division Vice President, Finance, and **Charles W. Thierfelder,** Division Vice President, Manufacturing.

Government Engineering

Edwin S. Shecter, Manager, Government Product Assurance has announced the appointment of **Harry P. Howard** as Manager, Quality Assurance and Field Liaison.

Electromagnetic and Aviation Systems Division

Ramon H. Aires, Chief Engineer has announced the organization of Engineering as follows:

Gerald P. Benedict, Manager, Radar Indicator Design; **William J. Davis,** Manager, Rapid Score Engineering; **Warren D. Ellis,** Administrator, Administrative Services; **Edward B. Gamble,** Manager, Standard Products Engineering; **Raymond C. Hayes,** Manager, Radar Design; **George A. Lucchi,** Manager, Advanced Avionics Systems; **Daniel A. Mancini,** Manager, Engineering Graphics; and **Alex J. Virnig,** Manager, Avionics Equipment Design.

James L. Parsons, Manager, Avionics Products Management has announced the organization as follows:

Linden L. Carter, Manager, PSI Administration, **William P. Doyle,** Manager, Avionics Programs; and **Arthur J. Miller,** Manager, Product Assurance.

RCA Global Communications, Inc.

James C. Hepburn, Vice President Operations announced the election of **Eugene M. Gaetano** as Vice President, Pacific Coast.

George Weisberg, Director, System Telex Operations has announced the organization as follows:

Vincent Bailey, Manager, International and System Liaison; **Robert Fitzmaurice,** Manager, Kingsbridge Campus Telex Operations; **Rudolf Lang,** Manager, System Technical Support; **William Meehan,** Supervisor, Telex System Programming; **Willard Schaefer,** Manager, Traffic Engineering; and **Vernon Wellington,** Manager, New York Telex Operations.

Lee Wilson, Director, Leased Services Engineering Implementation and Computer Systems has announced the organization as follows:

Saul Schadoff, Director, Leased Services Engineering and Implementation; **Russell Blackwell,** Manager, Leased Computer Programming; **Arnold Smith,** Manager, Government Leased Channels; **John Terry,** Manager, Leased Services Implementation, United Kingdom; and **Samuel Thompson,** Manager, Leased Computer Projects.

A. William Brook, Director, Systems Engineering and Facilities Planning has announced the organization as follows:

K. W. Ekeland, Manager, Plant Extension Engineering; **Lloyd Ottenberg,** Manager, Transmission Engineering; and **Jack Ray,** Manager, Traffic and Switching Engineering.

James Walsh, Director, Earth Station Radio and Construction Engineering has announced the organization as follows:

James Cuddihy, Manager, Earth Station Engineering; **Edward Doherty,** Manager, Radio Engineering; **Frank Woelfle,** Manager, Earth Station Implementation; and **Stephen Latargia,** Acting, Facilities and Construction Engineering.

James McDonald, Manager, Switched Services Engineering has announced the organization as follows:

Maurice Cha Fong, Manager, Computer Systems Engineering; **David Epstein,** Manager, Computer Telex Engineering; **Anthony Falco,** Manager, Switched Data Systems Engineering; and **Chummy Ng,** Administrator, Engineering Project Control.

RCA Annual Report available

A limited number of copies of the RCA 1974 Annual Report are available to RCA scientists and engineers. The Annual Report contains the full text of the Report to Shareholders by Chairman Robert W. Sarnoff and President Anthony L. Conrad, as well as highlights of RCA Operations in 1974 and a Five-Year Financial Summary.

As a member of the scientific and engineering staff of more than five thousand people responsible for the creation of many of the new products, developments, and services that contribute to RCA's diversified business, you should find the report interesting.

If you want to receive a copy, fill out the form below and send it to:

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RCA 1974 Annual Report

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Subject Index

Titles of papers are permuted where necessary to bring significant keyword(s) to the left for easier scanning. Author's division appears parenthetically after his name.

VOLTAGE-PROGRAMMABLE TIMER, CA3096E and CA3099E extended range — A.C.N. Sheng (SSD,Som) **20-3** RCA Reprint 20-3-25.

WAVEFORM synthesis, Digital — B.A. Bendel (GCASD,Burl) **20-6** RCA Reprint 20-6-10.

225 Antennas and Propagation

antenna design and performance; feeds and couplers, phased arrays; randomes and antenna structures; electromagnetic wave propagation, scatter, effects of noise.

ANTENNA for satellite communication, S-band resonant quadrifilar — R.W. Bricker, H.H. Rickert (AED,Pr) **20-5** RCA Reprint 20-5-4.

MINI-STATE — a small tv antenna — Dr. J.J. Gibson (Labs,Pr), R.M. Wilson (P&A,Dptfd) **20-5** RCA Reprint 20-5-21.

UHF TV antenna, New indoor — P.J. Mikulich (P&A,Dptfd) **20-5** RCA Reprint 20-5-20.

240 Lasers, Electro-Optical and Optical Devices

design and characteristics of lasers, components used with lasers, electro-optical systems, lenses, etc. (excludes: masers).

CHARGE-COUPLED IMAGE SENSOR for 525-line television — R.L. Rodgers (EC,Lanc) **20-1** RCA Reprint 20-1-1.

ELECTRO-OPTIC MODULATORS for lasers, Closer look at — A Waksberg (Ltd., Montreal) **20-2** RCA Reprint 20-2-16.

FOCUSED-IMAGE HOLOGRAMS for micropublishing, Color-encoded — M.T. Gale, Dr. K. Knop, Dr. J.P. Russell (Labs,Zurich) **20-3** RCA Reprint 20-3-16.

LASER SCANNING as a tool for testing integrated circuits — P.V. Goedertier, R.W. Williams, J.D. Knox (Labs,Pr) **20-1** RCA Reprint 20-1-4; PE-626.

LASER systems used on the MADOS project, Operational — F.H. Aaron, D.V. Carney (Sv Co.,Lanham,Md) **20-6** RCA Reprint 20-6-20.

LIQUID CRYSTALS, Observing integrated-circuit operation with — Dr. D.J. Channin (Labs,Pr) **20-2** RCA Reprint 20-2-12.

LUMINESCENCE due to impurities and excitons — Dr. W. Czaja (Labs,Zurich) **20-3** RCA Reprint 20-3-15.

RADIOMETER, Very high resolution — A.I. Aronson (AED,Pr) **20-1** RCA Reprint 20-1-18.

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DOCUMENT viewer, Holographic — R.C. Plaisted, V.J. Stakun (GCASD,Burl) **20-6** RCA Reprint 20-6-15.

SPACE MOUNTAIN, RCA — R. Flory (Labs,Pr) **20-3** RCA Reprint 20-5-1

VISUAL CAPACITY — an image quality descriptor for display evaluation — R.W. Cohen, I. Gorog (Labs,Pr) **20-3** RCA Reprint 20-3-1.

250 Recording Components and Equipment

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LASER/FILM RECORDING, PARS — a breakthrough in — C.R. Horton, F.P. Tyrell (GCASD,Cam) **20-2** RCA Reprint 20-2-1; PE-642

OPTICAL RECORDING, Solid State — G.M. Claffie, J.E. Roddy (ATL,Cam) **20-5** RCA Reprint 20-5-16.

RECORDING system, Data cartridge — L.W. Dobbins, C.R. Horton (GCASD,Cam) **20-6** RCA Reprint 20-6-19.

TAPE RECORDER system, High-capacity high-data-rate instrumentation — O.E. Bessette (GCASD,Cam) **20-1** RCA Reprint 20-1-21.

VIDEO TAPE RECORDER/REPRODUCER, Basic, highly maintainable airborne — P.F. Muraco (GCASD,Cam) **20-3** RCA Reprint 20-3-3.

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FOAM PLASTIC as a structural component — W.T. Bachman, F.R. DiMeo (P&A,Deptfd) **20-5** RCA Reprint 20-5-17.

SEAMS for inflated structures, Quality control of — E.L. Crosby (Sv.Co., Patrick AFB) **20-5** RCA Reprint 20-5-25.

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PYROELECTRIC DETECTION of moving warm bodies — Dr. P.D. Southgate (Labs,Pr) **20-2** RCA Reprint 20-2-10.

TEMPERATURE PROGRAMMING of laboratory furnaces, Millivolt source for — R. Fehlmann, A.E. Widmer (Labs,Zurich) **20-1** RCA Reprint 20-1-25.

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310 Spacecraft and Ground Support

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MORE INFORMATION and less data from space — Dr. H. M. Gurk (AED,Pr) **20-2** RCA Reprint 20-2-3.

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SHIP TRANSPONDER SYSTEM, Operational requirements for a — E. Jellinek (GPSD,Cam) **20-2** RCA Reprint 20-2-14.

315 Military Weapons and Logistics

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DATA ACQUISITION, CONTROL, AND DISPLAY for Navy ORTS — M. LeVarn, T. Taylor (GCASD,Burl) **20-1** RCA Reprint 20-1-23.

DISPLAY CONTROL/STORAGE AND RETRIEVAL EQUIPMENT for tactical military use — P.T. Frawley, E.H. Miller (GCASD,Burl) **20-4** RCA Reprint 20-4-8; PE-640.

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PROJECT PRESS, Pacific Range Electromagnetic Signature Studies — W.S. Hahn (MSRD,Mstn) **20-3** RCA Reprint 20-3-2.

RADAR RANGE, World-wide instrumentation — L.E. Kitchens, M.D. Wilker (MSRD,Mstn) **20-3** RCA Reprint 20-3-5.

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AIRCRAFT HYDRAULIC pumps and motors, Automated test facility for — R. Blanchard, L.R. Hulls (GCASD,Burl) 20-6 RCA Reprint 20-6-7.

AUTOMATIC TEST EQUIPMENT, Twenty year with — O.T. Carver (GCASD,Burl) **20-6** RCA Reprint 20-6-14.

AUTOMOTIVE Testing, Simplifying — H. Fineman, T. Fitzpatrick, A. Fortin (GCASD,Burl) **20-6** RCA Reprint 20-6-8.

ENGINES AND MACHINERY, Automatic testing of — R.T. Cowley, L.R. Hulls (GCASD,Burl) **20-6** RCA Reprint 20-6-5.

EQUATE — RCA's third generation test system — R.J. Monis (GCASD,Burl) **20-6** RCA Reprint 20-6-9.

IMAGE DEVICE EVALUATOR, Automated — E.W. Kettler (GCASD,Burl) **20-6** RCA Reprint 20-6-16.

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COMMUNICATIONS SATELLITES—around the world in 800 milliseconds — D.R. Ellis (GlobCom,NY) **20-3** RCA Reprint 20-3-6.

DATA LINK, Japanese — J.P. Gillen (GCASD,Cam) **20-3** RCA Reprint 20-3-21.

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RADIO on modern technology and industry, Impact of — Dr. G.H. Brown (Staff,Pr) **20-2** RCA Reprint 20-2-15.

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TELEX SWITCHING, Computer-controlled — L.P. Correard (GlobCom),NY) **20-5** RCA Reprint 20-5-7.

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VIKING mission to Mars, Communication system for the — I. Brown (AED,Pr) **20-2** RCA Reprint 20-2-2.

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STEREO for in-car entertainment — C.C. Rearick, J.M. Shuskus (P&A,Dptfd) **20-5** RCA Reprint 20-5-19.

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TELEVISION EXCITER, TTUE-4A uhf — J.B. Bullock (CCSD,ML) **20-1** RCA Reprint 20-1-20; PE-623.

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MICROCOMPUTER SYSTEM, low-cost, home/school — J. Weisbecker, J. (Labs,Pr) **20-5** RCA reprint 20-5-9.

PROCESSOR, Geometric-correction constant-resolution — T.A. Altman, J. Danko, M. Hecht (AED,Pr) **20-5** RCA Reprint 20-5-6.

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languages, software systems, and general applications (excluding specific programs for scientific use).

BUILDING MANAGEMENT systems — J.H. O'Connell, D. Priestly (GCASD,Burl) **20-6** RCA Reprint 20-6-21.

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Solid State Technology Center

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Government and Commercial Systems

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Palm Beach Division	B. B. BALLARD* Palm Beach Gardens, Fla.

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Laboratories	C. W. SALL* Research, Princeton, N.J. A.L. STRADER Solid State Technology Center, Somerville, N.J.

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RCA Engineer

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