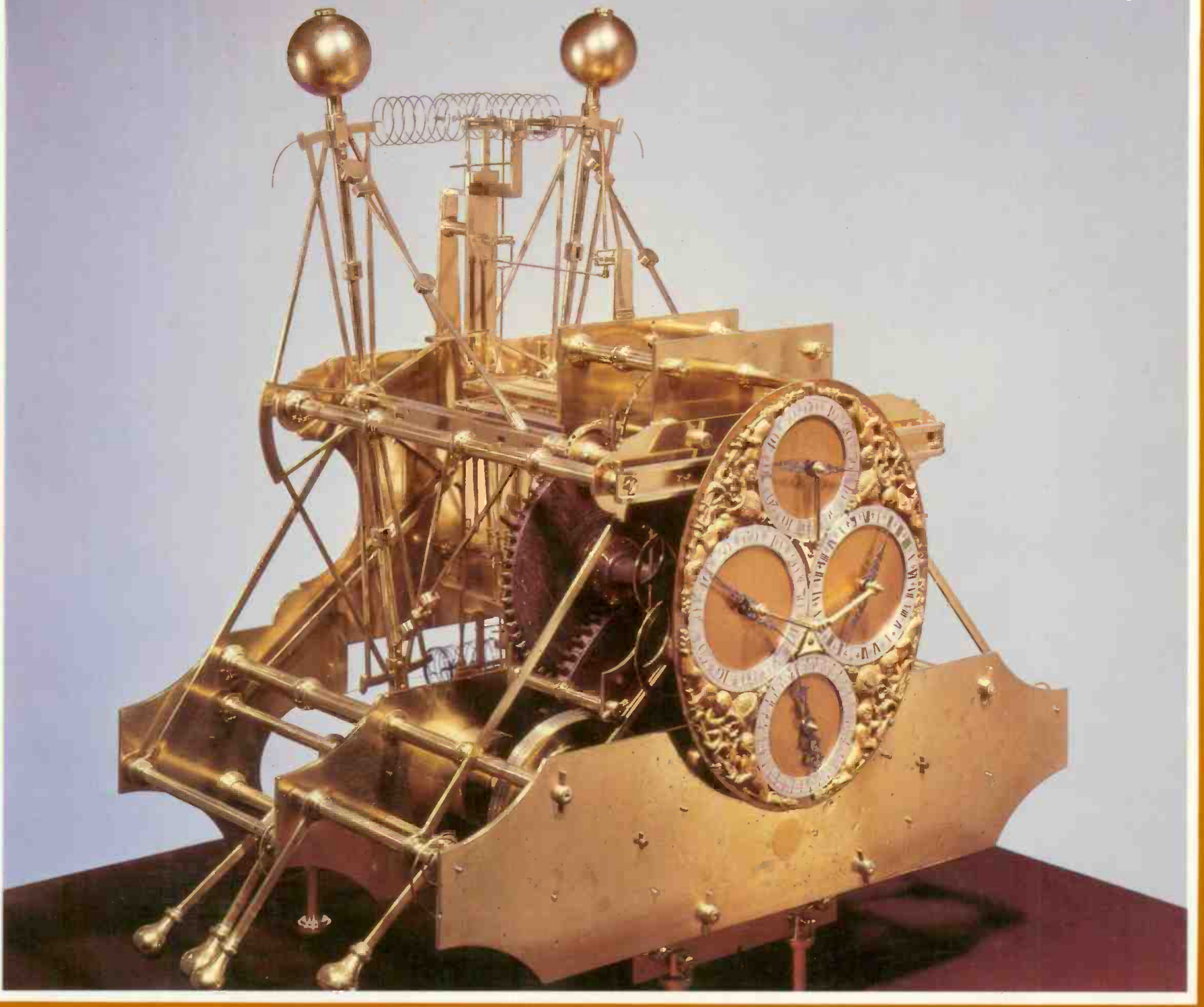
Electrical Communication



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Navigation Aids

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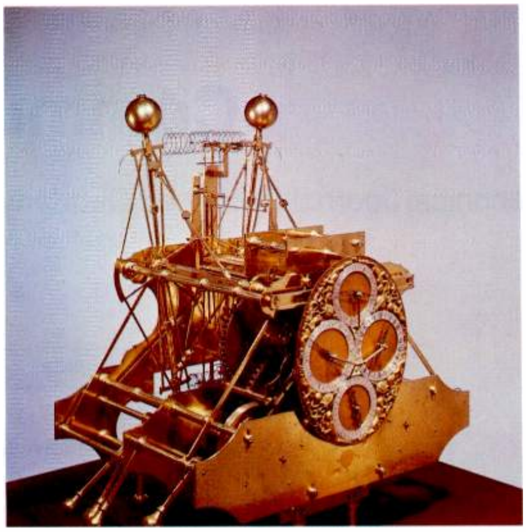


Global navigation depends on accurate timekeeping. This early Harrison chronometer was one of the first really accurate and reliable timepieces for use on ships. Today the required worldwide navigational accuracies are so high that atomic clocks are used on board the satellites of the new global positioning system – and even then relativistic effects must be taken into account.
(Photograph by courtesy of the National Maritime Museum, London)

Overview

Landmarks, stars, and time were the foundations on which the art of navigation flourished throughout the centuries before electromagnetic waves were discovered. "Self-contained" global navigation based on compass, sextant, and chronometer allowed ships regularly to cross the world's oceans – which cover two-thirds of our globe – long before inertial navigation was invented in the 1920s.

However, a new era of navigation was heralded at the turn of the present century when radio waves began to be used to guide aircraft and ships. Finally the uncertainties inherent in the "art" of navigation were succumbing to scientific advances. Since the early days of radio-based navigation systems ITT has made substantial contributions to their growth by developing sophisticated equipment offering improved reliability and ever greater accuracies. Both these factors have become increasingly important in view of the explosive growth in air travel over the past two or three decades.

In the 1930s instrument landing systems were invented and pioneered by ITT engineers in Europe, and are still in use worldwide. During the 1940s, ITT scientists and engineers in the USA made two major contributions. Hyperbolic navigation, based on very low frequencies, aided naval vessels during wartime. As shown in this issue, the Loran-C system is still alive and in wide use. Tacan, an ingenious en-route 1 GHz navigation system, became a NATO standard and evolved into the world standard distance measuring equipment for civil aviation.

During the 1950s and 1960s, a variety of radio navigation aids for aircraft and ships were developed and produced by ITT houses on both sides of the Atlantic, with ILS, VOR, Doppler-VOR, DME, and Tacan and its derivatives still serving many users throughout the world.

The dramatic performance increase of digital technology based on sophisticated computers and microprocessors, made possible major advances in air and maritime navigation systems in the 1970s. The marriage of radio systems and digital technology has made it feasible to use new techniques for air and maritime navigation. The new international standard microwave landing system with its associated precision distance measuring equipment, and the extraordinarily accurate satellite-based global positioning system (GPS) have both seen major ITT contributions in the USA and Europe.

Inertial navigation is currently entering a phase of innovative change in which mechanical gyroscopes are being replaced by "gyros" that do not rotate. Light is now performing the task of inertially sensing rates of rotation. ITT has entered this field by developing low cost fiber optic gyros based on the Sagnac effect, which was discovered in 1913. Fiber optics, widely promoted by ITT for communication, is thus having a spin-off in the field of low cost inertial navigation.

Cutting the perceived and real distances between people is a goal that ITT has pursued since the corporation's inception, both by improving communication, and by promoting safe and reliable navigation of aircraft and ships worldwide, following the guideline "Preserve tradition while pushing innovation". As this special issue on Navigation Aids clearly illustrates, ITT is working on a broad front developing entirely new systems and improving existing ones, and offering a wide range of products from the simple VHF radio lighthouse to receivers for the very sophisticated global positioning system. For the future, the trend is to combine the functions of communication, navigation, and identification in a single system to increase operational safety and reduce the cost per function. ITT will continue to play a major and growing part in this area.

M. Böhm

M. Böhm
Director
Research, Development and Engineering
Radio and Navigation Systems
Standard Elektrik Lorenz, Stuttgart

Civil Navigation Aids in ITT

Over the past 10 years there have been a number of changes in civil navigation aids, including the standardization of the time-referenced scanning beam microwave landing system and the development of the very accurate global positioning system. However, the more traditional systems continue to be used by the great majority of civil users.

S. H. Dodington
ITT Headquarters, New York, United States of America

Introduction

Electrical Communication last devoted a special issue to navigation aids in 1975 (volume 50, no 4). Since then, there have been a number of changes on the world scene. One of the most important moves has been the standardization by ICAO (International Civil Aviation Organization) of the time-referenced scanning beam for the MLS (microwave landing system). ICAO is also about to adopt an L-band precision DME (distance measuring equipment), compatible with the en route DME.

Great interest has been generated in the satellite-based global positioning system, although the Aerosat concept has died.

Finally, the Loran-A system has been discontinued.

Navigation is only one leg of the three-legged stool of communication, navigation, and surveillance that supports the air traffic control system. For the past several years it has been by far the strongest of the three, there being really no part of the world where some type of navigation cannot be obtained – self-contained, if nothing else. However, over the oceans, over mountainous terrain, and over much of the developing world there is *no* surveillance, and communication is subject to the vagaries of high frequency transmission.

These deficiencies, as well as some remaining navigational problems, are the subject of a special committee SC-155 which was established in 1983 by the United States Radio Technical Commission for Aeronautics (RTCA). This will be the first major attempt to review the whole problem, particularly in the light of the use of satellites, since the famous RTCA SC-31 established the basis of the present ICAO system in 1948 (see Figure 1). The new committee's influence will probably not be felt until the 1990s.

Otherwise, the main radio systems in use remain much the same as in 1975. They are summarized in Table 1.

Systems

Within each system, while signal formats have remained unchanged, there have been a number of changes since 1975:

Omega
All eight stations are now operating and a truly worldwide service is in place[1,2]. Many oceanic airlines, which formerly used three inertial sets per aircraft, are now using two inertials and one Omega with consequent large savings in both initial and operating costs. Most airborne receivers also make

Today's basic ICAO air traffic control system.

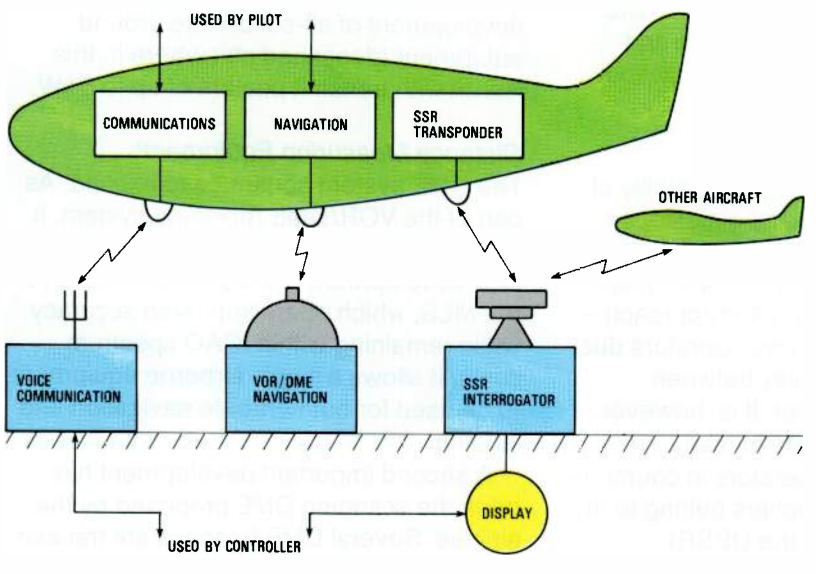


Table 1 – Main radio navigation systems used by the world

System	Frequency	Stations	Users		ITT activity
			Air	Marine	
Omega	10 to 13 kHz	8	10600	7000	
Loran-C	90 to 110 kHz	33 chains	2000	60000	ITT Avionics
Decca	70 to 130 kHz	50 chains	1000	30000	
* Beacons/DF	200 to 1600 kHz	5000	200000	500000	FACE
* ILS	75, 108 to 112, 329 to 335 MHz	1600	70000	—	SEL, FACE
* VOR	108 to 118 MHz	2000	200000	—	SEL, FACE
Transit	150, 400 MHz	5 satellites	—	38000	
Tacan	960 to 1215 MHz	2000	17000	—	ITT Avionics, FACE, SEL
* DME	960 to 1215 MHz	1000	80000	—	ITT Avionics, FACE, SEL
* SSR	1030, 1090 MHz	1000	100000	—	
* MLS	5031 to 5091 MHz	Implementation about to start			

* Signal format standardized by the International Civil Aviation Organization

use of VLF communication stations as a back-up in the rho-rho mode. Selection is entirely automatic.

Loran-C
This system[1,3] has been greatly aided by automatic receivers which reduce cockpit workload to the mere punching-in of waypoints, to which the pilot can then read direction and distance "just like rho-theta". Loran-C is being widely used, at least in the United States, by helicopters flying to and from offshore oil-rig platforms.

Beacons and Automatic Direction Finding[1,4]
This remains the world's most popular navigational aid. The trend is to eliminate voice in order to reduce bandwidth and allow closer frequency spacing of stations.

Instrument Landing System
ILS[1] is still going strong. The availability of wide-aperture localizers and glideslopes that are independent of ground reflections[5], has reduced site-effects. (The other major landing aid – ground controlled approach – has not found favor with civil operators due to the divided responsibility between ground controller and pilot. It is, however, widely used by the military in many countries and by civil operators in countries in which pilots and controllers belong to the same organization (e.g. the USSR).

VOR[1]
There have been major improvements in ground hardware for VOR (very high frequency omnidirectional range), as described elsewhere in this issue, together with a steady growth of Doppler-VOR.

Transit[6]
This system originated for some 500 ships of the United States Navy, but is now also used by some 38000 merchant ships of all nationalities who pay nothing to use it. The system provides a worldwide service with an accuracy 10 times better than Omega, albeit at 90-minute intervals.

Tacan[1]
The main evolution has been the development of all-solid-state ground equipment (described elsewhere in this issue) with transmit powers of up to 5 kW.

Distance Measuring Equipment[1]
The DME system continues to expand. As part of the VOR/DME rho-theta system, it will be around for a long time. An interesting new development is the precision DME for the MLS, which offers improved accuracy while remaining within ICAO spectrum limits. It allows a single airborne equipment to be used for both enroute navigation and landing.

A second important development has been the scanning DME proposed by the airlines. Several DME beacons are tracked simultaneously to give a very accurate fix independent of the VOR.

Secondary Surveillance Radar (SSR)[1]
Just as it appeared that the long-awaited DABS (discrete address beacon system) or ADSEL (address selective) interrogation coding, now known as "Mode S"[7], was about to be introduced, the situation was complicated (at least in the United States) by an elaborate air-to-air anticollision system called TCAS[8] (traffic alert and collision avoidance system).

Microwave Landing System[9]
Although ICAO selected a signal format in April 1978, six years later there is only one commissioned runway in the world (at Valdez, Alaska) and not a single commercial user. The reasons are many, not least being the well known "chicken-and-egg" stalemate. The high cost of implementation, with little immediate economic benefit, must surely be a major factor in these days of financial austerity. Recently, however, the Federal Aviation Authority ordered 176 MLS systems, with further orders expected in the near future.

Other Areas
In the field of *self-contained* aids, there is relatively little new to report on radio altimeters and Doppler navigation systems. However, in the field of inertial navigators, the laser gyroscope is rapidly displacing mechanical gyroscopes, and the color cathode ray tube, long used in weather radars, is now becoming the all-purpose cockpit display device. At the flick of a switch it can be used as a radar display, for the pre-takeoff checklist, as an ILS crosspointer, or for many other functions. Helicopters flying regular services to offshore oil rigs are now utilizing weather radar in conjunction with X-band beacons as an approach aid to the rigs.

Loran-C transmitter control console manufactured by ITT Avionics Division.

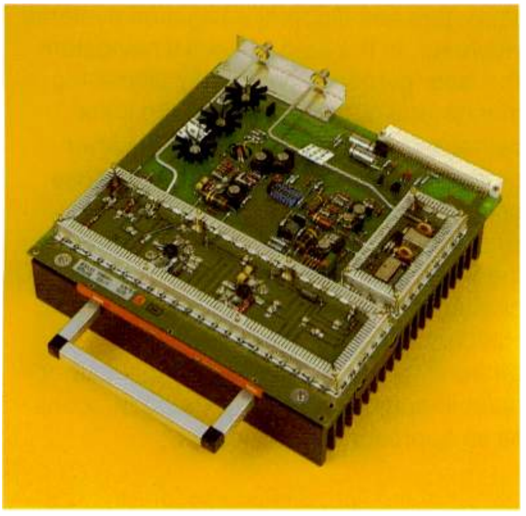
Systems under Development

Two major systems are at present under development. The mode S/TCAS occupies the same frequencies as SSR, but offers new features. The global positioning system[10], a new satellite-based navigation system, aims to provide very high accuracy throughout the world, albeit at a cost exceeding that of all other navigation systems combined.

Mode S/TCAS
The SSR, interrogating at 1030 MHz and replying at 1090 MHz, started life as a military IFF (identification – friend or foe) system during the mid 1940s and later became an ICAO standard. Since all interrogators interrogate all transponders in a given area, it has long been subject to excessive "garble" and as long ago as 1969 the Alexander Report[11] recommended that each aircraft's identity be encoded on the interrogator. ICAO has now adopted such a plan, called "Mode S".

However, in 1981 the United States Federal Aviation Authority proposed the development of a scheme of airborne interrogation, called TCAS which would allow interrogator-equipped aircraft to "see" transponder-equipped aircraft (of which there are some 100 000) and thus hopefully avoid collisions. On some large aircraft, antenna directivity of about ±10° or so would be used to cut down on excessive unwanted replies. The system is so complex that the RTCA SC-147 proposed standard is over 300 pages long. Much work remains to be done. Meanwhile, there has been no implementation of Mode S.

Global Positioning System
Also known as Navstar, GPS has been under development by the United States Air



Module for SEL's System 4000 family of navigation aids.

Force since about 1960 and is currently proposed as using 18 satellites in 12-hour orbits, transmitting phase-coded continuous wave signals around 1200 and 1500 MHz. (Details are described elsewhere in this issue). Continuous accuracy of about 20 m anywhere in the world is claimed. The initial cost is estimated at $6 billion and the annual operating cost $250 million, both figures greater than those for the sum of all other radio navigation systems in existence. For this reason, the United States Department of Defense is anxious to secure its use by the civil sector and the shutdown of all other civil aids. However, to preclude the use of GPS by potential enemies, civil users will only be allowed 100 m accuracy (by coding the signal) and they will also be charged $400 per year each. (There are no user charges for any of the present navigation aids). Civil users have unanimously rejected these conditions; even helicopter operators, who are not happy with VOR/DME, have balked at the 100 m limitation on accuracy. Furthermore, there is little indication that any of ICAO's 130 countries cares to abandon its home-based navigation aids in favor of one controlled by the military service of a foreign government.

At present, about 100 receivers of various types are being produced by two non-ITT contractors in the United States. Five usable satellites are in orbit. Within ITT, the Defense Communications Division has built the satellite L-Band transmitters, Bell Telephone Manufacturing Company (Antwerp, Belgium) and Standard Elektrik Lorenz (Stuttgart, Federal Republic of Germany) have study and hardware contracts. ITT affiliate Standard Telecommunication Laboratories (Harlow, England) has built eight receivers.

Personal Forecast for the Year 2000

The following is a personal prediction of the status of navigation aids in the year 2000:

- GPS will be in use as a military system, with some civil users. There will probably be no user fees and no accuracy restrictions.
- All systems in Table 1 will still be in use, with the possible exception of Transit, which, as a purely United States-paid system, might be shut down to help pay for GPS.
- Increased use of self-contained systems of all kinds.
- Systems will increasingly use digital circuits and electronic systems will replace electromechanical systems.
- ILS installations will continue to outnumber MLS, both airborne and ground.
- Only modest use will be made of Mode-S, and even less of TCAS.
- Any "new" systems will attempt to use existing signal formats and hardware; SSR/Mode S/TCAS is probably an extreme example of this. Precision DME is another example and, to a lesser extent, so is STL's radio lighthouse. MLS is an example of the opposite approach. New ground, airborne, and test equipment are all required – a formidable set of hurdles to overcome.

The fiber optic gyroscope has no moving parts. The model shown here illustrates a possible future design.

The effects of SC-155's recommendations will begin to be felt, but are likely to be in the realms of communication and surveillance more than in navigation.

Conclusions

The articles in this issue describe some of the equipment that ITT companies, on both sides of the Atlantic, are building to fit into the world environment. As in the 1975 issue, emphasis is on equipment that fits into standard systems with well established signal formats.

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Sven H. Dodington was born in Vancouver, Canada, in 1912. He was awarded an AB degree from Stanford University in 1934. The following year he joined Scophony Ltd, London, to work on the design of large-screen television projectors. In 1941 he joined ITT in New York and has been with them ever since. From 1941 to 1945 he headed much of the wartime effort on airborne radar counter measures of the deceptive type. He was then appointed head of the ITT radio navigation laboratory in Nutley, New Jersey, where the groundwork was laid for today's distance measuring equipment. As a result he won the IEEE/AESS Pioneer Award. He became president of ITT Avionics Division in 1958, a post he held until moving to the Technical Department at ITT headquarters in New York as a consultant on avionics and radio navigation. Since 1969 he has been a technical advisor to the Radio Technical Commission for Aeronautics. In 1982 he was named "Inventor of the Year" by the New York Patent Law Association.

Second Generation Vortac Equipment

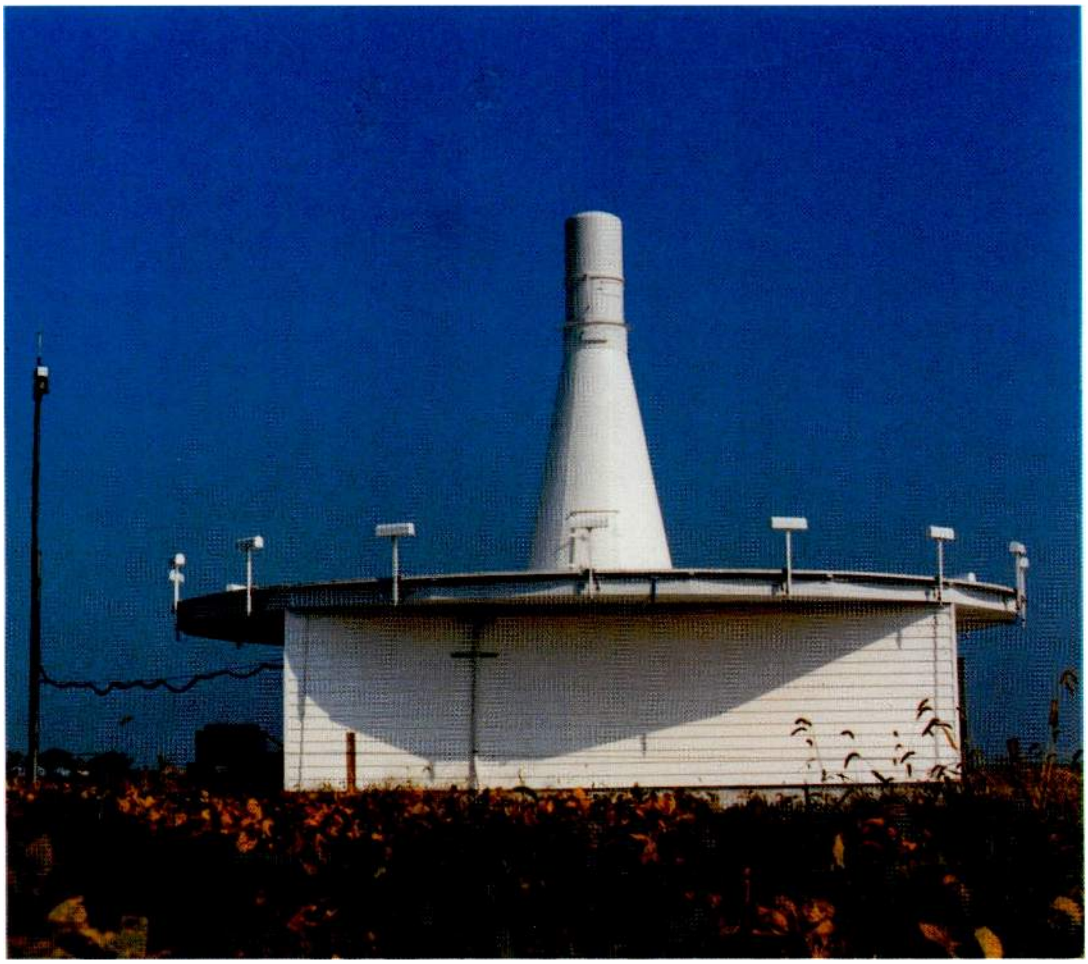
The old Vortac systems are being replaced by solid-state equipment with remote maintenance and monitoring capabilities to extend the service to 1995 and beyond. Higher reliability, reduced running costs, and microprocessor-based remote maintenance ensure that the new systems will pay for themselves over five to six years.

A. H. Lang
ITT Avionics Division, Nutley, New Jersey

Introduction

Vortac and VOR/DME (very high frequency omnidirectional range/distance measuring equipment) have become the standard prime navigation aids for the United States national airspace system. The national airspace plan has been updated to ensure the continuation of this service until 1995, and present indications are that these systems will remain prime elements in a mix of future navigation systems in plans which extend to beyond the year 2000. The problem for the FAA (Federal Aviation Agency) was that ground beacons installed between 1950 and 1965 were becoming expensive to maintain and operate, and there were difficulties in obtaining spares.

To resolve this situation, the FAA awarded a joint contract to ITT Avionics Division and Wilcox Electric Company to replace all the old vacuum tube VOR, DME, and Vortac equipment with a new system architecture based on the latest technology. Development of these all-solid-state systems, including qualification and



Second generation Vortac installation.

reliability testing, has now been completed. By the end of 1983, hundreds of old units will have been replaced with second generation systems which will have a useful life of over 20 years. These systems incorporate a new maintenance concept which, combined with their high reliability, will reduce maintenance costs, enabling the acquisition costs to be offset in five to six years.

Background

The FAA operates and maintains some 725 Vortac installations throughout the national airspace system. These installations, together with about 145 VOR/DME and 80 VOR-only units, provide a navigation service to civil and military aircraft over the continental United States, Alaska, Hawaii, and other United States territories. The first of the new systems was installed in July 1982; all installations will be completed by late 1985.

The primary objective of the new equipment is to reduce the lifecycle costs for the Vortac and VOR/DME beacons while continuing to provide the same navigation service with some performance improvements. This has been achieved by employing a new maintenance concept based on the use of highly reliable solid-state technology, remote maintenance monitoring equipment combined with computerized test and failure analysis and reporting, and centralization of the maintenance staff. This concept allows an ever-growing inventory of air navigation equipment to be maintained by a small, centralized technical staff as minimal preventive maintenance is required.

The cornerstone of this project has been the application of computer technology to allow remote monitoring of Vortac performance, to measure equipment parameters, and to predict potential failures. This has resulted in routine maintenance trips to each unit being reduced from one or two trips per week to once every three months.

The new FAA Vortac equipment can also reduce lifecycle costs for users operating fewer Vortac or Tacan beacons. ITT Avionics Division has developed the 9996G Tacan beacon system for such applications. This beacon includes all the advanced features of the FAA Tacan (including the 5 kW power output), plus a remote monitor and control unit that can be installed in an airport control tower. In addition to improved reliability, a significant advantage to limited-system users is that the automated test, maintenance, and fault isolation features of the remote monitoring equipment allow the equipment to be maintained by a technician with limited experience or available time. The FAA's remote maintenance network is reduced to a dial-in capability from a remote location to enable centralized control and analysis of the operation of all systems. More importantly, this dial-in capability permits a centrally located, higher-skilled technician to test the equipment remotely and provide technical assistance without visiting the site. Together, these features minimize maintenance costs for the limited-system user.

ITT Avionic's 9996-G solid-state Tacan beacon.

FAA Second Generation Vortac

Sixteen new VOR monitor antennas are mounted around the periphery of the counterpoise to provide an automatic 16-point VOR ground check to determine course errors, thereby eliminating the lengthy tests required previously. In addition a DME antenna with a higher gain than the Tacan antenna is being added so that the system can change to a DME mode

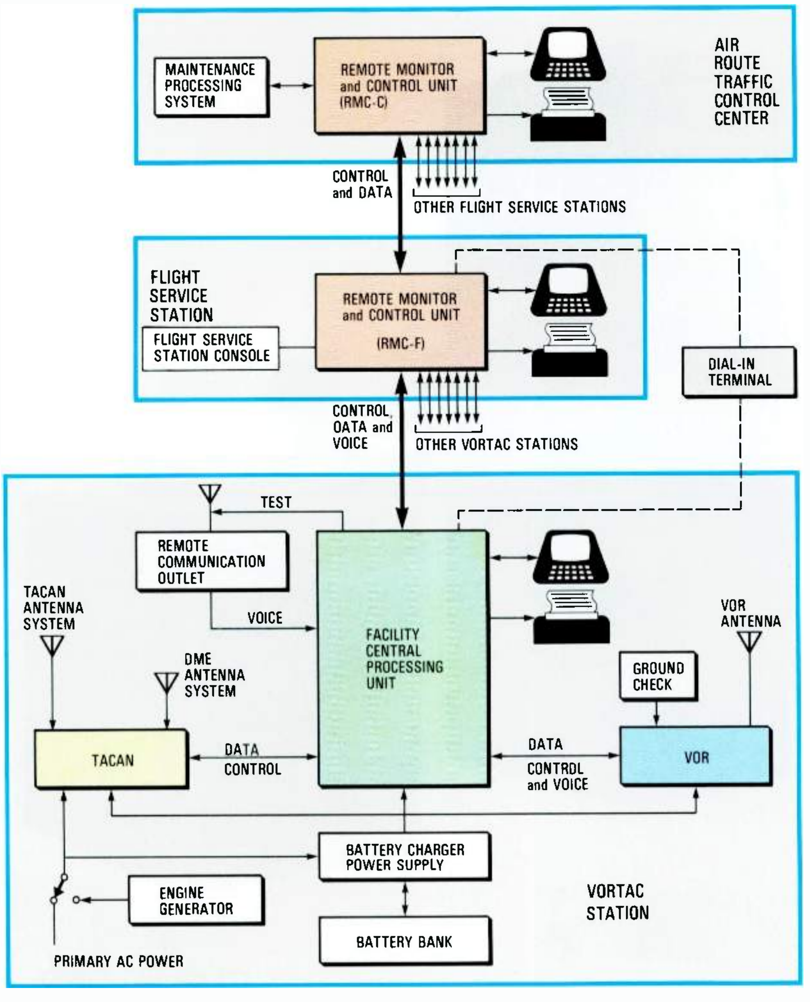


Figure 1
Block schematic of the Vortac system with remote maintenance and monitoring facilities.

of operation in the event of a Tacan azimuth-function failure, partial loss of Tacan output power, or loss of AC power. This feature has been used on numerous occasions in winter at a mountain-top site in California where sudden storms caused ice and snow to accumulate on the Tacan antenna radomes, resulting in azimuth monitor alarms. Automatic transfer to the backup DME mode maintained DME navigation service to civil aircraft on these occasions.

Inside the Vortac shelter, the new system occupies only three equipment cabinets, compared with the 16 previously required. The IOT (input/output terminal) and printer provide control and data display for the equipment. The small equipment size allows most of the shelter to be partitioned off. Together with the wide operating temperature range of −40 °C to +50 °C and the lower power dissipation of the solid-state equipment, this reduces heating and cooling requirements, and cuts operating costs.

In all respects the performance of the new FAA Vortac is equivalent to or better than that provided by the previous system. A 5 kW power output from the Tacan power amplifier and a receiver sensitivity of greater than −94 dBm ensure the required 130 n mile (240 km) coverage at 18000 feet (5486 m) with a high availability. The VOR power output of 150 W provides the same coverage. Performance improvements of the Tacan system include backup modes of operation such as fallback to DME operation, first pulse timing, Y-channel mode, increased traffic handling capability, and improved system accuracy. Also, problems such as false distance lock-on have been resolved. New VOR features include solid-state voice message recording, automatic 16-point ground check, and a solid-state goniometer and RF (radio frequency) amplifier that can operate with the Y-channel 50 kHz VOR channel spacing.

The operational configuration of the second-generation system is shown in Figure 1. All of the units, apart from the basic Tacan and VOR equipments, have been provided to meet the maintenance objectives. Microprocessor technology has been used extensively; both the VOR and Tacan include dual monitors which contain microcomputers, permitting multiple usage of a minimal amount of hardware. In addition to monitoring the key navigation functions, the microcomputers provide system control, remote adjustment of the transmitter operating parameters and monitor alarm limits. Also, the operation and sequencing of all automatic maintenance tests, and the storage and reporting of all data are performed by these microcomputers. The built-in test equipment is automatically programmed by the computer monitoring and test programs to perform repetitive and routine measurements. Special tests can be performed by operating the test equipment in the manual mode; this allows a technician to set up the frequency, power output, pulse rates, etc.

Control of the monitors and data collection from the monitors are remoted by the FCPU (facility central processing unit). This microcomputer-controlled unit includes the interfaces with the local IOT and teleprinter. The FCPU also provides other facility control and status reporting functions, such as remotely turning the obstruction lights on and off, and test and control of the remote communication outlet receivers.

The battery charger power supply provides the main DC voltages to the Tacan, VOR, and FCPU. This unit, in conjunction with the associated battery bank, ensures uninterrupted service during switchover to the standby engine generator in the event of failure of the AC primary power. More than two hours of battery operation are available after complete loss of AC power. The float-type approach to the battery system provides transient-free DC power to the system microcomputers, thereby reducing transient-related computer faults.

The Vortac equipment communicates, via the FCPU, with an RMC-F (remote monitor and control unit F) located at a flight service station. Up to eight Vortac facilities can communicate with one RMC-F over standard telephone lines. Each RMC-F is connected to an RMC-C at one of the 23 air route traffic control centers via a communication network that permits up to 128 Vortacs to report to a single RMC-C. The system allows status reporting and facility maintenance to be implemented at the flight service station as well as at a centralized status and control terminal in the air route traffic control center. Also, dial-in telephone ports enable a remote terminal with a modem to access the system, allowing a technician to perform tests from any telephone.

Maintenance and Monitoring Operation

Initial experience with the systems has confirmed that the operational objectives of the maintenance and monitoring system are being achieved. The system has proved its value in isolating faults, especially in the early stages of installation. Design engineers were able to remain at the factory, dial into any Vortac installation, and remotely diagnose a fault, thereby aiding the technicians. As the FAA assumes control of the new installations, its technicians are now performing these functions.

All system operation, control, and testing can be performed from any IOT in the network. Additionally, the status of the facilities is continuously displayed on the IOTs. A system alarm initiates a flashing display on the IOT screen and an alarm bell.

If an operator wants to observe the monitor or test data, or to perform tests, he first requests access to the FCPU. A special security code, which prevents unauthorized access or tampering with the system, must then be entered. A high-level security code (released to only a few people) allows parameters to be changed, tests to be run, and data to be observed. A person with a lower security code only has access to the data screens.

Every screen that is available to the user may be selected via a menu. Prompts are provided on each screen to facilitate parameter entry or testing.

A trend data test displays the critical equipment parameters which could vary as degradation occurs. Since digital techniques are extensively used, trend data generally applies to DC voltages, control-loop levels and, in the case of Tacan, the number of failed power amplifier output transistors. Any change in equipment operation can thus be ascertained and, if required, a maintenance trip scheduled to repair the equipment. If a marginal condition is observed, it may be possible to improve system operation by transferring to a backup mode or changing an operational parameter. The system can thus remain in operation until a repair can be effected.

Routine certification tests of the key transponder parameters and monitor alarm limits can be run automatically without

Second generation Vortac beacon equipment installation.

interrupting system operation. These tests, which previously took two days a week, are now performed in less than four minutes. All certification data is automatically displayed and printed, providing a permanent time-tagged log of test results. Similarly, a number of other tests that previously took a long time can now be carried out automatically using built-in test equipment.

During normal operation, if any of the monitored parameters is outside the limits, a system alarm is initiated. A fault isolation test is then run automatically, followed by changeover to the backup mode or shutdown. The operator can request different types of data and tests. First he can analyze the fault-history file, which contains the monitored data at the time of the problem, to determine which parameters were out-of-limits and what their measured values were at that time. Second, he can observe the fault isolation file which indicates the exact time at which the event took place, the state of the system at that time and, finally, the most-likely failed module which was selected as a result of the fault isolation test. Based on this data, he can plan a trip to the facility. If the system is operating in a backup mode, an immediate trip is not necessary as a second failure of the highly reliable equipment is unlikely. The technician can also determine which modules are needed for the repair. Experience indicates that the failed module is correctly identified by the fault isolation tests in at least 90% of failures. In conjunction with other remotely available data, generally the remaining failures can be isolated to a group of no more than three modules, thereby expediting repair.

Tacan/DME System

Some of the major issues for the second-generation Tacan/DME system illustrate the approaches used in the Vortac equipment design to meet the primary objectives of high reliability and remote maintenance.

Reliability and Availability

High reliability and availability are provided by solid-state circuits in a judicious mix of dual and redundant circuit elements and fallback modes of operation. The previous Tacan tube-type equipment exhibited very poor reliability by today's standards (a few hundred hours mean time between failures). However, by utilizing dual transponders, carrying out extensive maintenance, and immediately repairing failed units, a high navigation system availability (approximately 99.7%) was achieved.

Basic requirements for the second generation Vortac were:

- Availability of 99.7%; this was specified as a MTBO (mean time between outages) of 9600 hours for the Tacan system.
- Lowest possible system procurement costs, consistent with the low lifecycle cost requirements.
- Single-string elements, where used, must be at least as reliable as the single-string elements (e.g. control and transfer unit) of the previous dual tube system.

The resulting Tacan design is shown in Figure 2.

Reliability testing has verified that the FAA's MTBO specification has been met. Indeed, the calculated MTBO is greater than 12000 hours even if a failed dual or redundant element is not repaired until the next scheduled maintenance trip. Thus a full dual system is not required, resulting in lower procurement costs.

Solid-State 5 kW Power Amplifier

Redundancy and protection circuits in the 5 kW power amplifier permit up to 10 output

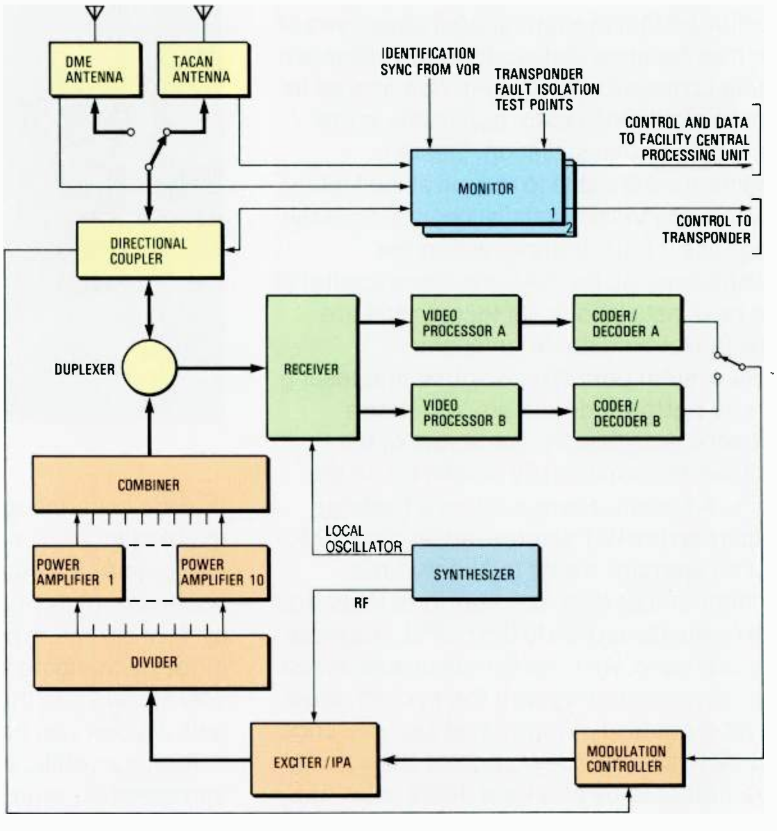


Figure 2
Block schematic of the new Tacan system which uses a judicious mix of dual and redundant circuit elements and fallback modes of operation.
IPA - intermediate power amplifier.

transistors to fail before the power drops by 3 dB, thereby greatly improving reliability. The FAA specification required solid-state devices to be used to produce an RF output signal of 5 kW at any Tacan channel frequency without retuning. FAA operational tests and path-loss calculations established this as the power needed to provide reliable reception within the required service volume, even for civil interrogators with sensitivities of only −82 dBm.

A power output of more than 5 kW has been achieved by combining the output of ten amplifier modules using low-loss, 10-way divider and combiner networks. Each power amplifier module contains one high-power transistor driving four parallel identical transistors in the final stage. An array of efficient two-way RF power dividers, which provide equal power distribution across the frequency band with low insertion loss and an isolation in excess of 20 dB between transistors, ensures fail-soft operation (i.e. failure of one transistor may reduce the RF power, but operation of the other transistors is unaffected). The outputs of the ten modules are then combined in a 10-way combiner to produce more than 5 kW.

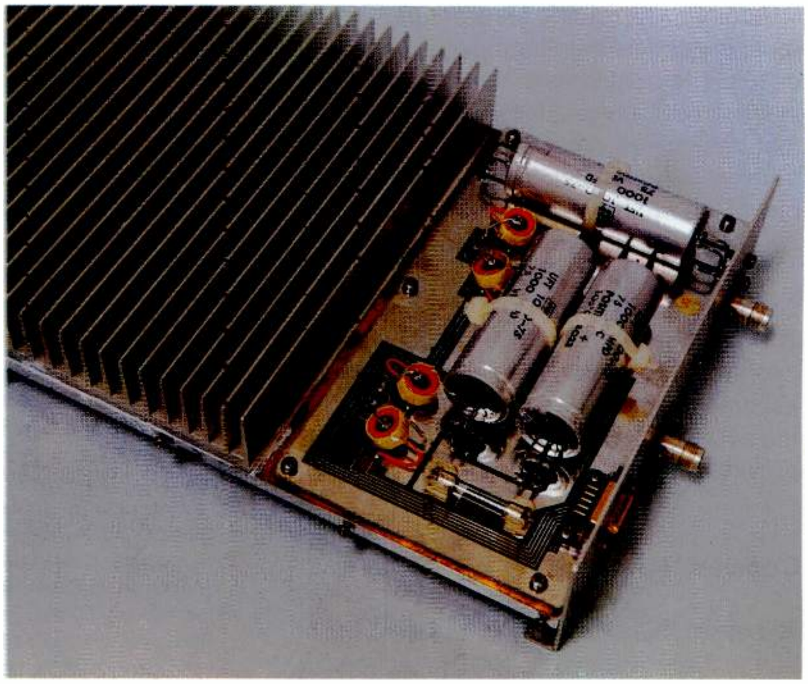
Development of the wideband, low-loss combiner was a key element in the amplifier design. The 10-way combiner utilizes a coaxial transformer section with a divider network to produce a low-loss device with a typical interport isolation of 25 dB at any frequency.

Microcomputer-Controlled Monitor
Microcomputer-controlled dual monitors are provided for:

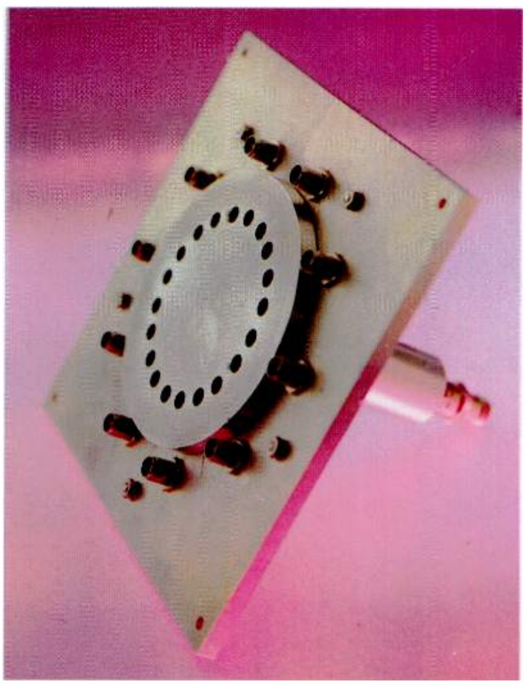
- executive monitoring of key system parameters and changeover or shutdown control if they are out of tolerance
- transmitting measured, monitored, and test result data to a remote test center
- local and remote system control
- automatic testing and certification
- built-in test equipment setup and control
- automatic fault isolation.

In the interests of increasing the system MTBO, dual monitor units are employed for these functions. Each includes an RF signal source to interrogate the transponder receiver. RF detectors and processor circuits detect the transmitted signals and convert them to a format for analysis by the microcomputer. These same circuits are also dynamically reconfigured by the microcomputer to provide built-in test equipment.

The critical transponder parameters are measured and compared with limits once every second. An alarm occurs if any measurement is out of tolerance. Both monitors must agree that an out-of-tolerance condition exists before the transponder is switched to a backup mode or shut down. Should the monitors disagree, the FCPU runs an integrity test on the monitor indicating the OK condition; if this test fails, the monitor is made inoperative.



Solid-state Tacan power amplifier module.



Ten-way Tacan RF divider-combiner.

Additionally, routine tests are performed on every critical monitor measurement circuit. The monitor is automatically inactivated if any test fails. These fail-safe features make it safe to use this unit to perform other functions. For system control, one of the two monitors is designated as the "controller" which then interfaces with the FCPU for the transmission of all status and control data, and controls transponder operation. In the event of a fault in the "controller" monitor, the second monitor assumes control. Complete redundancy of the system control functions is thereby provided with no additional hardware.

Conclusions

The basic goal of extending the useful life of Vortac systems beyond 1995 has been achieved by the second-generation Tacan equipment. This completely integrated system is reliable and inexpensive to procure and maintain, ensuring that initial replacement costs will be paid back in five to six years. Extensive use of microcomputer technology means that the remote maintenance and monitoring system can be readily reconfigured to tailor a system to a particular application, including those users operating only a few installations.

Arnold H. Lang was born in Hackensack, New Jersey, in 1932. He received his BS degree in 1954 and an MS degree in 1960, both from Stevens Institute of Technology. He joined ITT Laboratories at Nutley, New Jersey, in 1954, initially working on missile guidance system design. Subsequently, he was responsible for system engineering of telemetry and missile test range instrumentation. Since 1969, Mr Lang has been responsible for system engineering for DME and Tacan systems. He was the lead systems engineer for the second-generation Vortac programme.

Ground-Based Air Traffic Control Communication Equipment

ITT Aerospace/Optical Division produces single channel ground-to-air receivers and transmitters which have become the standard for air traffic control voice communication. New technology will lead to improved performance and capabilities to meet the needs of expanded air travel in the future.

D. W. Walters
ITT Aerospace/Optical Division,
Fort Wayne, Indiana, United States of America

Introduction

The primary objective of air traffic control is to guarantee the safe and effective control of aircraft. The timely arrival and departure of aircraft, movement of cargo, operational costs, and passenger and crew safety all depend on effective air traffic control. Intelligible and reliable radio communication between flight crew and air traffic controllers is generally cited as the most critical element of such control.

Air Traffic Control Communication Requirements

An ATCCS (air traffic control communication system) has to perform varied tasks to facilitate orderly operation of an airport.

VHF/UHF transmitter.

Peak traffic loads at major airports reach one aircraft per minute, demanding clear voice channels and close teamwork between the pilot and controller. The importance of pilot-controller coordination is illustrated by the considerable exchange of information that must take place to handle a single arrival or departure:

- Assignment of heading, altitude, air speed, communication frequency, configuration, and transponder code for efficient use of the air corridor and for separation of air traffic within the vicinity.
- Reports of aircraft and passenger status to controller.
- Reports of airport, weather, navaid, and traffic status to aircraft.
- Changes and clearances with acknowledgments as each flight progresses.
- Direction of aircraft and vehicular ground traffic within the airport.

Ground-Air Radio System Requirements

One proven voice communication equipment offering the clear, dependable performance required for safe air traffic control operations is the VHF (very high frequency) and UHF (ultra high frequency) carrier amplitude modulated equipment described in this article.

The VHF band between 118 and 136 MHz and the UHF band between 225 and 400 MHz are allocated for voice communication between pilot and controller for departing and arriving aircraft. The VHF band is more frequently used because of the availability and lower cost of hardware.

Basic to system performance are the operational characteristics of the individual components which make up the system. Many of the performance criteria discussed here for ground equipment also apply to the airborne system. The ATCCS consists of three basic units: receiver, transmitter, and antenna. The operational performance of these units is affected by the ground station installation. A critical parameter is the transmitter to receiver antenna isolation as it affects transmitter to receiver colocation performance. Availability of building land and the required number of communication channels also put constraints on the ground installation.

Overall Characteristics

When considering the system characteristics, it is first necessary to establish a minimum performance requirement. A receiver signal + noise to noise ratio $(S+N)/N$ of 10 dB provides good intelligibility, where the noise term includes the interfering signal and a 15% maximum audio distortion.

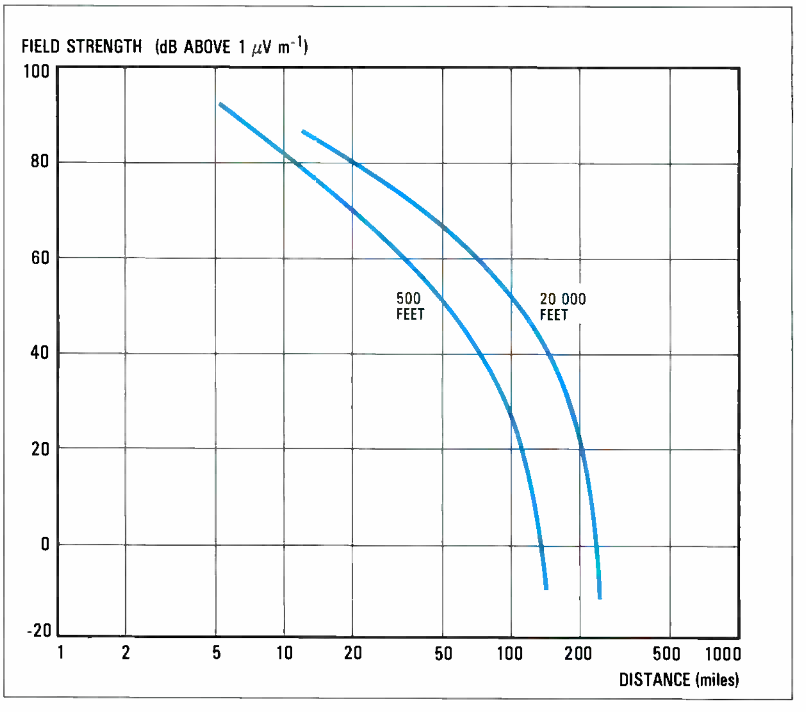


Figure 1
Field strength as a function of distance for airborne antenna heights of 500 and 20000 feet. Curves were taken for a 1 kW radiated power with the transmitter antenna at ground level.

As the operational range of VHF and UHF communication is generally limited to line-of-sight, the ground antenna height and aircraft altitude significantly affect the communication range. The radio path distance is approximately 15% longer than the tangential geometrical distance as a result of bending of the radio waves.

Figure 1 illustrates the rapid fall-off of signal strength beyond the line-of-sight distance. Neither increased transmitter power nor receiver sensitivity improves the range significantly. The curves illustrate the importance of antenna installations and their placement[1,2].

System performance characteristics must take into account the worst case combination of required range, colocation with interfering signals, and environmental performance factors.

Colocation

Receiver degradation caused by off-channel transmitters has been recognized since the early days of radio. This effect, now known as crossmodulation distortion, has in many cases been made more severe by the use of solid-state technology in modern communication equipment. At the same time, the number of radio systems has increased and user requirements often dictate colocated operation. Receiver degradation due to noise and off-channel signals is often referred to as desensitization.

General Considerations
When two or more radio antennas are located close together (colocated), there is a possibility of interference. Successful communication system design requires careful consideration of the many possible sources of interference.

The variables involved in colocation design are the basic performance of the individual radios, the minimum isolation between individual antennas in the antenna system, and the improved performance obtainable from such add-on devices as narrowband tunable bandpass filters. The use of such filters in the antenna lead of the radio improves rejection of nearby signals for receivers or provides greater attenuation of spurious outputs from transmitters. The following paragraphs discuss the effects that must be taken into consideration when designing a colocated system.

Transmitter-Transmitter Intermodulation

When two transmitters radiate simultaneously using closely spaced antennas, some signal from each is cross coupled into the opposite antenna. The transmitted signal and the cross-coupled signal interact in the nonlinearities of the transmitter output stages and produce many spurious products. For the usual system, the most important is given by:

$$f_s = 2f_1 - f_2$$

where

f_s – frequency of the spurious product
f_1 – frequency of transmitter *1*
f_2 – frequency of transmitter *2*.

This is a third-order product, but in general many other products are generated given by the general term:

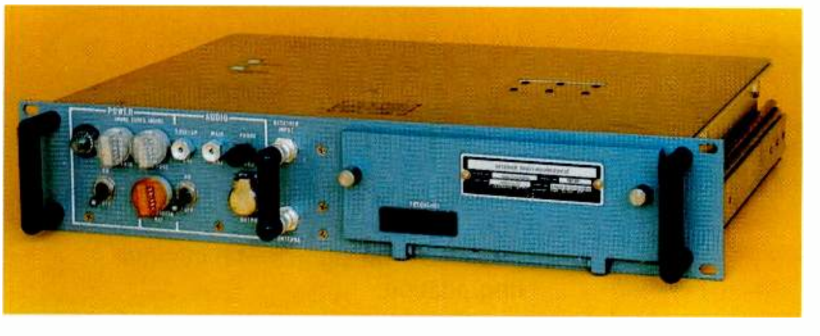
$$f_s = mf_1 + nf_2$$

where m and n are positive integers. The order is given by $(m+n)$.

The third-order term represents the worst case. The level of the third-order intermodulation products for an ITT air traffic control communication transmitter is at least 40 dB below the generating transmitter's carrier level when the coupled carrier from the adjacent transmitter is 20 dB below the generating transmitter's carrier. Furthermore, the value of 40 dB increases by 1 dB for every dB increase in the 20 dB value.

Receiver desensitization caused by front-end overload. High level signals entering a receiver from a colocated transmitter can cause receiver front-end circuits to saturate and reduce the receiver's sensitivity. ITT air traffic control receivers will accept a −10 dBm signal without significant saturation desensitization.

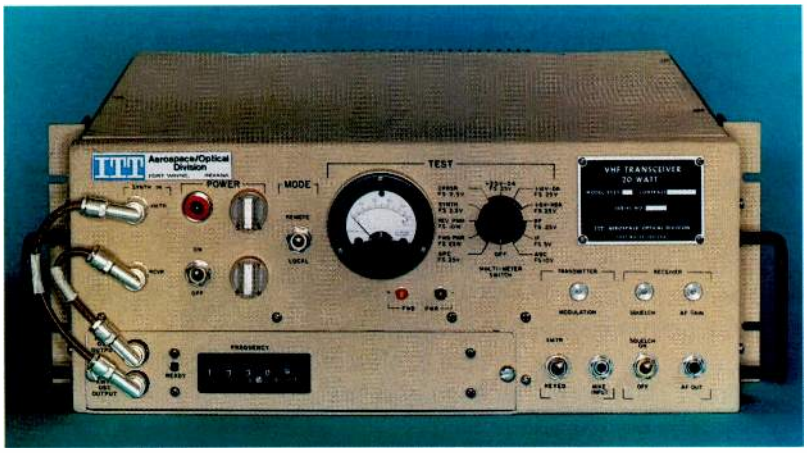
Receiver desensitization caused by transmitter wideband noise and receiver local oscillator noise. These two effects are treated together because they are, in most cases, difficult if not impossible to observe separately. They occur because both the signal from a colocated transmitter and the receiver local oscillator are not spectrally pure but exhibit components that extend from the desired carrier out to several tens or hundreds of MHz on either side. Noise from the transmitter enters the adjacent receiver and masks the desired signal. Local oscillator noise is transferred to the intermediate frequency pass band by mixing with strong off-channel signals impinging



VHF/UHF receiver.

on the receiver front end. This again masks the desired signal. For ITT air traffic control radios, a total transmitter-to-receiver isolation of 24 dB at UHF and 30 dB at VHF is required for satisfactory operation at frequency separations of 7 MHz and 3 MHz, respectively.

Receiver crossmodulation. This occurs when a strong off-channel signal interacts with the desired signal in the receiver front-end circuit nonlinearities. As a result of this interaction, the interfering signal's amplitude modulation is transferred to the desired signal and reduces the resultant signal-to-noise ratio. The effect is often difficult to observe due to desensitization caused by transmitter and local oscillator noise. In most cases, measures taken to eliminate front-end overload and noise desensitization also ensure that crossmodulation is insignificant.



VHF/UHF transceiver.

Receiver intermodulation. This is similar to transmitter-transmitter intermodulation. In this case, signals from two transmitters interact in the receiver front-end nonlinearities to produce the worst case signals:

$$f_s = 2f_1 - f_2$$

where

f_s – spurious signal frequency

f_1, f_2 – two interfering transmitter frequencies.

Interference occurs in the receiver when f_s equals the tuned frequency of the receiver. The ITT receiver is designed to withstand two −10 dBm signals with minimal degradation.

Transmitter harmonics and spurious outputs. When a spurious transmitter output coincides with a receiver tuned frequency, desensitization results. In ITT's air traffic control equipment all harmonic and spurious outputs are at least 80 dB below the carrier.

Receiver spurious responses. Because of the nonlinear characteristics of receiver front-end circuits, especially the mixer, a receiver will respond to signals at frequencies other than that to which it is tuned. In ITT air traffic control equipment, all spurious responses are at least 80 dB below the desired response.

RF System Design for Colocation

If adequate care is taken over frequency management, it is possible to select channel assignments that cause receiver and transmitter intermodulation products to fall at unused channel frequencies. Further reductions in frequency spacing can be obtained by using more selective filters, or by improving the basic performance of the radios.

Another possibility is to increase the spacing between adjacent antennas. This is considered impractical because the isolation increases very slowly with spacing beyond 100 feet (30 m) and the building land requirement as well as cable losses would be prohibitive.

Current Operational Systems

Over the past few years the United States Government has undertaken a comprehensive programme to modernize fixed ground radio communication equipment, the primary aim being to replace vacuum tube hardware with solid-state devices. ITT has played a major part in this programme for the United States Military Departments and the Federal Aviation Agency by developing and producing equipment that combines high performance and reliability with ease of maintenance. These new equipments, which set the standard for air traffic control, are in worldwide use at United States military bases and air traffic control installations; approximately 100000 receivers, transmitters, and transceivers are operational on a worldwide basis.

Transmitters

Transmitters were developed using solid-state technology, high quality components, and rugged construction to ensure high technical performance. The AN/GRT-21 (VHF) and AN/GRT-22 (UHF) equipments are used for dependable voice and data links for both civil and military users. These units are available in 10 W and 50 W configurations; both have excellent colocation characteristics, allowing operation in dense signal environments. Table 1 summarizes the performance of the 50 W configuration.

Receivers
The AN/GRR-23 (VHF) and AN/GRR-24 (UHF) receivers incorporate solid-state devices and high quality components; they are also ruggedly constructed. These features ensure continuous high performance and reliability under the most severe air traffic control conditions. Narrow front-end selectivity and a high level signal handling capability meet the stringent colocation requirements. Table 2 summarizes the receiver performance.

Table 1 — VHF/UHF transmitter performance

Frequency range	VHF – 116 to 149.975 MHz UHF – 225 to 399.95 MHz
Channels VHF UHF	680 (50 kHz) 1 360 (25 kHz) 3 500 (50 kHz) 7 000 (25 kHz)
Stability	0.001 %
RF power output	
Solid-state exciter	VHF 10 W carrier minimum UHF 10 W carrier minimum
Linear amplifier	VHF 50 W carrier minimum UHF 50 W minimum
Carrier noise	45 dB below 90% modulation
Harmonics	80 dB below carrier
Intermodulation	40 dB below for 20 dB coupling at 0.5 MHz (VHF) or 1 MHz (UHF)
Modulation capability	90% amplitude modulation, – 35 to + 10 dBm input
Distortion	15% maximum at 90% modulation
Audio frequency range	0.3 to 6 kHz (voice) 0.3 to 25 kHz (data)
Primary power	105/120, 210/230 V AC ± 10% (47 to 420 Hz) Exciter only 24 to 30 V DC
Operational temperature range	– 29 °C to + 60 °C
Storage temperature range	– 62 °C to + 71 °C

Table 2 — VHF/UHF receiver performance

Frequency range	VHF – 116 to 149.975 MHz UHF – 225 to 399.95 MHz
Channels VHF UHF	680 (50 kHz). Optional: 1 360 (25 kHz) 3 500 (50 kHz). Optional: 7 000 (25 kHz)
Stability	0.001 %
Sensitivity	10 dB signal-plus-noise to signal ratio at 3 μv, 30% modulation
Audio frequency range	0.3 to 3 kHz (voice)
Audio outputs (2)	100 mW (600 Ω)
Audio hum and noise	50 dB below 100 mW
Harmonic distortion	10% maximum at 30% modulation
Automatic gain control range	6 μv to 1 v (± 3 dB)
Image rejection	80 dB minimum
Spurious response	80 dB minimum
Selectivity	± 18 kHz (6 dB) 50 kHz channel spacing ± 9 kHz (6 dB) 25 kHz channel spacing
Squelch	Adjustable, 3 to 50 μv
Primary power	105/210, 120/250 V AC ± 10% (47 to 420 Hz), 22 to 30 V DC
Operational temperature range	– 29 °C to + 60 °C
Storage temperature range	– 62 °C to + 71 °C

Multichannel Equipment
FA 8190 (VHF) and FA 8191 (UHF) solid-state 20 W synthesized, remotely controlled, multichannel transceivers provide the colocation performance demanded in high signal density air traffic control areas. These units were specifically developed for the United States Federal Aviation Agency for backup emergency communication to provide positive continuity of communication during major outages of primary equipment caused by power line or equipment failure. The performance of the backup emergency communications transceiver is similar to the transmitter and receiver performances given in Tables 1 and 2.

ITT Aerospace/Optical Division's REFLEX radios are a derivative of the single-channel receivers (AN/GRR-23, -24) and single-channel transmitters (AN/GRT-21, -22). The REFLEX modification introduces full electronic tuning while maintaining many of the desirable features of the single-channel equipment. Electronic tuning allows full remote control of the radios via direct wire connections or via standard telephone lines.

Future Ground-Air Communication Requirements

The movement of passengers and cargo by air is rapidly expanding. However, the air corridor space and radio frequency spectrums that must support this expansion are fixed. Management of air space and the frequency spectrum have thus become major factors in ensuring the safe and orderly growth of air traffic. This expansion will be realized in concert with three primary goals of the air traffic control system: increased safety, increased efficiency, and increased productivity of individual controllers. In addition to these goals, the cost of operating air traffic control systems will have to be minimized. This cost pressure will probably lead to fewer operational sites and more equipment per site[3].

As the system evolves, increased automation will affect ground-to-air radios. This will require computer interfaces in the radios along with improved colocation performance because there will be more equipment at fewer sites. The critical question in designing the air traffic control system of the future is not what can be done, but what should be done. Exactly how much and what kind of automation should assist or replace the human controller. Once the system has been designed, then the concern becomes how it should be implemented. All this means that new air traffic control ground-to-air radios will need improved control flexibility and improved colocation capabilities[4].

A number of projects underway at ITT Aerospace/Optical Division are designed to meet the challenge of the new air traffic control system. A sophisticated remote control system has been developed which is compatible with computer automation. This can control radios from any distance via compatible telephone interface circuits. It permits complete control of any radio at any location giving the flexibility necessary for a future air traffic control system. The microprocessor control circuits give it flexibility for future changes and requirements. Control units that interface with telephone lines are available for direct wire connections to radios for local control.

ITT Aerospace/Optical Division is also engaged in improving the colocation performance of receivers and transmitters. One development is the electronically tuned bandpass filter which can switch between channels within a few microseconds. It has a 2% 3 dB bandwidth and is capable of handling transmitter powers of up to 120 W. This filter is suitable for both transmitters and receivers.

Other development projects include a reduction in the broadband noise generated in transmitter RF circuits. Lowering the noise floor will reduce receiver desensitization in a colocated environment. Improvements of up to 20 dB have been made and are being studied prior to implementation.

Developments other than those directly related to colocation improvement work include the development of built-in test and remote monitoring circuitry. The use of microprocessors, along with key test points, makes it economically feasible to provide the above features in the next generation radios. These circuits will be able to monitor and analyze radio performance on a continuous basis, without affecting its performance or operation, and send the performance data to a central depot or maintenance facility where appropriate maintenance action can be initiated. These features will significantly reduce maintenance and support costs.

Remote control unit.

Conclusions

Worldwide aircraft passenger and cargo volumes are rapidly increasing whereas the air corridors and radio frequency spectrum that support them are fixed. Fortunately rapidly changing electronic technology makes it possible to design higher performance radio systems to resolve this conflict. Inherent fault isolation and quality monitoring indicators will become features of the next generation equipments, minimizing downtime and reducing maintenance and operating costs.

Management of airspace and the frequency spectrum will require continuing research and development of air traffic control communication technology to maintain and improve the enviable passenger air safety record.

Acknowledgment

The author extends his thanks to Dr William Robertson of ITT Aerospace/Optical Division, Fort Wayne, Indiana.

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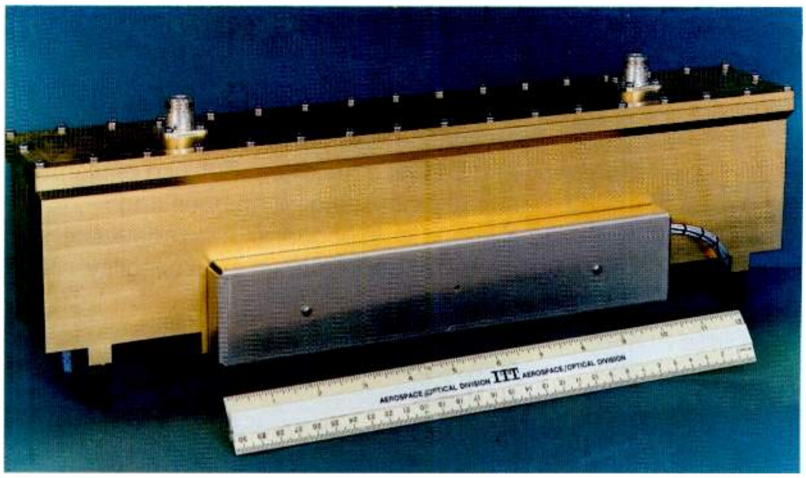


UHF electronically tuned filter.

D. W. Walters was born in Indiana, USA, in 1934. He received his BSc in electronic engineering from Purdue University in 1956, and an MSBA from St Francis College in 1981. Mr Walters joined ITT in 1956 where he is engaged in the development of VHF/UHF air traffic control communication equipment. He is at present manager of the air traffic control engineering department at ITT Aerospace/Optical Division.

System 4000 Navigation Aids

System 4000 is a new generation of navigation aids which includes ILS, VOR, and DVOR equipment. Full use of digital signal processing techniques and microprocessor control has produced excellent performance and reliability.

H. Kleiber
N. Knoppik
H. Vogel
Standard Elektrik Lorenz AG, Stuttgart, Federal Republic of Germany

Introduction

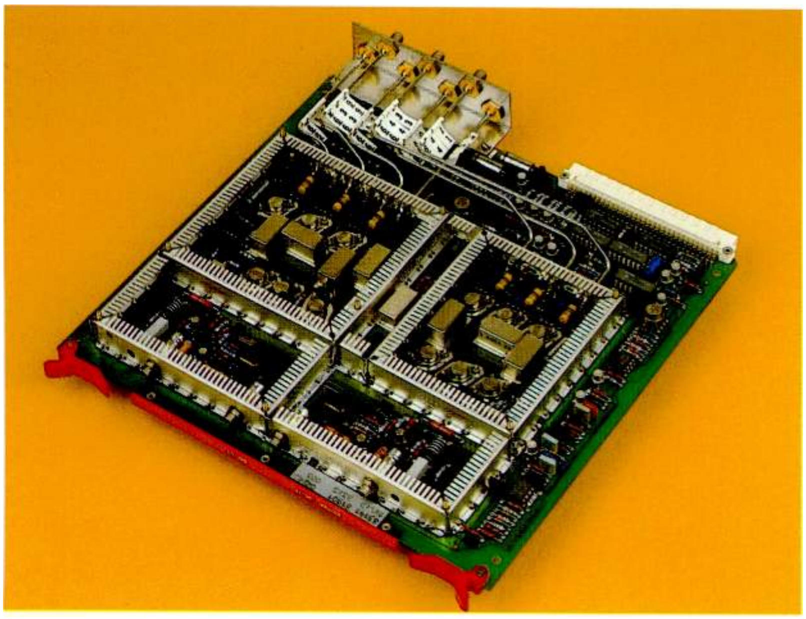
System 4000 is a new generation of air navigation aids which includes ILS (instrument landing system), VOR (very high frequency omnidirectional radio range), and DVOR (Doppler VOR).

ILS, the internationally approved landing aid, offers course and glideslope guidance. It was standardized in 1952 and will continue until 1995. Each ground station transmits signals via a VHF course transmitter for linear horizontal guidance, and via a UHF glideslope transmitter for nonvariable vertical guidance to the touchdown point. On board the aircraft, a crosspointer instrument indicates lateral deviations from the approach course as well as any deviation from the desired glideslope.

VOR is internationally used for navigation on medium-range flights and in the terminal areas. Standardized by ICAO (International Civil Aviation Organization) in 1960, its use as a standard navigation aid is planned to continue until 1985, with an expected extension until beyond the year 2000. The functional principle of VOR is based on a ground station transmitting signals from which the airborne equipment derives a visual indication of the course deviation between the actual aircraft track and the azimuth selected by the pilot.

Doppler VOR – a wide aperture system – is employed if conditions on the ground (unfavorable terrain and the presence of many obstacles which could cause spurious signals) are such that a standard VOR ground station would give erroneous readings. As far as the onboard equipment is concerned, VOR and DVOR signals are equivalent. Although the method of generating and radiating navigational signals is different, DVOR is completely compatible with the conventional VOR system.

System 4000 radio frequency module.



Main Design Features

Based on SEL's long experience with air navigation aids, a number of basic requirements were specified for the System 4000 family, including:

- wide use of microprocessor technology
- automated operation
- built-in test equipment with fault location
- even higher reliability than the previous model
- modular construction
- reduced lifecycle costs.

The most important of these is the use of microprocessors since it influences the other design criteria. These are used to

Table 1 – Main parameters of modern navigation aids

Specific parameters		VOR	Doppler VOR	ILS localizer	ILS glideslope	Range of parameters
Radio frequency range (MHz)		108 to 117.975		108 to 112	328.6 to 335.4	108 to 118 and 325 to 340
Carrier power (W)		25 to 100		20 to 25	10 to 15	25 to 100
Modulation frequencies (Hz)		9960	30	90.150		30 to 9960
		1020		1020	—	
		300 to 3000		(300 to 3000)	—	
Modulation depths	Navigation signals %	30		2 × 20	2 × 40	5 to 85
	Identity %	10		5 to 15	—	
	Voice %	20 to 30		(20 to 30)	—	
Modulation sum (carrier) %		60 to 70		45 to 55 (65 to 85)	80	
Monitoring	Input	RF		RF		Field strengths
	Level	30 Hz, 9960 Hz (1020 Hz)		RF, 90 Hz, 150 Hz		Modulation signal levels
	Phase	Reference/variable		—		Bearing

control equipment functions, thereby simplifying and automating operation and maintenance, and to generate all sinusoidal modulation signals and control the amplitudes and phases of the RF (radio frequency) signals. By using digital technology, analog circuits with their critical adjustments have been eliminated, with a consequent improvement in the quality and long-term stability of the radiated signals.

System 4000 Concept

The main components of the ILS and VOR systems are the antenna system and dual transmitters, monitors, and power supplies. The standard signals for VHF/UHF navigation systems are summarized in Table 1.

Signal quality is particularly significant for the ground error component of system accuracy. Signal quality depends on several parameters:

- phase and frequency stability of the modulation frequencies
- stability of the carrier and sideband amplitudes
- phase and frequency stability of the RF signal
- distortion of the modulation waveforms
- stability of the depth of modulation.

The use of digital components, such as microprocessors and memory and analog/ digital converters, simplifies partitioning of the hardware and software into modules.

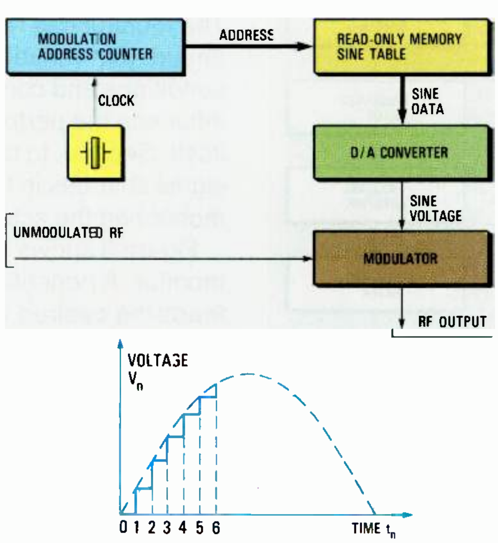


Figure 1
Signal generation concept for System 4000.
D/A - digital/analog

Signal Generation Concept

As already mentioned, excellent navigation signal accuracy and stability are required. Advances in semiconductor technology allow cost-effective generation of tone modulation signals which can be called up from a stored sine table, as shown in Figure 1. A crystal oscillator clock controls an address counter which calls the allocated

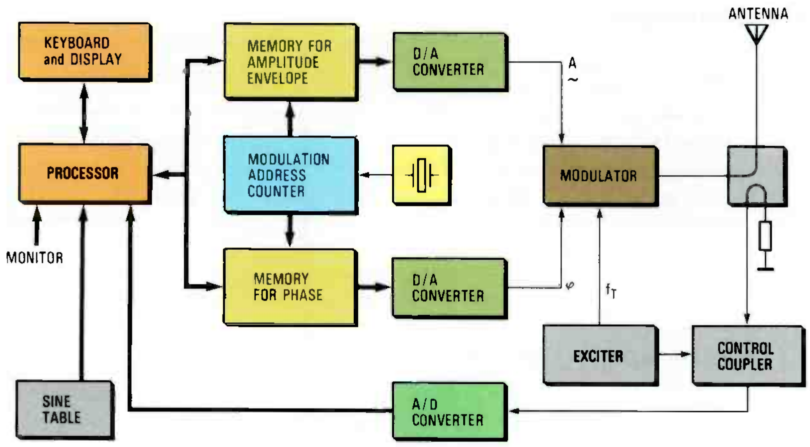


Figure 2
Concept of System 4000 transmitter showing how the sideband signal is generated using digital techniques.

amplitude value from read-only memory. The amplitude values, presented in binary form, are converted into analog form to produce a sine shaped voltage for envelope modulation of the RF signal. Using such an arrangement the tone frequency can be selected by changing the clock frequency.

To minimize the roughness of the stepped sine waves, a sufficient number of stored amplitude values and a high enough amplitude resolution are needed. For ILS, 1024 addresses are required for a 30 Hz sine half-period, with 10-bit resolution of amplitude.

Figure 2 shows how the sideband signal is generated using digital techniques; no analog filters are used and no circuit adjustments are required[1].

Audio signal generation is realized by the clock generator, address counter, and sine table, as already mentioned. In addition, the equipment data processor and an A/D (analog/digital) converter with translator are important components. These additional components allow control of the amplitude and phase of the RF signals, using random access memory for storing the control values. The values are calculated from the nominal values given by the processor, the fed back digitized actual values, and the existing control values. The translator delivers the envelope curve which has been demodulated by a precision demodulator, and the so-called *zero IF signal* to the A/D converter. The zero IF (intermediate frequency) signal is generated as a mixture product from the decoupled transmitter output signal and a reference output from the control oscillator. By shifting the reference output in phase quadrature a mixture product $u_s \cdot \sin \Phi$ and $u_s \cdot \cos \Phi$ is obtained from which the RF phase can be derived using an *arc-tan* calculation under the control of the processor. This process is continuous.

The above procedure is valid for sideband signals. For carrier signals, however, tone modulation signals for speech and the station identity must also be considered. Digital control using the equipment processor is not technically feasible owing to the quasistatistical nature of speech signals. In this case the analog signal is fed back directly to the modulator. Generation of the carrier modulation signal also uses sine tables; the modulation factors are set via the processor data bus. Multiplying D/A converters are used as control circuits.

The equipment processor not only controls the transmitter signals but also evaluates monitor signals; thus results can be displayed on request in the same way as transmitter data.

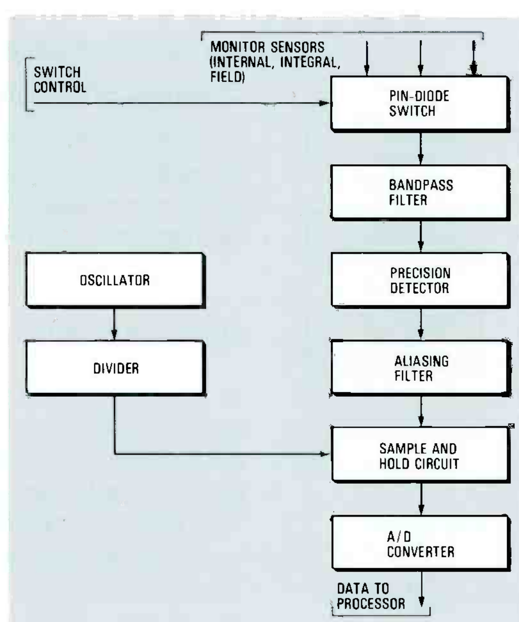


Figure 3
Monitoring concept for the Sytem 4000 family of navigation aids.

Monitoring Concept

The monitor has two functions. First to ensure that variable environmental conditions and component aging do not influence the performance of the monitor itself. Second, to detect impermissible signal changes in the radiated field by monitoring the actual field signals.

Figure 3 shows the concept of the ILS monitor. A noncritical high frequency filter feeds the desired VHF carrier frequencies to the sample and hold circuit. The demodulated envelope is sampled 32 times during a cycle of 30 Hz, and the sampled amplitude values are then digitized. These signals are separated into the modulation components (90 and 150 Hz) in the equipment processor by Fourier analysis and the signal parameters (modulation depth, RF level, etc) are calculated and compared to programmable alarm limits. The critical 90 and 150 Hz filters which were previously necessary have been eliminated. The VOR monitor also utilizes discreet Fourier transformation of 32 sampling values during a 30 Hz period; in addition, an FM (frequency modulation) discriminator is provided for the reference signal[2].

Equipment Design

Figure 4 shows the main functional modules of the System 4000 family, including the dual transmitters with modulation signal generators, dual central processing units and monitor signal processors, keyboard and display, and dual power supplies.

As mentioned before, many of the ILS and (D)VOR functions can be realized in the same basic manner, making it possible to use a modular design with common modules for the different systems. In particular, microprocessor control allows common transmitter modules to be used with the actual functions being determined by the software. Automatic monitoring, and control and display of operational status also use microprocessor techniques.

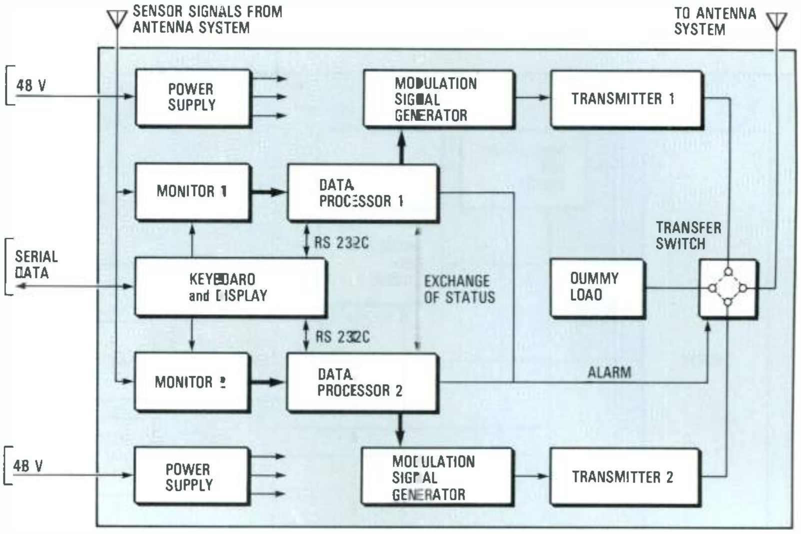


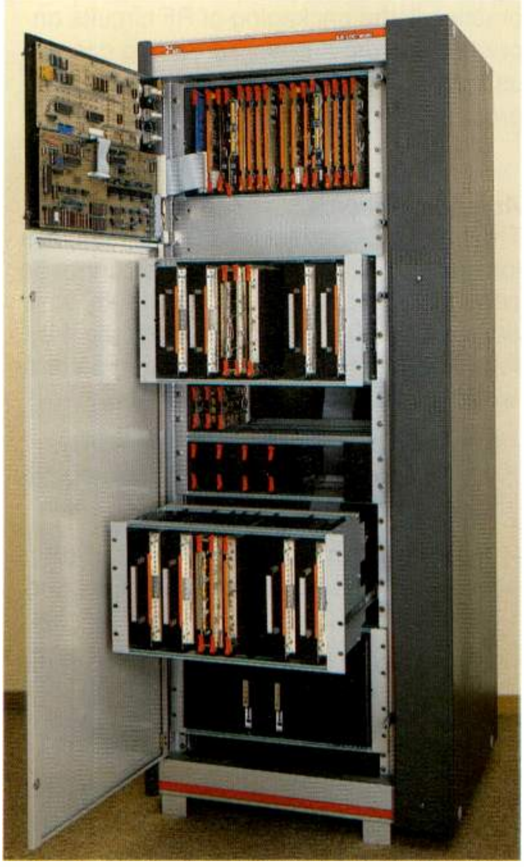
Figure 4
Dual transmitter concept.

The block diagram of a dual ILS localizer 2F system (Figure 5) illustrates the basic equipment design for the various systems.

The signals from the crystal controlled exciter (functions and number of channels adapted to the requirements of VOR, DVOR, or ILS) are amplified by a modulator module. For the carrier signal, the modulator output power is increased by 10 dB using an amplifier module rated for 25 W continuous wave and 80 W peak emitted power. A 100 W transmitter power is achieved by connecting four amplifiers in parallel; a fifth amplifier drives the output stage.

Crystal controlled, digitally generated audio signals modulate the RF carrier and sideband signals. The modulation signal for the carrier is provided by a carrier signal generator; sideband modulation signals are generated by the sideband signal generator. The modulation clock generator provides control signals for the carrier signal and sideband signal generators.

A microprocessor, equipment data processor, and memory extension form the basis for equipment control and digital signal processing. Real-time discrete Fourier transformation in the monitoring process required a 16-bit central processing unit. A monitor signal processor and part of the control and transfer unit, together with the data processor and memory extension, form the monitoring system. Different sensing points allow the navigational signals to be monitored. After detection the signals are converted to a 12-bit binary word at a sampling rate of 960 Hz. Data is evaluated and in the event of an incorrect signal being detected, an alarm is displayed and switchover or shutdown is initiated automatically.



System 4000 transmitter cabinet.

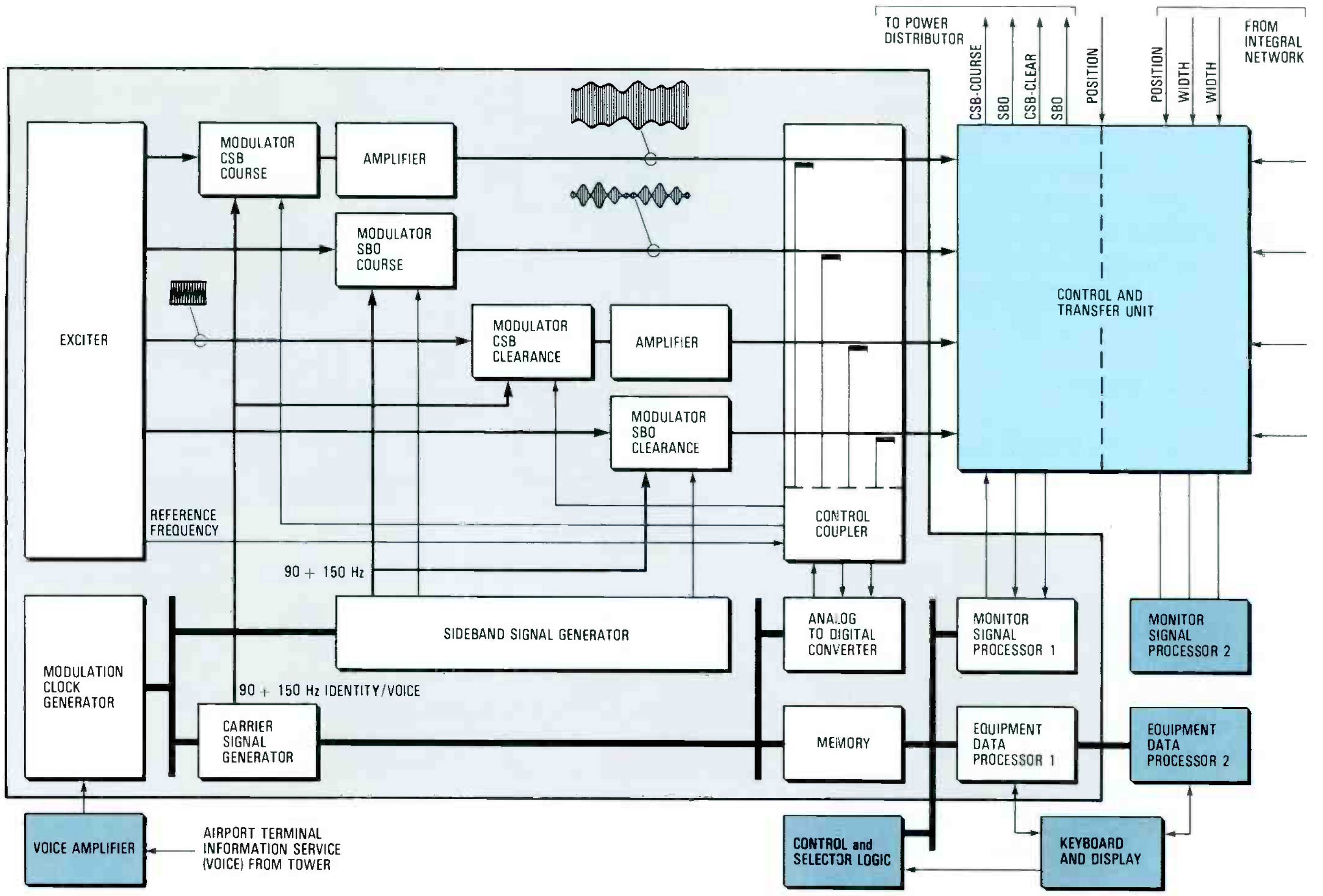


Figure 5
System 4000 block diagram.

The keyboard and display are used to enter data, indicate data and measured values, and display system status and performance. Remote control is possible via a V.24 modem to an additional keyboard and display unit in the maintenance center. All functions are controlled by a microprocessor with a 40 kbyte memory.

All System 4000 transmitters employ a keyboard and display together with the following subracks housed in a 19 inch (483 mm) cabinet: audio frequency subrack, two RF subracks (SBR-D/F), a subrack for the voice amplifier, modem, etc, and a power supply subrack. The transmitter amplifier is in a separate side compartment.

Integration of dual equipment into a single 19 inch rack means that the power dissipation is high despite the use of microelectronics. Efficient maintenance required the elimination of blowers within the rack, even in the case of 100 W output power per equipment. Thus the equipment practice is designed to optimize the flow of air; additional transmitter power amplifiers are mounted on a large heatsink in a separate cabinet, achieving a power dissipation of 500 W without blowers.

A feature of the System 4000 equipment practice is the packaging of RF circuits on printed boards. A novel screening concept using springy sheets made by an etching process simplifies manufacture.

Antenna Systems

The antenna systems for VOR, DVOR, ILS localizer, and the ILS glideslope cannot be constructed from common elements, as is done for the transmitters. In principle the following horizontal aerial radiation patterns are required:

- omnidirectional pattern for the VOR carrier signal and the DVOR carrier and sideband signals
- figure-of-eight pattern with exact 6 dB beamwidth at 90° for the VOR sideband signals
- conventional bidirectional pattern for the ILS localizer course signal
- V-dipole patterns for the ILS localizer clearance signals
- specially formed antenna pattern for the ILS glideslope signals.

To meet these requirements, the following radiators have been provided:

- Alford loops for the omnidirectional pattern
- magnetic dipoles for the figure-of-eight pattern
- $\lambda/2$ dipoles for the conventional bidirectional pattern
- V-dipoles for the "filled in" bidirectional pattern
- staggered dipole arrays for the specially formed pattern.

The required antenna systems are built using these elements.

The VOR antenna is designed to minimize the vertical signal component and to achieve an angle for the cone of silence (cone of confusion) of less than 60°. It consists of two crossed slotted magnetic dipoles for the sideband radiation and two Alford loops for carrier radiation. The Alford loops are arranged above and below the slot antennas. Horizontal screens between the magnetic dipoles and the loop elements prevent interaction. All the elements and the screens are mounted on an extruded aluminum tube which is fixed to the solid counterpoise. This tube forms the axis of symmetry of the antenna system[3].

The DVOR antenna system, which consists of 50 Alford loops on a 13 m circle for true double-sideband radiation with one Alford loop in the center for carrier radiation, employs minimum aerial crosscoupling to avoid distortion of the desired omnidirectional pattern. A special decoupling module directly in front of the antenna feed decreases crosscoupling by a reactance transformation and by feeding some energy to the next but one element. This concept minimizes crosscoupling of the sideband elements and ensures that the transmitted frequency spectrum complies with ICAO Annex 10 requirements[4, 5].

New aluminum profiles make it possible to use a modular construction with a variable baselength to build the various ILS localizer antenna versions.

Operation and Maintenance

Special consideration was given to the interface between operator and equipment. Since all control values and all variable data can be altered via the processor data bus, and as a variety of analog test signals and discrete data are measured in time multiplexed mode for both the control loop and the BITE (built-in test equipment), the processor memory stores full data for the evaluation of transmitter status. As monitoring is also controlled by the microprocessor, the monitor status and the values of the monitored signals with the corresponding alarm limits are stored in the processor memory[6].

The keyboard and display shows status and measured data values. Data is entered via an ergonomically designed keyboard, and is displayed on two alphanumeric readouts with 16 characters each. With the aid of ITTE ESC, Harlow, and the German Civil Aviation Authority, a novel display concept was worked out; only the current status is shown and nonrelevant displays are unlit and therefore not visible.

During on-site installation and commissioning of the system, the BITE and monitor allow adjustment of the antennas without the need for external measuring equipment. After antenna adjustment for the complete system (antenna and transmitter) the parameters are programmed to the individual local requirements (i.e. sideband power level, RF phases, etc). The final setting of data, which is done during the commissioning flight, can be programmed at the remote control center (in the maintenance area).

System 4000 antennas: from left to right these are VOR, DVOR, ILS localizer, and ILS glideslope.

As already mentioned, data transfer from the local keyboard and display to the remote one is via an RS232C serial interface, using frequency shift keying with a 2-wire line. From one equipment in the remote central site up to seven facilities can be interrogated in time multiplex mode. In the event of an alarm, the main alarm status signal in the central maintenance station is set automatically. At the local site, the equipment data processor checks the BITE signals continuously; in the event of an equipment fault the BITE routine detects the faulty module. Maintenance personnel obtain the information by pushing the corresponding keys in the operational data field of the keyboard and display. Replacement of the detected faulty module by a spare module can be carried out without the need to make measurements on site. No adjustments are required after changing modules. Automatic dial-up service is possible for VOR/DVOR using additional optional hardware. The concept of equipment control by microprocessor reduces commissioning and maintenance to a minimum.

Conclusions

The new generation System 4000 navigational aids have been developed in close cooperation with West Germany's Federal Authority for Flight Safety with the support of the Federal Ministry of Research and Technology. Modern technology combined with high reliability and system integrity ensure that this new navaids family will serve aviation till the end of the century.

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Herbert Kleiber was born in Neutitschein, CSR, in 1942. He attended Gesamthochschule Kassel and graduated as a Dipl-Ing. He joined SEL in 1966 as an R & D engineer and worked on the development of navigational systems. Since 1979 he has been project engineer for Navaids System 4000 and is responsible for civil navigation ground equipment.

Norbert Knoppik was born in 1944 in Henzegrund, Lower Silesia. He graduated in telecommunication engineering from the Technische Hochschule, Aachen. He holds a Dipl-Ing and received a Dr-Ing for research in millimeter-wave technology. Dr Knoppik joined SEL in 1982 and is the RD & E manager for avionics, navigation, and surveillance. He is a member of VDE/NTG.

Horst Vogel was born in Stuttgart, Germany, in 1936. He studied communications engineering in Esslingen and graduated as a Dipl-Ing. He joined SEL in 1962 and was active in the fields of large computers, Tacan, and civil navigation. In 1967 he became development manager for avionics and then in 1976 he was appointed chief engineer for civil navigation, responsible for all development activities in this field. In 1983 he took over as program manager in which capacity he supervises large scale SEL projects.

Hardware and Software Structures for System 4000 Navigation Aids

The application of digital techniques to controlling and monitoring the System 4000 family of navigation aids enables ILS, VOR, and DVOR functions to be realized using common hardware and software modules.

F. Limbach
K. Pählig
Standard Elektrik Lorenz AG, Stuttgart, Federal Republic of Germany

Introduction

A standard navigation system such as VOR (very high frequency omnidirectional range), DVOR (Doppler VOR), or ILS (instrument landing system) consists of dual transmitters, antenna systems, and dual monitors. Figure 1 shows the configuration for the System 4000 family of navigation aids, including the control and monitoring functions.

In System 4000, the control and monitoring functions are clearly separated from each other (Figure 2). While the monitor bus works continuously during normal system operation, the transmitter control bus need not be used if the corresponding transmitter is switched off. The transmitter control bus is used to carry out all I/O (input/output) operations necessary to initialize the transmitter control logic and transfer the modulation signal waveforms. It is also used for digital adjustment of sideband signal curves and RF (radio frequency) sideband phases. The processor has direct access to transmitter parameters such as carrier power, modulation depth, built-in test equipment signals, and some other control functions, but has no direct access to the independent MSG (modulation signal generator) bus. The memories of the MSG, which contain the modulation envelope curves, the parameters to control RF sideband phases, and the station identity morse code, can be read or written only via an interface. Data transfers are carried out using handshake procedures with the ECPU (equipment central processing unit) as the active partner.

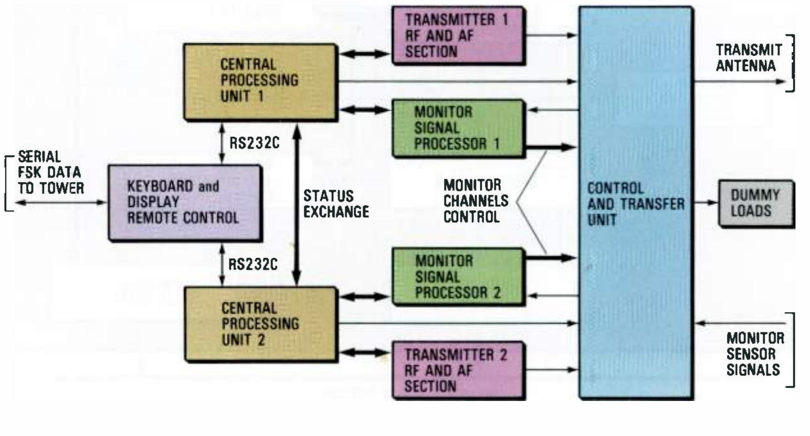


Figure 1
Block diagram of a dual equipment Navaids System 4000.
AF - audio frequency
FSK - frequency shift keying.

Modulation Signal Generator

The MSG and its bus system appears to the ECPU as an I/O subsystem decoupled from the central processor and working independently (Figure 3). Amplitude and phase memories are loaded from the CPU when the transmitter is switched on, or during monitoring. Normally the operator selects test mode, adjusts the equipment for correct operation, and then switches the test mode off to allow the monitors to take control.

The MSG random access memory is written with defined values during transmitter initialization. The bus control unit of the MSG cyclically reads these values and transfers them to D/A (digital/analog) converter registers. Thus, in the case of an ILS station the following five quasiparallel signals are generated:

– $K90 * \sin(2 * \pi * 90 * t) + K150 * \sin(2 * \pi * 150 * t)$ for amplitude modulation of the course and clearance carrier transmitter

– $Ki * (\sin(2 * \pi * 90 * t) - \sin(2 * \pi * 150 * t))$ for envelope modulation of the course sideband transmitter

– appropriate RF phase control voltage

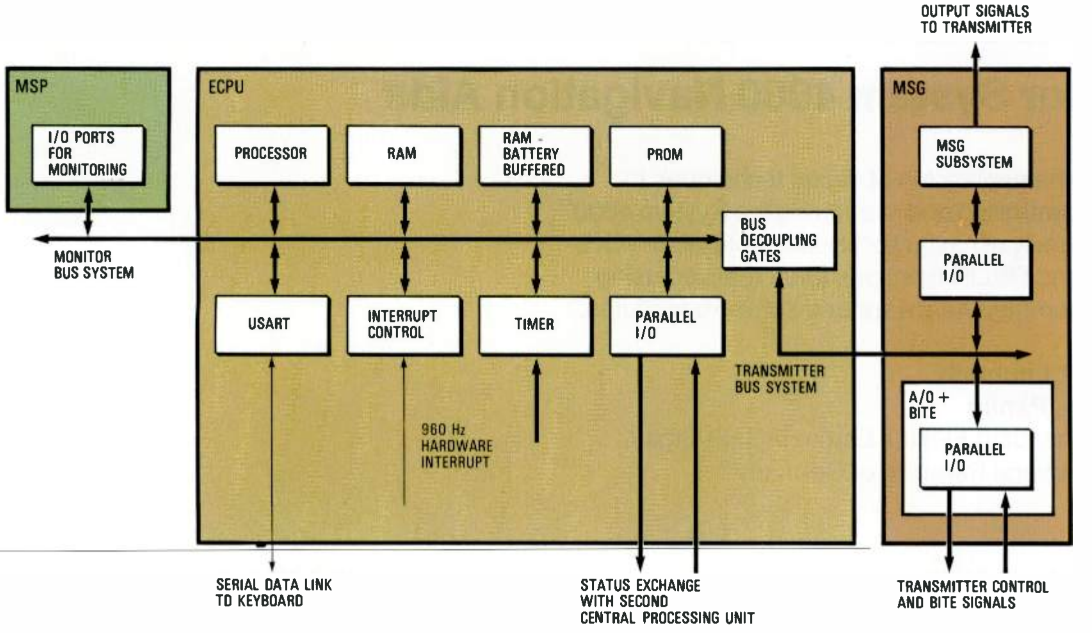


Figure 2
Simplified block diagram of the System 4000 control and monitoring equipment.
A/D - analog to digital
BITE - built-in test equipment
MSP - monitor signal processor
USART - universal synchronous-asynchronous receiver-transmitter.

– $K2 * (\sin(2 * \pi * 90 * t) - \sin(2 * \pi * 150 * t))$ for envelope modulation of the clearance sideband transmitter.

– appropriate RF phase control voltage.

Distortion of the generated carrier signals caused by modulation can only be eliminated by analog feedback loops because of the additional modulation with voice and identity tones. However, the sideband envelopes and RF phases can be corrected by digitally controlled loops. The CPU only has to undertake this additional processing during the adjustment procedures in the test mode; program modules are provided that facilitate adjustment of the sideband levels and RF phases. In the monitoring mode, however, the main task is evaluation of the monitor sensor signals. In this mode, the processor uses otherwise inactive periods to service the keyboard. Furthermore, it adjusts the sideband envelope curves and RF phase voltages and collects data from the built-in test equipment. To accomplish this, data in the MSG memory is manipulated via the interface or corresponding actions are triggered by the MSG.

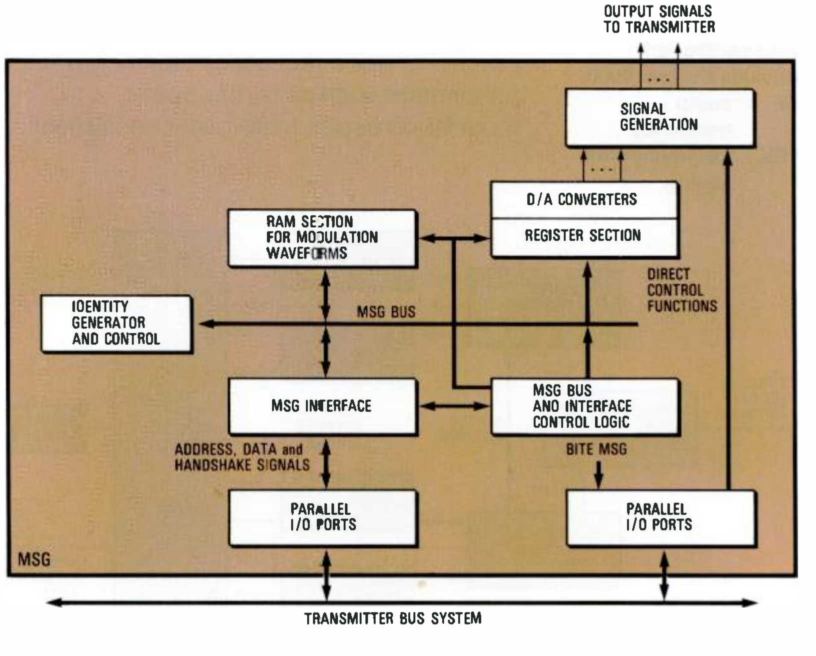
The bus control logic of the MSG provides the timing for up to eight quasiparallel analog signals with a bus access rate of 61.44 kHz, reads and transfers the station morse code, and controls data transfer to and from the ECPU. These tasks require very fast control logic which cannot be realized using standard microprocessors. However, the control functions are relatively simple, allowing the MSG control part to be built with discrete logic components.

The keyboard incorporates its own processor, primarily to serve the interface that connects the system to its environment.

Hardware Components for Monitoring

The processor controls the monitoring components directly via the monitor bus. Parallel I/O ports are used to control the RF multiplexers that select the monitor sensor signals. The demodulated monitor signals are converted into digital form and read by the processor for signal analysis. The results relating to equipment status and the self tests are exchanged by the ECPUs over the status exchange bus.

Figure 3
Block diagram of the MSG subsystem. MSG bus operations are independent of ECPU activities.
RAM - random access memory.

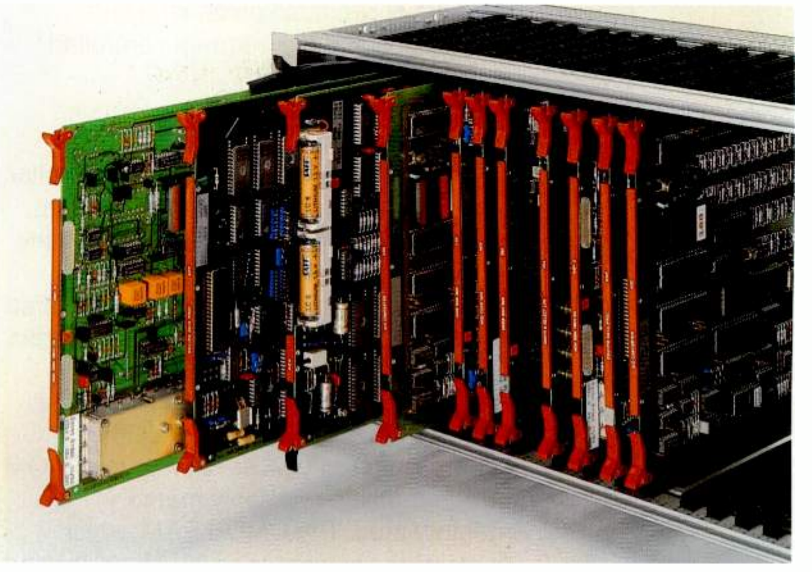


Status exchange plays an important part in checking switchover or switch-off conditions in the event of a malfunction. In addition it ensures that a defective monitor is detected and excluded from further decisions. Self-monitoring ensures that an ECPU recognizes a failure in its own monitor system or is recognized as faulty by the other ECPU. Should both monitors be defective, simple hardware logic switches the equipment off.

The configuration is shown in Figure 4. If one monitor has been brought into the *monitor fault* state, the other monitor alone decides which actions are to be taken. This status does not necessarily lead to a system shutdown as this decision still depends on the quality of the monitor sensor signals evaluated by the other monitor. However, the equipment is decategorized and the warning indicator of the keyboard main status field is set. Assuming that the faulty monitor's transmitter is in standby mode, then the main transmitter is still operating correctly. If the functional monitor detects a fault in the radiated signal, it will disconnect its own transmitter from the antenna and switch over to the other transmitter with the deactivated monitor. If the failure is in the monitor section and there are no other malfunctions this transmitter will generate correct signal outputs, thereby enabling the system to continue operating at a decategorized level. If the faulty monitor is associated with the main transmitter and there is no failure in the remaining hardware, this processor will still correctly adjust the sideband signal envelopes and RF phases. Even if the processor's hardware fails, causing a *halt*, the MSG will continue to operate. In this case, the effects of temperature on the corresponding RF section may cause incorrect sideband signal levels and RF phases. However, this is a slow process and may take hours or days to reach the defined alarm limits. Should this happen, the functional monitor switches to the standby transmitter, which is still operating correctly, and system operation continues.

The principal aim is to maintain system operation for as long as possible, even at a decategorized level, so that only fatal malfunctions cause system shutdown. The state transition diagram in Figure 5 shows the basic operational functions of the control and monitoring section in System 4000.

In the monitoring mode the system does not accept data entries which change transmitter or monitor data; in this state only the monitors are authorized to make decisions concerning the system. The operator has to switch back to test mode before he is allowed to alter transmitter or monitor data. Information on system status is still sent to the keyboard, and system parameters and measurement results can be displayed at the operator's request.

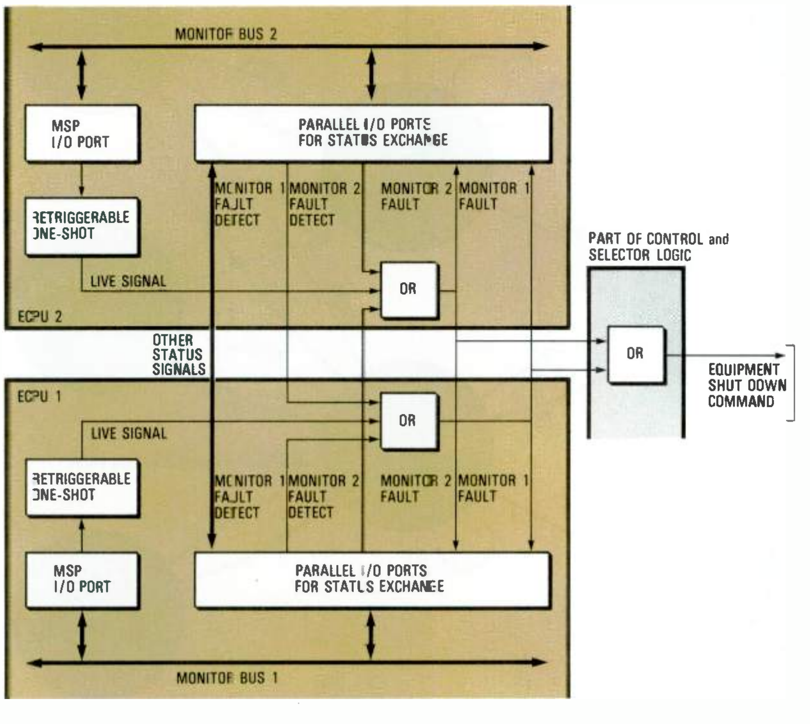


Audio frequency subrack showing typical System 4000 construction.

Software Structure

The software structure of the System 4000 ILS equipment is described here; the structures for other equipment (VOR, DVOR, and ILS glideslope) are similar. It

Figure 4 Monitor fault detection logic.



consists of two main parts: start and initialization and the interrupt controlled main program.

The start program clears the working memory area (random access memory, RAM) and initializes the interrupt controller, timers, serial interface with the keyboard, and various parallel interfaces used by the processor to control and monitor the transmitter. Next the working memory area is loaded with data that is needed for correct running of the main program and for comparing the measured and calculated values. This data is taken from either a battery-buffered CMOS RAM or the PROM (programmable read-only memory) memory area. The CMOS RAM, which contains the newest specific values, is used only if it contains three recognized test bytes at the beginning and if the sum of all used bytes equals the sum buffered at the end of the CMOS RAM. Otherwise the standard values of the PROM, that is, ICAO (International Civil Aviation Organization) Annex 10 recommended data, are used.

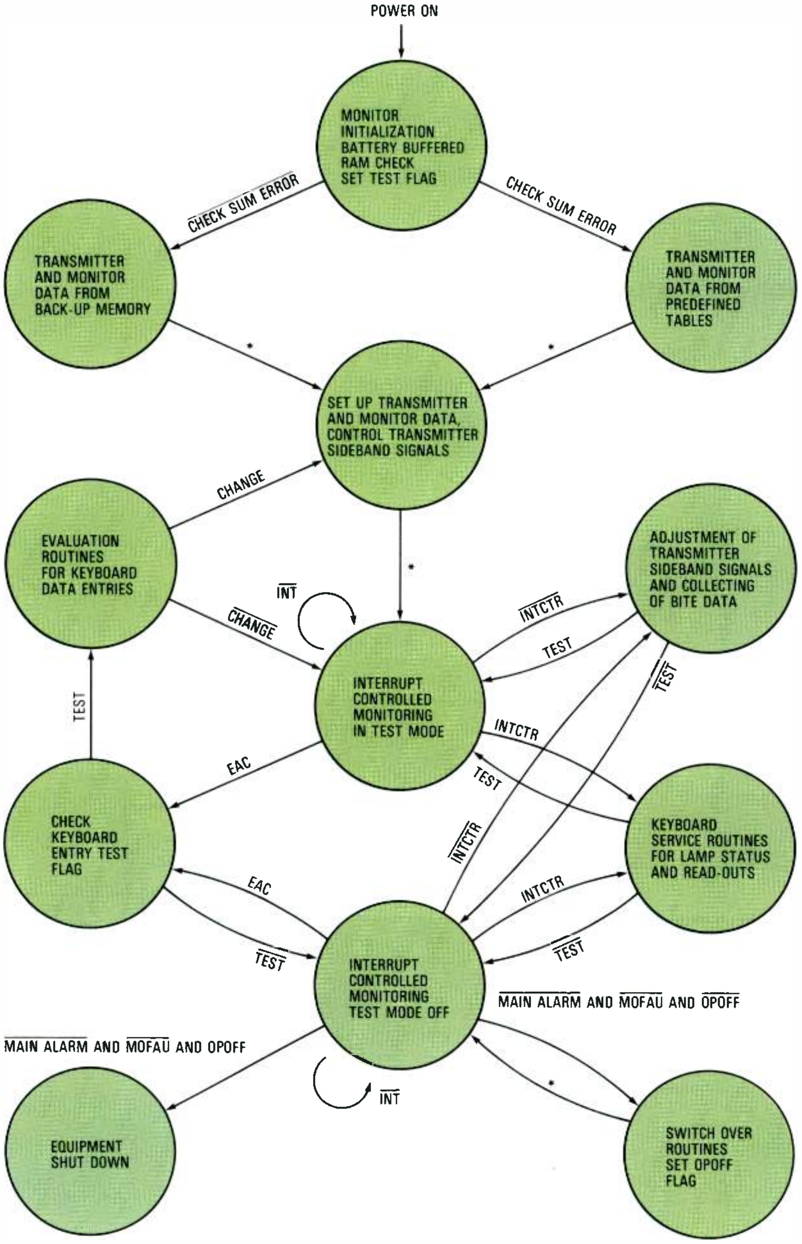


Figure 5
State transition diagram of the System 4000 transmitter and monitor control unit.
EAC - end-of-alarm check
INTCTR - condition for servicing keyboard routines
MOFAU - monitor fault flag
OPOFF - operation off flag
*** - transition without any condition.**

Main Program

The essential tasks of the main program are:

- monitoring and supervision of the equipment
- control of the modulation (amplitude and RF phase)
- operation of the keyboard and display.

The equipment is monitored and supervised by receiving measured values at each interrupt. These measured values relate to the monitoring signal of a channel, which is strobed every 1.04 ms (960 Hz), converted to digital form, and sent to a parallel interface. Each channel is activated for 41.6 ms (40 interrupts); the first eight measured values are not used, so 32 values are used for the analysis. The channels are separated into first order channels and second order or single channels, the main difference being in the time of reaction for alarms. With first order channels, two consecutive alarms cause a reaction, whereas with single channels 20 consecutive alarms are needed. First order channels are chosen six times per second and single channels only once per second. Thus first order channels react after 0.5 s at most, whereas single channels have a reaction time of 20 s. The reaction is usually a switchover or a shutdown. Alarm messages are transmitted from one equipment to the other; alarm parameter messages (indicating which values of which channel are incorrect) are shown on the keyboard display panel.

Structure

The main program, which is controlled by a 960 kHz interrupt, consists of eight program modules, all written in PL/M86. Some program modules incorporate further submodules written in PL/M86 and assembler. The submodules, written in assembler to minimize processor and memory requirements, can be used for all System 4000 equipment (ILS localizer, ILS glideslope, DVOR, VOR) without modification. The main program is controlled by a 960 Hz interrupt. The

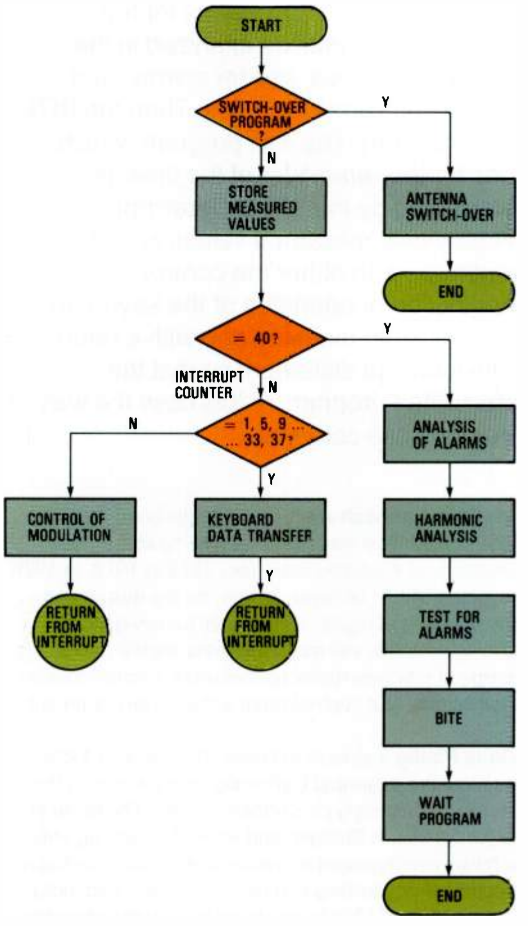


Figure 6
Flowchart of the interrupt-controlled main program.

flowchart in Figure 6 shows the program sequence and the assignment of program modules.

Program Modules

The functions of the program modules are outlined below:

Control of modulation signals. Amplitude and phase of the modulation signal are compared point by point with nominal values and adjusted as necessary.

Operation of keyboard and display. The keyboard processor has three main activities (seen from the monitor processor):

– write the equipment status to be displayed at the keyboard

– write specified measured values or limits

– read and store specified values or limits.

The last activity makes it possible to change limits for computed values such as SDM, DDM, or RF level. These values are stored in the CMOS RAM, so when it is necessary to restart and the CMOS RAM is correct, these new values will be used.

Antenna switchover. During antenna switchover one equipment acts as master (not necessarily the one that is "main") and the other as the slave. The master first informs the slave that switchover is to start. The slave stops its normal program and waits while the master controls switchover. When switchover has been completed, both master and slave programs continue in normal status.

Equipments that operate in the cold standby mode (one transmitter active, the other shut down) require further procedures. Power must be supplied to the passive transmitter, giving a short period in hot standby. Then the formerly active transmitter must be shut down and control of modulation provided by the newly active transmitter.

Analysis of alarms. Results from the test alarms module are analyzed for first order and single channels, and the result is compared with that of the other equipment. The following actions are possible:

– No further actions are taken if no alarms are indicated.

– If there is a continuous alarm which is confirmed by the other equipment, antenna switchover starts. However, if a previous switchover has occurred within a specified period the equipment is shut down. The alarm message probably indicates a transmitter error.

– If there is a continuous alarm which is not confirmed by the other equipment, there is probably a fault in the monitor. This monitor fault is transmitted to the other equipment via a bit in one of the parallel interfaces. No further actions are taken by the faulty equipment but the other equipment knows that it must act on its own and that an alarm in its own equipment cannot be confirmed by the other unit.

Harmonic analysis. The 32 measured values $X(n)$ of a channel are used to compute values for A_m using the following formula:

$$A_m = \sum_{n=0}^{31} X(n)\, e^{-i\frac{2\pi}{32}nm}$$

where $m = 0, 1, \ldots, 5$
$e^{-i\psi} = \cos\psi - i\sin\psi$.

To save computer time the following formulas are used:

$$\sin\psi = \cos(90-\psi)$$

$$\cos(180-\psi) = -\cos\psi$$

$$\cos(-\psi) = \cos\psi.$$

Thus instead of over 100 multipliers, just seven remain: cos 11.25°; cos 22.5°; cos 33.75°; cos 45°; cos 56.25°; cos 67.5°; and cos 78.75°.

These seven multipliers are known constants in the PROM and do not have to be computed. A_0 is the sum of all values. A_1 to A_5 are computed; first the real part, then the imaginary part:

$$|A_m| = [\mathrm{Re}^2 (A_m) + \mathrm{Im}^2 (A_m)]^{\frac{1}{2}}.$$

Test of alarms. Equipment values are computed from the harmonic analysis (e.g. RF level, sum and difference of depth of modulation) and compared with predefined limits. The result – alarm or no alarm – is stored and can be displayed at the keyboard; it is also fed to the alarm analysis module.

Built-in test equipment (BITE). Equipment parameters such as temperature, voltage, and time of use of battery during power failure are tested and compared with predefined values. An out-of-limit result is stored and shown at the keyboard by *BITE WARNING.*

Wait program. Forty interrupts (= 41.6 ms) are taken for one channel. As long as these values are stored, the values for the preceding channel are analyzed in the harmonic analysis, test for alarms, and analysis of alarms modules. Then the BITE module is run. The wait program, which runs for the remainder of the time, is interrupted by the 960 Hz interrupt to receive new measured values and then continues with either the control of modulation or operation of the keyboard module. Both modules end with a return from interrupt statement so that the interrupted program, in this case the wait program, can continue.

Friedrich Limbach was born at Winterborn, Pfalz, in 1952. He studied electrical engineering at the Technical University of Kaiserslautern from 1973 to 1978. In 1978 he joined SEL in Stuttgart to work on the design and development of digital control units for navigation landing systems. His major interests are the structured design of complex digital control units, microprocessor applications, and sophisticated software development.

Klaus Pählig was born at Freital, Germany, in 1939. He received the degree of Diplommathematiker from the Technical University of Stuttgart in 1965. The same year he joined SEL in Stuttgart and worked on coding and software development for various applications, including radar systems, landing and navigation aids, and military systems. Since 1980 he has been head of the laboratory for software development.

VHF Radio Lighthouse

Existing nondirectional beacon navigation systems are difficult to use in small vessels, particularly in rough seas. In contrast, bearing information from the radio lighthouse is unaffected by the ship's movement. The prime advantage is that accurate bearing information can be obtained using an existing communication receiver.

R. Johannessen
Standard Telecommunication Laboratories Limited, Harlow, England

Introduction

The VHF (very high frequency) radio lighthouse is designed for small vessels so it is important that a bearing can be taken easily in rough seas. As small craft are unable to smooth out wave motion, they are tossed about vigorously in rough seas. Under these conditions today's NDB (nondirectional beacon) system is very difficult to use if the on-board instrument is a hand held receiver, because the receiver must be moved continuously to ensure that the antenna always points towards the transmitter.

The radio lighthouse is based on the philosophy that navigation is simpler if there is no need to stabilize the receiver antenna. Directional control is therefore built into the fixed transmitter, enabling the receiver to use a simple omnidirectional antenna of the type used for communication. Thus the roll, pitch, and yaw that continuously affect a small boat do not affect navigation.

A fundamental consideration that affects all radio navigation systems is the relationship between the antenna baseline (length of the antenna in wavelengths) and the error protection achievable in an azimuthal multipath environment. The longer the baseline the smaller the error, subject to certain constraints. There are two important considerations. First, as the NDB system operates around 300 kHz with wavelengths of about a kilometer, it would be difficult and costly to use transmitters with antennas several kilometers long. The radio lighthouse, on the other hand, has a

Radio lighthouse antenna mounted on the North Foreland lighthouse.

2 m wavelength and so the 4.5 m antenna is more than two wavelengths long, thus offering significant error reduction potential. The second consideration is that it is simpler to locate, mount, and maintain a large antenna structure ashore than on board a vessel which is subject to violent pitch, roll, and yaw.

Operation

The radio lighthouse operates in the international marine VHF band at approximately 160 MHz. An audio tone is heard when the receivers are tuned to the correct channel. The transmitter is so arranged that within the coverage sector the tone is heard in all directions from the transmitter, except one radial along which there is a marked reduction in tone level. This *null radial* is slowly rotated by the transmitter at 4° per second. Knowing this rate and the reference time at which the radial passes through a *reference bearing*, which is published for each beacon, the receiver's bearing is obtained by noting the duration from the reference time until the null radial passes through the bearing at which the receiver is located. To simplify this still further, the transmission is broken into a series of 0.5 s beats so that the bearing can be obtained by counting beats from the reference time until the null radial passes through the receiver. While the radial is approaching, the tone gradually decreases in intensity and after the radial has passed, the tone increases again.

The transmitting antenna is fixed and the null radial is rotated electronically, eliminating all moving parts.

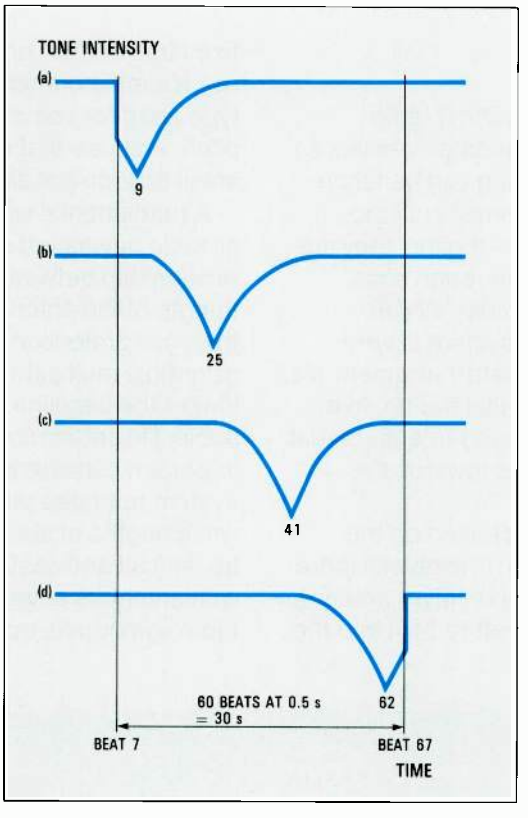


Figure 1
Tone level variation at different bearings
(a) bearing 4° into the coverage sector
(b) bearing 36° into the coverage sector
(c) bearing 68° into the coverage sector
(d) bearing 110° into the coverage sector.

Signal Format for Each Beacon

Transmissions commence on the hour and every minute thereafter. Each transmission lasts 58 s and is followed by a 2 s pause before the next one commences. The 58 s are made up from three parts:

- morse identification which identifies the transmitting beacon
- navigation signal which enables the navigator to determine his bearing with respect to the transmitter
- morse identification which repeats the identity of the transmitting beacon.

Pauses between these parts of the transmission simplify signal recognition. Between the first and second parts, and after the third part, digital data is transmitted for use by test instruments.

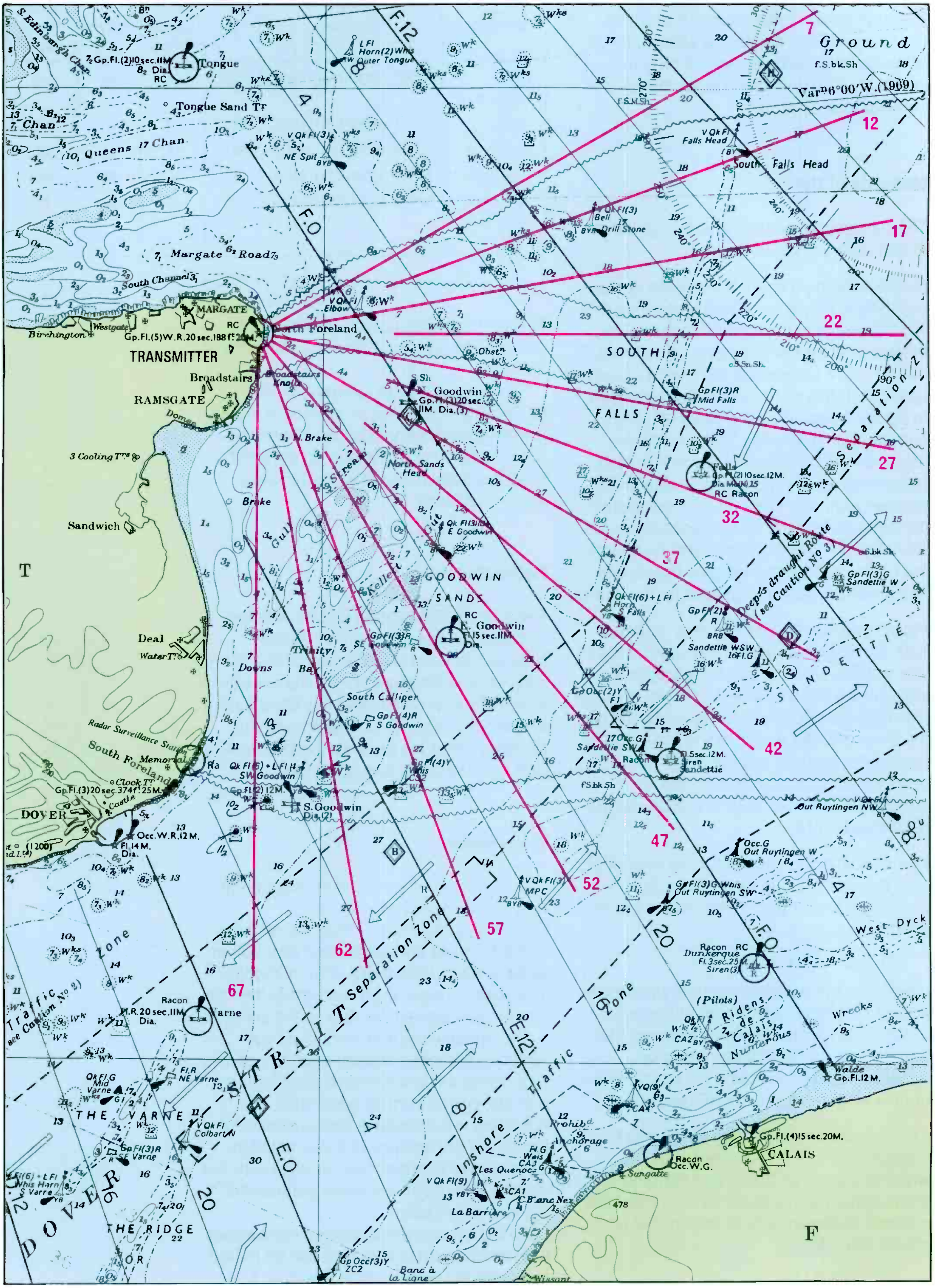
The navigation signal comprises 70 beats each made up of a 0.4 s tone and 0.1 s silence. Of these, beats *7* to *67* (inclusive) are used for navigation. During these beats, the null radial sweeps a 120° azimuth sector which is the beacon's published coverage sector. As seen on a chart, the radial sweeps clockwise from the bearing corresponding to beat *7* to the bearing corresponding to beat *67*. Beats *1*, *2*, *3*, and *4* help the navigator get the counting rhythm, while beat *70* marks the end of the sequence. Figure 1 shows how the tone intensity varies at different bearings from the transmitter.

The further the navigator is into the 120° sector, the higher the beat number he gets to before the null radial passes. If the null is heard during beats *3*, *4*, *5*, *6*, *68*, or *69*, the navigator should conclude that he is outside the published sector.

Time Sharing of Several Beacons

To conserve the frequency spectrum, it is possible to arrange several beacons to time share a common frequency channel. Two beacons may transmit alternately for 58 s

Figure 2 Navigation radials for the radio lighthouse at North Foreland on the south coast of England.



each with 2 s in between when neither transmits, or there may be three or six beacons transmitting in turn. In all cases, the navigator can determine which beacon is transmitting by listening to the morse identity before and after the navigation part of the signal.

Methods of Use

The navigator may use the radio lighthouse in four different ways:

Radials drawn on chart. If a beacon is used regularly, it may be worthwhile drawing the 120° information sector on the chart. The extremities of the sector are marked beats *7* and *67*, and a convenient number of equally spaced intermediate radials may be drawn. In Figure 2 the radials for every fifth beat, corresponding to every 10°, have been drawn on the chart for the North Foreland transmitter showing the information sector as used from mid 1983. To use the system, the navigator listens to the transmissions, waits for the correct morse identity, counts the beats until the null radial is heard, and reads the corresponding radial on the chart.

Plastic overlay. An alternative is to draw a 120° arc on a clear plastic sheet and divide it into suitable sectors, say 10° wide, each of which is marked with a beat number, starting with beat *7* at the left edge. This is placed on the chart with the center of the arc at the transmitter location and the radial corresponding to beat *7* along the direction R given in Table 1. The procedure is then as before.

Formula based on counting. If the overlay is lost, the bearing may be obtained by applying the beat with minimum tone to the simple formula:

$$B = R + 2\,(N - 7)$$

where B is the true bearing from transmitter to ship, N is the beat number at the null radial, and R is the reference bearing. This formula and the published reference bearings could be written in the chart margin or on a label fixed to the VHF receiver.

Time measurement. A stopwatch may be used as an alternative to counting. The watch is started on beat *7* and stopped on the minimum signal beat. If T seconds have elapsed, the bearing from transmitter to ship is given by:

$$B = R + 4T.$$

Table 1 — Characteristics of radio lighthouse transmitters from 1983

Transmitter	Position	R	Range (nautical miles)	Channel	Morse identi-fication
North Foreland	51°22′28″N 1°26′48″E	060°	20	88	ND
Calais	50°57′44″N 1°51′18″E	270°	20	88	CL
Anvil Point	50°35′30″N 1°57′33″W	067°	14	88	AL
High Down	50°39′42″N 1°34′36″W	157°	30	88	HD
Holy Island (Pillar Rock Point)	55°31′03″N 5°03′34″W	341°	17	88	PK

This method is particularly useful when taking bearings involving a large number of beats.

To ease the task of counting to 70, particularly when tired or seasick, a marker is transmitted every 10th beat. Thus the 10th, 20th, up to and including the 60th beat, are transmitted at a slightly lower audio frequency.

Radio Receivers

The system is designed for use with the standard marine transceivers already installed on most ships. Whether the set is frequency synthesized or crystal controlled is immaterial provided that it is fitted for the frequency in use. Thus, it is possible to navigate using the communication receiver with no extra on-board equipment.

Transmitter

The transmitter consists of an equipment rack and an antenna array with interconnecting cables. The rack contains all the RF units and associated distribution system, controlling logic, integral monitor, and power supplies. Six sockets at the rear connect the equipment rack to the antenna.

The antenna system comprises six vertically polarized dipoles each in a corner reflector to minimize mutual coupling and provide a good front-to-back ratio. The reflectors are aluminum rods and most of the rest of the antenna is constructed in aluminum to combine low windage with low weight. The main transmitter parameters are shown in Table 2.

As the system employs electronic rather than mechanical scanning, it can be bolted to a concrete wall, a lattice tower, or a balcony; it could even be mounted between uprights poles. Thus it is generally easy to mount the system on a lighthouse, a coastguard site, or other building.

At the North Foreland lighthouse in Kent, Southern England, the antenna is bolted to guard rails immediately below the focal plane. As another example, at Anvil Point, also on the south coast of England, the antenna is bolted to the roof of the foghorn housing.

The connecting cables can be simple coaxial cables with a 50 Ω impedance, good phase stability, and a maximum insertion loss of 3 dB.

It should be noted that the equipment is designed for automatic operation and can therefore be used on unattended sites.

Range and Information Sector

The system range depends upon a number of factors including the elevations of the transmitter antenna and receiver antenna, feeder losses at both ends, receiver antenna type and mounting method, and receiver type.

In a typical case, the working range is about 20 n miles (37 km) for a receiver dipole aerial mounted at the masthead 28 feet (8.5 m) above the sea surface and a transmitter elevation of 57 m. Halving the transmitter antenna elevation reduces the range by about 40%.

The information sector is 120° end to end. If 240° coverage is required, two transmitters may be used each covering its own 120° sector.

System Testing

During 1981 over 1000 measurements of system accuracy were carried out; these indicated a standard deviation of about 2°. System improvements made during 1983 reduced the standard deviation to only 1.6°.

In the period 1981–1983, far-field monitors were installed in three fixed locations so that long-term transmission stability could be assessed. Between 4 December 1981 and 10 September 1983, 2406 readings were taken with a standard deviation better than 0.6°.

Radio lighthouse antenna mounted on the fog signal housing at Anvil Point, England.

During extensive sea trials, tests were carried out to determine the ease of use of the system. A number of observers on board the testing ship were asked simultaneously but independently to determine the ship's bearing from a shore station by counting beats until the null radial passed. For each position of the ship, the spread of the observations was studied. Clearly the smaller this spread, the easier the system was to use. During the trials 3952 bearings were taken and in 99.2% of cases the options expressed were within one beat of the mean bearing, corresponding to a spread of only ±2°.

Table 2 – Specification summary for transmitter

Output frequency:	Any marine channel in the range 160.625 to 162.125 MHz
Frequency stability:	Better than 10 parts per million
Aerial gain:	Nominally + 7 dBi*
Power out of equipment bay:	2 W ± 3 dB
Input power:	Both (a) and (b) (a) 110 to 120 V or 220 to 240 V AC 45 to 400 Hz at 280 VA (b) 22 to 30 V DC, less than 1 A

* dBi: decibels relative to an isotropic source.

Steps Taken to Safeguard the Navigator

It is important for the navigator to have confidence in the integrity of the system. To ensure this, a built-in monitor in each transmitter automatically and continuously checks that the carrier power is above a preset level, the sideband energy is above a preset level, and the electronic alignment which controls the directional information is between preset limits.

If a fault develops (permanent or transitory) the system immediately signals this to the navigator by warbling the audio tone (varying it between two distinct frequencies). If this happens, the navigator should not use the bearing information.

At the end of the transmitter sequence, the system tries again. If the fault persists, the transmitter is closed down until it can be repaired.

Periodically, maintenance engineers examine the system. If for any reason they need to cause unreliable information to be transmitted, they first alter the morse identity to *TEST*. Thus, the navigator is recommended always to check that the morse signal received is that published for the station.

Development History

The radio lighthouse was developed by Standard Telecommunication Laboratories in conjunction with STC International Marine and the Corporation of Trinity House on behalf of the General Lighthouse Authority.

The first system was made available to mariners at North Foreland, Kent, in England, from March 1980. In 1981 four more transmitters were added, so that by the end of 1981 systems were under evaluation in England, Scotland, and France. During 1983, their morse identities and signal format were brought into line with the details given in Table 1.

Plans are now in hand for the production systems to be manufactured at STC International Marine.

Conclusions

The radio lighthouse allows small vessels to receive accurate bearing information using an existing communication receiver. As the bearing information is under the control of the transmitter, it is unaffected by the vessel's movement, even in rough seas. Neither the ship's heading or the magnetic deviation are required to determine the ship's bearing.

R. Johannessen was born in 1937. In 1962 he was awarded a BSc from the University of St Andrews in Scotland. For three years he worked with STC in London on aircraft radio navigation systems. Following this he spent a period with International Computers before joining STL in Harlow where he has worked since then. He was responsible for the concept and development of the VHF radio lighthouse, and his work in this area gained him a PhD from London University. Dr Johannessen is a Fellow of the Institution of Electrical Engineers in London.

New Family of Tacan and DME Equipment

The use of digital techniques and RF solid state technology in a new family of Tacan and DME navigation aids has improved their performance. Reliability has been enhanced, maintenance simplified, and lifecycle costs reduced.

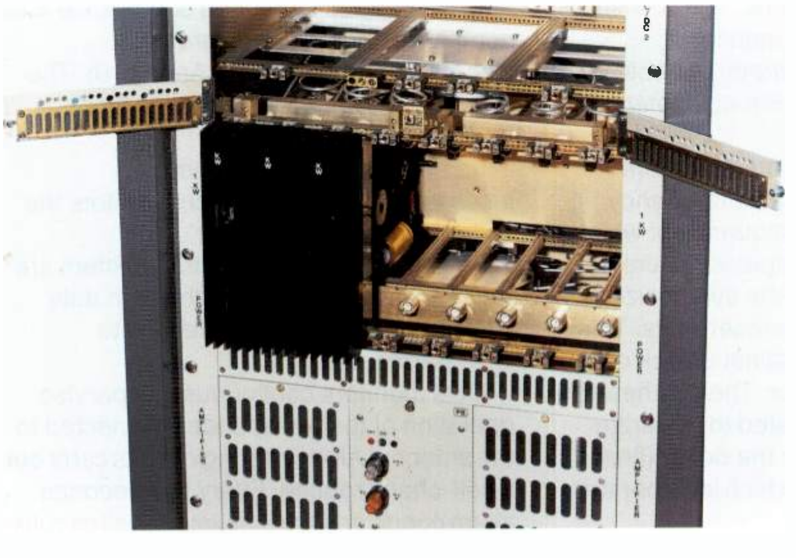
G. Bertocchi
Industrie FACE Standard SpA, Milan, Italy

Introduction

A new family of Tacan and DME (distance measuring equipment) ground beacons has been developed by Industrie FACE Standard to provide advanced performance and reduce the overall lifecycle costs. The latter has been achieved by introducing solid state digital circuits that improve reliability and reduce maintenance. In addition, the fully modular construction simplifies fault location and maintenance.

The first equipment in this family was the 3 kW Tacan FTA-10 which incorporates a tube type final amplifier. Other units are the 1 kW DME FSD-15, the 100 W DME FSD-10, the 1 kW Tacan FTA-10/S, and the 3 kW Tacan FTA-13/S which all use all solid state transmitters. They can be colocated with VHF equipment to provide Vortac, VOR/DME, or ILS/DME stations.

Four different types of antenna are used: a solid state static Tacan antenna, two high gain omnidirectional DME antennas, and one sectorial DME antenna. The Tacan equipment can also operate with existing Tacan antennas.



The 1 kW peak power amplifier used for the new family of Tacan and DME equipment. Some modules have been removed to show the overall layout.

Tacan/DME Equipment Description

The Tacan/DME equipment consists of a dual transponder, dual monitor, control unit, and programmable built-in test equipment. In the FSD-15, FTA-10/S, and FTA-13/S, the single final amplifier, which can be fed by either driver, has a parallel redundancy of eight power amplifier modules.

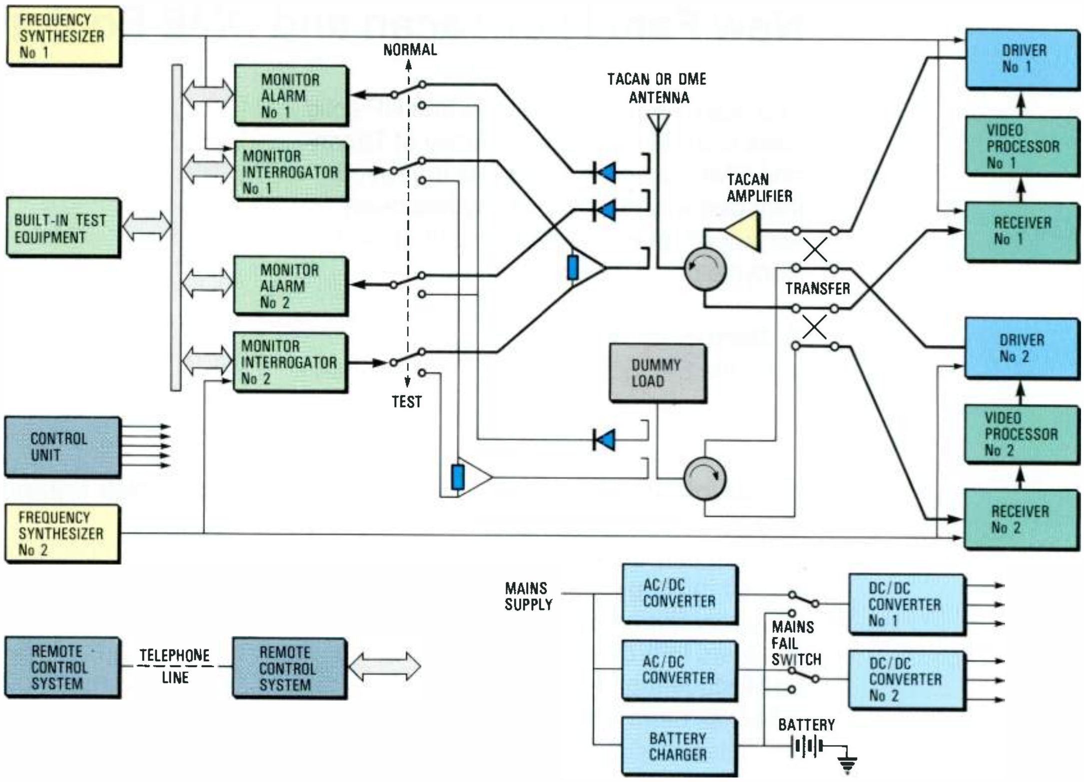
The standby transponder with its low power (100 W) driver can be connected to the antenna should a lower power be required (e.g. when reduced coverage is acceptable). This provides full performance at a lower output power.

Figure 1 is a block diagram of the FTA-10/S, FSD-15, and FTA-13/S equipments. All Tacan and DME equipment uses the units, although the power amplifiers and power supply modules vary according to the required output power.

The RF (radio frequency) interrogating signal from the antenna is applied through the directional couplers, duplexer, and transfer switch to the receiver input circuits. The receiver has a sensitivity of better than −92 dBm, an input dynamic range of more than 80 dB, and a rejection capability in excess of 80 dB to all out-of-channel signals. Receiver sensitivity can be reduced to −70 dBm. High accuracy is obtained by using a dual channel receiver: interrogation timing detection is performed at the output of a moderately wide bandwidth channel while validation is performed by a narrowband channel output. Two echo suppression circuits desensitize the receiver in proportion to the level of the interrogation. Echo suppression threshold and gate width can be adjusted for the echo conditions at a particular site.

The video processor and coder/decoder circuits make the maximum possible use of digital techniques. *X*/*Y* channels, Tacan/DME mode, 1st or 2nd pulse timing operation, and dead time gate width can be

Figure 1
Block schematic of the Tacan FTA-10/S, DME FSD-15, and Tacan FTA-13/S equipments.

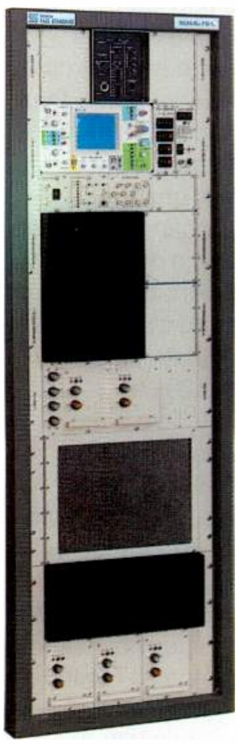


selected. Synchronous counters in the video processor introduce a stable delay between interrogations and replies; beacon reply delay accuracy is as high as $\pm 0.2\,\mu s$ (± 30 m distance accuracy). Synchronous counters are also used to generate azimuth reference bursts and identity pulses, in response to Tacan antenna triggers, and to control random squitter pulses. The replies and squitter are added with the correct priority to the azimuth reference bursts and the identity code signals to form the modulation pulse train.

Demand mode operation can be selected as required. Interrogations received and decoded by the ground equipment are counted; the transmitter is turned on if the count exceeds a preset limit. The demand mode circuit also counts monitor interrogation decodes thereby controlling receiver operation when the equipment is on standby.

The RF carrier is generated by a direct-frequency/indirect-synthesis frequency synthesizer, the output frequency of which is also controlled by a frequency counter; this counter switches off the synthesizer if the frequency is outside preset limits. This provides high integrity against unlock or mislock of the synthesizer. The synthesizer output is amplified and gated to generate rectangular RF pulses for the driver (final amplifier of the FSD-10) which incorporates the modulator RF stage.

Tacan FTA-13/S, 3 kW solid state beacon.



The 1 kW power output of the FTA-10/S and FSD-15 is derived by combining the amplified outputs of eight modules using low loss eight-way divider and combiner networks. These networks provide an isolation of about 25 dB between arms, ensuring fail-soft operation. As a result the amplifier continues to operate at a lower power, but without any other performance degradation, should one or more modules fail. Failed modules can be replaced during service without any interruption or adjustment.

The transfer characteristic of the RF power amplifier requires a particular modulation waveform generation to provide precise shaping of the RF drive to the final amplifier, thereby ensuring compliance with spectrum emission standards (i.e. STANAG 5034 and ICAO Annex 10). The output pulse shape is controlled by a negative feedback loop.

Each power amplifier module incorporates a sensor which monitors the status of the final transistor.

All the new Tacan/DME transmitters are rugged and can withstand the high duty cycle required to provide service to 200 interrogators.

Dual monitors continuously supervise operation of the transponder connected to the antenna. All monitoring circuits carry out a self-check routine. Every two seconds alarm conditions are simulated to all circuits;

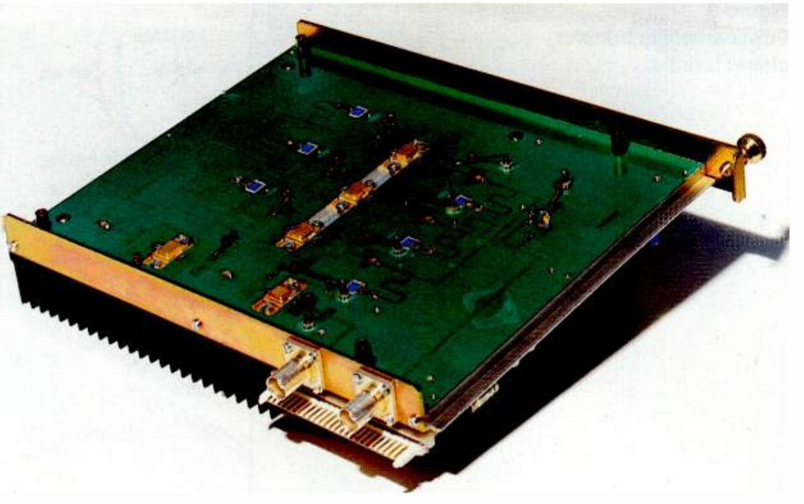
the monitor must react with a temporary alarm status for each parameter, following which it returns to normal operation. If this alternation of states fails for between 4 and 10 seconds (adjustable), an "unhappy" monitor condition is forwarded to the control unit which decides whether to switch over to the standby transponder or shut down the equipment.

Monitoring is initiated by RF signals applied to the receiver input through the antenna line directional coupler. In the normal monitoring mode, the monitor interrogator alternately sends strong and weak pairs of interrogation pulses. The former monitor transponder reply delay and the latter monitor receiver sensitivity. The monitor takes the replies from the antenna line directional coupler or, in the case of DME, from the antenna probes. Pulse spacing, peak power, duty cycle, and identification are also monitored. All parameters may be chosen as primary or secondary alarm, except for reply delay which is always a primary alarm. Only a primary alarm can cause the equipment to be shut down.

In addition to normal operating conditions, either or both monitor interrogators may operate as versatile RF or video generators in conjunction with the built-in test equipment.

The RF output, which can be either continuous wave or pulsed, is adjustable from −110 to 0 dBm; the *on* channel and the ± 200 kHz and ± 900 kHz test frequencies can be selected. Pulse pair spacing and delay can be varied in 0.1 μs steps and the pulse rate is selectable from 2 to 10000 pulses per second.

Using the built-in test equipment, the most important tests can be carried out on the transponder connected to the antenna, on the standby transponder, and on the two monitors without service interruption.



Single 600 W power amplifier module.

Measurements that can be performed include: reply delay (within the dynamic range of the receiver), reply pulse spacing, receiver decoding window, output pulse count, azimuth bursts count and repetition rate, receiver sensitivity and reply efficiency, receiver bandwidth, receiver adjacent channel rejection, operation of echo suppression circuits, receiver dead time, peak output power, transponder and monitor output pulse duration, and rise and decay times, and alarm limits of the monitor parameters.

All equipment can be battery powered.

A cost-effective remote control system allows controls and indications to be remoted to a central operations facility.

Solid State Power Amplifier Operation

Figure 2 is a block diagram of the 4 kW power amplifier which meets all civil and military specifications. It does not require tuning or readjustment, and the use of microstrip techniques makes it highly reproducible. The 100 W amplifier drives

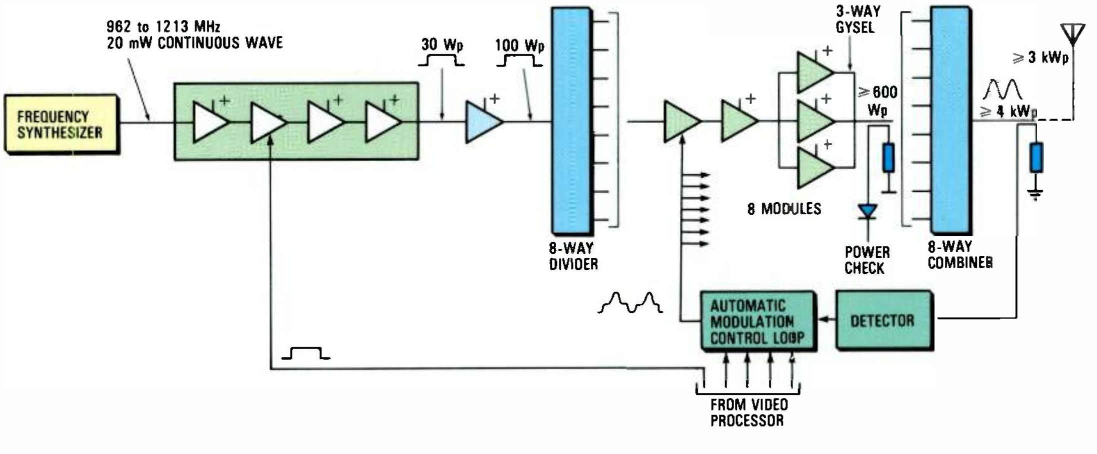


Figure 2
Block schematic of the 4 kW peak power, solid state transmitter used in the FTA-13/S Tacan ground beacon.

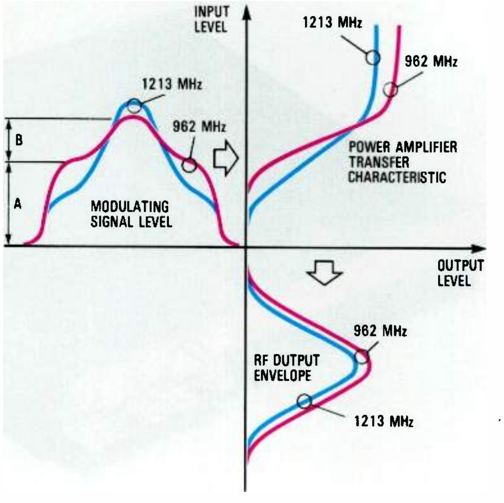


Figure 3
Power amplifier transfer characteristic.

the modulator stages (one for each 600 W module). The RF modulator, with its output power capability of more than 80 W, is collector fed with a waveshape which generates the RF signal required to drive the final transistors.

A typical final amplifier input/output characteristic (Figure 3) exhibits a quasilinear region when the modulating input level exceeds the threshold required to turn on the two stages in cascade. The slope of the curve, set by the overall gain of the three stages, and the threshold required to turn on the transistors may change with conditions (e.g. input RF, ambient temperature), but the linearity does not alter significantly. Thus once the shapes of components *A* and *B* have been fixed to obtain the best spectrum, they need not be automatically controlled, although their levels will need to be. During north-reference bursts, the transfer characteristic of the power amplifier may vary slightly. In particular heating of the transistors may cause a power variation from pulse to pulse.

The automatic modulation control loop is a negative feedback loop that maintains the output pulse time widths at nearly 15% and 85% of the voltage peak. The detected time widths are continuously compared with digitally generated rectangular pulses of fixed duration, thereby generating control voltages that set the levels of components *A* and *B* without altering their shapes.

The automatic modulation control is fast enough to ensure that any power variation in the last pulses of north-reference bursts is well within specified limits.

Conclusions

Synchronous digital circuits and the latest solid state RF technology have been used to realize highly reliable Tacan and DME equipment. High modularity and system integration allow a dual transponder, dual monitor, and all the units necessary to operate and maintain the equipment, to be housed in a single, small cabinet.

Giuseppe Bertocchi was born in Vertova, Bergamo, in 1950. He graduated in electronic engineering at the Milan Polytechnic in 1975. On graduation he joined FACE where he was engaged in development of the Tacan and DME equipment. He is at present project engineer for the FACE Tacan and DME ground beacons.

Civil Use of Tacan

The Tacan system is a proven navigation aid which has been used mainly for military applications. However, modern technology has made it possible to reduce the cost of Tacan installations, opening up a range of new civil applications including helicopter navigation to offshore oil rigs.

E. Lazzaroni
Industrie FACE Standard SpA, Milan, Italy

Introduction

Tacan has gained a predominant position among air navigation systems over almost four decades. While the system is mainly used for military aircraft, technological progress, particularly in microwave transistors and RF (radio frequency) switching circuits, now makes it possible to produce low cost solid state beacons and electronic antennas. As a result, the installation and operation of Tacan systems is now economically feasible as a navigation aid for some civil applications.

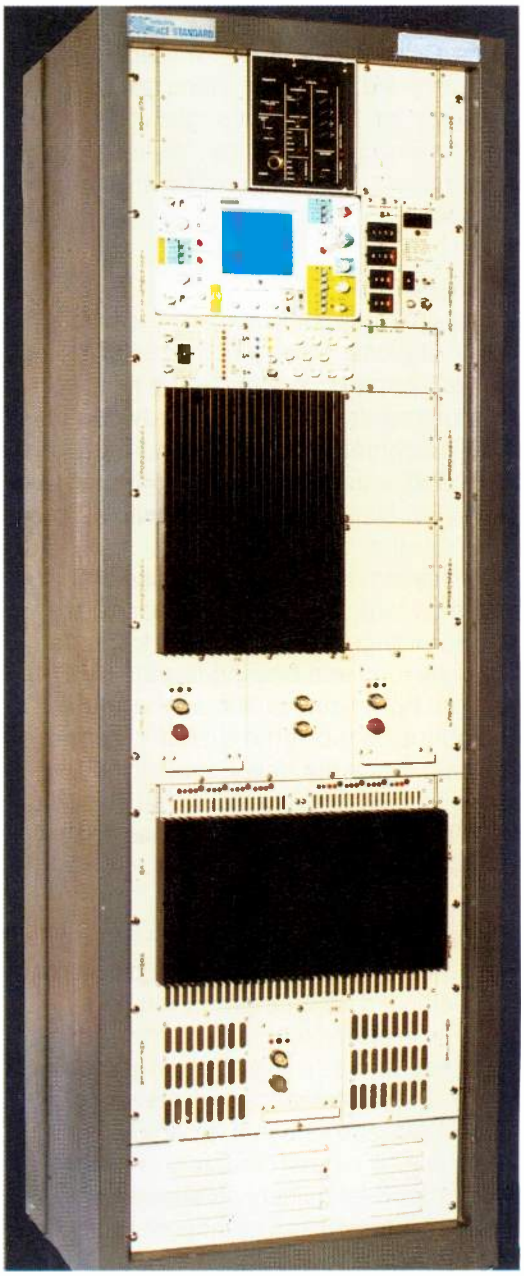
The operational flexibility of these new generation solid state Tacan beacons, equipped with electronic antennas, together with their low cost and ease of use, make them particularly suitable for helicopter navigation and as an approach aid for offshore oil rigs.

Benefits of Tacan

Tacan was conceived as a military system based on the addition of a bearing function to DME (distance measuring equipment) using the same frequencies. The resulting beacon is more portable than the VOR (very high frequency omnidirectional range)/DME ground station used for civil aviation.

The Tacan airborne equipment consists of a DME interrogator to which bearing circuits have been added. Thus Tacan beacons provide a full service to all DME interrogators, and DME beacons provide distance information to all airborne Tacan sets. Advantages over the VOR/DME system include:

- Higher frequency (960 to 1215 MHz compared with 108 to 118 MHz) allows the Tacan beacon antenna to be smaller, making it more suitable for mobile and shipboard service.
- Being a pulse system using the leading-edge detection technique, Tacan is less affected by site errors than continuous wave systems, minimizing VOR



Tacan beacon FTA-10/S manufactured by Industrie FACE Standard.

"scalloping" (cyclic variations in bearing error) caused by unwanted reflected signals from obstructions.

- Tacan multilobe technique can, in principle, provide higher accuracy than a single-lobe VOR system.
- Tacan signal is unaffected by the "rotor modulation" in helicopters which can cause erratic navigation indications.
- Equipment economies can be achieved by using the same frequency channel for both bearing and distance information.

Of the 2879 navigation aids at present in operation worldwide, 1276 can be used with airborne Tacan while another 694 offer DME-only operation.

Tacan Use Over Land

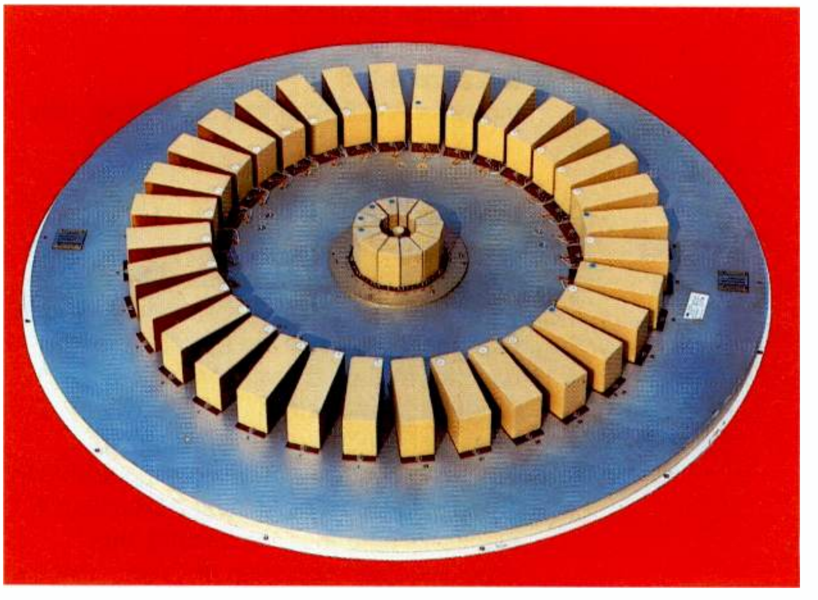
Since Tacan is the primary military navigation aid, ground stations can be found at military installations throughout the world. On occasions these military stations can be a convenient navigation aid for civil operators.

Vortac Stations
The largest civil application of Tacan is in Vortac stations. This system is used in several countries to remove the need for military aircraft, which are already equipped with Tacan interrogators, to install additional VOR/DME equipment. In the Vortac system each VOR station is colocated with a Tacan beacon rather than with a DME.

Military aircraft receive distance and bearing information from the Tacan beacon, while civil aircraft read distance from the Tacan beacon and bearing from the VOR beacon. Both types of aircraft therefore operate using the same air-traffic-control network. Since the new generation Tacan beacons cost little more than DME beacons, further development of the Vortac network seems likely.

Mobile Tacan Stations
Mobile Tacan stations can be employed as a navigation aid on emergency landing grounds in addition to their use for tactical purposes, and as a temporary replacement for fixed Tacan beacons in the event of a fault. In this application it is particularly useful during natural disasters or major accidents when military air support is urgently required and no airport equipped with navaids is available.

The low weight and small size of modern electronic Tacan antennas and the low power consumption of solid state beacons make it possible to produce flexible and efficient mobile Tacan stations that offer the same accuracy and reliability as fixed stations.



Tacan electronic antenna FAN-29, manufactured by Industrie FACE Standard, shown with the cover removed.

Tacan for Private Airport
Sometimes small private airports can benefit by installing a Tacan system. Typically, such an airport might be served primarily by a single small airline but be unable to use a VOR/DME station because of its location in a mountainous area. In such circumstances, a Tacan station can be used instead of a new VOR/DME installation as it is less susceptible to siting problems and much less expensive than a VOR/DME station even taking into account the cost of airborne interrogators.

Tacan Use for Offshore Oil Rigs

Offshore oil and gas exploration and production will require increased helicopter support over the next few years. This need will continue for 20 to 30 years depending on the size of oil deposits and the rate of production.

Strict scheduling of helicopter flights to and from oil rigs, together with possible emergency requirements for medical evacuation and rescue services, make it essential for helicopters to be able to operate in poor visibility (sea fog, night, heavy rain, etc) under the most severe IFR (instruments flight rule) conditions.

The Tacan system provides the pilot of a helicopter approaching an oil rig equipped with a ground Tacan beacon with his bearing and distance from the oil rig, as well as his relative speed and time-to-station. This ensures accurate navigation and the shortest possible flight time even in unfavorable weather, thereby reducing wasted fuel and the working time of the flight crew.

Offshore Helicopter Navigation Aids

Navigation aids used for offshore oil rig helicopter operations can be divided into the three categories discussed below.

The first category covers systems that enable a pilot to home in on the drilling platform. Other factors being equal, pilots prefer such systems as they dispense with maps, are simple to use, and provide improved accuracy as the target is approached. The major systems in this group are: NDB (nondirectional beacon)/ DME, Tacan, and Tacan/NDB. For technical and economic reasons, Tacan (Tacan/NDB) appears to be the most suitable system.

Tacan systems have already proved successful for navigation on oil rigs off Alaska. However, until now it was not possible to make extensive use of such systems because of their high installation and maintenance costs. These high costs were primarily the result of using obsolete techniques (e.g. Klystron and microwave tubes in the RF power amplifier), highly militarized construction, and mechanical rotating antennas.

In contrast, modern microwave power transistors reduce the size, weight, cost, and maintenance requirements of new generation Tacan systems, thereby simplifying their installation and operation on oil platforms.

The second category is self-contained systems which include inertial, Doppler, and airborne mapping radar. They are rather bulky and expensive.

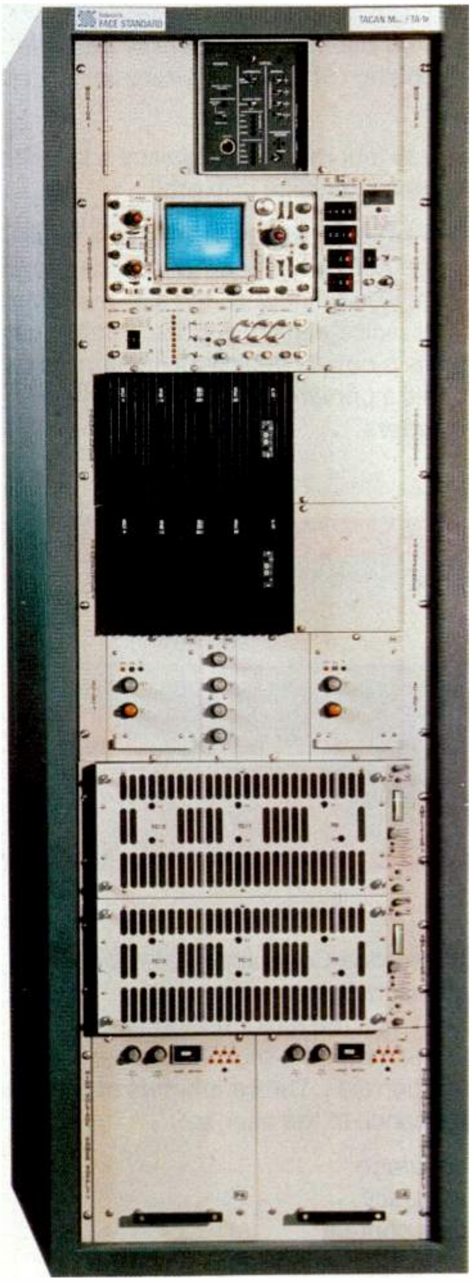
In the third category are systems that provide both the platform and the helicopter with their coordinates on some form of grid. These systems can rarely be used without an airborne computer to convert coordinates into steering information. The major systems are Decca (used in the North Sea), Loran-C, Omega, and the global positioning system.

So far none of these systems has been fully approved by any civil aviation authority for instrument approaches, although Loran-C has been approved in limited areas.

Omega appears to lack the required accuracy and instrument approach capability.

In the case of Loran-C, several fundamental questions still need to be resolved before this system can be considered as a possible primary IFR navigation and approach system for helicopters. Problems include:

- possible indication ambiguity
- low operating frequencies make it vulnerable to interference caused by adjacent frequencies being used for other purposes
- possibility of uncontrolled and unexpected service interruptions caused



Modern Tacan beacon suitable for civil applications.

by Loran-C station outages since users have no control of Loran-C stations which are operated by the United States Coast Guard

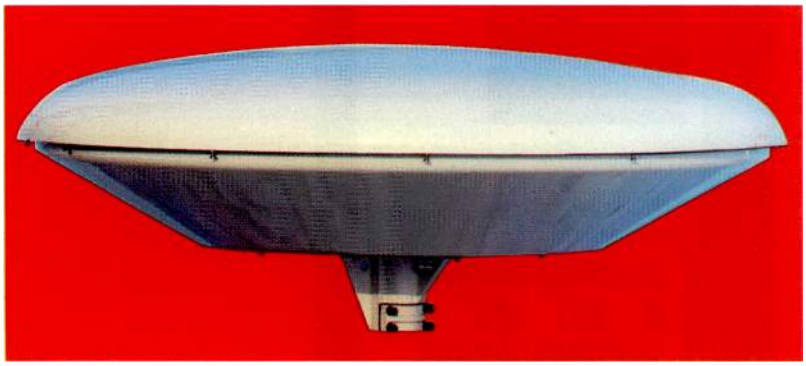
- timing errors depend on seasonal condition of the ground, and on local calibration; geometric dilution of precision adds further errors.

The satellite-based global positioning (Navstar) system will probably not be fully implemented before the mid 1990s. The main weaknesses of this system are:

- periodic outages over some areas if 18 satellites are used
- using 24 satellites, outages are overcome but there is no redundancy
- constant variation in geometric dilution of precision
- United States Department of Defense imposition of 100 m accuracy limit for civil use
- two to four months to replace a satellite if no spare satellite is in orbit.

Taken together with the FAA's (Federal Aviation Authority) recent decision to spend $111 million on new Vortac stations, these factors indicate that the global positioning system is not yet sufficiently mature to be used as a primary approach aid for civil helicopters.

Tacan electronic antenna FAN-29; the diameter is just 1.3 m.



Performance Comparison of Helicopter Navigation Systems

Table 1 lists the major performance parameters for the main helicopter navigation aids. The parameters of particular significance to the user are:

- coverage
- accuracy
- data content
- main application
- pilot's action to initiate
- readout to pilot
- signal reliability
- user equipment cost.

This comparison is only an approximate guide to the differences between the various navigation systems based on recently designed equipment in actual use.

Pilot's action to initiate lists the actions that are necessary to obtain a reading.

Readout to pilot lists the typical audible and visual readouts.

Signal reliability relates to the probability that a *usable* signal is available to provide navigation at any given time. Phenomena that affect this parameter include: atmospheric disturbances for systems operating above 10 GHz, sudden ionospheric disturbance for low frequency systems, and multipath or shading effects for line-of-sight systems.

The other parameters are self-explanatory.

Further Tacan Considerations

Reliability

Beacon reliability must be such that failure of part of the least reliable unit (transmitter) does not cause a complete loss of navigation. Modern solid state Tacan transmitters, consisting of multiple paralleled power modules, can easily satisfy this requirement. The power amplifier is usually arranged so that failure of one power module simply decreases the output power and does not cause station outage. The failed module can quickly be isolated and replaced.

Other beacon units can operate in a dual mode with automatic changeover, controlled by the monitor, in the event of failure. These techniques have resulted in a mean time between outages of 10000 hours for a Tacan station. Moreover, if the station operates in the *demand mode* (i.e. the transmitter is activated automatically upon reception of the first interrogating signal from the airborne equipment), as can be arranged on oil rigs, an even higher mean time between outages can be achieved.

Redundancy

As well as being suitable for helicopter navigation to and from oil rigs, should the standard DME fail during a flight overland helicopters can use the DME part of Tacan.

The Tacan bearing system is approved by FAA as a substitute for VOR in airway navigation (navigation along predetermined routes formed by VOR/VORTAC, DME, and other navigation aids) and for nonprecision approaches using a Vortac facility. Since the VOR and Tacan systems use separate equipment both in the aircraft and on the ground, a VOR failure in the airborne or ground equipment will not disable the Tacan system; if Tacan equipped, the helicopter can continue the flight using Tacan bearing information instead of VOR.

Area Navigation

Low cost area navigation airborne computers are available for helicopters, with preselection and storage of up to

Table 1 – Performance comparison of modern helicopter navigation systems

Parameter \ System	NDB/DME	Tacan	Tacan/NDB	Decca	Loran-C	Omega	GPS	Inertial	Doppler	Airborne radar
Coverage	NDB depending on transmission power (typically > 200 n miles DME: line-of-sight	Line-of-sight	NDB depending on transmission power (typically > 200 n miles Tacan line-of-sight	> 200 n miles (but not global coverage of the earth's surface)	1200 n miles (but not global coverage of the earth's surface)	Global	Global	Unlimited	Unlimited	Unlimited
Error	NDB: variable DME: 160 m*	Range <160 m* Bearing: <2°*	NDB: variable Tacan: Range: <160 m* Bearing: <2°*	20 to 3000 m depending on range	30 to 400 m depending on range	1 to 2 n miles RMS	100 m (civil use)	1.5 to 2 n miles per hour CEP	0.5 to 1% CEP	Variable
Data content	NDB Relative direction DME: distance	Relative bearing, distance, velocity, time to station	Tacan: bearing, distance, velocity, time to station NDB: relative direction outside Tacan coverage	Absolute 2D position	Absolute 2D position	Absolute 2D position	Absolute 3D position, 3D velocity, time	3D position 3D velocity	2D position 3D velocity	Relative Rho/theta 2D position
Main application	Medium range navigation	Short to medium range navigation, *approach*	Medium range navigation, *approach*	Long range navigation	Long range navigation	Long range navigation	Long range navigation	Long range navigation	Long range navigation	Intermittent position fix
Pilot's action to initiate	NDB: 1) Select one of 1400 channels 2) Place set in ADF mode DME: Select one of 252 channels	1) Select one of 252 channels 2) Select desired bearing	Tacan: 1) Select one of 252 channels 2) Select desired bearing NDB: 1) Select one of 1400 channels 2) Place set in ADF mode	1) Select one of 64 channels 2) Insert map in flight log	1) Select one of 40 rates 2) Insert start time difference (in some sets)	1) Select 3 of 8 stations 2) Correct for known delay using tables	1) Insert present position and time. This overrides automatic initialization reducing time to first fix	1) Start warm up 2) Perform initial alignment 3) Insert destination coordinates 4) Switch to "navigation" mode	1) Enter navigation data necessary for the flight	
Readout: to pilot	NDB: Read 360° dial: DME: Read distance on digital counter	1) Read distance on digital counter. Read bearing on 360° dial 2) Read left – right meter Read velocity and time to station	Tacan: Readout as previous column + NDB readout on 360° dial outside Tacan coverage	1) Read lanes and fractions or 3 decom-meters. Plot position on hyperbolic map 2) Read position on map	Read time delay on digital display. Plot position on hyperbolic map	Read time delay on digital display. Plot position on hyperbolic map	Read position in any 3D coordinate system	Read range and bearing to destination	Read on the display: – ground speed – left/right steering information – distance to go	Observe the maplike image on the radar indicator
Signal reliability	NDB: Fair (200 to 500 kHz) DME: High (L Band)	High (L Band)	Tacan: High (L Band) NDB: Fair (200 to 500 kHz)	Fair (70 to 130 kHz)	Fair (100 kHz)	Fair (10 to 14 kHz)	High (1230 to 1575 kHz)		Moderate (13 GHz)	Moderate (5 to 16 GHz)
User equipment cost	Low	Low	Moderate	Moderate	Moderate to high	Moderate to high	High	Moderate to high	High	High

* = in proximity to the station

10 way points (selected points on or near a course line which are used for navigation). The Tacan-based RNAV capability, besides permitting flights to a Tacan-equipped rig, also allows the pilot to use any other rig as a reference point provided it is in the area served by Tacan. The same station can even be used for the flight back to base.

Several Tacan stations can thus be simply interconnected to form a network allowing navigation over a wide area using either the same procedures as for VOR-DME stations or RNAV procedures.

Conclusions

The Tacan system has some interesting civil applications, among which its use for helicopter navigation to offshore oil rigs appears particularly promising. Comparison with other navigation systems shows that Tacan offers a better approach capability together with the highest data content in navigation information. In addition, the cost is lower than for the other systems.

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2 W. R. Fried: A Comparative Performance Analysis of Modern Ground Based, Air-Based, and Satellite Based Radio Navigation Systems: *Navigation*, Spring 1977, volume 24, no 1, pp 48–58.

3 E. Lazzaroni: A Solution for Helicopter Navigation to Offshore Oil Rigs: November 1982, Industrie FACE Standard, Milan.

Elio Lazzaroni was born in Genoa in 1939. He graduated as a telecommunication engineer from Genoa University. In 1969 he joined Industrie FACE Standard to work as a design and development engineer in the navigation aid laboratory. Mr Lazzaroni is currently project leader in the field of navigation aids within FACE.

Scanning Pencil Beam Precision Approach Radar

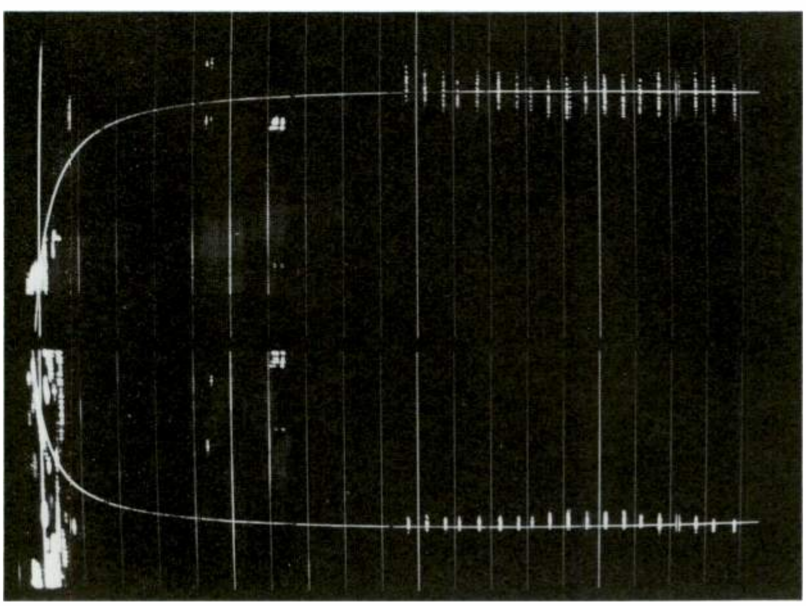
The PAR-80 scanning pencil beam precision approach radar provides accurate and reliable three-dimensional radar coverage of an airfield approach sector. The radar set operates unattended near the runway, using underground cables connected to radar displays located in an operations center near the control tower.

R. E. Johnson
ITT Gilfillan, Van Nuys, California, United States of America

Introduction

The PAR-80 precision approach radar (PAR) functions as an aircraft landing aid by scanning the sector of space immediately surrounding the approach path to an airport runway, then displaying the position of any approaching aircraft using a beta-scan display format. In this format, a profile of the sector (elevation versus range) is shown adjacent to a plan of the sector (azimuth versus range) on a CRT (cathode ray tube) display. The display format includes range marks referenced to the runway touchdown point, and glidepath and courseline cursors representing the preferred flight path, as shown in the photograph below. In operation, a controller views the display to determine aircraft position relative to the preferred flight path, and advises the pilot (via radio) to make flight path corrections.

Beta-scan display format of the PAR-80, showing an elevation *vs* range display above an azimuth *vs* range display. The glidepath and courseline cursors represent straight lines in space, but appear curved because of angular expansion of the origin.



PAR-80 is a modern enhancement of the original PAR concept, employing a scanning pencil beam antenna that systematically covers the total volume of the approach sector rather than employing separate azimuth and elevation antennas that sequentially scan segments of the sector. The resulting full volumetric coverage eliminates any need to reposition the scan sectors in azimuth and elevation (as was required with the older systems), gives maximum visibility of the service volume for intruder detection, and allows the PAR-80 to provide simultaneous service to parallel runways.

System Description

PAR-80 consists of a radar set group that operates unattended at a fixed site adjacent to the runway, and a display group that interfaces with the controllers at an indoor facility located up to 10 000 cable feet (3000 m) from the radar.

The radar set group consists of a planar array antenna, dual receiver-transmitter assemblies, scan programmer assembly, elevation drive mechanism, equipment pallet, and azimuth turntable, together with the necessary interconnecting waveguide and cables. The radar set group is designed for fixed installation, normally being bolted to a concrete base. An optional radome can be provided although the system meets its performance requirements even in extreme environmental conditions without the radome.

The display group consists of two control indicators, video processor, dual indicator switch box, and all the cables needed to

Radar set group of the PAR-80. The dual receiver-transmitter cabinets are located on either side of the turntable-mounted platform with the scan programmer and elevation drive between them.

interconnect these units with the remote line junction box. These units are installed in an operations center located away from the runway. The processor and dual indicator switch box are normally installed in an equipment room adjacent to the operations room where the displays are housed. If necessary, a third monitor display can be provided for maintenance. Figure 1 shows how the units are interconnected.

Antenna

The antenna is a slotted waveguide planar array that operates at X-band. The radiating aperture is 12.5 feet high (3.81 m) by 7 feet wide (2.13 m). The 85 vertical array elements each incorporate 176 edge-slot radiators located serially along the element waveguide. The slot coupling factors are adjusted to produce the desired amplitude distribution in the elevation plane. Each vertical array obtains energy through a latching 4-bit ferrite phase shifter with an integral driver. The 85 phase shifters housed at the base of the array provide the phase control needed to steer the radiated beam through a range of ±15° in azimuth. A horizontal line feed distributes power to the 85 array elements using a series of 3-port slot couplers located serially along the primary waveguide. Coupling factors are adjusted to produce the desired amplitude distribution in the azimuth plane. Coupler output ports incorporate small dielectric blocks that randomize the output phase of the horizontal line feed. When these fixed phase offsets are programmed out by the phase shifters, azimuth-plane quantization sidelobes are avoided.

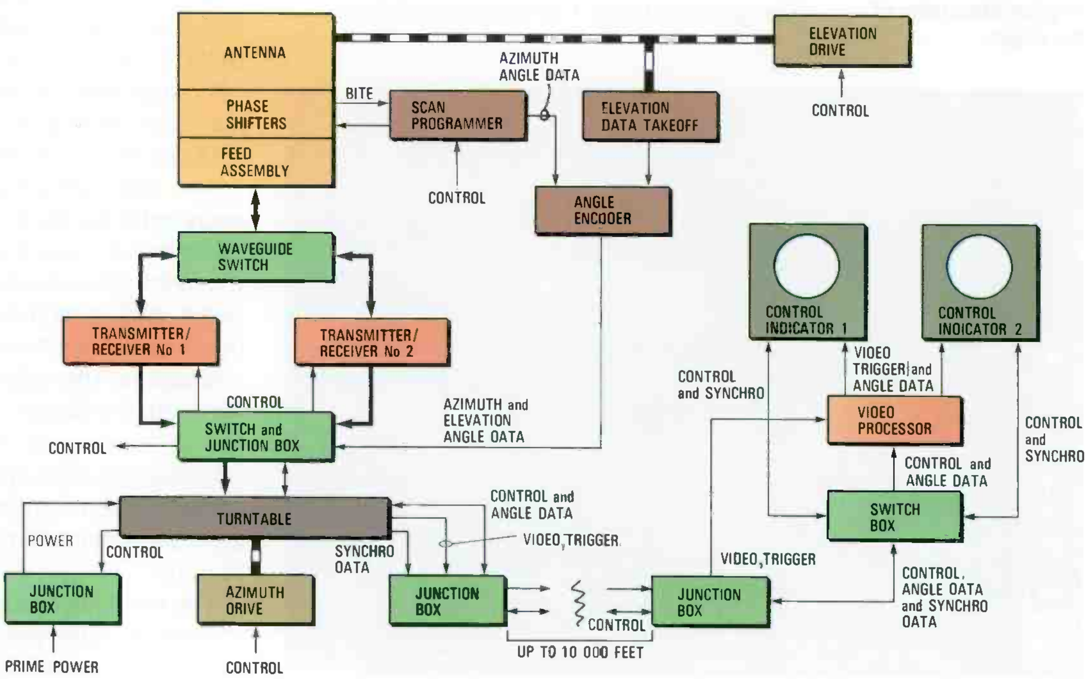


Figure 1
Block schematic of the PAR-80 system showing the provision of dual receiver-transmitter groups and dual displays for enhanced availability.

A planar three-skin transmission-type polarizer is mounted in front of the vertical slot arrays to produce circular polarization. The skins consist of wires and square or rectangular patches of copper etched on fiberglass panels, in which the patterns are aligned at 45° relative to the vertical polarization of the waveguide slots. The skins are spaced by nylon honeycomb cores, then laminated together to form the polarizer panel.

An off-line performance monitor, consisting of a horizontal slot array mounted behind the top edge of the antenna aperture, facilitates antenna testing and maintenance. The monitor is space-coupled to the array via an extra rear edge slot in each of the vertical array elements. It produces an output signal that has a fixed relationship to the far-field pattern and can be used to determine the status of the phase shifters and scan programmer.

The PAR-80 antenna's full array of 14 960 radiating elements ensures that the antenna pattern, gain, and circular polarization axial ratio remain well behaved across the full azimuth scan range (Figures 2 and 3).

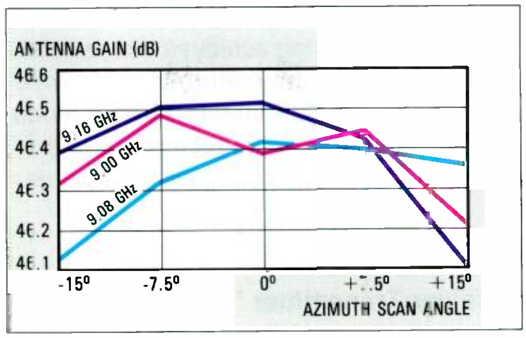


Figure 2
PAR-80 antenna gain as a function of the azimuth scan angle at three frequencies.

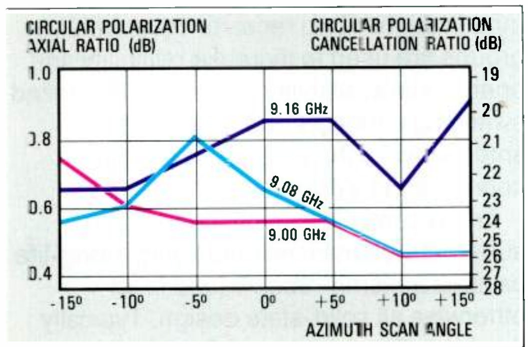


Figure 3
Measured PAR-80 circular polarization axial ratio as a function of azimuth scan angle.

Beam Scanning

PAR-80 functions as a scanning pencil beam system in which the azimuth is scanned electronically while the antenna is mechanically nodded to produce the 7° elevation scan. Several azimuth scan programs are available producing various target hit densities; the elevation scan rate is fixed at 1.5 looks-per-second.

The scan programmer unit stores the azimuth scan programs in read-only memory; it performs a beam steering buffer function, is the source of the azimuth angle data sent to the displays, and is the trigger synchronization source for the system. Typically, the scan programs cause the beam to move in stepping increments of 1.81 beamwidths in azimuth on a pulse-to-pulse basis. This agile beam movement produces antenna discrimination against ambiguous range responses, allowing the system to function correctly with a simple fixed-tuned magnetron transmitter operating at the relatively high pulse repetition frequency of 3450 pulses per second. A sequence of 16 steps of 1.81 beam widths completes one 30° azimuth scan. Successive scans are interlaced at 17/29 of the stepping increment to produce a uniform distribution of the transmissions within the service volume.

In addition to the uniform 30° scan program, eight enhanced zone programs are available that concentrate energy in the immediate vicinity of the preferred flight path; they cover any combination of glidepath angle and courseline offset. These programs reduce the azimuth coverage to 20° using the time thus gained to generate extra beam positions in a 5° sector encompassing the flight path. The enhanced zone produces approximately three times as many hits per scan as are obtained outside the zone.

Beam steering commands are stored in terms of azimuth beam number. The beam steering buffer function performs the necessary arithmetic processing to convert this stored data into the individual commands needed by the 85 phase shifters, including subtraction of the fixed phase shifts of the randomizing blocks.

Elevation scanning uses a motor-driven crank mechanism. The antenna pivots on two support bearings near each side of the antenna, while the crank arm attaches near the bottom of the antenna. An elliptical gear set within the crank drive linearizes the scan motion of the antenna and reduces the turnaround dead time between elevation scans. A digital transducer, connected to the antenna at the left pivot point, provides elevation angle data for transmission to the display group.

This combination of electronic and mechanical scanning achieves the desired beam placement agility without the expense of having one phase shifter for each antenna radiating element. The resulting antenna has excellent beamforming characteristics.

Receiver-Transmitter

The receiver-transmitter group is based on the proven MK-V Quadradar, with minor modifications. Two receiver-transmitter groups are used to increase reliability and operational availability. Remotely controlled switching connects one group to the antenna while the other is on standby connected to a dummy load.

The receiver is a single conversion superheterodyne type employing a long-life passive transmit-receive tube in an otherwise all solid-state design. Typically the noise figure is around 8.9 dB. A low-noise RF (radio frequency) amplifier was unnecessary because of the high antenna gain and relatively low instrumented range of 20 n miles (37 km). The receiver operates with a 30 MHz intermediate frequency, and has a bandwidth of 4 MHz. The receiver has 54 dB of sensitivity time control, and gives the operator a selection between linear, linear fast time constant, or logarithmic fast time constant video.

The transmitter employs a coaxial magnetron driven by a proven reliable line-type modulator. Resonant charging is utilized for the capacitance of a pulse forming network, then a ceramic thyratron is fired to discharge the pulse forming network through a pulse transformer to drive the cathode of the magnetron. The output is tunable between 9.0 and 9.16 GHz; the nominal peak power is 180 kW, with a pulsewidth of 0.24 μs and a pulse repetition frequency of 3450 pulses per second.

Video Processor

The video processor contains the remote video line compensation amplifier and the angle data decoding circuitry that converts the digital angle data from the radar set group into the analog format required by the displays. It also performs video time compression and clutter censoring.

In a scanning pencil beam system of this type, the received target video reports are relevant to both the elevation and azimuth parts of the display. A video time compression circuit retains all data for both parts of the display, and yet allows the display to operate with a single-gun CRT. The video time compression function is performed by converting analog video into digital form and writing it into memory at a 7 MHz clock rate, then reading the data from memory twice at a 14 MHz clock rate. Two video memories are used, each capable of storing all information received during an active radar interpulse period. While one memory is writing data, the other is reading data twice at the higher rate – once for the elevation display and once for the azimuth display.

Video processing circuits include clutter censoring, which prevents off-angle ground clutter from being superimposed with targets of interest on the display. This feature utilizes the inherent high resolution of the pencil beam antenna to detect targets and ground clutter separately, and then selectively eliminate clutter from the display. The censor consists of a series of three-dimensional cells that occupy approximately the bottom half of the radar service volume. Individual cells are 562 feet (170 m) in range, 1.034° in azimuth, and 0.35° in elevation (except for the top layer of cells which is adjustable in elevation). The clutter censor employs a sequential observer algorithm in which a cell is said to contain clutter if video threshold crossings are detected for a time greater than the normally expected dwell time of a moving aircraft. On each sweep of the elevation scan, the volume is examined for threshold crossings. If a preset number of crossings is detected in a cell, the count in the corresponding memory cell is incremented. The threshold level and required number of crossings are adjusted to establish the desired false alarm rate. If that number of threshold crossings is not detected, the count is decremented. When the accumulated count reaches a preset level, censoring is initiated for that cell unless it is deactivated by the *clear zone* logic. The preset switching level for the counter is adjusted to allow the slowest aircraft of interest to traverse the cell without switching.

Clear zones are preset volumes, within the clutter censor operating volume, in which the clutter censor is not allowed to perform its censoring function but allows whatever video is present to be displayed. The clear zones are normally adjusted to include the space immediately surrounding the flight path cursors. For test and

Typical operations center. The smaller CRT displays are for the PAR, the larger ones for airport surveillance radar.

alignment purposes, the clear zone map can be shown on the master display.

Although targets can be detected without using the clutter censor (even when overflying heavy ground clutter) by the difference in time between illumination of the clutter and the target, the censor reduces the flashing effects on the display that result from the elevation scan periodically scanning into the ground. This makes the display less tiring, thereby promoting controller efficiency and flight safety. The clear zone is also a safety feature, designed to prevent the possibility of censoring a target of interest.

Display

The display is based on proven reliable MK-V Quadradar hardware. Some redesign was necessary to provide the higher sweep rates and faster switching times required for compatibility with the video time compression function. Changes were also made to the front panel radar set controls for compatibility with the PAR-80 system.

Two range scales are selectable; a 10 n miles (18.5 km) logarithmic range scale, and a 20 n miles (37 km) linear range scale. The beta-scan format and the logarithmic range scale both expand the display for improved accuracy in the critical vicinity of touchdown. The range mark origin is adjusted to coincide with the range at touchdown. One-mile range marks, with the touchdown mark and every fifth mark intensified, may be displayed on both range scales. Four sets of glidepath and courseline cursors can be preset at each display. In conjunction with the antenna turntable, these facilitate rapid orientation to a new runway when the wind shifts (less than 60 s required to rotate and align to the new runway).

System Test Results

PAR-80 has successfully completed a series of environmental tests, flight tests, and reliability demonstrations. Environmental tests included bench handling, rain leakage, operating temperature (−30 to +52 °C), nonoperating temperature (−62 to +71 °C), humidity (95%), and Munson road tests[1]. The system proved its ability to meet all environmental requirements.

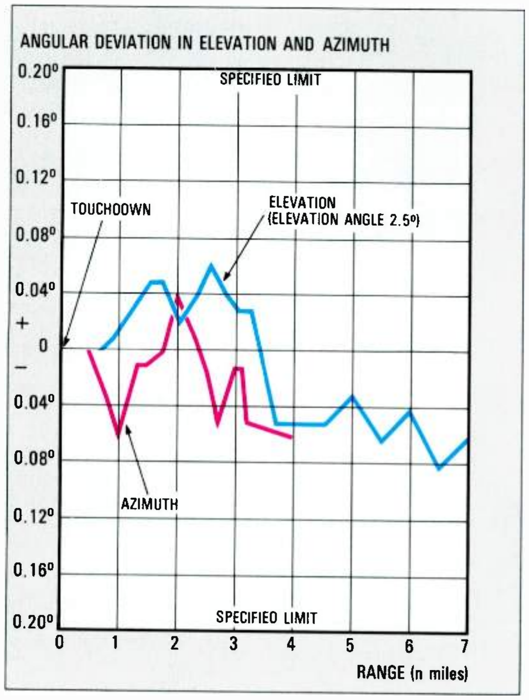


Figure 4
Elevation accuracy and azimuth accuracy of the PAR-80 shown by typical flight test data. Both are well within the specified limits.

Accuracy, resolution, and coverage performance of the system were thoroughly studied during prototype system testing, then each production system underwent flight certification testing prior to commissioning. Outstanding results are routinely achieved. The system has shown a 7 dB performance margin for detecting flight test aircraft at the maximum range of 20 n miles, and peak angular errors are only about one-third of the specified value. Data from accuracy flight tests is shown in Figure 4.

Outstanding system reliability has been demonstrated by PAR-80. Prior to delivery, the prototype system successfully completed a 96 hour burn-in test and a 1500 hour elevation drive test without failure. After delivery, the system completed three months of operational tests without failure. Field experience supports the predicted reliability of 1541 hours mean time between failures.

Conclusions

PAR-80 has the largest aperture antenna of any PAR system. Mainly as a result of its exceptional scanning pencil-beam antenna, the system offers several significant advantages. Full coverage of the approach sector is provided by the raster scanned pencil beam, and the wide azimuth scan capability increases siting flexibility. Resolution and accuracy surpass ICAO requirements.

Detection performance, enhanced by the 46 dB antenna gain, ensures a good safety margin even for detecting small aircraft at maximum range. The high antenna resolution allows targets to be detected separately from clutter, thereby enabling clutter to be eliminated from the display without degrading radar coverage along the flight path.

Angular resolution and circular polarization reduce the rain backscatter energy that is accepted within a radar target resolution cell, while the high antenna gain counteracts the effects of rain attenuation.

Operational availability is enhanced by the solid-state dual-channel design.

Reference

1 ITT Gilfillan: Service Conditions Test Report: ER 1195/1200-1, October 1977.

Robert E. Johnson was born in Iowa in 1930. He served as a radar technician in the United States Army during the Korean war. He received a BSEE degree from Iowa State University in 1956 and joined ITT Gilfillan (then Gilfillan Bros) the same year. His experience has been varied, contributing to the design of missile systems, simulators, ECM/ECCM devices, air defense radar systems, and air traffic control radar systems. He is at present system engineering manager for the air traffic control product line at ITT Gilfillan.

Further Development of the DPS Technique for Precision DME

The double pulse shaping technique is compatible with the latest requirements for precision distance measuring equipment defined by the ICAO. It is particularly suitable where high positional accuracy is required.

G. Corazza
Dipartimento di Elettronica, Informatica e Sistemistica, Università di Bologna, Italy
F. Vatalaro
FACE-RC, Industrie FACE Standard SpA, Pomezia, Italy

Introduction

The standardization of MLS (microwave landing system) by the International Civil Aviation Organization is already well advanced. Final approval of the standards for the elevation and azimuth functions was given in April 1981. The attention of the Organization's AWOP (All Weather Operations Panel) was then focused on DME/P (precision distance measuring equipment).

At the same time, FACE Standard was involved in a sponsored research program which led to an Italian proposal based on the DPS (double pulse shaping) technique, as previously described in *Electrical Communication* and elsewhere[1, 2, 3].

During 1981 and 1982 several meetings of the AWOP and its working groups were held, and many useful results were obtained. Some of the findings resulted in changes to the configuration of the original Italian proposals. In late 1982 the panel completed its work on drafting the SARPs (standards and recommended practices) and related guidelines for the new system[4].

Two accuracy standards were defined: *standard 1* for most conventional take-off and landing operations, and *standard 2* for short take-off and landing and vertical take-off and landing applications, and other special functions. Both standards specify remarkably low upper limits for path following errors: ± 30 m and ± 12 m, respectively, at the MLS approach reference datum. Guidelines were also drawn up for control motion noise, together with detailed error budgets.

In addition the AWOP chose the *two-pulse/two-mode* DME/P system concept which has the following main characteristics:

- Interrogations and replies are still carried out by pulse pairs.
- An initial approach mode is available for aircraft at ranges between about 7 and 22 n miles from the transponder site. In this case the equipment performance is essentially indistinguishable from conventional DME/N, although with slightly higher accuracy.
- At ranges below about 7 n miles the final approach mode applies; this uses a different time spacing between the pulses of the pair than in the initial approach mode (e.g. for *X* channels the time spacing changes from 12 to 18 μs). Clearly higher accuracies are specified in this mode.

During the discussions that led to the choice of system concept, the DPS technique was carefully considered[4]. The discussions recognized that it is a promising technique but too far from the traditional DME concept to be accepted without the support of a large number of field trials. Nevertheless it was also recognized that it is compatible with the *two-pulse/two-mode* concept and that potentially it offers scope for further improvements in system capabilities to cope with advanced applications.

Several requirements concerning the transmitted pulse waveform were also assessed: for the final approach mode the pulse shape is almost fully specified. The pulse must have:

- duration t_d of 3.5 ± 0.5 μs as measured between the 50% points referred to the peak value
- risetime t_r between the 10 and 90% points of less than 1.6 μs
- partial risetime t_{rp} between the 5 and 30% points equal to 250 ± 50 ns.

An example of a pulse with these characteristics is shown in Figure 1.

A further requirement is that the time of arrival estimation must be performed on the first pulse of the pair during the partial risetime; over this interval the pulse shape must be almost linear. In addition the feasibility studies showed up several problems and possible solutions[4]. In order to measure the range, an estimate is needed of the time of transmission of the pulses. This must be derived using the same circuits used to estimate the time of arrival. The receiver bandwidth must be wide enough not to affect received pulse linearity during the partial risetime; a bandwidth of about 3 MHz seems necessary. Therefore, owing to the 1 MHz DME channelization, a channel discriminator[5] is required. The most convenient time of arrival estimation technique seems to be the DAC (delay, attenuate, and compare) circuit; the optimum values of delay and attenuation must be a compromise that takes into account specular multipath signals, thermal noise, and other possible sources of instrumentation errors. It is important to underline that the SARPs impose only essential constraints, thereby allowing manufacturers to look for optimum solutions. In particular, they do not prevent use of the DPS technique.

Designs of the DME/P for Accuracy Standards 1 and 2

Transmission characteristics are rather tightly controlled by the constraint on partial risetime, leaving little room for optimization of the pulse shape. However, few constraints are imposed at the receive side, and those that do exist primarily limit the asynchronous garble produced by pulses in adjacent channels.

A system with the same transmitted pulse characteristics for interrogation and transponder reply is considered here. To comply with the specification, the transmitted signal is obtained by passing a cos/cos² pulse through a low-pass filter with a 10 MHz, 3 dB bandwidth. Figure 1 shows the transmitted pulse $x(t)$ with a partial risetime t_{rp} of 225 ns and maximum transponder effective radiated power of about 57 dBm. Moreover, since the spectral constraints for the interrogator do not limit the absolute effective radiated power, a value of 57 dBm is assumed[4].

To meet accuracy standard *1* the received pulse is passed through a 4-pole Butterworth bandpass filter with 3.5 MHz bandwidth, which has the main characteristic of not distorting the pulse leading edge during the partial risetime. The time of arrival of the detected pulse $u(t)$ is estimated by the use of the DAC circuit in Figure 2, with attenuation A_d = 6 dB and delay τ_d = 95 ns. This choice of parameters ensures that both pulses produced at the output of the DAC delay line and attenuator reach 10% and 20% of their respective peak values at the crossing instant t_c. Thus the crossing instant t_c is contained within the partial risetime of both pulses. The comparator with threshold level V_s protects the circuit against false alarms[3, 6]. Since $u(t)$ must cross the threshold before the instant t_c, V_s is chosen to be 17 dB below the peak value of $u(t)$, giving a 3 dB margin for possible pulse distortion.

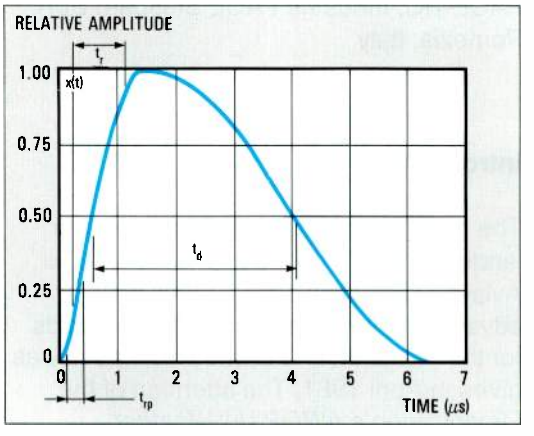


Figure 1
Envelope of DME/P transmitted waveform.

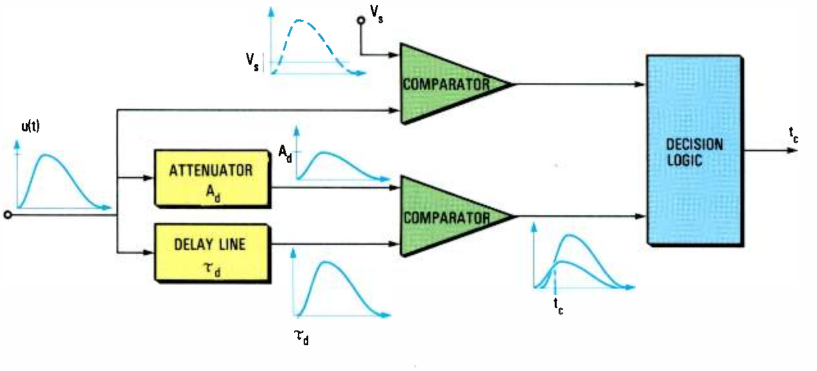


Figure 2
Pulse time-of-arrival estimation using the DAC.

To assess system performance it is necessary to distinguish between the up-link and down-link, to separately evaluate path following and control motion noise errors, and eventually to make sure that they are compatible with a preassigned error budget[4].

The outlined design must first of all comply with the 10 m maximum path following error, which is the upper limit for the one-way specular multipath. This approach is convenient because the containment of multipath error is the most challenging goal of the overall design. The eye-diagram of Figure 3 (curve A) applies; this shows a maximum error of 7.3 m for a multipath signal reaching the receiver with the opposite phase ($\Delta \Phi_e = 180°$), a delay τ_e of 60 ns, and a relative amplitude ρ_e of −3 dB with respect to the useful signal.

The performance with respect to thermal noise must also be in accordance with the SARPs: it is necessary to distinguish between the up- and down-links and to consider the worst case, which occurs during roll-out maneuvers. Assuming the minimum threshold-to-noise ratio Vs^2/N is 8 dB, the highly conservative value of about 1 Hz for the false alarm rate[6] follows. Correspondingly the peak signal-to-noise ratio must be at least 25 dB. The signal-to-noise ratios actually present at the DAC input are given in Table 1 together with the related control motion noise errors[7].

Other error sources must be reasonably controlled, remembering that the global error is given by the square root of the sum of the squares of individual errors. For example, a 60 MHz clock frequency produces a negligible contribution of 1.7 m to the global error when combined with thermal noise. Thus the global control motion noise error appears largely compatible with the error budgets suggested by the AWOP, especially taking into account the interrogator numerical filtering which provides at least a fourfold reduction in the error.

The system described achieves standard *1* accuracy without any special signal processing. However, DPS filtering could be utilized to give a higher threshold with some benefits for system design and manufacture. On the other hand it becomes essential to include suitable signal processing if standard *2* accuracy is required.

In order to reduce the influence of the specular multipath, one approach would be to reduce the DAC delay τ_d using a fixed attenuation A_d: this would give a τ_d of 50 ns, and a specular multipath error of about 4 m. Although this is sufficient for standard *2* accuracy, the crossing levels fall to 5.5% and 2.8%, which violates the requirement that both crossings must occur within the partial risetime. This shows that simple optimization of the DAC circuit is not suitable for achieving standard *2* accuracy. However, the DPS technique processes the received pulse, giving a higher threshold for a particular path following error. This concept is used here to outline a system based on DPS which achieves standard *2* accuracy without violating the SARPs.

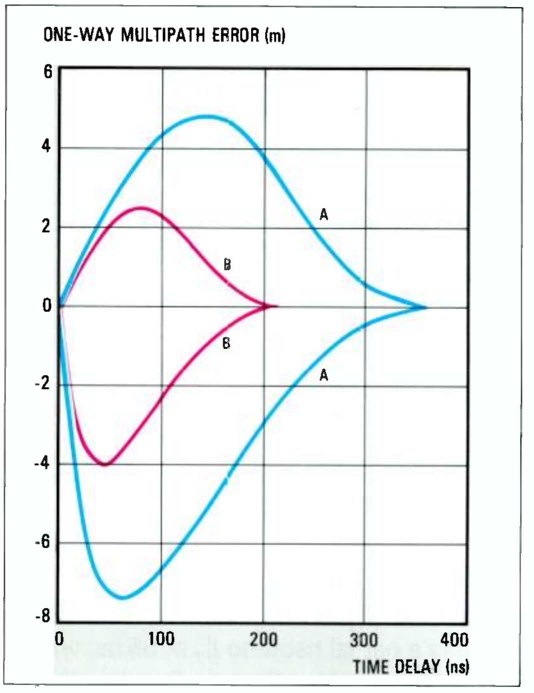


Figure 3
Performance in the presence of multipath of the two systems presented in this paper. Both curves A and B represent one-way errors versus multipath delay: the positive values of curves refer to in-phase ($\Delta \Phi_e = 0°$) multipath and the negative ones refer to out-of-phase ($\Delta \Phi_e = 180°$) multipath. Moreover curve A refers to the system suitable for conventional takeoff and landing operation (accuracy standard *1*), while curve B refers to the one suitable for vertical and short takeoff and landing operation (accuracy standard *2*).

For simplicity assume that up to the output of the receiving filter the system is as described above; as such it can meet accuracy standard *1*. At this point the DPS filter is inserted with the equivalent low-pass transfer function[5]:

$$A'(f) = \left(1 + j\frac{f}{f_1}\right)\left(1 + j\frac{f}{f_2}\right)^{-1}$$

where f_1 is 0.1 MHz and f_2 is 1.7 MHz.

Table 1 — Performance of the standard *1* system in the presence of thermal noise

	Down-link	Up-link
Transmitted power (dBm)	57	57
Received power at roll-out (dBm)	−67	−73
Noise figure (dB)	6	9
Signal-to-noise ratio (dB)	39	30
Thermal noise, control motion noise error (m)	4	12

Table 2 — Performance of the standard *2* DPS-based system in the presence of thermal noise

	Down-link	Up-link
Transmitted power (dBm)	57	57
Received power at 2.5 n miles (dBm)	−53	−52
Noise figure (dB)	6	9
Signal-to-noise ratio (dB)	40.5	38.5
Thermal noise, control motion noise error (m)	3	4

The computations assume that the DPS filter introduces a 13.5 dB attenuation of the useful signal and reduces the receiver noise equivalent bandwidth from 3.5 to 2.8 MHz.

The output pulse $y(t)$, given by $J^{-1}[X(f) \cdot A'(f)]$, is attenuated by 13.5 dB and has a partial risetime t'_{rp} of 65 ns, which is considerably less than t_{rp}. Sending this processed pulse $y(t)$ to the input of the DAC, which is characterized by an attenuation A_d of 6 dB and a delay τ_d of 50 ns, the two crossing points are at 21.4% and 10.7%, which is well inside the partial risetime of $y(t)$.

To evaluate the performance of this system design, first of all the path following error due to specular multipath is considered; this is represented by the eye-diagram of Figure 3 (curve B) which shows that echos delayed by more than about 200 ns do not produce any error at all, and that the maximum error is about 4 m for a τ_e of 40 ns and ρ_e of −3 dB.

The worst case condition for thermal noise effects occurs at a range of 2.5 n miles from the transponder site. Under these conditions the performance of the system based on the DPS technique is given in Table 2; these values are within the standard *2* accuracy limits laid down for vertical take-off and landing. Thus the DPS technique offers an attractive means of successfully designing standard *2* systems.

DPS Technique with Baseband Processing

The DPS technique requires two shaping filters, $A(f)$ in the transmit path and $A'(f)$ in the receive path, located in the linear part of the transmission system[2, 3]. However, it is important to investigate the feasibility of locating the shaping filter $A'(f)$ at the output of the amplitude demodulator in the baseband section of the receiver. If this arrangement achieves the same reduction of specular multipath error, overall system performance will certainly improve because of the reduced influence of garble from adjacent channels. In addition, it is more obviously compatible with the SARP specifications.

For these reasons specular multipath errors were numerically computed for the system with DPS filtering at baseband, following the usual echo model. The resulting eye-diagrams corresponded closely to those for a receiving DPS filter at intermediate frequency: a maximum one-way echo error of 4 m was again obtained, giving standard *2* accuracy.

An experimental setup was also constructed for system validation. A transmitter generates RF pulses which are sent into two channels to produce direct and multipath signals with adjustable relative amplitudes, phases, and delay. These two signals are added and presented to the receiver and the following processors. The envelope of the transmitted pulse has a risetime of 2.1 μs and is not exactly as defined by AWOP, but is satisfactory for validation purposes. The RF subsystems used inside the experimental setup are described elsewhere in this issue[8]. The DPS filter, which has an 18 dB signal attenuation, shapes the pulse at baseband to achieve a partial risetime of 220 ns. The DAC, which follows the DPS filter, has a 16 dB attenuation and a delay of 325 ns. Figure 4 illustrates the results of the measurements. The solid curves represent the theoretical errors due to multipath signals with relative amplitudes of −6 dB, −3 dB, and 0 dB. The points correspond to measurements in the presence of a multipath signal with relative amplitudes of −6 dB (+), −3 dB (×) and 0 dB (0). The measured results are all in good agreement with the theoretical computations.

Conclusions

Recent investigations have aimed at assessing how the DPS technique can be used within the framework of the new precision DME system. DPS is applicable to the new system, possibly providing some potential for growth. In particular, signal processing is needed to achieve the accuracy standard *2*; this has been demonstrated as feasible with a DPS-based system. Finally, DPS can also be implemented by locating the receiving filter at baseband, with the advantage of lower cost combined with good performance.

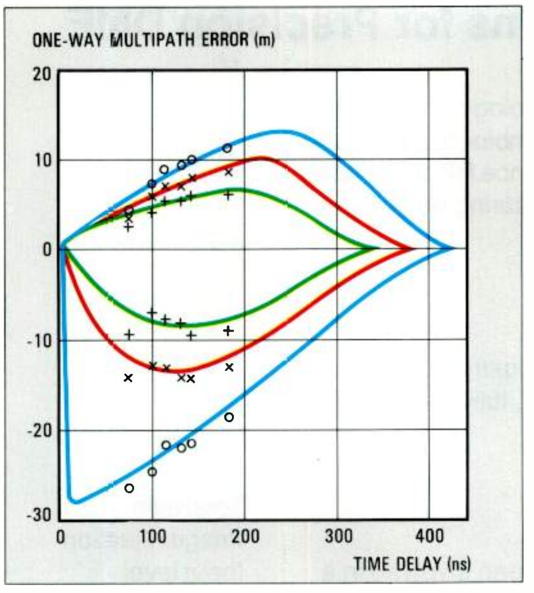


Figure 4
Comparison of theoretical and experimental results referred to multipath error. Green curve represents the theoretical error in the presence of one multipath signal with −6 dB relative amplitude: the +s indicate related measured errors. Red curve represents the theoretical error in the presence of one multipath signal with −3 dB relative amplitude: the xs indicate related measured errors. Blue curve represents the theoretical error in the presence of one multipath signal with 0 dB relative amplitude: the 0s indicate related measured errors.

Acknowledgments

The authors wish to acknowledge the technical direction of the CNR program "Aiuti alla Navigazione Aerea e ATC" and particularly Prof F. Valdoni and Prof M. Carnevale for valuable support during their research. Prof G. Falciasecca has also provided useful discussions and advice.

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Giorgio Corazza was born in Bologna in 1946. He received a Dr-Ing degree in electronic engineering from the University of Bologna in 1969, and then joined the Institute of Electronics at the University as assistant professor. From 1974 to 1976 he was associate professor for pulse and digital circuits. Since 1977 he has been associate professor and lecturer in electrical communication, specializing in digital systems and navigation aids. Dr Corazza is a member of the Italian Electrical Association and of the Institute of Electrical and Electronics Engineers.

Francesco Vatalaro was born in Vibo Valentia in 1953. He received a Dr-Ing degree in electronic engineering from the University of Bologna in 1977 and then joined the research center of Fondazione Bordoni at Pontecchio Marconi. In 1980 he joined FACE Standard to work on defining and developing the DME/P equipment. He is at present working on the reception of television signals broadcast from satellites. Dr Vatalaro is a member of the Italian Electrical Association.

RF Subsystems for Precision DME

Advanced device technology and design methods have been combined to produce compact, high performance RF subunits for precision distance measuring equipment.

F. Ardemagni
P. Basile
A. Clementi
Laboratorio Centrale Industrie FACE
Standard SpA, Pomezia, Italy

Introduction

Since 1977 FACE has been involved in a research programme sponsored by the Italian National Research Council to define an L-Band DME/P (precision distance measurement equipment) that will gain acceptance from international bodies such as the International Civil Aviation Organization.

Following an original report in *Electrical Communication*[1], further theoretical studies and hardware simulations have been undertaken[2]. A number of L-Band subsystems have been developed by the FACE research center for full system evaluation, including simulation of the airborne interrogator. Advanced technology, including high permittivity soft substrate microwave integrated circuits, has been combined with computer aided design techniques to achieve a state-of-the-art development.

Low Noise Front-End

The performance of a low noise, mechanically tuned front-end was considered appropriate for the DME/P ground equipment simulation. The main characteristics of the equipment are:

Frequency range	1 025 to 1 150 MHz
Noise figure	3.5 dB maximum
Total gain	20 dB minimum
Image rejection	80 dB minimum
Input level	−10 dBm maximum
IF	63 MHz
IF bandwidth	3.5 MHz (3 dB)

As shown in Figure 1, the subsystem consists of a 2-stage bipolar low noise amplifier directly coupled to a fifth order comb-line filter. This is followed by a Schottky diode balanced mixer and IF preamplifier for the first frequency conversion, and a steep IF filter with the characteristics necessary to meet the system requirements. The local oscillator signal is generated by an external frequency synthesizer.

A compact front end has been realized by using a multibox package with the relatively large comb-line filter placed underneath the RF (radio frequency) thin-film circuit. Connections to the filter are made by coaxial links through the separating wall.

To minimize their size, the low noise amplifier and mixer have been implemented in microstrip technology on a soft, teflon-based high permittivity substrate. The fifth order image rejection filter was realized using coaxial line owing to the resonator's high unloaded Q_o required to achieve the specified 80 dB minimum rejection. The comb-line configuration was chosen for its compactness and the convenience of end-adjustable capacitors all located on one side of the structure, thus facilitating integration into the complete assembly. Tuning to a required center frequency f_o is achieved by adjusting the micrometer screws to specific settings given on a calibration sheet. The open end of each screw forms a parallel plate capacitor with its opposing cylindrical resonator.

Critical design areas have been mainly concerned with direct coupling between the high gain, low noise amplifier and the filter, which could result in instabilities at lower

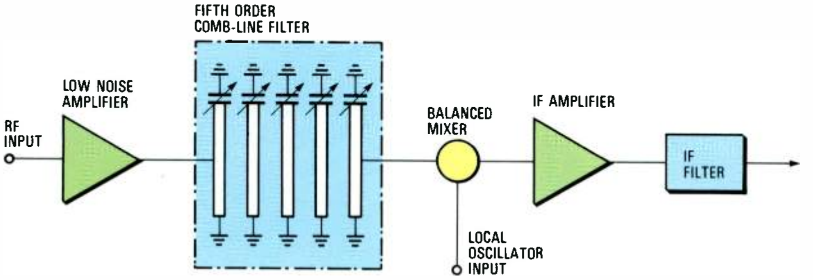
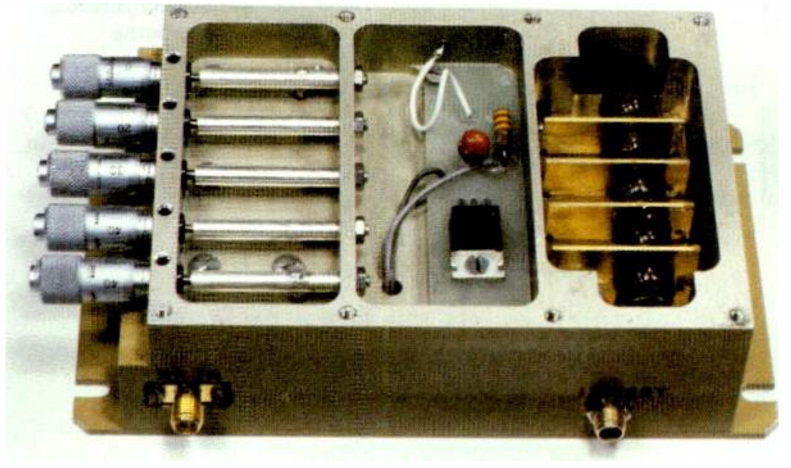


Figure 1
Low noise mechanically tuned front-end.



Top view of low noise mechanically tuned front end.

box. No significant improvements in the mixer conversion loss were found when the input line length was varied in an attempt to recover image frequency power.

Figure 2 shows the noise figure and the overall conversion gain (taken at the instantaneous center frequency f_o) over the full tuning range.

Table 1 — Design objectives

	Airborne	Ground
Peak power output	700 W	200 W
Frequency band	1 025 to 1 150 MHz	960 to 1 215 MHz
Gain	≥ 48 dB	≥43 dB
Pulse width (at 50%)	3.5 μs	3.5 μs
Duty cycle	0.1%	5%
Pulse shape output	See Figure 3	See Figure 3
Efficiency	≥ 20%	≥ 20%
Input voltage standing wave ratio	≤ 1.5	≤ 1.5

frequencies. For this reason a computer aided design program[3] has been used to optimize the input-output matching networks and to analyse the stability of the amplifier when terminated with highly reflective loads.

This design program was also used to analyze the optimum tapping position of the input and output lines to the first and last filter resonators. Some experimental adjustment were necessary in mechanical positioning of filter input/output lines in order to reduce excitation of waveguide modes and unwanted coupling inside the

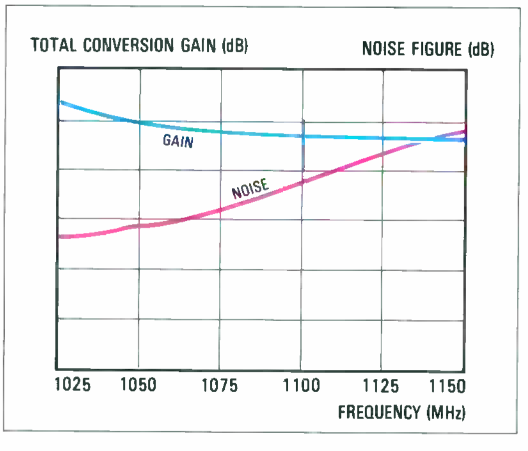


Figure 2
Noise figure and conversion gain for the overall front end.

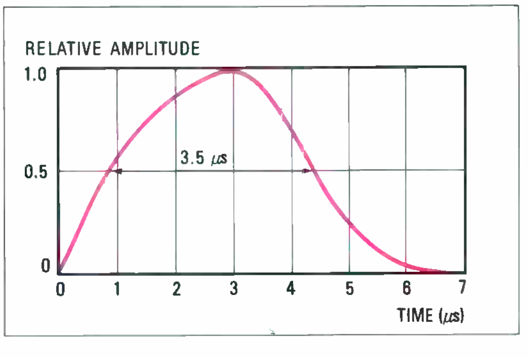


Figure 3
Envelope of transmitter output pulse.

High Power Transmitters

Solid state transmitters have been designed for both ground and airborne equipment. The main differences between them are the bandwidth, peak power, and duty cycle. Design objectives are summarized in Table 1. The general philosophy used follows the well-proven designs of Graziani[4] adopted for DME equipment produced by FACE over many years. The modulating waveform consists of an appropriate pedestal pulse plus a pulse with the true modulation shape, which in this case is not Gaussian but has the form shown in Figure 3. Although this waveform is slightly different from that specified by the International Civil Aviation Organization, it is considered suitable for experimental purposes.

Each RF amplifier consists of three main blocks: a preamplifier, a driver modulated with a pre-distorted pulse to obtain the requires waveshape, and a pseudo-linear power amplifier. As an example, Figure 4 shows a block schematic of the airborne transmitter. Computer aided design has been used extensively for both ground and airborne RF amplifiers. To demonstrate the methodology, the airborne transmitter is described in the following paragraphs.

The class AB preamplifier was designed by the S-parameters method in spite of the fact that some non linearity was present.

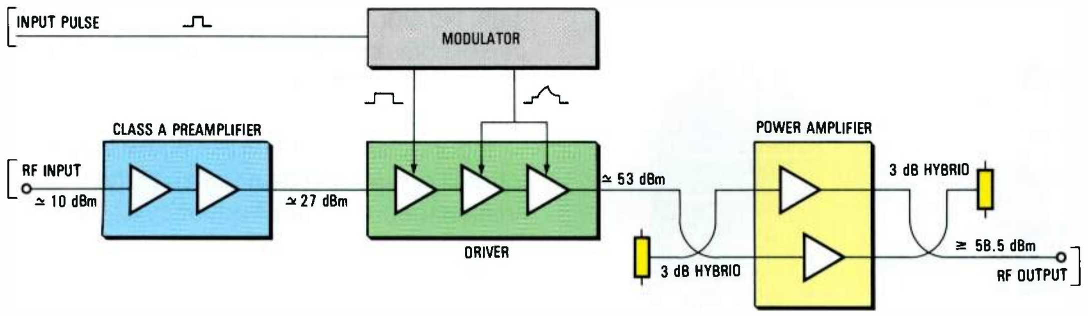


Figure 4
Block schematic of the airborne transmitter.

This was accepted because of the small measured variations of the S-matrix at working power levels. Transistor parameters were obtained by an automatic network analyzer over the required frequency band and processed to select input/output matching characteristics that combine flat input voltage standing wave ratio with gain roll-off compensation.

A final optimization over the complete bandwidth was then performed to achieve maximum flatness and stability. Obviously, this linear approach cannot be used for characteristics of the pulsed, class C amplifier stages that form the driver and final output. In this case each transistor was inserted in a special fixture with a pair of input/output tuners and fed with the nominal input power at a fixed frequency f_x. The tuners were then adjusted for minimum reflection and maximum gain. Optimum reflection coefficients $[G_{opt}(f_x)]$ and $[L_{opt}(f_x)]$ were determined by removing the transistor and looking from suitable reference planes towards the generator and the load with a low power network analyzer at the same frequency f_x. Repeating the procedure for a number of frequencies over the range of interest led to a full transistor characterization. The whole sequence of operation, except for tuner adjustment, was performed by an automatic test bench controlled by a microcomputer. An important feature of this experimental arrangement is the possibility of obtaining a great deal of related data, such as the transistor behavior when bias, peak power, or duty cycle are varied.

Once the active components had been fully assessed, suitable input/output and interstage matching networks were derived by computer aided design techniques, using the same methodology as for the preamplifier. Figure 5 shows the transmitter output peak power as a function of frequency.

The airborne transmitter and the L-Band amplifier for the ground equipment are shown opposite. The main difference between the two equipments is concerned with the modulator; in the case of the ground equipment, pulsed video signals are fed to the RF transistors by connections through the common wall of the double box package.

All the circuit stages except the balanced final stage of the airborne equipment are arranged transversely. This solution has proved to be compact and offers easy access for final testing.

As in the case of the previously described front-end, all the RF circuits have been constructed using microstrip on soft, high permittivity substrates.

Acknowledgments

The authors wish to thank P. Monti and G. Selvazzo for synthesizer development, and F. Cecchini and M. Caruso for support in thin-film circuit implementation.

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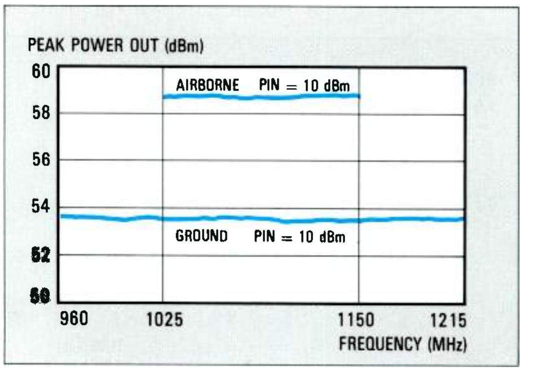

Figure 5
Transmitter output peak power as a function of frequency.

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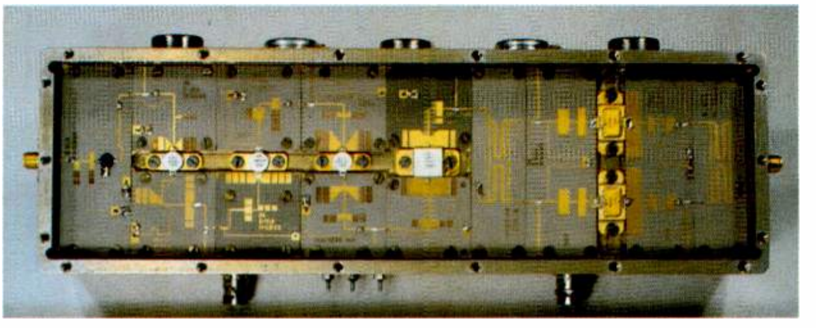
Fiorenzo Ardemagni was born in Milan in 1945. He studied telecommunications at the Istituto Radiotecnico A. Beltrami, Milan, where he was awarded a degree in 1964. After graduation he spent time at GTE Telecomunicazioni, Telettra, and Selenia working in the filed of microwaves. He was awarded a doctorate in physics from the University of Milan in 1976.
Dr Ardemagni joined FACE Standard in 1979 to create a microwave department, for which he is now responsible. He is a member of the Institute of Electrical and Electronics Engineers.

Piero Basile was born in Pescara, Italy, in 1948. He was awarded a Dr-Ing degree in electronic engineering from the University of Rome in 1975, and then joined GTE Telecomunicazioni. After a period at SIT Siemens he rejoined GTE to work on microwave subsystem design. Since 1980 he has been with FACE Standard working on the design of RF subsystems for the precision DME, and more recently as project engineer for terminal receivers for the direct broadcasting satellite. Dr Basile is a member of the Italian Electrical Association.

Armando Clementi was born in Rome, Italy, in October 1951. He was awarded a Dr-Ing degree in electronic engineering from the University of Rome in 1977, and then joined Litton Italia to work on military systems. In 1978 he joined the research center of FACE Standard where he has been involved in the design of microwave subsystems for avionics, and more recently as project engineer for a mobile communication system.



Airborne transmitter (above), and L-Band amplifier for the ground equipment (below).

Fiber Optic Gyroscope

Fiber optic gyroscopes are being developed for use as strapdown rotation rate sensors in inertial navigation systems. In this application, the major requirements are for low drift and high angular rate capability.

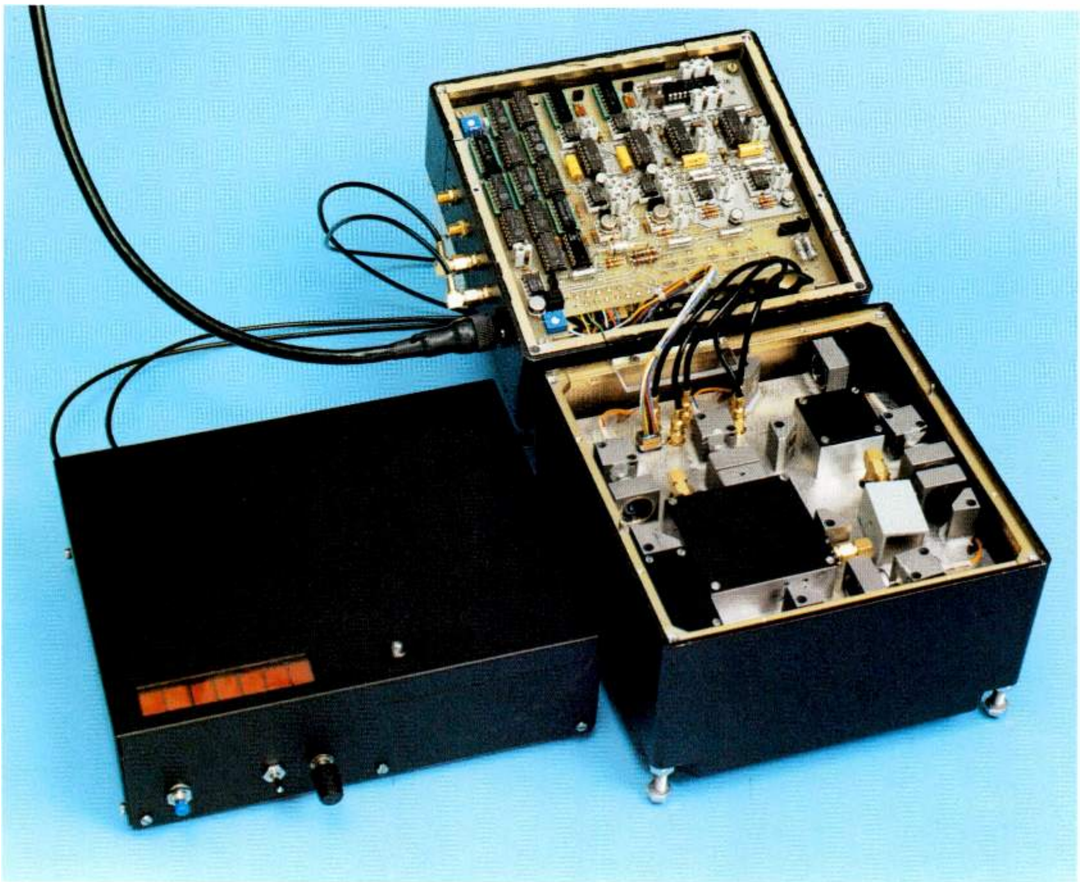
W. Auch
E. Schlemper
Standard Elektrik Lorenz AG, Stuttgart, Federal Republic of Germany

Introduction

In 1850 Foucault first used a momentum-free spinning mass to demonstrate the earth's rotation – just two years after his famous pendulum experiment. In the following decades, the development of rotating wheel gyroscopes as rotation rate detectors was strongly influenced by stabilization, orientation, and navigation requirements for ships, vehicles, and aircraft. Thus today many miniature conventional gyroscopes are available, some of which achieve scarcely believable accuracies. Nevertheless, the search for nonmechanical alternatives continues.

As far as can be ascertained, about 10 types of nonmechanical rotation rate sensor are being studied in various research laboratories. These include the nuclear magnetic resonance gyroscope, the superconductive absolute rotation-determining equipment, and different types of optical gyroscope.

One motivation for the considerable effort being expended on research and development of new gyroscope technologies is the manufacturer's dream of high sensor reliability, simplicity, easy manufacture, and low cost. Another aim of nonmechanical approaches is to provide the user with a gyroscope that combines



Model of an SEL fiber optic gyro.

low drift with a high dynamic range – the so-called strapdown sensor.

Optical Gyroscopes

Strapdown gyroscopes are rugged, high-performance sensors that can be attached directly to a vehicle; they must be able to operate under adverse conditions over a wide dynamic range. The major advantage of strapped inertial sensors is their ability to provide simultaneously data for navigation, heading, or altitude information, or any other function that requires inertial information.

A very promising technology for use in adverse environments is the optical gyro. This type of gyro is inherently free of the limitations at high angular rates and wide dynamic ranges that affect mechanical gyros with their spinning masses. The active ring laser gyro, which is based on a helium-neon laser, is already in production.

Compared with the ring laser gyro, the fiber optic gyro is at an early stage of development. It offers the potential, however, of becoming the first low-cost, all solid-state optical gyro. This potential is based on the full use of optical components and optical communication technologies (e.g. semiconductor lasers, light emitting diodes, optical fibers, detectors, integrated optics). The major effort and the millions of dollars being spent worldwide in the field of optical communication should pave the way for the cost-effective production of a fiber optic gyro. In addition, the fiber optic gyro does not exhibit the lock-in effect which prevents the ring laser gyro from working below a certain rotation rate threshold unless expensive modifications are made.

Sagnac Effect

As the principle of fiber optic gyros has been thoroughly described elsewhere[1 through 8], only an outline is given here. This gyro is basically a Sagnac interferometer (Figure 1), which was first described in 1913. Rotation of the interferometer about an axis orthogonal to the plane of light propagation induces a phase shift $\Delta\Phi_s$ between the counterpropagating light beams

$$\Delta\Phi_s = \frac{8\pi A}{\lambda c}\,\omega \qquad (1)$$

where

ω – angular rate of rotation
λ – freespace wavelength
c – freespace velocity of light
A – effective interferometer area.

With the advent of monomode fibers it became possible to enclose a large effective area within a small space by launching the counterpropagating waves into an optical fiber (length L) wound on a cylindrical spool of radius R. In this case Equation (1) becomes:

$$\Delta\Phi_s = \frac{4\pi RL}{\lambda c}\,\omega \qquad (2)$$

In a typical design with $L = 1$ km, $R = 70$ mm, and $\lambda = 850$ nm, the Sagnac phase shift $\Delta\Phi_s$ varies between 0.001 and 1000° for angular rates of rotation ω between 1° per hour and 300° per second, respectively.

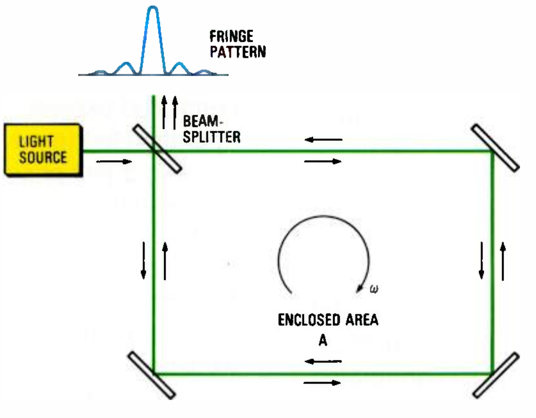


Figure 1
Sagnac-type interferometer.

An area of concern in any passive laser gyro is the readout of the Sagnac phase $\Delta\Phi_s$. The phase difference between counterpropagating waves is measured as a cosine-dependent change of intensity $I = I_0\,(1 + \cos\Delta\Phi_s)$ thus yielding an ambiguous output when ω exceeds about 50° per second in the above example.

Investigations into fiber optic gyros by various research groups have resulted in guidelines being drawn up for the design of a practical device. These guidelines are summarized in the so-called "minimum configuration" and are commonly agreed. According to this minimum configuration, a practical device has to possess:

- reciprocal construction to ensure that counterpropagating waves travel along exactly the same path
- means to stabilize or randomize polarization

- nonreciprocal modulation technique to achieve an AC readout in order to eliminate low frequency noise and drift associated with the detectors and electronics
- phase compensation loop to ensure a linear unambiguous readout over the angular rate of concern.

Concept

Figure 2 shows the configuration being developed at Standard Elektrik Lorenz. The laser beam passes through beamsplitter *1*, enters the spatial filter, and is separated at beamsplitter *2* into two coherent waves traveling clockwise and counter clockwise. After they have propagated through the fiber, beamsplitter *2* recombines the counterpropagating waves and the interference signal is fed back to the detector via the spatial filter and beamsplitter *1*. In this configuration, reciprocity of the complete light path is achieved by inserting beamsplitter *1* and the spatial filter[9].

The required nonreciprocal phase modulation and phase compensation are introduced by the frequency modulators (Bragg cells *1* and *2*)[10].

As soon as the driving frequencies of the two Bragg cells become unequal, a nonreciprocal phase $\Delta\Phi_{Bragg}$ is generated which is proportional to the frequency difference Δf between the counterpropagating waves in the sensor fiber:

$$\Delta\Phi_{Bragg} = 2\pi \frac{nL}{c} \Delta f \qquad (3)$$

This nonreciprocal and adjustable phase $\Delta\Phi_{Bragg}$ compensates, in closed loop operation, the rotation-dependent Sagnac phase $\Delta\Phi_s$ so that:

$$\Delta\Phi_s = \Delta\Phi_{Bragg} \text{ or}$$

$$\Delta f = \frac{2R}{n\lambda}\omega \qquad (4)$$

Hence in closed loop operation the frequency difference between the two Bragg cells is linearly dependent on the angular rate ω. The inherent pulsed output of the frequency modulator concept should be noted.

The nonreciprocal phase switching and phase compensation of this concept (Figure 2) can be easily understood. Bragg cell *2* is periodically switched between the two fixed frequency oscillators f_H and f_L. The frequency difference $f_H - f_L$ is chosen to produce a nonreciprocal phase $\Delta\Phi_{Bragg} = \pi$ according to Equation (3). Without rotation the output frequency f_{VCO} of the voltage controlled oscillator settles in closed loop operation to the mean value $(f_H + f_L)/2$, thus causing $\pm\pi/2$ phase switching (Figure 3). The resulting output at the photodetector is a DC signal.

On rotation of the fiber optic gyro, the Sagnac phase shift $\Delta\Phi_s$ gives rise to nonsymmetric phase switching, thus exciting an AC signal at the photodetector. The amplifier, bandpass filter, and integrator shift the VCO output frequency until the AC signal disappears. Hence $\Delta f = f_{VCO} - (f_H + f_L)/2$ becomes directly proportional to ω.

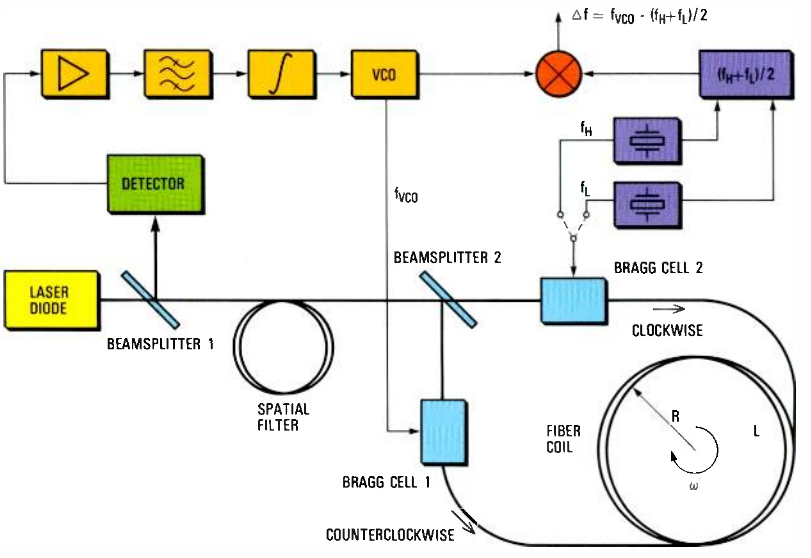


Figure 2
Fiber optic gyro concept being developed at Standard Elektrik Lorenz.
VCO - voltage controlled oscillator.

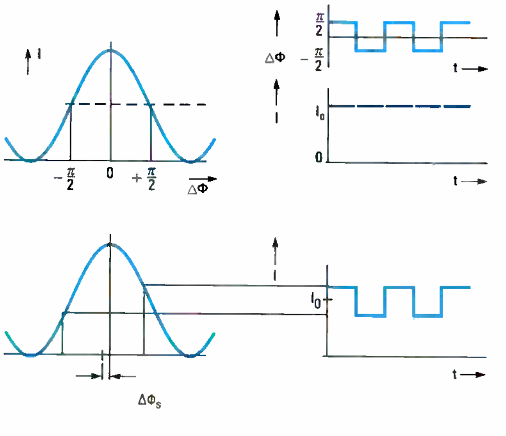


Figure 3
Fiber optic gyro readout.

Test Results

The fiber optic gyro concept shown in Figure 2 has been extensively tested during the past year with three experimental setups. Table 1 summarizes the geometric parameters and the scale factors of these models.

Figure 4 shows the short-term noise of the three interferometer output signals for open-loop operation. Open-loop measurements were taken to achieve noise values which were not influenced by the design of the phase-nulling control loop. The noise values were measured with a 125 ms integration time, which corresponds to a 1 Hz bandwidth in the case of the filter characteristics of the lock-in amplifier.

Noise density of the 850 nm laser diode models compares favorably with the helium-neon laser. Extended noise measurements with the helium-neon version showed that the major noise source was frequency switching itself, rather than shot noise, amplitude noise of the source itself, or Rayleigh backscattering of the fiber (which is suppressed by the different steering frequencies of the Bragg cells).

For inertial applications the required parameter is the integrated rotation rate, namely the rotation angle. Assuming that white noise is the limiting factor for the measurement of rotation rate, the standard deviation of the rotation angle can be calculated as a function of the noise of the rotation rate signal measured in a given bandwidth. A noise density of $(1°\ \text{hour}^{-1})^2\ \text{Hz}^{-1}$ leads to a standard deviation in the rotation angle of 0.013° $\text{hour}^{-0.5}$ which varies with the square root of the integration time ("random walk" in angle).

Comparing this standard deviation of 0.013° in the rotation angle with the results obtained for bias instability (± 3° per hour, measured in an 8 hour period), there is a difference of two orders of magnitude, which means that bias instability must be reduced before improved noise results can be achieved.

Assessment of Test Results

Any assessment of the performance of the fiber optic gyro must be related to future requirements for inertial navigation equipment. Many such requirements depend largely on the particular application.

Table 1 – Geometric parameters and scale factors of the tested gyro models

Model	(a)	(b)	(c)
	Standard single-mode fiber		Polarization-preserving fiber
Wavelength λ	633 nm	855 nm	829 nm
Radius R	0.15 m	0.07 m	0.06 m
Length L	1180 m	1055 m	937 m
Scale factor	1.57 Hz/°/h	0.54 Hz/°/h	0.46 Hz/°/h

As an example, the requirements for drift rate vary from about 0.02 to 100° per hour.

A typical application for the 5 to 100° per hour range is tactical weapon delivery. Gyros in air-to-air missiles with short flight times typically have to satisfy the following requirements: drift of 10° per hour; random walk of 1° $\text{hour}^{-0.5}$; angular rate of 1000° s^{-1}; and a scale factor stability of 5×10^{-4}. Although it is dangerous to compare laboratory test results with series production requirements, there is sufficient margin in the present results to meet these requirements.

The upper boundary on performance is required for navigation. Gyro accuracies will vary between 0.02 and about 3° per hour, depending on the flight time. Gyros in a 1 n mile per hour strapdown inertial system have to meet the following requirements: drift of 0.02° per hour; random walk of 0.001°

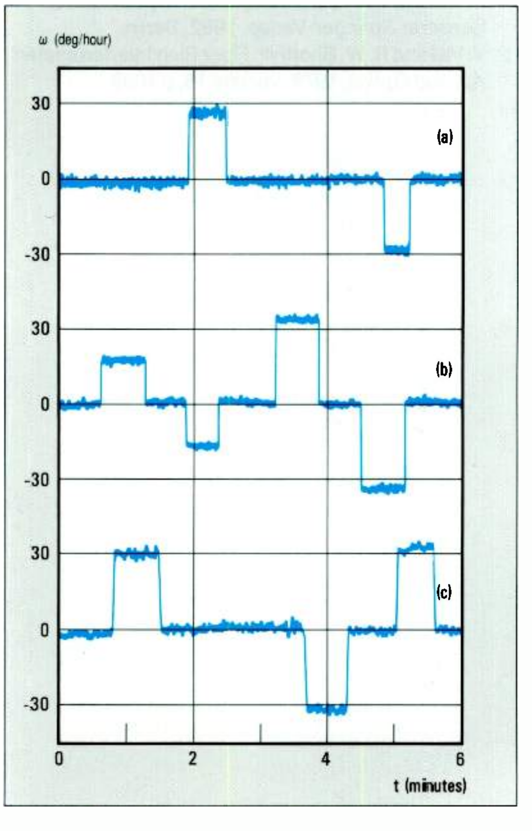


Figure 4
Open-loop output signals: (a) 633 nm standard single-mode fiber; (b) 855 nm standard single-mode fiber, and (c) 829 nm polarization-preserving fiber.

hour$^{-0.5}$; angular rate of 500° s^{-1}; scale factor stability of 10^{-5}.

At present it is difficult to project with any accuracy what drift improvements can be achieved in the near future. However, it must not be forgotten that fiber optic gyro drift analysis is a new area for study, that present test models allow precise separation of drift origins, and that recent test results already show that drift rates as low as ± 3° per hour can be achieved.

Conclusions

Initial test results show that medium-performance requirements can, in principle, be met with fiber optic gyros. Beyond this application, there are indications that such gyros will be able to satisfy the even more demanding requirements for navigation. In terms of dynamic range and noise, the fiber optic gyro already performs remarkably well. Dynamic range is clearly not a matter of concern in fiber optic gyros with frequency modulators. One can say that if the vehicle can cope with the dynamics, the gyro can do so as well. However, to become a viable option as a strapdown sensor in inertial navigation systems, considerable development is still necessary to improve the drift behavior.

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W. Auch was born in Waldenbucher, Germany, in August 1949. He received his Diplom-Physiker degree from Stuttgart University in 1977, and his Dr rer nat degree in 1980 for his work on optically pumped nuclear polarization in solids. He joined SEL in 1980 as a system planning engineer. Since 1982 Dr Auch has been head of fiber gyro development at SEL. He is a member of the Optical Society of America.

Eberhard Schlemper was born in Erbach, Germany, in 1945. He received a Dipl-Ing degree in electrical engineering from Stuttgart Technical University in 1971. The same year he joined SEL to work on the development of telemetry and telecommand equipment for satellites. In 1977 Mr Schlemper transferred to the system planning group, and is now technical manager of the SEL Avionics Division with responsibility for radio and self-contained navigation equipment.

Off-Shore Helicopter Radio Navigation Using DME-based Positioning System

A DME-based positioning system is being developed for all-weather helicopter operations in oil-rig terminal areas. The system combines proven DME techniques with advanced angle determination based on array signal processing.

M. Böhm
Standard Elektrik Lorenz AG, Stuttgart,
Federal Republic of Germany

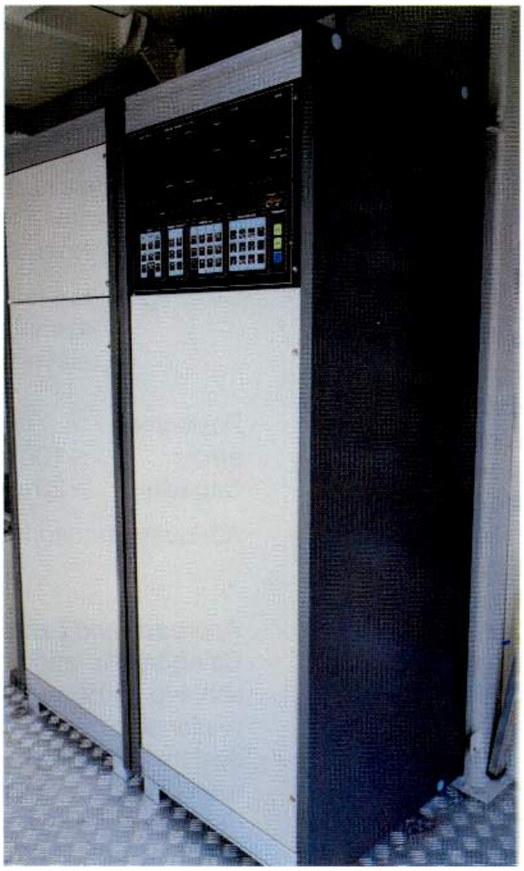
Introduction

The airborne supply system for oil-rigs in the rough environment of the North Sea is based exclusively on helicopters. While present regularity of flights in that area is already 95%, the ever increasing air traffic requires the improvement of navigational accuracy as well as air traffic control procedures, to at least maintain safety and economy of flight operations for the future.

Five flight phases have to be considered: take-off on shore, shore TMA, en-route, rig TMA, and landing on rig. The last three are of particular importance to improve the present situation:

- En-route, with 25 n miles minimum spacing owing to limited Omega accuracy in the eastern North Sea. A more accurate system is required to support Omega or to take over when loss of Omega signals occurs.
- TMA navigation is still frequently based on nondirectional beacons, with 5° to 10° azimuth error and no distance information. Complete and accurate positioning information is required.
- Present landing on Norwegian oil-rigs is characterized by the given visibility minima (range 800 m, altitude 200 ft) and the use of a conventional airborne radar and altimeter. This situation could be dramatically improved by using a Category IIIc landing aid, which would enable nearly 100% of flights to be completed.

To improve the situation for all phases of a flight, the application of a system called DPS (DME-based positioning system) has been proposed[1]. This multifunction L-Band system comprises the present ICAO DME, the future precision DME and DAS, and HAS (DAS with added direction finding for elevation). DPS will be very economic and able to meet present and future requirements for efficient and safe helicopter navigation over sea and land. The amount of airborne equipment will be about the same as for present DME. DPS is an evolutionary approach that takes advantage of proven DME technology (Table 1)[2] and avoids the technical and economic risks of complexity.



DAS electronic equipment.

Table 1 — Main specifications of DME systems

System		Nominal pulse risetime	Processing bandwidth	Trigger method	Interrogation pulse spacing	Reply pulse spacing	Maximum system error	
							Standard *1*	Standard *2*
DME/N		2.5 μs 10 to 90%	0.5 MHz	HAF	x: 12 μs y: 36 μs	x: 12 μs y: 30 μs	370 m or 0.25% of distance, whichever is the greater*	
DME/P	IAM	250 ns 5 to 30%	0.5 MHz	HAF	x: 12 μs y: 36 μs w: 24 μs z: 21 μs	x: 12 μs y: 30 μs w: 24 μs z: 15 μs	250 m at 22 n miles 85 m at 7 n miles	
	FAM	250 ns 5 to 30%	3.5 MHz	LL-DAC	x: 18 μs y: 42 μs w: 30 μs z: 27 μs	x: 12 μs y: 30 μs w: 24 μs z: 15 μs	85 m at 7 n miles 30 m at 2 n miles	85 m at 7 n miles 12 m at 2 n miles

HAF - half amplitude finder
LL-DAC - low level delay and compare trigger
IAM - initial approach mode activated at more than 7 n miles
FAM - final approach mode, activated at less than 7 n miles
* The DME/N transponder of the DAS ground station for the offshore TMA will have a smaller error, such that, combined with the DME/P (IAM) of the airborne DAS, a system error of less than 100 m is achieved.

Future Operational Requirements[3,4]

En-route Navigation

An appropriate navigation method should be available over the complete route down to altitudes of 1000 ft mean sea level. Requirements for en-route navigation are:

coverage: ≥200 n miles
positioning error: ≤1 n mile
capacity: 20 to 50 aircraft.

TMA Navigation

The requirements here may differ between a single isolated rig and a group of rigs such as the Ekofisk Field, in range as well as in azimuth coverage. System requirements are governed by the maximum size of the area to be served, the number of aircraft simultaneously using the TMA navigation aid(s), future air traffic control requirements, and guidance for rescue services.

The off-shore TMA navigation system should allow for simultaneous uninterrupted guidance of up to 20 helicopters under instrument meteorological conditions. Flights along parallel and opposite tracks between oil-rigs within the area should be safely conducted with a horizontal separation of about 1 to 2 n miles and without the need for vertical separation; altitude flexibility is essential during icing conditions in winter.

The navigation system should provide guidance with an accuracy to pass obstacles (oil-rigs, flare stacks) as close as 0.5 n mile. Approaches to a helideck should be safe to a point 0.5 n mile from the oil-rig.

Navigation guidance should be provided down to a minimum height of 200 ft within an area about 30 n miles in diameter, and down to 500 ft mean sea level within an area of approximately 50 n miles diameter. Maximum range should be 50 n miles at altitudes of 10000 ft.

Automatic transfer of information to all aircraft is desirable. Helicopter position data, if available on the ground (oil-rig station), would significantly improve air traffic control capabilities. Finally, navigation guidance down to sea level is desirable for rescue purposes.

The requirements for TMA navigation are:

Coverage:	range	≥40 n miles
	azimuth	360°
	elevation	≥20° (preferably from sea level)
Positioning error:	≤100 m	
Capacity:	≥20 aircraft	

Adequate monitoring is essential.

Approach and Landing Navigation

Category IIIc landing is necessary to achieve 100% regularity of flights. A reasonable interim solution would be a system allowing an approach in instrument meteorological conditions down to the final decision point 60 ft aside and 40 ft above a helideck. From there a standard approach could be made under visual meteorological conditions.

Coverage is largely determined by the landing procedure; briefly the requirements are:

Coverage:	range	≈ 2 n miles
	azimuth	≈ 270° total
	elevation	2° to 20° (from helideck)
Positioning error:	range	≤ 12 m
	angle	lateral error ≤ 4 m at 0.1 n mile ≤ 75 m at 2 n miles
Capacity:	≥ 5 aircraft	

Again, adequate monitoring is essential.

Air Traffic Control

If air traffic control is to be established in an oil-rig area, the control center must be able to locate all aircraft within its zone. Reporting of position, time, and altitude by aircraft at given reporting points or on request is the simplest way. A more convenient and safer method would be automatic continuous position reporting (e.g. using secondary surveillance radar), with coverage and accuracy of the same order as that of the navigation system.

DPS – A Navigation Method for Severe Environments

DPS is a sound method for meeting most future operational requirements. Figure 1 illustrates the coverage of its three subsystems. For en-route navigation, the well-known rho/rho approach based upon two DMEs on shore would be used (DME/N, Table 1). DME operates in the 962 to 1213 MHz band. The airborne interrogator transmits pairs of RF pulses which are received by a ground transponder. The latter replies to an interrogation by transmitting a pair of RF pulses. The airborne interrogator determines distance to the transponder by measuring each pulse pair round-trip time.

For flight operations in the terminal area of an oil field, high positioning accuracy is needed. Here DAS would provide high-accuracy azimuth guidance and distance measurement, and broadcast data, using only one ground station. The airborne equipment has the same physical dimensions as a conventional DME, but also provides azimuth information plus broadcast operational data (Figure 2).

The ground DME part of DAS meets the specifications for conventional DME/N, but has increased accuracy, while the airborne DME meets the requirements for the new DME/P (Table 1). The reason for this combination is that the permissible transmit power of DME/P ground equipment would not give the required range for TMA operations. However, the airborne equipment must be able to operate with all DME ground stations.

The DAS direction finder is a supplement to the DME ground station. The relative phases and amplitudes of incoming interrogation pulses are measured using a circular antenna array, each antenna element feeding its own coherent receiver. Receiver outputs are digitized and fed into a fast processor which determines the angle of arrival by array signal processing. The result, which is the azimuth position, is transmitted with the reply to the interrogating aircraft by a pulse position code. The time between the distance reply and the "azimuth reply", also a pair of RF pulses, is a measure of the azimuth of the aircraft with respect to geographical north. The chosen wavelength, signal format, and beam forming algorithms for processing ensure high resistance to multipath effects.

An additional service of DAS is the ground to air broadcast of data, also based on pulse position coding. Each data word consists of three RF pulse triplets. The spacings of the second and third triples relative to the first carry the information.

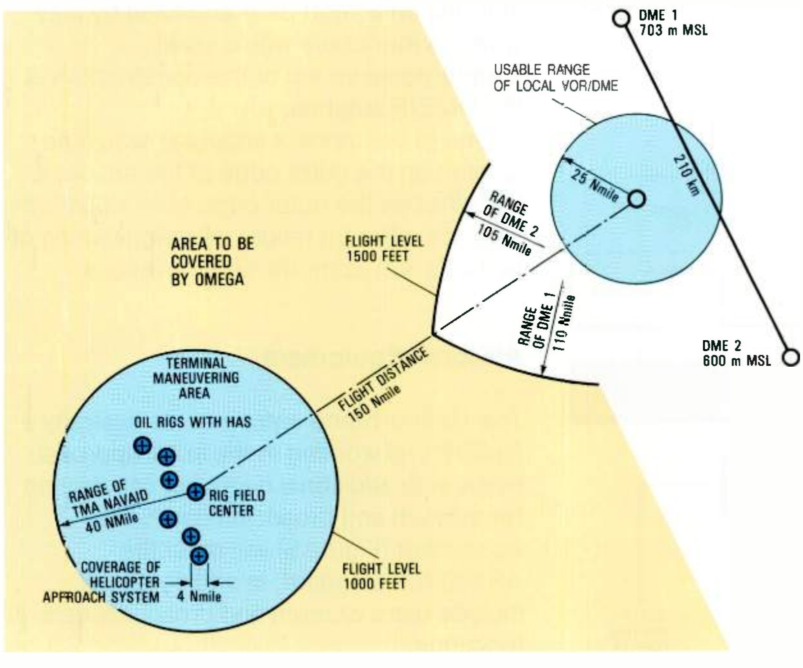


Figure 1
DPS coverage (example for mountainous shore).
MSL - mean sea level.

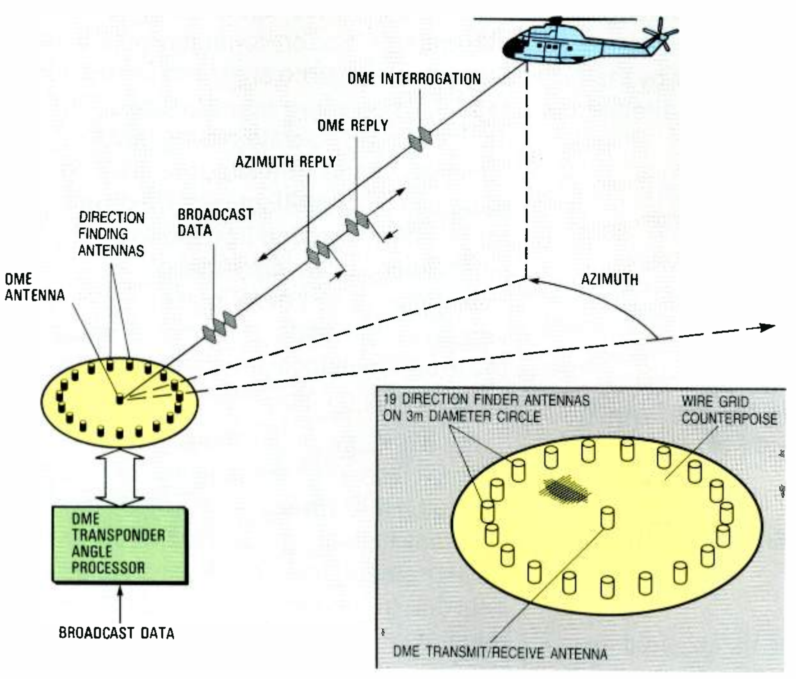


Figure 2
Functional principle of DAS.

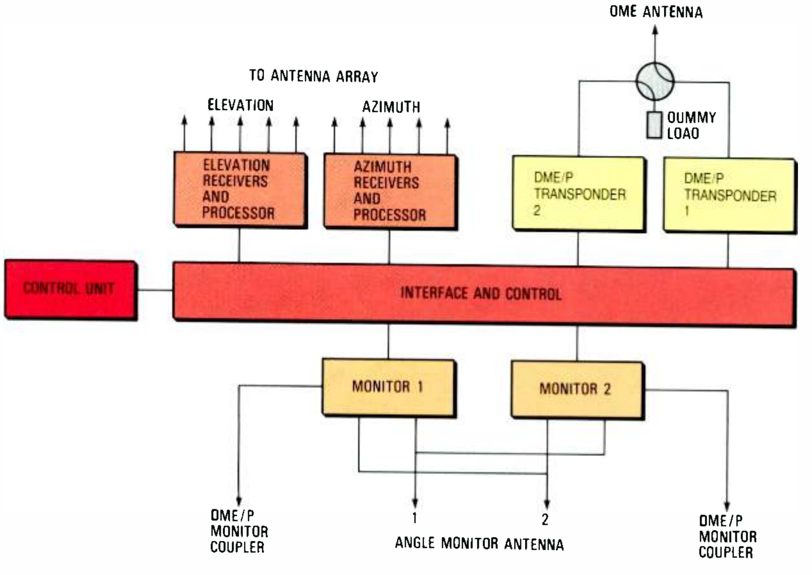
The proposed helicopter approach system HAS is a derivate of DAS, but with the following differences:

- Lower accuracy of azimuth angle measurement. This can be accepted because of the short range of HAS (2 n miles).
- Higher distance measurement accuracy using DME/P (Table 1).
- Additional measurement of elevation[5].
- Horizontal coverage reduced to 270°.
- Reduced transponder transmitter power for short range operation.

DAS airborne equipment needs a HAS attachment to decode elevation information, which is transmitted by an additional pulse position coded pulse pair. HAS also provides broadcast data. A block diagram of the ground system is given in Figure 3.

DME, DAS, and HAS are discriminated by separate RF channels.

Figure 3
Block diagram of HAS ground equipment.



Rig-Based Equipment

The rig-based equipment for DAS and HAS will be based on SEL's new System 4000 navigational aids. The DAS ground equipment is housed in two 19-inch cabinets. An additional cabinet is required for HAS to house the elevation system.

The antenna system of the DAS ground station is a circular array with one center element which is the transmit/receive antenna of the DME transponder. The circular direction finding array, consisting of 19 equally spaced elements, has a diameter of 3 m, corresponding to 10 wavelengths. All antenna elements are quarter wavelength monopoles; these are mounted on a counterpoise, which forms a ground plane for correct functioning. The counterpoise for the off-shore TMA-DAS will be a 5 m diameter wire grid.

The HAS antenna (Figure 4), which combines azimuth, elevation, and DME antennas, is mounted on top of a shelter. The antenna counterpoise can be utilized as the shelter's roof. The azimuth antenna is a circular array of 13 monopoles mounted on a 3 m diameter counterpoise.

The elevation antenna is a vertical array of about 10 shortened dipoles with an overall height of the active part of about 2 m. It is mounted in the middle of the azimuth antenna on a short pillar and fixed by stay wires. A monopole with a small counterpoise on top of this construction is the DME/P antenna.

One of the monitor antennas would be located on the outer edge of the helideck, the other on the outer edge of one platform side at a different height, allowing testing of two different azimuths and elevations.

Airborne Equipment

The DAS airborne equipment is basically a DME/P unit working in the initial approach mode with additional decoding capabilities for azimuth and broadcast data[6]. The equipment (Figure 5) will meet the ARINC 709 standard; in addition it will include extra azimuth and broadcast data functions.

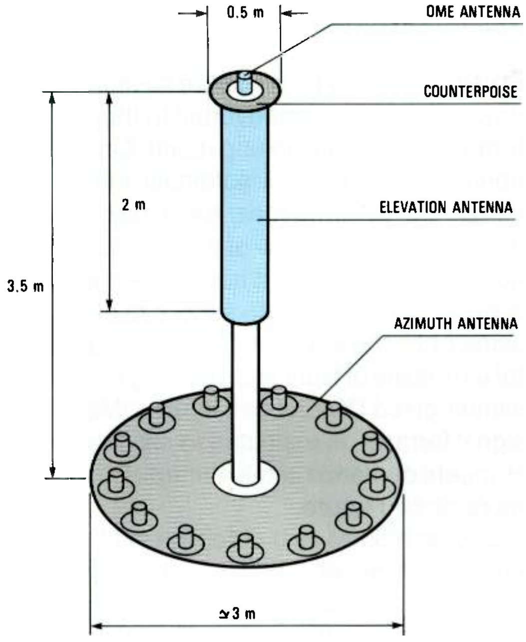


Figure 4 HAS antenna configuration.

The equipment is housed in four modular units, with one extra unit for the HAS attachment.

On board installations may have to cope with different indicator concepts, with or without flight management system or area navigation capability (Figure 6).

DAS angle and DME information can be handled as for VOR/DME, except that the increased accuracy of DAS has to be taken into account. DAS azimuth information corresponds to the VOR radial. The display modes of the horizontal situation video display may be regarded as appropriate to a helicopter approach system. Full advantage can be taken of the area navigation capability of the flight management system.

Operational Aspects

En-route Navigation

During the first en-route flight phase the error of rho-rho position determination decreases from high values down to 300 m. Even then, this cannot fully replace Omega because, owing to the low flight levels of helicopters, its range is not always sufficient to cover the distance to offshore terminal navigation aids. During the short flight period, when no access to other navigation aids is possible (except satellite navigation), Omega has to be used.

TMA Navigation

DAS primary data (radial and distance) can be presented to the pilot or fed into the flight management system where it is treated in the same way as VOR/DME data. The improved accuracy has to be utilized to gain full benefit from the DAS capabilities. Flight data is presented to the pilot on the horizontal situation video display, in either command or display mode.

Full advantage of DAS for structured area navigation can be taken by providing a complete net of instrument flight rules routes in a rig-field area, which can then be flown with high accuracy and safety. Reporting points can be defined, so that air traffic control and supervision is possible for all operations in an oil field area.

The signal format of DAS broadcast data allows for 256 different types of information to be distributed. Meteorological data, such as wind direction, wind speed, temperature, and visibility, navigational data, and information relating to the helidecks in the rig-field can be transmitted. Positions of the helidecks, waypoints for approach, and the entry gates for landing are given in a DAS-based coordinate system. Additionally, the helidecks' status is transmitted (clear for landing/occupied/unserviceable). Obstacles, temporary installations, and

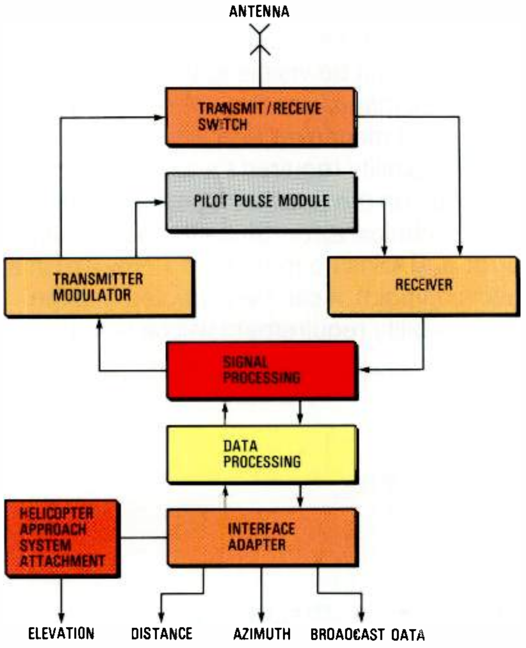


Figure 5 Block diagram of DAS airborne unit.

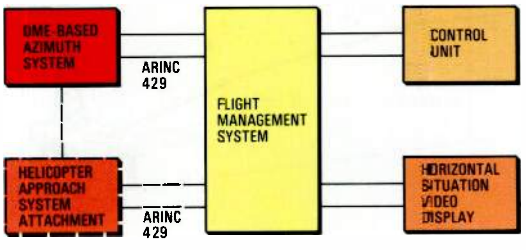


Figure 6 DAS airborne installation proposal.

DAS airborne unit and DME antenna.

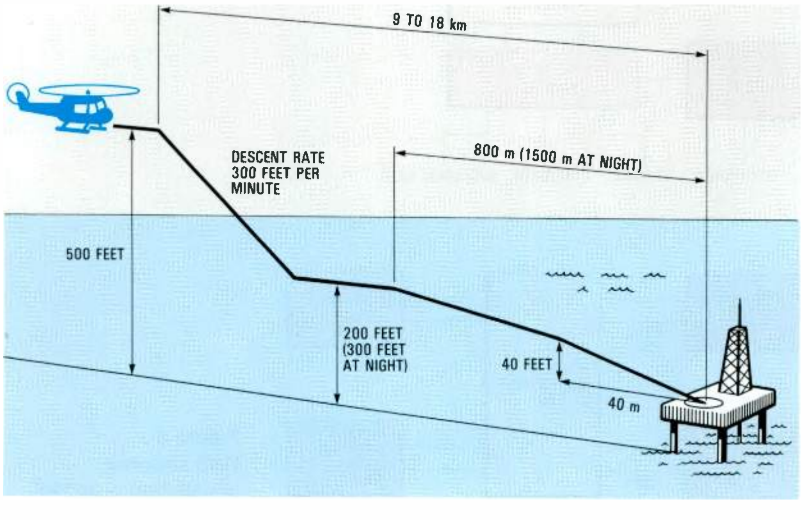
rescue areas can be specified in terms of DAS coordinates, which can be interpreted easily, without conversion.

Final Approach

The final approach using HAS is illustrated in Figure 7. According to the wind direction the pilot selects one of the predetermined decision points for his approach. The coordinates of this set of decision points are transferred from the ground station to the airborne equipment via the broadcast data link. All the possible decision points are located on a circle with a radius of 40 m around the center of the helideck. The elevation corresponds to the decision height of 40 ft above the helideck. When the decision point has been reached, the helideck must be visible to the pilot to perform a manual landing, otherwise a go-around maneuver is initiated.

The visibility required for an approach depends on the positioning error and the flight technical error. Since the positioning error of HAS is no more than 12 m (2 σ) at a decision point, it can be expected that the final visibility requirement will be less than 200 m.

Figure 7
Helicopter vertical flight profile using DAS and HAS (not to scale).



Expected Benefits

Present systems for off-shore navigation for en-route flights, maneuvering in the terminal area, and landing, using Omega, nondirectional beacon/automatic direction finder, and airborne radar have major disadvantages. In view of the increasing number of annual flight hours, the situation is becoming worse. The simplicity of DPS, using only one kind of airborne equipment for all phases of flight and applying the ICAO standardized DME/N and future DME/P signal formats, is expected to satisfy the stringent demands of the immediate and the more distant future.

DPS is offered as a precision aid for en-route, terminal, and landing navigation, but it could also support and promote a new method of air traffic control. This comprises continuous, safe, precise, automatic position reporting including identity and barometric altitude from all aircraft within the coverage region of a DAS rig facility[7].

Apart from solving a specific problem of helicopter aviation over the North Sea, the proposed DPS is expected to offer other performance and cost benefits for a variety of applications in many parts of the world. For example, it is applicable to ships' airborne logistics and small non-ICAO airfields, in order to improve service under adverse weather conditions.

Conclusions

DPS offers considerably improved performance for helicopter navigation without imposing new cost and payload penalties. Following an evolutionary approach based on the proven DME, DPS offers safety and superior economy, with reasonable development risks. Extensive use of modern computer technology, combined with latest antenna array signal processing techniques places DPS at the forefront of radio navigation systems design.

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List of abbreviations

DAS	DME-based azimuth system
DME	distance measuring equipment
DME/P	precision DME
DPS	DME-based positioning system
HAS	helicopter approach system
ICAO	International Civil Aviation Organization
TMA	terminal maneuvering area
VOR	VHF omnidirectional range

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Manfred Böhm was born in Schlewecke, Wolfenbuttel, in 1934. He studied telecommunications in Darmstadt and Berlin from 1954 to 1960. In 1960 he started work with Standard Elektrik Lorenz AG, in the field of digital remote control, but soon changed to radio navigation tasks, with special emphasis on digital signal processing. In 1977, Dr Böhm became director RD & E of navigation systems; since 1980 he has been director RD & E of radio and navigation systems.

Space Qualified L-Band Triplexer for Global Positioning System

The triplexer for the global positioning system had to meet stringent spectrum requirements for both astronomy and spectrum occupancy. These and other specifications, including low weight, are fully met by a design based on one 3-pole and two 6-pole Chebyschev bandpass filters combined as a noncontiguous triplexer.

G. Gorder
J. Ranghelli
ITT Defense Communications Division, Clifton, New Jersey, United States of America

Introduction

The GPS or Navstar system is a set of orbiting navigation satellites that transmit coded signals from which suitably equipped receivers can accurately calculate location in three space coordinates, and time. Scheduled production of the worldwide GPS (global positioning system) started in 1983. ITT Defense Communications has developed a space qualified triplexer for the GPS. The stringent spectrum requirements for astronomy and spectrum occupancy are met at L-Band by using one 3-pole and two 6-pole Chebyschev bandpass filters combined as a noncontiguous triplexer. Coaxial cavities with unloaded *Q*-factors greater than 6000 are necessary to achieve passband losses of less than 0.45 dB. A novel temperature compensation technique is used that carries no weight penalty – an important criterion in space applications. A transmission power of 100 W is handled without multipacting.

System Overview

Figure 1 is a block schematic of the pseudorandom noise signal assembly which generates and routes three modulated signals (navigation channels L*1* and L*2* and nuclear detection data channel L*3*) to the triplexer which combines them into one output feeding a satellite RF (radio frequency) transmitting antenna. In addition to combining these signals, the triplexer suppresses spurious radiation, or clutter, at non-GPS frequencies:

- space-ground uplink channel 1783.74 ±2.5 MHz
- astronomy bands 1345 to 1427 MHz, 1612 MHz, and 1665 to 1667 MHz

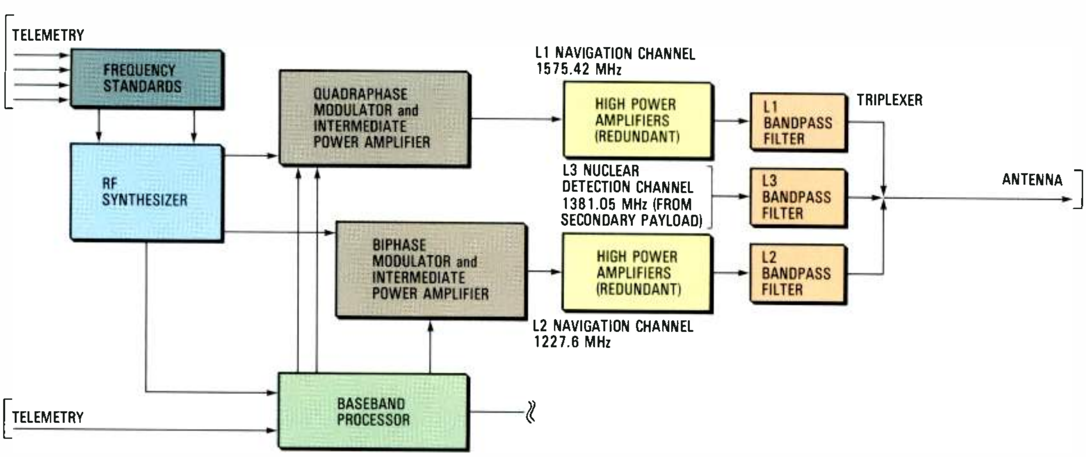


Figure 1
Pseudorandom noise signal assembly for the global positioning satellite.

– 99% spectrum occupancy L*1*, L*2*, ± 20.46 MHz.

System trade-offs for out-of-band emissions yielded two alternatives: RF filtering or baseband pulse shaping. Although RF filtering meets all requirements and is already used for combining transmitters, new spectrum requirements mean an increase in filter size, weight, and passband loss. Baseband shaping using a minimum of hardware can satisfy 99% occupancy requirements and reduce out-of-band emissions, thereby reducing RF filter requirements. However, shaping requires the following RF amplifiers to be linear to prevent restoration of suppressed sidelobes by amplitude modulation in the nonlinear amplifiers used on GPS. As a result, RF filtering was considered to be the most suitable technique. Figure 2 shows the attenuation requirements.

Triplexer Design

The triplexer has evolved from previous GPS multiplexers. The original noncontiguous diplexer used two bandpass filters and one bandstop filter to provide a rejection of more than 65 dB at the 1 783 MHz uplink frequency. The bandstop filter reduced the number of bandpass filter poles and allowed the use of a 145 MHz passband, thereby lowering the unloaded *Q* requirements for a 0.35 dB maximum passband loss. This allowed a dielectric cavity filler to be used for all filters, eliminating power breakdown as a result of multipacting. Multipacting is a resonant buildup of secondary emission electrons in a vacuum as a result of medium power RF field acceleration; it can cause arcing and impedance variations in RF circuitry, damaging equipment and disrupting communication.

Addition of a third transmitter resulted in the diplexer becoming a noncontiguous triplexer with selective bandstop rejection at 1 783 MHz and dielectric cavity suppression of multipacting in all four filters. However, a narrower passband (58 MHz) for the third channel resulted in a higher maximum passband loss of 0.7 dB.

Selection of Filter Type

The choice of filter type is a trade-off between electrical performance, size and weight, multipacting, and history of successful use in space. A 0.01 dB ripple Chebyschev filter was selected as the best compromise. The Chebyschev filter falls between the maximally flat and elliptic types for size and weight based on the number of poles needed to meet the stopband rejection requirements. Although an elliptic type requires only four poles, group delay variations in the passband are greater than for either of the other types, and there is a risk of multipacting in the resonant structures needed to produce zeros in the transfer function. Figure 2 shows the theoretical filter responses superimposed on the attenuation requirements.

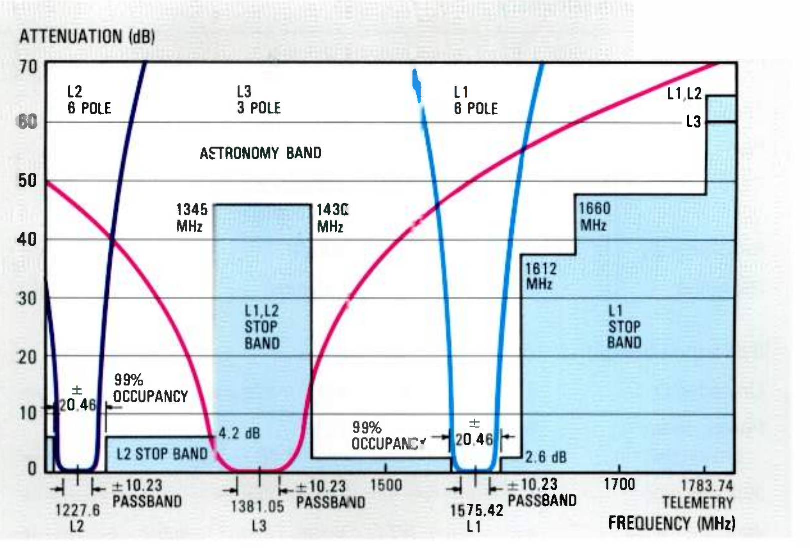
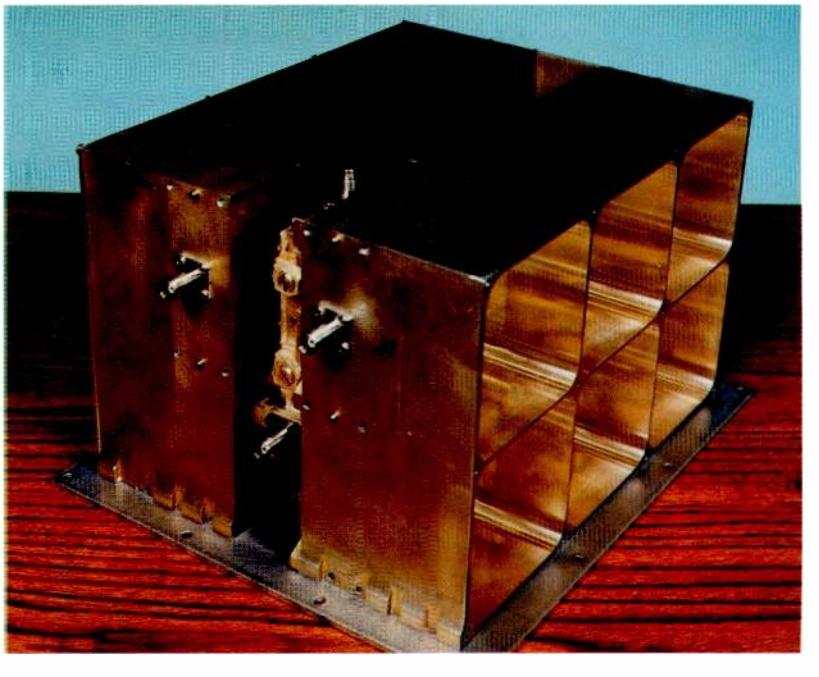


Figure 2
Triplexer frequency responses.

Combiner Selection

Series or parallel combining is possible using vacuum or dielectric filled



Engineering development model of the triplexer for the global positioning satellite.

Table 1 — Design summary

Filter	L*1*	L*2*	L*3*
Type	Chebyschev, 0.01 dB ripple		
Poles	6	6	3
Resonator type	$\lambda/4$ coaxial, iris coupled	$\lambda/4$ coaxial, iris coupled	Inter-digital
Resonator Z_0	100 Ω	100 Ω	70 Ω
Dielectric	Vacuum	Vacuum	Rexolite 1422, $\varepsilon = 2.56$
3 dB bandwidth (%)	2.3%	2.9%	4.2%
Unloaded *Q*	6000 minimum	4500 minimum	1000 minimum
Power, operating	85 W	15 W	30 W
design margin	← 6 dB →		
Junction type	← Parallel →		
Junction media	← 50 Ω coaxial, Teflon dielectric ($\varepsilon = 2.05$) →		
Construction	← Aluminum, silver plated, 15 μinch finish L*1*, L*2* →		
Temperature compensated frequency drift	1 MHz maximum	1 MHz maximum	Not required
Total weight	← 10 lbs (4.54 kg) →		

transmission lines. Parallel combining and a dielectric medium were chosen because of the reduced risk of multipacting and advantages in packing, size, and weight.

Selection of line lengths from filter to junction involves a further trade-off of size and weight against electrical performance. This issue was resolved by an analysis which showed that an unconventional configuration with mixed short and long line lengths provides an optimum compromise.

Construction Techniques

Realization of the design requirements depends critically on construction techniques in three areas: low weight and rugged housing, bellows temperature compensator, and plating and surface finish.

The filter housings for L*1* and L*2* enclose large evacuated volumes to meet the *Q*-factor and multipacting requirements. To minimize the weight, each 6-cavity filter housing is fabricated from a single block of aluminum to which a cover, input and output coupling connections, and six bellows-tuning assemblies are added. Single-block machining optimizes insertion loss by eliminating seams, and ensures dimensional accuracy. Each housing measures 10.76 × 7.23 × 3.58 inches (273 × 184 × 91 mm) with 0.08 inch (2 mm) exterior walls, 0.055 inch (1.4 mm) interior walls, and a 0.125 inch (3.18 mm) base.

Trade-offs

Present triplexer requirements have reduced the bandwidth to 35 MHz for channels L*1* and L*2*, thereby significantly affecting the selection of a multiplexing technique and filter types. The L*3* bandwidth remains at 58 MHz owing to prior filtering at the transmitter. The final design is summarized in Table 1.

The chosen multiplexing circuit (Figure 1) uses only bandpass filters as the narrow bandwidths and steep skirt attenuations provide sufficient attenuation at 1783 MHz. Since the three bands are widely separated, a noncontiguous design was chosen with doubly terminated component filters. Parallel combining at a junction is used for filter integration as it is less susceptible to multipacting and simplifies fabrication.

Filter selection was based on the need for low passband loss, prevention of multipacting, low weight, and wide operational temperature range (−20 to +71 °C). The previous 3-pole design for the L*3* channel satisfied all requirements and has therefore been used intact. However, the L*1* and L*2* channels required new 6-pole designs and a bandwidth reduction of close to 5:1; both these factors lead to increased passband loss. As the passband loss specification was unchanged, the potentially higher loss had to be offset by increasing the cavity unloaded *Q* from 1000 to at least 6000. This was achieved by increasing resonator size, polishing metal surfaces, and using a low loss dielectric. Any size increase had to be traded-off against weight increase and the possibility of higher order modes generating spurious passbands. Size and dielectric material can adversely affect multipacting and temperature performance in the space environment.

Coaxial Resonator Selection

Based on the above trade-offs, a transverse electric magnetic field, quarterwave coaxial cavity resonator without dielectric loading (i.e. vacuum) was chosen. Elimination of the dielectric was necessary to achieve the high *Q* and reduce weight, although it increased the possibility of multipacting breakdown. Careful sizing of all electrode spacings in the cavity helped to prevent operation in the multipacting breakdown region of the 'Woo'[1] curve of power versus frequency-distance product (Figure 3). The curve shows that to avoid the multipacting region, either very small spacings were required, as in L*3* which uses 0.01 inch (0.254 mm) maximum gaps, or very large gaps as in filters L*1* and L*2* which use spacings of 1.40 inches (35.6 mm).

The cavity resonator geometry is shown in Figure 4a. The square outer conductor increases the *Q*-factor and eases fabrication. The ratio of the inner conductor diameter to the side of the outer conductor is 0.2, corresponding to an impedance of about 100 Ω; this ratio optimizes the electrode spacing for multipacting margin as opposed to optimizing the unloaded *Q* by setting Z_0 at about 70 Ω. This trades off a small increase in passband loss for improved multipacting performance. The cavity dimension of 3.5 inches (89 mm) on a side results in a theoretical *Q* in excess of 14 000 which at 60% realization produces practical *Q*s of 8 000 – sufficient to meet the passband loss specification of 0.45 dB.

Figure 4 also shows the tap or loop input/output coupling, iris intercavity coupling, and temperature compensation. Both coupling techniques are predominantly magnetic and therefore lower the risk of multipacting.

Temperature compensation over the −20 to +71 °C qualification range is necessary for L*1* and L*2* because of their narrow 35 MHz bandwidth. Weight restrictions make fabrication of the filter from low temperature coefficient metals, such as invar, unacceptable. The chosen temperature compensation technique, shown in Figure 4b, is based on a bellows spring termination at the open circuit end of the resonator center conductor which is controlled by a rod through the center conductor. The temperature performance of this arrangement depends on the rod material since the rod length controls the center conductor length, the primary parameter determining resonant frequency. Thus, the major part of the filter can be fabricated from aluminum while offering the same temperature performance as a much heavier invar filter. An additional advantage is the use of the bellows assembly for fine tuning the cavities.

The bellows assembly is shown in Figure 4b. The tuning rod expands or contracts the bellows, varying the resonating center conductor length and cavity frequency. Subsequent temperature variations can only change the resonator length in line with the low thermal coefficient of expansion of the invar tuning rod.

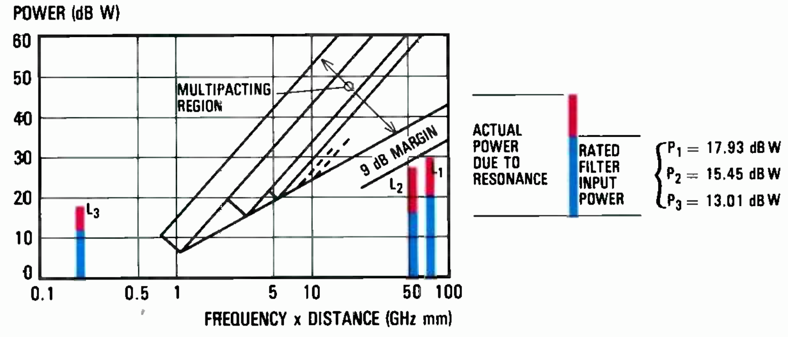


Figure 3
Multipacting analysis.

The finish on the inside RF surfaces of the housing and cover for the filters L*1* and L*2* significantly affects the insertion loss. To achieve unloaded *Q*s in excess of 6 000 requires a silver thickness of greater than 10 skin depths with a surface finish better than 15 μinch (0.38 μm) polished to a near mirror reflectance. One mil (25.4 μm) minimum thickness of silver was deposited on 0.4 mil (10.2 μm) copper and then tarnish proofed.

The other triplexer components, the L*3* filter and junction, are less critical and use conventional machining techniques and plating. The junction uses square coaxial inner and outer conductors with a dielectric (Teflon) filling.

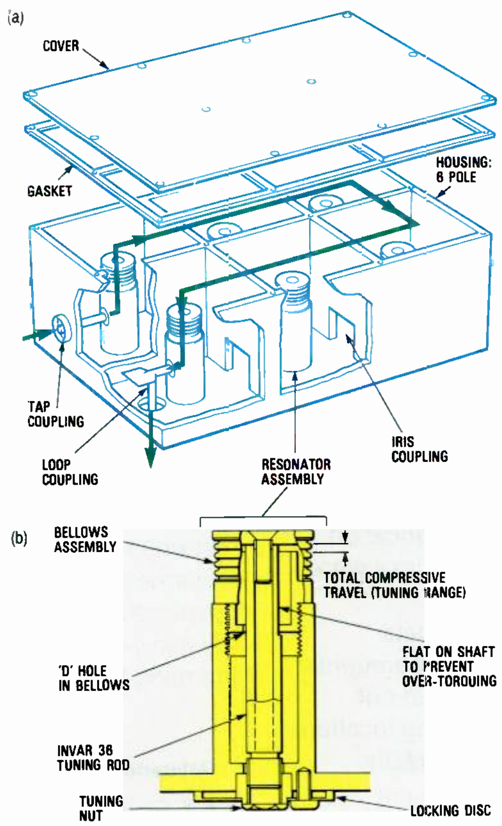


Figure 4
Resonator design showing (a) basic design, and (b) the coupling technique.

Two final construction features were the use of silver-plated brass gasket material set in channels in the covers of L*1* and L*2*, and strategically placed through-holes to allow efficient evacuation of air during the transition from atmospheric to vacuum conditions. The gaskets were vital in reducing insertion loss by providing a compressible seam of low resistance. The evacuation holes were designed as cutoff waveguide attenuators.

Experimental Results

Development of the L*1* and L*2* filters began with experimental verification of the basic cavity concept, and determination of intercavity coupling as a function of iris size. Based on these results, full 6-cavity filters were built and tested. Similarly, the junction concept was tested by simulating the filter terminations using 2-pole filters.

A single cavity was fabricated with bellows tuning and silver plated surfaces polished to 15 μinch (0.38 μm). Measured results included an unloaded *Q* of 7800 and a 6:1 reduction in frequency drift to ± 0.45 MHz. Power testing in vacuum at temperatures between −20 and +71 °C showed no multipacting. The powers used in both L*1* and L*2* exceeded the specification.

Iris coupling cannot usually be calculated accurately for practical cavity shapes. For the cavity used, a general equation is available which requires the constants to be determined experimentally[2]:

$$K = BL^3 \cos^2 (AL)$$

where

K – coupling factor
L – iris length
A, *B* – constants.

A 2-cavity filter was used to make measurements, using Dishal's method[3], for several iris sizes spanning the requirements for L*1* and L*2*; the constants *A* and *B* were then determined. The resulting curves are shown in Figure 5. Perturbation measurements indicated that fabrication tolerances of 5 mils (127 μm) or less were required.

Interpolating the iris coupled data provided the iris sizes for the experimental 6-pole L*1* and L*2* filters; these did not require modification. Tap coupling locations were also determined experimentally.

The junction design was validated experimentally by using 2-cavity filters as preliminary terminations. The design was based on an analysis which showed that an exact match could be achieved in all three bands with an unconventional arrangement of interconnecting line length: two at approximately quarter wavelength and the third at approximately half wavelength. Measured results showed excellent voltage standing wave ratio performance and therefore a valid baseline design from which the final design evolved.

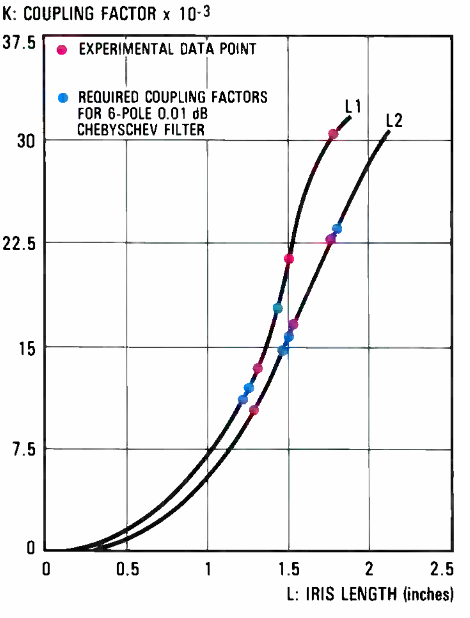


Figure 5
Dual cavity test results.

Triplexer Results

A full triplexer, incorporating filters L*1*, L*2*, and L*3* and the junction, was assembled and tested. Small adjustments to the junction line length were necessary to match the pre-integrated filter responses. Table 2 gives the measured results after line length optimization.

During development the housings were built without final details, such as irises, and updated as design information became available from the experiments. This allowed critical experiments on the vibration response of a realistic 'dummy' triplexer to be carried out concurrently with electrical development. Early vibration data validated the thin wall design and allowed judicious trimming to reduce the weight even further.

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Greta Gorder was born in Oak Ridge, Tennessee, USA in 1959. She received a BSEE from Brown University, Providence, Rhode Island in 1981 and has participated in graduate courses in electrical engineering. She has worked as a microwave design engineer in the field of filters and low noise amplifiers. Ms Gorder, who joined ITT DCD in 1981, is currently involved in the design of a low noise monolithic amplifier.

Joseph Ranghelli was born in Brooklyn, New York, in 1931. He studied electrical engineering at the Polytechnic Institute of New York, graduating as a BSEE in 1959 and MSEE in 1965. He worked in several companies doing research and development on microwave components and systems prior to joining ITT DCD. Mr Ranghelli has extensive experience in filter design, phased array antennas, adaptive arrays, and switching devices. He has been with ITT for ten years and is currently section head in the microwave group at DCD and project leader for the GPS triplexer engineering development.

Table 2 — Measured performance of the triplexer engineering development model (EDM)

Parameter	*L1* filter		*L2* filter		*L3* filter	
	Spec	EDM	Spec	EDM	Spec	EDM
F_0	1575.42		1227.6		1381.05	
3 dB bandwidth (MHz)	> 30	36.2	> 30	38	> 58	63
Width of passband (MHz)	+10.23		+10.23		+10.23	
Loss at F_0 (dB)	< 0.45	0.29	< 0.45	0.31	< 0.7	0.50
Passband loss variation (dB)	< 0.10	0.07	< 0.10	0.07	< 0.10	0.08
Stopband loss:						
1345 to 1427 MHz (dB)	> 50	>70*	> 50	> 70*	NA	
1612 MHz (dB)	> 35	44.23	> 50	> 70*	NA	
1665 to 1667 MHz (dB)	> 50	65	> 50	> 70*	NA	
99% bandwidth, maximum (MHz)	± 20.5	± 18.4	± 20.5	± 19	NA	
Cross coupling						
J2-J3 @ *L2* (dB)	NA		NA		> 39	47
J2-J1 @ *L2* (dB)	> 50	> 70*	NA		NA	
J1-J3 @ *L1* (dB)	NA		NA		> 39	52
J1-J2 @ *L1* (dB)	NA		> 50	> 70*	NA	
J3-J2 @ *L3* (dB)	NA		> 50	> 70*	NA	
J3-J1 @ *L3* (dB)	> 50	> 70*	NA		NA	
Impedance (Ω)	50	50	50	50	50	50
Passband VSWR (:1)	< 1.20	1.18	< 1.20	1.13	< 1.22	1.11
Group delay variation (ns)	< +1	0.22	< +1	0.05	< +1	0.26
Temperature range (°C)	−20/+71		−20/+71		−20/+71	
Power (W)	85	100	15	40	30	30
Uplink isolation at 1783.74 + 2.5 MHz (dB)	> 65	> 70*	> 65	> 70*	> 60	68.3
Number of poles	6		6		3	

* noise floor

Receiver for Global Positioning System

The satellite-based global positioning system will become a major system for position-finding and navigation within the next few years. SEL is developing a prototype receiver which will have one of its first applications in the German Spacelab navigation experiment.

A. Bethmann
H. Tschiesche
Standard Elektrik Lorenz AG, Stuttgart, Federal Republic of Germany

Introduction

Land based navigation systems for ships and air traffic are based either on the measurement of propagation delay of radio signals from stations with known coordinates or on bearing measurements. The progress in space technology now makes it possible to produce satellite navigation systems with very high accuracies. The GPS (global positioning system) satellite-based navigation system will become the most important system for position finding and navigation within the next six to seven years, providing users all over the world with position and timing information of unprecedented accuracy. The position finding procedure is based on the measurement of propagation delay times for radio signals from at least four satellites out of a constellation of 18.

Standard Elektrik Lorenz (SEL) is developing a prototype GPS receiver for civil applications, which can also be upgraded for military users.

GPS System

The United States' Navstar-GPS programme is divided into three operational phases. The original objective of establishing an operational system with 24 satellites by 1984 can no longer be achieved for technical and financial reasons. Nevertheless the programme is continuing and the system will be fully operational in 1987 with 18 satellites. Five satellites are

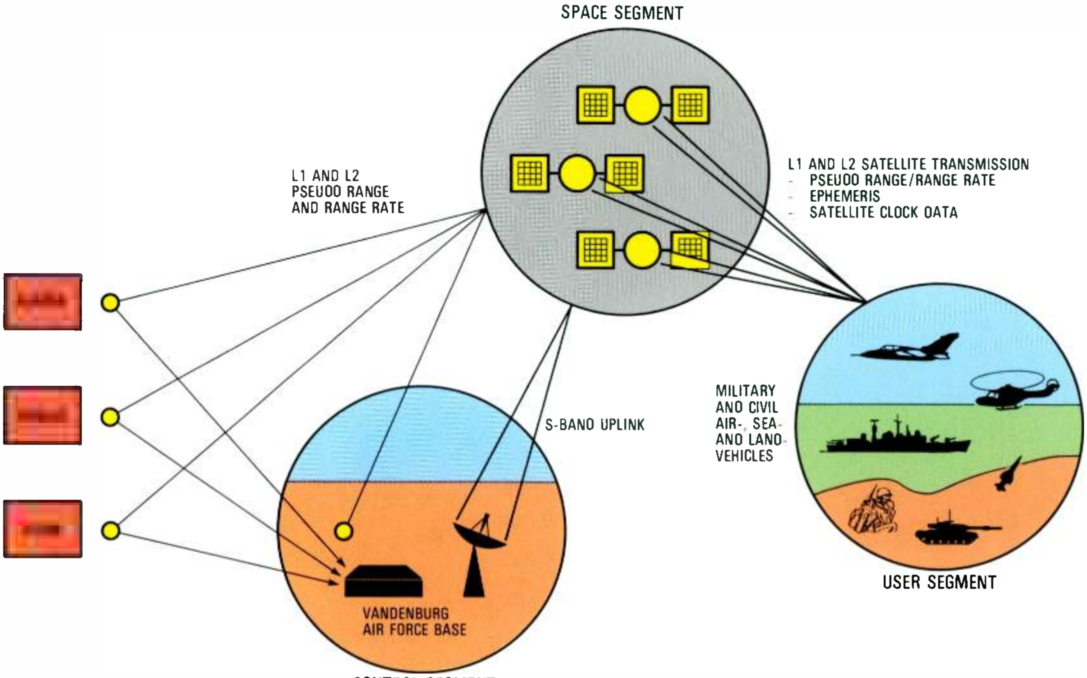

Figure 1
Navstar-GPS system.

already in operation. Figure 1 shows the three key components of Navstar-GPS: space segment, control segment, and user segment.

The space segment will consist of 18 satellites in six 12-hour orbit planes at an altitude of about 20000 km. These will provide visibility of at least four satellites at 5° or more above the horizon to users located anywhere in the world at any time. Signals are transmitted at two L-Band frequencies (Table 1) to permit corrections to be made for ionospheric delays in propagation time. Signals are modulated with two pseudorandom codes: *P* for precise time measurements, and *C/A* for easy lock-on to the desired signal with reduced accuracy. In addition, each signal is modulated with navigation messages (ephemeris, correction, system status, and system control parameters). The accuracy in position and time which can be achieved with the two codes is shown in Table 1. Each satellite has an atomic clock which is updated by the control segment once a day. A computer in each satellite calculates the actual ephemeris and updates the navigation message.

The control segment consists of four monitor stations, an upload station, and a master control station. Each monitor station serves as a data collection center; it contains a high performance four-channel receiver, an atomic clock, and a computer which controls data collection and provides the interface to the processor of the master control station. The upload station provides the interface between the control segment and the space segment via an S-Band radio link. The master control station performs the computations necessary to determine satellite ephemeris and atomic clock errors, generates satellite upload of user navigation data, and maintains a record of satellite processor contents and status.

The user segment (GPS receiver with antenna and periphery) depends on the application. It may vary from a five-channel two-frequency receiver for military users with high demands on accuracy and reliability down to a simple single-channel receiver for civil users. Thus the user segment must be constructed from modular hardware and software so that it can meet these varying requirements.

Table 1 – Signal characteristics and system accuracy

Satellite signal	Carrier frequency	Code	Bandwidth
L1 *L2*	1575.42 MHz 1227.60 MHz	*C/A* and *P* *C/A* or *P*	2 MHz at *C/A* and 20 MHz at *P* code signal
Parameter	*C/A* code	*P* code	Data
Chipping rate	1.023 MHz	10.23 MHz	50 bit s^{-1}
Code type	Gold code	200 day PRN* code	—
Period	1 ms	7 days	—
Navigation accuracy	Position	Velocity	Time
With *C/A* code	100 to 300 m	0.3 ms^{-1}	50 to 100 ns
With *P* code	17 m	0.2 ms^{-1}	11 ns

* pseudorandom noise

GPS Receiver

Figure 2 is a block schematic of SEL's prototype civil receiver. The main components are the antenna with preamplifier, receiver/processor unit, control/display unit, and power supply. The modular structure enables the receiver to be adapted to nearly all planned applications simply by changing or adding hardware or software modules. In addition, it can be expanded from a single-channel receiver for civil users up to a multichannel receiver with auxiliary sensors for military users. Figure 2 shows the receiver modules for the first application within the planned German test and trial programme and for use in the Navex ground segment.

The receiver has a data channel and a navigation channel. The navigation channel performs the sequential pseudorange measurements to the best four satellites while the data channel collects data from all visible satellites. A delay lock loop and a Costas loop are used for signal acquisition and tracking of the *C/A* code and the carrier.

The GPS receiver must be capable of measuring its range from four satellites. To do this it must amplify the signal, despread the code, demodulate, decode, and interpret the 50 bit s^{-1} data stream of each satellite signal. The data stream conveys the satellite status, correction parameters for the satellite clock and for signal delays through the atmosphere, the ephemeris of the satellite, and other system control and status parameters to the user. In addition the data stream contains the almanac information that defines the approximate ephemerides and status of all satellites[1]. Range measurements together with the information from the navigation data stream enable the user receiver to perform the computations necessary for successful navigation using GPS.

Application within Navex

A proposal for a Spacelab navigation experiment (Navex) on clock synchronization, time transfer, and one-way ranging has been prepared jointly by DFVLR and SEL. This will culminate in the Shuttle mission D1 in 1985 which will be followed by data evaluation. Navex[2,3] is a main step in gaining the know-how for satellite-based navigation systems. The objectives of the experiment are:

- Investigate the behavior of atomic clocks in orbit (stability, relativistic effect).
- Test precise synchronization techniques for onboard and ground-based atomic clocks by a two-way method (accuracy within 10 ns).
- Time distribution and time comparison between ground-based clocks and the onboard clock by one-way measurements.
- One-way distance measurement and position determination with an accuracy of 30 m or less.
- Determine shuttle position by one-way ranging to three ground stations (inverted GPS technique).
- Use and test code modulation with pseudorandom noise codes.
- Investigate propagation effects.
- Simulate future satellite-based navigation systems.

Figure 3 shows the Navex configuration. The hardware consists of the onboard station, one ground control station, and two receiving stations. It also includes an AN/MPS-36 radar and additional equipment for testing, data handling, and ground clock synchronization and frequency transfer.

The onboard equipment is housed in three containers which, together with three antennas, are mounted on a support structure in the shuttle's cargo bay. A cesium and a rubidium atomic clock are used on board. The relativistic effect on these clocks will be about $-25\,\mu$sec per day. Pseudonoise-modulated microwave links with different codes will be used for synchronization and ranging between the onboard station and the ground stations. A two-way synchronization method between the onboard station and the ground control station will be used for high precision clock comparison with an accuracy of better than 10 ns.

The one-way link between the onboard station and the receiving ground station employs the pseudorange measurement technique which allows the position of the ground station to be determined by the same sequential measurement and evaluation procedures used for GPS. Parallel pseudorange measurements of the three ground stations with synchronized clocks and known positions allow the position of the onboard station to be determined (inverted GPS technique). Precise synchronization of the ground clocks is necessary for proper evaluation of experimental data. This will be achieved by clock transportation and by GPS. Thus GPS receivers will be used for synchronization using the *common view technique*.

Outlook and GPS Applications

Civil use of GPS receivers is being widely considered in Germany and elsewhere. Requirement and market research studies have been carried out. It has been forecast that GPS receivers will be used in many applications, including the following:

- Land based: police, fire, and rescue vehicles; emergency medical vehicles; urban and interstate transit vehicles

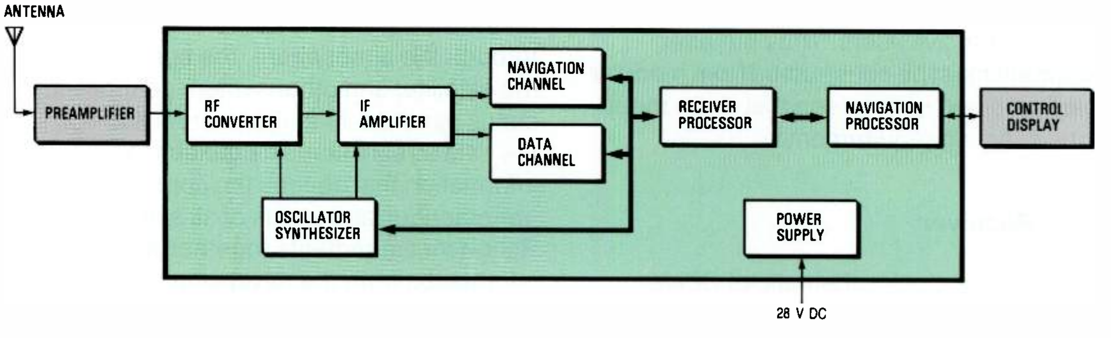

Figure 2
Block schematic of the GPS receiver.

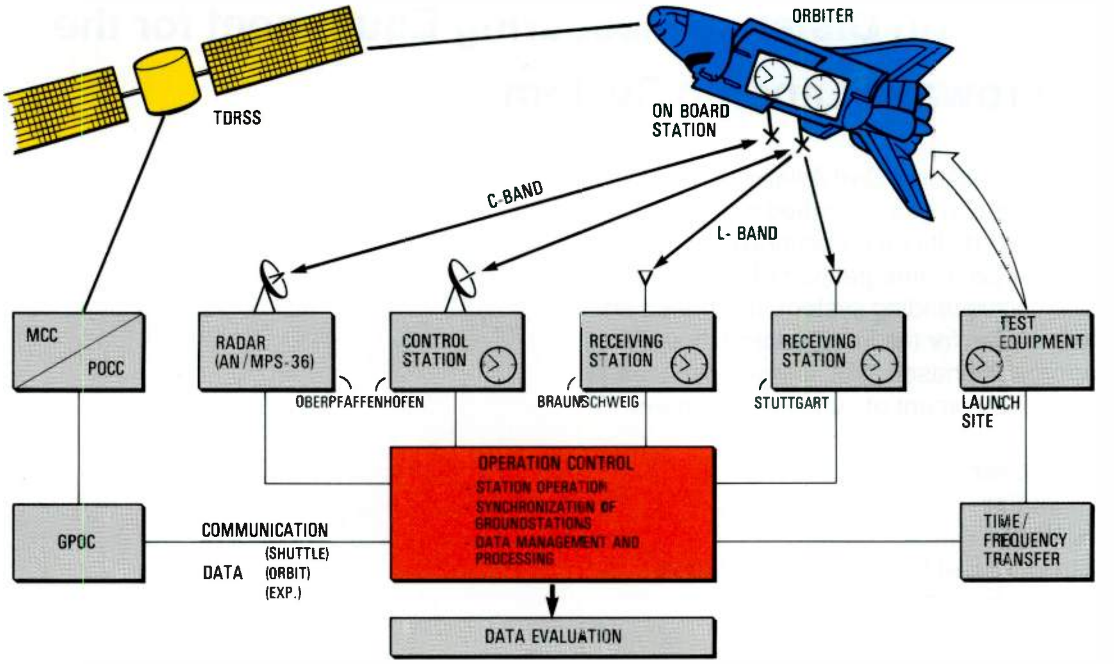

Figure 3
Equipment configuration for the Navex experiment.

(buses, trucks, taxis); and geological survey and exploration.

- Maritime: surface- and bottom-fishing; maritime commerce (offshore, shore, and inland navigation); leisure shipping; and map surveying.
- Air: inertial navigation system support; search and rescue; approach flight support; and distance and area navigation.
- General: worldwide time distribution for universal time coordination; synchronization of existing navigation systems (Loran-C, Omega); control of experiments and surveys (astronomy); synchronization of communication systems (time domain multiple access systems); and space shuttle navigation.

The federal government is defining a comprehensive trial and test program for GPS receivers to give potential users the chance to gain experience with the new navigation system. Prototypes of the SEL receiver will be used in these tests which are planned for 1984/85.

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Andreas Bethmann was born in Oberhausen, Germany, in 1951. He studied electrical engineering at the Rheinisch Westfälische Technische Hochschule, Aachen, qualifying as a Dipl-Ing in 1974. Mr Bethmann joined SEL in 1976 on the development of software for navigation systems. Since 1980 this has included responsibility for the Navex software development.

Hugo Tschiesche was born in 1945 at Osek, Czechoslovakia. He received his engineering education at the Technical University, Darmstadt, majoring in theoretical electrotechnics. After qualifying in 1973 as a Dipl-Ing, he joined SEL where he was engaged on the development of communication and navigation systems and the application of spread spectrum technology. Since 1981 Mr Tschiesche has been head of the laboratory for system integration.

Precision Distance Measuring Equipment for the Microwave Landing System

The International Civil Aviation Organization has described a new type of precision distance measuring equipment that will be an integral part of the future microwave landing system. It is based on two modes for the initial approach and final approach phases. SEL is well advanced in the development of suitable equipment.

K. Becker
A. Müller
H. Vogel
Standard Elektrik Lorenz AG, Stuttgart,
Federal Republic of Germany

Introduction

In 1982 the All Weather Operations Panel of the ICAO (International Civil Aviation Organization) completed an evaluation of the concept and operational characteristics for DME/P (precision distance measuring system), an integral part of the future MLS (microwave landing system). Since 1981 ground and airborne DME/P equipment has been under development at SEL; the first production models will become available by 1986.

DME/P System Concept

The All Weather Operations Panel described a concept based on two new operational modes, the IA (initial approach) mode and the FA (final approach) mode. The IA mode is fully compatible with the conventional DME/N. In the FA mode special techniques are used to maintain the required high precision during the approach and landing phases, even in the presence of strong multipath signals.

Transmission signals with steep edges are used in both modes. In the FA mode the pulse slope between the 5 and 30% amplitude points should be as linear as possible (Figure 1). The steep pulse shape increases the bandwidth, although it remains within the DME/N spectrum limits as long as the effective radiated power of the ground transponder, and thus the coverage, is correspondingly reduced.

The operational mode is selected by the airborne DME/P equipment according to the measured distance, and is identified by the spacing of the interrogation pulse pairs. The modes also differ in the way signals are processed. Narrowband processing based on the conventional half amplitude thresholding technique (HAF, half amplitude finder) is used for IA mode signals. In contrast, wideband processing is used for FA mode signals in conjunction with a novel trigger circuit with a very low threshold level (10% of the pulse amplitude). This is the so-called DAC (delay and compare) trigger.

In the FA mode the short risetime of the transmitter pulses improves echo immunity. Triggering at a low (i.e. early) point on the received pulse can significantly reduce distance errors caused by echo signals with a short multipath delay.

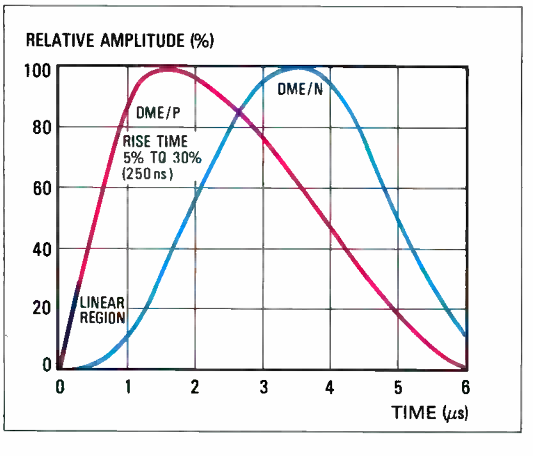


Figure 1
Pulse shapes for DME/P and DME/N.

General Technical Features

Implementation of the DME/P concept requires technical changes to the DME/N transponder and airborne equipment. These include the use of a broadband receiver section and special trigger circuits, and measures to generate fast risetime transmit pulses.

Broadband Receiver Branch
To preserve the fast risetime and linearity of the leading edge of the received signals, airborne and transponder receivers must have an IF (intermediate frequency) bandwidth of about 3.5 MHz. Compared with conventional narrowband receivers, this has the drawbacks of a lower signal-to-noise ratio and loss of channel selectivity because adjacent channels, spaced at 1 MHz, are not suppressed. The first problem can be ameliorated by using low noise high frequency preamplifiers. To ensure the required adjacent channel rejection, the receiver is equipped with an additional narrowband section (IF bandwidth of about 0.5 MHz). The corresponding narrowband video signal output is compared with that of the broadband section to determine whether the received signal is *on-frequency*, and whether it is so heavily distorted by adjacent channel interference that it should be suppressed and excluded from further processing[1].

Thresholding Technique for FA Mode
A possible solution for the required low level thresholding is the DAC method. As in the HAF trigger, the video pulse is fed to an attenuator and a delay line (Figure 2). The typical delay value used in the DAC is 100 ns – significantly lower than the 3 μs delay of the HAF. As already mentioned, only echo pulses that arrive prior to the occurrence of the DAC trigger cause trigger errors. Compared with the HAF technique, the immunity against echo-induced errors is thus increased considerably, although at the cost of a lower threshold-to-noise ratio, since the DAC triggers at about 10% of the pulse amplitude, whereas the HAF is at 50% by definition[2].

The present DME/P system offers little margin for improving this rather critical susceptibility to noise since the maximum permissible transmission power of the transponder is strictly limited by the spectrum requirements.

Steep Pulse Modulation
A fast rising transmission pulse is prescribed for the FA mode; tolerances are relatively tight, especially with respect to the linearity requirements for the 5 to 30% amplitude region. To maintain the required

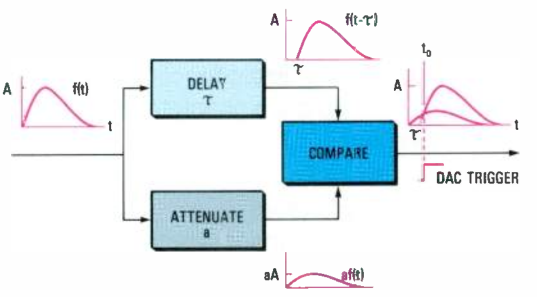


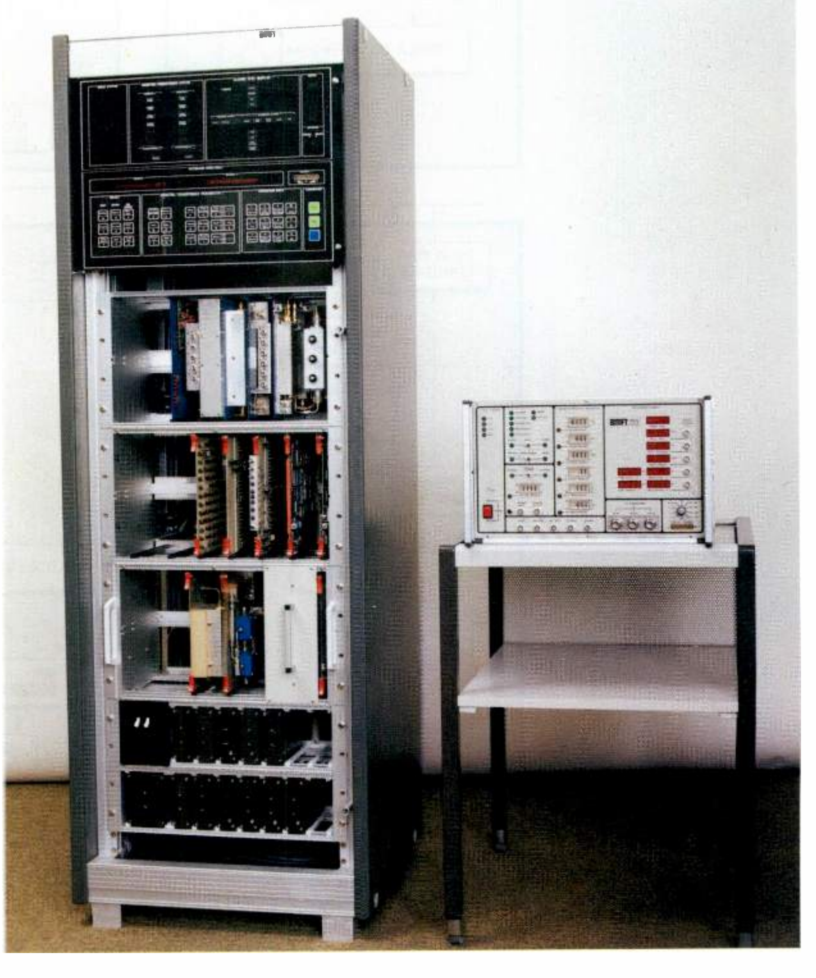
Figure 2
Principle of the delay and compare trigger method.

pulse characteristics irrespective of channel frequency and operational conditions, high performance modulation techniques have to be introduced. The ground transponder developed by SEL employs a digitally controlled modulator with programmable pulse shaping[3]. A comparable modulation circuit is under development for the airborne equipment.

DME/P Ground Transponder

The design of the ground transponder closely follows the standards of other SEL navaids. In addition to the transponder, the

DME/P ground transponder equipment.



ground equipment incorporates one (or two) monitor unit(s) and a control unit. Figure 3 shows the basic functions of the transponder. The main characteristics are given in Table 1.

Two-Mode Technique

When the ground transponder receives an interrogation from the airborne equipment it must first analyze whether it is a conventional DME/N, DME/P IA mode, or DME/P FA mode interrogation. This is achieved by pulse pair decoding of each interrogation to determine how it is to be processed. For the receiver section this implies simultaneous narrowband and broadband processing, and HAF and DAC thresholding.

Table 1 – Main characteristics of the DME/P transponder

Design specifications:	
AWOP-WP/401	(12/82)
FAA-E-2721/3	(9/82)
EUROCAE ED-31	(7/80) as applicable
Main features:	
Transmit power	300 W EIRP
Sensitivity	
IA mode:	< – 82 dBm } for 30 dB video signal-to-noise ratio
FA mode:	< – 76 dBm } for 30 dB video signal-to-noise ratio
Instrumentation error	< 10 m path following error (IA mode)
	< 8 m control motion noise (FA mode)

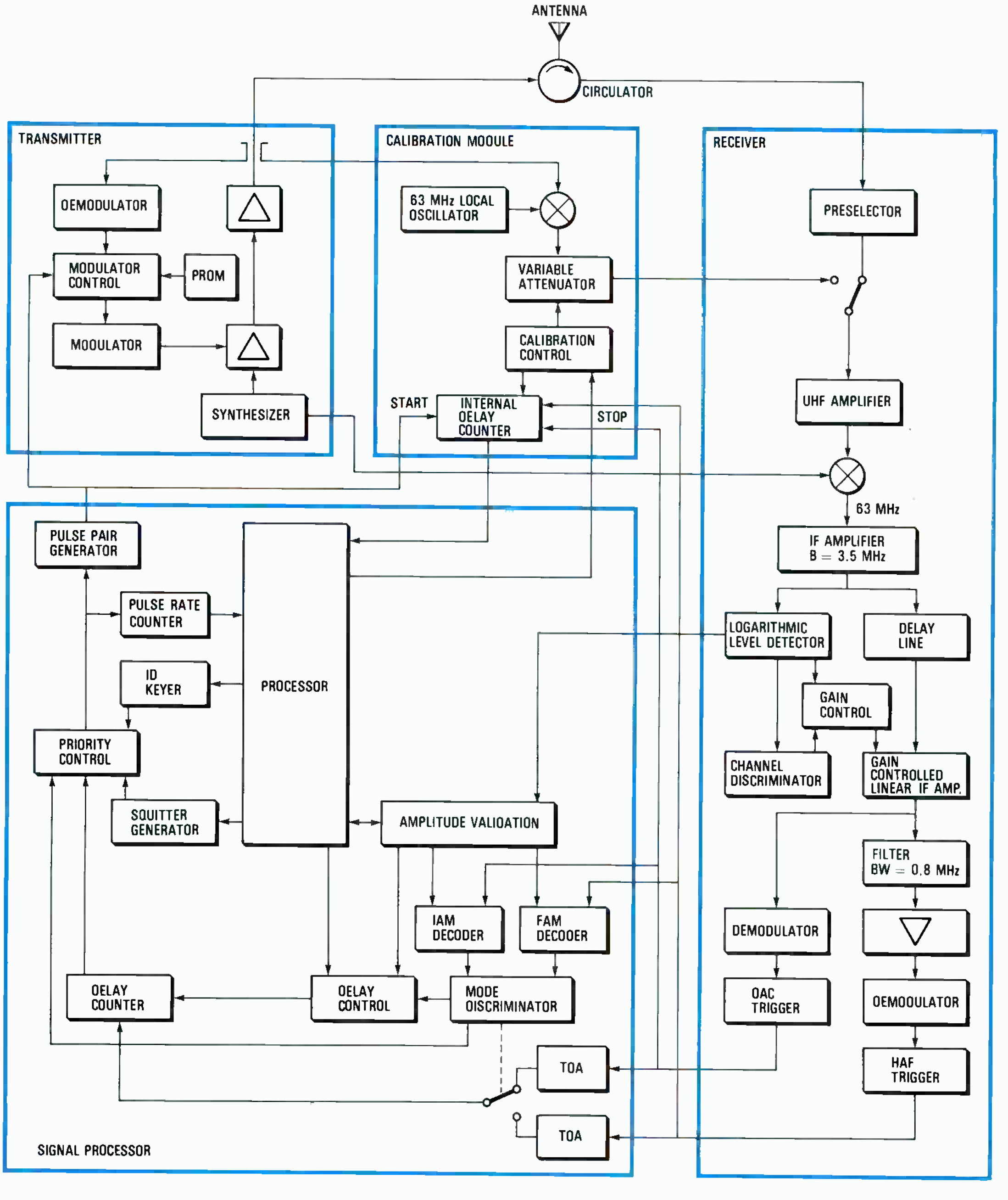
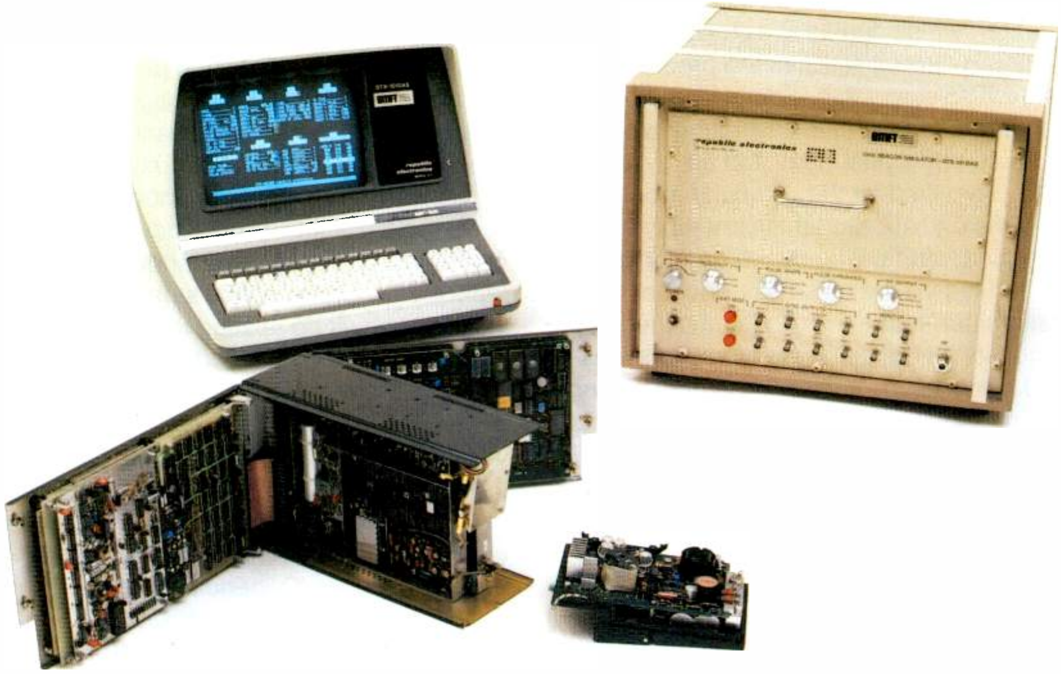


Figure 3
Simplified functional block diagram of the DME/P transponder.



DME/P airborne equipment.

Simultaneous IA and FA mode decoding is provided in the signal processing section of the transponder. The decoder is always fed with HAF triggers to improve interference rejection. Depending on the type of interrogation, subsequent processing is governed by the following factors:

- separate echo suppression techniques for IA and FA modes
- desensitization caused by overload in the IA mode only
- differing delay time for IA and FA mode signals
- priority scheme: FA mode replies, identification signals, IA mode replies, random pulses.

The first two features have to be dealt with by appropriate design of the receiver sensitivity control function. In contrast to conventional techniques, receiver sensitivity is always at the maximum value; thus signal suppression for echoes or overload conditions has to be achieved by processor controlled discrimination of the received signal levels.

Main Functional Units

Receiver

Wideband receiver design with a processing bandwidth of 3.5 MHz ensures that airborne DME/N or DME/P interrogations are transferred without pulse shape distortion. The signal path is split into two parallel IF branches. The narrowband branch has a bandwidth of 0.8 MHz and is followed by a demodulator and the HAF trigger. Wideband processing continues in the other IF branch; the DAC trigger is derived after demodulation.

The wide bandwidth of the receiver branch feeding the DAC trigger circuit can cause interference between adjacent channels. To prevent this, the output of the logarithmic level detector is coupled to a channel discriminator. When interrogation occurs on adjacent channels, the gain of the linear IF amplifier is reduced to inhibit erroneous triggering.

Simultaneous decoding of IA mode and/or FA mode interrogation pulse pairs is provided by equipping the transponder with two decoder circuits. They are enabled by the amplitude discriminator if the level of the receiver signal exceeds a specific value. This value is determined separately by the processor for each mode, depending on the actual echo suppression conditions and, in the IA mode, on the overload situation. The amplitude discrimination principle is used in lieu of the usual technique of reducing the receiver sensitivity.

After decoding of the interrogation mode, a mode discriminator decides whether DAC or HAF triggers are to be processed. During decoding, these trigger timings are stored as digital values with a resolution of 31.25 ns. The corresponding trigger datum is then used to preset and start the delay counter, which counts at a clock frequency of 32 MHz until it reaches the preset stop value. The stop value is determined by the combined result of the calibration cycles, the received signal level, and the system delay specified for the particular mode.

At the end of delay timing the reply trigger is issued; after gating by the priority logic it is then fed via the pulse pair encoder to the transmitter. In the event of simultaneous requests for transmission by reply pulses and identification pulses or random pulses, a priority logic is used to resolve the conflict. The specific priority requirement for DME/P is also catered for; FA mode replies have a higher priority than identification pulses.

Transmitter

The transmitter (synthesizer, amplifier, and modulator) outputs transponder pulses of up to 100 W peak power. A new digitally controlled modulator is used to maintain the required pulse shape accuracy irrespective of operational conditions. The modulation signal is applied to the preamplifier and power amplifier stages of the transmitter. Continuous comparison of the ideal pulse shape (stored in programmable read-only memory) and the actual pulse shape, which is sensed by a high precision demodulator, produces a control voltage which is used to maintain the optimum shape of modulation signal.

Calibration Pulse Module

The high precision of the delay time in the DME/P transponder is ensured by a relatively high clock frequency (32 MHz) and automatic equipment self-calibration. Calibration is controlled by the processor which periodically initiates calibration cycles and analyzes the results.

Prior to initiation of the next transmission pulse, the calibration cycle is started by switching the receiver input to the calibration module. The next transmitter trigger is used to start the calibration delay time counter. The corresponding RF transmitter pulse is coupled out, mixed with 63 MHz, and thus converted to the receive frequency. Prior to injection into the receiver, the level ordered by the processor is preset using a switchable attenuator.

At the receiver output, injected calibration pulses are triggered in the same way as any other receiver signal and then stop the calibration time interval counter. The processor decides whether DAC or HAF triggers will be used. The measured value includes the delay time of the transmitter plus that of the receiver (the delay time of the calibration module is negligible). This delay is correlated with the various input levels simulated by the attenuator settings and stored in processor memory.

As the calibration process cycles continuously through the various receiver input levels, two complete sets of delay time values are built up relating to the varying input levels of the received signals. One set refers to the IA mode, the other to the FA mode. The tabulated sets of calibration values are updated continuously, allowing compensation of delay drifts or variations caused by, for example, temperature and aging and the differences in level of the received signals. Depending on the operational mode and the measured received signal level, the processor derives a correction from the tabulated data which is used to preset the delay counter. In this way, the transponder delay time remains accurate to within one period of the clock frequency (31.25 ns).

DME/P Airborne Equipment

The new DME system permits DME/N and DME/P functions to be combined in a single interrogator. To ensure interchangeability, the form, fit, and function should meet the ARINC (Aeronautical Radio Inc) characteristics for conventional airborne DME.

The similarity between DME/N and DME/P made it practical to use a modern series DME as the kernel for a DME/P laboratory model. Its receiver and signal processing sections were replaced by newly developed units, and modules such as the modulator/transmitter and central processing unit were suitably modified. Figure 4 is a simplified block diagram of the DME/P airborne unit. The main characteristics are given in Table 2.

Two-Mode Technique

The airborne functions in the IA mode are similar to those in DME/N, although the accuracy requirements are more demanding. After selection of the DME/P beacon frequency and at an approach distance greater than 10 n miles, the aircraft transmits IA mode interrogation pulse pairs

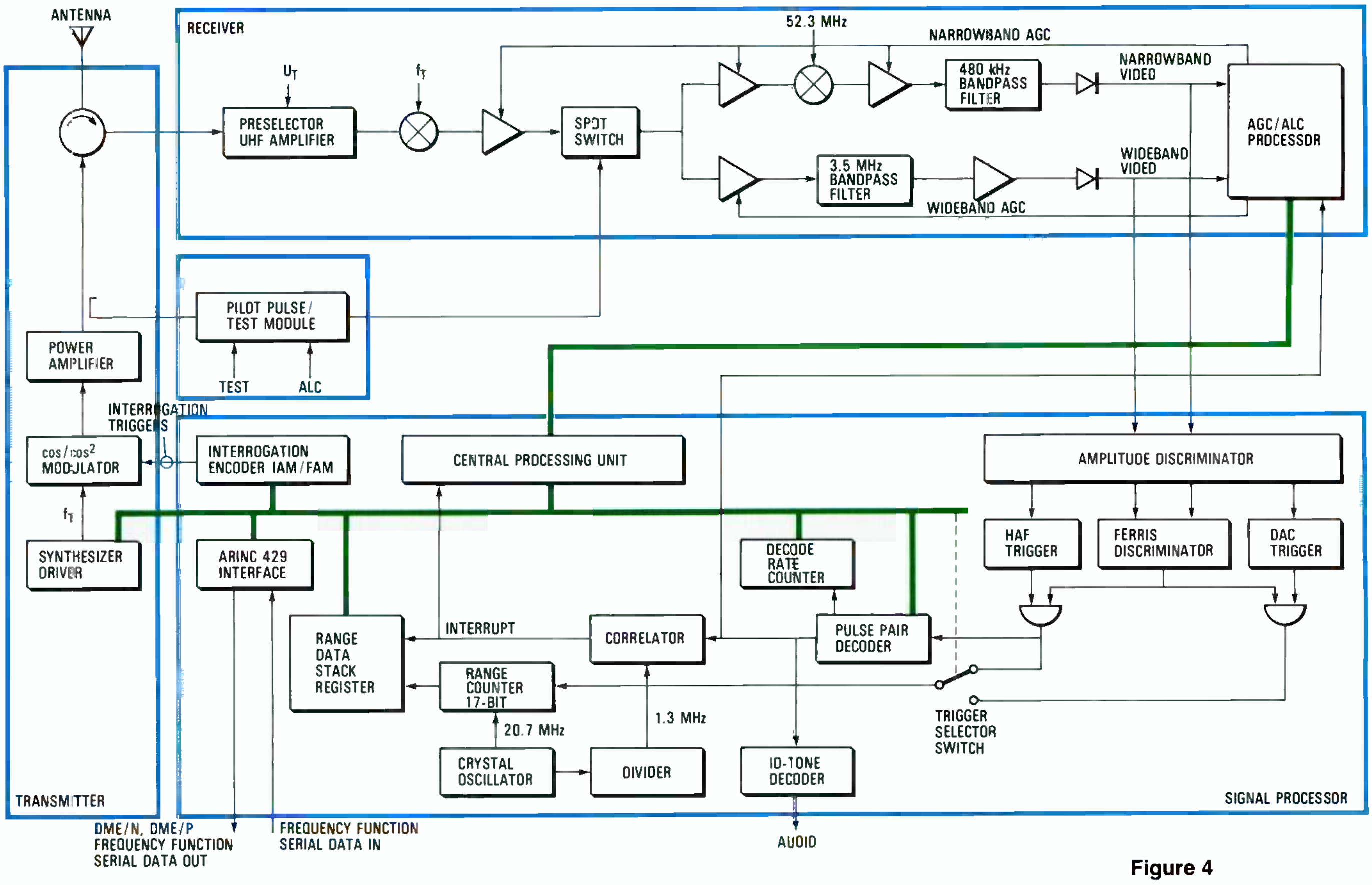


Figure 4
Simplified functional block diagram of the DME/P airborne equipment.

at a rate of 16 Hz. DME/P pulses from the ground transponder are processed in the narrowband branch of the receiver. As in *en route* operation, subsequent video signal processing, including range timing, is based exclusively on HAF triggers, which are processed in the range counter and the central processing unit to give range output data.

As the approach distance decreases to about 7 n miles, FA mode interrogation pulse pairs (with $\Delta = 6\,\mu s$ difference in spacing) are progressively added and interlaced with IA mode interrogations. The reply rate of FA mode interrogations is monitored separately, and the corresponding confidence level is based on that of the IA mode track operation which continues in parallel (mixed mode).

Once a sufficient reply efficiency for the FA mode interrogations has been established, the mixed mode is terminated and only FA mode interrogation pulse pairs are transmitted. Low level thresholding is applied for FA mode interrogation cycles (i.e. reply timing is achieved via the wideband receiver branch and the associated DAC trigger). For reasons of signal processing integrity, however, validation of the received DME/P signal, including pulse pair decoding and search/track correlation, is always done in parallel using the coherent output from narrowband processing.

Table 2 — Main characteristics of the DME/P airborne equipment

Design characteristics:	
DME/N function	TSO C 66a, ARINC 709, 429, DO 160
DME/P function	AWOP-WP/401 (12/82)
Technical features:	
Dimensions (form)	width 123 mm, height 194 mm, length 318 mm (4 modules)
Weight	approximately 6 kg
Power consumption	115 V/50 W
Transmitter power	500 W_p
Receiver sensitivity:	
DME/N mode:	< −87 dBm } for 23 dB video signal-to-noise ratio
DME/P mode:	< −78 dBm } for 23 dB video signal-to-noise ratio
Instrumentation error	< 15 m path following error (FA mode)
	< 10 m control motion noise (FA mode)

Main Functional Units

Transmitter Frequency Synthesizer

The synthesizer operates in the range 256.25 to 287.50 MHz. It is followed by a quadrupler/power-driver stage which provides the carrier and local oscillator frequencies. The transmitter is a 4-stage power amplifier; the steep DME/P interrogation pulse shape is generated by collector modulation. The pulse shape is the same in all operational modes of the airborne equipment.

Receiver

The receiver front end comprises a 2-pole preselection filter and 2-stage preamplifier followed by a 3-pole postselector; the bandwidth is about 25 MHz. Filter tuning is controlled by the central processing unit using varactor diodes. The noise figure is well below 8 dB.

After conversion to 63 MHz IF, the received signal is split and fed to the narrowband and wideband IF amplifiers. A second conversion down to 10.7 MHz takes place in the narrowband branch. The narrowband 6-pole LC filter has a bandwidth of about 480 kHz. The corresponding linear IF amplifier has a dynamic range exceeding 80 dB. The AGC voltage is derived from the narrowband video pulse amplitudes in conjunction with the linear signal processing circuitry. The characteristics of the narrowband IF amplifier determine the selectivity in both IA and FA modes.

In the wideband branch, the signal processing bandwidth is 3.5 MHz. The corresponding bandpass filter is a 10-pole filter/FET cascade. A Ferris discriminator is used to achieve the required 42 dB adjacent channel rejection. Its function is similar to that of the transponder. The wideband amplifier is also controlled by a linear AGC voltage derived from the narrowband AGC voltage already mentioned, with some fine adjustment to compensate for gain drift between the IF amplifier branches.

The wideband IF amplifier feeds the DAC trigger via a precision demodulator. Frequency response and dynamic range of the demodulator, in particular its low level linearity, are of prime importance for the precision and noise immunity of the DAC threshold performance.

Signal Processor

Precise time interval measurement is based on a range counter clocked at 20.7 MHz. The range count is started by the detected interrogation pulse. Upon arrival of any trigger pulse (DAC trigger in FA mode, or HAF triggers in all other modes) the corresponding range count – a 17-bit word representing the time of arrival – is transferred to a stack register. Final transfer to the CPU occurs only after detection and/or repetitive validation of the synchronous reply pulse by the correlator circuit. The CPU then sorts out time of arrival data belonging to the first pulse of the synchronous reply pulse pair.

The range correlator consists of a 10-bit shift register, which divides the DME range in a numbered sequence of 1024 time cells, each 6 μs wide. Associated with each cell is a counter, which is incremented when a trigger pulse occurs in the corresponding time cell; otherwise the cell counter is decremented. Only the counter associated with the cell that contains the synchronous range will attain a higher count than the others, thereby identifying the coarse value of the time of arrival of the synchronous reply pulse. To protect against noise and false lock-ons, correlation is always based on decoded pulse pairs from the narrowband video signal. Further processing of the DME raw data in the CPU includes range data limiting (outlier rejection), raw data filtering, and scaling and formatting of the output data.

For simplicity of software design a digital filter of the α/β type was chosen. It has the characteristics of a type II, second-order servo loop, and was implemented as an adaptive filter. Selection of the filter parameters is rather limited owing to their close interdependence on the prescribed spectral distribution of the path following error and control motion noise components. In the present design the value of α is varied within specific limits, depending on the operational mode and the variance of incoming raw data. Filter constants are chosen for a compromise between smoothing capability and dynamic response.

Self-Calibration Module

A self-calibration loop which closely follows the IF pilot pulse technique proven in MITAC airborne equipment, is incorporated to compensate for delay variations and equipment tolerances.

In the pilot pulse/test module the RF interrogation pulses are converted down to 63 MHz carrier frequency and the resulting pilot pulses are fed to the narrowband and wideband receiver branches. The pilot pulse level is adapted automatically to that of the incoming receiver signal. DAC or HAF triggers derived from the pilot pulse are processed in the same way as all other received pulses. After conversion into time of arrival data by the range counter and transfer to the CPU, a special filter algorithm is applied, yielding a high precision zero n mile reference value on which subsequent range computations are based.

The front end section of the receiver is excluded from the IF pilot pulse loop. However, the preselector filter bandwidth is wide enough for delay timing variation errors to be negligible.

The pilot pulse/test module also incorporates the test signal generation for built-in self-testing.

Simulation and Test Equipment

Special equipment was developed to test the DME/P ground and airborne equipment. The new DME/P ground beacon simulator became an indispensable tool for testing DME/P airborne equipment. It features a delay accuracy of better than 5 m and outputs range replies with superimposed echoes. Echo parameters such as delay time, amplitude, and RF phase difference can be preset, as well as the change rate of the phase difference, the so-called scalloping frequency.

The SEL DME/P interrogator simulator is used to test ground transponders: time interval measurement accuracy is better than 5 m. The parameters of the output test interrogations are presettable. Time interval, pulse pair spacing, pulse rate, relative reply rate, and pulse level are measured. Also, a new identification tone decoding standard for the FA mode is incorporated. Simulation of specific echo signal situations can be achieved by combining two of these equipments.

Conclusions

It will be some years before the first DME/P equipment goes into service since it depends on widespread installation of the new microwave landing system. Also the conventional DME is presumed to be adequate for MLS Category I installations at regional airports.

In general, however, DME is likely to become increasingly important. In scan mode, modern airborne DME provides multiplexed distance measurements to several ground transponders, enabling an airborne computer to calculate the position of the aircraft. As part of an area navigation system this cost-effective multi-DME could offer a major breakthrough.

The Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt is investigating a three-way DME which provides complete position data and aircraft identification information to the ground station, offering cost-effective air traffic control. This philosophy could culminate in a multi-three-way DME with three-way airborne DMEs operating in scan mode. The configuration could eventually lead to a combined navigation/air traffic control system based exclusively on the DME technique.

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Klaus Becker was born in Andernach, Germany, in 1943. He studied communications engineering at the University of Karlsruhe, graduating as a Dipl-Ing. He joined SEL in 1970, where he worked on the development and qualification of the MITAC airborne Tacan equipment, DME, and DAS. In 1981 he was appointed head of the development group for civil navigational airborne equipment and is responsible for the DME/P airborne system.

Albrecht Müller was born in Leipzig, Germany, in 1945. He studied communications engineering at the Technical University of Darmstadt. After graduating as a Dipl-Ing he became a lecturer at the same university. In 1978 he received the degree of Dr-Ing. He then joined SEL to work on development of DAS. In 1981 he was appointed head of the development group for civil navigation systems planning and in 1983 became chief engineer for civil navigation. Dr Müller has led development of the DME/P ground station.

Horst Vogel was born in Stuttgart, Germany, in 1936. He studied communications engineering in Esslingen and graduated as a Dipl-Ing. He joined SEL in 1962 and was active in the fields of large computers, Tacan, and civil navigation. In 1967 he became development manager for avionics; from 1976 to 1982 he was chief engineer for civil navigation. In 1983 Mr Vogel was appointed program manager and now supervises large scale SEL projects.

Loran-C Navigation System for Saudi Arabia

A major expansion of the Loran-C navigation service is underway in Saudi Arabia. Two new Loran-C chains will improve the safety and efficiency of maritime traffic in the crowded waters of the Red Sea, Arabian Gulf, and around the Arabian Peninsula.

W. J. Garmany
V. L. Johnson
W. J. Romer
ITT Avionics Division, Nutley, New Jersey, United States of America

Introduction

The use of Loran-C for marine navigation has advanced rapidly over the past decade as a result of the availability of low cost microprocessor-based receivers and continuing expansion of Loran-C coverage in the Northern Hemisphere. The United States completed a major expansion of the Loran-C service in 1980 with the installation of 13 new transmitter stations. In conjunction with five existing stations, these formed six new Loran-C chains that provide complete coverage of the coastal confluence waters of the continental United States and Alaska. ITT Avionics supplied the transmitter equipment for eight of the new stations.

At present 43 high power Loran-C transmitter stations (14 Loran-C chains) provide navigation service in the Northern Hemisphere. ITT Avionics has supplied the transmitter equipment for 19 of these stations. The number of users has grown from a few thousand in the mid 1970s to an estimated 70000 in 1981 and is expected to exceed 250000 by the late 1980s[1].

The next major expansion of the Loran-C service is being installed in Saudi Arabia by Standard Electric Alireza (an ITT/Alireza Saudi company) under a turnkey contract with the Saudi Ports Authority. Systems engineering and the Loran-C equipment are being provided by ITT Avionics.

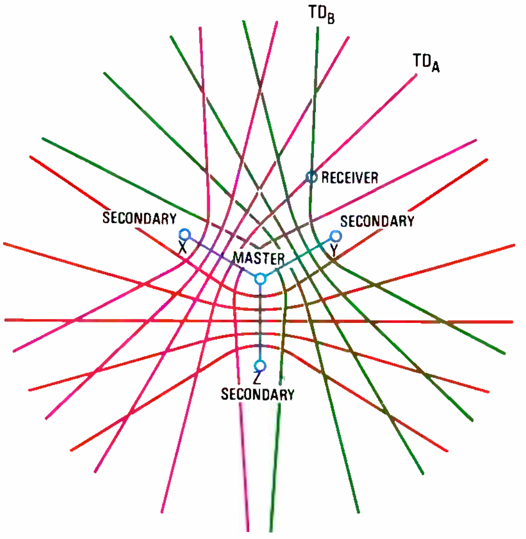


Figure 1
Triad and star transmitter configurations.

Basic Principles of Loran-C

Loran-C is a low frequency hyperbolic navigation system which uses pulsed transmission and time difference or time-of-arrival measurement of the signals from three stations to fix the receiver's position. Each Loran-C chain consists of a master transmitter station and two or more secondary stations. Chain layouts usually use as triad or star configuration (Figure 1). The solid hyperbolas are points of constant time difference or lines of position that correspond to the triad configuration formed by the master station and secondary stations *X* and *Y*. The intersection of two lines of position defines the receiver position. The complete array of hyperbolas corresponds to the star configuration obtained by adding secondary station *Z*. Stations are located so that signals from the master and at least two secondary stations can be received throughout the coverage area.

Area monitor stations in the service area continuously check the transmitted signals. These stations measure the time difference of each master-secondary pair with reference to predetermined time differences for each pair. This data is sent to a chain control station which controls system timing. Transmitter stations are equipped with cesium beam frequency standards that ensure high timing accuracy and stability.

All transmitters radiate groups of pulses at 100 kHz using the signal format shown in Figure 2. A unique GRI (group repetition interval) is assigned to each chain to allow the desired chain to the selected by synchronizing the receiver to the selected GRI. Transmitter stations are frequently used in two adjacent chains, in which case the transmitter uses both GRIs.

A detailed description of the Loran-C system is available in previous issues of *Electrical Communication*[2,3].

System Configuration

Two new Loran-C chains, consisting of seven high-power transmitter stations and three area monitor stations, are being implemented in Saudi Arabia. The principal requirements are to provide good Loran-C coverage throughout the Saudi Arabian waters of the Red Sea and Arabian Gulf and to site all stations within Saudi Arabia.

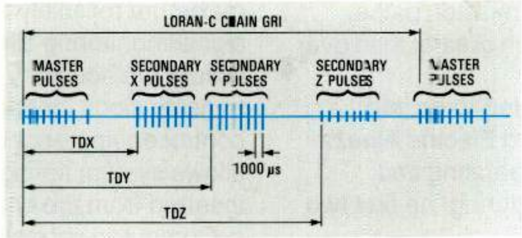


Figure 2
Loran-C signal format.

Figure 3 shows the system layout and the predicted coverage limits. A repeatable fix accuracy of 0.1 n mile (2 d RMS*) or better is projected in Saudi waters, including the principal ports of Jeddah, Yanbu, Jubail, and Dammam.

The system configuration has been expanded to extend coverage into the waters around the Arabian Peninsula, allowing circumnavigation of the peninsula using Loran-C. The predicted coverage is shown in Figure 3.

Modular solid-state transmitters allow the radiated power from each station to be tailored to the coverage requirements with an upper limit of 800 kW. This radiated power was selected for the four stations that are most important to coverage to the south

* The distance root mean squared (d RMS) is the radius of a circle that contains at least 95% of all possible fixes that can be obtained with a receiver at any one place.

Transmitter station at Afif in Saudi Arabia.

over long overland transmission paths, where attenuation is much greater than over the sea.

The system is scheduled to go into service in 1984. Standard Electric Alireza will be responsible for operating and maintaining the system during the first two years.

System Elements

The precisely timed Loran-C pulses required for accurate navigation are provided by radiating signals from seven transmitter stations and making timing corrections from a chain control station where tracking data from the three monitor stations is analyzed.

Transmitter stations use combined redundancy and fail-soft operation to ensure maximum reliability and availability. Local signal monitoring allows each station to assure the accuracy and stability of its transmissions independently. Remote control equipment built into the transmitter allows system timing corrections to be inserted from the chain control station.

Computer-controlled receivers at the monitor stations gather data on the radiated signals and transmit regular reports to the chain control station.

Central monitoring and control for the two Loran-C chains is provided by a continuously-manned chain control subsystem at the Al Lith transmitter station. Data from the monitor stations is recorded and continuously analyzed to determine whether the transmitter timing or signal characteristic needs to be adjusted. Remote control facilities allow operational changes to be made to any of the seven transmitters.

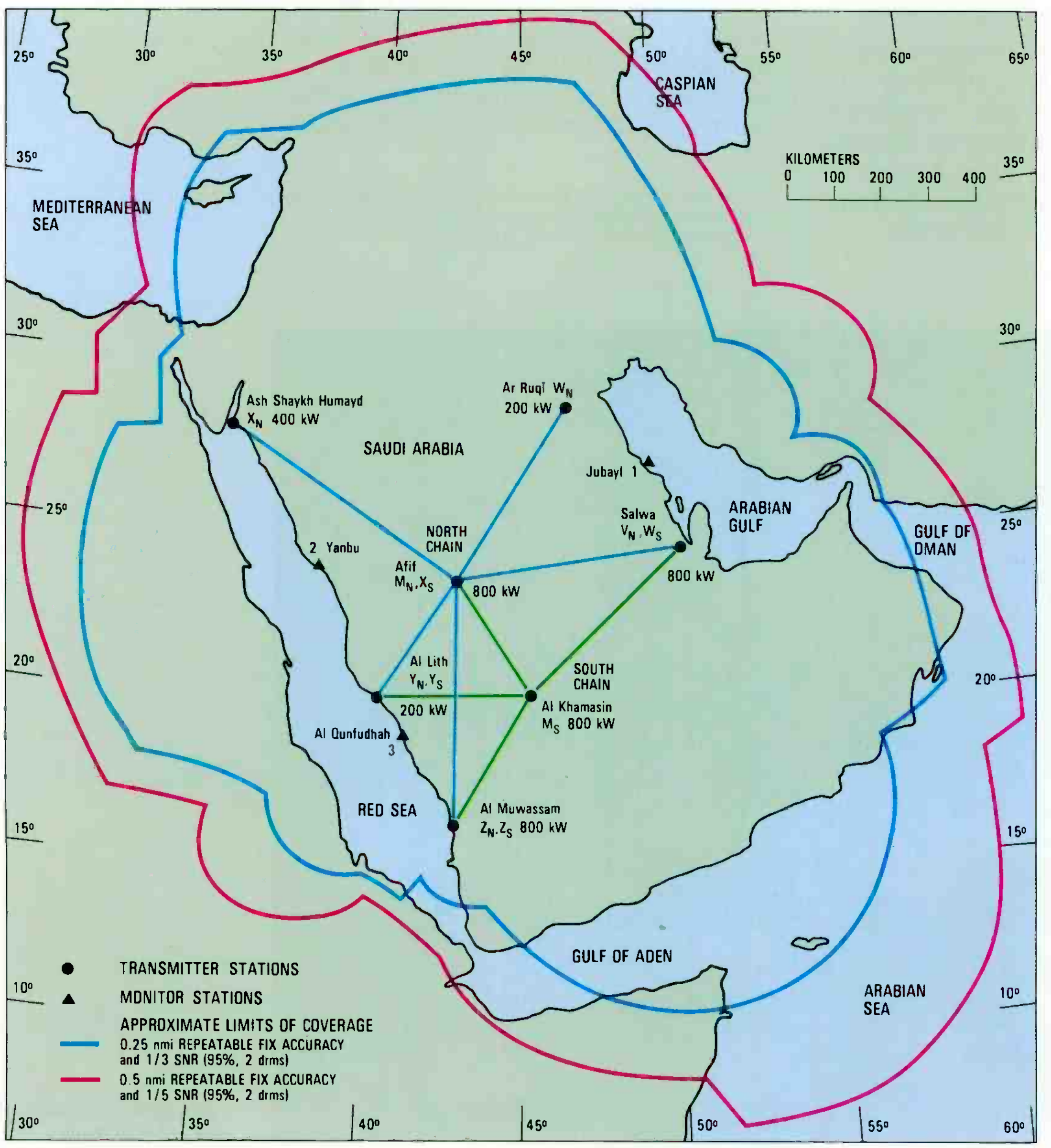


Figure 3
Loran-C system for Saudi Arabia.

A well equipped central maintenance facility is also provided at Al Lith.

Data communication channels are provided for monitor receiver operation, transmitter remote control, and an administrative teleprinter network. Multichannel modems at all stations are interconnected by a multiport dedicated network in the Saudi telephone system. Microwave links connect each station to the nearest access to the telephone network.

Transmitter Stations

Each Loran-C transmitter station is a self-supporting facility with its own living quarters and AC power generator. The key functional units are an antenna, transmitter, and signal analysis equipment.

Loran-C pulses are radiated from a 220 m high guyed steel tower. The uppermost guy level consists of 18 top-loading elements each 200 m long. The antenna system counterpoise consists of 120 radials each approximately 325 m in length.

High-power RF (radio frequency) pulses are generated by the modular solid-state transmitters. Stations are equipped with 16, 32, or 64 HCG (half-cycle generator) modules, depending on the radiated power requirements.

Timing of the transmitter RF output is based on ultrastable triggers generated in the Loran-C signal format by the timing and control equipment. Built-in fault sensing is incorporated for automatic switchover to redundant units. Primary transmitter functions may be controlled locally or from the chain control station.

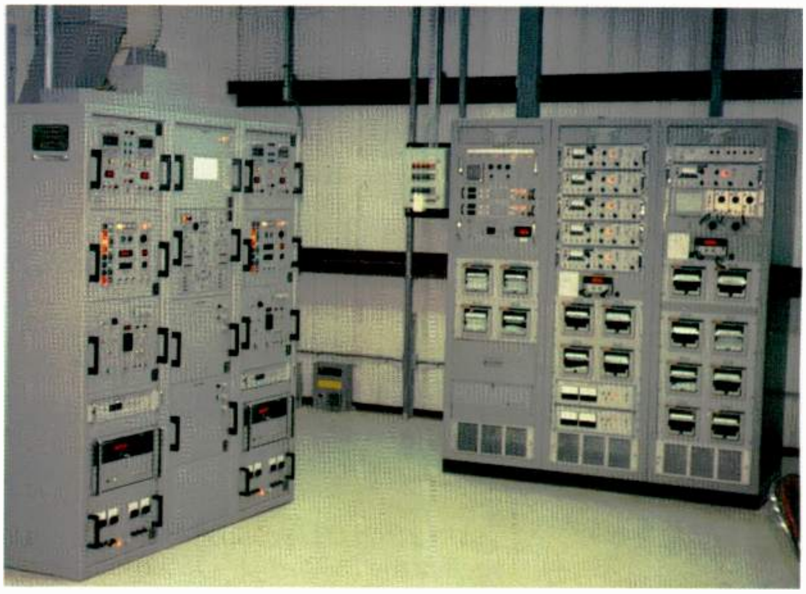
Correct transmitter operation is verified by signal analysis equipment. RF signal amplitude, shape, and envelope-to-cycle relationship are monitored; station timing relative to the signals received from other stations is also continuously checked.

Transmitter Equipment Set

The transmitter equipment set consists of two major equipment groups: a control console and a transmitter.

The control console incorporates all basic timing and control functions in an operate-standby configuration with automatic switchover if timing signals are lost. The transmitter consists of multiple identical HCGs together with redundant coupling and output networks. The multiple HCG configuration operates in a fail-soft mode to maintain the transmitter on-air with acceptable output signals even if several HCGs are off-line.

Figure 4 illustrates the basic technique by which the Loran-C pulse is generated. Transmitter control circuits divide the HCGs into four groups, each developing a 5 μs DHC (drive half cycle). The amplitude of each DHC is primarily a function of the number of HCGs assigned to that DHC. DHC timing is chosen so that the output of all the HCGs forms a 100 kHz RF pulse two cycles long. This two-cycle RF pulse is the



Transmitter control console and signal analysis set at the Afif station.

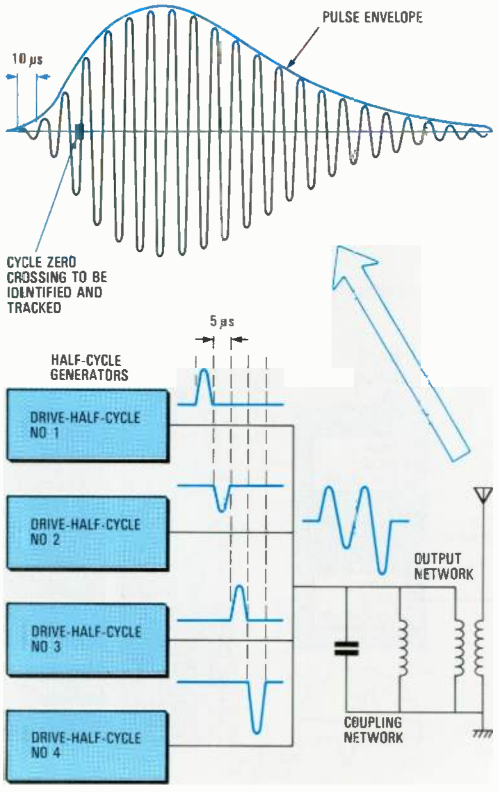


Figure 4
Loran-C pulse generation.

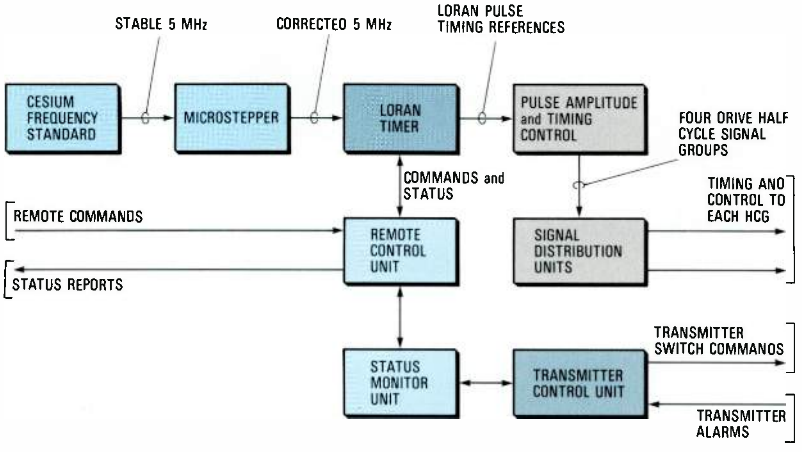


Figure 5
Control console functional diagram.

input to a high Q LC coupling network. Together the DHC amplitudes, coupling network, output-network transformation ratio, and antenna impedance produce a correctly shaped Loran-C pulse. Control of the pulse shape is achieved by minor adjustments to the DHC amplitude relationships.

The control console incorporates the transmitter timing and control circuits (Figure 5). The stable 5 MHz output from a cesium frequency standard is used to derive all Loran-C signal timing. A microstepper corrects for small frequency-standard offsets (a few parts in 10^{13}). The corrected 5 MHz signal is used by the timer to generate a sequence of triggers in the Loran-C format which act as timing references for the transmitted pulses. The timer also generates the signals that control phase coding of the pulses and the on-off blink pattern used to warn users if an out-of-tolerance conditions exists. In addition the timer includes a cycle-compensation control loop for maintaining a fixed transmitter system delay and a local phase adjustment capability which allows timing steps to be inserted, as required, to maintain the correct system time relationship of the radiated signal.

Pulse amplitude and timing circuits receive triggers from the timer and use them as a reference to develop the four DHC signal groups required by the transmitter. Each DHC signal group contains all triggers required by the power amplifier HCGs, an amplitude data word which commands the HCGs' output level, and a timing data word which controls timing of the HCG output. A signal distribution unit routes DHC signals to the individual HCGs. Built-in test circuits throughout the transmitter provide inputs to the transmitter control unit and status monitor unit for automatic switchover to redundant units and alarm generation. The status monitor unit also receives transmitter status data which, along with alarm data, is combined into an output to a teleprinter and becomes the station's log. A remote control unit permits the chain control station to control the transmitter.

Figure 6 shows the basic elements of the transmitter. The 64 HCGs are shown as a single pulse generator, the output from which forms the combined DHC input to the coupling network. A switch network is provided because the coupling network and output network circuits operate in an operate-standby mode. A current transformer at the input to the switch network provides a DHC sample to the control console where control loops maintain each DHC at its correct level. The

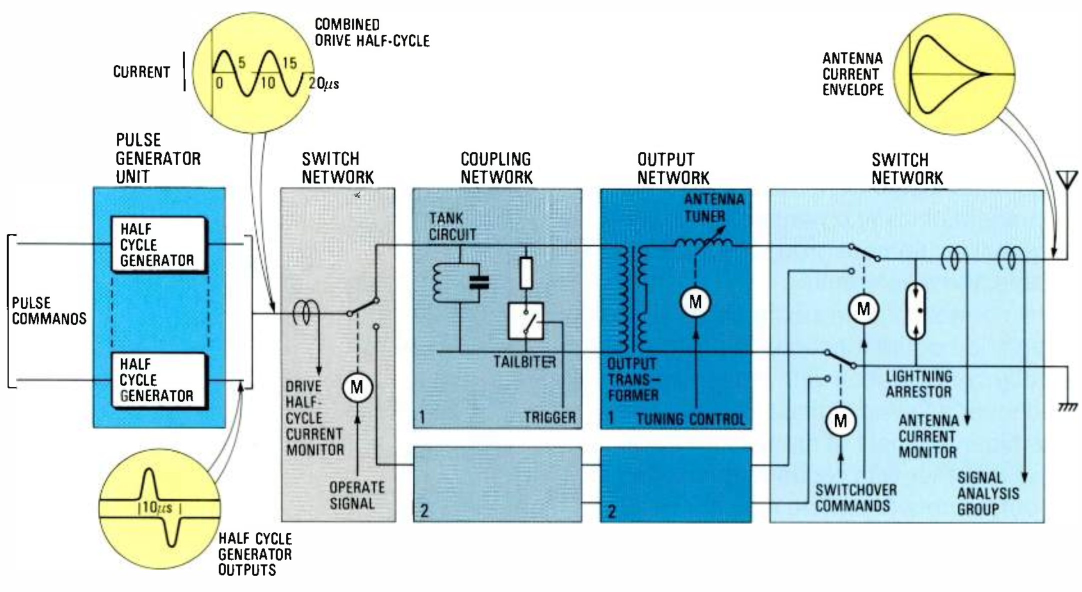


Figure 6
Solid-state transmitter elements.

Q factors of the coupling network and antenna are high enough to require a damping network for the pulse tail; this is switched on at the peak of each pulse to absorb excess energy and ensure that each pulse decays to zero before the start of the next pulse. An automatic antenna tuning circuit in the output network ensures that the antenna circuit is always tuned to 100 kHz. The switch network output to the antenna incorporates a current transformer from which automatic tuning control is derived. A second current transformer provides a signal for the signal analysis set.

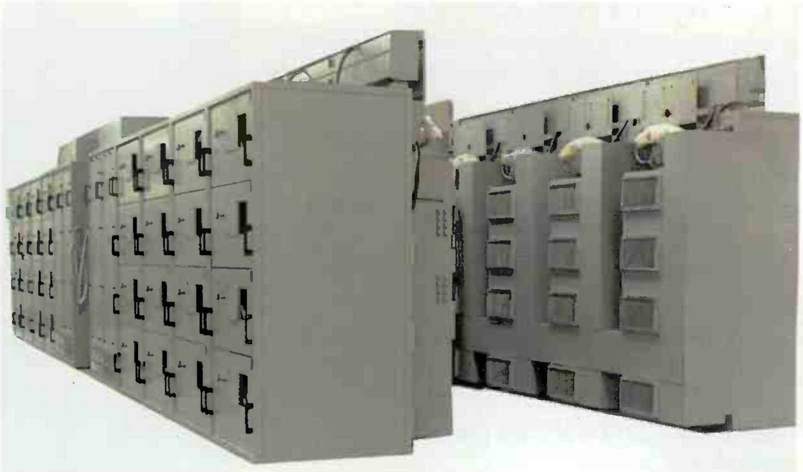
Signal Analysis Set

The signal analysis set verifies the Loran-C pulse shape and timing, and helps to maintain correct station timing should communication with the chain control station be interrupted. Timing receivers operating in conjunction with time interval counters establish a time relationship between the transmitter timers and signals received from other Loran-C stations. The frequency relationship of the operate and standby cesium frequency standards is recorded continuously to ensure that the standby frequency standard is stable. A recording of the transmitter cycle-compensation performance verifies that the transmitter time delay is being held constant. An electrical pulse analyzer measures the pulse amplitude and pulse shape of the transmitter antenna current waveform. The relationship between the pulse leading edge shape and the pulse standard RF zero crossing (the envelope-to-cycle difference) must be maintained within preset limits. The envelope-to-cycle difference is continuously recorded and monitored by an alarm system.

The envelope-to-cycle difference alarm, alarms from the transmitter, and a lost-carrier alarm from the carrier telegraph unit are among inputs to an alarm repeater unit which initiates both audible and visual signals to alert station personnel to any abnormal operating condition.

Monitor Stations

Monitor sets are located at the two Red Sea monitor stations. The Jubayl monitor set has two receivers to provide redundant monitoring for that area. Collectively the three monitor stations provide both primary and back-up monitoring of all the transmitter stations.



Loran-C transmitter.

Under real-time signal processor control, a monitor receiver filters, amplifies, and samples the Loran-C signals from transmitters in both chains, and formats the resulting digital data for transmission to the control station. Time differences are measured to an accuracy of 15 ns. Program-controlled gain stages give the receiver a dynamic signal range of 128 dB.

Red Sea monitor set.

Each receiver tracks stations and prepares reports according to instructions from the chain control station. These reports include information on time differences, signal levels, noise levels, and lost signals. Reports on all the tracked stations are encoded, multiplexed, and transmitted on one data channel. Full duplex communication to and from the processor is provided by a carrier telegraph modem.

A remotely controlled relay in the antenna coupler enables the antenna signals to be replaced by a simulator output so that the monitor set can be tested from the chain control station.

Although a monitor station is normally unattended, a data terminal with a cassette deck is supplied for maintenance. The deck is used to load operating and diagnostic programs, and the terminal to enter operating commands and receive reports locally.

Chain control subsystem.

Data Analysis Equipment

Monitor station reports are transmitted to data analysis equipment in the chain control subsystem. For each of the four monitor receivers, an information demultiplexer distributes the incoming encoded data to a teleprinter and to stripchart recorders. The teleprinter is used for remote control of the associated monitor receiver. Time difference data for each master-secondary pair is obtained from two monitor receivers and recorded on separate stripcharts. The envelope-to-cycle relationship for each transmitted signal is also recorded.

Three desktop computers analyze data from the south chain, the Red Sea section of the north chain, and the Arabian Gulf section of the north chain. Each computer receives data from two or more monitor receivers and drives a printer, a plotter, and an alarm unit.

The computers and their peripherals provide information for time-difference control, detecting and reporting abnormal transmitted signals, and producing records of Loran chain operation. Each computer carries out a statistical analysis of time difference data from the monitor receivers and issues transmitter timing adjustment recommendations. These adjustments, typically ±20 ns, are based on the long-term cumulative time difference error and current time difference data. An alarm is initiated and fault information printed out whenever analysis indicates that transmitted signals are not within the specified tolerances. The printer logs certain chain activities as they occur and each day summarizes time-difference averages and other data. The plotter continuously produces daily graphs of time difference averages and cumulative time difference errors for each selected master-secondary pair.

A multichannel carrier telegraph unit for this station is included. Thirteen 110 baud data channels are multiplexed on one 4-wire line for communication with all monitor and transmitter stations.

Remote Control Set

A remote control set is used by the chain control operator to monitor and control the Loran-C transmitters at all stations. This set consists of the central cabinet and three teleprinters. A status monitor unit converts encoded data to plain language log entries which are printed by the teleprinters.

Reports on abnormal situations are sent automatically by each transmitter to the chain control RCU. Such situations include equipment failure, over temperature, and antenna current changes.

The chain control operator can use the remote control equipment to send a variety of commands to any selected transmitter, including:

- insert timing adjustment
- switch to standby timing channel

– turn transmitter output *on* or *off*

– send status summary report.

One duplex data channel is provided for each chain control RCU. Each outgoing message includes an address code so that only the selected transmitter responds. Transmitter RCUs check the incoming line and delay data transmission when it is busy.

Conclusions

The Red Sea and Arabian Gulf are waterways of significant marine transportation. The increase in traffic through the Suez Canal together with rapid growth in the size and number of operational ports on both coasts of Saudi Arabia is leading to further increases in the already heavy traffic in these areas. Much of the coastline is almost totally devoid of natural or man-made landmarks and has reefs far offshore, thus making navigation difficult. The increasing use of offshore mining rigs and platforms also gives rise to the need for accurate all-weather navigation both to prevent collisions and to support such offshore operations.

The Saudi Loran-C system provides a repeatable fix accuracy of 0.1 to 0.2 n mile day and night and in all seasons within Saudi Arabia's coastal confluence waters of the Red Sea and Arabian Gulf. In addition, it provides good coverage in the waters south and east of the Arabian Peninsula, allowing circumnavigation of the peninsula using Loran-C. The signal availability of the system is estimated to exceed 99.5%.

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William J. Garmany received a BS degree in electrical engineering from Newark College of Engineering in 1942 and joined ITT in 1946. He has been closely involved in the design, manufacture, and installation of ITT Loran-C equipment. Mr Garmany is a principal member of the technical staff of the Loran system engineering group. He is a member of the Institute of Electrical and Electronic Engineers, the Institute of Navigation, and the Wild Goose Association (Loran professional organization).

Vernon L. Johnson received a BS degree in electrical engineering from North Carolina State College in 1949 and an MS degree in electrical engineering from Newark College of Engineering in 1954. He has been associated with ITT Avionics Division since 1949 and is at present the engineering manager for Loran programmes. He worked earlier on development of the rho-theta Tacan navigation system and on a naval shipboard communication system. Mr Johnson is a member of the Institute of Electrical and Electronics Engineers, the Institute of Navigation, and the Wild Goose Association.

William J. Romer received a BS degree in electrical engineering from Newark College of Engineering in 1950. He joined ITT Avionics Division in 1972 as a principal member of the technical staff in the Loran system engineering group. Prior to joining ITT he was a Loran systems engineer with the US Coast Guard. He is a member of the Institute of Navigation and the Wild Goose Association.

Satellite Navigation

Navigation of ships and aircraft using satellite transmissions is already a proven technique with the Transit system. The Navstar system, scheduled to go into full operation in 1987, offers even higher accuracies with virtually continuous worldwide coverage.

P. K. Blair
P. J. Hargrave
Standard Telecommunication Laboratories Limited, Harlow, Essex, England

Introduction

The basic measurements that can be made from satellite transmissions are range and relative line of sight velocity (or range-rate). Range can be measured from the transit time of a signal from the satellite to the observer, and the relative line of sight velocity can be deduced from the Doppler shift in frequency of the received signals. These measurements can be used to derive navigational information by observing a single satellite over a period of time as it passes across the hemisphere, as in the Transit system, or by making measurements to a number of satellites that are in view simultaneously, as in the Navstar system.

Range Measurement

The measurement of range requires that signals from the satellite contain a modulation of effectively marked time. In the Navstar system this is achieved by using PRN (pseudorandom noise) codes. A carrier is effectively multiplied by an apparently random sequence of $+1$s and -1s of duration $1/b_r$, where b_r is the bit-rate of the code. If the sequence is agreed rather than being truly random, the arrival of code states can be timed in order to derive range information.

PRN code modulation spreads the energy of the original carrier into a $[\sin x/x]^2$ power spectrum, centered on the carrier frequency and with the first nulls offset by $\pm b_r$. A receiver measures the arrival time of the code by aligning a locally generated code with the received signal. When the aligned local code is mixed with the downconverted received signal it removes all the phase reversals produced by PRN code modulation, leaving a carrier with a frequency that can be measured to provide range-rate information. In the Navstar signal the underlying carrier is slightly broadened by low bit-rate (50 bit s^{-1}) phase modulation which conveys ephemeris data detailing the position and motion of the satellite.

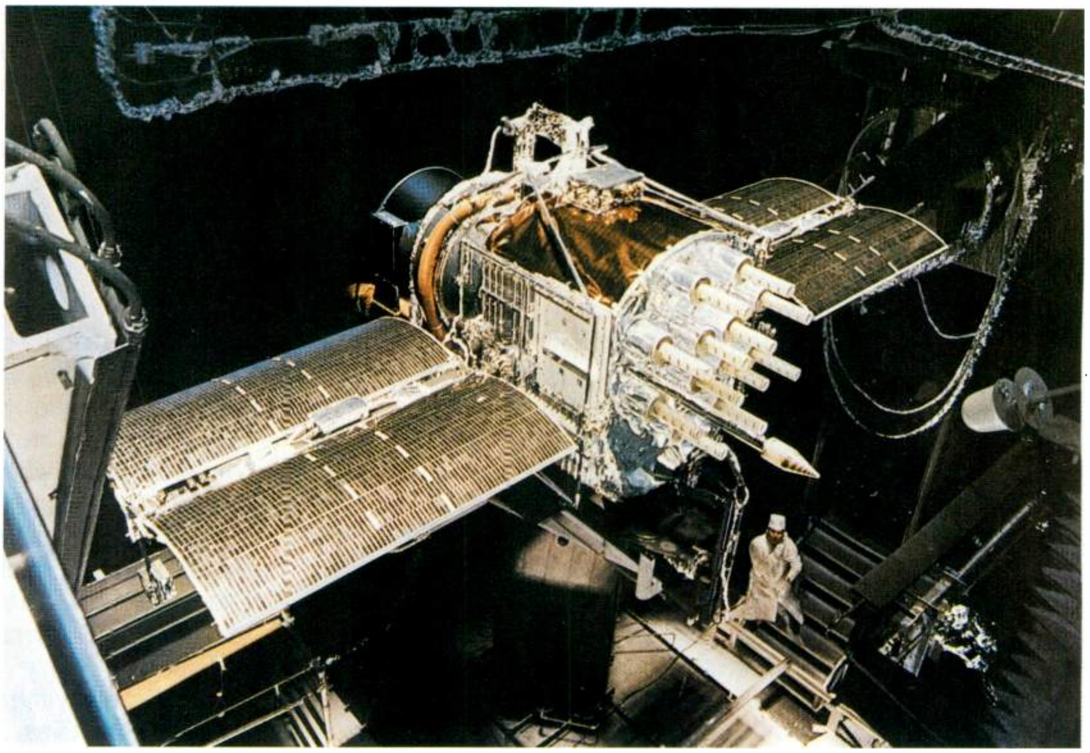
As well as providing range information, PRN codes give protection against jamming. As the phase reversals are being removed from the desired signal, they are applied to any narrow band jamming waveform, thus spreading the jammer power over a bandwidth of about b_r, so that after filtering the remaining jammer power is substantially reduced. The resulting increase in signal-to-noise ratio is said to be brought about by the *spread spectrum processing gain* available from the PRN code.

A third reason for employing PRN codes is that they may be used for spectral division. A number of satellites can transmit at the same frequency using modulating codes with low cross correlation functions. Families of codes can be constructed with good cross correlation properties by summing the outputs of two n-stage shift registers with each producing a maximal length sequence[1,2]. The two maximal length sequences are carefully chosen and give rise to (2^n+1) Gold codes. These arise because the two sequences can be combined with (2^n-1) possible shifts, and the two basic maximal length sequences are also members of the family.

PRN codes are employed for timing the transit of a radio signal along the line of sight from the satellite to the observer. Effectively what is measured is:

$$\Delta t = \int_{\text{Satellite}}^{\text{Observer}} [V_g(1)]^{-1} dl$$

Navstar satellite undergoing tests.



where $V_g(1)$ is the group velocity of the intervening medium and the integration path is along the line of sight from the satellite to the observer. It is necessary to include the effects of intervening media, which reduce $V_g(1)$ significantly below the speed of light in vacuo, to convert a measurement of Δt to the true range.

Range-Rate Measurement

The relative line of sight velocity between the satellite and the observer can be measured from the Doppler shift of a received signal. Doppler measurements actually yield a fractional frequency shift of the transmitted signal given by

$$\frac{\Delta v}{v} = -\frac{d}{dt}\left(\int_{\text{Satellite}}^{\text{Observer}} [V_g(1)]^{-1}\, dl\right)$$

which is the rate of change of the transit time of a signal from the satellite to the observer. If a modulation is being monitored, $V(1)$ is the group velocity of the intervening medium. If an unmodulated carrier is being monitored, $V(1)$ is the phase velocity.

In a Navstar receiver the range-rate is measured using a phase-locked loop. This is fed with a portion of the received signal which has been remodulated by a perfectly aligned code. The loop is designed to lock a voltage (or number) controlled oscillator to one of the phases of the underlying signal, which is still biphase modulated by the 50 bit s^{-1} data. The range-rate is then measured by monitoring the frequency at which the loop locks. The locked oscillator can also be used as a reference source to detect the 50 bit s^{-1} data, and the resulting information may then be passed to the processor that controls the receiver.

Information can be extracted from the phase locked loop using another technique, which forms the basis of the navigational algorithm for the Transit system. The total number of carrier cycles received from the satellite is monitored over an interval. Essentially this integrates the observed range-rate over the interval in order to derive the corresponding change in range to the satellite. Since the phase locked loop is tracking the received RF (radio frequency) carrier to a small fraction of a wavelength, this measurement can be extremely accurate. However, unlike the measurement of transit time, it only yields the change in range (or delta range) to the satellite over a period of time instead of the absolute range at a given instant. However, the data can be used to establish location by undertaking an iterative search of position until agreement is obtained with the measurements.

Control Segment Considerations

In order to be able to use the measured position and velocity data to provide navigational information relative to the surface of the earth, an observer requires information about the positions and velocities of the satellites as a function of time. This ephemeris data must also be transmitted by the satellites. In both the Transit and Navstar systems the data is phase modulated onto the transmitted carriers which are used for Doppler measurements.

The ephemeris data for Transit and Navstar satellites is computed from data obtained by ground tracking stations. These stations, which are at known locations, use the relative navigational information derived from the satellite's transmissions to compute the orbital parameters. The information is then communicated to the satellite via an uplink for processing and subsequent relaying to the observer. As uplink transmissions may be infrequent, satellites are equipped with clocks of sufficient accuracy to maintain the precision of the downlink transmissions between updates.

Any frequency error in the satellite master oscillator will produce a timing error $\Delta\tau$ in the transmissions. When the range to a satellite is being measured by monitoring the transit time of a signal along the line of sight, this timing error will produce a position error of about $c\Delta\tau$, where c is the velocity of light *in vacuo*. Systems using such measurements (e.g. Navstar) therefore require very accurate on-board timing systems, such as atomic clocks, and a procedure for locking the receiver clock to those in the satellites.

Measurement Corrections

Transmissions from satellite to observer traverse the ionosphere and troposphere. The group and phase velocities of radio signals in both media are significantly different from those in vacuo. Raw navigational measurements must therefore be corrected for the perturbing effects of these media before being processed in the navigational algorithm.

For a system measuring satellite range from the transit time and employing accurate timing standards in the satellites, the effects of special and general relativity must also be considered. Both affect the rate at which the satellites' clocks run, and must be allowed for if precise navigational fixes are to be obtained.

The Ionosphere

At Navstar and Transit frequencies the group velocity appropriate to transmission through the ionosphere can be calculated using a standard approximation. Then, using the expression for the group velocity, the extra transit time imposed on a modulation waveform passing through the ionosphere can be determined. It can be shown that the delaying effect of the ionosphere can be characterized by the surface density of electrons along the line of sight between the observer and the satellite.

If information about appropriate surface densities is available, the observer can correct for ionospheric delay. To make this possible, parameters characterizing a model of the ionosphere are transmitted by Navstar satellites as part of the 50 bit s^{-1} data stream. Alternatively, since Δt is proportional to $1/v^2$, ionospheric delay can be corrected by measuring the transit time at two frequencies. This technique is employed by the Navstar system to provide the most precise navigational service. Two L-band signals modulated by PRN codes are transmitted by all satellites.

The Doppler shift of an RF carrier is normally monitored when making range-rate measurements. The observer is then monitoring the rate of change of the transit time of a signal from the satellite, where the relevant velocity of propagation is the phase velocity in the ionosphere. Again it is possible to correct for the effect of the ionosphere by making range-rate measurements at two carrier frequencies.

The Troposphere

The transit time of a ranging signal is further increased by its passage through the troposphere. Unlike the ionosphere, the troposphere is a nondispersive medium at radio frequencies. That is, the group velocity is independent of the frequency of the radio carrier, and the medium can be characterized by a frequency-independent refractive index $n(1)$. Thus the extra delay imposed on the received signal by the troposphere can be expressed as:

$$\Delta t = c^{-1} \int_{\text{Satellite}}^{\text{Observer}} [n(1) - 1]\, dl$$

Since the troposphere is nondispersive, this delay cannot be corrected by multiple frequency observations. It becomes necessary to model the effect. The simplest models usually assume a height dependent refractive index.

Errors resulting from the use of such a standard atmosphere at low elevation angles can be large under extreme meteorological conditions. For this reason it is best not to employ observations of transit times from satellites below about 5° elevation when precise navigational data is required. A corresponding correction needs to be applied to measurements of range-rate if high accuracy is required.

Relativity Corrections

The satellite clock appears to an observer near the earth's surface to run slowly because of the effect of special relativity; this will corrupt any measurement of range based on transit time observations.

The satellite clock is also at a higher gravitational potential than the observer, and according to the general theory of relativity will appear to run fast. Again, formulas are available to estimate the magnitude of this effect.

For a satellite in an orbit close to the earth the effect of the special theory of relativity dominates, and the satellite's clock appears to the observer to run slow. Conversely, for a satellite in a high orbit, the general relativity effect dominates and the satellite's clock appears to run fast.

Considering the Navstar satellites with 12 hour orbital periods as an example, the effect from general relativity dominates. If uncorrected, a range error to the satellite would result, growing at a rate of about 500 m hr^{-1}. To correct for this the satellite clocks are built to run deliberately slowly on the surface of the earth. A further correction is applied in the navigational algorithm to allow for the slight ellipticity of the satellite orbits which means that satellite velocity and orbital radius vary with time.

Navigational Requirements and Satellite Navigation Systems

The criteria which a user applies when choosing a navigation system include: operational suitability, cost, coverage, reliability, and integrity (all weather operation, freedom from atmospheric interference). Satellite-based systems offer the attractions of line of sight propagation and worldwide coverage, and have occasionally been advanced as the solution to *all* navigational requirements. However, the history of navigation shows that combinations of systems, often diverse in their characteristics, generally provide the optimum solution.

Satellites are excellent for *en route* or oceanic navigation, but for the final phase as a ship or aircraft approaches its destination, the highest accuracy is required. An aid which references the vessel to its dock or runway is a more rational approach. In addition, there is only a very short time during an aircraft landing (as little as 2 seconds) in which to advise the user if something goes wrong. Satellites can meet these requirements, but the additional ground costs are prohibitive.

Navstar receiver developed by Standard Telecommunication Laboratories. From left to right the units are the program loading unit, RF front end unit, channel unit, and control and display unit.

It is also difficult to provide the satellite system user with the level of redundancy available with VOR, direction finding beacons, and secondary surveillance radar, for example, because of the high cost of satellite systems. Both Transit and Navstar have constraints on coverage and redundancy imposed by system cost factors.

Current and Proposed Satellite Navigation Systems

Transit

The only fully operational and generally available system is Transit, operated by the US Navy since 1959 and accessed today by nearly 40000 users – 90% of them civilian. Current plans are to discontinue operation after 1992 when Navstar is expected to be fully operational.

Transit consists of four operational satellites in 1075 km polar orbits. Each satellite transmits coherent stable carrier frequencies at approximately 150 and 400 MHz. The navigation message, containing orbital parameters, deviations from the elliptical orbit, message load time, etc, is transmitted every two minutes by phase modulating the two signals. The user receiver measures the Doppler frequency shift during a satellite pass and then calculates its geographic position.

Corrections are made for tropospheric and ionospheric refraction. The accuracy of the final position fix depends on the user's knowledge of velocity and height above the reference spheroid.

Transit has four US located ground based monitor stations which provide the information necessary to update satellite orbital parameters every 12 hours. Two dimensional RMS predictable positioning accuracy is quoted[3] as 25 m from a two-frequency measurement, but considerable errors can result from inaccurate velocity estimates. The coverage of Transit is perhaps its main drawback; the fix rate varies from about 30 minutes at 80° latitude to 110 minutes at the equator.

Considerable use has been made of Transit for surveying with differential accuracies of under one meter[4] and navigation receivers are available for a wide range of users from submarines to pleasure craft with the simplest sets costing less than £1000.

Navstar

The success of Transit provided the stimulus for the US Department of Defense to examine more advanced systems providing capabilities for high dynamic users. This led to the birth of the Navstar system which is currently under experimental evaluation and development in the USA and other countries, notably the United Kingdom.

The complete Navstar system is planned to consist of 18 operational satellites with three in-orbit spares arranged in nearly circular orbits with radii of 26 600 km and an inclination to the earth's equatorial plane of 55°. Each satellite transmits two navigation signals centered on 1575 and 1228 MHz. Both signals are derived from atomic frequency standards within the satellites, and convey range information by means of modulations which are locked in time to the atomic standards. These modulations are unique to each satellite. By measuring the phases of the received codes against a clock in the receiver, together with the Doppler shifts of the radio frequency carriers, an observer can calculate the range and range-rate to a particular satellite. These calculations contain uncertainties resulting from inaccuracies in the receiver clock which does not have the inherent stability of the atomic standards in the satellites.

However, by monitoring four satellites (and decoding data about their motions which are also modulated onto the transmitted signals), the observer can determine his three-dimensional position and velocity and apply corrections to his clock, making it conform to satellite time. Alternatively, if he is constrained to move on the surface of the earth or is at a known altitude, he can take two-dimensional measurements using three satellites. The software controlling the receiver must choose, from the satellites in view, the subset which gives the most favorable geometry for the navigational calculations. As in the Transit system, two signals can be used to correct for the perturbing effects of the ionosphere.

Two pseudorandom codes are transmitted by each satellite. The first, a *coarse acquisition code*, is used to aid acquisition of the satellite signals and to provide coarse navigation. (More recently this has been called the *standard positioning service*). The second, designated the *precision code* or *precision positioning service*, has a 10-times higher modulation rate which yields the full navigational accuracy of the system.

Satellite transmissions are continuously monitored by widely spaced fixed monitor station receivers which measure the satellite ranges and enable the master control station to accurately determine satellite positions and clock errors. This information is relayed via a master control station to the satellite, enabling it to update its navigation message[3, 5].

Navstar Navigation Process

To obtain a complete three-dimensional position and velocity estimation, a receiver must be locked to transmissions from four satellites. Four measurements of pseudorange are made by locking code tracking loops to the received signals and then timing the occurrence of certain states or epochs of the code generators within the loops with the aid of the receiver's clock. The measurements are of pseudorange rather than true range because of the (as yet) undetermined receiver clock offset. Similarly, by measuring the frequencies of the carrier tracking loop voltage controlled oscillators over a gating time determined by the receiver clock, four measurements of pseudorange rate are obtained. These differ from the true range rates because of the clock's frequency error. Together with the orbital data from each satellite, these measurements enable accurate navigational information to be obtained (Figure 1).

Receiver Types

All Navstar receivers have a similar generic form: RF amplification and down conversion, intermediate frequency code and carrier tracking loops, a control processor to "oversee" the operation, a navigation processor, and an operator interface.

Several receiver architectures have been demonstrated; parallel or sequential operation of the code and carrier tracking loops may be considered, depending on whether the receiver has to withstand severe or mild dynamics in operation. Multiple RF front ends may be employed if more than one antenna system is required to give continuous satellite visibility. In some applications, the operator interface or control-display unit may be integrated with an existing unit to conserve weight and space; in another it may be economic to use part of the processing capability of another on-board computer to calculate the navigational data.

STL has built eight Navstar receivers under a UK Ministry of Defence contract and these are currently under evaluation in aircraft and ships. They operate with five parallel channels and in addition interface with an adaptive antenna and inertial systems[6].

The absolute positioning accuracy of the precision positioning service is quoted[3] as 18 m (RMS in the horizontal plane) and 15 m (RMS) vertically, with time to an accuracy of 35 ns and an offset from UTC of 120 ns. The accuracy available to civil users will be controlled by US Government agencies. This level has recently been revised and is how set at 100 m (95%) which approximates to 40 m (circular error probable). Differential operation is possible with Navstar and is likely to give accuracies using the standard positioning service code which are comparable to those obtainable from the precision positioning service, but a data link is necessary to transmit the differential correction. There is the constraint that the user and the static receiver must be using the same satellite set.

Full operational capability is scheduled for 1987; the US Airforce has recently ordered 28 Navstar satellites, removing any doubts about the US Department of Defense's commitment to the system. Coverage by Navstar is nowadays quoted as "almost continuous"; with 18 satellites some holes in coverage occur, albeit for less than an hour a day. However, these holes occur in some important latitudes, such as the Mediterranean sea[7].

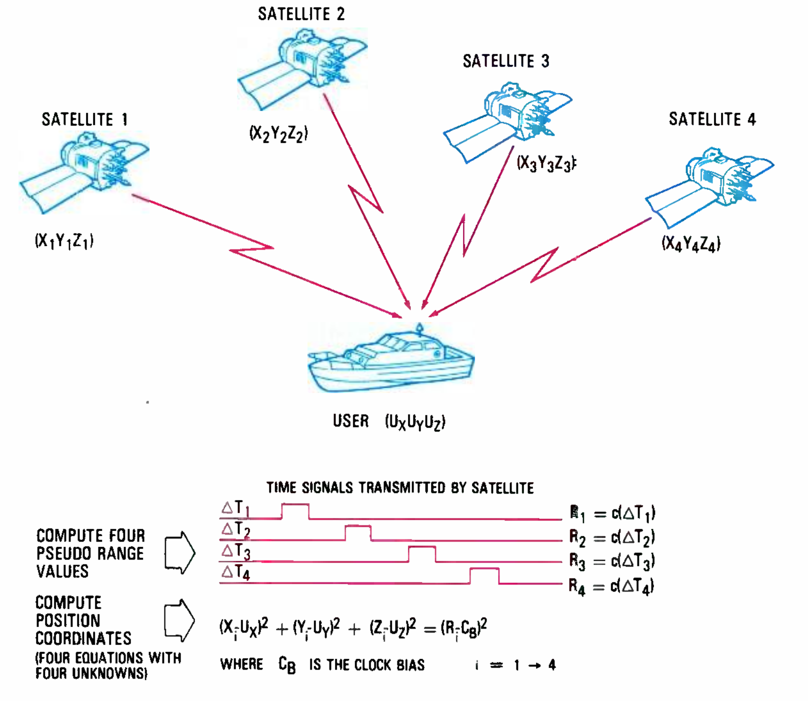


Figure 1
Principle of the Navstar system, showing how the user can compute his position using four simultaneous equations to solve for four unknowns.

Alternative System Suggestions

Spurred perhaps by the initial restrictions on Navstar civil operation, proposals have been made for satellite navigation systems specifically for civilian users. Perhaps the best known is Navsat which was formulated in studies for the European Space Agency[8]. Its aim is to minimize the cost of user equipment and the space segment by simplifying the signal format, although at the cost of ground station complexity. In this way, the overall cost is anticipated to be lower.

A constellation of 24 satellites, similar to that originally proposed for Navstar, is currently advocated although the operation of each satellite is greatly simplified. Since all the proposed link frequencies to and from Navsat satellites can be protected by international agreement, and the satellite control segment can be distributed between cooperating countries, constant uplink transmissions to the satellites can be maintained. Thus satellites can be designed to act merely as transponders, relaying navigational transmissions from the control segment and simplifying the space segment.

The method of determining position which is advocated for Navsat is again the measurement of pseudoranges to four satellites that are in view simultaneously. To simplify the user equipment, and since jamming protection of downlink transmissions is not required, a simpler signal format can be considered. One proposal is for the satellites to transmit time division multiplexed bursts. These may contain pseudorandom code modulations, but they need not vary from satellite to satellite. Thus the receiver does not need to know which satellites are in view initially, and need not perform any sequencing operation in order to receive transmissions from different satellites.

A requirement for the control segment is that each satellite is visible from at least one ground station at all times, which needs about five stations. These have the task of determining the precise orbits of the satellites and generating the uplink transmissions. Standard Elektrik Lorenz is proposing a system known as GRANAS which has similarities to the Navsat system.

It is not necessary to use dedicated satellites to provide positional information. In 1981 it was demonstrated that the position of a riverboat could be determined to an accuracy of 0.1 n mile by a technique which involved tone ranging through the ATS 6 satellite coupled with a time of arrival measurement from the NOAA-GOES satellite[9].

In the future one may envisage satellites providing communications, navigation, and surveillance, thus sharing the high cost over several functions and recovering them from at least some of the users.

Acknowledgments

The authors gratefully acknowledge the support of the UK Ministry of Defence (Procurement Executive) for the Navstar receiver development.

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Peter Kenneth Blair was born in 1937. He studied for his HNC in electrical engineering and DipEE while apprenticed to the Marconi Company. He joined STL in 1962 as a research engineer working on high speed PCM systems, solid state microwave transmitters, and television transposers. In 1971 he became department manager of the navigational aid and mobile radio department. Since 1977 he has been division manager of the Defence and Related Systems Division where his responsibilities include the Navstar GPS programme, radar systems, civil marine navaids, and advanced antenna research. Mr Blair is a member of the IEE.

Philip J. Hargrave received his BSc degree in physics from the University of Bristol in 1971. He then undertook research in radio astronomy at the Cavendish Laboratory, Cambridge, and was awarded his PhD degree in 1975. In 1977 he joined STL where he has been involved in the design of high performance Navstar receivers, the study of adaptive antenna systems, and more recently the mathematical modeling of a wide range of defense systems. Dr Hargrave is a member of the IEE and a fellow of the Royal Astronomical Society. He is currently manager of the adaptive systems department at STL.

This Issue in Brief

Dodington, S. H.
Civil Navigation Aids in ITT
Electrical Communication (1984), volume 58, no 3, pp 251 – 255

A number of changes have taken place over the past 10 years in the field of navigation aids. One of the most important of these is the standardization by ICAO of the time-referenced scanning beam concept for the microwave landing system. In addition, great interest has been generated by the satellite-based global positioning system which offers accuracies of 20 m. The author looks at these new developments and the evolution of existing systems, and provides a brief forecast of the status of the major navigation aids at the end of the century.

Lang, A. H.
Second Generation Vortac Equipment
Electrical Communication (1984), volume 58, no 3, pp 256 – 262

Vortac and VOR/DME are the prime navigation aids for the United States national airspace system. The existing vacuum tube equipment, which had become costly to maintain, is being replaced to ensure the continuation of this service beyond 1995. The author describes the new equipment which utilizes modern technology to provide higher reliability, remote maintenance and monitoring capabilities, and improved system availability. The introduction of microcomputer techniques permits the remote maintenance and control system to be used for all station control functions, automatic certification testing, and remote diagnostic and trend testing to improve maintenance even further. The resulting all-solid-state Vortac system provides the extended 20-year life at a reduced lifecycle cost.

Walters, D. W.
Ground-Based Air Traffic Control Communication Equipment
Electrical Communication (1984), volume 58, no 3, pp 263 – 269

Fixed tuned single channel receivers and transmitters produced by ITT Aerospace/Optical Division are being used in voice communications for ATC (air traffic control). Performance of the ATC radio, colocated with other radios and electronic equipment, is critical in terms of passenger safety, efficiency, and air controller productivity. Development of new technology will lead to improved radio performance and allow additional features to be added to the radios to meet the challenges of increasing air travel and tight budgets.

Kleiber, H.; Knoppik, N.; Vogel, H.
System 4000 Navigation Aids
Electrical Communication (1984), volume 58, no 3, pp 270 – 276

System 4000 is a new generation of navigation equipment for ILS (instrument landing system), VOR (VHF omnidirectional range), and DVOR (Doppler VOR). Higher performance and reliability than previous systems has been achieved by extensive use of microprocessors for control and monitoring, and the application of digital techniques to analog signal generation. All systems can be configured from a limited range of hardware and software modules. Equipment practice employs plug-in printed boards in 19-inch subracks. Good heat dissipation without fans is ensured by mounting transmitter modules on a large heatsink on the cabinet side. Comprehensive keyboard and display facilities are built in. A range of antennas is available for the various applications, providing omnidirectional and figure-of-eight patterns for VOR, and bidirectional, dipole and special patterns for ILS.

Limbach, F.; Pählig, K.
Hardware and Software Structures for System 4000 Navigation Aids
Electrical Communication (1984), volume 58, no 3, pp 277 – 282

The application of digital technology to the control and monitoring functions in the Navaids System 4000 has allowed common design and development of both low frequency signal processing and high frequency modules, enabling ILS, VOR, and DVOR functions to be realized with virtually identical hardware. System control and monitoring is performed by a 16-bit microprocessor which undertakes the main task of monitoring radiated and standby transmitter signals. The authors describe how these requirements have been met by using a modular hardware structure. The accompanying software is subdivided into modules which can be compiled and tested independently to perform specific functions for a variety of equipment configurations.

Johannessen, R.
VHF Radio Lighthouse
Electrical Communication (1984), volume 58, no 3, pp 283 – 288

The radio lighthouse is a radio navigation aid designed specifically for small coasters, in-shore fishing boats, and pleasure craft. Additionally, it has proved to be a very useful aid for larger vessels when other navigation receivers become unusable through, for instance, heavy electrostatic interference. It provides bearing information for any ship within the coverage area equipped with a suitable VHF communication transceiver or receiver. No other onboard equipment is required. As the radio information is independent of the ship's heading and of its roll, pitch, and yaw in heavy seas, taking a bearing is very easy. The system is attractive to the authorities responsible for the shore beacon since it is simple to install, has a very low cost antenna installation, and requires virtually no maintenance.

Bertocchi, G.
New Family of Tacan and DME Equipment
Electrical Communication (1984), volume 58, no 3, pp 289 – 292

Much of the existing Tacan and DME navigation equipment used worldwide has been in operation for many years and is becoming expensive to maintain. As both these navigation aids are likely to be widely used well into the 1990s, FACE undertook the development of a new family of Tacan and DME equipment with better performance and reliability, easier maintenance, and a reduced lifecycle cost. The author discusses how these objectives have been met in practice by using digital techniques and modern RF solid state technology, dual transponder and monitors, and built-in test equipment. The result is a broadband design that meets all civil and military specifications.

Lazzaroni, E.
Civil Use of Tacan
Electrical Communication (1984), volume 58, no 3, pp 293 – 298

The Tacan system is a proven navigation aid which has been used mainly for military applications. The author describes how modern technology has made it possible to reduce the cost of Tacan installations, opening up a range of new civil applications including helicopter navigation to offshore oil rigs. A broad comparison of Tacan with other major navigation aids leads the author to the conclusion that modern solid state Tacan beacons with solid state antennas offer several advantages for such applications.

Johnson, R. E.
Scanning Pencil Beam Precision Approach Radar
Electrical Communication (1984), volume 58, no 3, pp 299 – 304

The PAR-80 is a scanning pencil beam precision approach radar (PAR) developed and produced by ITT Gilfillan. This air traffic control radar is utilized to provide guidance to aircraft during approach to landing. The article describes the PAR-80 and shows samples of its excellent test results. The system is dual channel for enhanced operational availability. Its large aperture planar array antenna is instrumental in providing advantages in radar coverage, resolution, accuracy, and clutter performance. By combining a mechanical elevation scan with an electronic azimuth scan, these advantages which promote flight safety are obtained in a very cost-effective manner.

Corazza, G.; Vatalaro, F.
Further Development of the DPS Technique for Precision DME
Electrical Communication (1984), volume 58, no 3, pp 305 – 309

Recently the International Civil Aviation Organization decided on an almost final standardization of the precision DME system. The authors describe how the DPS (double pulse shaping) technique can be compatibly utilized with the latest ICAO standards; in particular it is useful in those applications requiring higher accuracies. The authors also outline a feasible implementation of the DPS technique using baseband analog signal processing, and show that it offers significant cost benefits combined with good performance.

Ardemagni, F.; Basile, P.; Clementi, A.
RF Subsystems for Precision DME
Electrical Communication (1984), volume 58, no 3, pp 310–313

Much theoretical and practical work has been undertaken in the area of RF subsystems operating at L-Band for precision distance measuring equipment. The performance of several system components has now been evaluated under a FACE research programme. Two designs are described in the article: a low noise, mechanically tuned front end and a solid state high power transmitter. State-of-the-art technology is used, including the use of soft, high permittivity substrate microwave integrated circuits. The designs have been optimized using computer aided design techniques.

Auch, W.; Schlemper, E.
Fiber Optic Gyroscope
Electrical Communication (1984), volume 58, no 3, pp 314–318

Although miniature mechanical gyroscopes offer very high accuracies, many different nonmechanical rotation rate sensors are under development in laboratories throughout the world. The authors outline the principle, construction, and test results of a fiber optic gyroscope which offers considerable potential as a strapdown sensor for inertial navigation systems. Test results on laboratory models indicate that it is already possible to meet the requirements for some applications, but that further reductions in drift are necessary in order to meet the exacting demands of navigation systems.

Böhm, M.
Off-Shore Helicopter Radio Navigation using DME-based Positioning System
Electrical Communication (1984), volume 58, no 3, pp 319–325

The DME-based positioning system will allow all-weather helicopter operations within offshore oil-rig terminal areas. The present regularity of flights in these areas is already 95%, but increasing traffic requires the improvement of navigational accuracy and air traffic control procedures to maintain safety and economy. The system combines proven DME (distance measuring equipment) techniques with advanced angle determination by array signal processing. The article considers each flight phase and describes ground based and airborne equipment suitable for en route navigation and final approach to the rig.

Gorder, G.; Ranghelli, J.
Space Qualified L-Band Triplexer for Global Positioning System
Electrical Communication (1984), volume 58, no 3, pp 326–331

The triplexer for the global positioning satellite system had to meet stringent spectrum requirements for both astronomy and spectrum occupancy. These and other specifications, including low weight, are fully met by a design based on one 3-pole and two 6-pole Chebyschev bandpass filters combined as a noncontiguous triplexer. The authors describe how the final design was developed from earlier versions, and the changes that were necessary to provide the high Q factor of around 8000. One feature of the design was a novel temperature compensation technique that allowed the operating temperature range of −20 to +71°C to be achieved without a weight penalty.

Bethmann, A.; Tschiesche, H.
Receiver for Global Positioning System
Electrical Communication (1984), volume 58, no 3, pp 332–335

Advances in satellite technology are now making it possible to use satellite-based systems to provide very high accuracy navigation throughout the world for both civil and military users. The authors describe the basic elements of the system and discuss a global positioning system receiver being developed for civil applications, including emergency medical services, fishing, and space shuttle navigation. A prototype of this receiver will form part of a navigation experiment. The experiment, which will be included in the shuttle/Spacelab system, is scheduled for the German D1-mission in 1985.

Becker, K.; Müller, A.; Vogel, H.
Precision Distance Measuring Equipment for the Microwave Landing System
Electrical Communication (1984), volume 58, no 3, pp 336–343

Standard Elektrik Lorenz has been closely involved in international standardization of DME/P (precision distance measuring equipment) for the future microwave landing system. Since 1981 ground and airborne DME/P equipment has been under development at SEL; series production will start in 1986. The authors give an account of the system operational requirements, concept, and general technical features, and describe the main functional units. The article is concluded with a summary of the prospects for DME/P.

Garmany, W. J.; Johnson, V. L.; Romer, W. J.
Loran-C Navigation System for Saudi Arabia
Electrical Communication (1984), volume 58, no 3, pp 344–351

Two new Loran-C chains are being installed in Saudi Arabia to provide a comprehensive and reliable navigation service in the Red Sea, Arabian Gulf, and other waters around the Arabian Peninsula where there is heavy maritime traffic. The authors describe the Saudi system which consists of seven high-power transmitter stations and three monitor stations. The new Loran-C installation will provide a repeatable position fix accuracy of 0.1 to 0.2 n mile day and night in all seasons, thereby increasing the safety and efficiency of marine transport in the area.

Blair, P. K.; Hargrave, P. J.
Satellite Navigation
Electrical Communication (1984), volume 58, no 3, pp 352–358

This paper examines the fundamental principles of satellite navigation with particular reference to the factors affecting the accuracy of basic measurements and their corrections. It then considers the usage and operation of current systems and concludes with an outline of alternative proposed systems.

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Lester A. Gimpelson
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