AD NUMBER: AD0860887
LIMITATION CHANGES
TO: Approved for public release; distribution is unlimited.
FROM: Distribution authorized to US Government agencies only; Export Control; 1 Jan 1969. Other requests shall be referred to Air Force Avionics Laboratory, Wright-Patterson AFB, OH 45433.
AUTHORITY
AFAL ltr dtd 12 Jan 1972

A 17:1 DUAL BAND CIRCULARLY POLARIZED TWO-CHANNEL MONOPULSE TRACKING SYSTEM

by

Paul A. Lantz, NASA, Goddard Space Flight Center,
Greenbelt, Maryland

George G. Chadwick, Roderic W. Hurlburt,
and Roger R. Yaminy,
Radiation Systems, Incorporated
McLean, Virginia

Prepared for

Nineteenth Annual Symposium
USAF ANTENNA RESEARCH AND DEVELOPMENT

Sponsored by
AIR FORCE AVIONICS LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

In cooperation with

UNIVERSITY OF ILLINOIS

14, 15, and 16 October 1969
Robert Allerton Park
Monticello, Illinois

12

RS

A 17:1 Dual Band Circularly Polarized Focused Two-Channel Monopulse Tracking System by Paul A. Lantz, George G. Chadwick, Roderic W. Hurlburt, and Roger R. Yaminy

ABSTRACT

This paper will describe a feed system designed for ultimate use in the 85-foot NASA STADAN dishes. This system uses a series of nested multi-arm spirals to provide sum and difference two-channel monopulse tracking outputs for simultaneous left- and right-hand circularly polarized signals. These outputs are simultaneously provided at frequencies of 136 MHz, 235 MHz, 400 MHz, 1700 MHz, and 2200 MHz. The paper will describe the theory of operation and the results obtained with the feed itself. However, the paper will concentrate on results obtained in the field with the unit mounted in a 60-foot test dish. This unit was used to track the Apollo VIII vehicle to the moon and back. In addition to this, the feed has also been used for star tracking to establish its boresight accuracy. The fact that the feed system has now been operationally checked out demonstrates that two-channel monopulse is a technically sound method of tracking, with the added advantages of simplicity in feed design and improved secondary pattern characteristics.

RSi

A 17:1 Dual Band Circularly Polarized Focused Two-Channel Monopulse Tracking System

By Paul A. Lantz, NASA, Goddard Space Flight Center, Greenbelt, Maryland, George G. Chadwick, Roderic W. Hurlburt, and Roger R. Yaminy, Radiation Systems, Incorporated, McLean, Virginia

Summary. - This paper describes a dual circularly polarized feed system for operation in incremental bands over the frequency range from 136 to 2300 MHz. The characteristics of a 60-foot parabola excited by the feed system are discussed. Tracking data for this system have also been obtained using a helicopter, the Apollo VIII vehicle, and Cassiopeia A. It will be shown that the two-channel monopulse technique allows the use of antenna feeds which, in turn, provide sidelobes of greater than -20 db relative to the main lobe peak for all frequencies. This sidelobe performance reflects the fact that the feed is approximately focused at all frequencies, unlike its earlier log periodic type predecessors.

The characteristics of a similar feed used in the Apollo Range Instrumented Aircraft (A/RIA) will also be described in this paper.

General Theory of Operation. - The block diagrams for two- and three-channel monopulse systems are shown in Figure 1. The details involved in the operation of a three-channel monopulse system are presumed to be well known and will not be delineated here. The two-channel monopulse system, as its name implies, utilizes only two channels: a sum channel and a complex difference channel. The complex difference channel may be viewed as a quadrature combination of the conventional difference channels of the three-channel monopulse system. The sum channel is identical to that of the three-channel monopulse system, having a beam maximum on-axis and being symmetric about the axis. The complex difference channel differs from its three-channel monopulse counterpart in that it is symmetric about the axis and has a point null on-axis. A very detailed description of the two-channel monopulse system has been presented earlier and will not be analyzed in this paper[1]. Rather, attention will be directed to the major advantages and disadvantages of the two-channel monopulse system.

First of all, the two-channel monopulse system requires two receiver channels as compared to the three receiver channels for a three-channel monopulse system. This advantage, however, is very often not of significant consequence in large systems where the cost of an additional receiver channel may not be a significant factor. Errors in the excitation of a two-channel monopulse system will cause motion of the null but will never cause null filling. Thus, nulls of greater than 40 db depth have been measured over greater than octave bandwidths[2]. The three-channel monopulse system

1. G. G. Chadwick and J. P. Shelton, "Two Channel Monopulse Techniques — Theory and Practice", International Convention on Military Electronics, September 1965.
2. Sydney B. Franklin, Charles L. Hilbers, Jr., and Walter E. Kosydar, "A Wideband Two Channel Monopulse Technique", MIL-E-CON 9, September 1965.

will either null fill or null shift, or both, as a function of network errors. In certain situations, particularly where tracking axis correction is possible, the deep null of the two-channel monopulse system may represent an advantage. The principal feature of the two-channel monopulse system lies in its ability to make use of relatively simple circularly symmetric feed systems. Examples of a number of different types of feed systems were described by Shelton and Chadwick[3]. The most common of these systems is a conventional multiple arm spiral antenna. This spiral antenna provides an aperture in the difference channel which is twice that of the sum channel, thereby allowing approximately equal edge illumination to be realized in both sum and difference channels. Equivalent performance in a three-channel monopulse system generally requires anywhere from five to twelve separately excited feed apertures. The spiral provides almost perfectly symmetric excitation, thereby making it ideal for the illumination of parabolic dishes. The symmetric pattern shape and controlled edge illumination allow very low sidelobes to be achieved in the two-channel monopulse system for both tracking functions. Thus, one of the most significant deteriorating factors in any tracking system — a high difference channel sidelobe level — is significantly mitigated in two-channel monopulse systems.

One disadvantage of the two-channel monopulse system occurs in the presence of in-line multipath for low angle tracking (i.e., where the main beam shape intercepts the horizon line). The azimuth channel of a three-channel monopulse tracking system has a vertical null and is essentially independent of the effect of in-line multipath. The elevation channel of the three-channel system is effected by the in-line multipath to the extent that an elevation error will occur. In a two-channel monopulse system, the complex difference channel will cause errors to exist in both planes as a function of in-line multipath. The total angular error resulting from the vector sum of the azimuth and elevation errors in the two-channel system will be no greater than the error in the three-channel elevation plane. For those cases where the integrity of the azimuth tracking channel is to be maintained, the three-channel monopulse system would offer an advantage providing the terrain was symmetric. In practical ground installations, where in-line multipath is less likely to occur because of environmental anomalies, both systems would perform in approximately the same manner.

In effect, the two-channel monopulse concept represents another addition to the designer's library. In the final analysis, the selection of the tracking system, whether it be two-channel, three-channel, or synthetic conical scanning, is dependent on many factors and no attempt is made in this paper to influence the designer in the direction of any of these three approaches. The decision must be made on the basis of the desired system characteristics, its intended use, the availability of system components, and other design and cost factors. It is the intent of this paper to update the reader with the latest available data for two-channel monopulse systems.

---

3. loc. cit

Background. - The first two-channel monopulse effort was implemented under the sponsorship of the National Aeronautics and Space Administration in early 1961[4]. This L and S-band system was used to demonstrate the broad bandwidth, low sidelobe and tracking characteristics of the technique. A series of contracts on this subject were subsequently funded by NASA, each adding to the technology needed for the technique. These efforts led to the development of an 8-foot diameter spiral of the type discussed herein. This preliminary developmental model also operated in incremental bands over the frequency range from 136 to 2300 MHz and was described in a paper by Lantz[5]. This developmental model was followed by a more refined model which is reported on in this paper. A continuous 8:1 bandwidth spiral was developed in 1964 and reported on by Franklin, et al[6]. It was this referenced program which initiated much of the broad bandwidth technology presently being used in broadband tracking systems of the present day. One of the very earliest two-channel monopulse systems was developed in 1961 to provide the tracking head for a communications link between Rome, New York and Trinidad via the Echo Satellite. This system differed from the prior described units in that it was a high power system formed in waveguide. Furthermore, it utilized the two-channel monopulse format to generate simultaneous dual polarized synthetically conical scanning beams[7]. This latter referenced paper is of particular interest to the designer who might wish to convert the two-channel monopulse system to a synthetic conical scanning system or "one-channel monopulse system".

One of the later systems which use the two-channel monopulse concept was developed for the Apollo Range Instrumented Aircraft (A/RIA)[8]. This system, shown in Figure 2, uses a six-arm cavity backed spiral to excite a 7-foot parabolic dish. It operates over the frequency range from 1435 MHz to 2300 MHz, providing simultaneous sum and difference channel outputs for both right- and left-hand circular polarizations. This system, which has been successfully used in tracking and communicating with Apollo VIII and Apollo X, is characterized by very low sidelobes. Its overall performance is summarized by the following Table.

---

4. "Two-Channel Phase-Monopulse Antenna Feed", RSi Final Report prepared under NASA Contract NAS 5-1589, March 1962.
5. Paul A. Lantz, "A Two-Channel Monopulse Reflector Antenna System with a Multimode Logarithmic Spiral Feed", NASA Report X-525-66-262, June 1966.
6. loc. cit
7. James A. Homola and Marvin E. Hansen, "A Dual Polarized High-Power Synthetic Conical Scan Tracking System", presented at the International Telemetering Conference, Washington, D.C., 1965.
8. "UHF Antenna Feed Assemblies", developed by RSi for Bendix Corporation under P.O. S-95281.

TABLE I

CHARACTERISTICS OF A/RIA SYSTEMS

Parameter	Computed Value	Measured Value	Band Performance
Frequency	2.2 GHz	2.2 GHz	1.4 - 2.3 GHz
Gain (100%)	33.9 db	---	---
Spiral Loss	0.7 db	---	---
Spillover Loss	0.7 db	---	---
Aperture Efficiency	1.1 db	---	---
Blockage Loss	0.2 db	---	---
Network Loss	---	0,65 db	---
Cable Loss	0.15 db	0.7 db	---
Gain	30.1 db	30.2 db	27 - 30 db
Sidelobe Level	23.3 db	21.0 db	> 21 db
HPBW	4.3°	4.3°	7° - 4.3°

In summation, the two-channel monopulse technique has been the subject of considerable investigation since its inception in early 1960. The above referenced efforts, with their attendant references, will provide a near complete bibliography for use in the design of such systems.

Feed System Description. - Figure 3 is a photograph of the 136 MHz to 2300 MHz spiral antenna feed. This spiral, ultimately designed to excite an 85-foot parabolic dish with an f/D of 0.425, consists of three nested spirals. The large outer spiral provides the sum and difference channels for the 136 to 138 MHz region. It also provides the difference channel for the 234 to 236 MHz region. The mid range spiral provides the sum channels for the 234 to 236 MHz region and the 400 to 402 MHz region. This spiral also provides the difference channel for the 400 to 402 MHz region. The center spiral provides operation over the frequency range from 1435 MHz to 2300 MHz in three discrete bands.

Simultaneous sum and difference excitations for both senses of circular polarization is achieved by the simultaneous excitation of the inner and outer feed points of the multi-arm spirals, as described by Yaminy[9]. The center spiral element uses six spiral arms whereas the two outer spirals each have four arms. All spirals were of the log periodic equiangular type.

A block diagram of the feed system is shown in Figure 4. This block diagram delineates the various bands needed for operation in the STADAN system. It also shows the diplexers needed to provide the necessary band splitting. All components were formed in strip transmission line and attached to the rear of the spiral cavity.

---

9. R. R. Yaminy, "A Two-Channel Monopulse Telemetry and Tracking Antenna Feed", presented at the International Telemetering Conference, Los Angeles, Calif., 1968.

Figure 5 is a plot of measured left-hand circularly polarized feed patterns at 400 MHz for the sum and difference channels. These patterns illustrate the near equal edge illumination attainable for both pattern formats. The patterns are typically symmetric about the boresight axis of the feed system. A more complete description of the feed characteristics is contained in the Table below.

TABLE II

Summary of Primary Characteristics of Feed 136 — 2300 MHz

Efficiency	> 40 %
Edge Illumination	12 to 21 db (Σ)
Axial Ratio	0.1 to 1.5 db
Boresight Error	-0.1° to $+2.2^{\circ}$
Σ to Δ Amplitude	0.5 db to 6.1 db
Σ to Δ Isolation	-15 to -37 db
VSWR	1.0 to 1.72
Phase Center Deviation	2.45 inches

The above characteristics indicate that the edge illumination is well controlled for achieving low sidelobes in the secondary far field patterns. The efficiency and input VSWR include the effect of both the strip transmission line matrices and the diplexers. The worst observed boresight shift is approximately 1/30 of the half-power beamwidth of the feed pattern. The apparent phase center was measured at a range simulating the approximate distance of the parabolic dish from the feed system surface. In actual operation, the individual spiral positions will be adjusted so that all three spirals are focused. Even without adjustment the defocusing at 136 MHz amounts to less than 1/35 of a wavelength, assuming the high band spiral is focused.

Tracking System Characteristics. - In order to evaluate the feed system (developed by Radiation Systems, Incorporated) as an integral part of a monopulse tracking system, a contract was negotiated by the National Aeronautics and Space Administration with the Collins Radio Company of Dallas, Texas. The Collins Arapaho tracking station is a fully instrumented satellite and data acquisition station. The solid surface 60-foot diameter reflector ($f/D = 0.417$) has a surface accuracy of 0.030-inch rms and is mounted on a hydraulically driven elevation-over-azimuth pedestal. A quadrapod spar arrangement supported the spiral feed at the focus allowing ± 12 inches of axial adjustment. Figure 6 is a photograph of the feed mounted in the 60-foot diameter reflector. Extensive tests of the drive and servo readout system were conducted after the feed system was mounted. A boresight camera was used to determine that the jitter was less than approximately 0.02° for either axis with an absolute error of less than 0.05° for the two axes (1σ). Two RF ranges were established with remote field generating sources located a distance, $R \geqq 2D^2/\lambda$, for the 60-foot system. A thorough program of range reflection probing was carried out to facilitate location of dual diffraction fences for minimizing spurious ground reflections. Tests conducted on the system consisted of focusing measurements, boresight measurements, pattern measurements, axial ratio measurements, gain and VSWR measurements, error channel cross-coupling measurements, and a tracking demonstration. All tests were conducted at frequencies of 136, 400, 1700, and 2300 MHz for both left- and right-hand circular polarizations. A helicopter-borne signal source, as well as radio stars and satellite sources, supplemented the test range capability.

The center feed was focused in the L and S-band ranges when the center of the spiral face was at the focal point. The phase centers for the mid and large outer spiral were found to lie between the spiral faces and the cavity backs. Therefore, it was necessary to move the feed slightly toward the reflector to focus at frequencies of 400 and 136 MHz. A slight adjustment of the relative cavity positions of the three spiral cavities will produce an in-focus feed over the 136 to 2300 MHz band with no need for adjustment.

The similarity of pattern performance for right- and left-hand circular polarizations is demonstrated in Figure 7 where sum and difference patterns are shown for a frequency of 2300 MHz. Later patterns at other frequencies are only shown for left-hand circular polarization in order that the presentation be simplified. Figure 7 indicates that the sidelobes are 30 db below the sum pattern maximum for the sum channel and 28 db for the difference channel. Figure 8 shows a theoretical 1700 MHz pattern computed for the Collins reflector. This theoretical pattern includes the effect of the measured illumination taper and the blockage by both the spars and the feed (the effect of reflector tolerances and phase front errors are not included in this calculation). The measured 1700 MHz pattern of Figure 8 shows that good agreement exists between theory and practice. This comparison of theory and practice was used as a measure of the quality of the test range. Figures 9 and 10 show that excellent pattern performance was maintained at frequencies of 400 and 136 MHz.

The axial ratio measurement was difficult to conduct because of specular reflections from the test range. Figure 11 shows a plot of axial ratio versus frequency and indicates that the axial ratio was generally better than 2 db except at 136 MHz. Measurements at 136 MHz were not conclusive because of the broad beamwidth of the 60-foot dish and the resultant effect of ground reflections at this frequency.

The gain of the antenna system was measured at each test frequency for each polarization. The measurement was accomplished using calibrated standards mounted on the rim of the reflector (see Figure 6). For this test, the RF field was generated both by the collimation tower and by a helicopter located in the far field at an elevation angle of 50 degrees. This latter method was found to be quite repeatable. Figure 11 is a plot of the measured data showing the gain ranging from 50 db at 2300 MHz to 25 db at 136 MHz. The efficiency is estimated to range from 50 percent at 136 MHz to 55 percent at 2300 MHz.

The coalignment of the effective boresight axis with the mechanical boresight axis is a factor which establishes the accuracy of a monopulse tracking antenna system. After the feed had been aligned by optical techniques the boresight error of the entire system was measured. Measurements were made against radio star sources as well as a helicopter-borne RF source. Figure 12(a) is a composite plot of measured data for all frequencies and polarization senses. The maximum error of 3-1/2 milliradians occurred at 136 MHz. For the most part, the boresight error is less than ± 1 milliradian.

The tracking error voltage of the receiver was measured as a function of angular error to the RF source to determine the tracking channel cross-coupling. With one axis locked on boresight, the RF source was scanned by the other axis from one to two beamwidths on each side of boresight. If no tracking channel cross-coupling was occurring, this error voltage for the locked axis should read zero. Any voltage recorded was defined as coupling voltage. Figure 12(b) is a plot of data from the analog strip chart recorder for one of these tests at 2300 MHz. The analog voltages are shown to be 1 volt/degree for the azimuth axis and 0.7 volt/degree for the elevation axis. Coupling in the figure is shown to be 25 percent for the azimuth channel and 6.6 percent for the elevation channel. These values for all cases ranged from 0 percent to 50 percent.

Operational Tracking Data. - The sun, moon, Cassiopeia A and Cygnus were autotracked in the open loop mode at all four frequencies. Acquisition for this purpose was easily accomplished using a nautical almanac and computer printouts of azimuth and elevation angles by four-minute intervals. Figure 13 illustrates one track of Cassiopeia A in which the source was tracked to the horizon. During the period December 22-24, 1969, the Apollo VIII spacecraft was tracked in the phase locked mode of operation. Figure 14 illustrates the schematic of the equipment used for this operation. Acquisition was easily accomplished and it was demonstrated that the sense of polarization could be freely reversed with no loss of track. Following the transearth injection, high gusty winds in the Dallas area forced abandonment of the tracking operation.

Acknowledgments. - The authors would like to express their gratitude to the Collins Radio Company for conducting the measurements on the spiral system. The authors would also like to extend their appreciation to Mr. Jay Kaiser of the National Aeronautics and Space Administration, Greenbelt, Maryland, for assistance in the testing phase and to Dr. Bing Chiang of Radiation Systems, Incorporated, who performed the theoretical calculations, some of which are shown in Figure 8.

RSi

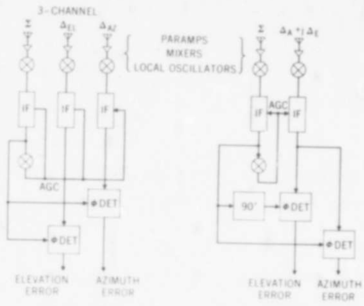

Figure 1. Comparison of 2 and 3 Channel Monopulse Systems

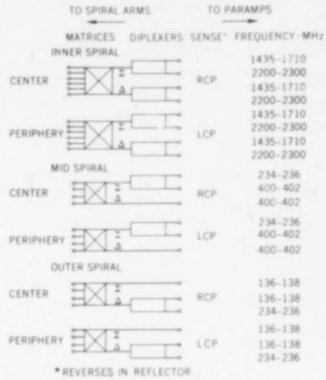

Figure 4. Feed Excitation Schematic

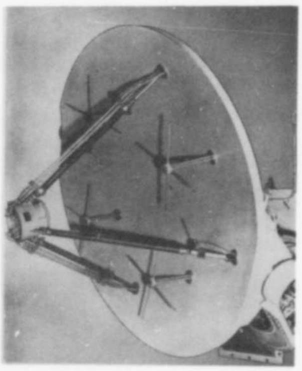

Figure 2. APOLLO Range Instrumented Aircraft (ARIA) Antenna

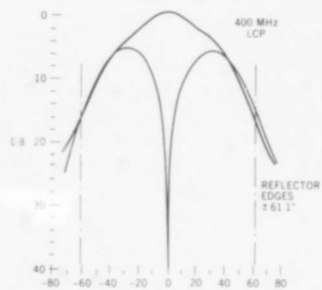

Figure 5. Typical Primary Patterns

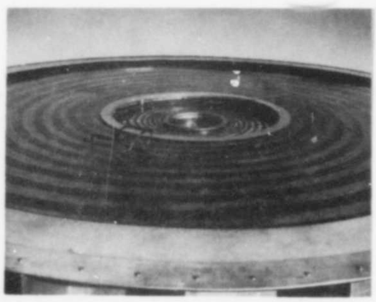

Figure 3. Feed Prior to Application of Face Cover

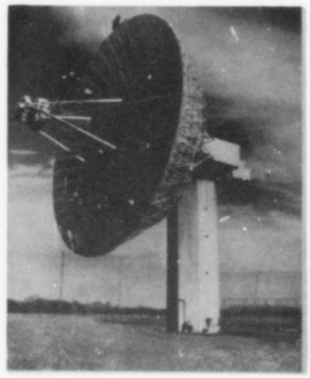

Figure 6. Feed in Collins 60-Ft Paraboloid

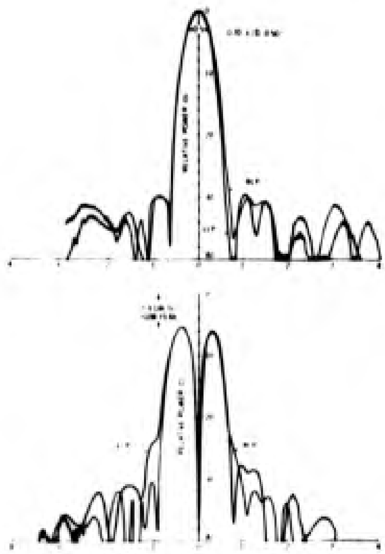

Fig. 7. RSi Feed in Collins 60-Ft Dish
2300 MHz Mar. 17, 1969

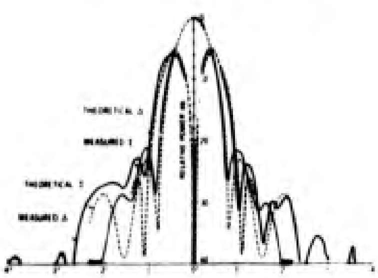

Fig. 8. RSi Feed in Collins 60-Ft Dish 1700 MHz
Comparison of Theoretical to Measured LCP

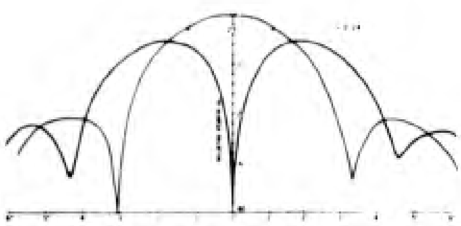

Fig. 9. RSi Feed in Collins 60-Ft Dish
400 MHz Feb 17, 1969 LCP

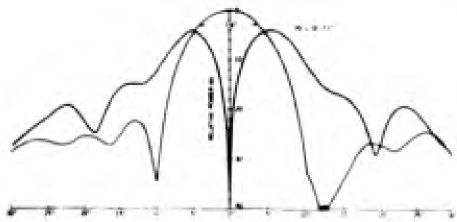

Fig. 10. RSi Feed in Collins 60-Ft Dish
136 MHz RCP Feb 18, 1969 LCP

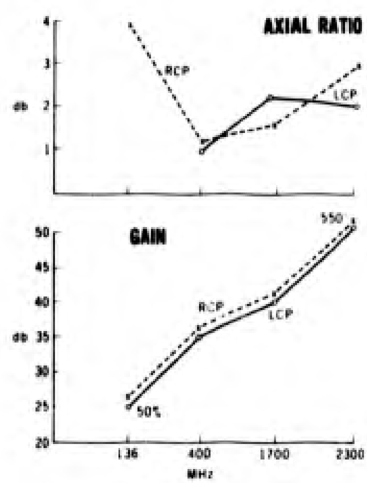

Fig. 11. Axial Ratio vs Gain

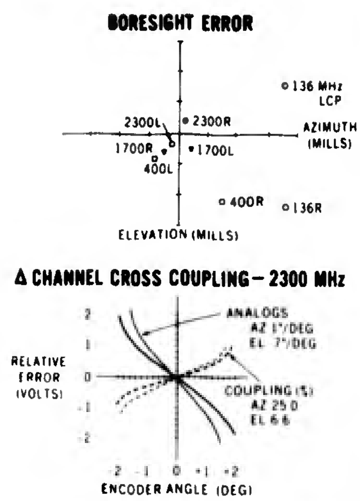

Fig. 12. Boresight Error vs Δ Channel
Cross Coupling 2300 MHz

RSi

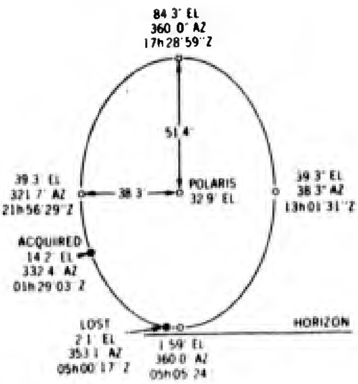

Fig. 13 Track of Cassiopeia A Dallas
Mar 25 - 26, 1969

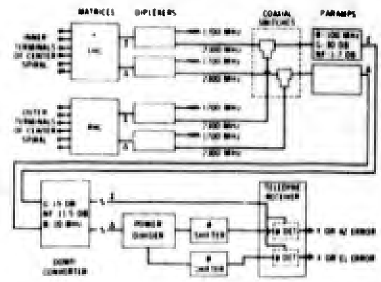

Fig 14 Schematic for Tracking Apollo VIII
2287 5 MHz

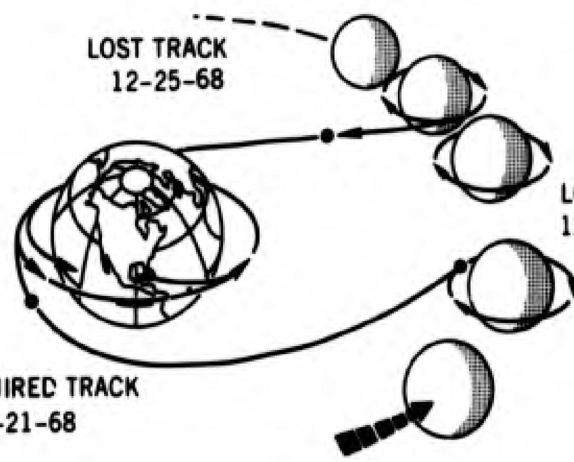

Fig. 15 Tracking Apollo VIII RSi Feed in
Collins 60-Ft Dish