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**Final Report**  
**for**  
**ADVANCED TECHNOLOGICAL SATELLITE**  
**ELECTRO-MECHANICAL DESPUN ANTENNA**

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**Sylvania Electronic Systems Eastern Division**

**Sylvania Electronic Systems**

**An Operating Group of Sylvania Electric Products, Inc.**

for

**National Aeronautics and Space Administration**

**Goddard Space Flight Center**

**Greenbelt, Maryland**

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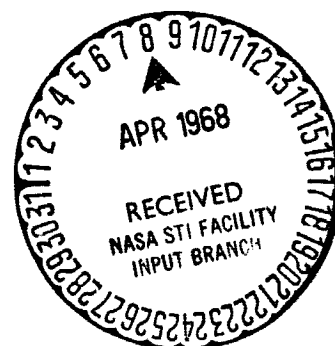
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**Final Report  
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ELECTRO-MECHANICAL DESPUN ANTENNA**

**19 October 1967**

**F181-1**

**Contract No. NAS 5-9521**

**Prepared By**

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## **SECTION 1**

### **INTRODUCTION**

Sylvania was contracted by NASA/GSFC under contract number NAS5-9521 to design, fabricate and test five microwave-frequency mechanical despun antenna systems consisting of an RF subsystem, a control electronics subsystem, and a mechanical drive subsystem.

The five units to be delivered were:

- 1) Two breadboard models
- 2) One qualification prototype model
- 3) Two flight model

The two breadboard antennas were not required to meet any specifications or design criteria, but were intended to be learning models and test vehicles. The remaining three deliverable units were fully specified systems.

Because the RF subsystem is an integral part of the mechanical drive structure, the total antenna system consists of two physically separate subsystems, as shown in Figure 1-1. These are the Mechanical Drive Assembly and the four Control Electronic Packages.

The RF subsystem provides highly directional transmitting and receiving pencil-like beams at 4 GHz and 6 GHz, respectively, characterized by a 17-db nominal gain figure at each band. Intended for use on satellites in synchronous orbits, the 3-db beamwidth at each band is 20° providing total earth coverage.

The antenna beam is despun by counter-rotating a parabolic cylindrical reflector assembly about a linearly polarized feed system located coincident with the spin axis of the spacecraft. A synchronous stepping motor is used to drive the reflector assembly at a speed synchronous with the satellite but opposite in direction, so as to despun the RF beam. Figure 1-2 shows an artist's concept of the mechanical despun antenna mounted on the spacecraft.

Two control systems called the Mark I and Mark II, respectively, were fully developed for the mechanical despun antenna. The experimental Mark I system contained an automatic digital positioning loop. In the Mark II design, the one actually used in the flight hardware, this feature was eliminated in favor of full redundancy in the control electronics. These two designs are discussed separately in subsection 4.2.

The antenna system is mechanically and electrically compatible with a cylindrical, spin-stabilized spacecraft for satellite communications with earth stations. It is designed to operate in the space environment for a one-year minimum period with a five-year design goal.

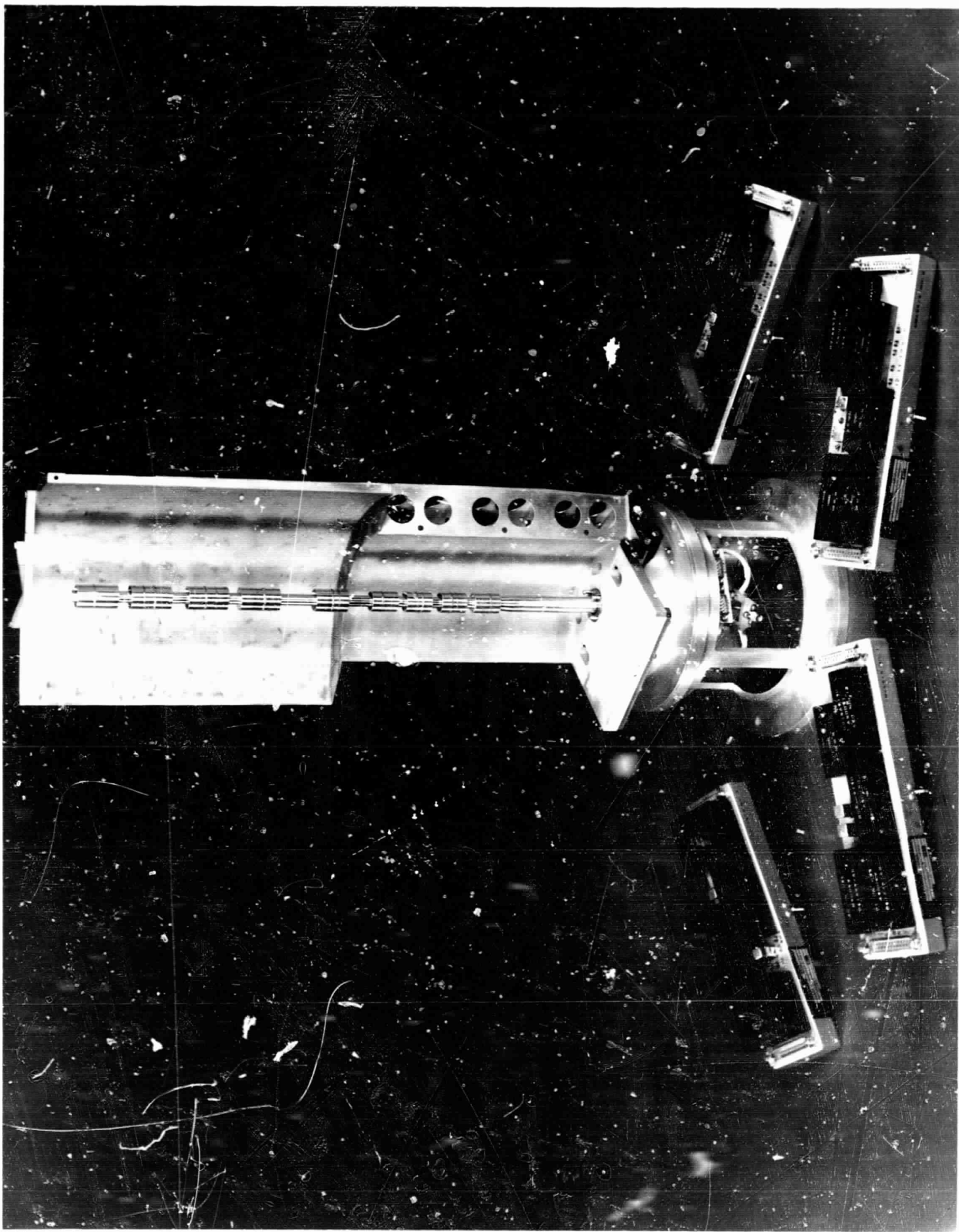


Figure 1-1. ATS Mechanical Despun Antenna System

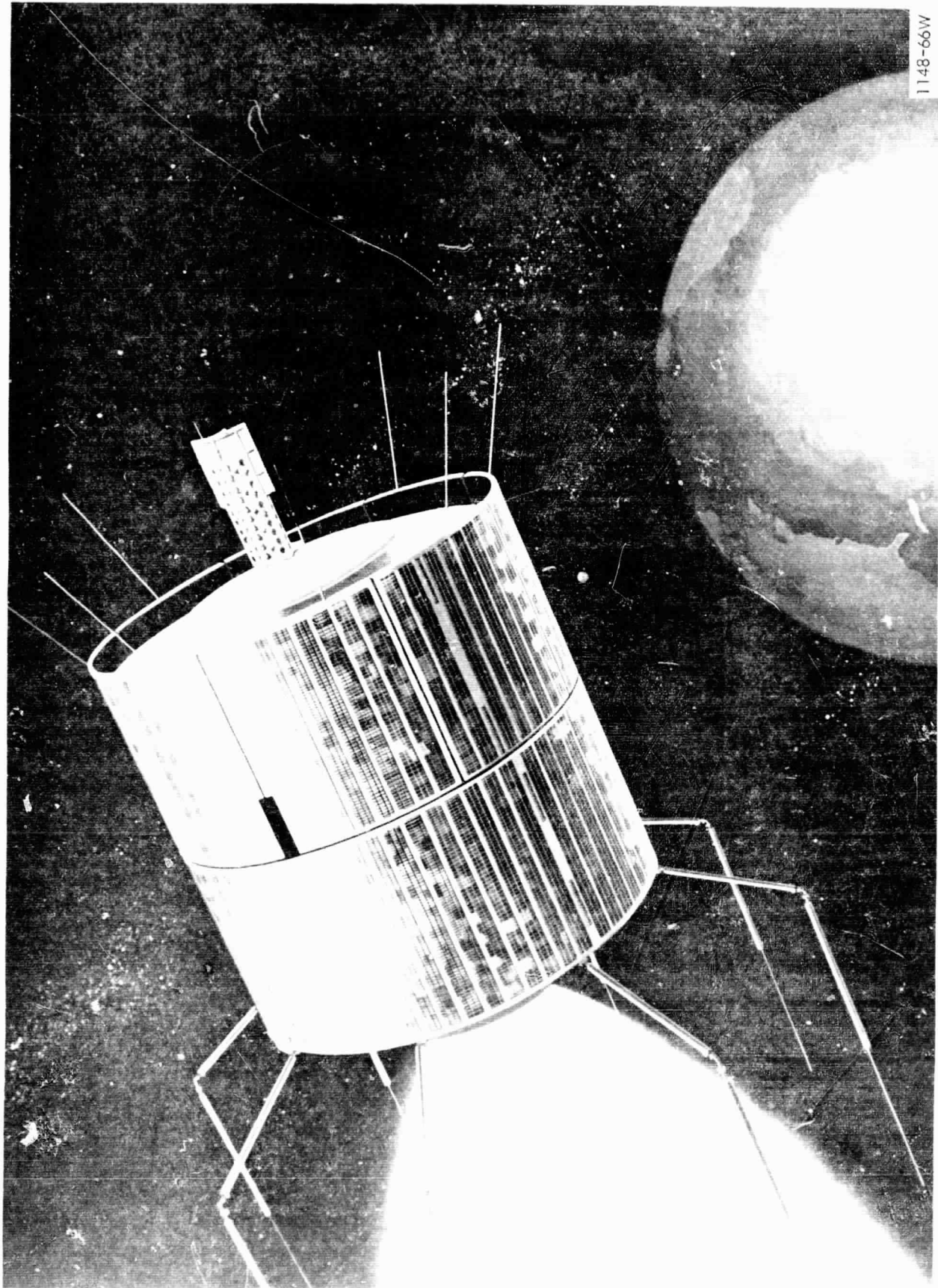


Figure 1-2. Artist's Concept of Antenna Mounted on Spacecraft

Section 2 summarizes the overall performance of the mechanical despun antenna against the specifications and requirements. Section 3 defines the detailed specifications and requirements in three basic areas: RF; control electronics; environmental and mechanical.

Section 4 summarizes the design development and test programs in each area. The intent is to give the reader a complete description of the final design configuration in each case and a summary of how and why this design differs from the original concept in those areas where design changes were incorporated.

Since no separate test report is required, a complete summary of the data from the qualification and acceptance test programs is included as Appendices A through F.

Appendix G is a copy of an analysis of the thermal interface between the mechanically despun antenna and the spacecraft.

## SECTION 2

### SUMMARY

The Mechanical Despun Antenna System has completely satisfied all design specifications and all performance requirements in accordance with NAS-5-9521 MOD 25, and all environmental requirements per NASA Spec S2-0102. In addition, a motor drive, bearing and lubrication system performed successfully for 7800 hours in a vacuum of  $10^{-7}$  Torr.

Preliminary RF testing of the Qualification Model Mechanical Drive Assembly mounted on the spacecraft indicates that the antenna surpasses expectation. The RF performance exceeded specifications intended to apply to the antenna only in the absence of the satellite. This RF testing was conducted after the Mechanical Drive Assembly had been subjected to vibration testing while mounted on a mock-up spacecraft.

Problems experienced during qualification testing were corrected without changing the basic design. In all instances, the cause of malfunction was specifically identified and corrective action initiated.

The change of scope from the Mark I to the Mark II control electronics system improved the performance, reliability and physical configuration. The control electronics system's most sensitive environment is temperature. The flight systems were successfully tested to temperature limits equal to the Qualification Test limits.

Waivers were requested and granted on several phases of the qualification and flight acceptance testing. In all cases, the waivers were requested to expedite the testing. No design or performance type waivers were required, since all qualification and acceptance test requirements and specifications had been met.

## SECTION 3

### DESIGN REQUIREMENTS

#### 3.1 RF SUBSYSTEM

The following RF requirements are applicable:

##### Receiving Channel Requirements (6 GHz) Off the Satellite

The receiving channel shall meet the following minimum requirements:

- 1) Frequency Bands:  $(6301 \pm 12.5)$  MHz and  $6212 \pm 12.5$  MHz
- 2) Nominal Gain: 17 db above isotropic
- 3) Antenna Beam Width:  $20 \pm 2^\circ$  at 3 db points
- 4) Amplitude Pattern Ripple: Shall be less than 1/2 db (Amplitude pattern ripple is defined as ripple caused by antenna rotation)
- 5) Linear Polarization: Cross-polarized components shall be greater than 20 db below level in principal plane of polarization
- 6) Pattern symmetry shall be better than  $\pm 1/2$  db within  $\pm 10^\circ$  about the center line of the main beam.
- 7) The radiation pattern measured normal to the aperture shall be no more than 0.4 db down from the peak of the main beam.
- 8) Transmission Line VSWR: shall be less than 1.45 over a 10% bandwidth.

##### Transmission Channel Requirements Off the Satellite

- 1) Frequency Bands:  $(4178 \pm 12.5)$  MHz and  $(4119.9 \pm 12.5)$  MHz
- 2) Nominal Gain: 17 db above isotropic
- 3) Antenna Beamwidth:  $20 \pm 2$  degrees at 3 db points
- 4) Amplitude Pattern Ripple: Shall be less than  $\pm 1/2$  db
- 5) Linear Polarization: Cross-polarized components shall be greater than 20 db below principal plane of polarization
- 6) Pattern symmetry shall be better than  $\pm 1/2$  db within  $\pm 10^\circ$  about the center line of the main beam
- 7) The radiation pattern measured normal to the aperture shall be no more than 0.4 db from the peak of the main beam.
- 8) Transmission Line VSWR: shall be less than 1.35 over a 10% bandwidth.

### 3.2 CONTROL SUBSYSTEM

The electronic control subsystem provides the following operational characteristics:

- 1) Rotational Speed/Range: 100 rpm  $\pm$  50 rpm (continuously adjustable)
- 2) Antenna Beam Pointing Accuracy:  $\pm 1/2^\circ$
- 3) Control System Resolution: 0.7°
- 4) Power Drain: 15.35 watts
- 5) Supply Voltage: -24V  $\pm$  2%
- 6) Earth Rotation Compensation: Compensation is provided by a variable phasing control to enable an additional 360° rotation per day
- 7) External Adjustment: Gross and vernier adjustments are provided by a telemetry link to ground
- 8) Provisions for firing squibs by ground command for fail-safe mode operation.

### 3.3 ENVIRONMENTAL AND MECHANICAL REQUIREMENTS

The mechanical structure and control electronics packages are composed of light-weight materials capable of withstanding the hazards of the outerspace environment. An absolute minimum of dielectric material was used in areas exposed to the space environment. The motor, bearings and lubrication selected permit long periods of operation in a vacuum.

The environmental and mechanical requirements are:

|                                 |                                                                                                                     |
|---------------------------------|---------------------------------------------------------------------------------------------------------------------|
| Controlled Thermal Environment: | 20° F to 120° F                                                                                                     |
| Space Environment:              | Typical of a synchronous equatorial orbit of 22,300 mile radius                                                     |
| Launch Requirements:            | In accordance with NASA specification S2-0102 Rev. C                                                                |
| Balance:                        | The c. g., offset under static conditions not to exceed 0.010 inch                                                  |
| Weight:                         | Not to exceed 14.0 pounds                                                                                           |
| Ejection Mechanism:             | Provisions for separating the reflector from the antenna structure (upon command) by means of a pyrotechnic device. |

## **SECTION 4**

### **TECHNICAL DISCUSSION**

#### **4.1 RF SUBSYSTEM**

##### **4.1.1 Introduction**

Several considerations dictated the design of the RF subsystem:

- 1) The design must provide for the despinning of the RF beam.
- 2) Desirably, it should eliminate the need for any RF rotary joints.
- 3) The RF configuration must be compatible with a required fail-safe mode of operation in which an omni-directional radiation pattern is provided in the plane normal to the spin axis.

These features are all incorporated in the RF subsystem of the ATS mechanically despun antenna described in this section.

##### **4.1.2 Final Design Description**

###### **4.1.2.1 General**

The final RF configuration provides two-band operation (transmission at 4 GHz and reception at 6 GHz) by means of two separate apertures. At each band there is a parabolic cylindrical reflector and a two-element, collinear, full-wave dipole array feed as shown in Figure 4-1, an artist's concept of the RF subsystem.

As indicated in the figure, the larger 4 GHz system is mounted in "piggy-back" fashion on the 6 GHz system. This particular configuration was chosen to minimize any effects of the satellite structure on the RF performance of the 4 GHz down-link. The 6 GHz up-link is less critical, its performance being dependent on the ground station's high-power transmitter and high-gain antenna.

The dipole feeds radiate an omni-directional pattern in the plane of the parabolic contour of the reflector. The antenna beam can, therefore, be despun by counter-rotating the reflector assembly relative to the spinning satellite. This design also allows the RF feed to be rigidly attached to the spinning satellite thereby eliminating the need for a rotary joint to carry RF signals to and from the antenna. Thus, two of the three design goals listed earlier have been achieved.

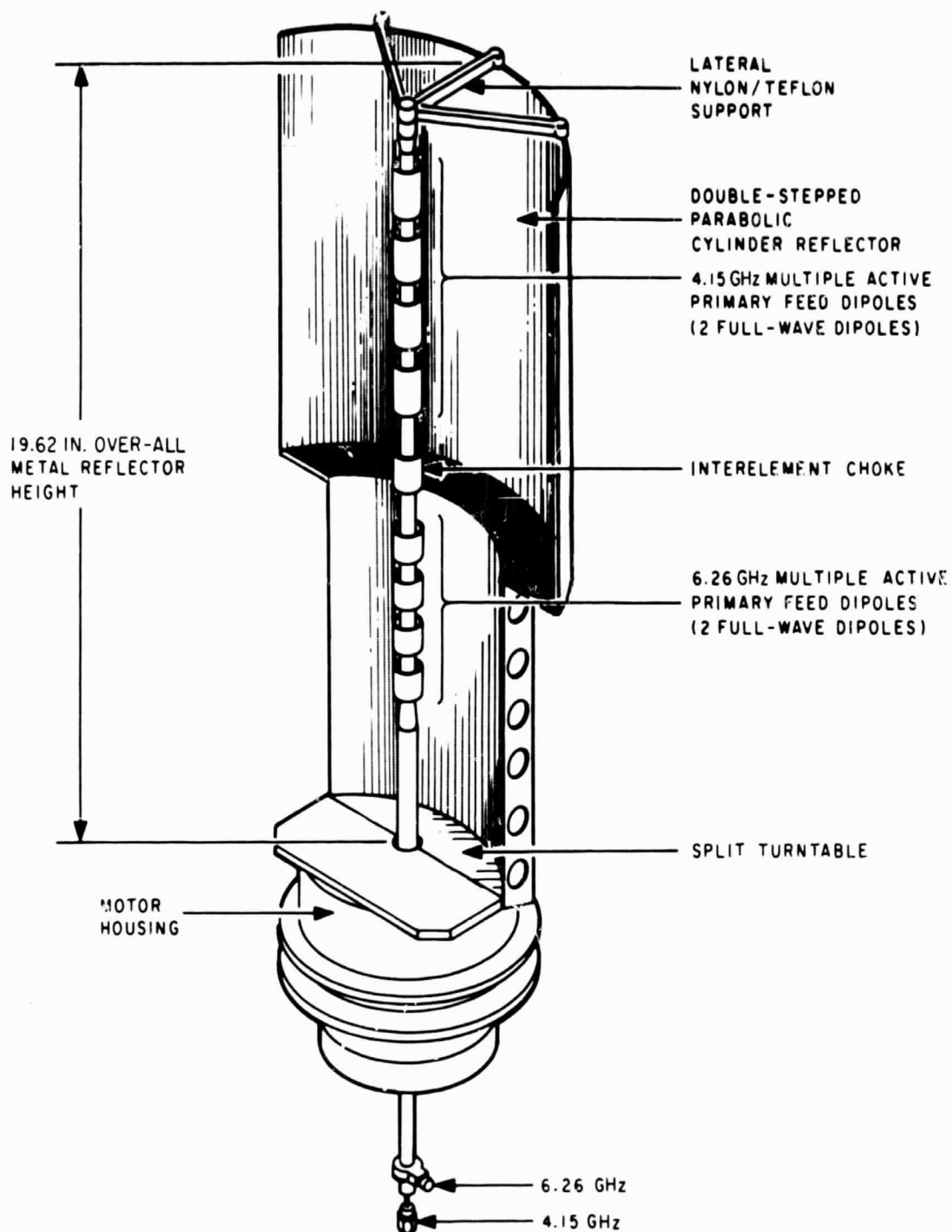


Figure 4-1. Artist's Concept of Despun Antenna

In operation, the mechanical despun antenna is mounted on the satellite so that the center line of the RF feed assembly is coincident with the spin axis of the satellite. Ejection of the dual section reflector assembly provides the required fail-safe mode of operation in which an omni-directional pattern in the plane normal to the spin axis is obtained. Sub-section 4.4 describes this ejection mechanism.

#### 4.1.2.2 RF Feed Assembly

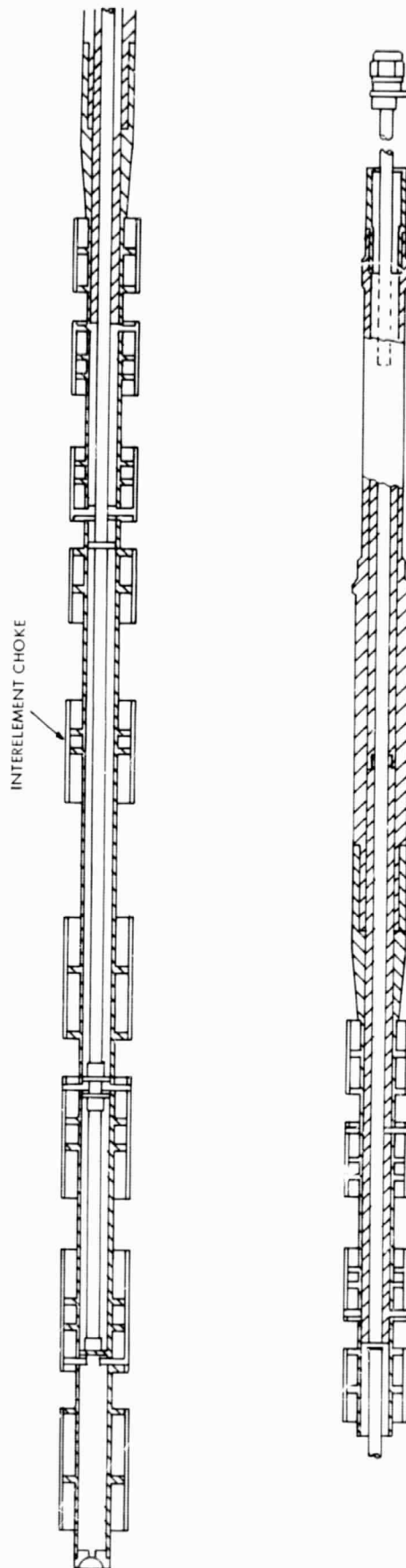
At each band, a  $20^\circ$  beam is formed in the vertical plane (along the satellite spin axis) by the dipole array feed which is approximately  $3\lambda$  long, electrically. Each feed consists of two full-wave dipoles spaced approximately  $1-1/2\lambda$  apart along the dielectric filled coaxial line used to drive them. The two elements are fed  $180^\circ$  out-of-phase, thus the radiated fields from the two dipoles add in-phase in the far field.

Since the 4 GHz dipoles are mounted on the same feed support tube as the 6 GHz dipoles, a triaxial feed system is required, as illustrated in the feed assembly drawing of Figure 4-2. Aluminum-jacketed RG-141 coaxial cable is used to excite the 4 GHz dipoles at the top of the feed structure. Cable containing only high radiation resistant FEP-100 teflon is used. Its total dissipative loss in the antenna system is 0.6 db.

The outer conductor of this cable serves as the center conductor for the 6 GHz coaxial feed line. Again, only FEP-100 teflon is used in this special line in which the feed support tube serves as the coaxial outer conductor. The calculated loss of this line is  $1/4$  db. Male and female OSM connectors are used at 4 GHz and 6 GHz, respectively.

In the final design, T-feeds were used at each dipole to force the excitation of the desired TEM mode in the dipole choke region. In this way, unwanted  $TE_{11}$  and  $TE_{21}$  modes were not excited. The design of the T-feeds is indicated in Figure 4-2.

Between the 4 GHz and 6 GHz systems on the feed assembly, there is an inter-element choke to increase the decoupling between the transmit and receive terminals. One end of the double-ended choke is a quarter wavelength long at 4 GHz; the other end is a quarter wavelength at 6 GHz. Through no specification was imposed, Sylvania believed that a minimum decoupling of 30 db was desirable. This objective was realized with the inter-element choke.



2050-67W

Figure 4-2. RF Feed Assembly, Cross-Section Drawing

#### 4.1.2.3 Reflector Assembly

In the plane orthogonal to the spin axis, a  $20^\circ$ , 3-db beamwidth is obtained at each band by virtue of the size of the parabolic contour of the reflector. This size, which is 9 inches and 6 inches, at 4 GHz and 6 GHz, respectively, is approximately  $3\lambda$ . In this way, two  $20^\circ$  by  $20^\circ$  pencil beams are formed.

It is of interest to note that in the final design, the relationship between the reflector and feed is phased so that direct radiation from the feed adds in-phase with that from the reflector. Specifically, the centerlines of the feed and the reflector are spaced  $3/4\lambda$  apart at both bands. (Hence, there is a step in the reflector assembly.) With a  $180^\circ$  phase reversal at the reflector surface, the reflected energy and direct radiation from the feed add in phase. Consequently, there is by definition no aperture blocking by the feed system, since it is active. This results in a more efficient aperture than would be obtained if, for example, a reflecting rod were used behind the feed to direct energy into the reflector. Because of diffraction, the smallest wire would have an effective blocking diameter of approximately  $\lambda/3$  which, with the relatively small apertures used in this system, is significant.

However, the pattern bandwidth is necessarily limited in this design in which the feed and reflector are phased. Though it is quite adequate for the approximately 2% pattern band required of this antenna, data taken outside this band show that the bandwidth of this system, as determined by significant gain degradation, is approximately 10%.

#### 4.1.3 RF Development Program

As in any antenna program, the RF development consisted of achieving the required pattern/gain performance and impedance characteristics over the operating bands. In the process of this development, several changes occurred in the original design.

First, in the initial RF configuration, the larger 4 GHz reflector/feed assembly was below, not above, the 6 GHz system. This design had the obvious advantage of minimizing the moments and loads imposed upon the structure during launch. This consideration was of particular concern in fail-safe mode ejection mechanism which has to withstand the launch vibration stresses without falsely ejecting and still function properly thereafter.

However, the RF patterns and gain data of the 4 GHz system measured on a full-scale mock-up of the satellite showed significant effects of the satellite on the antenna

performance. The 4 GHz down-link from the satellite is generally signal-to-noise limited. Consequently, it is more critical than the 6 GHz up-link. Therefore, from a systems point of view, it is desirable to minimize the satellite effects on the down-link. For this reason, although not responsible for the satellite effects on RF performance, Sylvania chose to reverse the location of the two systems to favor the more critical 4 GHz path.

A second change occurred in the area of the feed system. In the original design, a reflecting rod was used behind the feed to aid in directing energy into the reflector. The rod was designed to despin with the reflector around the feed proper. It was, accordingly, ejected with the reflector in the fail-safe mode.

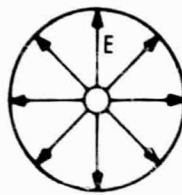
However, preliminary impedance data showed a large change in the characteristic as well as the magnitude of the impedance plot in the presence (or absence) of the reflecting rod. Although impedance matching had not been accomplished at that point, it was evident that the antenna could not be matched for both conditions. The only alternative was to eliminate the reflecting rod in both normal and fail-safe modes and phase the feed/reflector relationship as previously described. This approach was successful in that the specified gain, beamwidth and match was achieved over the required band.

The third significant change in the preliminary RF design is also in the feed area. This change concerns the method of exciting the feed dipoles.

A number of different methods of dipole excitations were considered. These included gap feeds as depicted in Figure 4-3, variations of the post feed shown in Figure 4-4, and the T feed used in the final design.

Because of its simplicity and structural integrity, the post feed was tried first. However, being an asymmetrical method of excitation, the  $TE_{11}$  mode was excited in the dipole feed choke. (Because of the structural support tube, the dipole diameter is approximately  $0.83\lambda$  and  $1.13\lambda$  at 4.15 GHz and 6.26 GHz, respectively). This mode results in an asymmetrical current distribution around the dipole and associated end-fire radiation. The situation is described diagrammatically in Figure 4-5. Instead, a symmetrical TEM mode excitation is required as also shown in Figure 4-5. This mode provides the desired dipole radiation.

To solve the unwanted mode problem, a two-point excitation of the dipole was tried. The resultant T-feed configuration, which eliminated the  $TE_{11}$  mode, is shown conceptually in Figure 4-6. The details of the final design are available in the feed assembly drawing (Figure 4-2).



TEM MODE

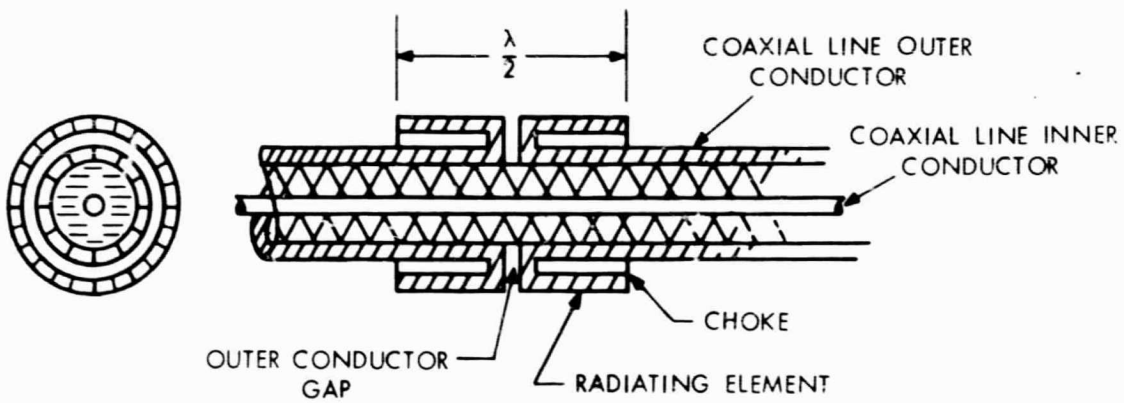
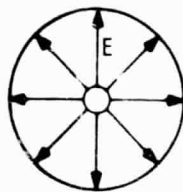


Figure 4-3. Dielectric Support Gap Feed



TEM MODE



TE<sub>11</sub> MODE

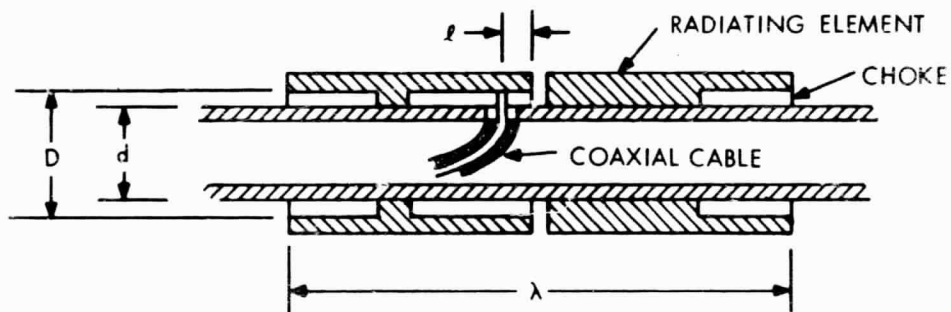
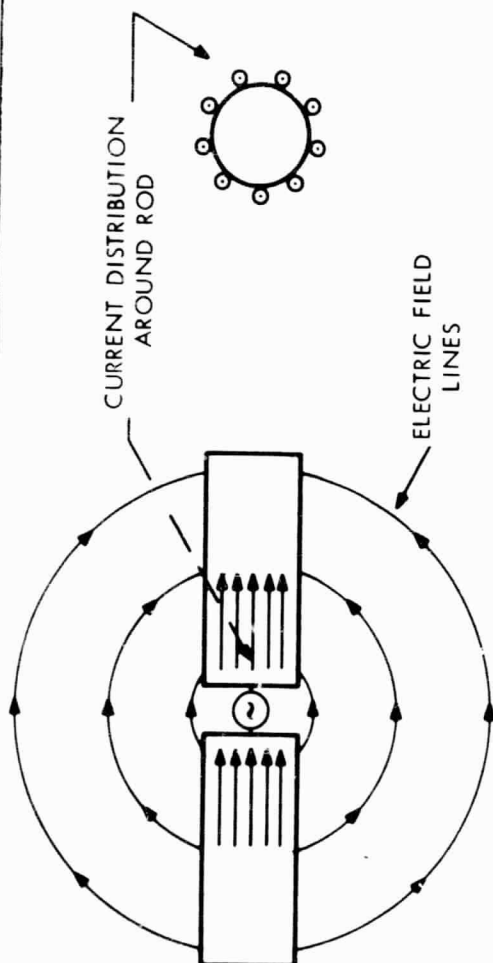


Figure 4-4. Variations of the Post Feed

(A) SYMMETRICAL CURRENT DISTRIBUTION



(B) ASSMETRICAL CURRENT DISTRIBUTION

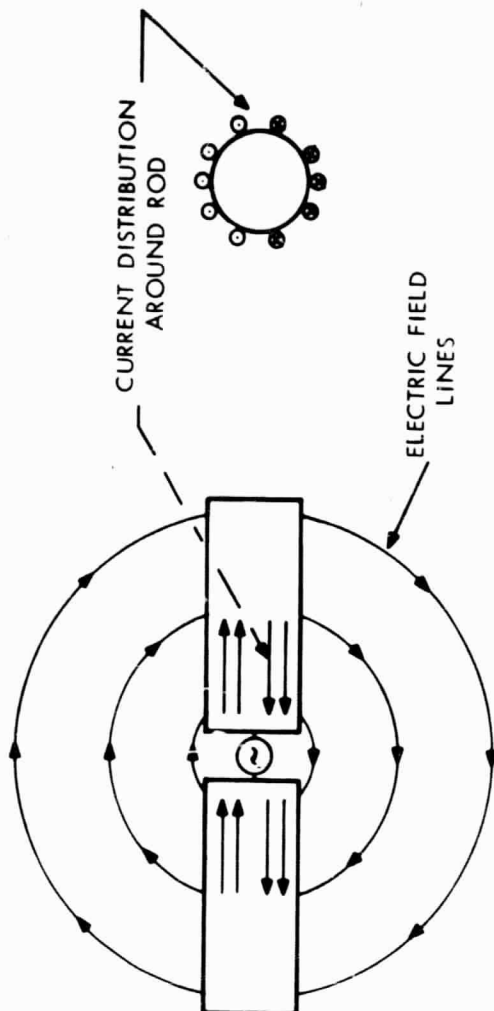


Figure 4-5. Current Distribution Diagrams

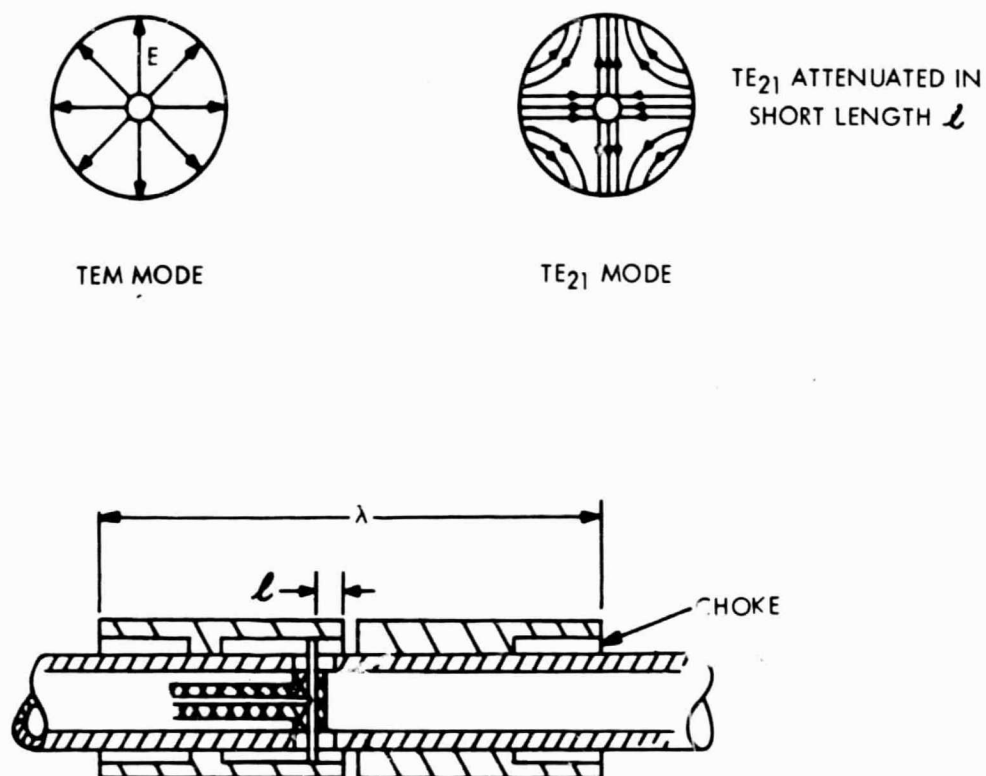


Figure 4-6. T-Feed Configuration

It should be noted that the  $TE_{21}$  mode is cut off in the dipole feed choke. However, because the cut-off region is extremely short ("1" in Figure 4-6), care must be exercised not to excite this mode. Fortunately, it was not excited with the T-feed. If it is, a three point excitation of the dipole would have been required.

#### 4.1.3.1 Pattern Optimization

The development program required to satisfy the pattern and gain requirements for the antenna was straight forward. An adjustable reflector assembly was designed and built, in which the height and position of the two reflectors relative to the feed assembly were adjustable. It was then a routine matter to optimize these parameters to obtain the specified azimuth plane beamwidth and gain characteristics at each band. The parabolic contour of the reflector had been initially calculated to give the desired beamwidth with a uniform illumination and to have a focal length of  $3/4\lambda$  as required for reflector/feed phasing as previously discussed.

The elevation beamwidth was, of course, determined by the electrical size of the two-element dipole array. An experimental feed assembly in which the gap between the two dipole halves as well as the spacing between the two dipoles themselves could be adjusted was used to optimize this parameter. It was found that a gap between the two halves of the dipole of 0.56 inch at 4.15 GHz and 0.35 inch at 6.26 GHz gave the best results. However, in the final configuration, these dimensions were altered slightly to optimize the impedance match with no significant effect upon the patterns.

It is worth noting that the optimum pattern was affected by several additional factors which influenced the overall electrical size of the array:

- 1) The design of chokes in the ends of the dipoles were found to be quite critical, as might be expected. Parasitic excitation of the feed support tube was influenced by this design.
- 2) Elevation plane pattern symmetry and beam squint were influenced somewhat by the design and position of the inter-element choke between the transmit and receive systems. This, too, is understood in terms of currents flowing along the support tube.
- 3) Similarly, the length of the dipole support tube extending beyond the top 4 GHz dipole as well as the extension of the reflector beyond the end of the feed assembly affected the transmit patterns. Because of limitations on the maximum height of the assembly, it was necessary to keep the reflector height to a minimum.

All of the above factors were optimized empirically using the experimental reflector/feed system described previously. The result of this effort was a pencil beam with very nearly equal principal plane beamwidths as indicated by the qualification mode test data found in subsection 5. 2.

#### 4. 1. 3. 2 Impedance Matching

In this particular antenna, the more difficult development problem was impedance matching. This program is discussed in the following paragraphs.

The initial approach to matching the antenna required three steps:

- 1) Each dipole was first matched to 50 ohms in the presence of the other. In this way, effects of mutual coupling were taken into account.
- 2) Second, with both dipoles driven, the pair of shunt elements was optimized to a 25-ohm line over the required 10% band.
- 3) A quarter-wave transformer was to be used to match the combination to 50 ohms.

Because of the small size of the RG-141 coaxitube used at 4 GHz, the fabrication of a mechanically and electrically satisfactory transformer proved to be an unrealistic goal. Therefore, the final design was achieved by matching the pair of elements directly to 50ohms, thereby eliminating the need for a quarter-wave transformer at 4 GHz. This design was both simpler and more reliable than the initial one.

The matching was primarily empirical aided by theory and intuition. The following parameters of the design were optimized experimentally to achieve the desired performance:

- 1) At 4 GHz, the major control over the dipole impedance was provided by varying the distance between the center line of the T feed to the plane of short circuits between the 4 GHz coaxitube tube and the I. D. of the feed support tube (see Figure 4-2). Reducing this distance reduces the series inductance of the dipole.
- 2) Decreasing the dipole gap and length by moving the dipole halves closer together than previously determined for optimum pattern performance served to tighten the impedance plot. Small changes in this parameter had substantial effect upon the impedance characteristic with but minor effect on the pattern.
- 3) At both bands, changing the depth of the T-feed chokes provided one of the major impedance controls. Increasing this depth reduces the real part of the impedance and the impedance cluster.

- 4) Reducing the diameter of the hole in the feed support tube through which the T-feed screw passes again reduces the real part of the dipole impedance while adding series capacitance, as would be expected. Reducing the hole in the teflon through which the 6 GHz T-feed screws pass had the same effect, though to a smaller degree.
- 5) The location of the T-feed screw in the dipole shell also influences the impedance character of the dipole. Specifically, increasing the distance from the T-feed to the edge of the dipole at the gap while maintaining a constant shunt susceptance (choke) depth behind the T-feed adds series inductance and increases the diameter of the impedance plot.

The effects of varying these parameters was the primary output of the initial matching program in which the impedance of each element was individually matched to 50 ohms. As mentioned, the final matching was done by working with both elements of the array, not individual elements. Consequently, the impedance characteristic of each element in the final design is not known. The schedule did not permit the academic investigation of this question.

However, the ease with which the matching was accomplished when approaching it as a pair of elements suggests that, rather than each element individually being matched to 100 ohms, the impedance characteristics of the two elements were simply made identical. Being located 1-1/2 wavelengths apart along the feed line, their reflections cancel. The situation is analogous to a double stub tuner in which one reflection is used to cancel another. However, in this case, the two mismatches have identical impedance plots. Consequently, the match is broadband.

There is one difference in the impedance matching systems used at 4 GHz and 6 GHz. At the 4 GHz transmit band, the coaxitube feeding the dipoles is 50 ohms. However, because of the restrictions imposed upon the diameter of the feed support tube which forms the 6 GHz receive band feed outer conductor, the impedance of this line is 32.2 ohms. Consequently, a quarter-wave matching transformer is required at the receive band to match to 50 ohms. This transformer, however, was not a problem because the diameters involved (a 0.141 inch center conductor and 0.305 inch outer conductor I.D.) are relatively large.

The 4 GHz coaxitube is terminated in a male OSM connector. A female GSM connector mates at right angles to the 6 GHz line. The RG-141 coaxitube serves as a quarter-wave matching stub for this 6 GHz transition, as shown in the feed assembly drawing of Figure 4-2.

Between the 6 GHz and 4 GHz sections of the feed system is a short circuit used to terminate the 6 GHz line a quarter wavelength beyond the second 6 GHz T-feed. This short provides a high impedance (open circuit) at the T-feed itself.

The pattern bandwidth for the antenna system as specified was approximately 2% at both the transmit and receive bands. The impedance bandwidth was specified as 10%. Although the original intent was to center this 10% band around the pattern band in each case (the frequency limits of the impedance band were unspecified), the schedule did not allow this to be done. Rather, at the time, the customer had requested a schedule acceleration. Consequently, the design was frozen when the specified match had been achieved over a 10% band that included the pattern band in each case.

#### **4.1.4 Final Performance Summary**

##### **4.1.4.1 Patterns**

Typical azimuth and elevation patterns at the transmit and receive frequencies, respectively, are found in Figures 4-7 through 4-10. These data were obtained on the experimental model reflector-feed assembly described previously. (Final data on the qualification and flight models is found in Section 5.) They serve as the basis for the discussion that follows.

It is observed from these patterns that at both bands, the azimuth plane side lobe level is high. As noted before, the illumination function across the reflector in this plane is approximately uniform. This fact dictates 13.5-db first sidelobe level from a rectangular aperture. The data, however, shows a typically 10-db sidelobe level at the transmit band and 12 db at the receive frequency. The following discussion is not intended to explain an exact sidelobe level; but it is only intended to give qualitative reasons why this sidelobe level is poorer than would normally be expected.

With a uniform aperture illumination, the radiation pattern is ideally of the form  $\sin X/X$ . For this characteristic, the first null in the radiation pattern is nearly at two beamwidths ( $20^\circ$  off axis). The peak of the first sidelobe level for this case, then, should be at  $30^\circ$ .

However, the pattern data at both bands has a filled-in null, not a sidelobe peak at  $30^\circ$ . Instead, there is one broad sidelobe with a peak at approximately  $50^\circ$  off-axis. This is, for a  $\sin X/X$  radiation characteristic, where the second sidelobe peak should be.

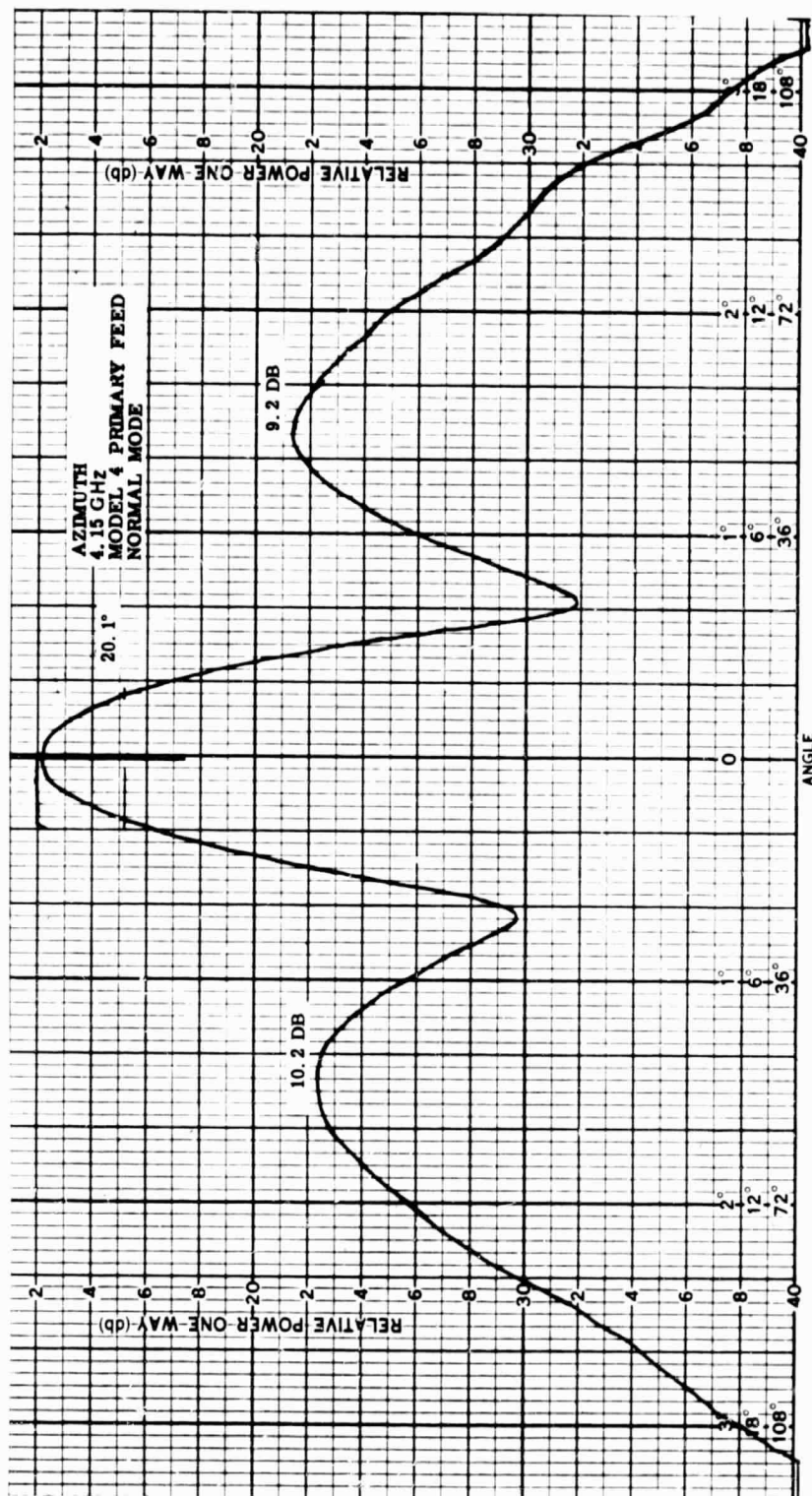


Figure 4-7. 4 GHz Azimuth Pattern

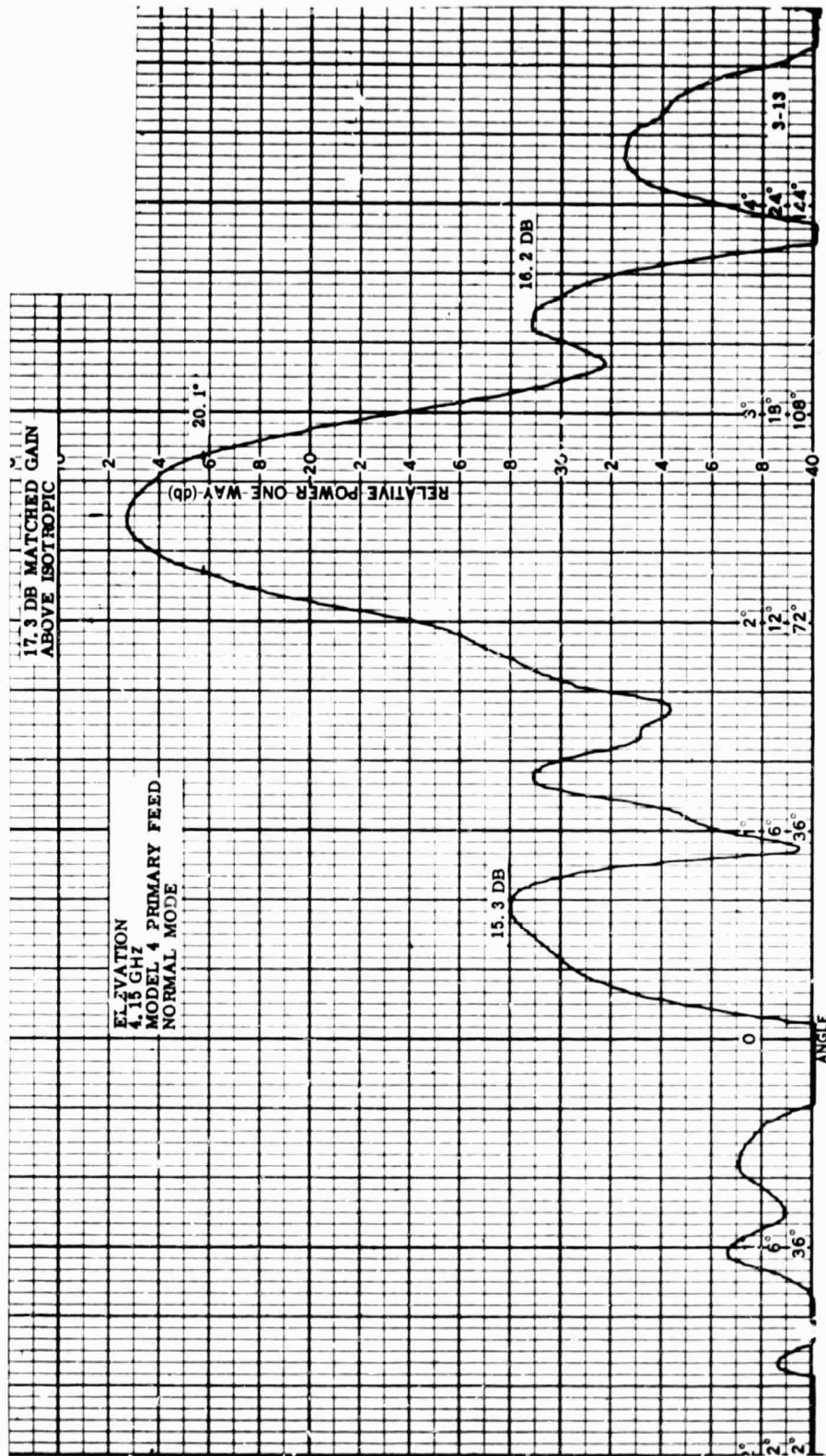


Figure 4-8. 4 GHz Elevation Pattern

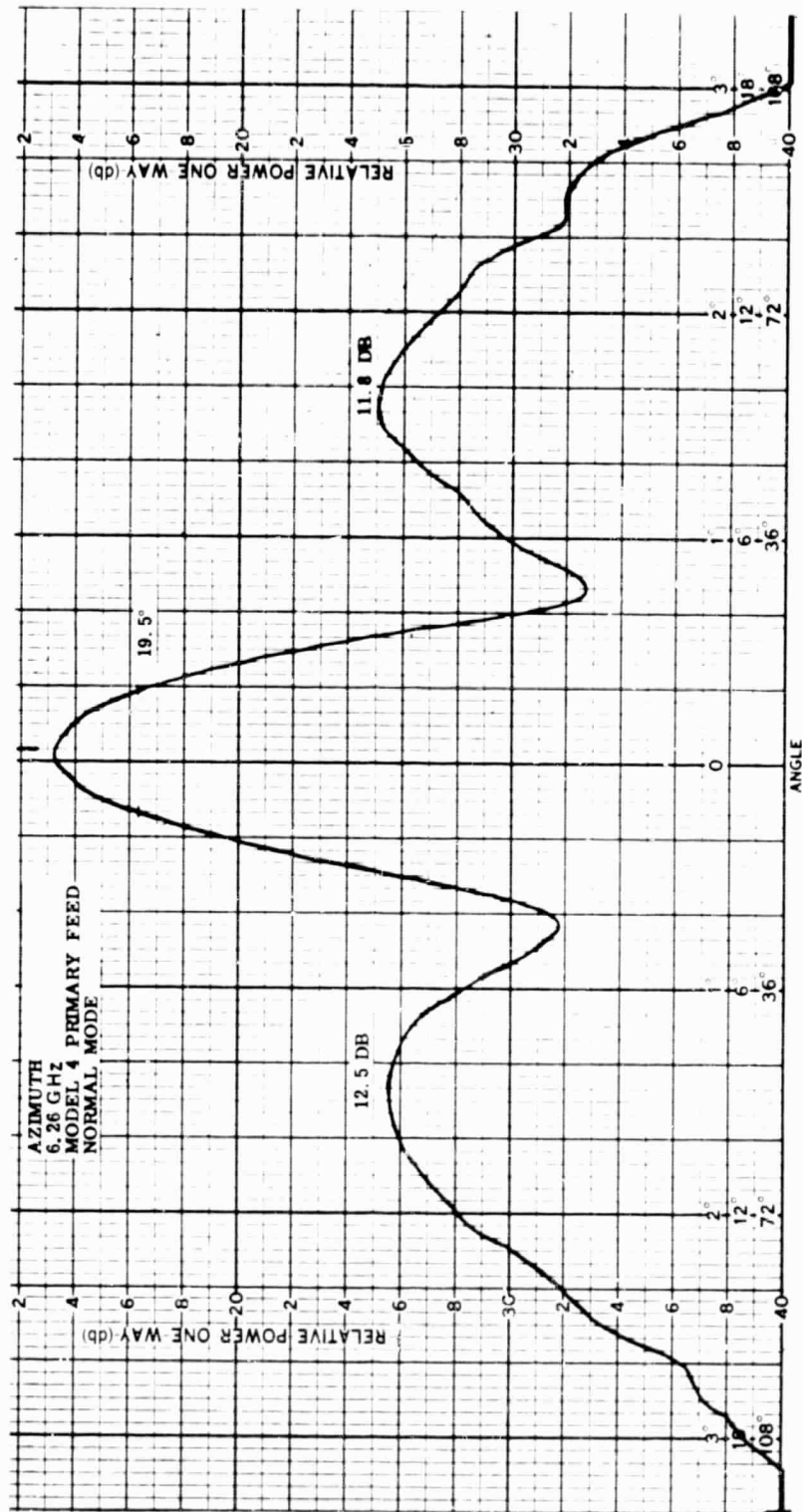


Figure 4-9. 6 GHz Azimuth Pattern

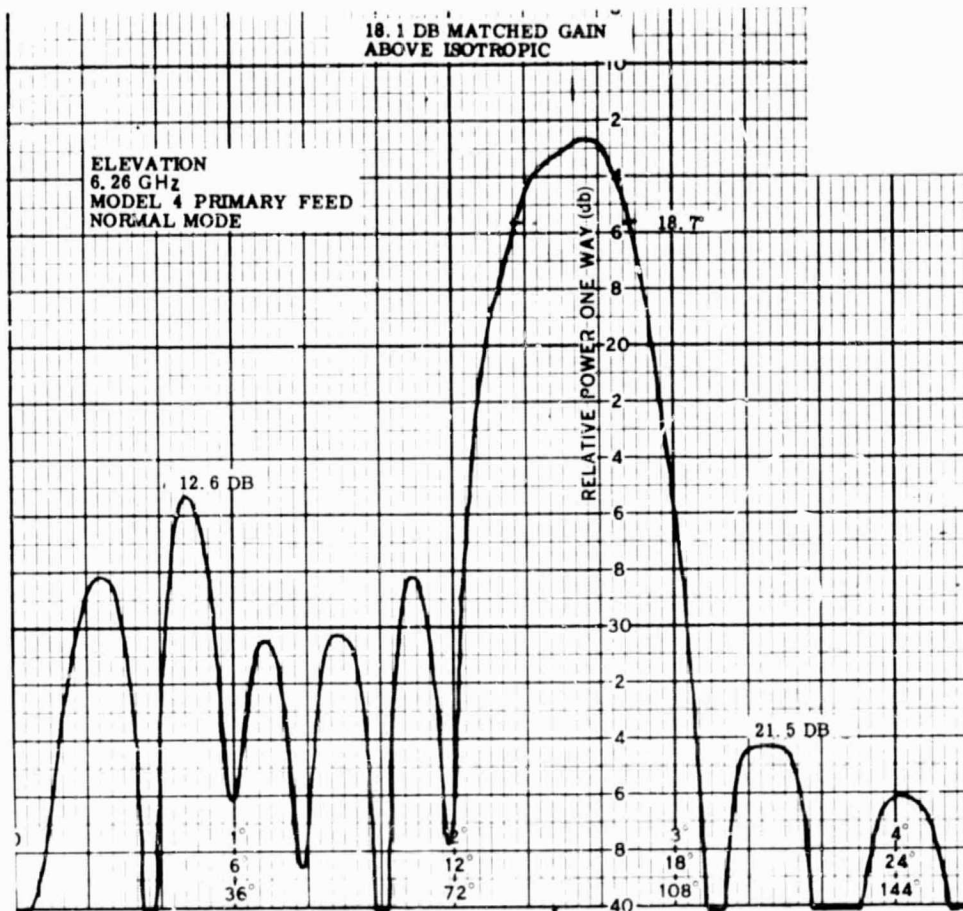


Figure 4-10. 6 GHz Elevation Pattern

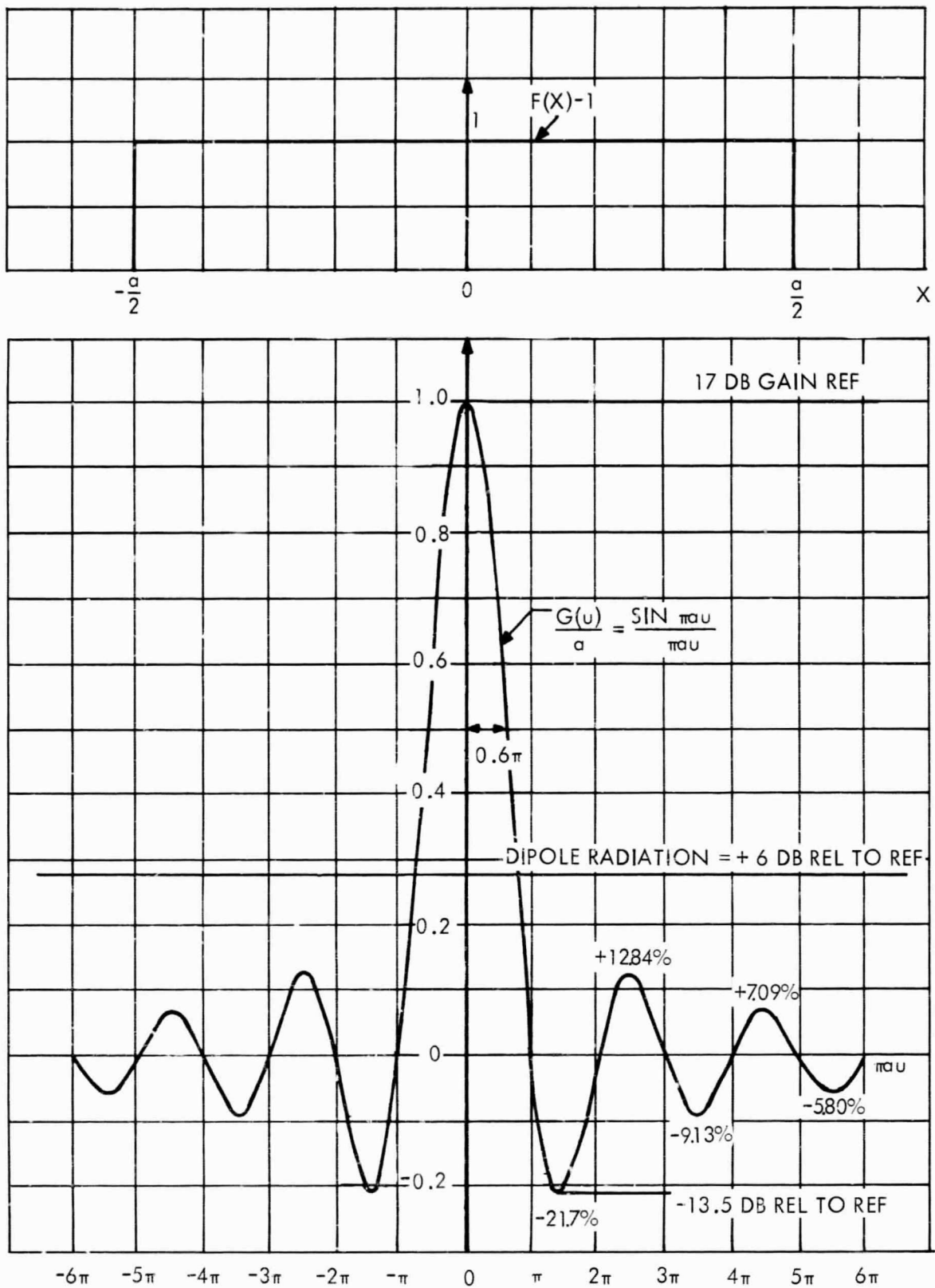
The explanation of the azimuth plane sidelobe level characteristic is believed to lie primarily in the effects of the omni-directional radiation characteristic of the primary feed in that plane. The situation is depicted in Figure 4-11. As shown in this figure, the peak gain of the full aperture is nominally 17 db. In the azimuth plane, the feed pattern, which has a gain of about 6 db, is omni-directional.

Now the first sidelobe is  $180^\circ$  out-of-phase with the main beam while the second sidelobe is in-phase with it. Consequently, from the above discussion, the feed radiation at the angle of the first sidelobe will tend to cancel the -13.5 db first sidelobe, and add to the normally -18 db second sidelobe. On this basis, the second sidelobe level would be approximately -8 db. However, since the feed and antenna aperture have different phase centers, the two signals do not add directly in-phase. Also recognizing that there is a variation of  $\pm 1$  db in the omni-directional feed pattern, 10-db to 12-db sidelobes at  $50^\circ$  off-axis are to be expected.

While this analysis is primarily qualitative, it does provide a general explanation of the azimuth plane pattern characteristic. From this analysis, a minimum would be expected at the angle of the first sidelobe and a maximum at the angle of the second sidelobe ( $50^\circ$ ), as observed in practice.

There are, of course, factors other than those considered above which influence the pattern in detail. For example, the relatively fat feed undoubtedly causes some defocusing in the antenna aperture analogous to spherical aberration. However, the predominant factor is believed to be the effect of the off-axis feed radiation which accounts, at least qualitatively, for the azimuth plane pattern characteristics.

In general, it is observed from the data that the elevation plane sidelobes are better than those that would be expected from a uniformly illuminated rectangular aperture. This is undoubtedly because the illumination in the elevation plane is not uniform, but tapered. Although the two dipoles in each elevation plane array are excited equally, the physical size of this array is slightly over two wavelengths. However, the elevation plane beamwidth indicates an aperture that is at least three wavelengths long. The electrical size of the array is not determined only by the two, full-wave dipoles, but also by the parasitic excitation of the feed support structure. This excitation, it will be recalled, was also evident in the behavior of the feed impedance. The total elevation plane array, then, does have a tapered illumination.



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Figure 4-11. Azimuth Sidelobe Analysis

It is noted that on one side of the pattern, far out sidelobes are worse than those close to the main beam. This is particularly true at the 6 GHz receive band. The explanation lies in the effects of the antenna structure on the elevation plane pattern. Specifically, the motor housing and ground plane on which the reflector assembly is mounted cause the sidelobe distortions noted. Because the 6 GHz receive system is closer to these structural parts, it receives the major effect.

A word is in order about cross-polarized energy. Theoretically, cross-polarized energy can be zero from a rectangular aperture. In practice, it is limited by the mechanical and electrical symmetry of the antenna system. The amount of cross-polarized energy present is an indication of how well the antenna was built. Final data on the deliverable hardware shows that it is normally down more than 40 db.

#### 4.1.4.2 Impedance

Final impedance plots measured on the development model feed are found in Figures 4-12 and 4-13 for the transmit and receive bands, respectively. The dotted portion of the curve is outside the acceptance test limits.

As will be observed, most of the impedance characteristic falls within a 1.25:1 VSWR circle, the original design goal. The final specification was 1.35:1 at the transmit band and 1.45:1 at the receive band. The somewhat-better-than-required performance of the development model provided a margin in the fabrication of the feed assembly.

#### 4.1.5 Power Breakdown Considerations

At low pressure, antennas are susceptible to voltage breakdown.\* When such breakdown occurs, the observed effect is four-fold: the radiated power decreases, the radiation pattern changes, the input impedance changes, and, in the case of pulse modulation, the pulse shape changes.

Studies of RF breakdown show that a minimum breakdown voltage exists where the electron collision frequency in the air is approximately equal to the radio frequency. This may be expressed by:

$$P_{\text{Torr}} = f_{\text{GHz}}$$

\*Space Materials Handbook, second edition, page 416, Technical Document Report No. ML-TDR-64-40, January 1965, AF Materials Laboratory, Research and Technology Division, Air Force Systems Command-Wright Patterson Air Force Base, Ohio. Prepared by Lockheed Missiles and Space Co.

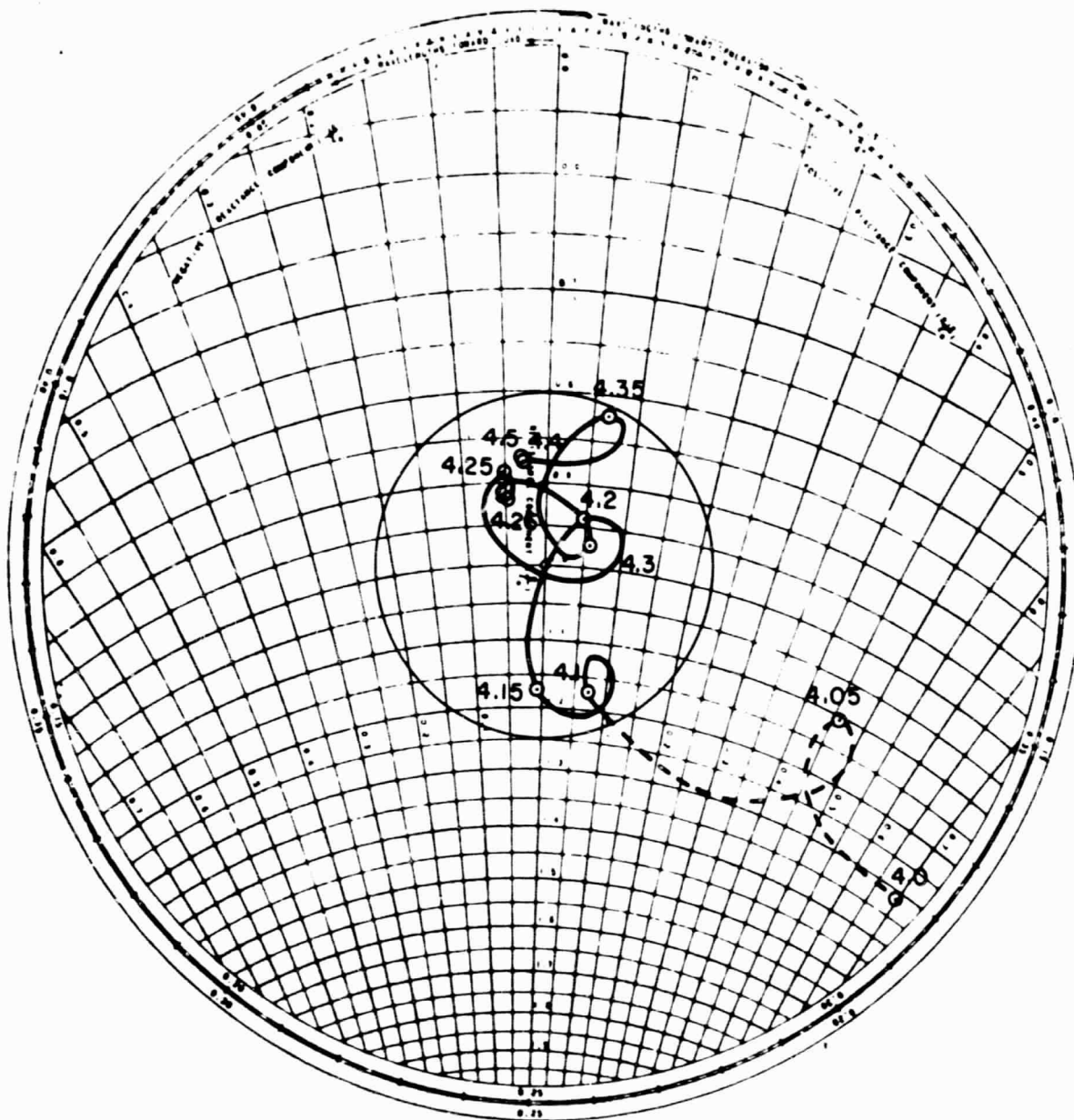


Figure 4-12. Final Impedance Plot - Transmit Band

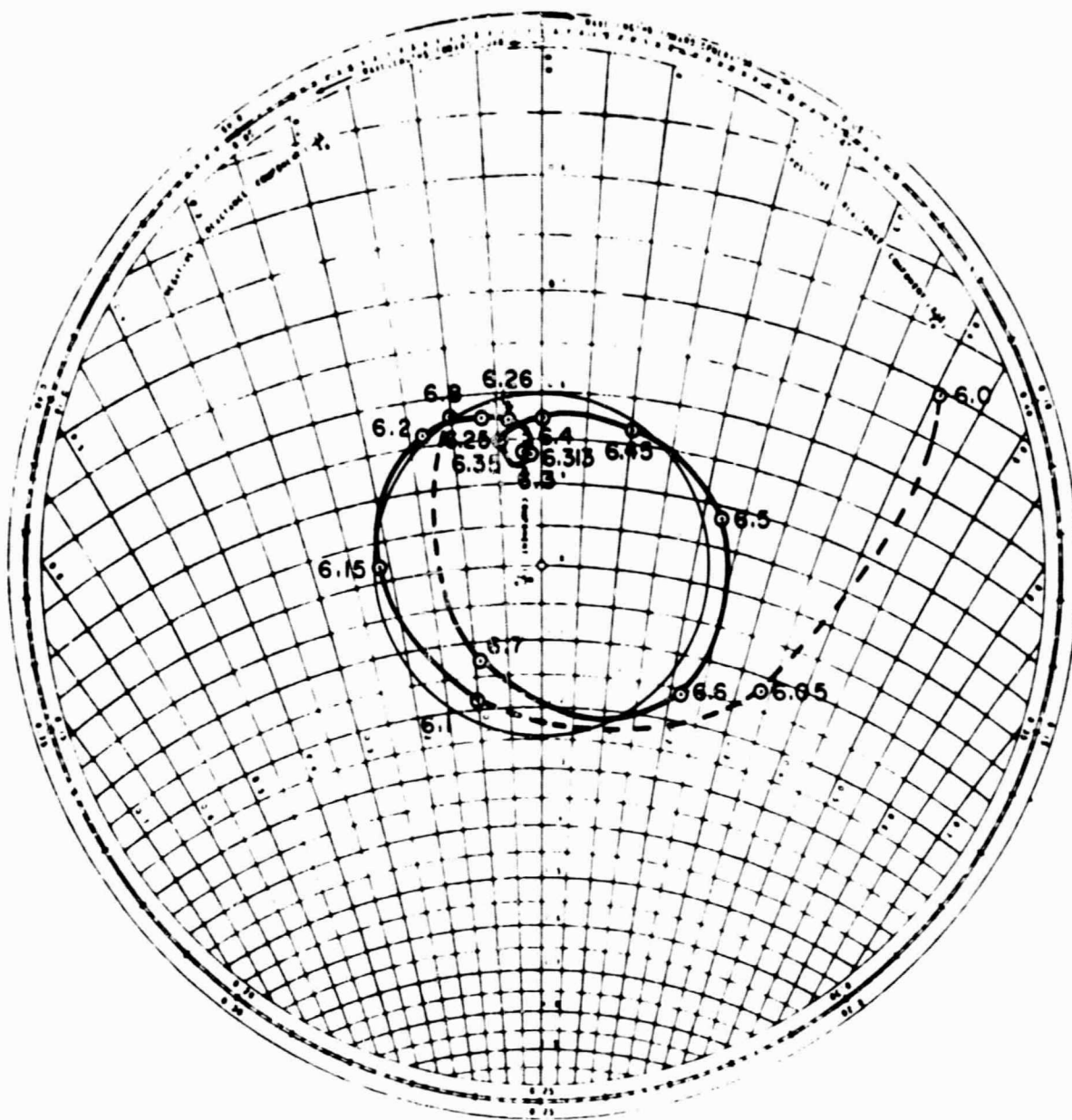


Figure 4-13. Final Impedance Plot - Receive Band

That is, the minimum breakdown condition corresponds to the pressure measured in Torr being equal to the radio frequency measured in gigahertz. The power at which breakdown occurs is a function both of the radio frequency and the antenna geometry. The theoretical minimum electric field strength at which breakdown will occur is

$$E/P = 165V/cm-Torr$$

Experimental results obtained by measurements on a wide variety of antennas have verified this formula. Generally, antenna breakdown will not be a problem on satellites and space vehicles.

Specifically, the point limiting breakdown in the RF feed is between the RG-141 coaxitube outer conductor and the T-feed block in the center conductor subassembly (see the RF feed assembly drawing, Figure 4-2). The gap at this point is nominally 0.022 inch. Using the above formula and assuming an orbit atmospheric pressure of  $10^{-10}$  Torr, the minimum electric field strength at which breakdown could occur is 92 volts.

Assuming 12 watts of RF power at each of the 4 GHz dipole T-feeds (24 watts total input power), and a VSWR of 2:1 relative to 50 ohms, at each T-feed, the electric field across the subject gap is 34.6 volts. This figure represents a safety factor in orbit of 2.6:1.

However, it should be pointed out that during ascent of the vehicle, the critical 4-Torr pressure for breakdown will be reached. Therefore, the RF transmitter must not be turned on until the satellite is in final orbit.

## 4.2 CONTROL ELECTRONICS

Two control systems were developed for the ATS Mechanically Despun Antenna. The initial program required a positioning loop to be provided which would automatically maintain the beam pointing toward the earth. Development of this design, called the Mark I control system, was successfully completed including final packaging. A complete, packaged qualification model control system was built to this design.

After a firm decision had been made to fly the Mechanically Despun Antenna, complete redundancy was desirable. Therefore, to provide this redundancy with a minimum weight and power drain, the automatic digital positioning loop was eliminated from the control system. In this (Mark II) design, positioning capability is provided through ground command. The elimination of the positioning loop and the provision of complete redundancy are the two basic differences between the Mark I and Mark II control system. The Mark II system is the one actually delivered in the flight hardware.

In this subsection, the Mark II control system is described in detail. In addition to the theory of operation, the design of the basic circuits is described. At the end of the section is a brief description of the Mark I control system block diagram with the automatic digital positioning loop.

#### 4.2.1 Mark II Control System

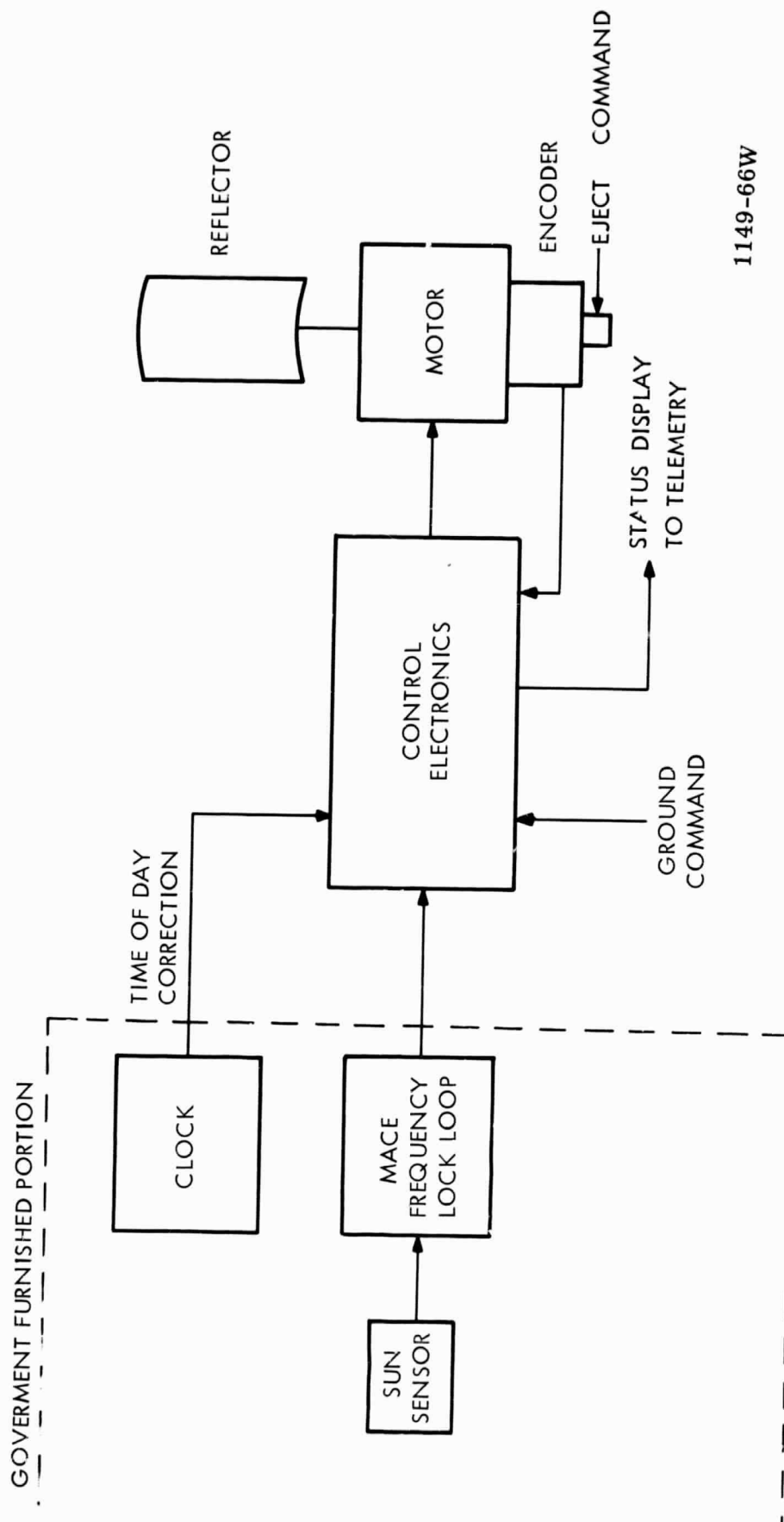
##### 4.2.1.1 Overall System Block Diagram

A simplified system block diagram is shown in Figure 4-14. The complete control system consists of a frequency lock loop provided in the satellite, the control electronics, the drive motor/encoder assembly, a clock and a directional Command System. The principle of operation is as follows: For each revolution of the satellite, the sun sensor generates one pulse which is used as the timing pulse for the MACE frequency lock loop. This circuit is a digital servo loop which consists of a voltage controlled oscillator, an integrator, an error detector and a binary counter. The output of the frequency lock loop is a 512 cycle/revolution square wave, coherent with the sun sensor pulse. The frequency of the square wave is proportional to the satellite rotational velocity. In essence, the FLL is a frequency multiplier delivering a coherent signal having 512 pulses/revolution.

In the control system the 512 cycle/revolution output of the frequency lock loop is counted down to 128 cycles/revolution for operation with the 128 step synchronous stepping motor used to despin the reflector. This signal drives the logic circuitry to generate the proper phase sequence for the synchronous motor. The motor speed, being fixed by the frequency, is exactly equal to the satellite speed but the motor rotates in the opposite direction. Consequently, the antenna beam stands still in space. The stepping motor having a large inertia attached to its shaft operates in the slew mode; thus a smooth operation is obtained over the design speed range of 50-150 RPM.

Circuitry is provided in the control system to position the antenna reflector to any direction by ground command.

The overall control system includes a fail-safe mode in which the antenna reflector can be jettisoned by ground command and communications maintained with an azimuthal omni-directional antenna having a 5-db to 6-db gain. Squibs for this operation are provided in the structure. The firing circuitry is part of the control electronics.



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Figure 4-14. Overall System Block Diagram

#### 4. 2. 1. 2 Mark II Control Electronics Block Diagram

The Mark II Control System block diagram is shown in Figure 4-15. The system is designed with dual redundancy, with the exception of the motor and shaft encoder, to increase its reliability. To keep the complexity and the power drain to a minimum, no antenna-pointing angle telemetry is included in the system. The electronics consists of two separate open loop control systems. One system is powered; the other is on standby. To change the antenna position, a temporary frequency change of the drive signal is required. This is accomplished by the directional command circuit. An appropriate number of pulses of the frequency lock loop signal are added or subtracted, depending in what direction the antenna is to point. The two commands required to accomplish this are called:

Directional Command - It determines the direction (left or right-hand turn) of the correction to be applied.

Incremental Command - It determines how many pulses are to be added or subtracted. For example, 256 pulses cause an antenna-pointing angle change of 180°.

Another function of the directional command circuit is to execute the "time of day" correction required to compensate for the earth rotation, since the system reference is the sun.

The motor is a vernier-synchronous type and is not self-starting in the speed range of 50 to 150 RPM. It is started with a special starting circuit at reduced frequency and then gradually increased to the actual satellite speed. Equality of the speed is then sensed by the starting circuit, and the lock loop signal is transferred to the motor input.

In the paragraphs that follow, the operation of the basic circuits and components in the block diagram is described starting with the motor itself.

##### The Motor

The design speed range for the motor is 50-150 RPM. This is a very low speed for a synchronous machine, as can be seen from the following brief analysis. The driving frequency for a synchronous motor is determined by:

$$f = \frac{p \cdot n}{60}$$

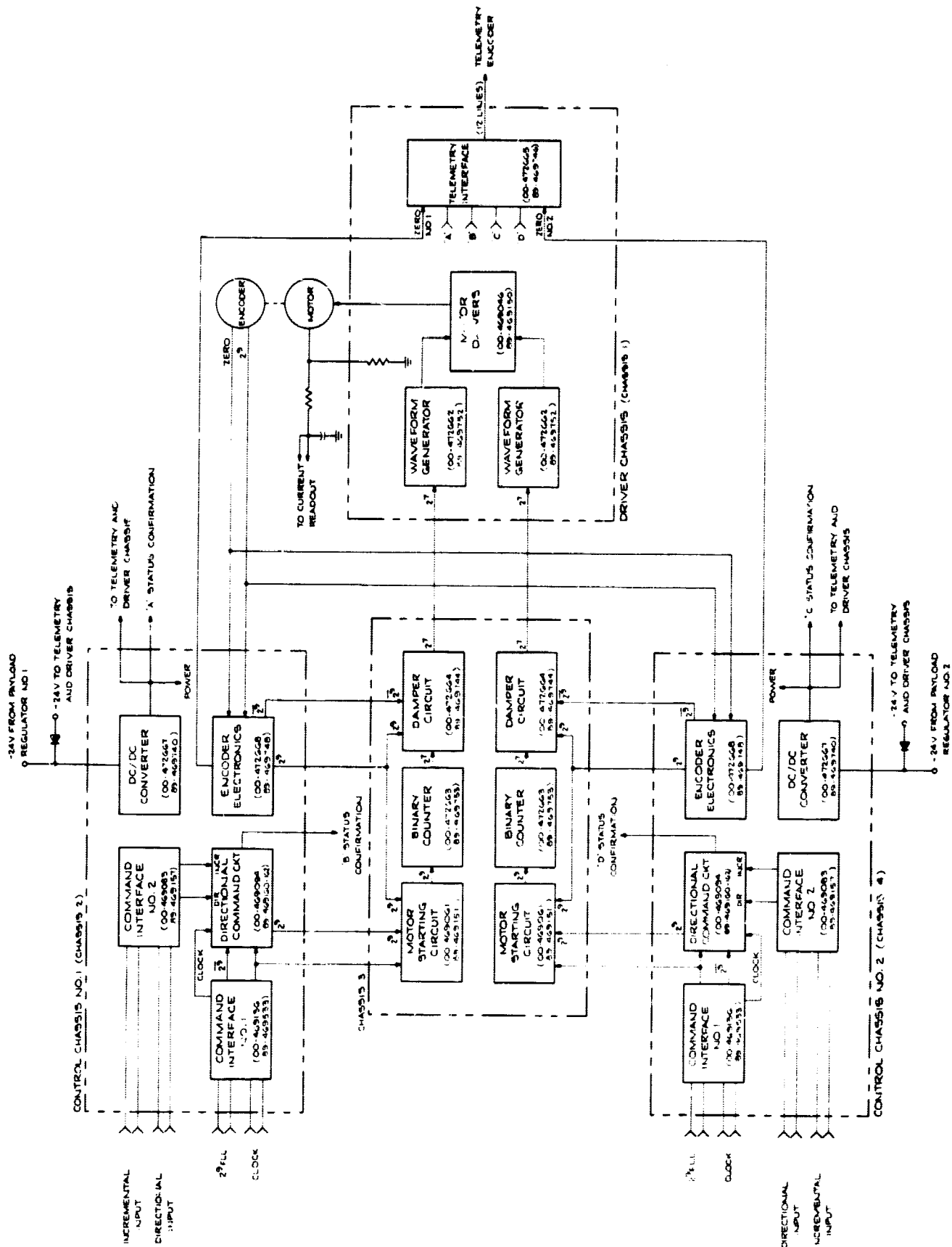


Figure 4-15. Mark II Control System Block Diagram

where  $p$  is the number of pole pairs,  $n$  is the motor speed in RPM. Assuming a two-pole motor ( $p = 1$ )

$$f_{\min} = \frac{50}{60} = 0.834 \text{ Hz}$$

and

$$f_{\max} = 3 \times 0.834 = 2.5 \text{ Hz}$$

The general machine equation, used to calculate the number of field winding turns required for a particular frequency, is

$$E_{\text{RMS}} = 44.44 \times f \times N \times \Phi_{\max} \times 10^{-8}$$

where  $E_{\text{RMS}}$  is the terminal voltage (V)

$f$  is the frequency (Hz)

$N$  is the number of turns

$\Phi_{\max}$  is the maximum air gap flux (Maxwell).

As can be seen from the equation, the number of turns required is inversely proportional to the frequency. A two-pole machine operated at a frequency of 0.834 Hz would require a very large number of turns. The result would be that the copper losses would run very high. This results in a low machine efficiency. To solve this problem, the number of poles must be increased. There is, however, a physical limitation on how many poles may be put on a given motor diameter.

Three basic types of synchronous motors are available for the design. Each type has its own merits.

The first type is the cylindrical rotor type, such as the hysteresis synchronous motor. The advantage of this motor type is that it is self-starting. A disadvantage for this application is that this motor has no magnetic detent torque. This would cause a problem in the control system, since a digital control system is used.

The second type is the salient pole type synchronous machine. The advantage of this motor is that a magnetic detent torque is present; the disadvantage is that it is not self-starting.

The third type is the vernier or stepping motor. This motor is equivalent to a salient pole synchronous motor with an electrical gear reduction. Various forms of this motor exist. One type has different numbers of rotor and stator teeth. Another version has two parallel stators with a rotational offset between the two stators.

The vernier type motor has the advantage that for a given air gap diameter the highest number of equivalent poles may be put into the machine. Its disadvantage is that it is not self-starting when supplied with a drive signal of the operating frequency. This type of motor was chosen because it provided the largest number of equivalent poles for a given air gap diameter.

Figure 4-16 shows stator and rotor arrangement. The two stators are assembled with an offset of one half of a tooth. The rotor consists of a cylindrical permanent magnet, axially magnetized. Two endbells with 32 teeth are attached to the permanent magnet. The two endbells have an offset of one quarter of a tooth. The pulsing of the motor windings proceeds in the following sequence:

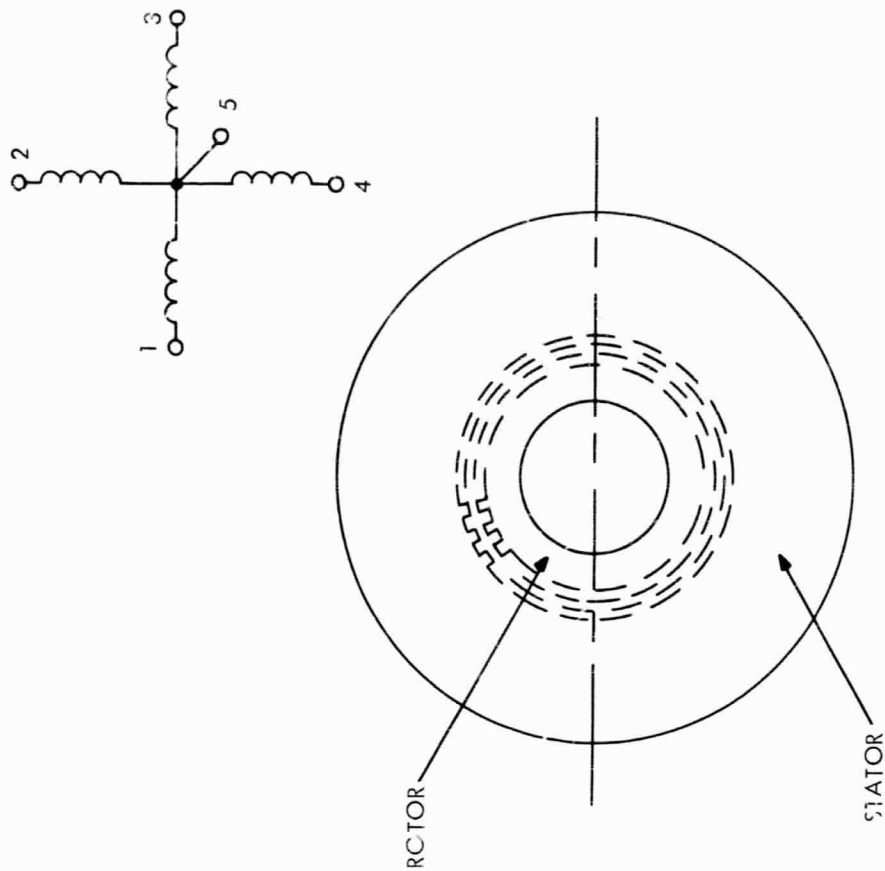
|        | Winding No. | 1 | 2 | 3 | 4 |
|--------|-------------|---|---|---|---|
| Step   | 1           | 1 | 1 | 0 | 0 |
|        | 2           | 0 | 1 | 1 | 0 |
|        | 3           | 0 | 0 | 1 | 1 |
|        | 4           | 1 | 0 | 0 | 1 |
| repeat |             |   |   |   |   |

The rotor advances by one quarter of a tooth with each step. If the stepping rate is slow enough, the motor follows instantaneous start and stop commands. This mode, the stepping mode, of operation is used to start the motor. The frequency of pulsing is then gradually increased at a rate which the motor with its inertial load can follow.

In the design speed range of 50 to 150 rpm the motor is operating in the slew mode. In this mode no stepping of the rotor is observed. The load inertia acts as a filter to smooth the rotation.

#### The Shaft Encoder

To obtain continuous antenna position information, a shaft encoder is attached to the motor shaft. The encoder used is an incremental type operating on a variable reluctance principle. In essence, the encoder is a generator generating 512 sine wave cycles per



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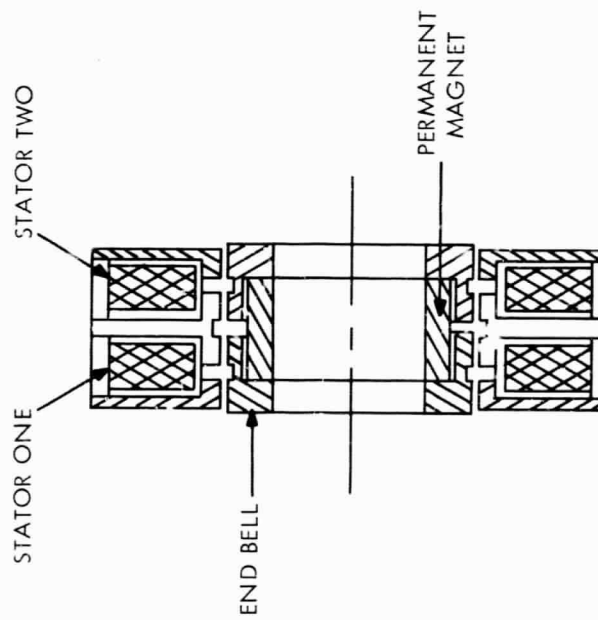


Figure 4-16. Rotor and Stator

revolution in one channel and a single reference pulse in another channel. The reference pulse occurs at boresight of the antenna reflector.

### The Encoder Electronics

Figure 4-17 shows the schematic diagram of the encoder electronics. The purpose of the encoder electronics is to change the sinusoidal count channel signal of  $2^8$  cycles/revolution to a square wave of the same frequency. The encoder zero reference pulse, which also contains sinusoidal noise output, is conditioned in another channel of the encoder electronics.

The encoder  $2^9$  count output is filtered by a low-pass filter network consisting of the resistors R3 and R4 and the capacitors C5 and C6. This is done to remove motor field spikes which are coupled from the motor field into the encoder magnetic circuit. The resulting cleaned sine wave having an amplitude of approximately 0.5V P-P is amplified by a monolithic operational amplifier Texas Instrument Type SN524A. The amplifier has a gain of approximately  $10^5$  to  $10^6$ . The input signal overdrives the amplifier in both directions. The resulting output waveform is a sharp square wave. The output swing is attenuated by the voltage divider R5 and R6 so that the input voltage limitation of the following SG40 gate is not exceeded. The SG40 gate is a dual unit and is used as a dual inverter. The outputs are  $2^9$  and  $\bar{2}^9$  which are used to drive the clamper circuit. In the Mark II control system, the encoder serves only as a tachometer for damping of the motor. No position data are generated.

The zero reference channel output is also sharpened by another operational amplifier. No filter network is required in this channel. The operational amplifier is unsymmetrically biased by R9 and R10 to eliminate the noise output contained in the reference channel. The amplifier output is also attenuated, is for the count channel, by R7 and R8. Its output is used during the system test.

The amplifiers are powered by +12V and -12V. Both voltages are decoupled to avoid power supply ripple from being amplified by the operational amplifiers. The zero reference channel is powered by inserting jumpers between A - C and B - D. After the test has been completed, the jumpers may be removed to conserve power.



## Damper Circuit

Without the damper circuit, stable operation of the synchronous motor is impossible as shown by the following considerations.

The equation of motion of a synchronous motor is:

$$J \frac{d^2\theta}{dt^2} + F \frac{d\theta}{dt} + K_1 \sin \theta + K_2 \sin 2\theta = T_L$$

where

$J$  = Load inertia

$F$  = Friction constant

$K_1$  = Peak magnetic torque

$K_2$  = Peak reluctance torque

$T_L$  = Load torque

$\theta$  = Load angle

This is a non-linear equation. It is common practice to linearize the equation and solve it for small angles. The simplified equation in Laplace operator form is

$$J\theta S^2 + F\theta S + K\theta = T_L$$

or in standard form

$$(S^2 + 2W_n S + W_n^2)\theta = T_L$$

where

$$\frac{F}{J} = 2\zeta W_n \text{ and } \frac{K}{J} = W_n^2$$

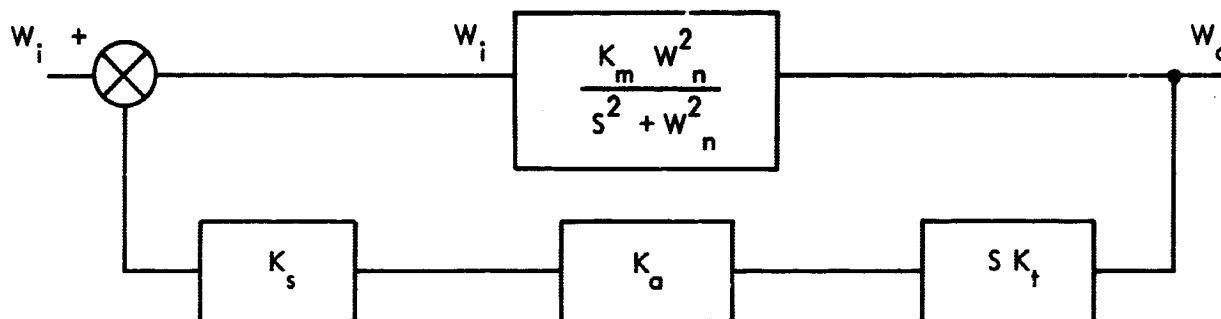
$\zeta$  = damping ratio and  $W_n$  = natural frequency

The time domain solution of this equation is an exponentially decaying sinusoid if  $\zeta > 1$ . In the case of  $\zeta = 0$ , a sustained sinusoid is the result. In this particular motor,

the damping ratio is very small ( $\zeta \approx 0.005$ ).<sup>\*</sup> Any disturbance will cause a load angle oscillation to build up until the motor falls out of synchronism and stalls.

The damper circuit, Figure 4-18, consists of three basic subcircuits; a tachometer circuit, an AC amplifier and a pulse position modulator. The purpose of the damper circuit, in conjunction with the shaft encoder whose output serves as a tachometer signal, is to form a tachometer feedback loop around the motor to stabilize the motor speed. The following brief analysis shows how a completely unstable motor can be stabilized.

Analysis of the Tachometer Feedback Loop



$W_n = 12.56$  (measured) Angular natural frequency

$K_m = 1/32$  (since the motor has 32 pole pairs) Motor gain constants

$K_t = 1.06$  V/rad/sec (measured) Tachometer gain constant

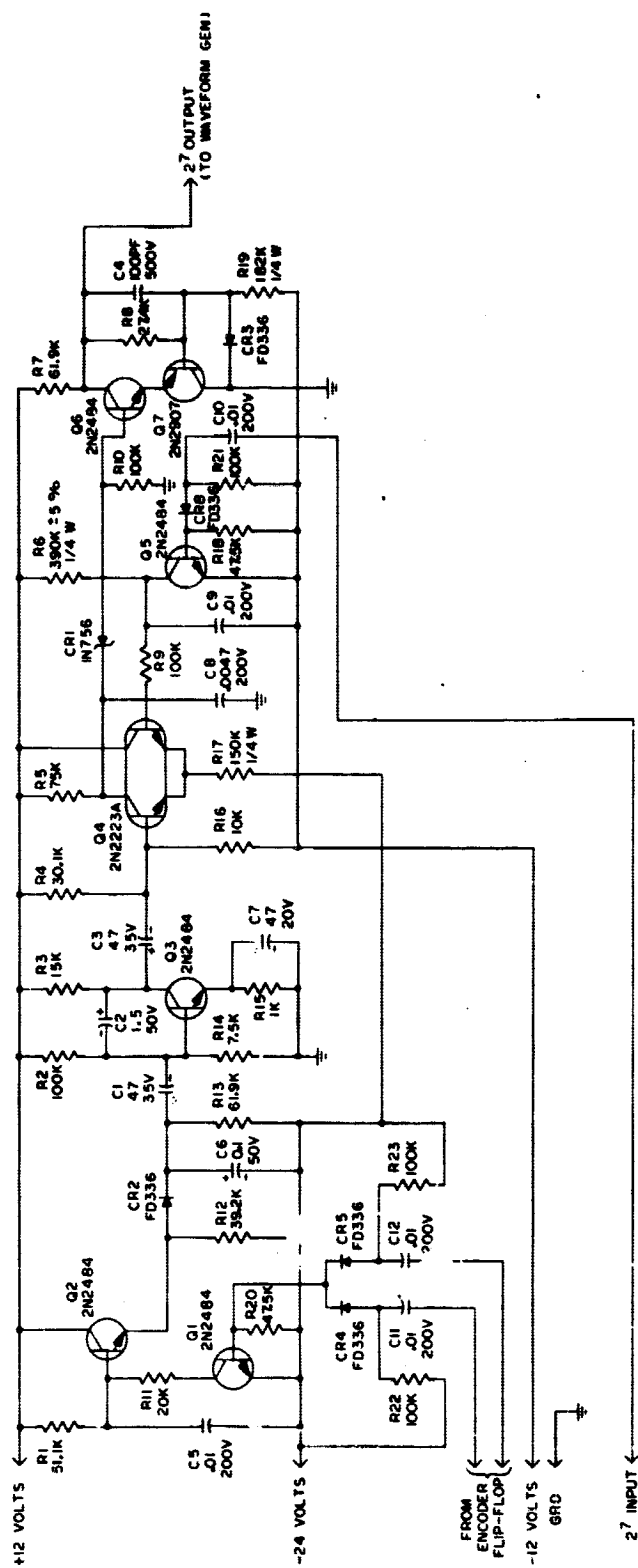
$K_a = 15$  V/V amplifier gain (calculated)

$K_s = 0.198$  rad/sec/V pulse position modulator gain (measured)

$$1 + HG = 0$$

$$1 + \frac{K_m W_n^2 K_s K_a K_t s}{s^2 + W_n^2} = 0$$

<sup>\*</sup> Strictly considered,  $\zeta$  is nonlinear and might become negative; even though very small, it would then start the oscillation due to field pulsations.



NOTES:  
1. UNLESS OTHERWISE SPECIFIED,  
ALL RESISTANCE VALUES ARE IN OHMS, 21/2%, 1/8W.  
ALL CAPACITANCE VALUES ARE IN MICROFARADS.

Figure 4-18. Damper Circuit, Schematic Diagram

$$1 + \frac{1/32 \times 158 \times 0.198 \times 15 \times 1.06S}{S^2 + 158} = 0$$

$$S^2 + 15.55S + 158 = 0$$

$$S^2 + 2W_n S + W_n^2 = 0$$

Identifying:

$$2\zeta W_n = 15.55$$

$$\zeta = \frac{15.55}{2 \times 12.56} = 0.617$$

$$\zeta = \underline{0.617}$$

This damping ratio has been verified in the operating system. In the foregoing analysis, simplifying assumptions have been made. The AC amplifier has been treated as if it had infinite bandwidth. However, in the frequency range ( $W = 12.56$ ), the errors are very small and there are negligible.

As shown, a damping ratio of 0.617 can be obtained with total loop gain of 0.985.

The tachometer portion of the damper circuit operates as follows:

The basic tachometer circuit consists of an RC sweep circuit followed by a diode peak detector. The timing waveform for the sweep circuit is taken from the shaft encoder electronics. The period of this waveform is inversely proportional to the motor speed. Figure 4-19 shows the waveforms of the damper circuit. The  $2^9$  and  $2^9$  square waves are frequency modulated according to the speed variations. These two square waves are differentiated by C11, R22 and C12, R23, respectively. The positive going differentiator outputs are combined by the buffer diodes, CR4 and CR5. The result is a pulse train of double frequency or  $2^{10}$  pulses/revolution.

The transistor Q1 serves as a discharge switch for the integrator R1, C5. Pulsing of the transistor Q1 by the  $2^{10}$  pulse train will cause periodic discharge of C5 by an amount determined by the value of R11 and the duration of the discharge pulse. The resistor R20 serves as a reverse bias resistor to avoid turn-on of Q1 during the interpulse period due to leakage current.

HORIZONTAL SCALES BETWEEN CARRIERS AND MODULATION ARE EXAGGERATED

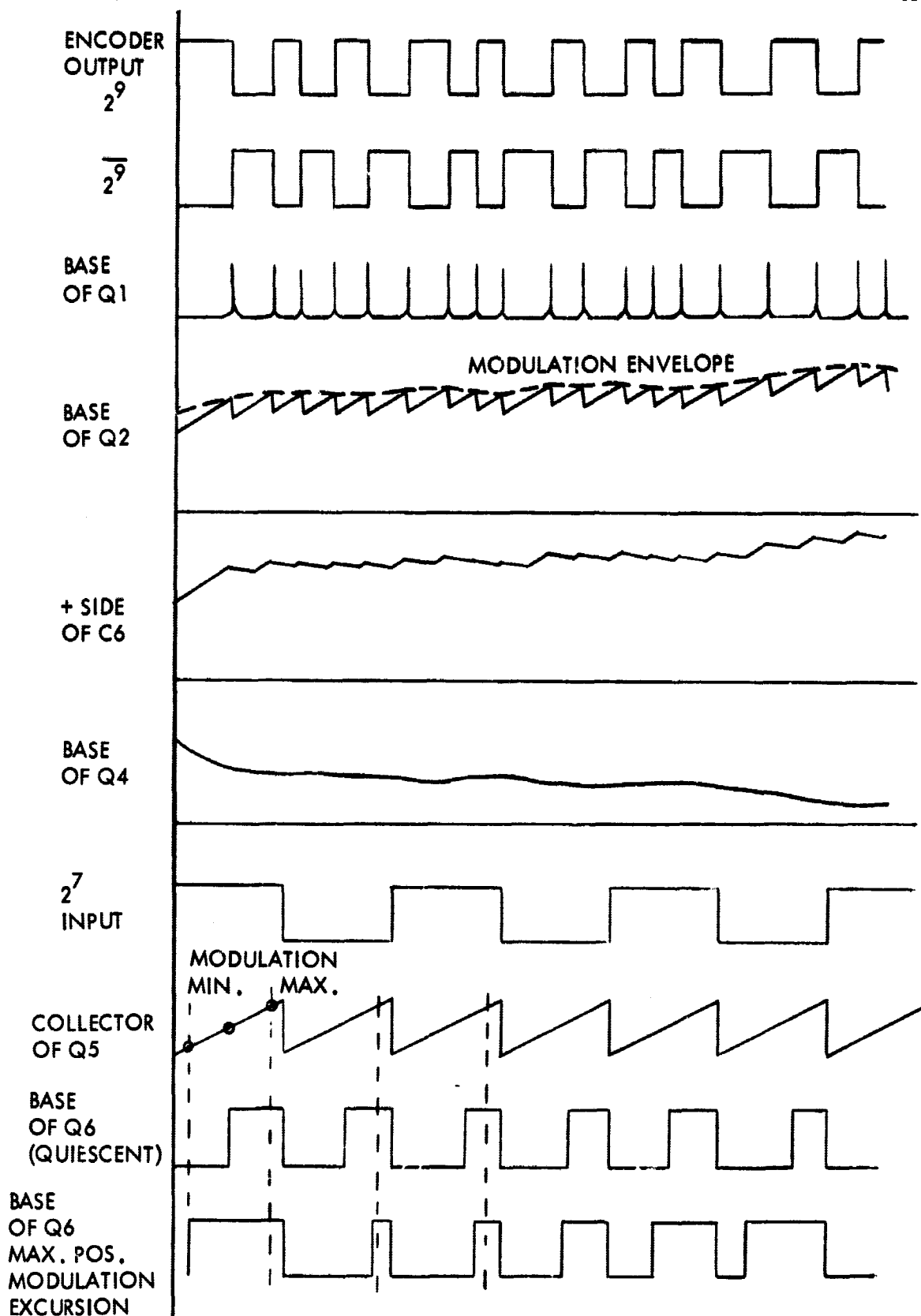


Figure 4-19. Damper Waveforms

The transistor Q2 serves as an impedance-matching device to avoid loading of the sweep voltage by the peak detector.

The peak detector consists of CR2, C6 and R13. The output voltage of the peak detector is inversely proportional to the motor speed. The AC component of the peak detector output is coupled to an AC amplifier.

The AC amplifier consists of Q3 and its associated components and has a very narrow bandwidth. This has been accomplished by the addition of C2, which makes the amplifier a "Miller Integrator". It is noteworthy that in the passband, the emitter bypass capacitor C7 is not effective. Its purpose is to increase the Miller capacity for high frequencies, which then serves to filter out the  $2^{10}$  ripple component of the peak detector. Otherwise, the amplifier design is standard.

The pulse position modulator consists of a differential amplifier, Q4 and its associated components, an RC sweep circuit, a threshold device and a Schmitt Trigger Circuit.

The differential amplifier is a standard single-ended design using a dual transistor. One input to the differential amplifier is the amplified speed information voltage from the AC amplifier. The other input is the attenuated  $2^7$  cycles/revolution sweep voltage.

The sweep voltage is generated by the RC integrator R6, C9, which is periodically discharged by Q5 at a  $2^7$  rate.

The output of the differential amplifier is the amplified combination of the control signal and the sweep voltage. The capacitor, C8, has been added to suppress some residual detector ripple. The zener diode, CR1, serves as the threshold device. If the differential amplifier output voltage exceeds the breakdown voltage of the zener diode, a complementary Schmitt trigger is turned on. Another function of C8 is to supply a transient current through CR1 to assure its proper turn-on.

The complementary Schmitt trigger consists of the transistors Q6 and Q7 with the associated components and is required to generate a fast-falling output waveform to operate the waveform generator. The time when the output pulse occurs is modulated by the control signal acting upon the differential amplifier.

The action of the damper circuit is similar to that of a phase shifter. For example, if the motor speed increases slightly, the input voltage to the motor is shifted back to counter the perturbation of the motor speed.

## The Waveform Generator (Motor Logic)

Figure 4-20 shows the logic diagram of the waveform generator. Its principle of operation is best explained by the waveform diagram, Figure 4-21.

The two flip-flops, WF2 and WF3, are connected as a binary counter. The output waveforms at their K and L terminals are shown by the four top waveforms in Figure 4-21.

In the "Exclusive Or" gate G14, the waveforms of WF2 and WF3 are Or'd together. The resulting output waveform is shown in the fifth trace. It can be seen that this waveform is shifted by 90° against the K output of WF3. Since the motor windings are center tapped, four driving waveforms are required for two-phase operation. The L output of WF3 is the complement of the K output of WF3. The L output of G14 is inverted by G15B resulting in the complemented L output of G14. These four waveforms are used to excite the four quaded motor drivers.

The other half of the G15 module is used in conjunction with the WF1 flip-flop to sharpen the  $2^7$  driving signal. This must be done to assure reliable triggering of WF2. The E and F inputs of G15A and the B and C input of G15B are paralleled for reliability reasons. For example, if the E terminal inside the flat-pack module should open, operation of the system is still assured by the C input.

## Quaded Motor Driver

Figure 4-22 shows the schematic diagram of a single quaded motor driver. Four motor drivers are required to switch the four motor windings in the sequence generated by the waveform generator. Quad redundancy is employed to increase the reliability of the circuit. The operation of the circuit is as follows.

The transistors, Q3, Q4, Q5 and Q6 are the main transistors switching the appropriate motor winding. Each one of the four transistors is shunted by a zener diode, CR5, CR6, CR7 and CR8. The zener diodes are used as "back-swing clippers" when the winding is switched off. The high-inductive kickback voltage would probably destroy the switching transistors after some time.

Not shown on the schematic is a diode inserted into the motor line. This diode will eliminate inverse voltages, generated by transformer action in the motor, from the switching transistors. The switching transistor, Q3, is driven by a preamplifier consisting of transistor Q1 with its associated components. Assuming Q1 is cutoff, it can be seen that Q3 is also cutoff. Referring back to the input of Q1, it can be seen that the

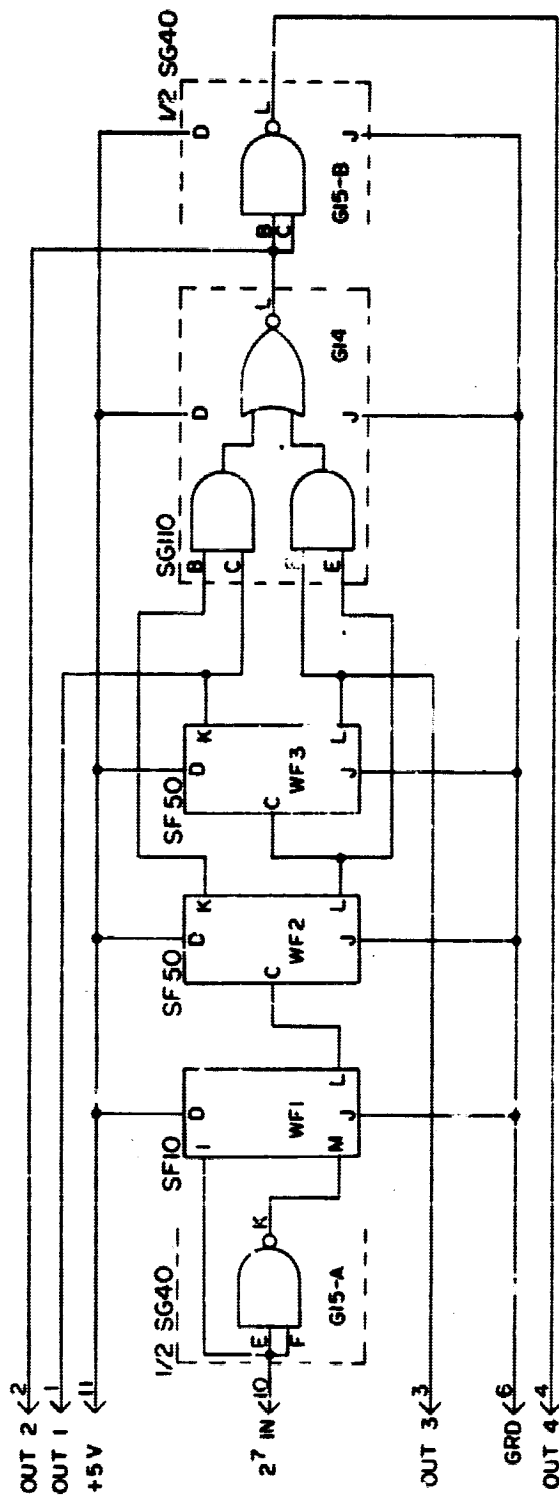


Figure 4-20. Waveform Generator, Logic Diagram

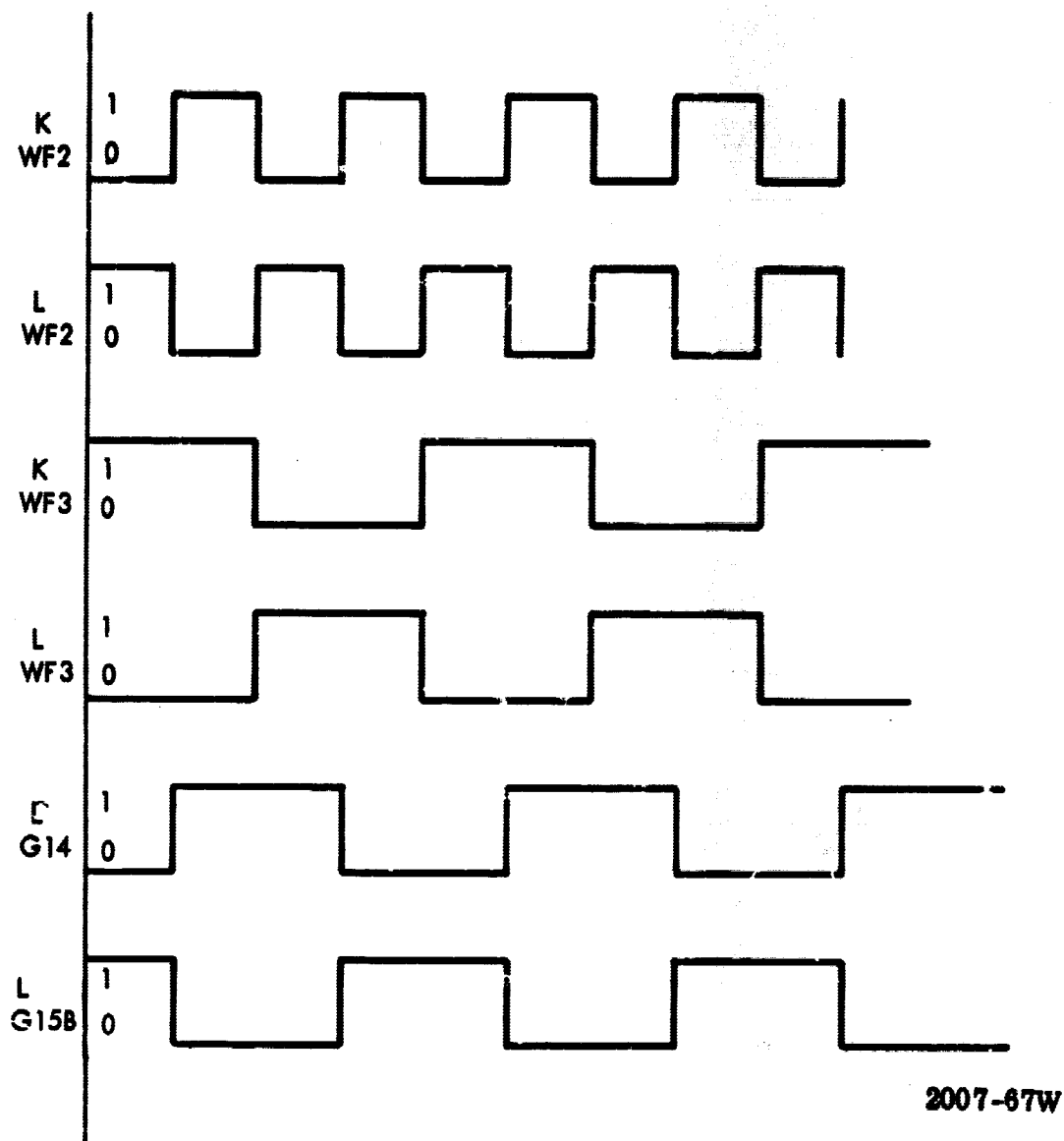
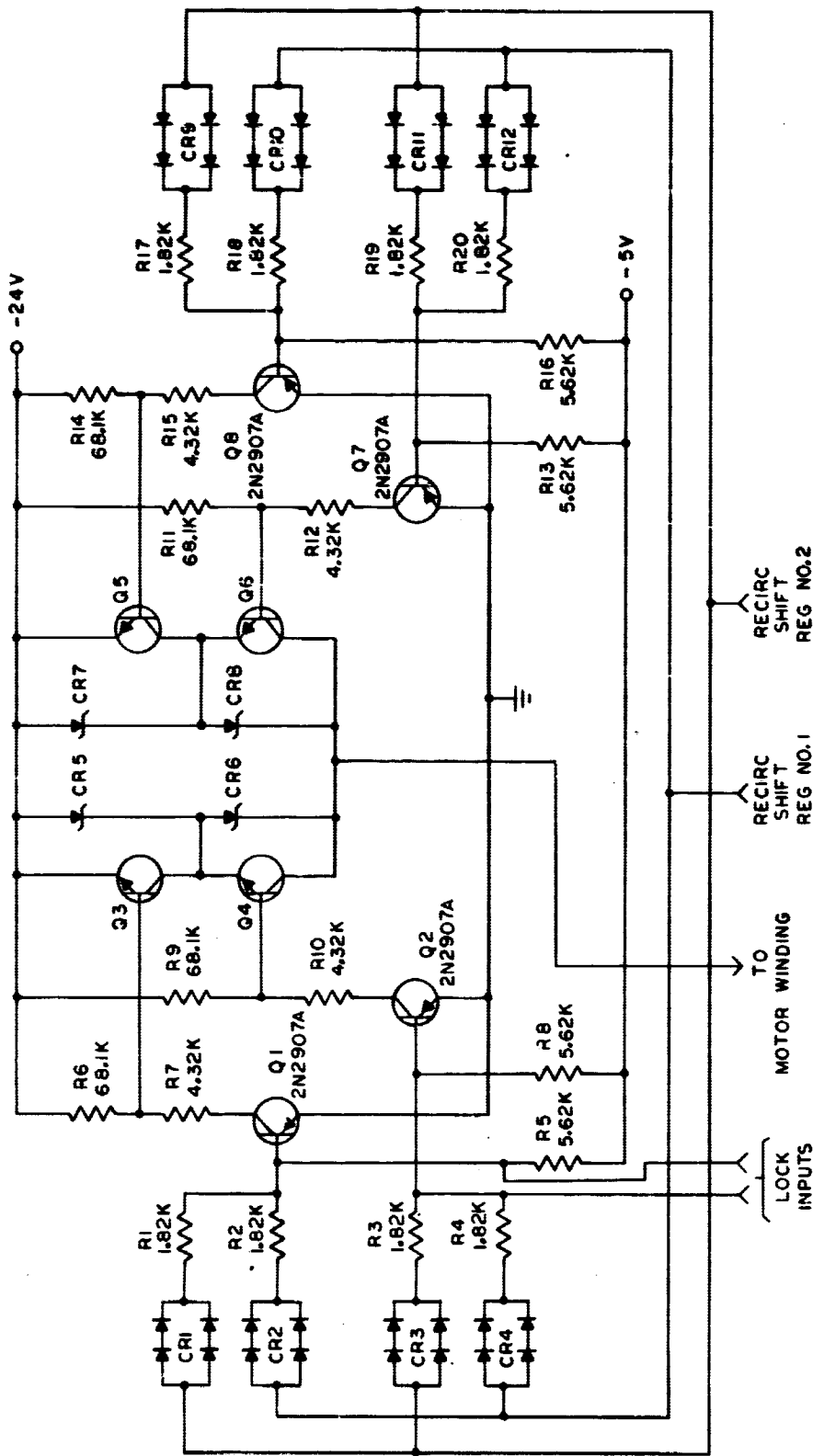


Figure 4-21. Waveform Generator, Timing Diagram



## NOTES:

1. CR1-CR4, CR9-CR12 ARE SYLVANIA INTEGRATED DIODES MO061
2. CR5-CR8 ARE IN3039B
3. Q3-Q6 ARE 2N2849

Figure 4-22. Quaded Motor Driver, Schematic Diagram

inputs of all preamplifiers, Q1, Q2, Q7 and Q8 are cutoff. This, in turn, causes cutoff condition for the switching transistors, Q4, Q5, and Q6.

If the preamplifiers are biased on, the switching transistors are also biased, causing current flow in the appropriate motor winding.

Now assume that one of the switching transistors, Q3, Q4, Q5 or Q6, should open or become shorted. For example, let Q4 open. Then, Q5 and Q6 still allow operation. Even if Q4 were open and Q3 were shorted, service would not be disrupted. The zener diodes are 60-volt units. Thus, if Q4 is open, no current will flow through CR6, since only 24 volts exist across it.

It can be seen from the schematic that many different fault conditions of the switching transistor quad still allow operation of the system.

The base current of Q3 is determined by the combination of R6 and R7. The resistor, R6, is required to cut off Q3 when Q1 is cut off.

In the inputs of the preamplifiers, the diode quads, CR1 to CR4 and CR9 to CR12, can be seen. These diodes serve as decoupling diodes to decouple the waveform generator No. 1 and No. 2 inputs. Single diodes could have been used, but again for redundancy reasons, quads were used.

In the absence of an input signal, all preamplifiers are turned on by the resistors, R5, R8, R13 and R16. The presence of an input signal back-biases the preamplifiers.

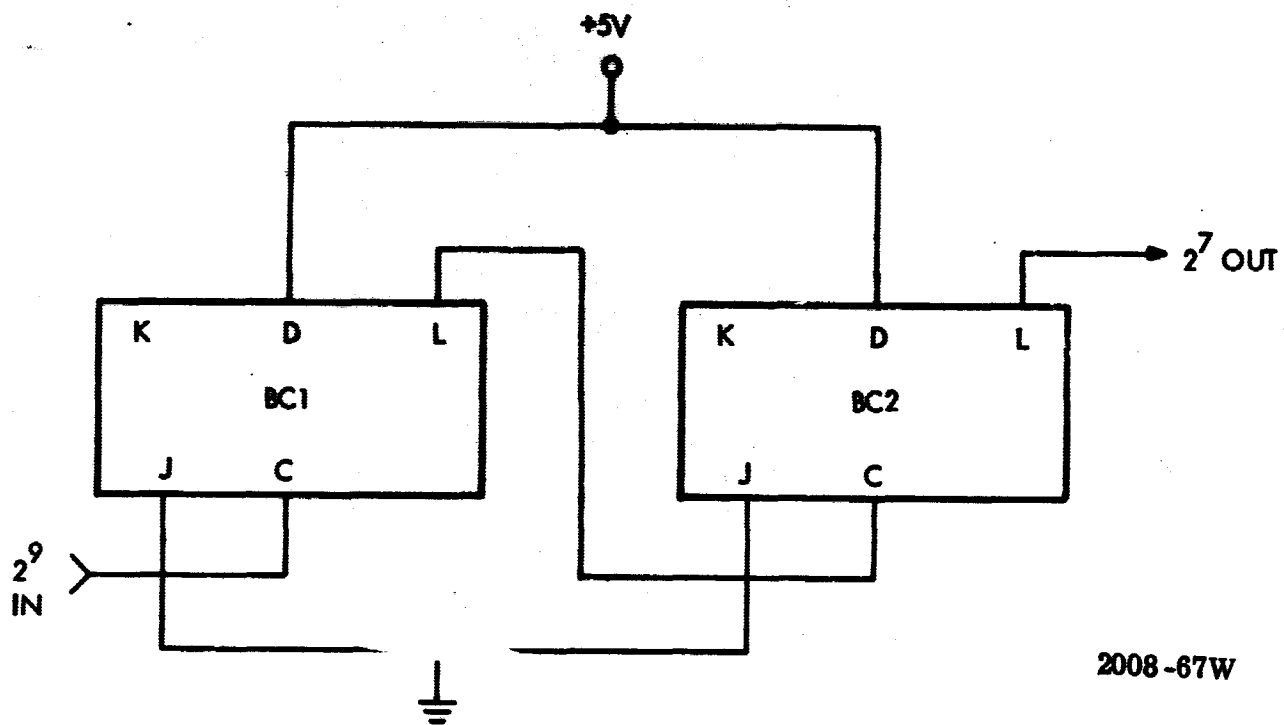
The input voltage swing to the motor driver is approximately 0.5 volts for OFF condition and approximately 3.0 volts for ON conditions.

### The Binary Counter

The purpose of the binary counter is to convert the  $2^9$  signal to the  $2^7$  signal required to operate the damper circuit. The binary counter, Figure 4-23 consists of two SF50 flip-flops connected as a standard two-stage ripple counter.

### Motor-Starting Circuit

Motor Characteristics Related to Starting - The motor used in this system is a stepping motor operating in the slew mode. While operating in the slew mode, it operates as a true synchronous machine and is not self-starting. The drive frequency must be slowly increased until synchronous speed is reached. At this point, the motor drive is switched from the slowly increasing frequency to the operating frequency of the frequency lock loop and then latched in this condition. During the transition from the variable frequency pulse train to



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Figure 4-23. Binary Counter

the command pulse train, the motor must not be presented with a discontinuity larger than the maximum load angle of the machine. This condition is met by running the motor-starting circuit at  $2^9$  pulses per revolution. The damping circuit must be in use during the starting cycle. To make the motor restart automatically - should it stop for some reason - the latch circuit is unlatched when the encoder output disappears.

**Motor-Starting Circuit Block Diagram** - Figure 4-24 shows a block diagram of the motor-starting circuit. The operation of this circuit is as follows: When the power is applied to the system, the motor is not running and there is no  $2^9$  output from the encoder. The latch circuit which rectifies the encoder square wave, produces no output voltage; hence the latch is inoperative. The command tachometer takes the  $2^9$  command pulse train and converts it to a voltage proportional to the rotational velocity of the satellite. This sets the differential switch in the proper state to switch the DC flip-flop to the starting state. The output of the flip-flop initiates the following functions:

The Voltage-Controlled Oscillator (VCO) is started at a low enough frequency to start the motor. The "Exclusive Or" circuit is switched to pass the output of the VCO. The motor then starts running, and its speed is sensed by the VCO tachometer. When the VCO and the command tachometer have equal output voltages, the differential switch is actuated. This changes the state of the DC flip-flop. The output of the "Exclusive Or" is switched from the VCO output to the command pulse train. The VCO is stopped, and the latch circuit is energized to insure that the circuit does not switch back to the previous state. The latch now operates because the encoder is giving an output. If the motor for some reason did not start or if it is stopped for any reason, the circuit will unlatch and the whole starting procedure will automatically be re-initiated.

**Motor-Starting Schematic** - The motor-starting circuit schematic is shown in Figure 4-25. The command tachometer consists of the following parts.

Q1 and the associated resistors are a current source used to charge capacitor C2. Q6 is a dump transistor to discharge C2 once for each command pulse. The voltage to which C2 charges is then a function of the spacing of the input pulses. One half of Q4 is an emitter-follower to provide isolation and power gain to drive the following peak detector made up of one half CR2 and C3. The DC voltage across C3 is dependent on the rotational velocity of the satellite and provides a reference voltage for the differential switch. The VCO tachometer is identical to the command tachometer. To equalize temperature variation, the emitter-follower transistor, Q4, and the peak detector diodes are matched pairs in the same physical package. The differential switch is another matched pair. The

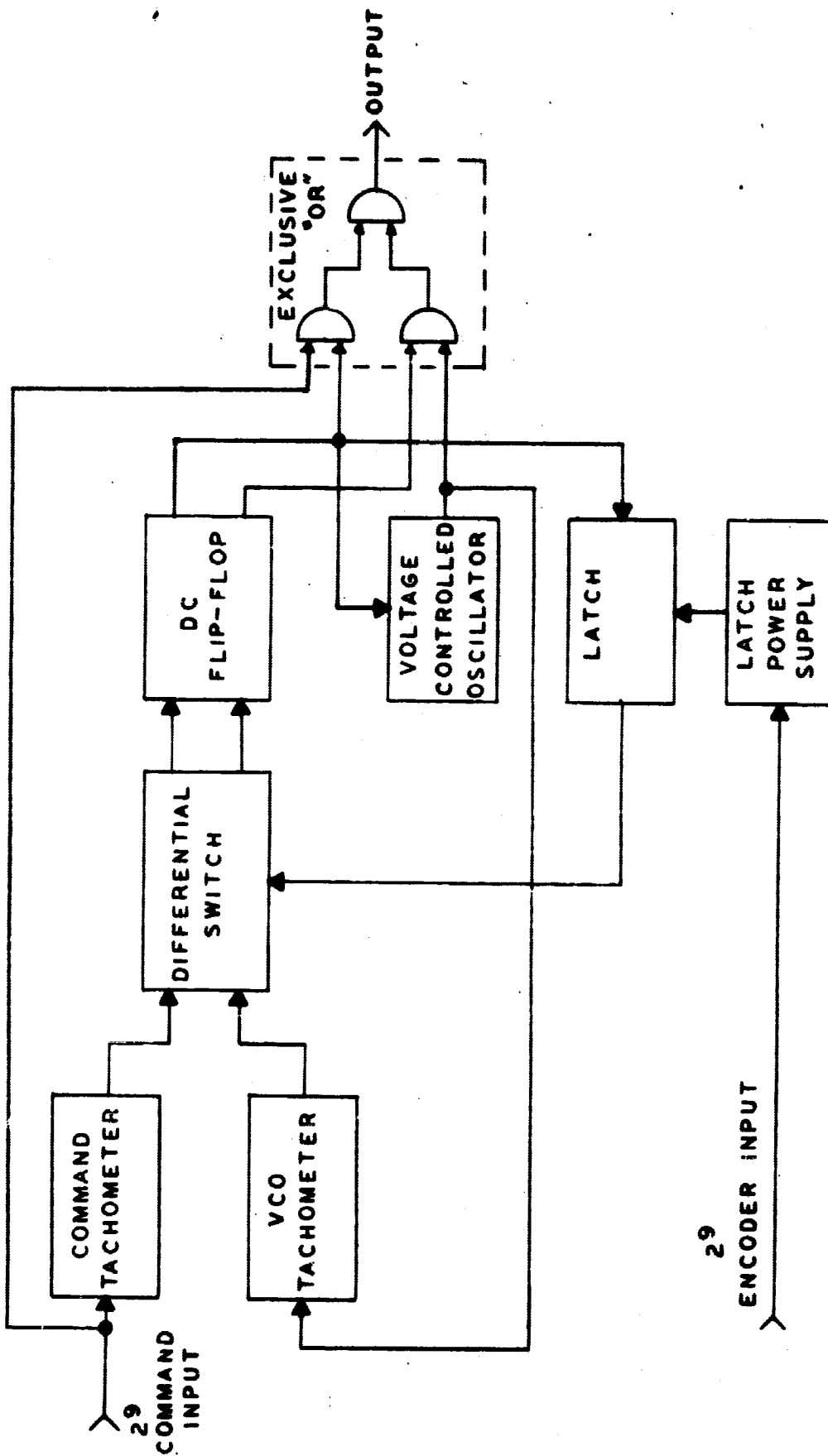


Figure 4-24. Motor Starting Circuit, Block Diagram

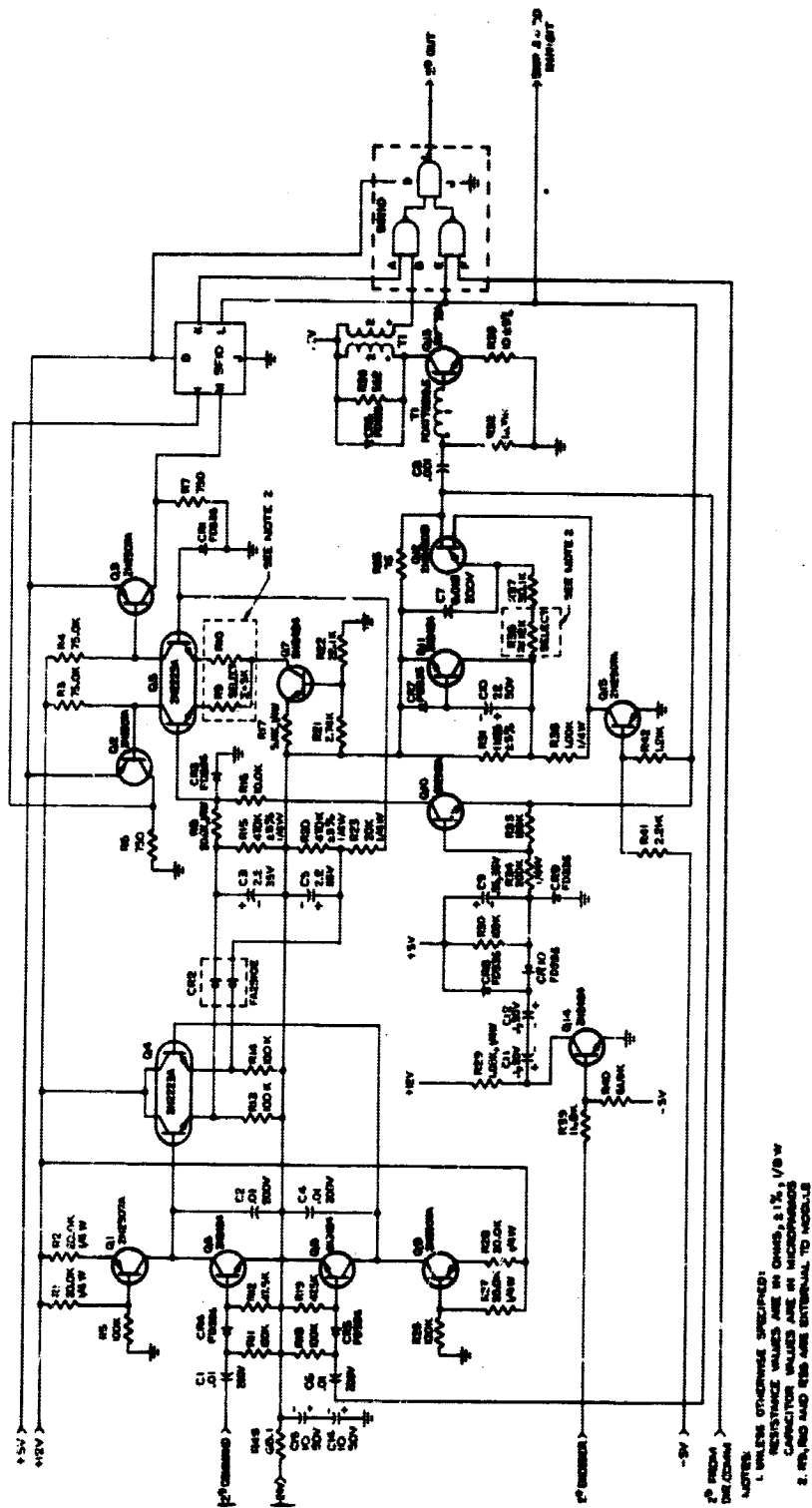


Figure 4-25. Motor Starting Circuit, Schematic Diagram

current supply for the differential pair is a current source made up of Q7 and associated resistors. This technique isolates the switching action of the differential pair from the absolute magnitude of the voltage from the tachometers.

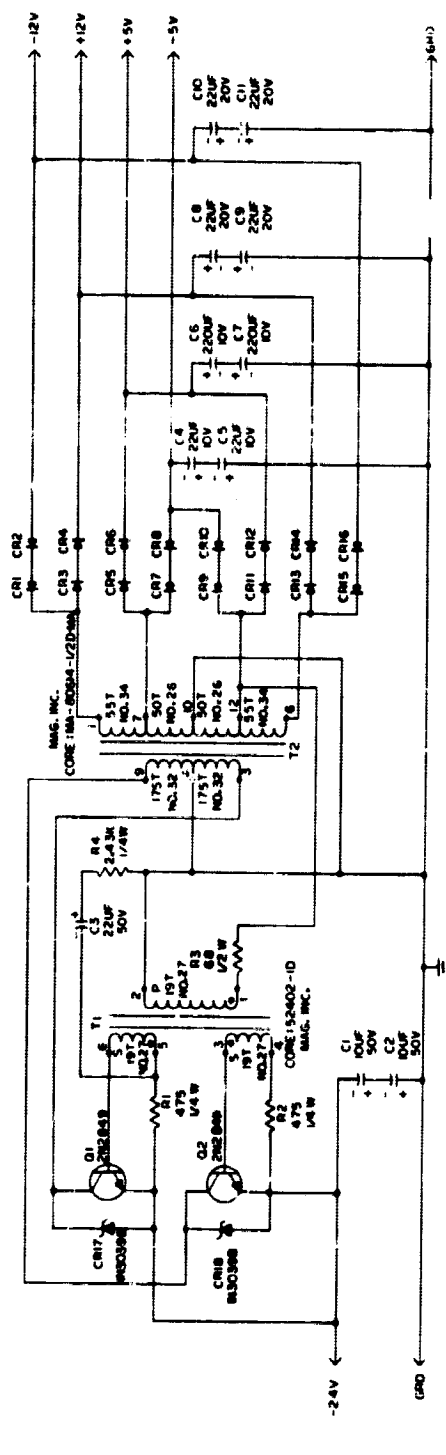
As the motor is starting, the right half of Q5 is saturated and the left side is cut off. This sets the output of Q2 at "zero" and the output of Q3 at "one". The SF10 flip-flop will then be set to "zero" on its L terminal and "one" on its K terminal. This inhibits the E-F side of the "Exclusive Or" circuit SG110. The SG110 now passes the output of the VCO, and the VCO switch, Q15, becomes saturated. The voltage across R38 is initially -24V. This voltage starts to fall toward zero according to the time constant made up of R38 and the capacitor multiplier consisting of C10 and Q11. The time constant is of the order of 30 seconds.

When the voltage drops sufficiently, the VCO - made up of the uni-junction transistor Q12 and R36, R37, R25, and C7 - begins to oscillate. The frequency is low in the beginning and increases slowly. The uni-junction oscillator output fires a blocking oscillator made up of Q13 and associated parts. The output of the blocking oscillator passes through SG110 to the system. When the motor reaches speed, the differential switch resets the flip-flop SF10. The L output goes from "zero" to "one". This saturates the latch transistor Q10, thus ensuring that this state will be maintained. The latch power supply is made up of switch amplifier Q14 and a peak detector. The switch amplifier is capacitively coupled to the detector, since the encoder input level could be either "zero" or "one", with the motor stopped. The capacitor insures zero output when the motor is stopped.

### The DC-DC Converter

The DC-DC Converter (Figure 4-26) is a standard Jensen type and is required to supply the system with  $\pm 5$  volts and  $\pm 12$  volts. The input voltage to the converter is the -24 volts from the payload regulator. The converter input terminals are bypassed by a redundant tantalum capacitor, C1 and C2. The transistors, Q1 and Q2, are shunted by zener diodes, CR17 and CR18, to eliminate avalanche breakdown in the transistors due to spikes generated by the leakage inductance of the main transformer, T2. The capacitor, C3, and the resistor, R4, serve as a starting circuit. After the oscillation of the converter has started, no need exists for C3 and R4. The frequency of oscillation is approximately 30 kHz to reduce the size of the transformer cores required.

The four DC output voltages are generated by center-tap connected rectifiers. The rectifiers are series connected for reliability. The diodes are "Adams" diodes, which have virtually no open circuit failure mode, thus quad redundancy is not required. The filter



NOTES:  
 1. UNLESS OTHERWISE SPECIFIED;  
 ALL RESISTANCE VALUES ARE IN OHMS.  
 2. CR1-CR10 ARE 1N4148.  
 3. TRANSFORMER WAVE IS HEAVY FORWARD.

Figure 4-26. DC-DC Converter, Schematic Diagram

capacitors are also series connected to eliminate system failure in case one capacitor is shorted out.

### Digital Telemetry Interface Circuits

The basic digital telemetry interface circuit shown in Figure 4-27 is a common base transistor stage. This design was chosen to provide the conversion from a positive-going signal to a negative-going signal. Six identical circuits of this type are used for the status displays and zero reference.

### The Command Interface Circuit

The command interface circuits (Figures 4-28 and 4-29) are standard ATS interface circuits No. 4. An inverter stage has been added to suit the input requirements of the SUHL integrated circuits.

### Directional Command Circuit

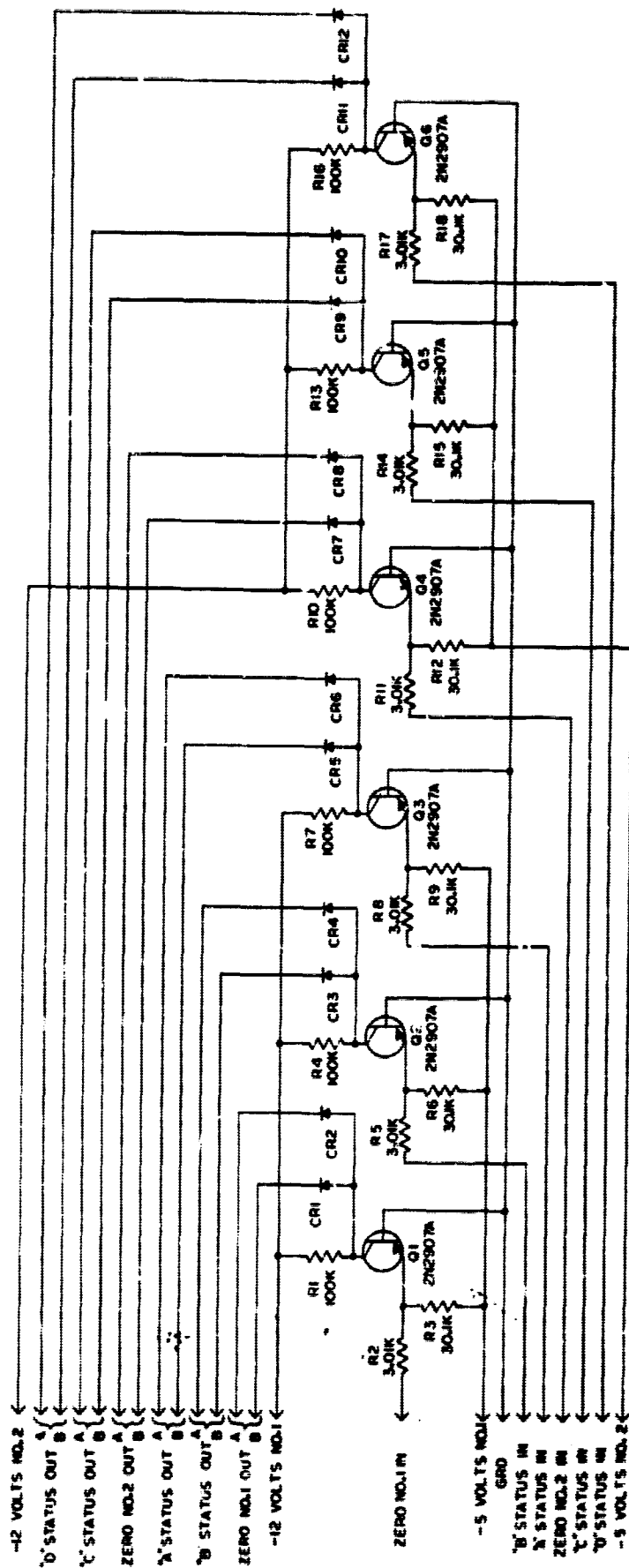
The purpose of the Directional Command Circuit is to allow the execution of the ground antenna pointing commands. The direction of the antenna (left or right) and the angle can be commanded. Also, the time of day correction is executed by the directional command circuit. The complete directional command circuit logic diagram is shown in Figure 4-30.

Before the frequency lock loop output (which is a square wave) can be used by the directional command circuit, it must be converted to two staggered pulse trains. The conversion is accomplished in the A1 module, Figure 4-31 of the directional command circuit.

The A1 module consists of two standard blocking oscillators. One is triggered on the leading edge of the  $2^9$  pulse/revolution square wave; the other is triggered by the inverted  $2^9$  pulse/revolution signal. This, in effect, generates two pulse trains which are staggered by one half a pulse period. The actual execution of the incremental command is accomplished by the pulse selection circuit which is part of the directional command circuit.

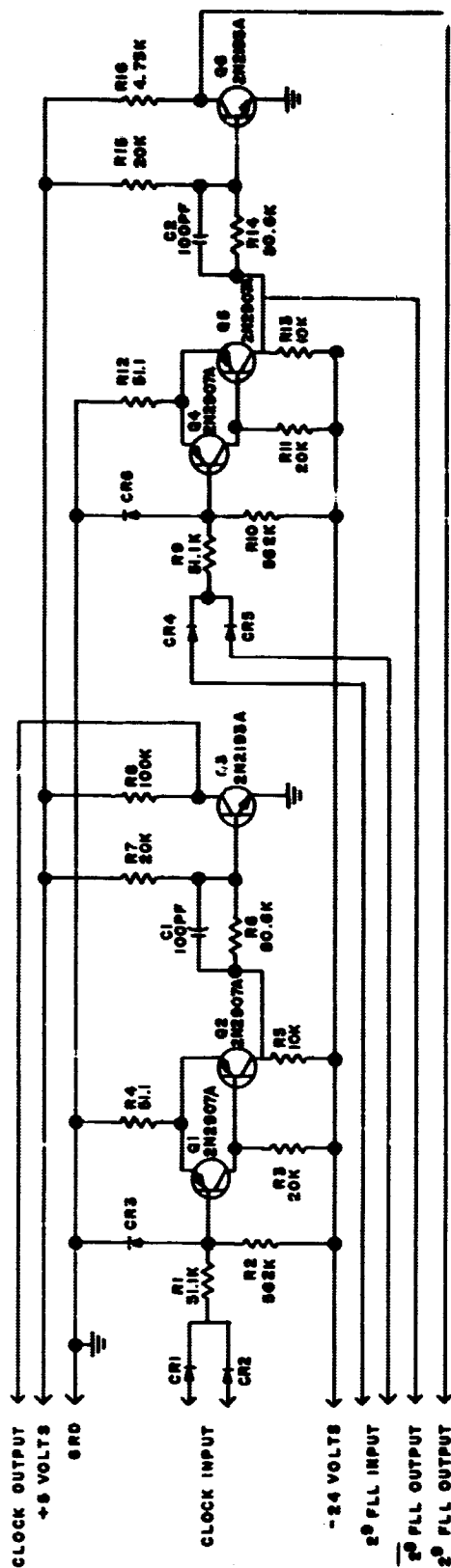
The purpose of the pulse-selection circuit is to insure that only one pulse of a given pulse train is passed to the output for each command input. In addition, it insures that the single-pulse output is not sliced or otherwise distorted by coincidence of the pulse and the command signal. The inputs to the circuit are shown in Figure 4-32.

There are two pulse trains having the same repetition rate but staggered in timing. Before a command pulse is received, DC4 has a zero output. This prevents G34A from



NOTES:  
 1. UNLESS OTHERWISE SPECIFIED,  
 ALL RESISTANCE VALUES ARE IN OHMS,  $\pm 1\%$ , 1/8W.  
 2. CR1-CR12 ARE 70336.

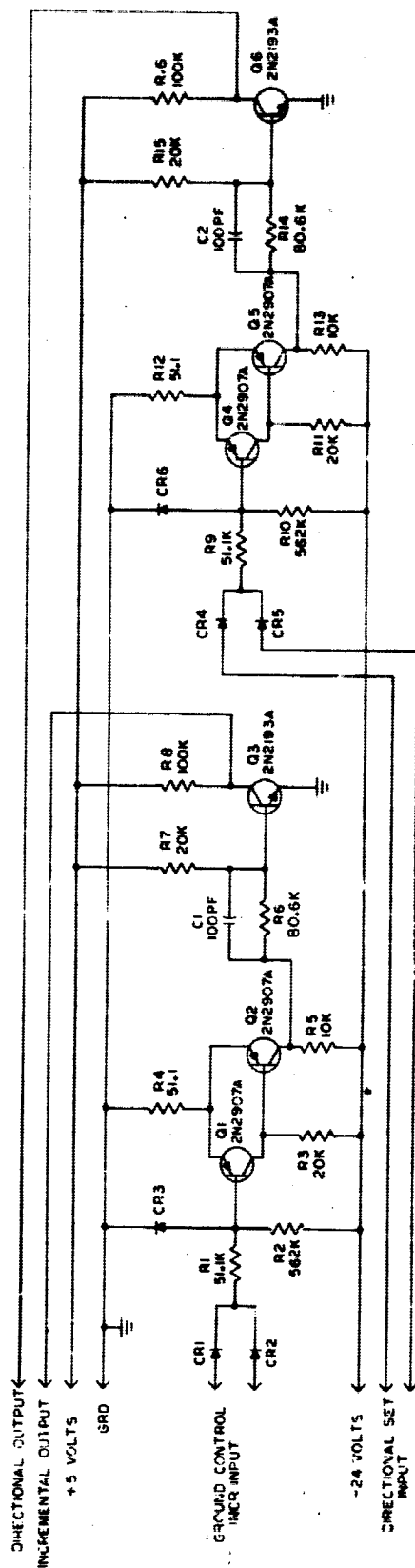
Figure 4-27. Telemetry Interfaces Circuit, Schematic Diagram



NOTES:  
 1. UNLESS OTHERWISE SPECIFIED ALL RESISTANCE VALUES ARE IN OHMS,  
 2. 1%, 0.25 WATT.  
 3. C1-C6 ARE PDSOC

Figure 4-28. Command Interface Circuit No. 1, Schematic Diagram

X



NOTES:  
1. UNLESS OTHERWISE SPECIFIED ALL RESISTANCE VALUES ARE IN OHMS,  
2. CR1-CR6 ARE FD300.

Figure 4-29. Command Interface Circuit No. 2, Schematic Diagram



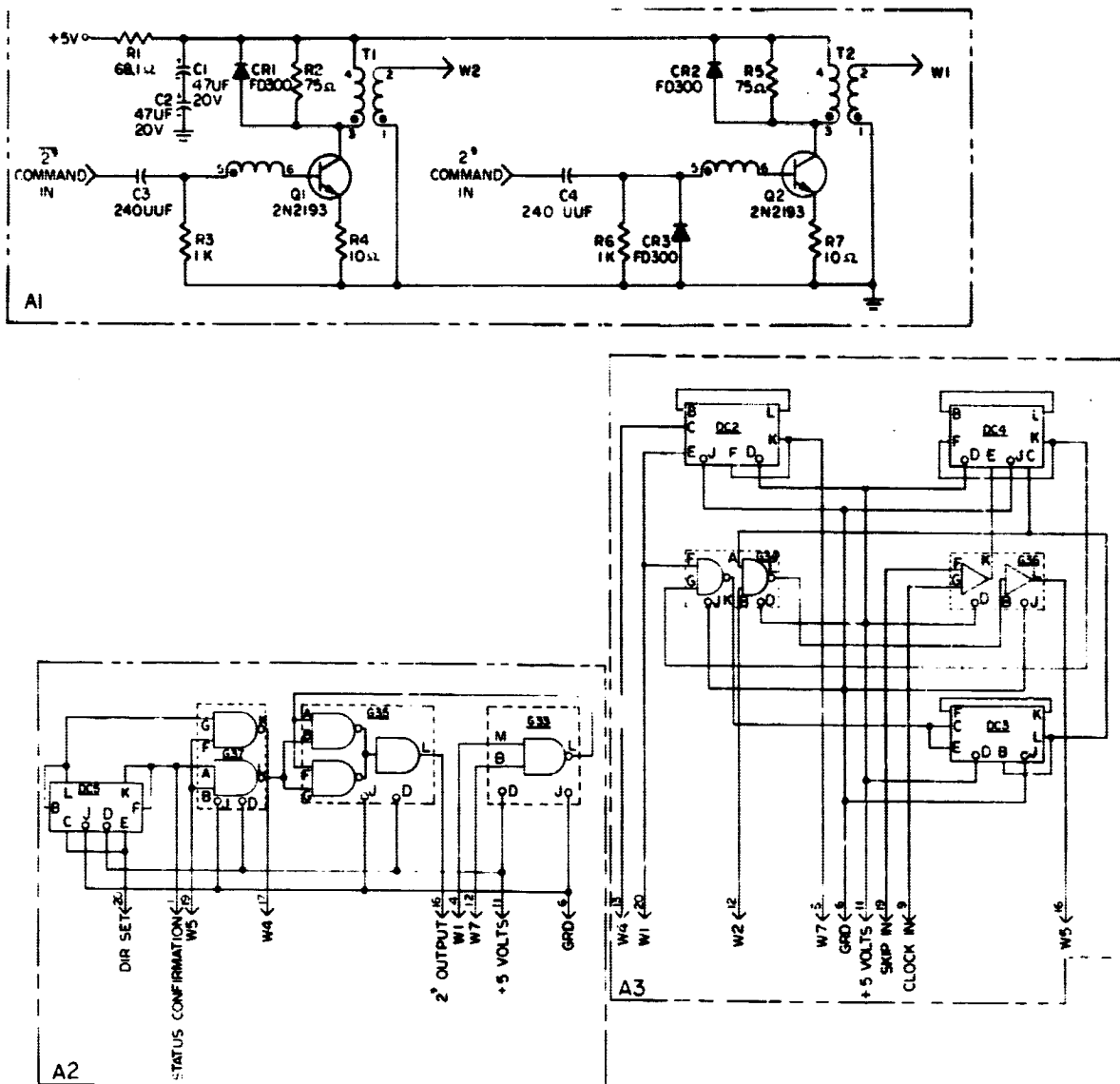


Figure 4-31. Directional Command, Schematic Diagram

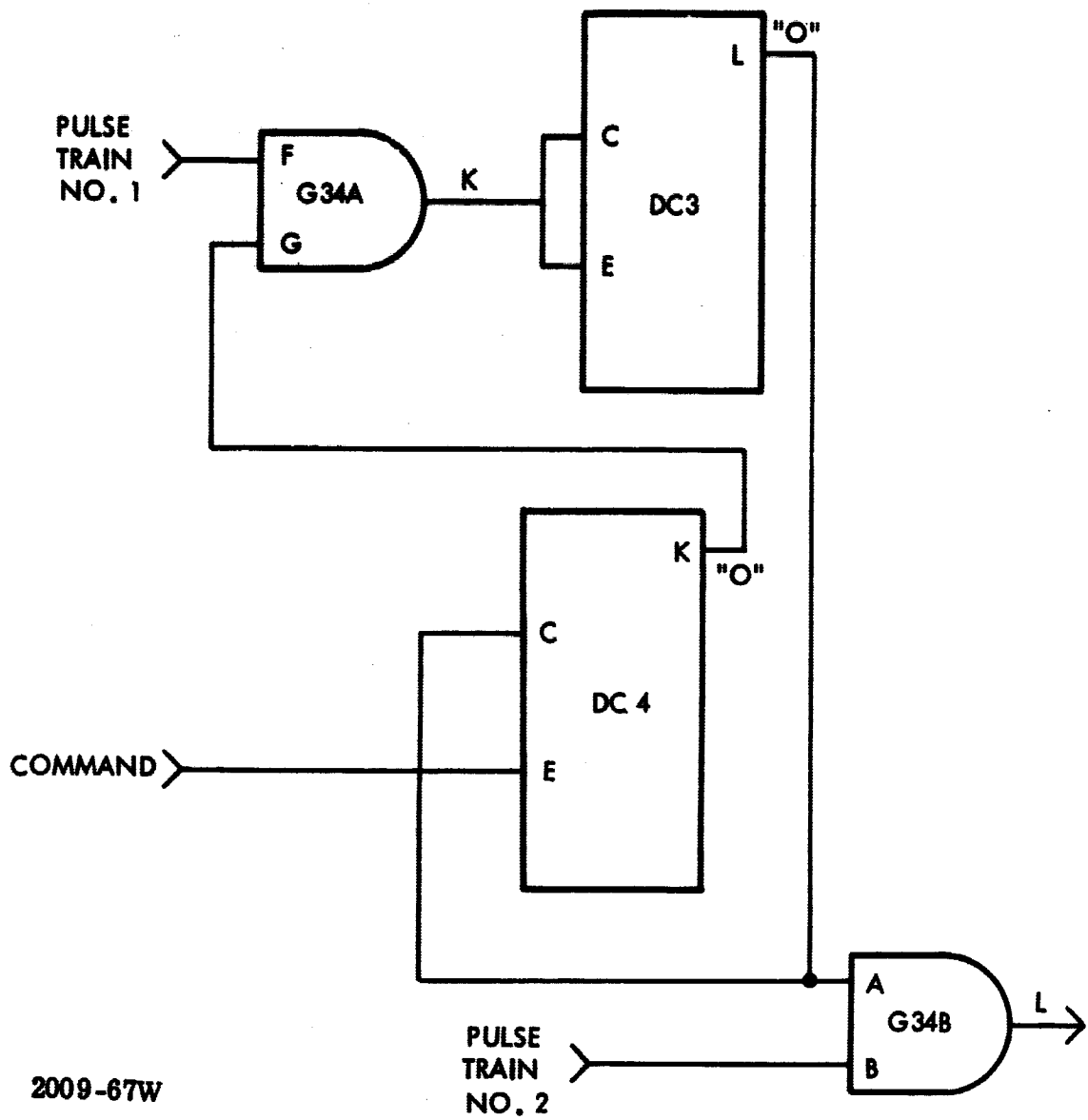


Figure 4-32. Pulse Selection Circuit

passing any pulses in pulse train No. 1 to DC3. The output of DC3 is zero. This prevents G34B from passing any of the pulses in pulse train No. 2 to the output. The reception of a command pulse sets the output of DC4 to a one. This allows the next pulse from pulse train No. 1 to pass undistorted to trigger DC3, producing a "one" at the output of DC3. G34B then passes one pulse to the output of the selection circuit. The next pulse from pulse train No. 1 passes through G34A and resets the output of DC3 to zero. This closes G34B and resets DC4 to the original state. No additional pulses from pulse train No. 2 can pass to the output until the next command pulse is received.

The gate G33B and flip-flop DC2 in Figure 4-30 execute a pulse subtract command. Its principle of operation is as follows.

The first pulse of the  $2^9$  pulse train sets the K output of DC2 to "one". This allows the following pulses to pass through G33B and G35. Assume that the output of DC5 is "one". This will allow transmission of a command pulse out of the pulse selector circuit through the left-hand gate of G37A. The result is that DC2 is complemented. The complementing occurs in the middle of the two pulses of the  $2^9$  pulse train. A pulse occurring after this cannot pass through G33B, since its A input is "zero". At the trailing edge of the pulse, the flip-flop is reset again by virtue of the connection of the E terminal of DC2 to the input pulse train. The next pulse occurring will again pass through G33B. Only one pulse has been deleted in the signal pulse train.

Next, consider the addition of a pulse to the signal pulse train No. 1. Assume that the K output of DC5 is "one". This will allow passage of a command pulse out of the pulse-selector circuit through the right-hand gate of G37. The pulse will pass through G35. The gate G35 was already passing the pulse train No. 1. The pulse output of G37 occurred in the middle of the spacing between the No. 1 pulses. The output pulse train of G35 contains one extra pulse.

The G36A gate serves to "Or" the incremental with the "Time of Day Correction" pulse and to eliminate additional circuitry for the "Time of Day Correction". The other half of G36 serves as an inverter G36B for the pulse-selector output.

The status of the DC5 flip-flop is telemetered to the ground where it is displayed. The occurrence of a directional command pulse will complement DC5, for example from an "add" to a "subtract", condition.

#### 4.2.1.3 The MARK I Control System

In this design, the reflector position is maintained by a digital positioning loop. Figure 4-33 shows the simplified block diagram of this control loop.

The only way to change the speed of a synchronous motor is to change the input frequency. In this case, this frequency is fixed by the spacecraft speed as described in the frequency lock loop discussion. However, the instantaneous position of its rotor can be changed a little by phase-shifting the input voltage. This can be done equivalently by adding or subtracting pulses in the pulse train driving the motor.

The basic control system, Figure 4-33, consists of a command register 9 bit binary counter containing the ground commanded antenna angle, a binary counter and correction circuit to count down from  $2^9$  to  $2^7$  pulses/revolution, a damper circuit to stabilize the motor, a four stage recirculating shift register for the motor driving waveform generation, a motor driver, the motor-encoder assembly, the encoder electronics, a 9-bit binary counter which serves as an encoder register, a digital comparator which compares the contents of the encoder register with the command register, and sign detector which senses the sign of the error between the command register and the encoder register.

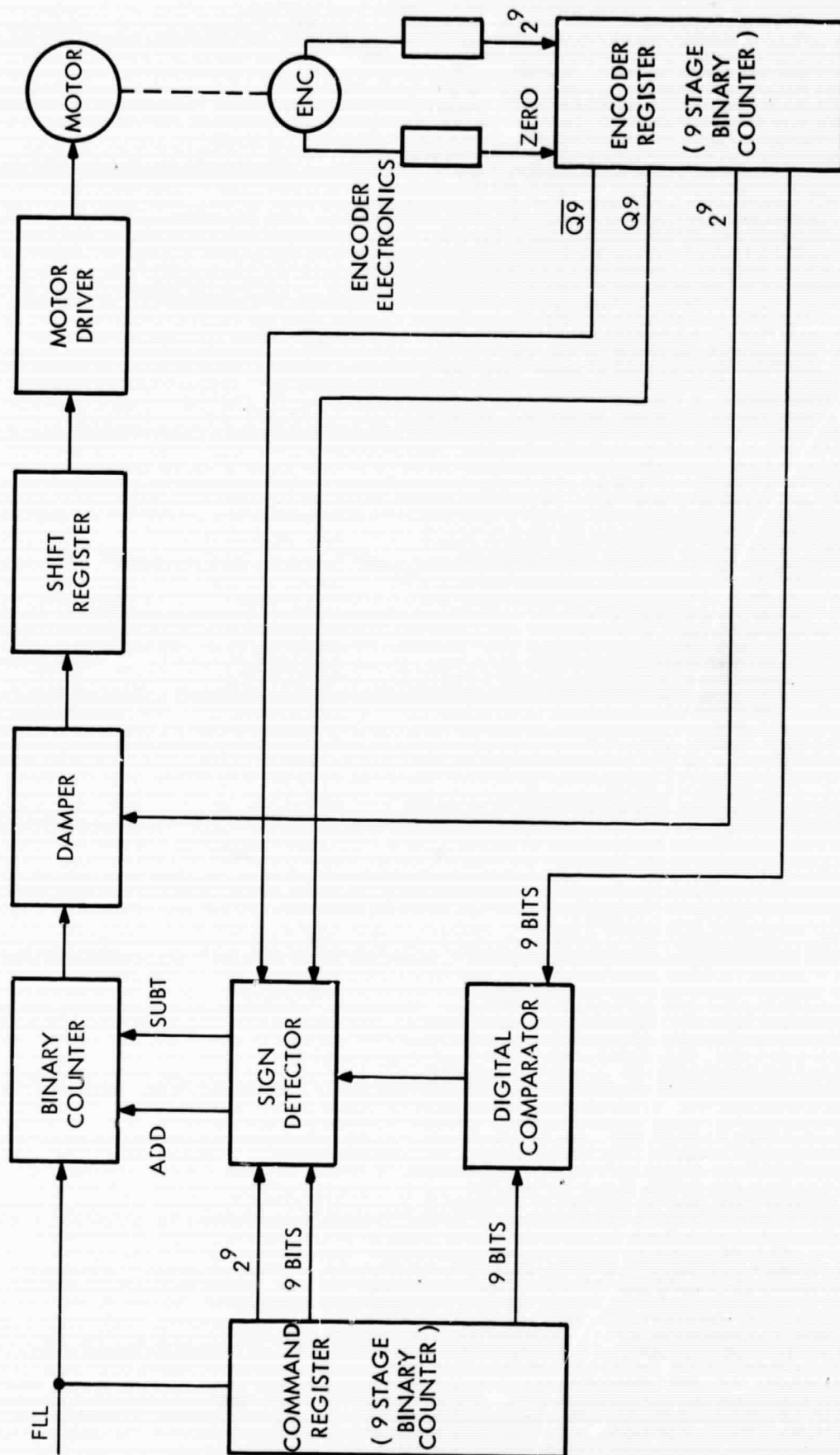
The basic control system operates as follows:

The input to the system is the  $2^9$  pulse/revolution pulse train from the frequency lock loop (FLL). The command register, which is a 9 stage binary counter, is connected to the  $2^9$  pulse/revolution pulse train and continuously counts from 000 000 000 to 111 111 111 during one satellite revolution. A one bit change in the counter corresponds to a  $360/512 = 0.703$  degree increment.

The shaft encoder register is identical to the command register with the exception that it has a zero set provision. Both counters are simple ripple counters constructed from Sylvania Universal High-Level Logic (SUHL) elements.

The contents of both counters are continuously compared by a digital comparator. The digital comparator consists of 9 identical "exclusive or" modules used as a coincidence detector. Their nine outputs are OR'ed together to give a single output if all nine bits of the command register are equal to those of the encoder register. The digital comparator is also constructed of Sylvania SUHL elements.

Since the digital comparator gives no indication of the sign of the antenna pointing error, a sign detector is required to assure that the proper correction to the loop is



1151-66W

Figure 4-33. Basic Control System, Block Diagram

applied. The sign detector compares the status of the most significant bit flip-flop of the shaft encoder register to the status of the identical flip-flop of the command register at the time the command register reads all zeros. The sign detector has two outputs, an "add" output and a "subtract" output. The presence of a digital comparator output and the sign determines which one of the two outputs is activated.

The sign detector outputs are connected to the binary counter and correction circuit. An "add" command from the sign detector changes the counter from a Modulo 4 counter to a Modulo 3 counter during one counting period. This causes a premature counter output after the third pulse is passed. Normally, the counter gives an output after the fourth pulse. The counter output is a square wave which drives the motor through the damper circuit and shift register. When the "add" command appears, one-half of a cycle of the square wave is foreshortened by one increment on the  $2^9$  pulse/revolution basis. The square wave, after the "add" command is executed, is then advanced against the original waveform by 45 degrees.

If the "subtract" command is activated, one pulse in the  $2^9$  pulse train is deleted. This requires five input pulses for a counter output. As with the "add" command, the "subtract" command is cancelled after the pulse has been deleted. The dropping of the pulse causes the counter output waveform to be shifted back by 45 degrees.

In a synchronous motor, the load angle is defined as the angle between the driving current waveform and the instantaneous rotor position. The load angle is a constant for a given load torque. If the input waveform is phase shifted, the rotor position must change to keep the load angle constant, since the load torque is unchanged.

The result is that the antenna position changes according to the sign of the applied phase shift, which also causes a change in the shaft encoder register.

The "adding" or "subtracting" of pulses is continued until the digital comparator senses equality between the two registers. After the system lockup is accomplished, the antenna position can be commanded to any direction by a ground command through the directional command system.

The recirculating shift register, which is driven by the damper output signal, is required to generate the four driving waveforms for the motor. It serves the same function as the waveform generator in the Mark II system. The four waveforms are generated in the register by shifting the binary number 1100. The number is automatically inserted into the register after the first pulse appears at its input. If for some reason a wrong count

should arise in the register, a correction circuit will insert the right count and the proper operation will continue.

Two registers are provided on a standby redundancy basis. By ground command, the alternate register can be selected if a failure in the operating shift register should occur.

The outputs of the shift register excite the motor driver. The motor driver is essentially a transistor switch driven by the shift register outputs. Quad redundancy is applied in this circuit; hence, certain transistor failures in this circuit will not impair the operation of the system.

The encoder electronics takes the encoder output voltages and conditions them so that they can be used to drive the encoder register.

The remaining circuits in the original Mark I control electronics are essentially the same in function and operation as their counterparts in the Mark II system. This statement includes the motor starting circuit, directional command circuits and interface circuitry. Exceptions are the DC DC converter and the binary counter and correction circuit.

#### **4.3 CONTROL ELECTRONICS PACKAGING**

##### **4.3.1 Introduction**

A high-density flatpack module design was developed by the Advanced Electro-mechanical Systems Department of the Sylvania Electronic Systems Division for the NASA Applications Technology Satellite (ATS) Project. This work was supported by a Sylvania-financed independent research and development program on advanced packaging.

This design was based on the requirement for a low-volume, minimum-weight package with high reliability and conductive cooling that would survive the rigors of a rocket launch and operate in the environment of space in a synchronous orbit at 22,300 miles altitude. The life expectancy target is a minimum continuous five-year operating period.

##### **4.3.2 Despun Antenna Module**

The basic module consists of a militarized 20-pin, hermetically sealed header in a mating metal can which can accommodate up to seven integrated circuit flatpacks. For certain types of circuitry, pin limitation may reduce the number of flatpacks in a package. On the ATS Program, an average of five flatpacks were used per module.

Point-to-point welding with nickel ribbon, supplemented by nickel foil overlays (interconnection webs) was the method used for electrical circuit interconnection.

A typical module is composed of the parts shown in Figure 4-34.

On the far left of the figure is a flatpack with leads trimmed to the required length, an interconnecting web and a fiberglass-epoxy insulating shim. Note that the unused leads are cut off close to the flatpack body.

The interconnection web is a Sylvania innovation that was developed to improve and facilitate the interconnection of flatpacks. The web greatly reduces the required external maze of wiring and provides a simple method of cross-connecting through the stack. It also provides jumpers from lead to lead at the flatpack level without additional wiring. The webs may be connected to the leads of the flatpack on which they are mounted, the leads of an adjacent flatpack, a ladder connection, or ribbon to the header. This technique has contributed to increased efficiency, greater reliability, lower interconnection error possibilities and higher packaging density. The webs are chemically milled from 3-mil nickel sheet using standard photographic techniques.

The next assembly in the figure shows a nickel interconnection web bonded between the insulated face of the flatpack and the insulating shim. After cure of the bonding agent, the outside support frame is trimmed from the web and the web leads are trimmed to the same length as the flatpack leads.

These subassemblies are now stacked in a fixture and bonded into a solid mechanical assembly using a small amount of epoxy adhesive between each subassembly.

After bond cure, the stack is ready for interconnection. Stack wiring involves joining the webs to the flatpack leads and attaching all jumpers not associated with the leader.

Jumpers involving a series of flatpack terminals, typically voltage and ground buses, are made by a unique ladder connection technique developed by Sylvania for this program. This ladder not only facilitates wiring, but avoids potential damage caused by rotation of the flatpack leads to accomplish the usual straight-run flat-joint welded assembly. The ladders are pre-formed in a simple hand fixture and made from 4 by 18-mil nickel ribbon, as are all the electrical interconnections. Insulating sleeving is used on interconnection ribbons where close physical spacing requires the added assurance of solid insulation.

Also shown in the center group of Figure 4-34, is a plastic riser used to space the stacked assembly from the header to allow the proper lead dress of the connections to the to the header.

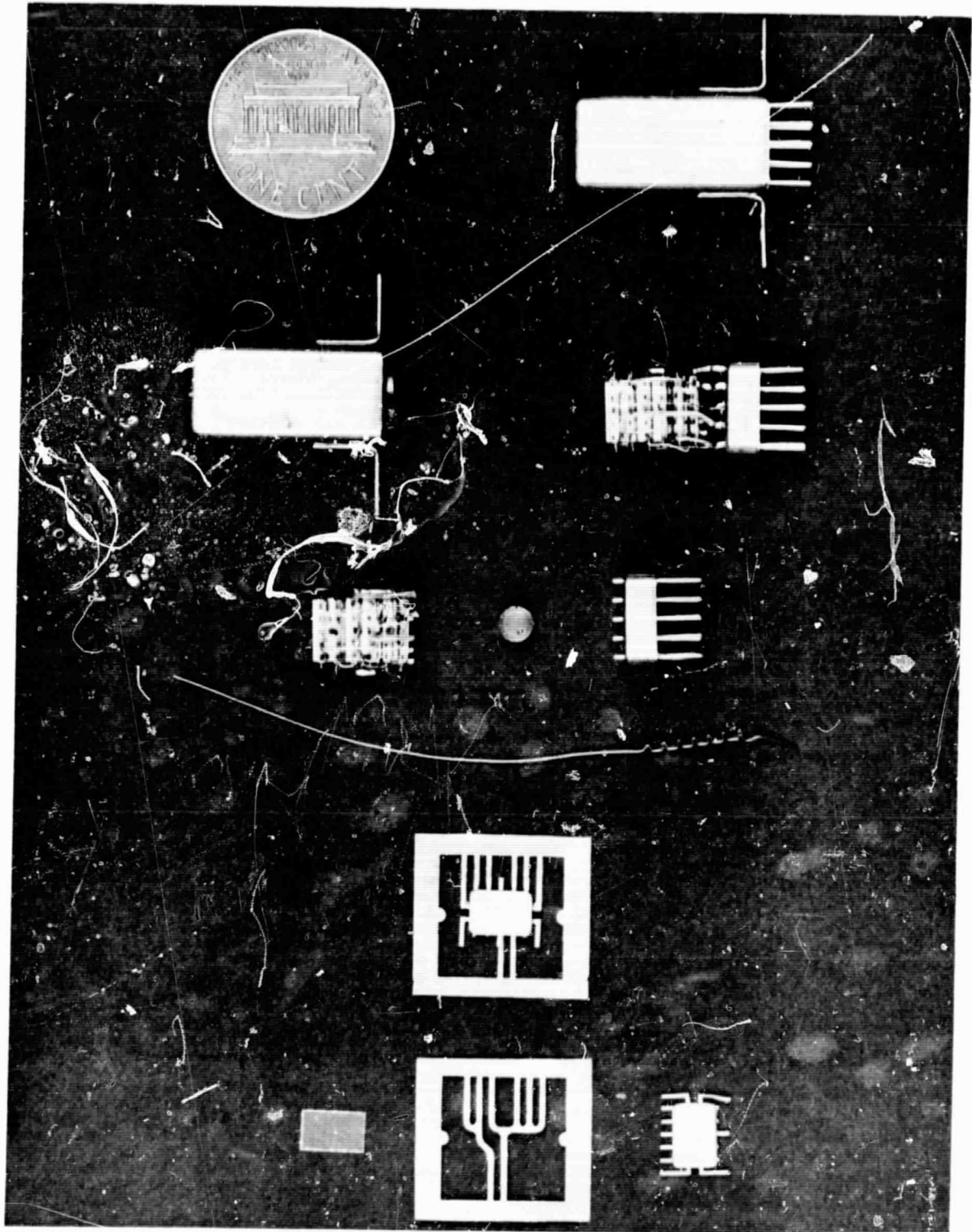


Figure 4-34. Despun Antenna Module

The header shown is a militarized 20-pin hermetically sealed plug that is pre-wired as a subassembly by welding nickel ribbons to the pins. These nickel ribbons are later welded to the stack. The header pins are 16-mil diameter gold-plated kovar in a glass seal.

The next group to the right shows the assembled header and integrated circuit stack ready for insertion into the can. The upper view shows the can with kovar ears used for mounting the modules and to provide a thermal path under conditions of space vacuum. This view also shows a mylar liner used inside the can to provide electrical insulation from ground.

The unit at the far right shows all parts assembled. A larger view of the stack-header assembly is shown in Figure 4-35. After successful electrical testing, the can is spot-welded to the header. The module is filled, through a pre-drilled hole in the top of the can, with electronically-pure aluminum oxide. This is performed while the model is vibrated at very low frequency to assure a compact fill. The aluminum oxide has an extremely high thermal conductivity and due to its granular structure protects the integrated circuits from stresses that may be created under cyclic temperature changes in its normal environment.

During this project, we were at times faced with design changes that affected finished stacks. It was quickly demonstrated that a stack could be modified to the extent of removing and replacing a given flatpack or changing circuit wiring within reason.

Workmanship errors in circuit wiring were kept to an absolute minimum by using a standard format for all types of modules.

An example of the format used to convey information to the wirer is shown in Figure 4-36. This page carries the identification of the required interconnection webs and shows the necessary ribbon runs and the weld configuration to be used. On the flat-pack views, any lead not marked with a black square for connection is cut off close to the flatpack body. This drawing also shows the connections of the stack to the header.

Figure 4-37 shows the welding operation on the stack and the header-ribbon weld as performed.

Figure 4-38 shows a typical assembled electronic chassis mounting thirteen of the subject modules. Not all the circuitry has at present yielded to integrated circuit design. The larger blocks are cordwood assemblies of the power supply and a filter. The smaller block is the sun sensor.

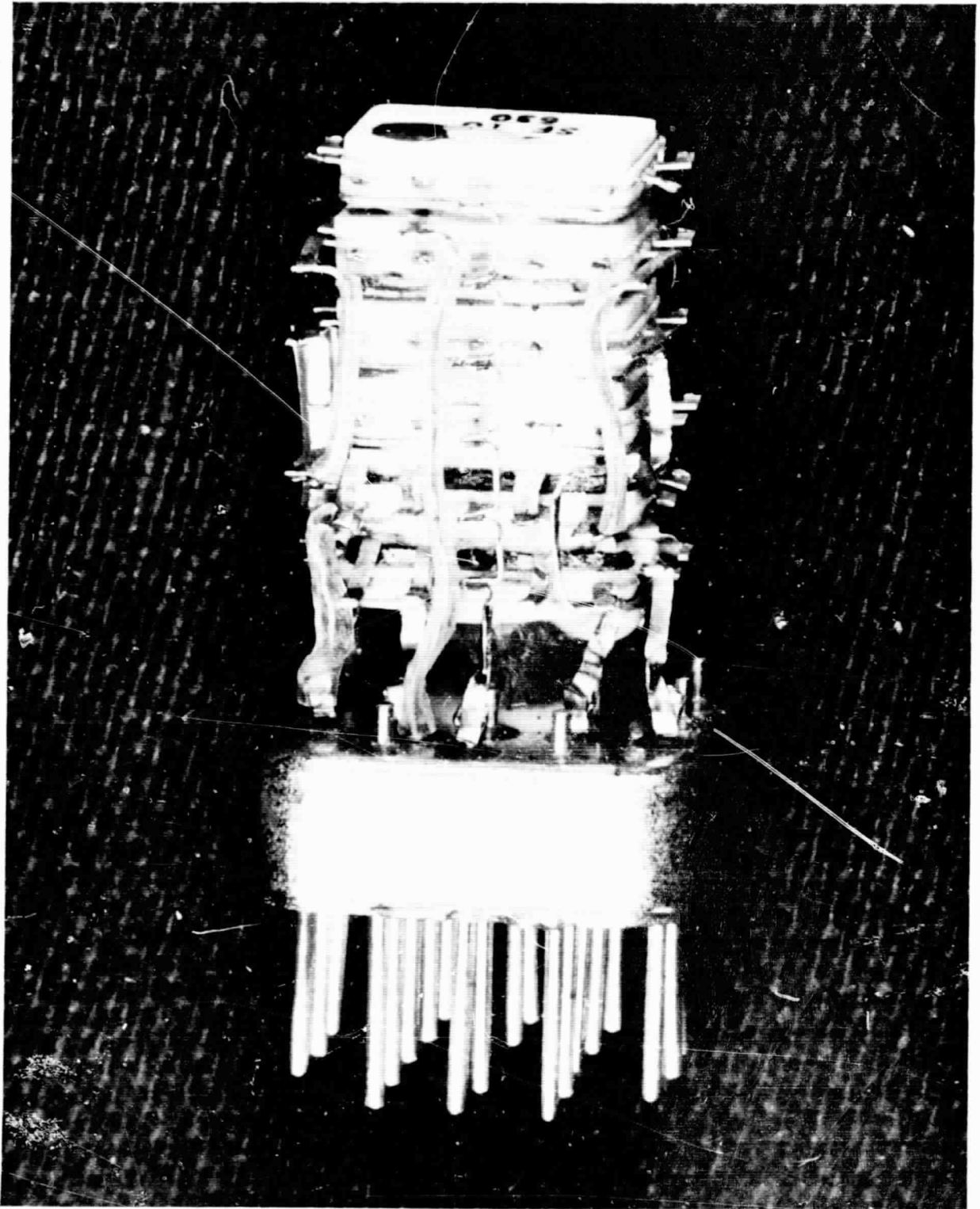


Figure 4-35. Stock and Header Assembly

NOTES:

1. SEE SYL DWG. NO. 00-463094 FOR INTEGRATED CIRCUIT PARTS LIST AND SCHEMATIC.
2. ENCL. PAGES PER SYL SPEC. 00-463542.

11-11-11

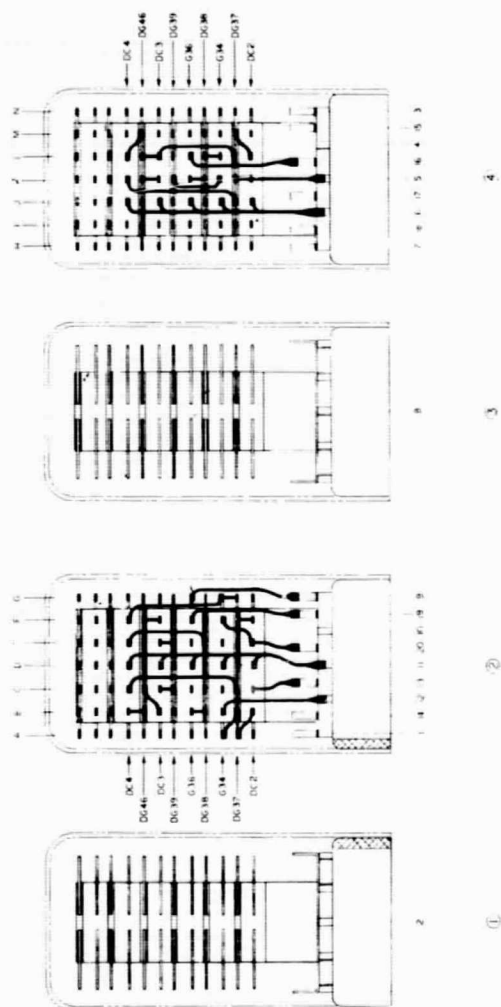


**Figure 4-36. Wiring Diagram for Typical Module**

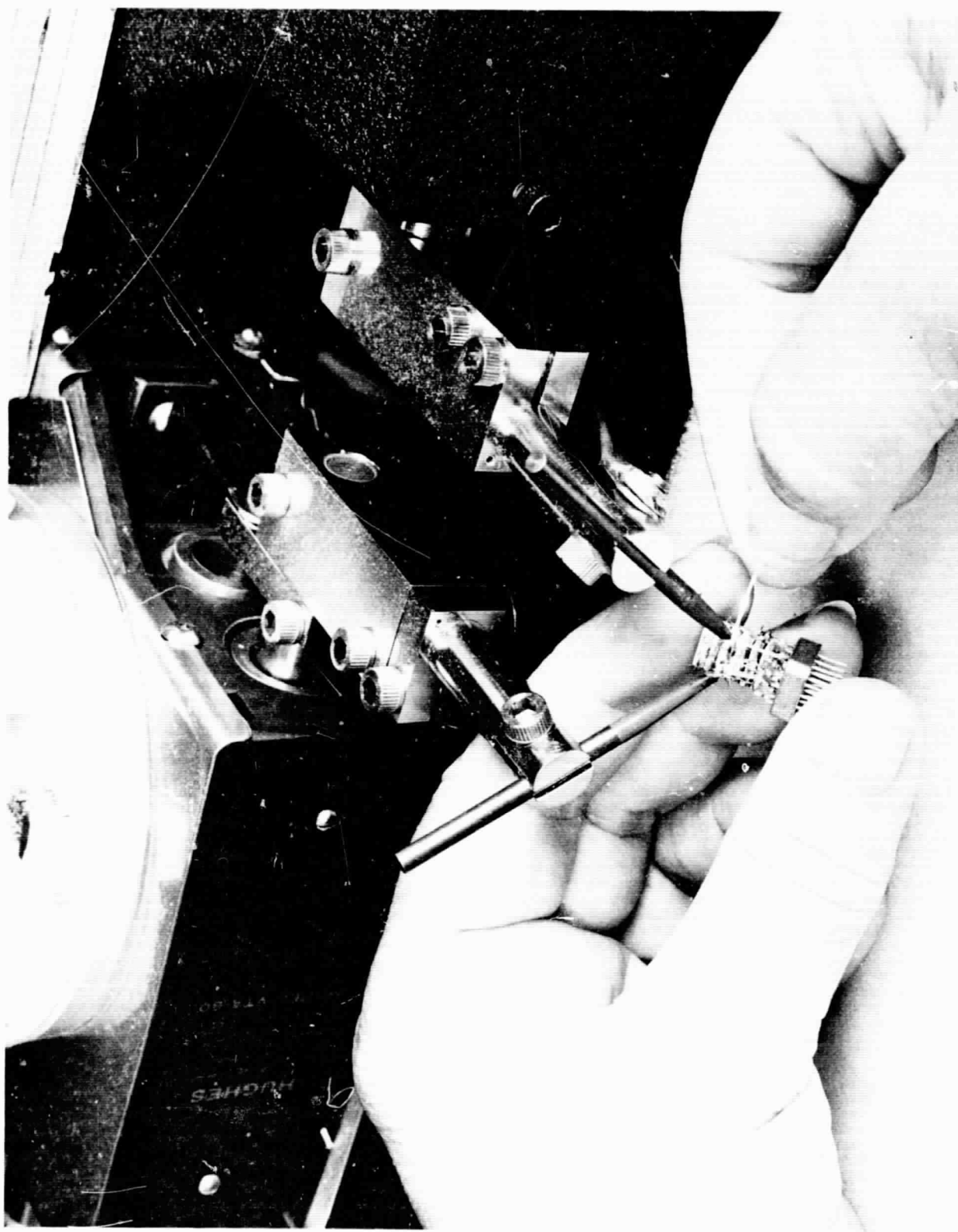


Figure 4-37. Close-up View of Weld Performance on Stack

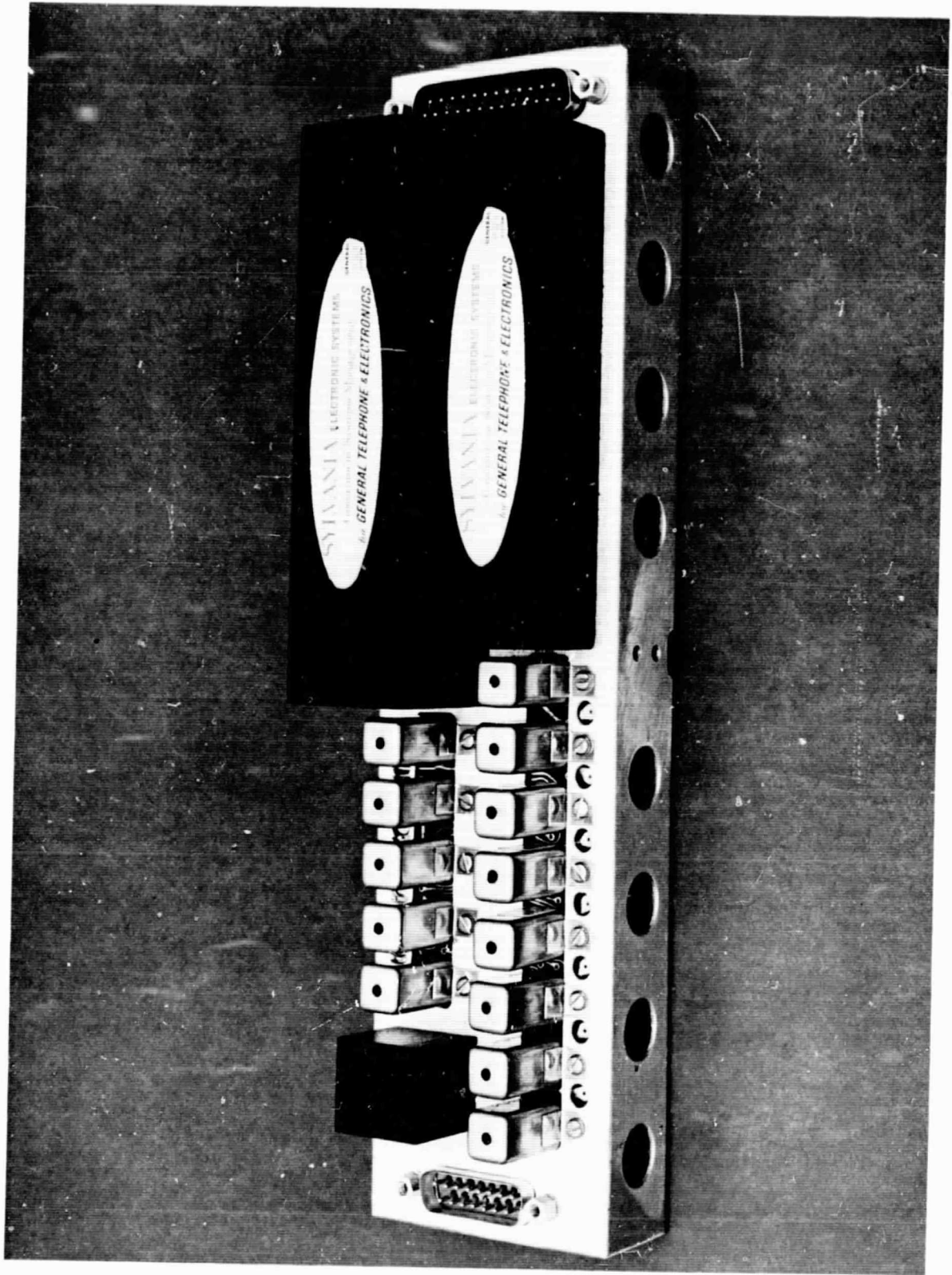


Figure 4-38. Typical Assembly of Modules in Mechanical Despun Antenna System.

### **4.3.3 The Mark II System**

In carrying out the packaging of the control electronics, maximum use was made of established module and system design concepts from the Mark I system shown in Figure 4-39. As before, the integrated circuits are packaged in high density welded volumetric "flatpack modules"; the welded "cordwood" module is used to house the discrete components in the system.

The general concept for system packaging was identical to that used on the Mark I system. Briefly, both the flatpack and cordwood modules are assembled to a mother board (2-sided printed circuit board) as shown in Figure 4-40 supported in a light aluminum chassis. The chassis serves as a positive heat transfer path for the modules and as a mounting area for the connectors. To take advantage of the system redundancy feature, two of the four required chassis assembly units are identical.

Unlike the Mark I system which contained five chassis assemblies, each of a different size (i. e., in length), the Mark II control system chassis are all the same length. In other respects, they are identical to those used on the earlier system with the exception of the elimination of the lightening holes around the sides. These were removed assuming that this might be necessary to meet the system RFI requirements not defined at the time.

Designations and definitions for the four chassis assemblies in the Mark II system are listed below:

Chassis Assembly No. 1 - Telemetry and Driver Chassis

Chassis Assembly No. 2 - Control Chassis No. 1

Chassis Assembly No. 3 - Motor Starter-Binary Counter-Damper Chassis

Chassis Assembly No. 4 - Control Chassis No. 2

#### **Fabrication and Assembly Procedure - (Cordwood Module)**

The cordwood module was used to house the discrete components in the system, although when necessary, an integrated circuit mounted on a carrier was also packaged within its configuration.

Basically, the unit consists of two parallel glass epoxy boards between which components are vertically mounted. Interconnections along either board are made with nickel wire welded directly to the component leads on the outer surfaces of the epoxy boards. Interconnections required between boards are made using the nickel wire as a feedthrough.

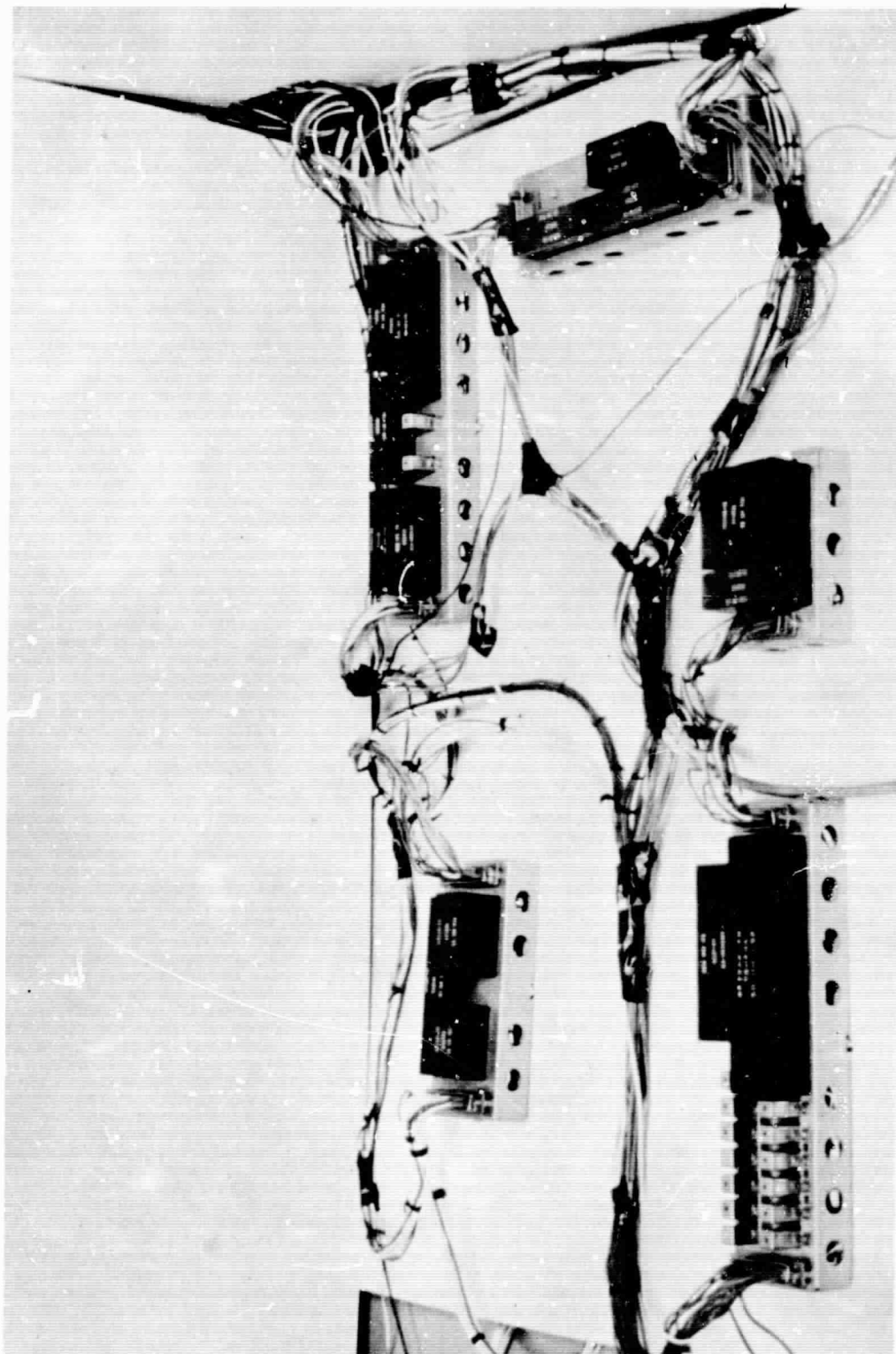


Figure 4-39. Packaging of Control Electronics

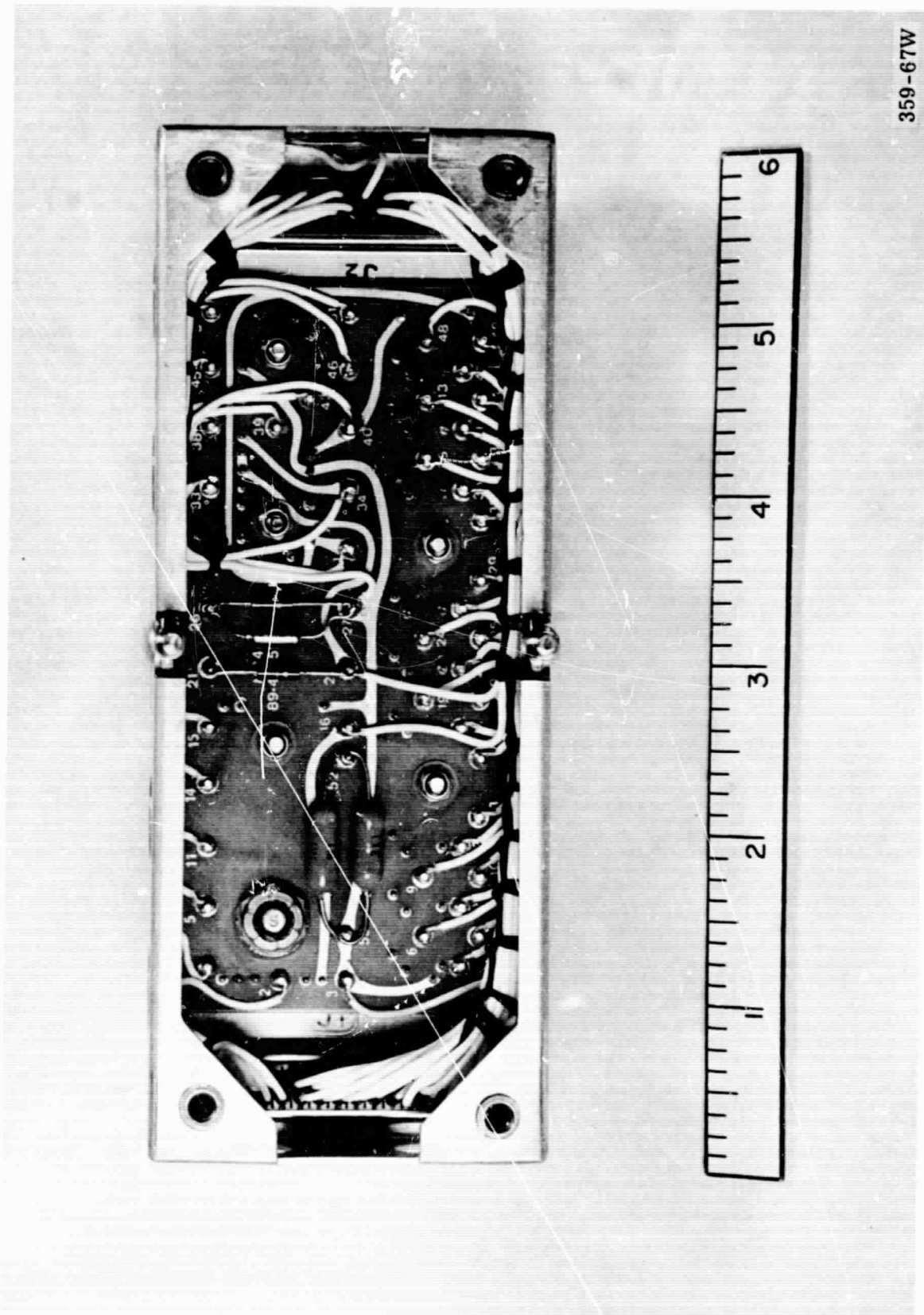


Figure 4-40. Modules Assembled on Two-Sided Printed Circuit Board

**The steps in fabrication and assembly of the cordwood module are:**

- 1) A photographic negative for both boards is made from information developed on the unit wiring diagram.**
- 2) Two 0.015-in. thick un laminated glass epoxy boards, rough cut 3 by 5 in. are photo-sensitized with photo resist. The negatives are then exposed, under ultraviolet light, to the epoxy boards and developed. The inter-connecting wiring information is thus transferred photographically to the two boards.**
- 3) The boards are registered to each other and 0.030-in. diameter holes drilled where required for component leads insertion.**
- 4) The boards are trimmed to fixture size and inserted into open positions of the assembly fixture.**
- 5) Components are next loaded between or on the inner sides of the boards as required.**
- 6) The fixture is then closed to give the proper width between boards.**
- 7) Following the dyed photo lines on each board, interconnecting wiring, (0.010X-mil nickel wire laid flat along the board) is welded directly to the component leads.**
- 8) The component leads are trimmed to 0.015 in. above weld, excluding external connecting wires on the outer side of the bottom board.**

**After final inspection, the unit is tested for proper electrical function. Since weight on this program is a prime consideration, minimum potting requirements were used for proper heat transfer and unit rigidity.**

**All heat producing components were placed on or near the bottom epoxy board. These components were then encapsulated in rigid epoxy. Flatness of the mounting surface was assured by a potting mold; mounting of the unit directly to its chassis thus provided a positive heat transfer path. The remainder of the unit was potted with a closed cell epoxy resin foam material.**

**It should be noted that all components were coated with a one-half to one-mil coat of RTV rubber prior to encapsulation. This coating relieves stresses on the components cast in the epoxy.**

**Each cordwood module is normally tested three times during the assembly cycle. Testing is done before and after encapsulation and again after a 24-hour temperature cycling between temperature extremes of -10° F and +150° F.**

## 4.4 MECHANICAL DRIVE ASSEMBLY

The Mechanical Drive assembly shown in Figure 1-1 is composed of the RF structural components, the motor drive, the lubrication system and the ejection mechanism. The Control Electronics are functionally an integral part of the antenna system but are physically separate from the Mechanical Drive Assembly. The Control Electronics and the packaging are discussed in other sections of this report.

### 4.4.1 Structure

The principal structure is the motor housing. It houses the lubricant reservoir and bearings as well as the motor stator and rotor. The structure includes a mounting flange for mounting the Mechanical Drive Assembly on the spacecraft. In addition, the encoder housing is mounted on one end of the cylindrical structure along with the feed assembly and the ejection mechanism.

The rotating elements (not fixed to the satellite) are the motor shaft, the split ground plane and the reflector. These are supported in the motor housing by bearings which provide the rotating interface.

Most of the structural members are made of an aluminum alloy. Aluminum is considered the best all-around material for space applications from the point of view of weight and life in the hard vacuum of outer space.

Specific coatings and finishes were used in areas where direct exposure to solar energy would create severe temperature problems. The coatings and finishes are used to control the temperature of the components. Temperature control on the RF structures is particularly important since extreme temperatures can disturb the geometric stability of the parts, and RF performance can be affected by distorting the geometry of the structures. The coating and finish determines the absorptivity ( $\alpha$ ) and emissivity ( $\epsilon$ ) of the heat energy. This provides the passive temperature control for reducing temperature extremes.

Optimum  $\alpha/\epsilon$  ratios were determined by a comprehensive thermal analysis (see Appendix G) and the analysis was supported by thermal vac tests.

Specific thicknesses of a chromic anodize coating were applied to produce the proper  $\alpha/\epsilon$  ratio. The reflector surface was sand-blasted so that the reflected solar energy, normally directed at the focal point of the parabolic section (the approximate location of the feed), would be dispersed.

A hard anodize coating (Sanford hardcoat) was applied on surface of structural members subjected to wear or high bearing stresses.

#### **4.4.2 Bearings**

The bearings selected to provide the rotating interface are thin section, high precision, instrument type angular contact bearings. The bearing bore size was governed by the amount of space needed to accommodate the RF transmission line; a smaller bearing could be capable of handling the load requirements. The resulting bearing load-carrying capacity is an order of magnitude larger than otherwise required.

The bearings are preloaded to provide optimum rotational stability and to assure that the bearings do not operate in a no-load condition. Proper loading is important to maximize bearing life. Bearings rotating without a load will cause excessive ball skidding on the races and retainer. To maintain a relatively constant torque and bearing load at temperature range limits, the preload is supplied by a spring washer. If the bearings were fixed relative to each other temperature changes would create excessive loads and torques. The spring washer allows one of the bearings limited axial motion. This prevents the excessive torque variation.

#### **4.4.3 RF Structures**

Some of the most difficult problems were encountered in the feed and reflector design and fabrication.

The geometry of the feed in terms of length, outer conductor diameter and wall thickness, and spacing of dipoles was determined by the RF performance requirements. Likewise, the materials were selected on the basis of electrical characteristics. Dimensional tolerances for the most part were established on the basis of RF performance. This permitted very little, if any, flexibility of mechanical design to insure structural integrity except by the method of mounting the feed and by the method of construction. The feed is fixed at its base to the encoder housing structure, and supported at the end by the reflector. Extremely precise fixturing and gauging was used in conjunction with electron beam welding to obtain dimensional control and to insure good weld joints. Dimensional stability was achieved by in-process stress relieving and rigid process control.

Two environmental factors were used to determine the success of the feed design:

1) vibration testing, and 2) temperature control. Extensive vibration testing was done on

mechanical models during and after the development of the feed configuration and fabrication technique. Early in the program when the ground rules for vibration test forcing loads were less severe than present values, the cantilever mounted feed survived without permanent distortion even though the amplitudes at the end were quite large. The support bracket at the end of the feed was added for insurance. Later in the program when it was determined that far more severe vibration requirements were necessary, the support bracket was mandatory. At the resonance frequency, the feed behaves like a cantilever beam whose amplitude is restrained by the limits of the reflector motion. At higher modes, the feed behaves more like a simple beam fixed at one end and supported at the other. The amplitudes are much smaller so that the stress levels are tolerable.

Temperature control was introduced by specific coating and finishes as explained previously.

The stepped reflector configuration was also a product of RF performance requirements. The fabrication was feasible by either dip brazing or electron beam welding. The conventional honeycomb adhesive bonded construction proposed in the original design would have been a desirable technique. However, the technique was rejected because of doubt regarding the use of adhesive bonding in a long-life space application. The present reflector is fabricated by dip brazing the entire structure at one time. Complex fixturing was necessary to maintain dimensional control during the dip braze process. Several mechanical models were built as the configuration development progressed so that the vibration characteristics of the latest configuration were generally known when each phase or development change was completed. As was the case of the feed, vibration and temperature control were the key factors influencing the reflector design.

#### **4.4.4 Ejection Mechanism**

A design requirement calls for a fail-safe mode of operation during which the reflector is ejected so that the feed can transmit and receive in an omni-directional mode. The separation is made where the split ground plane to which the reflector is attached is mounted on the antenna shaft. The mounting platform for the reflector must be rigid. Also, the ground plane, even though rigidly mounted on the shaft, must also be easily separated. A ball detent locking arrangement was selected to perform this function. In this design, steel balls are forced into detents in the two halves of the split ground plane by a steel ball lock ring. The split ground plane is disengaged by an unlocking mechanism

actuated by an explosive prime mover. After the lock ring is disengaged from the shaft, the ejection force is supplied to the ground plane by springs. The ground plane is split so that the parts clear the feed.

This ball lock ejection mechanism was perhaps the most difficult part of the structural design. It had to provide a positive lock between the motor shaft and the ground plane (to which the reflector assembly was attached) which would meet two requirements: 1) it would not falsely eject during launch, 2) it would function properly after withstanding the severe vibration loads imposed during launch.

To provide additional counter-movement to the movement imposed on the locking mechanism by the reflector structure during vibration, roller detents were added below the surface of the ground plane. These detents were provided in blocks attached to each side of the ground plane. They are clearly visible in the picture of Figure 1-1. In addition to removing much of the load from the ball detents in the ejection mechanism, the roller detents tie the motion of the two halves of the split ground plane together. In this way, the load imposed by the reflector movement is distributed more uniformly to all the balls of the locking mechanism.

#### 4.4.5 Weight Summary

An estimated weight summary of the Mechanical Drive Assembly and Control Electronics was continually maintained and updated each month. Weight summaries reflecting actual weights of components were used after the prototype unit had been fabricated.

The weight requirement was adjusted to accommodate change of scope in vibration requirements, and control electronics circuit requirements.

The final adjusted weight requirement is 14.0 pounds.

A weight summary listing the components is shown in Table 4-1. Actual weights of the qualification unit and the two flight model units are listed below:

##### Qualification Unit

|                           |                   |
|---------------------------|-------------------|
| Mechanical Drive Assembly | 8.55 pounds       |
| Control Electronics       | <u>5.1 pounds</u> |
| TOTAL                     | 13.65 pounds      |

#### Flight Model Unit (No. 2)

|                           |                    |
|---------------------------|--------------------|
| Mechanical Drive Assembly | 8.44 pounds        |
| Control Electronics       | <u>5.07 pounds</u> |
| TOTAL                     | 13.51 pounds       |

#### Flight Model Back-up Unit (No. 1)

|                           |                    |
|---------------------------|--------------------|
| Mechanical Drive Assembly | 8.46 pounds        |
| Control Electronics       | <u>4.99 pounds</u> |
| TOTAL                     | 13.45 pounds       |

Several changes were incorporated in the initial design. These were the result of analytical and/or empirical evaluations, or were changes in design requirements. Some of these were physical changes affecting weight and center of gravity. The physical changes were evaluated in terms of their effect on bearing performance. These changes and the calculations of their effects are presented next.

##### 4.4.5.1 Increased Weight

Many configuration-type changes were made, but the principal effect was the change in weight. The additional weight increases the load on the bearings during launch only, when the bearings are subjected to vibration forces. The weight increase affecting bearing loads was estimated to be 0.75 pounds.

After the unit is in orbit, the weight increase is meaningless because it operates in a zero-gravity environment.

##### 4.4.5.2 Increased Vibration Requirement

NASA introduced a change in the vibration test requirement that was far more significant, in terms of bearing load, than the weight increase. The maximum increase in forcing function was from 7.5 g's to 18.5 g's in the frequency band of 250 to 400 cps. Although a 42% increase in Hertz stress is experienced, the maximum stress is still far below that allowed.

**TABLE 4-1**  
**WEIGHT SUMMARY**

| Component                                                          | Weight in<br>pounds  |
|--------------------------------------------------------------------|----------------------|
| Reflector, Ground Plane, (counter balance &<br>Stiffener Brackets) | 2.300                |
| Shaft, Antenna                                                     | 0.170                |
| Holder, Squib                                                      | 0.018                |
| Support, Radiator                                                  | 0.147                |
| Housing, Motor Sub Assembly                                        | 1.838                |
| Pumper, Squib (2 pieces)                                           | 0.002                |
| Ejector                                                            | 0.055                |
| Spacer, Shaft                                                      | 0.007                |
| Sleeve, Ball Lock                                                  | 0.023                |
| Spacer, Large                                                      | 0.006                |
| Nut, Spanner                                                       | 0.060                |
| Locknut                                                            | 0.042                |
| Cap, Enc Lower Bearing                                             | 0.041                |
| Washer, Spring                                                     | 0.0004               |
| Shim, End Cap                                                      | 0.009                |
| Screw Special (4 pieces)                                           | 0.003                |
| Reservoir Oil                                                      | 0.235                |
| Spring, Bumper Retainer                                            | 0.0002               |
| Ring Motor Clamping                                                | 0.038                |
| Shield Oil                                                         | 0.027                |
| Pin, Anti Rotato (2 pieces)                                        | 0.0006               |
| Spring, Separator                                                  | 0.0055               |
| Locking Balls (4 pieces)                                           | 0.004                |
| Upper Bearing                                                      | 0.080                |
| Lower Bearing                                                      | 0.050                |
| Motor Stator                                                       | 1.710                |
| Motor Rotor                                                        | 0.440                |
| Feed Assembly                                                      | 0.375                |
| Encoder                                                            | 0.440                |
| Hardware                                                           | 0.156                |
| Piston Actuators                                                   | 0.002                |
| Reflector Support Bracket and Journal                              | 0.026                |
| Vernier, Shaft Encoder                                             | 0.029                |
| Bracket, Vernier                                                   | 0.040                |
| Support, Coax                                                      | 0.022                |
| Squib Connectors (2)                                               | 0.044                |
| Encoder and Motor Connectors (2)                                   | 0.044                |
| Bracket, Connector                                                 | 0.032                |
| Sub-Total                                                          | 8.550 pounds         |
| Control Electronics System                                         | 5.100                |
| <b>TOTAL</b>                                                       | <b>13.650 pounds</b> |

#### 4.4.5.3 Increased Bearing Preload

The bearing preload affects life and friction torque. It was increased from ten to twelve pounds. The calculated increase in friction torque is 0.0025 inch-pounds. The calculated bearing life is 20 times longer than the 5-year design goal.

The Hertz stress, friction torque and life - allowable, original, and final - are shown in the table below:

|           | <u>Hertz Stress</u> | <u>Friction Torque</u> | <u>Life</u>        |
|-----------|---------------------|------------------------|--------------------|
| Allowable | 350,000 psi         | 0.2 in-lbs.            | Design Goal 5 yrs. |
| Original  | 72,300              | 0.014 in-lbs           | 171 yrs.           |
| Final     | 103,000             | 0.0165 in-lbs          | 101 yrs.           |

#### Analyses

##### 1) Increase in Hertz stress on bearing race at ball contact

The worst bearing load condition occurs in vibration while the bearings are not rotating. Vibration in the lateral plane is worse than in the thrust axis. In thrust loading, all the balls are uniformly loaded; in the radial direction, approximately half the balls are loaded. The maximum load on the ball in the line of action of the load is 4.37 times the theoretical average load.

$$P_{\max} = 4.37 PG/N$$

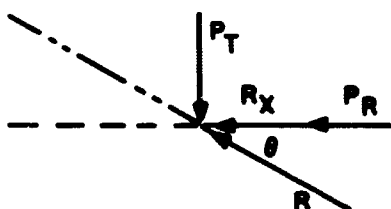
where

$P$  = average load

$N$  = number of balls

$G$  = g load

$$P = \text{average load} = R_x + P_R$$



$P_T$  = thrust load

$\theta$  = contact angle

$P_R$  = radial load

### Hertz stress

$$S_c = 0.616 \sqrt[3]{P_m E^2 \left( \frac{D_1 - D_2}{D_1 D_2} \right)^2}$$

where

E = modulus of elasticity

D<sub>1</sub> = diameter of race curvature

D<sub>2</sub> = diameter of ball

for

$$G = 7.5$$

$$18.5$$

$$P_m = 18 \text{ lbs}$$

$$1.5 \text{ lbs}$$

$$S_c = 72,300 \text{ psi}$$

$$103,000$$

- 2) Increase in Friction Torque when Preload is increased from 10 to 12 pounds

Friction Force  $F_f$  = Coefficient of friction,  $F_c$ , x normal force,  $F_N$

Bearing 3 TAR 17-24

Measured friction torque  $T_f$  with a 10-pound load = 16 gram-centimeters

This friction force is applied at the race of the bearing at approximately 1.25 inch diameter,

$$F_f = 16 \text{ gms} / 1.25 \text{ in} / 0.3937 \text{ cm/in} = 5.05 \text{ gms.}$$

Normal Force,  $F_N$  = 10 lbs.

$$fc = F_f / F_N$$

$$= \frac{5.05}{10 \times 453.6} = 0.0011$$

Friction Torque,  $T_f = F_N \times fc \times D$  [10-lb. preload]

$$= 10 \times 0.0011 \times 1.25 = 0.01375 \text{ in-lbs}$$

for 12-lb. preload

$$= 12 \times 0.0011 \times 1.25 = 0.0165 \text{ in-lbs}$$

The design torque of the motor = 0.19 in-lbs.

Conclusion: The increase in friction torque due to the increased preload is negligible.

3) **Reduced Bearing Life when Preload is Increased from 10 to 12 pounds**

The design life is one year: 8760 hours or  $3 \times 10^6$  revolutions (approx)

The design goal = 5 years: 43800 hours or  $15 \times 10^6$  revolutions (approx)

This bearing application has a thrust load due to the axial preload. There is no radial load since the parts are weightless in a zero-gravity environment. The preload was introduced to improve ball rotation on the races.

Bearing life is calculated in terms of radial load. For bearing applications having pure thrust or combined thrust and radial load, they must first be converted to an equivalent radial load.

**Rating Life in Hours (B-10 life)**

By definition, the rating life is the number of hours 90% of a group of bearings will attain or exceed before the first evidence of fatigue develops.

$$L_H = \frac{16667}{100} \left( \frac{C}{R_e} \right)^3$$

where

C = rated dynamic capacity

$L_H$  = life in hours

1) For a 10-pound preload,

$$L_H = \frac{16667}{100} \left( \frac{390}{18.6} \right)^3 = 1.5 \times 10^6 \text{ hours} \\ (> 171 \text{ years})$$

2) For a 12-pound preload,

$$L_H = \frac{16667}{100} \left( \frac{390}{22.32} \right)^3 = 0.89 \times 10^6 \text{ hours} \\ (101 \text{ years})$$

A significant difference in bearing life resulted from the increase in load. However, this comparison is purely academic in terms of the 5-year design goal for this application.

To theoretically achieve a higher survival rate, the rated BRG capacity is reduced. For 98% survival, the rated capacity is reduced about 40%.

#### 4) Calculated Bearing Life in Terms of 98% Survival

$$L_H = \frac{16667}{100} \left( \frac{0.6C}{R_e} \right)^3$$

For a 10-pound thrust load

$$L_H = 166.67 \times \left( \frac{234}{18.6} \right)^3 = 3.3 \times 10^5 \text{ hours} \\ (37 \text{ years})$$

For a 12-pound thrust load

$$L_H = 166.67 \left( \frac{234}{22.34} \right)^3 = 1.93 \times 10^5 \text{ hours} \\ (22 \text{ years})$$

#### Equivalent Radial Load ( $R_e$ )

$$R_e = X_2 VR + Y_2 T \text{ STD AFBMA Equation}$$

w/o radial load

$$R_e = Y_2 T$$

where

T = Thrust Load

$Y_2$  = Thrust Factor - (varies with  $T/nd^2$ )

where

n = no. of balls and d = dia. of balls

$$= 1.86$$

1) for 10-pound preload,

$$R_e = 1.86 \times 10 = 18.60 \text{ pounds}$$

2) for 12-pound preload,

$$R_e = 1.86 \times 12 = 22.32 \text{ pounds}$$

#### Conclusion

The calculated bearing life with a 12-pound load and 98% survival rate is more than four times longer than the 5-year design goal.

## 4.5 BEARINGS AND LUBRICATION SYSTEM

### 4.5.1 Introduction

The Mechanical Despun Antenna depends on a mechanical rotating interface to permit pointing of the beam at a fixed object when mounted on a spin stabilized satellite. The design of the mechanical rotating interface for this application takes into account the usual problems of a hostile spatial environment (primarily hard vacuum and radiation), and extremely high reliability. At the inception of this program, a space application design life requirement was rarely more than six months. The requirement for the antenna system design life was a minimum life of one year, with a design objective of five years. It was immediately obvious that the most difficult problem would be to provide substantial evidence that the rotating interface would meet the design life requirement.

The rotating interface consists of a pair of angular contact bearings. The key factor contributing to the successful operating life of a bearing is lubrication. The spatial environment imposes severe restrictions on the methods of lubrication and the types of lubricants that could be used.

Design requirements directly affecting bearing and lubrication are:

- 1) One year life - five year goal
- 2) Temperature range 20°F to 120°F
- 3) Speed 50 to 150 rpm continuous rotation
- 4) Bearing load - 12-pound preload
- 5) Total radiation dosage per year - approximately  $5 \times 10^6$  ergs/gram.

The bearings selected are a standard design thin race angular contact bearing made by Miniature Precision Bearing Inc.

The lubricant is a proprietary lubricant, developed by Ball Brothers Research, called "Vac-Kote".

This report presents the basic considerations involved in determining bearing and lubricant life in space. It outlines the basis for selecting Vac-Kote. It discusses the lubrication test program and bearing analyses that were performed to offset the lack of statistical reliability data.

#### **4.5.2 Lubricants - General Considerations**

Rolling contact bearings have been successfully lubricated in space applications with various types of lubricants. In practically all cases, the life requirement was relatively short (six months or less). Bearing lubrication tests in a hard vacuum were also of relatively short duration in most cases. Nevertheless, it was necessary to rely heavily on this information as a basis for selecting the lubricant for this antenna system. With the exception of long life, the requirements for the ATS-MDA were quite moderate. Therefore, most of the lubricants successfully applied or tested in a hard vacuum were investigated. These lubricants fall into three general categories:

- 1) Solid film coatings
- 2) Solid lubricant in the retainer structures
- 3) Oils and greases.

##### **Solid Film Coatings**

Some of the more common solid film coatings that have been used in terrestrial and space environments as well as in many tests are molybdenum disulfide, gold, silver and teflon.

The use of solid lubricant films would eliminate such problems as evaporation of the lubricant. However, solid lubricant films appear to be least capable of providing long life because of the limited wear of the film and the fact that wear debris from the film can cause erratic torque behavior and contribute to premature bearing failure. Since the film cannot be replenished, shortly after wear penetrates through the film to the parent material, failure is eminent. Also, uniform performance between bearings would be difficult to achieve because of film thickness variation from bearing.

##### **Solid Lubricant in the Retainer Structure**

The idea of using a retainer material with a solid lubricant incorporated in the structure appears more promising than using the solid film lubricant. One of the advantages is that the solid lubricant provides a replenishing supply of lubricant to the bearing. However, much work remains to be done to demonstrate reliability and life characteristics of this type of lubrication system; it is an unproven design.

## Oils and Greases

In contrast to the solid lubricants, greases and oils have long been satisfactorily used in rolling contact bearings under normal environmental conditions. One of the major problems associated with using these lubricants in space is the evaporation life of the base oils at low pressure. With some types of oil, especially mineral oils, light fractions can be rapidly removed, leaving a very viscous residual material which may affect the torque characteristics of the system. Other oils, composed of a single molecular species, will give fairly constant rates of evaporation and will leave residual oil having the same characteristics as the original charge of lubricant.

In determining the evaporative life of an oil, some consideration should also be given to the wetting characteristics of the oil. Oils have good wetting characteristics (low surface tension) will have a tendency to spread or creep out over any continuous surface of higher surface energy. This will increase the amount of surface available for evaporation to take place and will result in significantly higher evaporation rates.

Greases are subject to greater physical changes than oils when evaporation takes place at a significant rate. As the base oil is lost from the grease, the concentration of the thickener in the grease increases, resulting in a drastic change in properties. Long before all the oil is gone, the grease is transformed into a semi-solid material which provides little or no lubricant to the bearing. This "sludge" can result in premature bearing failure.

Based on these considerations, oil was selected as being the most reliable type of lubricant for this application. Sylvania has proposed the following type of oil and lubrication system for the bearings in their motor:

- a) A cotton fabric-reinforced phenolic retainer vacuum impregnated with a low vapor pressure mineral oil, Ball Brother Vac-Kote lubricant.
- b) A Nylasint reservoir impregnated with the same low vapor pressure oil.

### 4.5.3 Effect of Environment

With this type of bearing and lubrication system, the major environmental condition which could affect bearing performance is low pressure. Low pressure results in lubricant evaporation, since the rate of evaporation is a function of pressure. To obtain data on these lubricant characteristics, tests are conducted which must be as nearly as possible a true simulation of space.

The problem is discussed briefly in the following paragraphs.

To obtain a true simulation of the evaporation of lubricants in space, it is essential to note that once a molecule leaves a surface which is exposed to outer space, it is completely lost. Only rarely will escaping molecules collide with other bodies and be returned to the surface. This means that the evaporation of organic molecules or the abrasion or decomposition of surface films will ultimately result in the production of chemically clean surfaces. These bare surfaces are often prone to welding and surface damage.

To simulate this condition in the laboratory, more than low pressure is required. If one places a fluid sample in a clean vacuum chamber, a high initial evaporative loss rate will be noted. This is because the walls will collect evaporated molecules, thereby providing pumping capacity in addition to that of the attached pumping system. As soon as the surface is partially covered, re-evaporation begins. At this time, a molecule leaving the fluid surface may make a large number of collisions before it is removed by the pumping system.

Statistical calculations on a typical vacuum system suggest that the measured fluid evaporative rate is significantly less than the true rate. To avoid this pitfall there are two basic requirements for simulation:

- 1) The chamber pressure must be low enough to provide a mean-free molecular path which is large compared with the dimensions of the chamber. This will minimize random collisions with gas molecules in the chamber. A pressure of  $10^{-5}$  Torr or less is necessary for this requirement.
- 2) A condensing surface will be required which will collect and hold all molecules leaving the fluid surface. Generally, cryogenically cooled condensing surfaces which "view" the fluid surface will fulfill this requirement.

In addition, both temperature and time will affect the evaporation rate. Temperature is particularly critical since there is a rule-of-thumb guide which states that the evaporation rate of a fluid will increase tenfold for each ten percent rise in the absolute temperature.

#### **4.5.4 Bearings**

Bearings have a long history of successful performance in a terrestrial environment that includes demonstrations of long life. Loads, speeds and temperature as well as lubrication are crucial factors affecting bearing life. If these conditions are carefully

observed when selecting a bearing, an extremely high degree of reliability can be achieved.

Statistics have been compiled which show correlation between calculated and actual bearing life when actual loads and speeds are representative of the value used in calculating bearing life. When these conditions are observed and the calculations show high reliability, extremely high reliability is achieved.

The same conclusions can be made for long term space applications provided:

- 1) Lubrication can be maintained throughout the bearing life.
- 2) Contamination such as solid particles, residue from corrosion or from the evaporated lubricant are avoided.

In a terrestrial environment, the lubricant helps to carry off contaminants harmful to bearing performance. Since it helps to keep the bearing clean, there is less concern about maintaining an absolutely clean environment. Bearings operate in space on molecular film thicknesses of lubricant. It is of prime importance that no contamination be present, first, because it can penetrate the lubricant film, and second, because the lubricant does not perform a cleaning function as it does in the case of terrestrial applications.

There is no statistical reliability data on long life bearing operation in space. However, reliability is demonstrated by uniform performance of a quantity of identical parts. Stringent quality control procedures were used to insure greater than normal uniformity of parts in addition to maintaining dimensional discipline. This was done by selecting bearings having close similarity in:

- 1) Race and ball hardness
- 2) Bearing friction torque
- 3) Race profile
- 4) Smoothness of operation.

Another useful operation performed on the ATS MDA bearings was a 50-hour run-in. Random failures that result from hidden manufacturing flaws are often eliminated by this run-in.

#### 4.5.4.1 Bearing Life Calculation

Assuming that the above conditions (adequate lubrication and no contamination) are satisfied, the wear life of the ATS Despun Antenna bearing has been calculated based upon the known bearing loads. These calculations are summarized next.

The dynamic load capacity of the smaller of the two bearings used in the mechanical drive system based on a 98 percent survival rate is 223 pounds. In terms of the load-life relationship, a bearing operating for five years under the load conditions of the subject application, the calculated dynamic load is 137.5 pounds, or approximately 61 percent of the rated capacity.

All formulae used for calculating bearing life are based on AFBMA standards

$$L_N = \left( \frac{C}{R} \right)^3 \quad (4-1)$$

where

$L_N$  = rated life in millions of revolutions that 90% of the bearings will attain or exceed before the first evidence of failure

$C$  = Dynamic load rating in pounds

$R$  = applied radial load in pounds

Since the loads in this application are not pure radial, an equivalent radial load is substituted in the formula

$$L_n = \left( \frac{C}{R_e} \right)^3 \quad (4-2)$$

where

$R_e$  = equivalent radial load in pounds

If life is desired in hours

$$L_H = \frac{16667}{N} \left( \frac{C}{R_e} \right)^3 \quad (4-3)$$

where

$L_H$  = rated life in hours

$N$  = speed of rotation in RPM

### Equivalent Radial LOAD

$$R_e = X_1 VR + Y_1 T \quad (4-4)$$

$$R_e = X_2 VR + Y_2 T \quad (4-5)$$

where

Factor V = 1.0 for inner ring location

R = applied radial load in pounds

T = applied thrust load in pounds

$X_1$ ,  $X_2$ ,  $Y_1$ ,  $Y_2$  are radial and thrust factors, value of which are normally obtained from radial and thrust factor tables.

### Speed and Life Factors, SF and LF

Equation (4-3) can be rewritten

$$C = R_e \sqrt[3]{\frac{L_H N}{16667}} \quad (4-6)$$

$$L_F = \sqrt[3]{\frac{500}{L_H}} \quad (4-7)$$

$$SF = \sqrt[3]{\frac{33 \frac{1}{3}}{N}} \quad (4-8)$$

Substituting these factors in equation (4-6)

$$C = \frac{R_e}{SF \times LF} \quad (4-9)$$

### Solving for Equivalent Radial Load

Using equations (4-4) and (4-5)

$$R_e = (1)(1)(0.20) + (1.25)(10.0) = 12.7$$

$$R_e = (0.7)(1)(0.20) + (1.86)(10.0) = 18.74$$

Use the larger of the above values

### Solving for Speed and Life Factors

Assume desired rated life for two conditions

1) Required design life of 1 year

2) Design goal of 5 years

$$L_{F(1)} = \sqrt[3]{\frac{500}{8760}} = 0.385 \quad (4-10)$$

$$L_{F(5)} = \sqrt[3]{\frac{500}{43800}} = 0.229 \quad (4-11)$$

$$SF = \sqrt[3]{\frac{33.33}{150}} = 0.605$$

### Solving for Dynamic Load

$$C_{(1)} = \frac{18.74}{0.385 \times 0.605} = 80.0 \text{ lbs.}$$

$$C_{(2)} = \frac{18.74}{0.229 \times 0.605} = 137.5 \text{ lbs.}$$

### For Higher Degree of Reliability

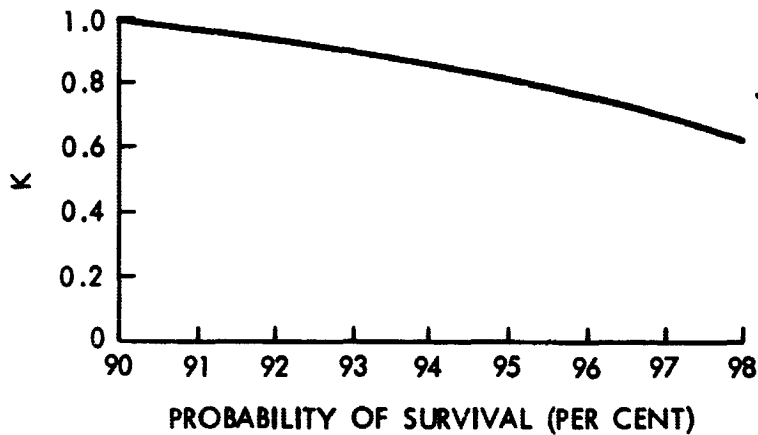
The preceding life-load relationship is based on a survival rate of 90%. For a higher survival rate

$$C_A = KC$$

where

$C_A$  = resulting adjusted load for a higher survival rate

$K$  = Factor - function of minimum percentages of survival from the following chart



#### Solving for Dynamic Load Based on 98% Survival Rate

$$C_A = KC_R$$

where

$C_R$  = rated dynamic load

$K$  = factor from the chart

For a MPB 3TAR-17-24 bearing  $C_R = 360$  lbs.

$$C_A = 0.62 \times 360 = 223 \text{ lbs.}$$

$C_A$  is the derated allowable dynamic load for above bearing for 98% probability of survival.

#### Bearing Life - Using Dynamic Load Capacity $C_A$

$$L_H = \frac{16667}{100} \left( \frac{223}{18.74} \right)^3$$

$$= 280,000 \text{ hours}$$

#### 4.5.5 Lubrication System

The MDA lubrication system is shown in Figure 4-41. Two narrow annuli - one at each end of an otherwise totally enclosed motor housing - form the exit passageways for the lubricant. The bearings are located just inside those exits. The flow path of the lubricant vapors is through the bearings and replenishes the lubricant on the bearings. The lubricant is stored in a Nylasint reservoir as a liquid. It evaporates from the

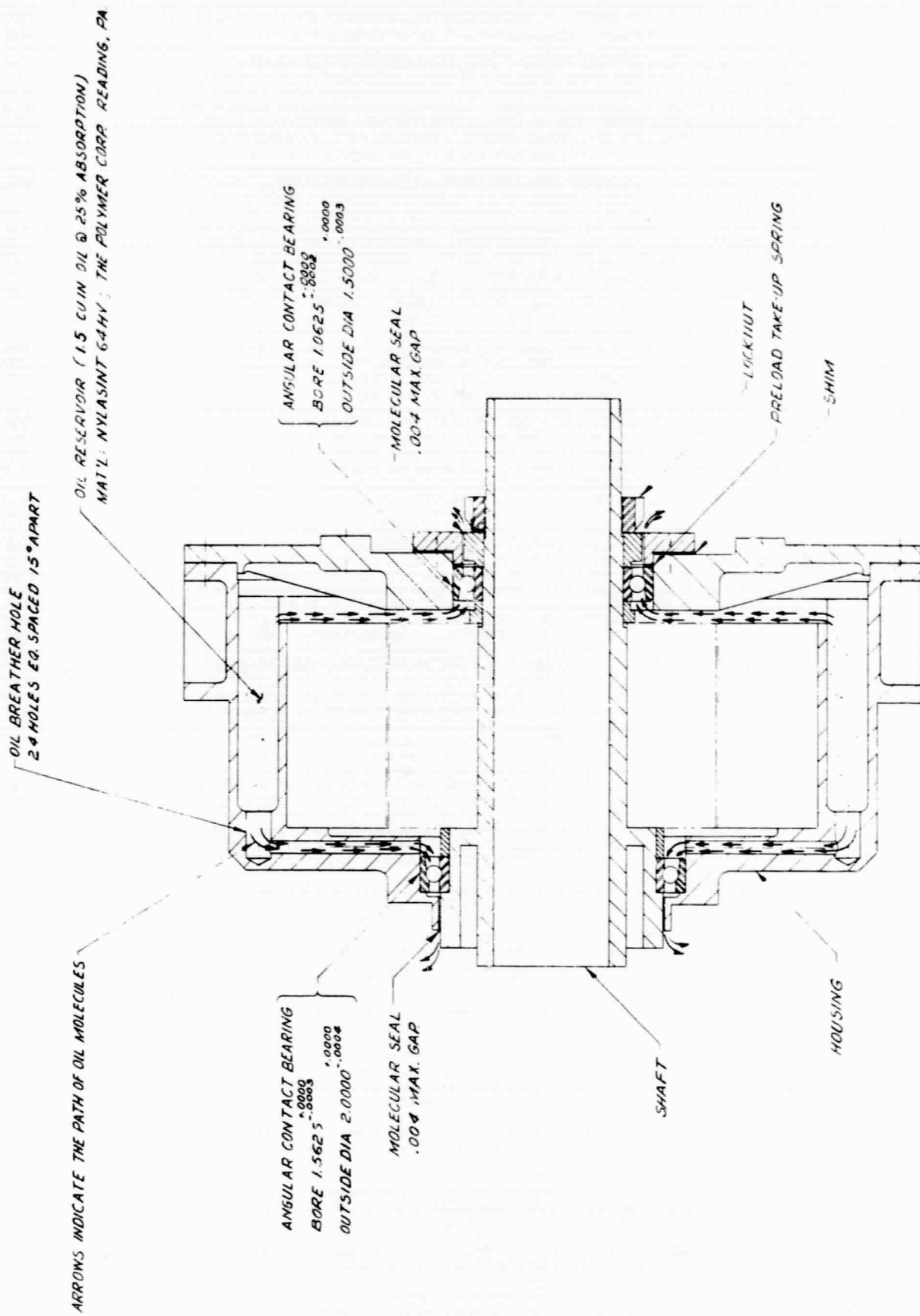


Figure 4-41. Bearing Lubrication System for Mechanical Despun Antenna

reservoir to form an artificial atmosphere of lubricant vapors within the enclosure. This tends to retard the evaporation from the bearing. The exit passages form a limited access of 0.004 inch around the shaft, thus retarding evaporation. The reservoir can store approximately 25 gms of lubricant.

To determine the required reservoir capacity, it is necessary to determine the amount of lubricant which will evaporate and escape from the closed housing volume. The following equation is useful for this purpose

$$S = (5.832 \times 10^{-2}) P_v \left(\frac{M}{T}\right)^{1/2} \quad (4-12)$$

where

$X$  = weight of lubricant evaporated in gms/cm<sup>2</sup> sec (or escaping through the shields)

$P_v$  = vapor pressure of the lubricant at temperature  $T$  in degrees Kelvin

$M$  = molecular weight of lubricant

$T$  = temperature in deg. Kelvin

Equation (4-12) is derived from kinetic gas theory and can be found in most texts on vacuum technology. It actually results from a calculation of the number of molecules striking a given plane. Since the plane can be taken as either the surface of a lubricant or the escape apertures, it can be used for both calculations. The basic assumption which allows its use for evaporation calculations is that when a material is at equilibrium with its vapors, the number of molecules striking a surface in a unit time is equal to the number of leaving the surface.

To determine the vapor pressure as a function of the temperature, the Clausius-Clapyron relation can be used. In the simplest form, this relation is expressed as

$$P_v = \ln P_v = A - B/T \quad (4-13)$$

where

$A$  = constant in mmHg

$B$  = constant

Equation (4-13) is not general and should be used over limited temperature ranges. BBRC has conducted weight loss measurements in vacuum at 50 and 100°C to determine the evaporation characteristics of the lubricant. Data from these tests confirmed the supplier's specifications as determined by independent tests. The A and B values calculated from this data are

$$A = 1.017 \times 10^6 \text{ mmHg}$$

$$B = 9.718 \times 10^3$$

Since  $\ln P$  is a linear function of  $(1/T)$ , equation (4-13) can readily be plotted on semi-log paper for use with equation (4-12). Using these equations and the temperature profile, the following values were determined for the yearly loss of lubricant from an exposed reservoir.

| <u>°F</u> | <u>°C</u> | <u>°K</u> | <u>Percent of<br/>Time at Temperature</u> | <u>Lubricant Loss<br/>gm/cm<sup>2</sup> yr</u> |
|-----------|-----------|-----------|-------------------------------------------|------------------------------------------------|
| 120       | 49.4      | 322       | 25                                        | 0.0617                                         |
| 73        | 23        | 296       | 50                                        | 0.0073                                         |
| 20        | -7        | 266       | 25                                        | <u>0.0001</u>                                  |
| Total     |           |           |                                           | 0.0691                                         |

Assuming a 25 percent porosity of the Nylasint and a density of 0.88, the reservoir volume required for the above total loss per year is

$$\frac{4(0.0691)}{0.88} = 0.313 \text{ cc/cm}^2 \text{ yr}$$

$$= 1.565 \text{ cc/cm}^2 \text{ yr}$$

This loss rate for an unshielded reservoir is the maximum loss and does not allow for the actual lubricant area exposed on a reservoir surface. It will approximate the "worst case" condition. A comparison of the data thus obtained with the data already taken would provide a measure of the reservoir efficiency.

Two factors which will reduce losses are the sealing effects of the bearings and the external mounting parts which already have provisions for sealing effects. Adequate design of these parts can reduce the loss by at least an order of magnitude.

In addition, the highly polarized molecules of the Vac-Kote materials will be attached to the bearing surface by forces which are greater than the cohesive forces

between molecules in the film. Thus, the last molecular layers will evaporate at a rate slower than that indicated by the weight loss data. But, again, to approximate a worst case condition, this effect was not considered in calculating the required reservoir volume.

#### **4.5.6 Proof of Design Test Program Description**

Successful operation of mechanical devices in the environment of outer space will require components which can withstand a variety of unusual environmental conditions.

Exact duplication of the entire space environment in the laboratory would be practically impossible because of cost and complexity. Therefore, to evaluate components in the laboratory, it is necessary to select the major environmental conditions which would affect the function of the component, and to simulate these particular conditions as closely as possible.

An experimental study has been made of the capability of the Motor-Bearing Assembly for the ATS Despun Antenna to function properly in space for a minimum of one year. The original intent of this work was to perform a 5000-hour motor life test in vacuum to demonstrate the capability of the motor. However, since this motor test would be on a single component, additional evaluations were thought to be worthwhile to achieve greater confidence in the bearing and lubricant system. The most obvious mode of failure for oil-lubricated bearings operating in high vacuum would be the loss of oil by evaporation. Therefore, in addition to the motor test, a series of short-time ball bearing tests were also run in vacuum at various elevated temperature levels to measure the actual evaporation rate of the lubricant. From these results, an extrapolation was made to predict the effective life of the lubricant in the motor drive unit at the operating temperature level which would be encountered in the satellite. An experimental check could therefore be made on the reservoir capacity calculations presented above.

Both the life test and the lubricant evaporation tests were performed by an independent test facility, Mechanical Technology, Inc., under contract to Sylvania. The best way to present this test program is by using the following excerpts from the MTI sub-contract and test report.

#### **4.5.6.1 5000 Hour Qualification Test**

The 5000 hour test on the drive system will demonstrate the motor, bearings and lubrication system design capabilities. The analysis of the data and of the test components will be used for interpreting extended bearing life.

The following measurements will be made. Mechanical torque and power consumption measurements will be recorded before, during, and after the 5000 hour test. Torque characteristics for normal operation at the extreme temperature limits will be obtained. Abnormal performance of the drive unit will also be detected in the process of making these measurements. A hi-pot test on the windings of the motor before and after the test will detect winding insulation deterioration. Several critical parameters of the bearings such as eccentricity and runout will be recorded before and after the test. Measurements of 20 millionths of an inch are possible. The bearing parameters will be measured by the bearing vendor.

A difference in readings before and after running would indicate wear. The magnitude of this difference can, within reason, be interpreted in terms of per cent of the total wear expected at the end of the useful life of a bearing. The evidence of wear and the type of wear can usually be analyzed to pinpoint the cause.

The following factors will compositely demonstrate bearing design capability for a minimum of one year design life:

- 1) Acceptance testing by the bearing vendor consisting of:
  - a) A no-load friction torque test
  - b) "Smoothrotor" test (this is performed with an electronic device that determines vibration characteristics caused by surface finish, accuracy of manufacture and contamination)
  - c) Specified material uniformity
- 2) The 5000-hour performance test
- 3) Bearing friction torque test before and after the 5000 hour test, Microscopic inspection and bearing race profile check after the test.

In the ATS-MDA application, the loads, speeds, and temperature range are much less than what the bearings are capable of carrying. The bearing life is primarily dependent on the maintenance of adequate lubrication.

Therefore, supplementary testing will be performed on additional bearing and lubrication systems to establish a lubricant evaporation rate versus temperature relationship. This will be done by running lubricated bearings at loads and speeds specified for this application. The results would also provide an independent check on the data accumulated in the 5000 hour motor-bearing assembly test.

#### 4.5.6.2 Lubricant Evaporation Rate Test

It has been shown that the evaporation loss of liquid lubricant increases roughly tenfold for each ten percent rise in the absolute temperature.\* This suggests that the evaporation loss of oil from a bearing could be determined in a relatively short period of time if the test temperature level were raised.

For example, if it were necessary to determine the rate of evaporation of an oil at 100°F (560°A), this could be determined by the following procedure:

1. A test could be run for a pre-determined period of time at a constant temperature of 156°F (616°A) which is an increase of ten percent in absolute temperature over the 100°F point. At periodic time intervals, the sample would be weighed to determine how much weight loss had occurred because of evaporation.
2. A second test could then be run at some higher temperature (for example 268°F) which would be a thirty percent increase in Absolute temperature over the original 100°F value. This sample would also be weighed at periodic intervals. The results could then be plotted as shown in Figure 4-42. (As a rule, these curves will not pass through the origin since the initial weight loss is generally much higher than the steady-state values.)

The slopes of these two curves represent the rate of oil loss. If these slopes are then plotted as a function of temperature, a curve is obtained which can be extrapolated to lower temperatures. This is illustrated in the graph shown in Figure 4-43.

In this manner, it is possible to determine how much evaporation should be anticipated over much longer periods of operating time at a lower operating temperature. The results will be very conservative since the slope of the evaporation curve will usually decrease with time.

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\* Lewis, P. Murray, S.F. and Peterson, M.B., "Lubricant Evaluation for Bearing Systems Operating in Spatial Environments", Trans., ASLE Vol. 6, 1963, Pp. 67-79.

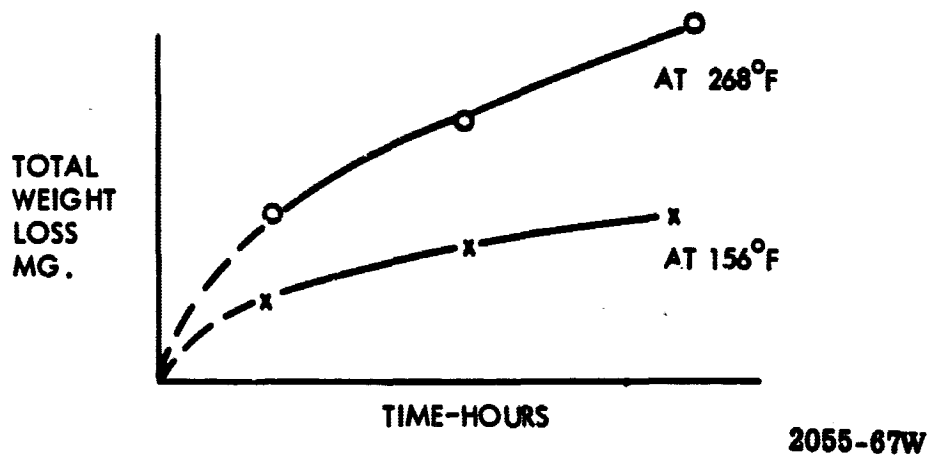


Figure 4-42. Lubricant Loss, Weight Versus Time

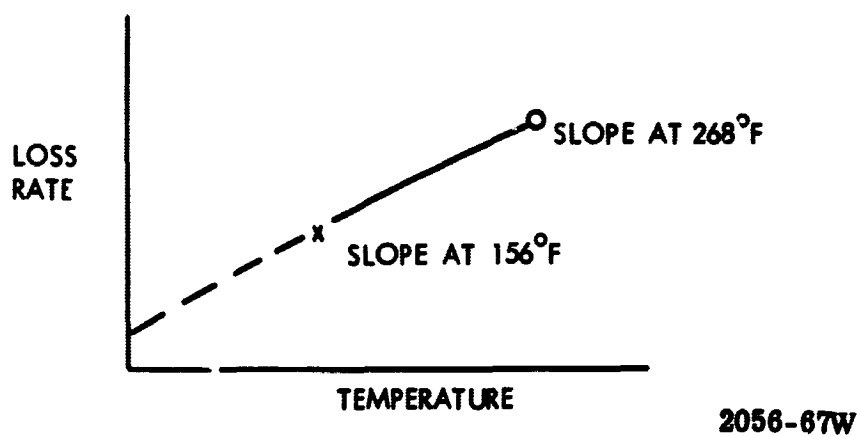


Figure 4-43. Lubricant Loss, Loss Rate Versus Temperature

#### **4.5.6.3 Test Plan**

##### **Section I - 5000 Hour Motor-Bearing Assembly Test**

**I. Scope -** The purpose of this test is to demonstrate the drive system design capability for 5000 hours, and also demonstrate extended life based on a wear analysis of the bearings and a hi-po. test on the windings of the motor.

**II. Test Component -** The component to be tested is the motor-bearing assembly of the mechanical drive system for the ATS Despun Antenna. The following parts, or assimilated parts, will constitute the motor-bearing test component:

- 1) Drive Motor**
- 2) Bearings**
- 3) Shaft and Shaft Apron**
- 4) Upper End Cap**
- 5) Housing**
- 6) Encoder Housing (or an Assimilated Part)**
- 7) Split Turntable (Modified)**
- 8) Lower End Cap**
- 9) Reservoir**

The approximate weight of the test assembly is five pounds; the approximate space envelope is six inches in diameter by six inches in height. The above items 1 through 9 can be identified by name in Figure 4-44. These parts will be furnished by Sylvania as an assembly to the sub-contractor who will perform the tests.

##### **III. Test Conditions**

- 1) The test condition shall be  $1 \times 10^{-8}$  torr with temperature cycling between 20°F and 120°F according to the following schedule:**
  - 25 percent of time at 120°F**
  - 50 percent of time at 50°F to 90°F**
  - 25 percent of time at 20°F.**

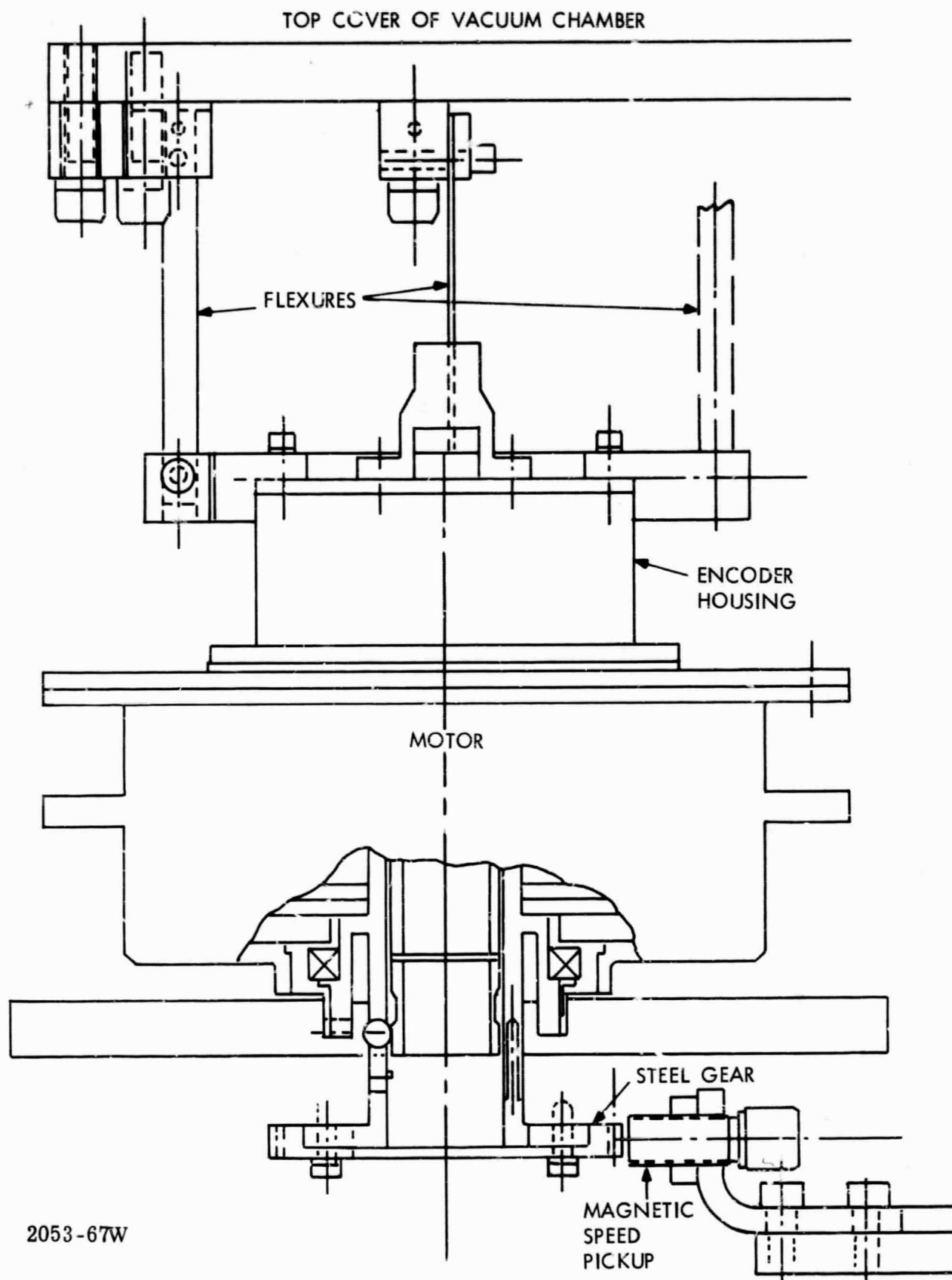


Figure 4-44. Motor Mount in Vacuum System, Schematic Drawing

- 2) The operating mode shall be 100 RPM constant speed for 5000 hours
- 3) Provisions will be made for mounting thermocouples on the test component at the following points:
  - a) one on each bearing outer race
  - b) one on the motor stator.

#### IV. Test Equipment and Facilities

- 1) Vacuum chamber capable of  $1 \times 10^{-8}$  torr with test component installed
- 2) Power supply: 24 vdc  
5 vdc
- 3) Motor drive circuit (furnished by Sylvania)
- 4) Wattmeter for measuring input power
- 5) Copper-constantan thermocouples with automatic recorders
- 6) A tach. meter for monitoring motor speed
- 7) A dynamometer attached to the rotating element for periodic torque measurement, or the equivalent.

#### V. Checkout and Test Procedure

- 1) Contamination check on vacuum chamber dry and empty
- 2) Functional checkout of test system outside of vacuum chamber
- 3) Installation and checkout of system in vacuum chamber
- 4) Pump down and stabilization of temperature control system
- 5) 5000-hour test
- 6) Repeat Item 2.

#### VI. Test Data

- 1) Continuous monitoring of thermocouple temperature, speed, and input power
- 2) Periodic check on mechanical torque and chamber vacuum
- 3) Lubricant weight loss check at completion of test
- 4) Mechanical starting and running torque and spin axis run-out check before and after 5000-hour test.

## **VII. Test Unit Component Analysis**

- 1) Visual inspection for wear**
- 2) Recheck of critical parameters documented on bearing drawing (to be done by vendor)**
- 3) Bearing degradation results**
- 4) High pot test on motor windings.**

## **VIII. Test Conclusion**

- 1) Analysis of test data**
- 2) Interpretation of data**

## **IX. Test Reports**

- 1) Interim monthly progress reports**
- 2) Final report including results of data analysis and interpretation**

### **Section II - Lubricant Evaporation Rate Tests**

**I. Scope - The purpose of this test is to determine the evaporation rate of the Vac-Kote lubricant at several temperatures so that an evaporation rate-temperature relationship can be established.**

**II. Test Component - The components to be tested will be Vac-Kote processed MPB 3-TAR-25-32 size and type bearings equipped with MIL-P-79 type FBE phenolic retainers and Nylosint (25% porosity) reservoirs.**

**These parts will be mounted so that the oil passage to the bearings and escape aperture will be representative of the Despun Antenna application.**

**A total of six bearings and four reservoirs will be tested. Two bearings and reservoirs will be used in Parts I and II (defined below) of the test, and 2 bearings without reservoirs but with impregnated retainers will be used in Part III of the test plan. The third part of this test will establish a base line to determine how rapidly the oil reservoir is required to resupply oil to the bearings.**

### III. Test Conditions

- 1) Vacuum             $10^{-7}$  torr minimum
- 2) Temperature        part I 156 °F  
                             part II 268 °F  
                             part III 268 °F
- 3) Load - approximately two pounds thrust.
- 4) Speed - 100 RPM, constant.
- 5) Length of test - a total of 300 hours each for Part I, II, and III.

#### 4.5.6.4 Test Equipment

##### The Vacuum System

The vacuum system consisted of a vertical stainless steel cylinder with an inside diameter of 14 inches and a working depth of 14 inches. A 100-liter per-second triode ion pump was mounted in the bottom of the chamber. Rough pumping was done by a pair of sorption pumps. Liquid Nitrogen-cooled reservoirs and chill plates also provided very fast pumping for condensible vapors. The chamber vacuum was measured by means of a General Electric trigger gage mounted in the center of the chamber as shown in Figure 4-45.

##### Motor Test Configuration

Figure 4-46 is a photograph of the actual motor, mounted to the top cover of the vacuum chamber. This photograph was taken before the cryogenically-cooled copper shielding was placed around the motor. This shielding was made of thin sheet copper which was mounted in overlapping sections around the motor to provide an optically-tight baffle.

Several large gaps were left behind the sections for pumping purposes. This copper baffling was bolted securely to the liquid nitrogen reservoir system for good heat transfer.

In this test, the vacuum system pressure was held lower than  $1 \times 10^{-8}$  Torr. This low pressure, coupled with the fact that cryogenically-cooled condensing surfaces surrounded the motor, satisfied the requirements for Evaporative Simulation which was necessary to simulate both low pressure and lack of an atmosphere.

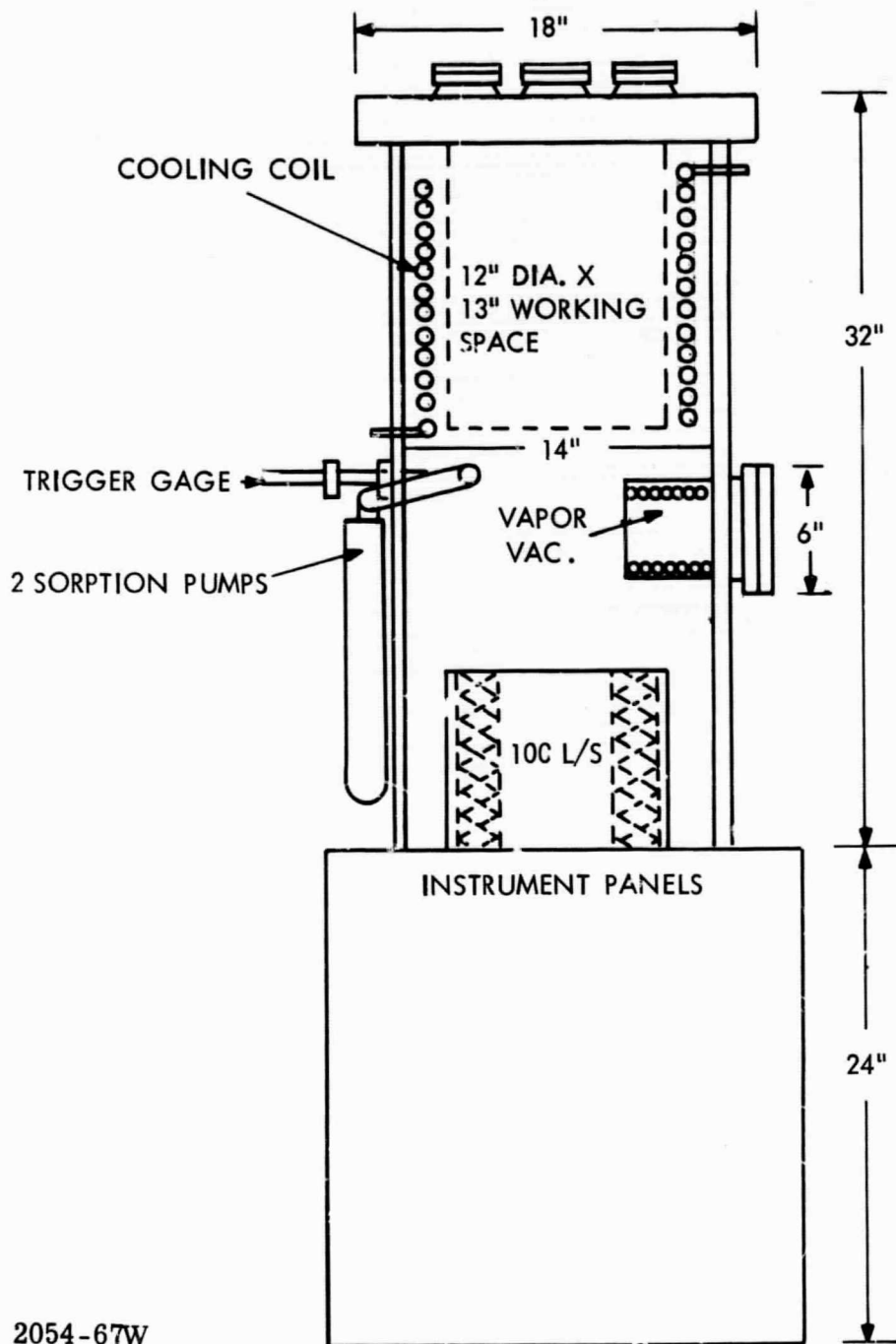


Figure 4-45. Vacuum System Layout, Schematic Drawing

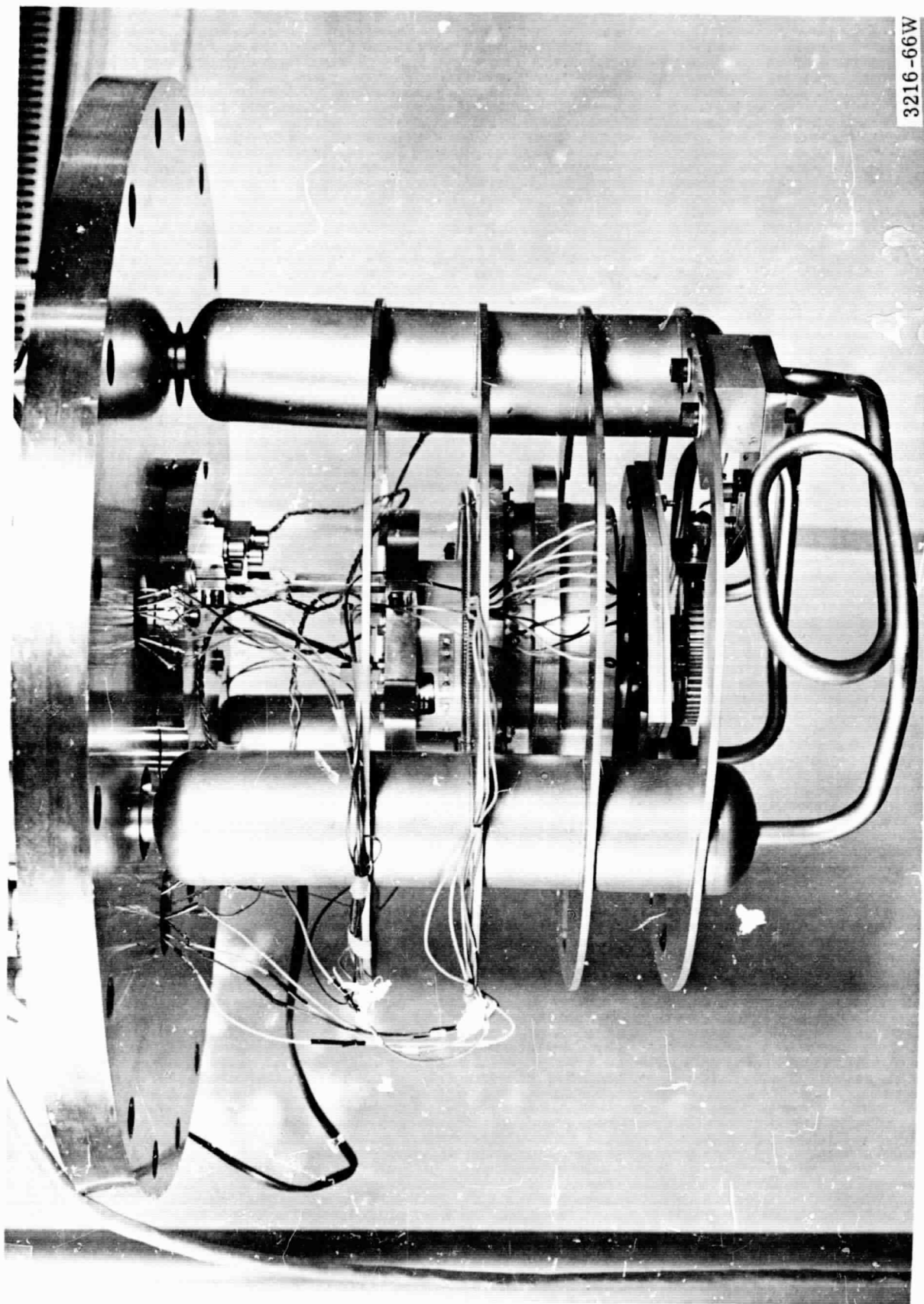


Figure 4-46. Motor Mounted to Top Cover of Vacuum Test Chamber

The test temperature of the motor was maintained by means of two nichrome coil wire heaters which were mounted on the top and bottom of the motor casing. Power to these heaters was controlled individually by two Variacs. This system satisfied the requirement for environmental temperature control.

### Instrumentation

The motor was suspended from the top cover of the vacuum chamber by means of three flexure arms on which strain gages were mounted. These flexure arms were attached to an adaptor plate mounted on the encoder housing. The tendency of the encoder housing to rotate was restrained by the flexure arms and the resulting deflection was sensed, measured and recorded by the calibrated strain gage instrumentation circuit.

The motor was driven by means of three individual power supply units. Two of these were used for the  $\pm 5$  volt-dc auxiliary circuits and one was used for the 24 volt-dc motor drive.

Temperatures were measured by means of four copper-constantan thermocouples. Two of these thermocouples contacted the outer races of each of the ball bearings, one couple was used to measure the motor stator temperature and one couple monitored the support structure. These temperatures were recorded continuously.

A magnetic pickup was used to monitor speed continuously. Input power to the motor was also determined as a check against the torque measurement.

### 4.5.6.5 Test Results

The test sequence consisted of the following steps:

- 1) A check-out of the motor characteristics in air
- 2) A fifty-two day run at a constant temperature of 120°F
- 3) A fifty-two day run at 90°F
- 4) A fifty-two day run at 50°F
- 5) A fifty-two day run at 20°F
- 6) A final check-out of the motor characteristics in air
- 7) Partial disassembly of the motor to examine the bearings and estimate the condition of the lubrication system.

The system was then pumped down and the 5000-hour test was started on October 19, 1965. A temperature cycle test was then run to determine the torque behavior of the motor at the four test temperature levels. During this temperature cycling, small changes in motor power consumption were measured. The lowest torque values were noted at +20°F. While the motor temperature was being raised from +20°F to +70°F, the torque increased steadily. Heating from +70°F to +120°F had no effect on the torque. The same results were obtained in other temperature cycle tests which were run later in the program. Although these torque changes seemed significant, it should be noted that the absolute values of torque are very low, and remained low throughout the 5000 hour run. The absolute torque values varied from 0.020 to 0.040 in-lbs.

On November 9, a general power failure occurred and the test was shut down for four hours. The vacuum was maintained during this time, but no attempt was made to run the motor.

The first of two 24-volt dc power supply failures during the 5000 hour motor test occurred on Friday afternoon November 26th. This forced a shutdown of the motor for four days until a new calibrated power supply could be obtained. Both the vacuum and temperature control levels were maintained during this shutdown. The motor restarted easily, at essentially the same power level, when the power supply was replaced.

On December 20, 1965, the 120°F test was concluded and a second temperature cycle test was run. The average torque was constant at approximately 0.020 inch. The general trend of this temperature cycle test was the same as the results obtained at the beginning of the 120°F run, i.e., the torque increased as the temperature was raised. One high torque peak was also noted when the temperature was being increased from 70°F to 120°F, but the torque dropped back to a lower value before the temperature reached 120°F. The test at 90°F was concluded on February 6, 1966. The average torque was constant but about .015 in-ounces higher than it was during the 120°F temperature run. A third temperature cycle test was run. The trend was about the same as in the two previous runs.

The test at 50°F was concluded on April 6, 1966. The torque was about the same as during the test at 90°F and continued to be constant. The +20°F test was concluded on June 8, 1966. No change in performance was observed.

From June 8 to July 15, 1966, the test unit was held under vacuum with the motor shut down and without heat being supplied to the chamber. The motor temperature during this time was about -80°F.

On July 15, 1966, the motor temperature was brought up to +120°F. The motor was restarted without difficulty.

The torque at start up at 20°F was about 0.05 inch-pounds and it subsequently leveled off at about 0.04 inch-pounds for the next 1500 hours.

At this time the test was terminated. The test unit was removed from the chamber and partially disassembled.

No gross quantities of condensed lubricant could be found on the cryogenic shield or motor housing. Nothing unusual was observed in the disassembled parts. No bearing wear could be detected from a visual inspection. The bearings were returned to the manufacturer for a complete analysis.

#### 4.5.6.6 Conclusions

The changes in torque observed throughout the 7800 hours under vacuum resulted from changing temperatures.

The maximum (peak) torque observed (less than 0.1 inch-pounds) was considerably less than the motor design torque of 0.2 inch-pounds. The actual demonstrated torque of the motor was in excess of 0.5 inch-pounds. The results of the oil evaporation tests indicated that the evaporation life of a 1.0 gram quantity of oil at 120°F would be about one year. These results are based on bearings whose races were exposed to full evaporation to space. These values are extremely conservative, since the area of the escape aperture on the test unit is less than the full exposed bearing by a factor of ten. The relationship of the exposure area to the evaporation rate is shown by the classic kinetic theory of gases.

$$W = 0.0583P(M/T)^{1/2} A \text{ gr/sec}$$

where

P = Vapor pressure in Torr at temperature K

M = Molecular weight of the oil

A = Area of aperture in cm<sup>2</sup>

W = Weight loss of oil

The extrapolated evaporation rate for the test unit is about 0.1 grams/year. The capacity of the reservoir is 24 grams. The expected lubricant life based on complete evaporation of all the lubricants is 240 years at a temperature of 120°F.

No bearing wear could be detected. A dull finish on the cryogenic shield was found to be a very thin film of condensed oil. There were no other indications of oil either on the test unit or in the vacuum chamber.

No high torque or high power consumption was observed during the test.

The results are highly indicative of the anticipated performance in actual space.

#### **4.5.7 Bearing Analysis Results**

##### **4.5.7.1 Discussion**

There are two bearings on the test unit. Both were removed and sent to the bearing manufacturer. One of the bearings came apart when it was being removed, and the balls were thereby damaged. However, the damage was clearly identified and could be isolated from other possible changes that might have occurred during the test. The balls had a ridge mark which occurred where they rolled over the edge of the ball groove on the outer area. The second bearing was lost by the bearing manufacturer.

The bearing races, retainer and balls were initially examined - under a 25X microscope - for the normal and abnormal physical changes that would be associated with bearing operation. Some of the physical changes that could be expected are:

- 1) a pronounced ball track on the race ball groove,
- 2) polished areas in the retainer ball packets,
- 3) pitting in the races,
- 4) scratches or scuff marks on the balls,
- 5) a change in bearing friction torque and a noticeable change in the race profile.

These changes would be considered normal as long as the magnitude, in the judgment of bearing specialists, was not excessive.

Since the inner race is the weaker member of the two races, it was subjected to more critical examination. The ball track, which is the race surface on which the balls roll, could be detected, but only with the aid of a microscope. The ball track appeared to

have a more polished surface than the adjacent areas. The hone marks were still very distinct. (Honing is the final machining process used to provide the desired surface finish on the bearing race.) The appearance of the hone marks strongly indicates negligible burnishing and no wear on the race. The ball track was straight, and its width uniform. These characteristics are associated with bearings that are in good alignment.

The inner race profile and smoothness was checked and then compared with an identical bearing that had been Vac-Kote processed, and run-in for 50 hours. The test bearing profile was as good, if not better than the other bearing.

Pronounced ridge lines were observed on the balls, but they had occurred when the bearing was inadvertently pulled apart. Except for the ridge lines, no other marks were visible on the balls.

Normally, the retainers are first to show signs of wear. The rubbing area where wear would persist is in the ball pockets of the retainer; areas where pronounced rubbing occurred would show up as polished areas. However, the retainer of the test bearing looked unused.

Several dark areas were randomly located on the ball groove of the inner race. They appeared to be slight surface depressions when observed under a 15X microscope. In order to examine them more closely they were inspected under a 100X microscope, and the following observations were made:

- 1) The areas were irregular in shape
- 2) They were not carbides exposed at the surface
- 3) They were randomly located
- 4) The tool marks (honing) were visible in these areas
- 5) The largest of the areas was about 0.006 inch across at the widest point.

It was concluded that they were not pits or gouged areas. However, the areas could not be explained. Therefore, the race was re-examined under 200X and 400X microscopes respectively. If these areas were depressions with any depth, it was not perceptible. Photo-micrographs were taken at 200X and 400X. It is apparent that these areas were not caused by foreign particles imbedded in the race, or distorting the surface. There are no indications that surface deterioration had occurred.

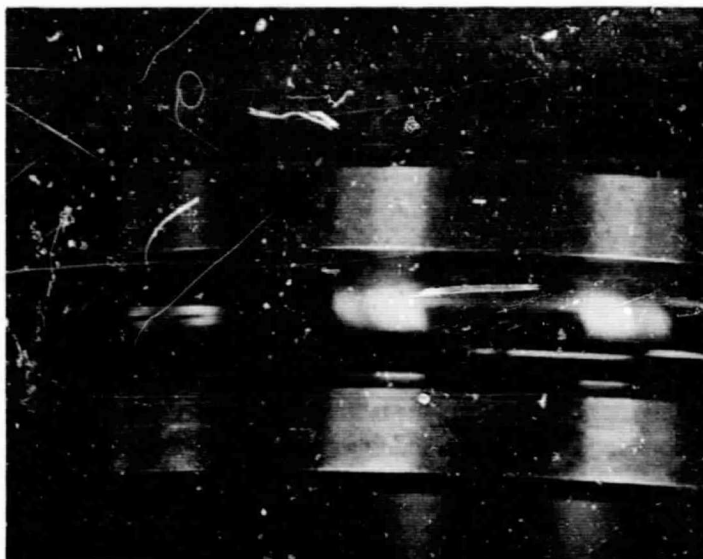
#### 4.5.7.2 Conclusion

Examination of the bearing confirms the test data indications. The bearing performance was normal. There was no evidence of wear, pits, surface scratches or cold weld.

The dark areas observed cannot be explained. However, they did not affect the bearing performance. It is possible that they are associated with the material itself.

#### 4.5.7.3 List of Bearing Analysis Figures

| <u>Figure Number</u> | <u>Description of Figure</u>                                                                                                                             |
|----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| 4-47 (part A)        | A 7X photomicrograph of the inner race of the test bearing. In the center of the photo there are two spots that appear to be depressions in the surface. |
| 4-47 (part B)        | A 25X photomicrograph showing the same two spots as in Figure 4-47 (part A). It also shows a typical surface finish of the race.                         |
| 4-48 (parts A, B, C) | 200X views of one of the spots seen in Figures 4-47 (part A) and 4-48. Note the uninterrupted tool marks through the spots.                              |
| 4-48 (part D)        | A 200X view of the other spot seen in Figure 4-47 (part B)                                                                                               |
| 4-48 (part E)        | A 400X view showing the tail portion of Figure 4-48 (part A)                                                                                             |
| 4-49                 | A photograph of the inner race.                                                                                                                          |
| 4-50                 | A profile trace of the test bearing inner race.                                                                                                          |
| 4-51                 | A profile trace of an identical bearing with 50 hours run-in.                                                                                            |

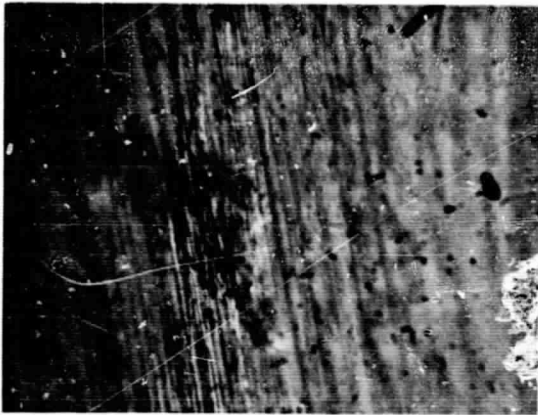


(A) 7X MAGNIFICATION

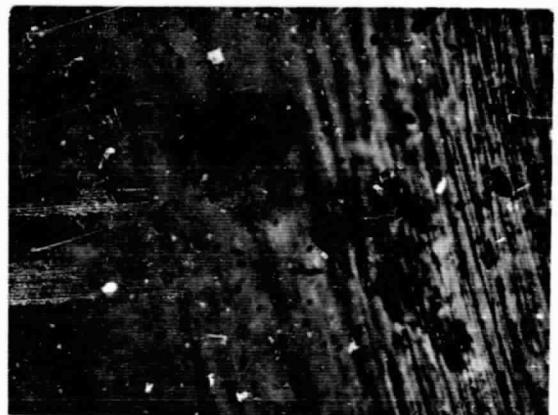


(B) 25X MAGNIFICATION

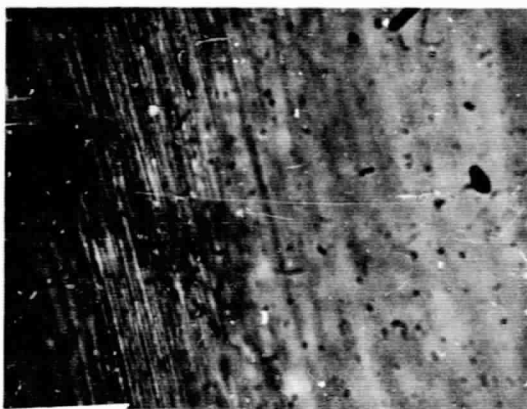
Figure 4-47. Photomicrographs of Test Bearing After 7800 Hours of Operation, 7X and 25X Magnification



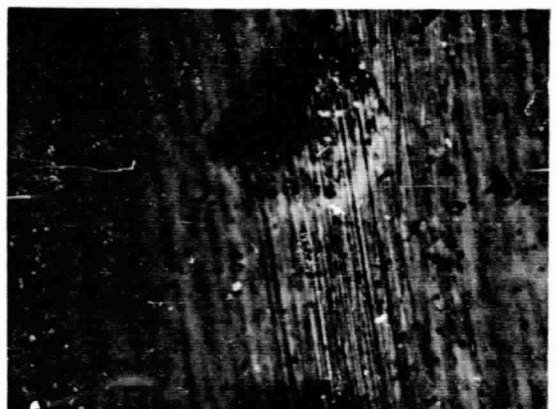
(A) 200X MAGNIFICATION



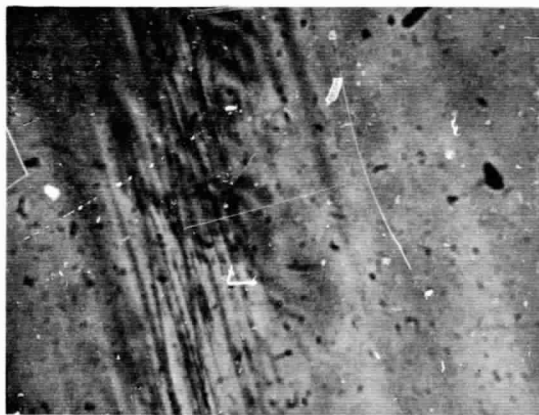
(B) 200X MAGNIFICATION



(C) 200X MAGNIFICATION



(D) 200X MAGNIFICATION

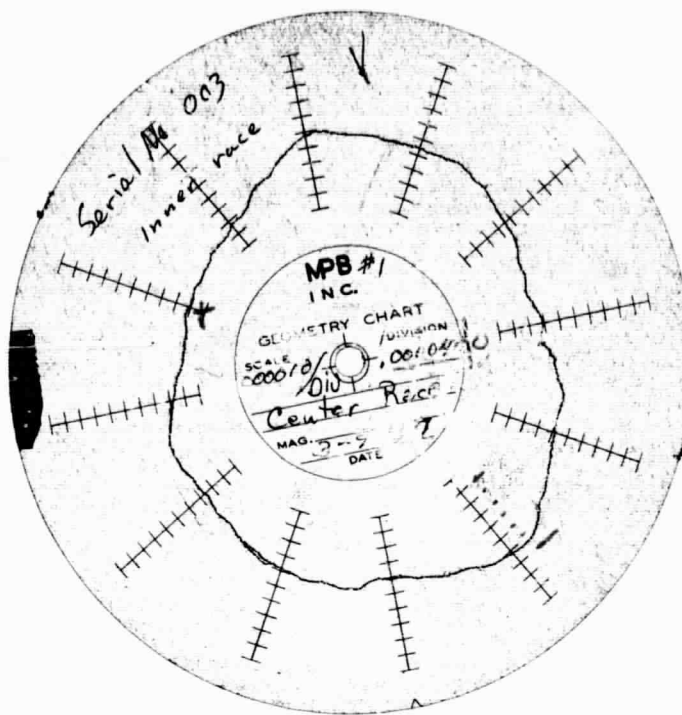


(E) 400X MAGNIFICATION

Figure 4-48. Photomicrographs of Test Bearing After 7800 Hours of Operation, 200X and 400X Magnification

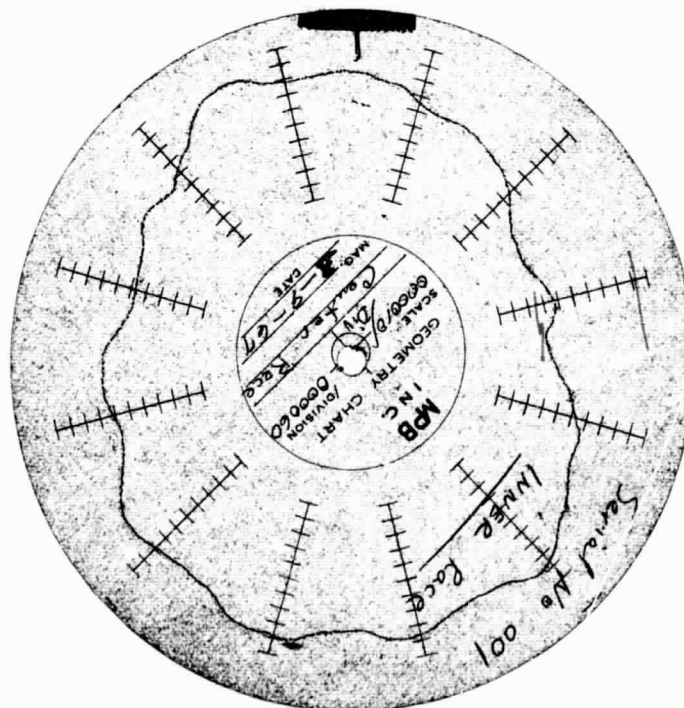


Figure 4-49. Test Bearing Inner Race



6 DIV  
 .000040  
 .00024  
 1.000061

Figure 4-50. Profile Trace of Test Bearing Inner Race After 7800 Hours of Operation



6.5

Figure 4-51. Profile Trace of Bearing After 50-Hour Run-in

## **4.6 RELIABILITY**

### **4.6.1 Introduction**

The reliability of the ATS Mechanically Despun Antenna - Mark II System is a result of all aspects of its design and manufacture. Key factors contributing to the achievement of a reliable product were:

- 1) Theoretical Design for Reliability - taking into account the mission requirements, application of reliability analyses and predictions for making design decisions regarding redundancy techniques, application of the appropriate redundancy techniques, careful parts selection and screening, etc.
- 2) Special practical attention to the critical motor-bearing-lubrication system.
- 3) Implementation of failure reporting, analysis and corrective action to assure the capture and correction of reliability hazards escaping the theoretical design process.
- 4) Test programs to verify the theoretical design, verify the soundness of choices of component parts and eliminate infant mortality failures.

The following paragraphs summarize the results of accomplishments of the program elements listed above and support the conclusion that:

The Mark II Mechanically Despun Antenna is inherently capable of performing its essential functions for a period of five years, with a probability of 96.5 percent. This inherent reliability is achievable in the end-use environment.

### **4.6.2 Analysis and Prediction Summary**

Reliability evaluation of this system takes into account the application of redundancy incorporated in the design. This redundancy is accomplished by parts QUAD, parts pair, and switched standby techniques. Probability of proper system function is the criterion of success and has been calculated for mission times of 1, 3 and 5 years. The results are summarized in Table 4-2.

The failure rate estimates have been listed in Table 4-2 for each circuit or portion of the system. Figure 4-52 is the Mark II Control System reliability model block diagram to which the analysis is addressed.

The Control System is designed to be switched standby redundant with two complete electronic subsystems. The Motor Drivers are designed QUAD redundant, such that no single (nor multiple) part failure will cause system malfunction.

TABLE 4-2

**ATS MECHANICALLY DESPUN ANTENNA - MARK II SYSTEM  
FAILURE RATE,  $\lambda$ , AND PROBABILITIES OF SUCCESS, R.**

| Circuit                    | Dwg. No.    | $\lambda$ %/1000 hrs. | 1 yr    | R(t)<br>3 yr. | 5 yr.   |
|----------------------------|-------------|-----------------------|---------|---------------|---------|
| Command Interface No. 1    | 00-469136   | 0.0208                |         |               |         |
| Command Interface No. 2    | 00-469083   | 0.0208                |         |               |         |
| Directional Command        | 00-469094   | 0.0877                |         |               |         |
| Motor Starting             | 00-469061   | 0.0810                |         |               |         |
| Binary Counter             | 00-469056   | 0.0100                |         |               |         |
| Damper                     | 00-472664   | 0.0516                |         |               |         |
| Encoder Electronics        | 00-472668   | 0.0762                |         |               |         |
| Wave-form Generator        | 00-472662   | 0.0250                |         |               |         |
| DC-DC Converter            | 00-472667   | 0.0663                |         |               |         |
| Decoupling Diode           |             | 0.0010                |         |               |         |
| Connectors                 |             | 0.0200                |         |               |         |
| Path Total                 |             | $\lambda = 0.4604$    |         |               |         |
| Parallel Standby Redundant |             | $R_A =$               | 0.99921 | 0.99324       | 0.98220 |
| Motor Drivers & Connector  | 00-469046   |                       | 0.99981 | 0.99933       | 0.99876 |
| Motor, Bearing & Connector |             | 0.0220                |         |               |         |
| Encoder, Coils & Connector |             | 0.0070                |         |               |         |
| RF Coax & Connector        |             | 0.0080                |         |               |         |
| Non-Redundant              | $\lambda =$ | 0.0370                | 0.99676 | 0.99032       | 0.98392 |
| Telemetry Interface        | 00-472665   | 0.0162                | NA      | NA            | NA      |
| Essential System           |             |                       |         |               |         |
| Reliability, $\pi R$       |             |                       | 0.99578 | 0.98297       | 0.96521 |

### 4.6.3 Component Failure Rates

#### 4.6.3.1 Integrated Circuits-SUHL

The results of extensive testing performed by the Sylvania Semiconductor Division have been evaluated to obtain a more realistic figure for their failure rates than was previously available. Tests were performed, obtaining many circuit hours of operation, under various conditions at very high temperatures. To obtain a correlation of these data with the expected use conditions involving junction temperatures not exceeding 50°C, acceleration factors were determined. For the first analysis, a doubling of failure rate for each 12.5°C rise above 50°C was assumed. A second assumption also used was that no acceleration factor would be assumed to be greater than 64. The 60 percent confidence figure with this latter acceleration factor, 0.005%/1000 hours, was used in this analysis. This figure is believed to be quite conservative in that the one failure which occurred

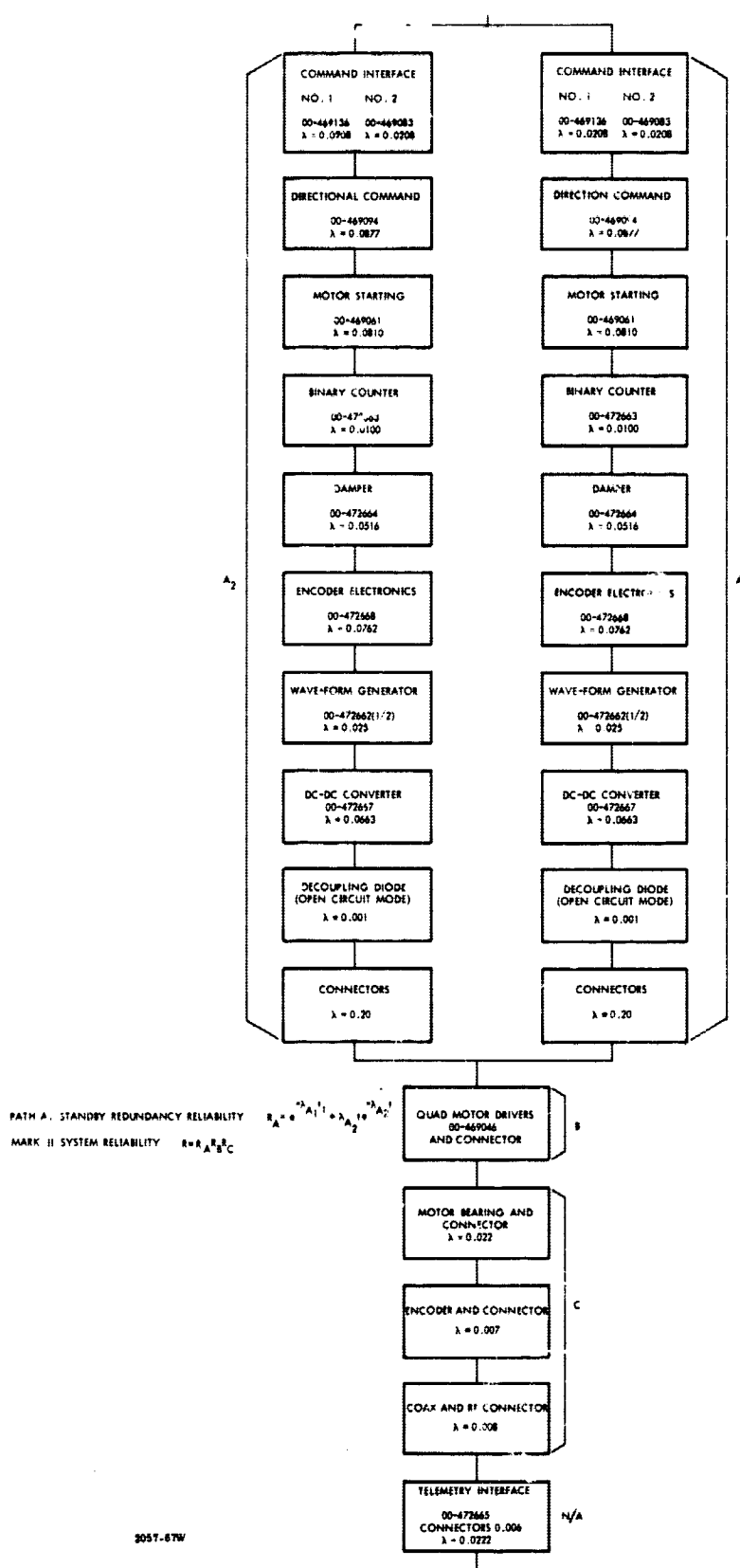


Figure 4-52. Mark II Control System Reliability Model, Block Diagram

in these tests was traced to a processing defect now precluded by a processing change and controls.

#### **4.6.3.2 Other Electronic Parts**

Failure rates for the parts used in the cord-wood modules were obtained from either MIL-HDBK-217A or from AVCO RAD (IDEP 347.40.00-B8-01) compilations. Although the parts are subjected to burn-in screening tests and are used, generally, at very low stress level, values of MIL-HDBK-217A have been used. In addition, vendor test data were used to develop part failure rates where applicable.

Specification requirements for some of these parts require data supporting low failure rates that have been used in the circuit estimates and analyses.

**Capacitor, Metallized Paper-Polyester:** This capacitor is supplied to a specification (45-504019) requiring tests and burn-in necessary to assure that the failure rate shall not exceed 0.0003 percent per 1000 hours at a 60 percent confidence level at 50 percent of rated power and +25 °C.

**Capacitor, Tantalum, Solid electrolyte:** This capacitor type is supplied to a specification (41-326435) requiring qualification to MIL-C-39003, presently 0.1 percent per 1000 hours, symbol P. These tests include life at 125 °C and 85 °C at respective rated voltages. The goal failure rate for these capacitors, at half-rated voltage, 25 °C and with 60 percent confidence level is 0.004 percent per 1000 hours.

**Capacitor, Glass Dielectric, Corning Types CYFR10 and CYFR15:** This capacitor type is procured to a specification (40-326446) requiring qualification to MIL-C-11272, presently 0.1 percent per 1000 hours, symbol P, 60 percent confidence limit at 125 °C, and full rated voltage. Under derated conditions of mx 60 °C and 1/2 rated voltage, the failure rate is 0.001 percent/1000 hours.

**Resistor, Fixed-Film Corning Types NBW55 and NBW60:** These resistors are produced to Corning Control Procedure LR-163 to achieve an established reliability level less than 0.0001 percent per 1000 hours at 25 °C and 1/2 rated power with 60 percent confidence level.

All semiconductors are procured to a screening requirement on a 100 percent basis after acceptance tests. Various critical and sensitive parameters are measured, the devices subjected to 100 hours of operation at 100 °C at specified voltages and

dissipations and the parameters then remeasured and tabulated by individual devices. Both parameter limits and changes are used as screening criteria.

#### 4.6.4 Redundancy Techniques

Each system or portion of a system requires its own special treatment in the effort to optimize reliability by the various techniques available - especially redundancy.

Opportunities for the use of quaded parts and also for switched Standby Redundant functional groups can be found in the Despun Antenna electronics. The extensive use of functional circuit micro-modules, such as flip-flops and gates, limits the use of the parts QUAD configuration to the module level. Other techniques, such as majority voting, effective with maintained systems, do not appear promising since repair is not possible in the present application.

These applications of redundancy can be analyzed mathematically and are all dependent upon the mission time involved, being reliability expressions.

##### Quad

This type of redundancy is accomplished at the part or device level by 1) making each device series redundant to virtually eliminate circuit failures caused by shorts and 2) paralleling with another series pair to virtually eliminate circuit failures caused by opens.

A QUAD greatly improves the probability of success for satellite mission times of a few years when applied at or close to the piece parts level. However, circuit problems of power dissipation, gain, loading, and levels are increased. Also, detection of failed or defective parts in a QUAD during checkout is more difficult to accomplish.

The QUAD reliability equation is:

$$R(t) = e^{-4\lambda t} + 4e^{-3\lambda t}(1 - e^{-\lambda t}) + 4e^{-2\lambda t}(1 - e^{-\lambda t})^2 [1 + p(1 - 2p)] \\ + 8e^{-\lambda t}(1 - e^{-\lambda t})^3 p(1 - p)^2 \quad (4-14)$$

where

$\lambda$  = device failure rate,

$p$  = the proportion of failures due to "opens",

1 - p = the proportion of shorts,

t = mission time.

The first two terms are the most significant. They represent the probabilities that:

- 1) No part in the QUAD will fail; and
- 2) One of the four parts will fail, yet the circuit will continue to function properly for the duration of the mission.

The other terms involve the probabilities that two or three failures will occur during the time of the mission, yet in such a manner that the circuit will still continue to function. Circuit failure would occur only with the shorting of two elements in series or the opening of two elements, one in each series path.

### Switched Standby

This type of redundancy achieves an improvement in reliability, by providing a duplicate functional group to be switched into operation in place of the failed group.

For the case where only the on-line equipment and the switch can fail with failure rates  $\lambda$  and  $\lambda_s$  respectively (and where failure of the switch only makes the second block of equipment unavailable) we have:

$$R(t) = e^{-\lambda t} + t e^{-(\lambda + \lambda_s)t} \quad (4-15)$$

For the case where the equipment failure rate,  $\lambda$ , is constant, for both on-and off-line equipment, and the switch failure rate is  $\lambda_s$  (with switch failure only making the second equipment unavailable) we have:

$$R(t) = \frac{2\lambda + \lambda_s}{\lambda + \lambda_s} e^{-\lambda t} - \frac{\lambda}{\lambda + \lambda_s} e^{-(2\lambda + \lambda_s)t} \quad (4-16)$$

In a practical circuit, however, it is usually impossible to avoid having the signal path dependent on the functioning of some portion of the switch, failure of which will cause a system failure. In other words, part of the switch is an essential reliability series path which may have a failure rate designated as  $\lambda'_s$ . This path of the switch will, therefore, distinctly limit the effectiveness of any redundancy and the previous reliability equations must be modified thus;

$$R(t) = e^{-\lambda'_s t} \left[ \frac{2\lambda + \lambda_s}{\lambda + \lambda_s} e^{-\lambda t} - \frac{\lambda}{\lambda + \lambda_s} e^{-(2\lambda + \lambda_s)t} \right] \quad (4-17)$$

### Device Pair

In the case of devices, whose failure mode is virtually 100 percent short circuit, entirely satisfactory reliability protection may be achieved, - particularly when the failure rate is low - by using only a series pair (Case I). Similarly, for a predominantly open circuit failure mode, a parallel pair suffices (Case II). The circuit must still be capable of operating with the changed value due to failure of one of the parts.

The pair reliability equation is:

$$R(t) = e^{-2\lambda_1 t} (2e^{-\lambda_2 t} - e^{-2\lambda_2 t}) \quad (4-18)$$

where

$\lambda_1$  = the open circuit failure rate (Case I)  
or short circuit failure rate (Case II)

$\lambda_2$  = the short circuit failure rate (Case I)  
or open circuit failure rate (Case II)

### 4.6.5 Reliability Analysis

During the circuit design effort, considerable attention was given to the conservative stressing of parts and to the reduction of the causes and the minimization of the effects of failure. This has been a cooperative effort between design and reliability engineers with the following analysis results by circuit function.

#### 4.6.5.1 Quaded Motor Driver (00-469046)

Reliability evaluation of this circuit is facilitated if one considers that several piece parts together constitute a device. This circuit is then a QUAD of "devices". In addition, the inputs to these devices consist of a pair of resistor - diode QUAD combinations, redundantly switched with the Recirculating Shift Registers. Their contribution to the device failure probability is deemed to be less than that of the resistor.

### Device Combination

|                       |         |        |                          |
|-----------------------|---------|--------|--------------------------|
| 1                     | 2N2849  | 0.005  | 0.005                    |
| 1                     | 2N2907A | 0.0024 | 0.0024                   |
| 1                     | 1N3039B | 0.010  | 0.010                    |
| 3                     | R       | 0.0001 | 0.0003                   |
| CR(QUAD)R/taken twice |         |        |                          |
|                       |         |        | <hr/> 0.0177%/1000 hours |

The probabilities of success,  $P_s$ , and equivalent failure rate, e.f.r., expressed as a constant, for such a QUAD of "devices" are:

| <u>Time Period</u> | <u><math>P_s</math></u> | <u><math>\lambda t</math></u> | <u>e.f.r. (X <math>10^{-5}</math>)</u> |
|--------------------|-------------------------|-------------------------------|----------------------------------------|
| 1 year             | 0.99999                 | 0.00001                       | 0.00011                                |
| 3 years            | 0.99986                 | 0.00014                       | 0.00053                                |
| 5 years            | 0.99964                 | 0.00036                       | 0.00082                                |

Estimated failure rate for four non-redundant drivers is at least 0.096%/1000 hours for mission times of a year.

The prices paid for this reliability protection are:

- 1) Fourfold increase in parts count and cost
- 2) Less than fourfold increase in weight and volume
- 3) Slight reduction in driver efficiency (controlling about 4.6 watts motor power with maximum driver losses estimated less than 1.232W against 0.308W for the non-redundant circuit)
- 4) Increased difficulty of complete circuit inspection and detection of pre-launch failed or defective parts in the module.

#### 4.6.5.2 DC-DC Converter

The converter is included in the control electronics subsystem. Two such subsystems are used in parallel standby redundancy. The duplicate subsystem is to be switched into operation should the first subsystem fail. The converter is not made redundant since this added complexity is not needed in order to achieve satisfactory reliability. However, due to their small size, rectifier diodes and filter capacitors are used in series pair redundancy. The simplified non-redundant circuit is self-starting, operates more efficiently at a higher frequency with less output ripple, and is not a disproportionate contribution to the probability of failure of the redundantly implemented subsystem of which it is a portion.

#### 4.6.5.3 Data Telemetry

The shaft position data, 9 bits, is entered from the operating Control Electronics into the Encoder Register, Transfer Gates strobed by the Sun Sensor Interface, to the Storage Register for the Telemetry Interface. A degree of redundancy exists since most of the possible failures would only degrade the information supplied for transmission.

Errors or missing bits can be corrected by processing the data in the ground station. In addition, this register is activated by command only when ground control desires to receive its data, conserving satellite power and reducing the duty factor for these circuits. The status of the Control Electronics is provided by additional telemetry. The zero bit from which the shaft position data may be reconstructed is also passed through this telemetry interface.

It is evident that data transmission sufficient for antenna control purposes will be provided to the telemetry encoder. But for the purposes of this estimate (the overall total Despun Control Electronics reliability estimate) 25 percent of the failure rate of these non-essential circuits was used. Thus, the most meaningful estimate is that for the Essential System Reliability in Table 4-2.

#### **4.6.6 Motor Bearing Lubrication System Reliability**

One of the areas of the Mechanical Despun Antenna that is most frequently questioned is the reliability of the motor-bearing-drive system. This report reviews two different analyses that have been performed in this area. One analysis is patterned after the Avco-RAD method reported in IDEP. The second follows the procedure used by RCA-Montreal for Reliability assessment of mechanical and electro-mechanical parts. This method is also found in IDEP.

The Avco-RAD analysis neglects wearing, effectively assuming that the wear life is greatly in excess of a random failure (constant), and is primarily concerned with a random defect in the bearings or motor windings. The RCA-Montreal method, on the other hand, assumes that wear is the principal consideration. The latter method, therefore, results in a failure rate which is a function of time whereas the former does not. The results of the two methods of calculation are summarized below.

|               | <u>Failure Rate</u>          |
|---------------|------------------------------|
| Avco-RAD      | 0.020%/1000 hours (constant) |
| RCA-Montreal  |                              |
| First 1 year  | 0.0025%/1000 hours (ave.)    |
| First 3 years | 0.006%/1000 hours (ave.)     |
| First 5 years | 0.028%/1000 hours (ave.)     |

In the calculation by the RCA-Montreal method, a Mean Wear Life of 1,000,000 hours (approximately 11.4 Years) is obtained. Specific calculations for the wear life of the chosen bearing (found in Appendix C) show a Mean Wear Life of 28 years. Were this number used in the RCA-Montreal method of calculations, the contribution of wear to the life of the system would have been negligible compared to the life based on a random failure. This condition would have been inconsistent with the assumption of that method of calculation that the wear life was the predominating factor.

Based on the above considerations, a random failure and not wear should determine the bearing-motor-drive system life. On this basis, the Avco-RAD method of calculation is probably the more applicable.

#### 4.6.6.1 Avco-RAD Reliability Assessment Method (1)

The Avco-RAD procedures and data compiled by D.R. Earles are extensions and additions to the methodology first 'popularized' by RCA's TR-1100. The methods enable reliability estimates to be made by taking both stress (voltage, power, temperature) and installation environment into account. A comprehensive tabulation of generic failure rates is included covering many of the kinds of parts having low usage for which data are ordinarily difficult to obtain.

The Despun Antenna motor may be considered either as a "Motor, Electrical, AC" or as a "pair of Bearings, Ball, Light Duty and four Coils, Motor Winding."

1) Numerical data listed in reference (1) is as follows:

a) Application Factor

1. Motors at 150 rpm  $K_A = 0.001$  (extrapolation p47)
2. Coil at 65 °C  $K_A = 2.0$  (p40)

b) Generic Failure Rates, GFr in F/10<sup>6</sup> hr.

|                             | <u>Lower Limit Mean</u> |       | <u>Upper Limit</u> |
|-----------------------------|-------------------------|-------|--------------------|
| 1. Motor, Electrical, A.C.  | 1.12                    | 5.24  | 9.36 (p78)         |
| 2. Bearings, Ball, Lt. Duty | 0.035                   | 0.875 | 1.72 (p69)         |
| 3. Coils, Motor Winding     | 0.01                    | 0.03  | 0.45 (p71)         |

(1) D.R. Earles, Avco Corp. RAD Div., Wilmington, Mass. (IDEP 347.40.00.00-B8-01)

c) Installation environment factor,  $K_E$ , for orbiting satellite is 1.0. (p29)

d) Failure rate  $Fr = GFr K_A K_E$

2) Motor Reliability Assessment:

$$Fr = GFr K_A K_E$$

$$Fr = 1.12 (0.001) 1.0 = 0.00112 F/10^6 \text{ hr.}$$

$$= 0.000112\%/1000 \text{ hr.}$$

Doubtless, the degree by which the life characteristics of this Despun Antenna motor diverge from the usual AC motor are extreme and the extrapolation of the application factor for so low a rotational speed is also questionable; therefore, this failure rate, not considered to be truly representative, was not used.

3) Bearings and Coils, Reliability Assessment

$$F = 2 (\text{bearings}) [GF (K_A) K_E] + 4 (\text{coils}) [GF (K_A) K_E]$$

$$F = 2 [0.040 (1.0) 1.0] + 4 [0.015 (2.0) 1.0]$$

$$= 0.08 + 0.12 = 0.20 F/10^6 \text{ hr.}$$

$$= \underline{\underline{0.020\%/1000 \text{ hr.}}}$$

There is ample justification in the super-ultra precision class bearings, their assembly and extensive testing (smootherator and torque), not ordinarily performed on motor assemblies, for using the lower limit failure rates. This use would result in an estimated failure rate  $FR = 0.015\%/1000 \text{ hr.}$  However, since the installation environment is known to include moderate temperature cycling, generic failure rates slightly higher than the listed lower limit values were used in the above calculation.

#### 4.6.6.2 RCA-Montreal Reliability Assessment of Mechanical and Electro-Mechanical Parts (2)

This procedure for parts exhibiting wear-out life characteristics is primarily based on wear and degradation failure modes. In the absence of extensive data to actual wear-out, manufacturer's and other test data are used to obtain an estimated mean life,  $M$ , for the part. The conservative assumption is then made that the life characteristic of the part may be described by a normal distribution function about the mean,  $M$ , with time zero,  $t = 0$ , located  $-4\sigma$  limits from  $M$  (i.e.,  $M = 4\sigma$ ).

#### (2) RCA-Montreal, Proposed Procedures for Reliability Assessment of Mechanical and Electro-Mechanical Parts (IDEP 347.25.00.00-F8-01).

## Despun Motor Reliability Evaluation

The best estimates in this reference (2) of the ratio of random (exponential distribution function) to wear and/or degradation (normal distribution function) failure rates for motors is given as 0.01. Thus, neglecting the non wear-out failure rates is presumed to have negligible effect on the validity of the results.

The RCA-Montreal procedure for evaluating wear-out parts uses the following steps:

1. **Classification** - The motor is classified according to size, stator windings, and rotor windings. Motors size 8 and smaller are given a derating by multiplying the Total Wear Failure Rate by 1.5. (The Despun Antenna motor is "large", and its evaluation is not affected by this factor).
- 2) **Duty Cycle** - Means are given for calculating duty cycle under various conditions of usage. (The Despun Antenna motor is used at simply 100 percent duty).
- 3) **Brushes and Slip Rings** - Contribution to failure rates of these items is considered. (The Despun Antenna motor has no brushes or slip rings, thus has no failure rate from these sources.)
4. **Gearing** - The contribution to failure rates by a gear train is considered. (The Despun Antenna motor drive has no gearing.)
- 5) **Reverse Drive** - The effect of sudden motor reversals is considered. (The Despun Antenna motor is not operated in such fashion.)
- 6) **Additional Output Loading** - The effect of driving against a stop or clutch is considered. (The Despun Antenna motor does not operate against such devices.)
- 7) **Speed Size Rating** - The product of bearing size, I.D. in mm., and shaft RPM gives the DN Value. (For the Despun Antenna motor this is  $40 \text{ mm} \times 150 \text{ RPM} = 6000 \text{ DN}$  for the larger bearing.)
- 8) **DN Value-Temperature Rating** - This DN Value is modified by multiplying it by the duty cycle. This modified value is used with the Hot-Spot Temperature, entering the curves given, with interpolation if necessary, to obtain a Failure Rate component. (For the Despun Antenna motor, at a temperature of  $70^\circ\text{C}$  ( $-153^\circ\text{F}$ ) maximum, the Failure Rate component is conservatively 1%/1000 hours by a slight extrapolation.) This Failure Rate is then corrected for the 10 percent load limit. Useful life of a bearing (all other things being equal) is inversely proportional to the cube of the load. For the Despun Antenna motor with less than 10 percent load limit, maximum, the resultant Total Wear Failure Rate is 0.001 percent.

- 9) **Total Wear Failure Rate** - All the calculated component failure rates are added together and multiplied by any class derating factor. The reciprocal is the Calculated Wear Life Period or Mean Wear Life. (For the Despun Antenna motor 0.001%/1000 hours gives a Mean Wear Life M of 100,000,000 hours.)

#### Note

These wear failure rates should not be confused with the usual electronic part failure rate. They are distinctly not constant and are for determining Mean Wear Life only.

The resultant Mean Wear Life,  $M = 100,000,000$  hours, is truly of astronomical proportions. This points up the difficulty of relating data from practical bearing tests (at relatively high speeds and loadings), by which significant numbers of units actually reach wearout, to a practical low speed, lightly loaded application.

The bearing life calculation based on AFBMA formulae (Appendix C) could be used as an alternative. Fitting the results - 98 percent survival for a life expectancy of 280,000 hours - to the assumed normal distribution function of the RCA-Montreal procedure, where  $M = 4\sigma$  yields a calculated Mean Wear Life,  $M = 575,000$  hours. The effect of using this value is that the initial value of the function at time zero ( $M - 4\sigma$ ) looms large in proportion to those at 1, 3 and 5 year times. The RCA-Montreal procedure assumes that time zero is at  $-4\sigma$  limits and that the probability of success at this point in time is unity. The values based on an  $M - 4\sigma = 575,000$  hours are shown in the following table:

|        | <u>Time (hours)</u> |                   | <u>P Success</u> | <u>P Failure</u> | Equivalent F.R. (constant)  |
|--------|---------------------|-------------------|------------------|------------------|-----------------------------|
|        | 0                   | $M - 4\sigma$     | 0.9999683        | 0.0000317        | Undefined                   |
| 1 yr.  | 8,760               | $M - 3,939\sigma$ | 0.9999591        | 0.0000409        | 0.00047%/1000 hr.           |
| 3 yrs. | 26,280              | $M - 3,817\sigma$ | 0.9999325        | 0.0000675        | 0.000257                    |
| 5 yrs. | 43,800              | $M - 3,695\sigma$ | 0.9998901        | 0.0001099        | 0.000292                    |
|        | 280,000             | $M - 2.05\sigma$  | 0.9800000        | 0.0200000        | Not of comparative interest |
|        | 575,000             | M                 | 0.5000000        | 0.5000000        | Not of comparative interest |

The values in the column headed Equivalent F.R. are those of a constant failure rate which would result in the same probabilities of success for this mission duration. These values are listed for the purpose of comparison with the failure rates obtained by the Avco-RAD method.

In Step 8 of the RCA-Montreal procedure, extensive derating taking the low speed operation into account has already been included by the calculation of the DN value. It seems likely that still further derating by the load factor will no longer realistically extend the Mean Life. Failure mechanisms other than wear and metal fatigue undoubtedly become dominant. Accordingly, the much more conservative value for Mean Wear Life,  $M = 100,000$  hours, which results from the DN value without load derating is retained as being more probably valid for this wear-out assessment.

The one-sided values, Probabilities,  $P$ , of survival and failure, for the normal distribution about  $M = 4\sigma = 100,000$  hours are as follows:

|        | <u>Time (hours)</u>   | <u>P Survival</u> | <u>P Failure</u> | <u>Equivalent F.R. (constant)</u> |
|--------|-----------------------|-------------------|------------------|-----------------------------------|
|        | 0 $M-4\sigma$         | 0.9999683         | 0.0000317        | Undefined                         |
| 1 yr.  | 8,760 $M-3.65\sigma$  | 0.9998689         | 0.0001311        | 0.0015%/1000 hr.                  |
|        | 25,000 $M-3\sigma$    | 0.9986501         | 0.0013499        | *Not of comparative interest      |
| 3 yrs. | 26,280 $M-2.95\sigma$ | 0.9984111         | 0.0015889        | 0.006                             |
| 5 yrs. | 43,800 $M-2.25\sigma$ | 0.9877755         | 0.0122245        | 0.028                             |
|        | 50,000 $M-2\sigma$    | 0.9772499         | 0.0227501        | *                                 |
|        | 75,000 $M-\sigma$     | 0.8413447         | 0.1586553        | *                                 |
|        | 100,000 $M$           | 0.5000000         | 0.5000000        | *                                 |

#### 4.6.6.3 Discussion of Significance of Both Methods of Reliability Calculation

Under the vacuum conditions of space, lubrication of moving parts is recognized as a crucial area. To achieve significantly normal wear-life, the presence of lubricant must be maintained. The lubricant reservoir supply life is estimated to be adequate for 522 years.

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\*Values for the normal distribution function from Biometrika, Volume I.

Also, for a constant failure rate approximation to apply, bearing wear-or fatigue-life must greatly exceed the expected equipment operational life. This condition is met according to the calculations by AFBMA standards indicating that 98% survival for more than 28 years can be expected.

Of the factors which make up the overall Despun Motor failure rate, the constant random failure rate portion may have a ratio greater than 0.01 to the wear failure mode because of the special conditions of this application.

- 1) Super-Ultra Precision (SU) class bearing
- 2) Testing of the completed assembly beyond the usual production QC procedures, proving each assembly by smootherator and torque measurements.
- 3) Maximum loadings, both static and dynamic, less than 10 percent of the design ratings of the smaller bearing.

These exceptional design and assembly conditions may push the wear-out limits so far out as to leave constant random failure modes dominant. If so, an estimating procedure such as that of Avco-RAD, (D.R. Earles, Avco Corp., RAD Division, 201 Lowell Street, Wilmington, Massachusetts) would in all probability have considerable validity - with certainly no higher failure rates than have been used.

The results of both these Reliability Assessment methods, Avco-RAD and RCA-Montreal, are close to each other in magnitude. Each of these methods uses assumptions having strong conservative influences on the results. Engineering judgment is that these results form a reasonable a priori basis for assessing the reliability that may be expected from this Despun Antenna Motor. A review of both analytical techniques and results obtained from each indicates that either will yield a valid reliability assessment of the Despun Antenna Motor.

#### **4.6.7 Malfunction Reporting, Analysis and Corrective Action**

The Malfunction Reporting, Analysis and Corrective Action system developed and used by SES-East is established to report all failures occurring in items designed by or for SES-East as a basis for analyzing failures and maintenance actions, feedback of information to the reporting activity, predicting trends, affecting corrective action and minimizing recurrent problems. This reporting system was employed during the reliability testing and the formal testing of the ATS Mechanically Despun Antenna. Table 4-3 presents a description of the malfunction reports (MR's) written and acted upon during the program.

TABLE 4-3  
MALFUNCTION REPORTS

| Model      | MR. No. | Unit            | Description of Problem                                           | Corrective Action                                                      |
|------------|---------|-----------------|------------------------------------------------------------------|------------------------------------------------------------------------|
| Qual No. 1 | 100651  | Damper          | Instability at low temperature - traced to a noisy Zener diode.  | Replaced faulty Zener diode.                                           |
| Qual No. 1 | 100652  | DC-DC Converter | System lost power - traced to bad solder joint.                  | Repaired faulty solder joint.                                          |
| Qual No. 1 | 100653  | Dir Command     | System would not subtract pulses - traced to defective IC.       | IC was replaced.                                                       |
| Qual No. 2 | 100654  | Dir Command     | Unit was intermittent - G37 was found marginal.                  | IC was replaced.                                                       |
| FLT No. 1  | 100655  | Starter         | Motor Starter does not switch over to VCO.                       | New starting circuit was built.                                        |
| Qual No. 2 | 100656  | Chassis No.     | Blocking oscillator triggering was marginal at low temperature.  | Design change was made by adding a resistor which improved triggering. |
| FLT No. 2  | 100657  | Dir Command     | Unit was intermittent - traced to bad solder joint.              | Board was resoldered.                                                  |
| FLT No. 2  | 100658  | Starter         | Motor Starter does not switch over to VCO - traced to open weld. | Weld was repaired.                                                     |
| FLT No. 1  | 100659  | Damper          | Damper unstable - traced to noisy Zener diodes.                  | Diodes were replaced with low noise selected units.                    |
| FLT No. 1  | 100660  | Damper          | Damper unstable - traced to noisy Zener diodes.                  | Diodes were replaced with low noise selected units.                    |

TABLE 4-3 (Continued)

MALFUNCTION REPORTS

| Model     | MR. No.                    | Unit                    | Description of Problem                                                                                                                                                                                                                                            | Corrective Action                                                                                                       |
|-----------|----------------------------|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| FLT No. 1 | 100661                     | Binary Counter          | Binary Counter unstable with voltage change at high temperature - traced to a slow fall input waveform.                                                                                                                                                           | A design change was made by addition of a jumper in starting circuit.                                                   |
| Qual      | Vibration Test<br>1-9-67   | Mechanical Drive Ass'y. | The reflector and split ground plane ejected as the unit was being vibrated along its X-Y axis due to the ball lock sleeve which became disengaged and allowed the ground plane and reflector to eject. The locking diameter on the ball lock sleeve was tapered. | A design modification was made to prevent this condition from recurring.                                                |
| FLT No. 1 | Acceptance Test<br>5-17-67 | Ejection Mechanism      | The ejection mechanism failed to properly eject the ground plane and reflector due to excess solid lubricant which created too snug a fit between the ground plan and shaft.                                                                                      | Worked as much of the solid lubricant into the surface of the Sanford Hardcoat as possible. Removed the excess coating. |
| FLT No. 1 | Acceptance Test<br>5-17-67 | Squib                   | Squib did not fire due to a break where the leads were welded together. This was caused by mis-handling of the squib brackets during assembly and disassembly.                                                                                                    | Replaced squibs.                                                                                                        |

From the table, it can be seen that early life failures (MR's 100659 and 100660), manufacturing errors (100657 and 100658) and a design deficiency were discovered during reliability testing. Some of these, and other malfunctions which occurred in the qualification system, led to design changes which were incorporated into the system to prevent these particular malfunctions from occurring in the end product. Specifically, Malfunction Reports 100656, 100661 and a mechanical malfunction during qualification testing led to design changes which were incorporated into the flight models.

#### **4.6.8 Reliability Testing**

Prior to start of formal testing, reliability tests were performed on the control system, whose purpose was to eliminate incipient failure due to manufacturing defects or part infant mortality. As a result of this testing, the delivered product was in the "constant failure rate" region of its life characteristic, the "bathtub curve".

The system tests that were conducted consisted of:

- 1) "Soaking" the non-operating system at +150°F for eight hours
- 2) "Soaking" the non-operating system at -20°F for eight hours
- 3) Exercising the system for eight hours at +150°F
- 4) Exercising the system for eight hours at -20°F.

The purpose of using these extreme temperatures was to weed out a majority of early life failures.

In addition, the cordwood modules were tested prior to their assembly into the system. These modules were exercised by temperature cycling for 24 hours between -20°C and +80°C, at one hour intervals.

### **4.7 TEST PROGRAMS**

#### **4.7.1 Qualification Test Program**

The Qualification Test Plan includes the requirements of NASA Specification S2-0102 Revision C on environmental testing.

The following functional and environmental tests were included in the test plan:

- 1) Pre-environmental RF long form test
- 2) Pre-environmental control electronics long form test
- 3) Storage temperature
- 4) Operational temperature
- 5) Sine and Random Vibration
- 6) Post-vibration RF short form
- 7) Acceleration
- 8) Thermo-Vac (operative)
- 9) Post-environmental RF long form test
- 10) Post-environmental CE long form test
- 11) Ejection Test

At NASA's request, the Qualification Model unit was not completely tested in accordance with the Qualification Test Plan. Items 7, 8, 9, 11 of the functional and environmental tests listed above were not performed. After the vibration tests were successfully conducted on the Mechanical Drive Assembly, the unit was shipped to HAC for further testing on the spacecraft.

Difficulties were experienced in sinusoidal vibration, initially. The difficulty was traced to a malfunctioning ball lock sleeve, which would not stay engaged. This allowed the reflector and ground plane to disengage from the shaft mount. The deficiency was corrected and the unit subsequently passed all phases of the qualification vibration testing. The initial failure was caused by a discrepant part and not by a design deficiency. The details of the failure, the analysis, and the corrective action taken are included in a failure report located in Section 4.6.

One of the two redundant control systems in the qualification model control electronics did not meet the full qualification temperature test requirements. At temperature extremes of  $-8^{\circ}\text{F}$  and  $+140^{\circ}\text{F}$ , system operation was unstable. Specifically, the motor periodically fell out of lock and stalled. Though automatic restart functioned normally, the system would not stay locked-up.

The problem was traced to a noisy zener diode in the damper circuit. A similar problem had been experienced earlier in the other section of the redundant system. Replacing the diode had completely eliminated the problem. Consequently, NASA/GSFC authorized shipment of the qualification model control system without correction of this malfunction which, as stated, occurred only at temperature extremes.

The control system was subjected to the thermo-vac test and subsequently shipped to HAC.

#### **4.7.2 Flight Acceptance Test Program**

The flight acceptance test plan covers the environmental requirements of NASA specification S2-0102 Revision C.

The following environmental and functional tests were included in the Acceptance Test Program:

- 1) Pre-environmental RF long form test
- 2) Pre-environmental CE long form test
- 3) Sine and Random Vibration
- 4) Post-vibration RF short form
- 5) Control Electronics temperature cycle
- 6) Thermo-Vac (operative)
- 7) Post-environmental RF long form
- 8) Post environmental CE long from
- 9) Ejection Test.

Though not originally required of the acceptance test, temperature testing to the full qualification temperature limits was done on each flight model control system. This testing was done as a precautionary measure because of the temperature malfunctions experienced during qualification testing.

##### **4.7.2.1 Flight Unit Acceptance Test**

The flight model unit No. 2 Mechanical Drive Assembly successfully passed the Flight Acceptance Test without any malfunctions or failures.

The flight model control electronic system No. 2 experienced some difficulties during the temperature test. The first malfunction caused by an open weld in a cordwood module was successfully repaired. A second malfunction occurred. This was caused by an intermittent connection between the output of the directional command module and PC board. This was also successfully repaired.

During the Thermo-Vac Test, the Control Electronics and the Mechanical Drive Assembly are operative. No malfunctions occurred.

Unit No. 2 met all design and performance requirements, including pre- and post-environmental RF tests.

#### **4.7.2.2 Spare Flight Unit Acceptance Test**

Because of malfunctions, vibration and reflector ejection tests were repeated on the spare flight unit mechanical drive assembly.

The vibration test was repeated because of out-of-specification performance in the post-vibration RF impedance test. Though meeting the performance requirements at pre-vibration tests, the feed VSWR changed as a result of vibration.

A similar problem was experienced during the fabrication of that particular feed assembly. VSWR tests are performed at various points in the welding sequence of the feed. After one set of welds, the VSWR which previously had been satisfactory, was found to be unacceptable. It was discovered at that time that a weld previously made in the area of the 4-GHz dipole T-feed had failed. The parts were realigned successfully and rewelded. However, this same weld apparently failed again during the vibration test.

The entire feed assembly was replaced with a spare unit, and the vibration test was repeated. This time, all RF performance specifications were met.

A second malfunction occurred during the reflector ejection test. Two things happened. First, one of the two redundant squibs did not fire because of a defective lead wire. Second, though the reflector did finally eject, there was an abnormal delay between the firing of the squib and the ejection of the reflector. This delay was caused by an excess of solid lubricant on the ground plane that caused the fit between the ground plane and motor shaft to be too tight. Details of these malfunctions are included in the reliability section.

After removing the excess solid lubricant and replacing the squibs, the ejection test was successfully repeated.

The Control Electronics for the flight back-up unit successfully passed the Flight Acceptance Testing without malfunction. Again, all design and performance requirements were met on the delivered spare flight system.

The Qualification and Flight Acceptance Test data are included in Appendices A through E.

#### **4.7.3 Spacecraft Vibration Test**

Vibration test evaluations of the independent tests on the Mechanical Drive Assembly and of the spacecraft revealed a potential problem in the fact that one of the spacecraft principal frequencies was very nearly the same as that of the RF structural system on the antenna. Therefore, the Mechanical Drive Assembly was vibrated on a mock-up spacecraft at the earliest date possible.

A qualification level vibration test (sinusoidal and random) was conducted with the Qualification Model Mechanical Drive Assembly mounted on a mock-up spacecraft. The results were extremely favorable; no damage or deterioration of the Mechanical Drive Assembly could be observed. A detailed report on the details of this test is given in Appendix D.