# EVOLUTION OF THE HIGHEST-PRECISION RADAR
## . . . The Story of MIPIR

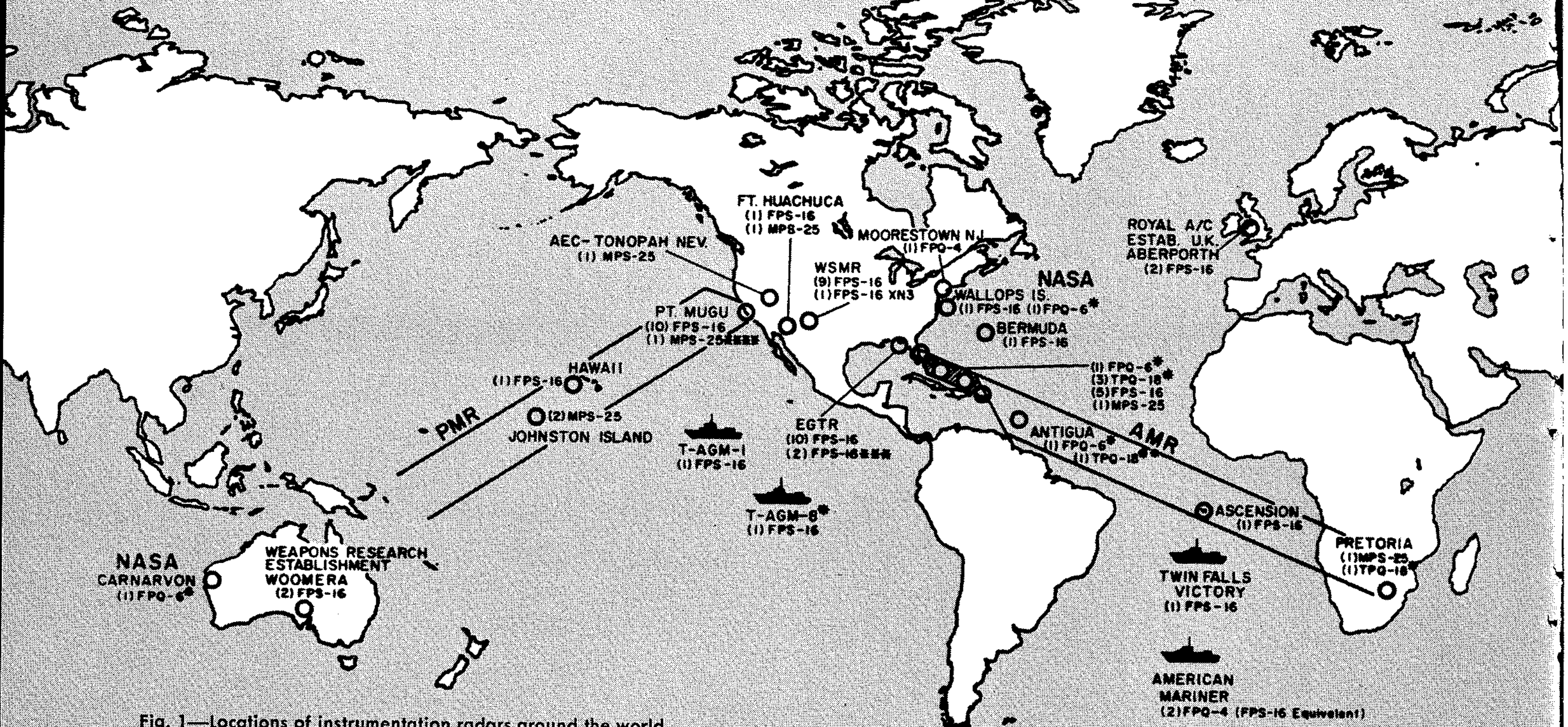

Fig. 1—Locations of instrumentation radars around the world.

Missile and space programs have presented industry with the need for ever more accurate knowledge of the location, speed, and direction of travel of the vehicle. Over the years, the pulsed radar has played a primary role in this measurement mission. This paper tells the story of the latest and most accurate of these radars: the AN/FPQ-6 and its transportable companion, the AN/TPQ-18. Collectively, these radars are known as MIPIR, MIssile Precision Instrumentation Radar.

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In the early days of post World War II, the determination of the performance of the various missiles under test depended solely upon modified equipment originally developed primarily for anti-aircraft gun direction. These units, in particular the SCR 584, underwent modifications by each user to better meet his needs in the way of data output. By the early 1950's, the Government recognized that a radar specifically designed for instrumentation was required, and the Bureaus of Aeronautics of the Navy Department was designated the central procurement agency for all the services.

### LEADING UP TO MIPIR—THE AN/FPS-16

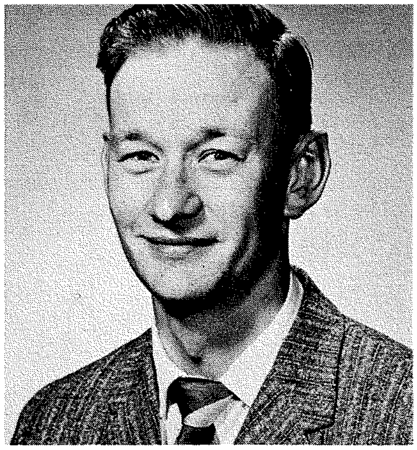
Because of its experience in precision radar trackers for the BUMBLEBEE and TERRIER programs, RCA was chosen to develop the new radar. Early in the design phases of the TERRIER field model radar, the design was redirected with the result that the *first true instrumentation radar*, the AN/FPS-16 (XN-1)—still in service at Patrick Air Force Base—was finished in 1954. Late in 1954, BuAer and the U. S. Army Signal Corps sponsored two production prototypes of a much more elaborate version, the AN/FPS-16 (XN-2).

This procurement became the forerunner of a large number of production radars, the AN/FPS-16. This, the first precision, monopulse tracking radar developed solely for range instrumentation uses, was so successful that over 50 units are currently in operation all over the world (Fig. 1).

The development of this radar resulted in the most precise tracking radar in production in the free world, yet a unit requiring a minimum of maintenance and suitable for use over environments ranging from deserts to the very edge of tropic sea shores. In addition, the unit could be operated by one man and was designed for use in multiple-radar "chains." In this way, despite the range tracking limitations of one radar, precise data could be obtained from the instant of missile launch until the missile impact hundreds or thousands of miles away. This in turn would provide for range safety information, so critical at launch, for missile control prior to burn out, and for impact prediction and ballistic measurements.

However, it wasn't long after the first AN/FPS-16's were operational that users began to determine that their planned needs were pressing even the capabilities of the AN/FPS-16. During

**WILLIAM J. ROSE,** has 25 years in electronics which include 14 years in military applications of communications and tracking radar systems as a member of the U. S. Marine Corps and 9 years of activity at RCA as project engineer and supervisor in instrumentation radar and allied systems. Prior to joining RCA in 1954, he served the Marine Corps in developmental programs covering the test and evaluation of radar, radio, and other electronic items. He participated in the development of the TALOS-TERRIER guidance radar, the missile receiver and tracking beacon, and the launch computer. At RCA he became Project Engineer for the later development of the AN/FPS-16 (XN-1). He directed the conversion of this radar for use on the VANGUARD program, integrated it into the Atlantic Missile Range tracking complex, and served as radar consultant to the Naval Research Laboratory during the launching tests. He managed the program resulting in the AN/MPS-25, the trailerized version of the production model AN/FPS-16 radars. Upon assuming the responsibility of Project Leader in 1960, he was directly involved in the conception and development of the AN/FPQ-6 and AN/TPQ-18.



**JOHN W. BORNHOLDT,** following 1½ years with the Pennsylvania State University as a research assistant on an ionospheric physics program, joined RCA in 1951 as a design and development engineer. For the next three years, he worked on a VLF receiver, VHF automobile antennas for the New Jersey Turnpike, and TV station test equipment. In 1954, he was called to duty with the U. S. Air Force. He returned to RCA in 1956, where he was design engineer responsible for the TALOS system analog computer. In 1957, he transferred to the Range Instrumentation Group as a project engineer on the AN/FPS-16 program. Following his promotion to Leader in 1959, he was selected in 1960 to attend the first Program for Management Development at Harvard University, which he successfully completed in December 1960. Following his return to RCA, Mr. Bornholdt assumed responsibility for Project Management for the production of the AN/FPQ-6 and AN/TPQ-18 (MIPIR) radars. In 1961, he was promoted to Manager and currently serves as the MIPIR and instrumentation radar production Project Manager.

1958 and 1959, modifications improved the AN/FPS-16 in accordance with particular local requirements. During this same period, RCA engineers proposed still other improvements to the radar. Although these other proposals were well received, their implementation was delayed while the planners studied the new ground radar tracking requirements of the dawning space age.

By the end of 1959, however, the trend of actual and requested modifications became clearer. The desire for longer range, more accuracy and precision, and increased operational flexibility called for spectacular advances in the state of the art. On the other hand, the realization that such advances would be incorporated into radars carrying a heavy load of test range activity caused the emphasis to be placed on reliable, conservative, and evolutionary designs.

## GROWTH OF TEST RANGE REQUIREMENTS

During this period of the inception of modifications to the AN/FPS-16, Government planning engineers were attempting to predict their range requirements for the years ahead. The coming era of satellites, manned and unmanned, planetary probes, and more complex missiles called for increased capability in almost every respect. At the Atlantic Missile Range, in particular, the requirements in early 1960 were beginning to firm up. These could be summarized as follows:

1) Higher-performance boosters placed a new premium on range safety. Not only must the impact predictions become more accurate, but they must also be made at longer ranges. This requirement, in terms of pulse radar characteristics, was eventually translated into a specification for tracking a target of 1-square-meter cross-section to a range of 300 nautical miles with a precision of 0.05 mils-RMS.
2) The synchronous satellite represented the upper limit imposed by charter upon AMR, and it required precision transponder tracking at ranges to at least 22,000 nautical miles in order to determine accuracy of location and drift rates. This drift measurement plus many other instances of targets having very low angular rates resulted in the need for a tracker with extreme smoothness in its angular serves at these very low velocities.
3) The intermediate stations on the range had to track high performance passing targets at almost any altitude, and this necessity required an instrument featuring very high antenna-mount angular velocity and acceleration capability.
4) The measurement of target trajectory to the accuracies desired meant that the basic data capability of the AN/FPS-16 had to be maintained or improved. Considerable improvement over presently existing modification kits in the area of dynamic lag error correction had to be achieved.
5) The increased mission complexity expected in the years ahead produced an operational paradox. On the one hand, faster reaction times required more automatic target acquisition and tracking features. On the other hand, the inability to predict future mission requirements with certainty called for more manual operational flexibility. Experience on the range also pointed to more reliance on operator judgment in situations where the criteria for automatic operation were unreliable.
6) The requirements for each of the various range stations resulted in specifications for an instrument having a high degree of common features with those at all other stations. Therefore operation, maintenance, and logistics considerations indicated that the same basic radar should be used at any range location.

An examination of the range safety requirements, the most stringent of those mentioned above, provides an insight to the type of equipment needed.

On the same mission involving a single target versus time, a range safety radar could be expected to have to track both *skin* (reflected echo) and *beacon* (transponder). In most circumstances, more than one radar would track the same beacon during some portion of the flight. In order to be properly received by the beacon, all radars must be on the same transmitting frequency with a high degree of assurance. While the AN/FPS-16 has a fixed tuned magnetron of 1-Mw rating, possible frequency variations among magnetrons indicate the use of a tunable transmitter.

The tunable magnetron of the AN/FPS-16 is rated at 250 kw, and the standard AN/FPS-16 on the range in 1960 had a 12-foot antenna and a receiver noise figure of 11 db. With this combination of parameters, the

AN/FPS-16 must have an IF signal-to-noise ratio of about 20 db to achieve 0.1-mil precision, and the lower curve of Fig. 2 shows that this performance is attained at ranges to 35 nautical miles when skin-tracking a 1-square-meter target. By increasing the antenna size to 32 feet and lowering the receiver noise figure to 8 db, a precision of 0.05 mils can be obtained with a signal-to-noise ratio in the IF receiver channels of 10 db. By increasing the transmitted power to 3 Mw, the desired 300 nautical miles can just be achieved as shown by the upper curve of Fig. 2. (This precision, limited by thermal noise, is a function of antenna beamwidth, signal-to-noise ratio, pulse repetition rate, and the servo bandwidth. Examinations of this and other tracking limitations are contained in the references cited in the *Bibliography.*[1-5])

This oversimplified example of the solution to the range safety problem shows the kind of reasoning applied. Similar solutions were posed for each of the many test-range situations. The final result was a radar specification representing the best compromise between requirements and previous equipment developments. Late in 1960, therefore, the Government awarded a contract to RCA to produce the radar to these specifications. As nearly as possible, consistent with the specifications, the radar was to utilize the proved designs of the AN/FPS-16 modification program. Table I shows some of the more significant characteristics of the original AN/FPS-16 compared to those of the new radars, now called the AN/FPQ-6.

## MIPIR DESIGN BACKGROUND

Although originally conceived as a series of modifications to an existing AN/FPS-16 radar, it quickly became apparent that a complete new design was involved. Despite this, the initial contract was for procurement of five units, with no development, preproduction, environmental testing, or test model. Indeed, this order was shortly amended to increase the number of units to eight, and then to nine. This contract has been cited by Air Force officials as an excellent example of "concurrence"—the cutting short of all steps leading to eventual on-site full operational capability. In so doing, it required great engineering skill to permit paper designs to be released for production without incurring high costs for subsequent redesigns.

Design of the radar proceeded on this basis from contract authorization; maximum use was made of ultra-reliable component and module designs from the BMEWS system, and where applicable, the well-tried AN/FPS-16 designs were also incorporated. But major design efforts were required—including such state of art developments as the 20-bit single-speed shaft encoders that were the only feasible way to reliably provide the angular data output precisions required.

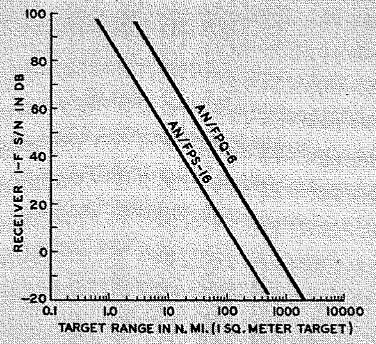


Fig. 2—Range performance.

**TABLE I—Comparison of 1960 Standard AN/FPS-16 With Present AN/FPQ-6.**

| ITEM | *AN/FPS-16 | †AN/FPQ-6 |
|---|---|---|
| *Frequency* | 5,400–5,900 Mc | 5,400–5,900 Mc |
| *Antenna:* | | |
| *gain* | 44 db* | 51 db |
| *size* | 12 ft | 29 ft |
| *feed* | 4-horn | 5-horn |
| *polarization* | linear vertical (circular with grating) | linear vertical, circular |
| *beamwidth* | 1.2° | 0.4° |
| *type* | feed at focal point | cassegrain |
| *Transmitter:* | | |
| peak pwr tunable | 250 kw, nom. | 3.0 Mw, nom. |
| peak pwr, fixed tuned | 1.0 Mw, nom. | — |
| pulse width | 0.25,0.5,1.0 μsec | 0.25,0.5,1.0,2.4 μsec |
| pulse rep freq | Variable to 1,707 pps | 160–640 pps |
| average pwr, tunable | 250 w | 4.8 kw |
| average pwr, fixed tuned | 1.0 kw | — |
| output tube | magnetron | klystron |
| *pedestal (antenna mount)* | | |
| est. total wt | 18,000 lbs | 125,000 lbs |
| azimuth bearing | ball | hydrostatic |
| servo bandwidth (max) | 5.0 cps, nom. | 4.8 cps, nom. |
| max tracking rate | 750 mil/sec | 500 mil/sec |
| tracking precision | 0.1 mil-RMS | 0.05 mil-RMS |
| *Receiver noise figure* | 11 db | 8 db |
| *Range System:* | | |
| range meas capability | 500 nmi | 32,000 nmi |
| max tracking rate | 10,000 yd/sec | 20,000 yd/sec |
| tracking granularity | 1 yd | 2 yd |

* Values common to AMR in 1960
† Present, 1963, values.

To get the required antenna gain, consistent with requirements for reduced mechanical inertias (for maximum servo bandwidth) and capability for both linear and circularly polarized operation, it became necessary to develop RCA's first production Cassegrainian antenna system. The 29-foot, 4,000-pound parabolic reflector on this antenna system is the largest such structure with static surface tolerances in the order of 0.005 inches from the nominal curve and mechanical resonances in the region of 30 cps.

Included in the pedestal design were the conflicting requirements of air transportability and subsequent field erection without degradation of precision or accuracy, the capability of providing better than 0.05 mil precision, a low-speed tracking capability of one revolution per week and an operating servo-pedestal bandwidth of 5.0 cps to allow for rapid acceleration of the mount during target tracking. The resultant antenna pedestal mount represents the current state of the art in such devices—at an overall weight of 125,000 pounds. It has been air-transported to Ascension Is, in the South Atlantic; has been shipped by sea to Australia and the West Indies; and has been trucked overland to Florida and subsequently reassembled *without performance degradation.*

In order to realize the full precision inherent in the system, it was early determined that rapid, real-time correction of the raw data outputs was required for two types of errors, *bias* and *dynamic.* The former, sometimes called *systematic,* includes such items as out-of-level pedestal positioning, non-orthoganality of the pedestal's azimuth and elevation axes, shift of the radar's antenna beam axis with frequency and with antenna position. The dynamic correction is applied to reduce the lag of the pedestal pointing position behind the target position for moving objects. The decision to do the correction digitally led to the need to incorporate a digital processor, which in turn led to the use of the RCA 4101 computer. With this unit, the above corrections can be automatically programmed into the machine prior to a mission, and the data can be transmitted from the radar either in real time, corrected or uncorrected form, merely by the radar operator pushing a button. This became then, the first radar containing an integral general-purpose digital computer.

The conflicting demands for both increased automaticity of radar operation plus increased flexibility for the operator were met by the design of the radar operator console (Fig. 3). This unit features a *T*-shaped grouping of control panels, situated so that an operator at the left can control and monitor primarily ranging functions, the operator at the right primarily angle functions, while a central crew chief will direct them both and can monitor radar performance. The console includes an RCA closed-circuit TV system monitor, with the associated camera mount on the elevation axis of the antenna pedestal, to allow for radar boresighting and visual checking of close-in-targets. Among the many operator aids is the RCA-designed video integrator, used to enhance weak signal returns to quickly differentiate them from the surrounding noise in the display for quicker target identification and acquisition. A solid state switching network gives fast system mode changes, yet represents a significant increase in reliability over the relay system utilized in the AN/FPS-16 radars.

To meet the user's needs for transportable versions of the radar, the AN/TPQ-18 was developed. This radar is functionally identical to the AN/FPQ-6 building type (Fig. 4) and is mechanically identical except for mounting frames for the various racks. In the AN/FPQ-6 there are common housings of 12 racks, while in the AN/TPQ-18 they take the form of shelters, each 8 feet wide, 10 feet high, 16 feet long. Each shelter houses a radar subsystem (receiver, servo, ranging, computer, etc.) and is self-contained to the extent of having its own air conditioning unit and primary-power input control and regulation systems. The commonness between the two types of radar has facilitated several contract changes in plans: one configuration has been rapidly changed into the other.

With this general treatment in mind, the following sections detail the more important design features.

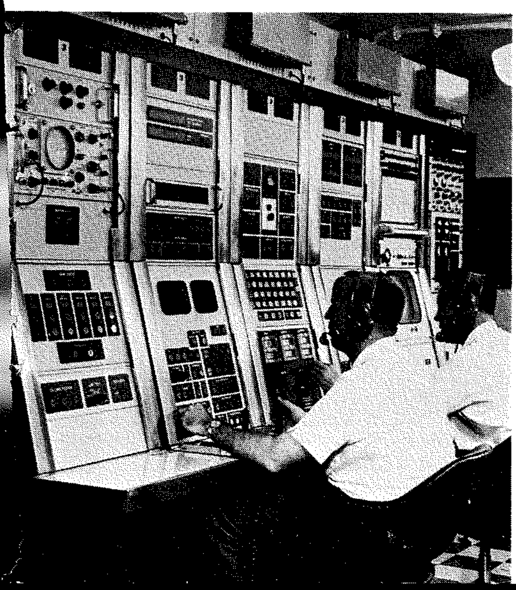
## ANTENNA

The antenna specifications called for a reference (sum) pattern gain of 51 db, a beamwidth of 0.4°, and close-in sidelobes not higher than 24 db below the peak of the main beam. Preliminary design studies pointed to the selection of a conventional four-horn "feed-in-front" and reflector, or of a Cassegrain approach. For the conventional feed-reflector configuration, a reflector of 32 feet would be necessary. At the expense of an increase in close-in sidelobes, the Cassegrain would have many advantages:

1) higher efficiency resulting in smaller size for the same gain and less back radiation—lower antenna temperature,
2) increased possibility of accommodating several frequencies C and S or X bands, for example,
3) higher mechanical resonance of the overall reflector-feed-hyperbola assembly—important to the servo design goal of 5.0 cps,
4) lower total mass of the assembly and closer to the elevation axis—also important to the servo design,
5) more nearly optimum feed position for future very low noise receivers, and
6) increased flexibility in achieving polarization diversity.

Government representatives agreed that the many advantages outweighted the "multipath-tracking" disadvantage of the higher sidelobes: the Cassegrainian approach was selected. Tests of the final design, a 30-inch hyperbola and 29-foot reflector with five-horn feed, have shown that the design goals have been met or exceeded.

Fig. 3—Front view of radar console.



## ANTENNA MOUNT

The antenna mount, commonly called the pedestal, is probably the greatest single contributor to the successful performance of the radar.

The first problem was the choice of mount configuration. The azimuth-elevation (AZ-EL) configuration represented the best compromise between the experience of U. S. industry and the performance desired. Tracking of high performance targets near zenith presented a special problem to this type mount. However, the *X-Y* mount, a theoretically better tracker at high angles, was not chosen because of physical limitations at low tracking angles—of equal importance in a general purpose instrumentation radar. During the proposal stages the Government considered the addition of a third axis to provide satisfactory performance at all elevation angles—but this mount could not be built within the funding and scheduling allocations.

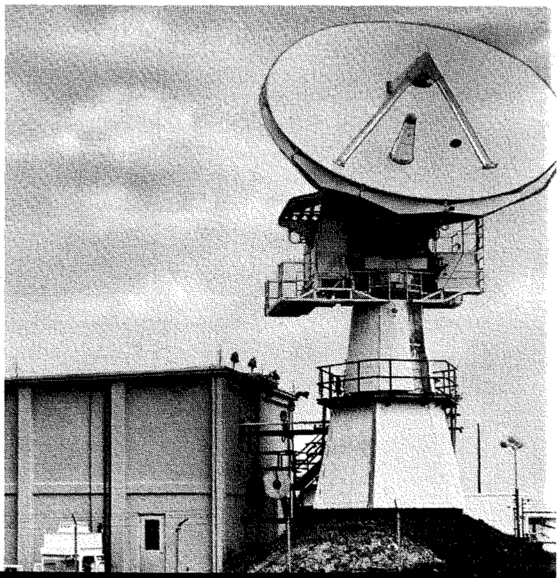
With the AZ-EL mount decided upon, a compromise had to be made: a very firm requirement for smoothest possible tracking at angular rates as low as 0.01 mils/sec (roughly equivalent to *one earth rotation per week)* took precedence over the need for fastest possible servo response at the higher angles. Dynamic range considerations and torque requirements for precision tracking in a 40-mph wind set the upper velocity limit at 500 mils/sec.

In order to limit the overall radar random error to 0.05 mil-RMS when tracking skin targets at low signal-to-noise ratios, the sticking and sliding friction components of the servo error are held to an absolute minimum. This is one of the requirements that dictated the use of a hydrostatic bearing[7] for the azimuth turntable.

Since it is impossible to design and cut perfect gears, tracking accuracy is degraded because the antenna position cannot be controlled to a precision greater than the magnitude of the drive gearing backlash. The hydrostatic bearing magnifies this problem since its lack of friction tends to cause servo oscillations equal to or greater than the backlash magnitude. Tracking accuracy is ensured by preloading the drive gear train in opposite directions, thereby minimizing backlash problems.

Minimizing the servo tracking lag errors for targets having high angular accelerations and velocities requires that the bandwidth and open loop gain be as large as possible. Bandwidth and gain, however, are limited by the frequency at which locked-rotor resonance occurs. This is the frequency of the mass of the moving parts of the antenna coupled with the spring of the drive gear train when the motor rotor is locked. In order to extend this frequency as far as possible, two drive gear trains in parallel give a gear stiffness twice that of one gear train. Hydraulic drive motors are used since this application requires higher torque-to-inertia ratio, better dynamic response, and smoother slow speed operation than can be obtained from electric motors. A valve-controlled motor system is used rather than a variable-displacement pump-controlled motor since the dynamic response is better.

Fig. 4—AN/FPQ-6 at Patrick Air Force Base.



The pedestal design was further complicated by the requirement for ease of transportation in C-124 and C-133 aircraft. Individual subassemblies are therefore designed to breakdown into suitable packages for loading into these aircraft and to keep the package weight below 25,000 pounds. The design provides for minimum system realignment and checkout when the pedestal is reassembled in the field.

To measure the antenna position and to provide data output to the required precision, RCA designed a new "one-speed" shaft-to-digital converter (encoder). This encoder can provide shaft position measurements to a granularity of twenty binary digits, or one part in 1,048,576. An encoder for each axis (azimuth and elevation) is used. The direct coupling to the shaft to be measured eliminates inaccuracies due to gears, couplings, and tolerance build-up of mechanical parts.

### DATA PROCESSOR

The data processing equipment of the radar must take the raw encoder readings in range, azimuth, and elevation and place these in the proper format for transmission to other stations on the range. A requirement also existed to correct the position data supplied by the pedestal encoders for antenna lags due to target dynamics. In the AN/FPS-16 radar, two independent special-purpose subsystems were used, and error correction occurred over a range of input signal-to-noise ratios too limited for the AN/FPQ-6 application.

To accomplish error correction, the monopulse tracking error in each axis servo loop is sampled, demodulated, filtered, digitized, and added to the raw pedestal encoder readings to provide corrected angular position data. Some method must be employed to compensate for the shape of the monopulse error pattern with off-axis targets and for nonlinearities in the receiver AGC system. While a special-purpose computer could again be built to provide the correction processing, cost, schedule, flexibility, and growth considerations favored the use of a reasonably fast, general-purpose instrument with a scientific repertoire. The RCA 4101 was selected as being uniquely suitable for this application.[6]

Error correction now involves digital processing of data resulting from premission calibration operations to generate and store a normalized angle error pattern independent of the signal-to-noise ratio. Subsequent real-time processing of target tracking and calibration data provides the capability for dynamic lag-error correction for all possible values of input-signal strength. Lag error correction to an accuracy of better than 5% is attained.

Having selected the computer primarily for the error correction operation, it is now possible to combine functions which would otherwise require additional special equipment. Therefore, the RCA 4101 also provides the following additional functions:

1) readout of position data,
2) auxiliary readout of range data,
3) correction for pedestal out-of-level condition,
4) correction for antenna droop versus elevation angle,
5) correction for non-orthogonality of azimuth and elevation axis,
6) correction for shift of antenna pointing axis versus frequency,
7) correction for atmospheric index of refraction, and
8) binary to decimal conversion for console display.

At present, no further exploitation of the inherent capabilities of the computer is included in the end-product equipment. However, the list of possibilities is seemingly endless—ranging from more sophisticated real-time signal processing to post-flight data reduction and "spare-time" computation of such items as preventive maintenance criteria.

### MIPIR RADAR OPERATION

Following initial erection and testing of the antenna pedestals at the Moorestown antenna pedestal facility and assembly and test of the radar electronics at Moorestown, the radars were shipped to various field sites for emplacement, installation, checkout and acceptance testing by the RCA Service Co. under Morrestown engineering cognizance. The first of these radars, placed in limited operation, was an AN/TPQ-18 on Antigua, W.I.F., used in support of the Polaris Missile Program on July 1, 1962, *only 18 months after the contract award date.* The first unit accepted by the government was the AN/FPQ-6 located at Patrick Air Force Base, Florida (Fig. 4) on June 5, 1963. Subsequently, another AN/FPQ-6 was accepted by the Government at Antigua, W.I. on June 26, 1963, and AN/TPQ-18 number two was accepted at Moorestown on July 1, 1963 and is currently in operation at Grand Turk Island. At this writing, seven of the nine radars under contract are in the field, including NASA installations at Wallops Island, Va., and Carnarvon, Australia.

Acceptance test data for these radars shows performance has in general met or exceeded requirements, especially as regards precision, which is 0.025 mil-RMS in angle and 2 feet-RMS in range, while the servo bandwidth was slightly below specifications in early units (ranging from 4.2 to 5.0 cps), but still *well above* comparable units of equal weight. Later units have been improved, and *exceed* the specification of 5.0 cps.

### FUTURE POTENTIAL

No sooner were these radars in operation before performance enhancements began to become required. The first of these was a C-band parametric amplifier[8] for the Antigua AN/TPQ-18; this reduced the receiver noise figure from 8 to 4 db and thereby enhanced radar acquisition and trackers precision on small or distant targets. Subsequently, similar paramps were ordered for the Wallops Island and Australian units.

Following difficulties in acquiring targets downrange with the Antigua AN/TPQ-18, an antenna beam broadener was developed and is being incorporated in three Australian radars. The development broadens the antenna beam to 1.0° from the present 0.4° by introduction of energy into the error horns of the five-horn feed.

With the incorporation of planned changes, such as pulse doppler, cooled paramps, digital radar designation, and higher transmitter power, the course of history of radar development is beginning to repeat again.

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