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FINAL REPORT

MILLIMETER-WAVE RADIOMETRY FOR RADIO ASTRONOMY

W. V. T. Rusch

S. D. Slobin

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Contract No. JPL 952210

Prepared for

JET PROPULSION LABORATORY
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ELECTRONIC SCIENCES LABORATORY

USC Engineering

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I. HISTORY OF THE PROGRAM

In September, 1963, the mm-wave instrumentation program was initiated as a joint effort between the Jet Propulsion Laboratory and the Electrical Engineering Department of the University of Southern California. The JPL participation was conducted through the New Circuit Elements Group of the Communications Elements Research Section, which provided equipment and personnel involved primarily with the electronic instrumentation.

The Electrical Engineering Department contributed the antenna, a converted 60-inch searchlight. Personnel were provided to design the antenna and feed system, the associated drive system, etc. USC personnel also directed the astronomical aspects of observation of the lunar eclipse of 30 December 1963. During this period, from September, 1963 to July, 1964 USC participation was sponsored by a grant from the Research Corporation, Contract AJ4-205 638 fromJPL, and financial support for salaries and equipment from the Electrical Engineering Department Joint Services Grant, AF-AFOSR-496-64.

In August, 1964 a JPL study contract was issued to the USC Electrical Engineering Department (JPL Contract No. 951 004). This contract continued the previous work as a joint JPL-USC program. Under this contract observations were made of a lunar eclipse on 19 December 1964, a lunation study of the moon was made, instrumentation was developed, and various atmospheric effects were studied. A second JPL study contract (JPL Contract No. 951 424) was issued in October, 1965. Under this contract a second lunation experiment was carried out, the sun was observed, atmospheric effects continued to be studied, and various items of instrumentation were designed and studied.

A third JPL study contract (JPL Contract No. 951 756) was issued in November, 1965 for a period of one year, terminating in November, 1966. During the period of this contract Mr. Stephen Slobin, a graduate student at USC who has been associated with the joint JPL-USC Millimeter-wave program since its inception, carried out the analysis and development of a nodding subdish system (NSS). During this period Professor W. V. T. Rusch, principal investigator, was at the Bell Telephone Laboratories in New Jersey on leave of absence from the University. This third study contract was later extended an additional two months until 31 December, 1967 for the purposes of investigating theoretical and experimental radiometric techniques to measure atmospheric weather dependent parameters, and to study the effect of variable atmospheric conditions on lunation and eclipse sun and moon observations.

A fourth JPL study contract (JPL Contract No. 952 210) was issued in March 1968 for a period of one year, terminating in March, 1969. Because of unseasonal rains causing a delay in the observational program, this contract was extended at no cost until the end of April 1969. The activities under this contract, which are the subject of this report, were primarily (1) the development of an automatic sun-tracking system, (2) the application of this system to solar observations for the purpose of obtaining atmospheric attenuation data, (3) continuing improvements in the nodding subdish mechanism.

II. INSTRUMENTATION

During the period of time covered by the various study contracts described in the previous section a 90-GHz (3.33 mm) radio telescope has been developed using a converted 60-inch searchlight as an antenna. Previous electronic systems used in the radio telescope were standard Dicke-type synchronous detection radiometers[1,2]. This radiometer scheme was used for measurements of lunar eclipses in 1963 and 1964, lunations in 1965 and 1966, and solar thermal emission studies.

The radiometer configuration used in the above studies required the use of a ferrite switching circulator or equivalent ferrite switching device in the RF path between the antenna feedhorn and the mixer. This device introduced considerable insertion loss (as high as 1 dB) in the main RF path, thereby degrading the sensitivity of the radiometer proportionately. Furthermore, it was anticipated that the operational frequency of the radiometer would be significantly increased at a later date, and the insertion loss of ferrite switching elements becomes prohibitive at shorter wavelengths.

Consequently a nodding subdish system (NSS) was developed which eliminated the ferrite device in the RF path and achieved the required switching by causing the antenna beam to alternate between the source being observed and a nearby position in the sky[3]. The beam-switching was accomplished by mechanically nutating the hyperboloidal subreflector in the

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[1] Rusch, W.V.T., S. Slobin and C. T. Stelzried, "Millimeter-Wave Radiometry for Radio Astronomy," Final Report, USCEE Rept. 161, University of Southern California, Los Angeles, California, February 1966.

[2] Rusch, W. V. T., S. Slobin, and C. T. Stelzried, "Millimeter-Wave Radiometry for Radio Astronomy," Final Report, USCEE Rept. 183, University of Southern California, Los Angeles, California, December 1966.

Cassegrainian feed system between two symmetric but off-axis positions. A second advantage of this beam-switching configuration is the cancellation of long-term (relative to the switching rate) atmospheric noise scintillations when the scintillating area is included in both positions of the antenna beam. Complete descriptions of the NSS are given in references 3 and 4.

A. IF Amplifier Development. As part of a program to increase the overall sensitivity of the radiometer, Mr. Charles Abronson designed and built a Mixer-IF Amplifier-Detector combination. The mixer was a single-ended mixer on loan from the Aerospace Corporation. A diagram of this instrument package is shown in Figure II-1 and a photograph of the unit is shown in Figure II-2. The performance specifications were:

3dB Bandwidth:	100 MHz to 450 MHz
IF Gain:	Approximately 36 dB
IF Noise Figure:	Less than 2.5 dB (average)
Video Gain:	50 dB
Video Bandwidth:	DC to greater than 20 KHz
Video Amplifier Noise Figure:	Approximately 3-4 dB, 100 Hz to 5 KHz
Detector:	Backward Diode

It was planned to replace the Raytheon balanced mixer in the radio-

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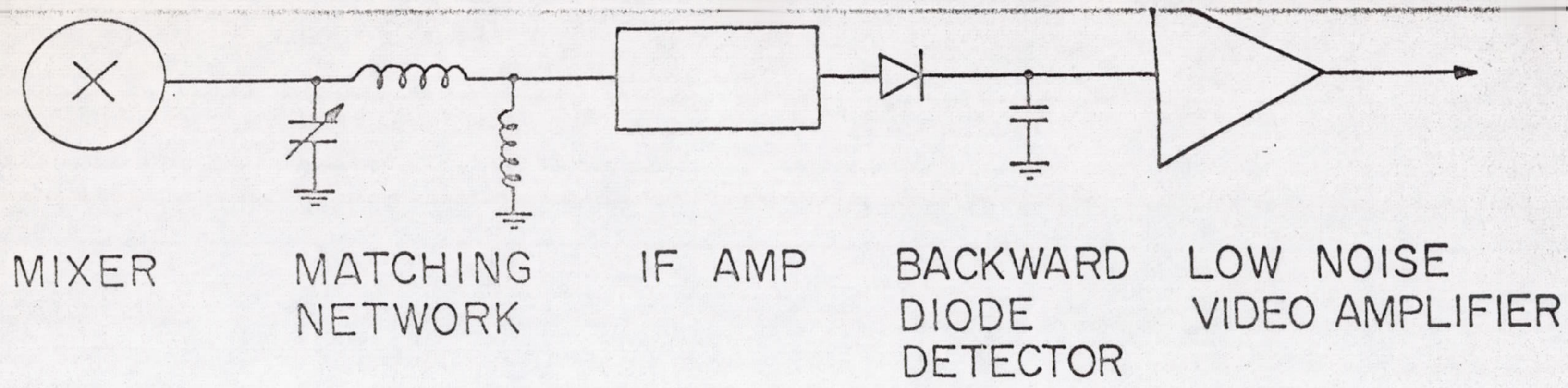
[3] Slobin, S. D., "A Study of an Asymmetric Cassegrainian-Antenna Feed System and Its Applications to Millimeter-Wave Radio-Astronomical Observations", USCEE Rept. 321, University of Southern California, Los Angeles, California, December 1968.

[4] Rusch, W. V. T., S. Slobin, and C. T. Stelzried, "Millimeter-Wave Radiometry for Radio Astronomy," Final Report, USCEE Rept. 263, University of Southern California, Los Angeles, California, March 1968.



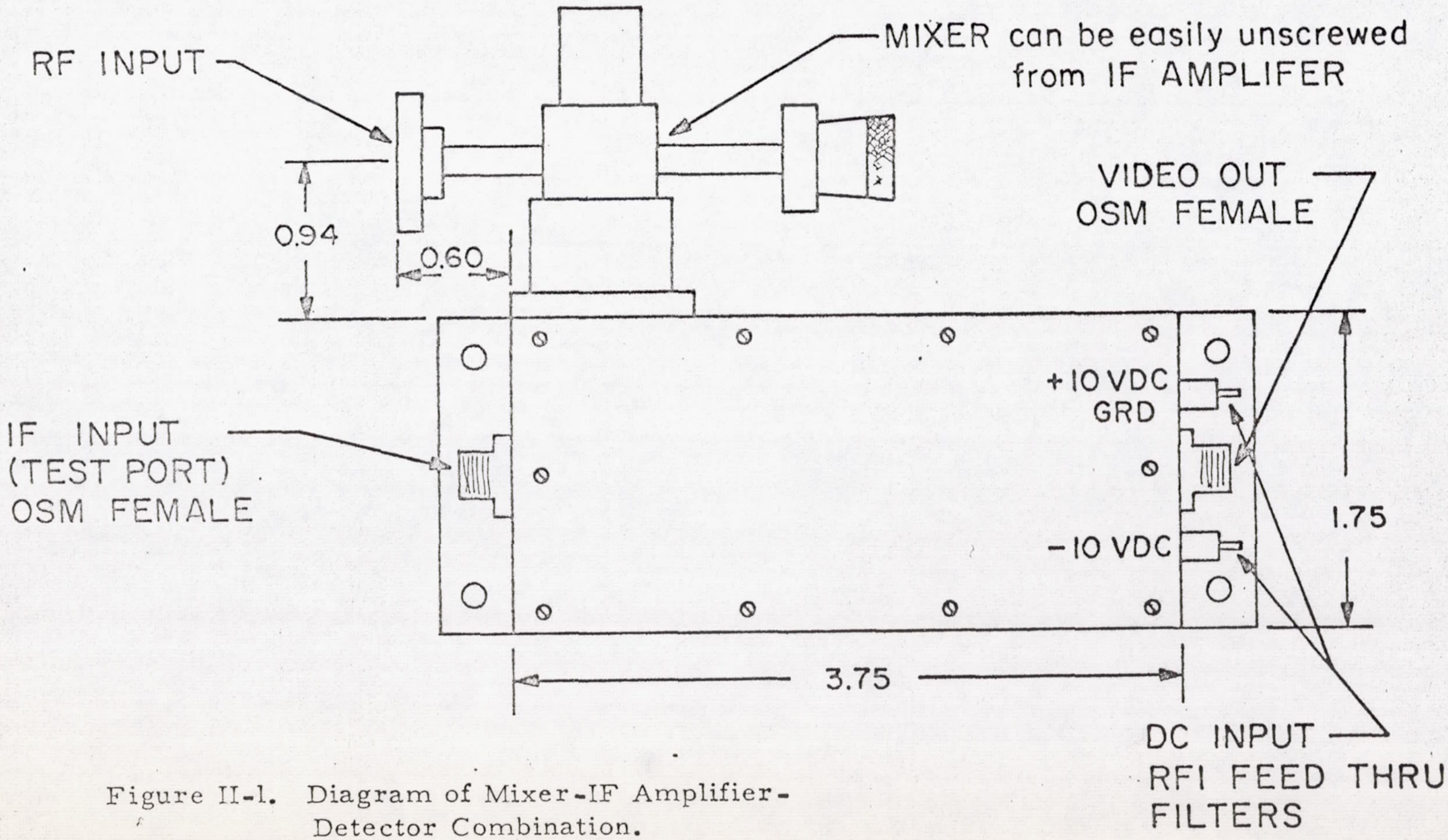


Figure II-1. Diagram of Mixer-IF Amplifier-Detector Combination.

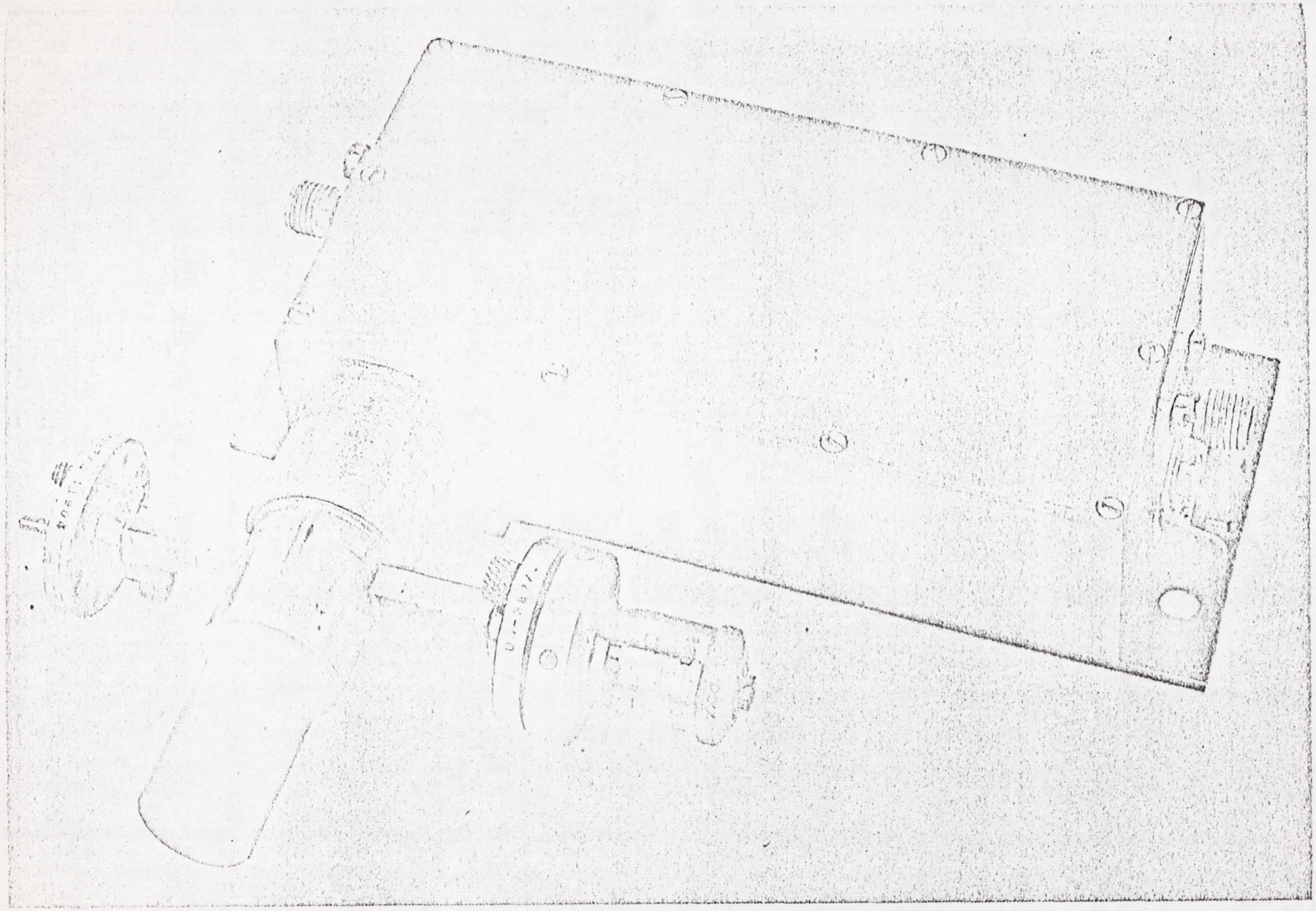


Figure II-2. Instrument Package Containing Mixer-IF Amplifier-Detector Combination.

meter with this unit for field testing with Schottky-Barrier diodes fabricated in the USC Microwave-Device Laboratory. However, abrupt termination of the operational program by JPL on 30 March, 1969 prevented these tests.

B. Improvement of the Nodding Subdish System. Following the eclipse measurements of 1967 and other field tests, it was recognized that certain mechanical improvements could be made in the nodding subdish. An appropriate redesign was carried out to provide the following improvements:

(1) Increase the operating speed from 2.7 to 5 cps

(2) Provide weather protection for the cam, cam followers, and precision bearings.

(3) Provide virtually silent operation

(4) Provide permanent camway lubrication

(5) Reduce wear

The increase in operating speed from 2.7 to 5 cps with the redesigned cam followers provided increased radiometer sensitivity as demonstrated in previous reports made under this program[3,4].

The redesign replaces the original stationary steel cam followers with roller followers made of "Teflon TFE". The roller is supported on a .062 spindle provided by the redesign of the original followers, 127318-2 and 127343. Wear and noise inherent in the first experimental model will also be reduced by this change. Use of Teflon TFE will eliminate the requirement for the regular application of lubricant to the camways during operation.

Plastic deformation and the new cylindrical shape provide adequate cam follower surface area to maintain the Teflon TFE follower rollers well below the maximum design compression loading of 3700 psi. Undesirable cold flow characteristics associated with the material are avoided by designing for dynamic loading only without a static preload.

A weather cover, 518 and 519, was provided because of desireability of protection from exposure to foreign material. This cover was made possible by the elimination of regular lubrication requirements on the camways. The incorporation of 518 and 519 allowed access to the camways and the reflector and counterweight support bearings and will not interfere with any previously established function of the Hyperboloid Reflector Mount Assembly.

Figure II-3 shows the original subreflector configuration with the exposed camways and counterweight. Figures II-4, II-5, and II-6 show the modified configuration with the weather cover mounted in place. The teflon cam followers, which may not be seen in the figures, were tested by operating the mechanism at speeds up to 7 cps. The reduction in noise and vibration was significant, and, although no additional field tests were conducted, it was concluded that the teflon followers would allow the system to operate at frequencies considerably higher than 2.7 cps.

In the process of installing the teflon cam followers, the original hardened steel followers were removed and examined. Magnified views of the reflector and counterweight followers are shown in Figures II-7 and II-8, respectively. The diameter of the cylindrical followers was 0.125 inch. There is no discernible wear on the reflector follower and only a slight amount on the counter weight follower, in spite of the fact that they had been in operation more than 10^6 cycles.

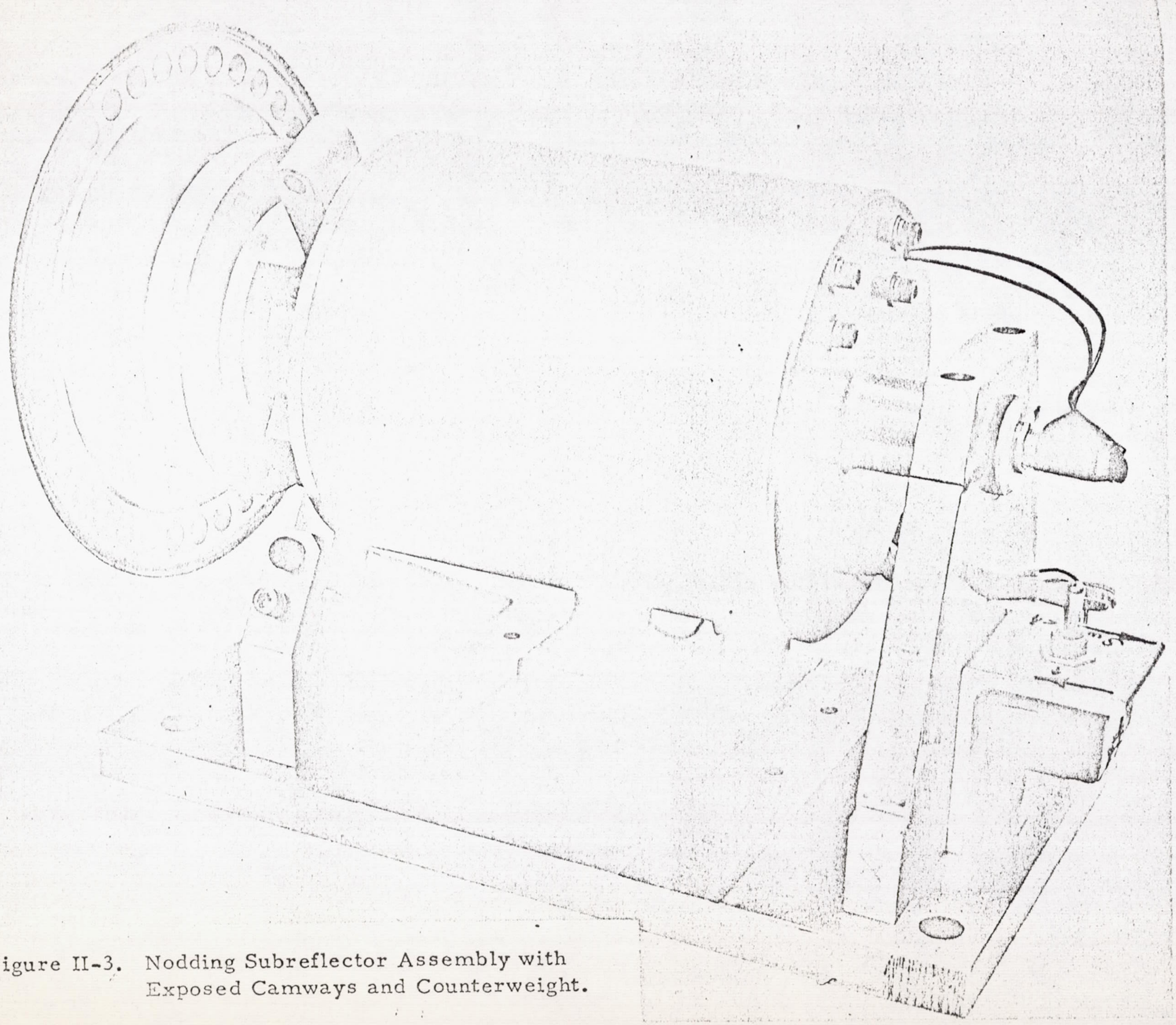


Figure II-3. Nodding Subreflector Assembly with Exposed Camways and Counterweight.

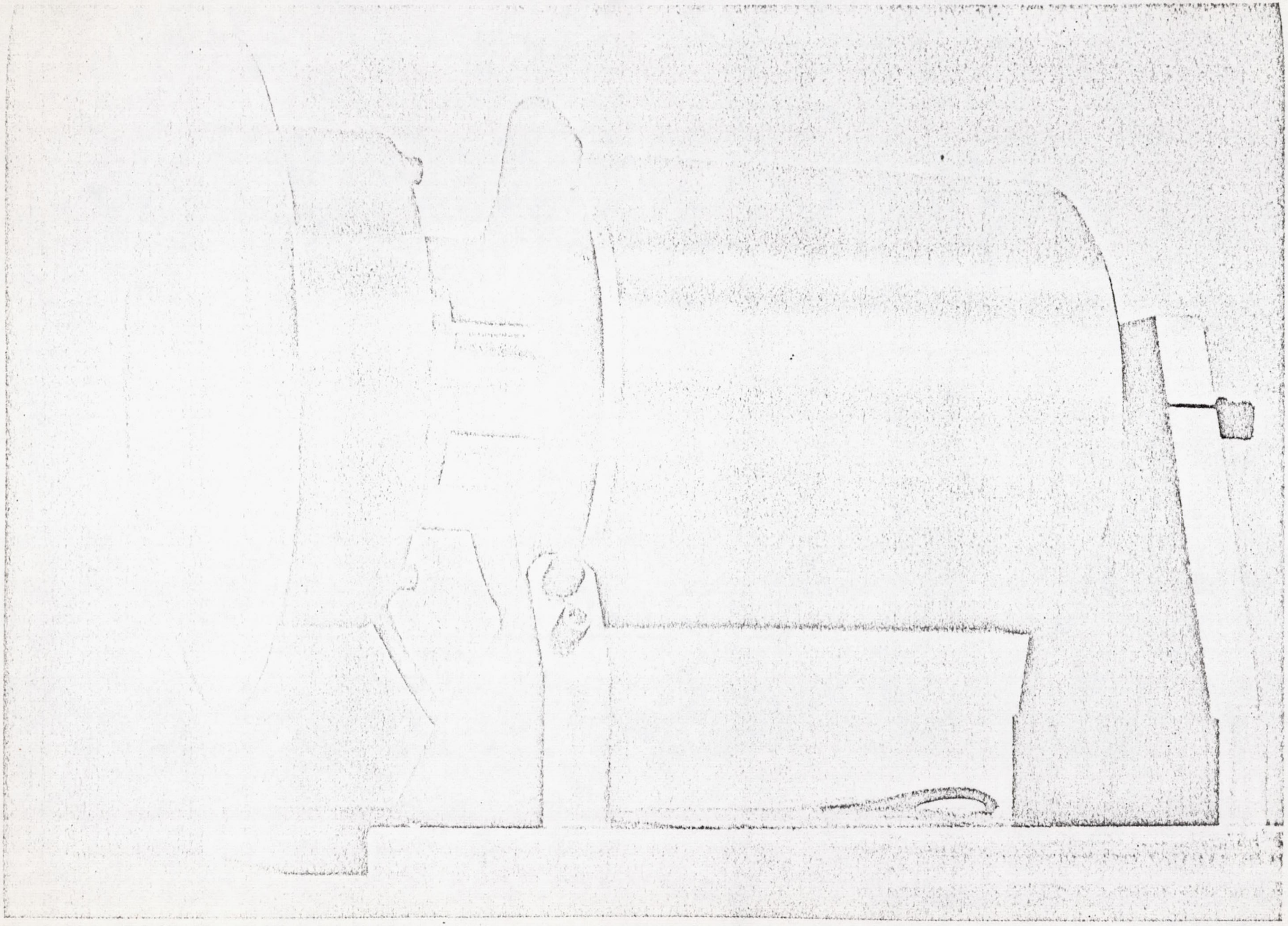


Figure II-4. Subreflector Assembly with Weather Cover.

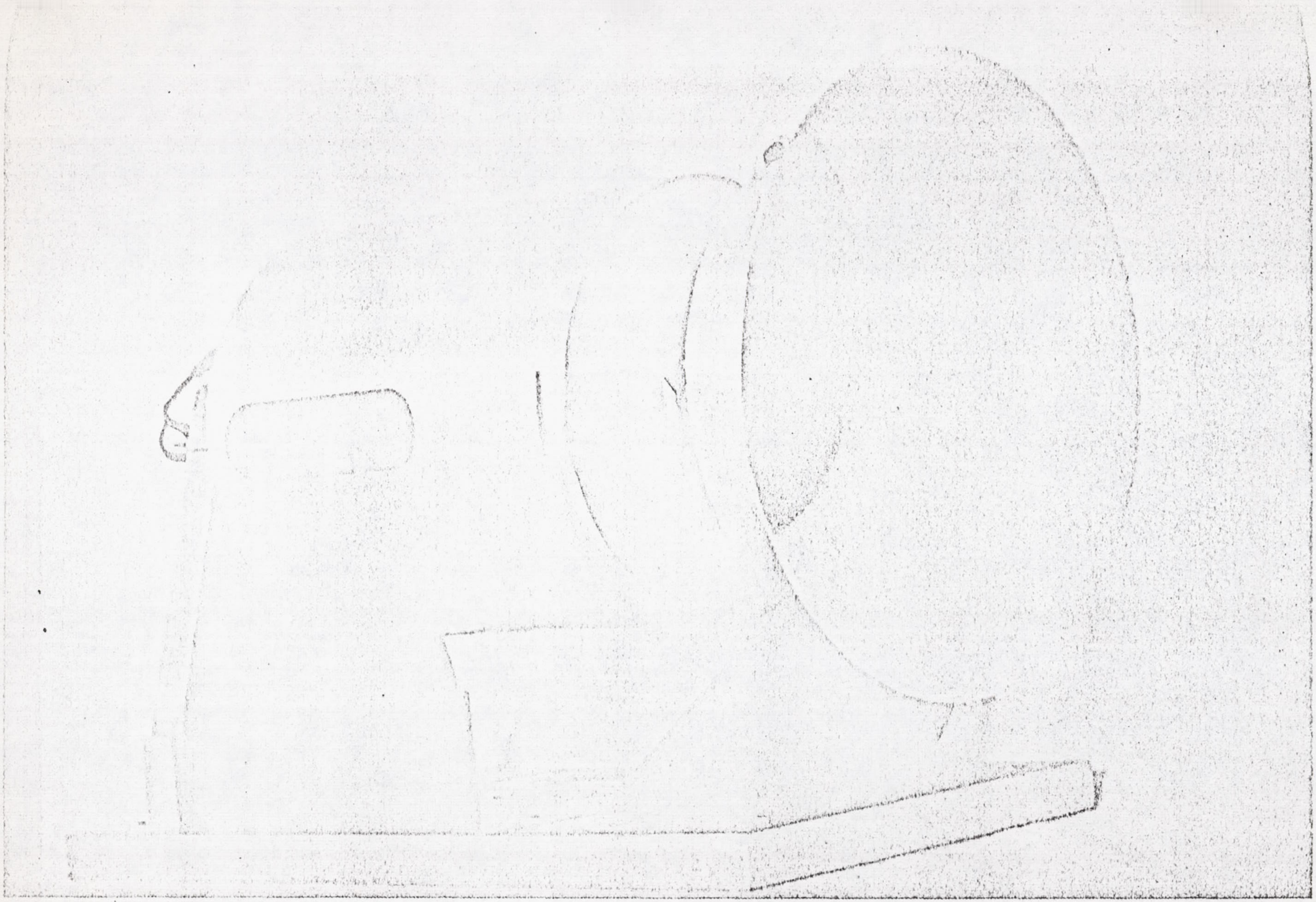


Figure II-5. Subreflector Assembly with Weather Cover.

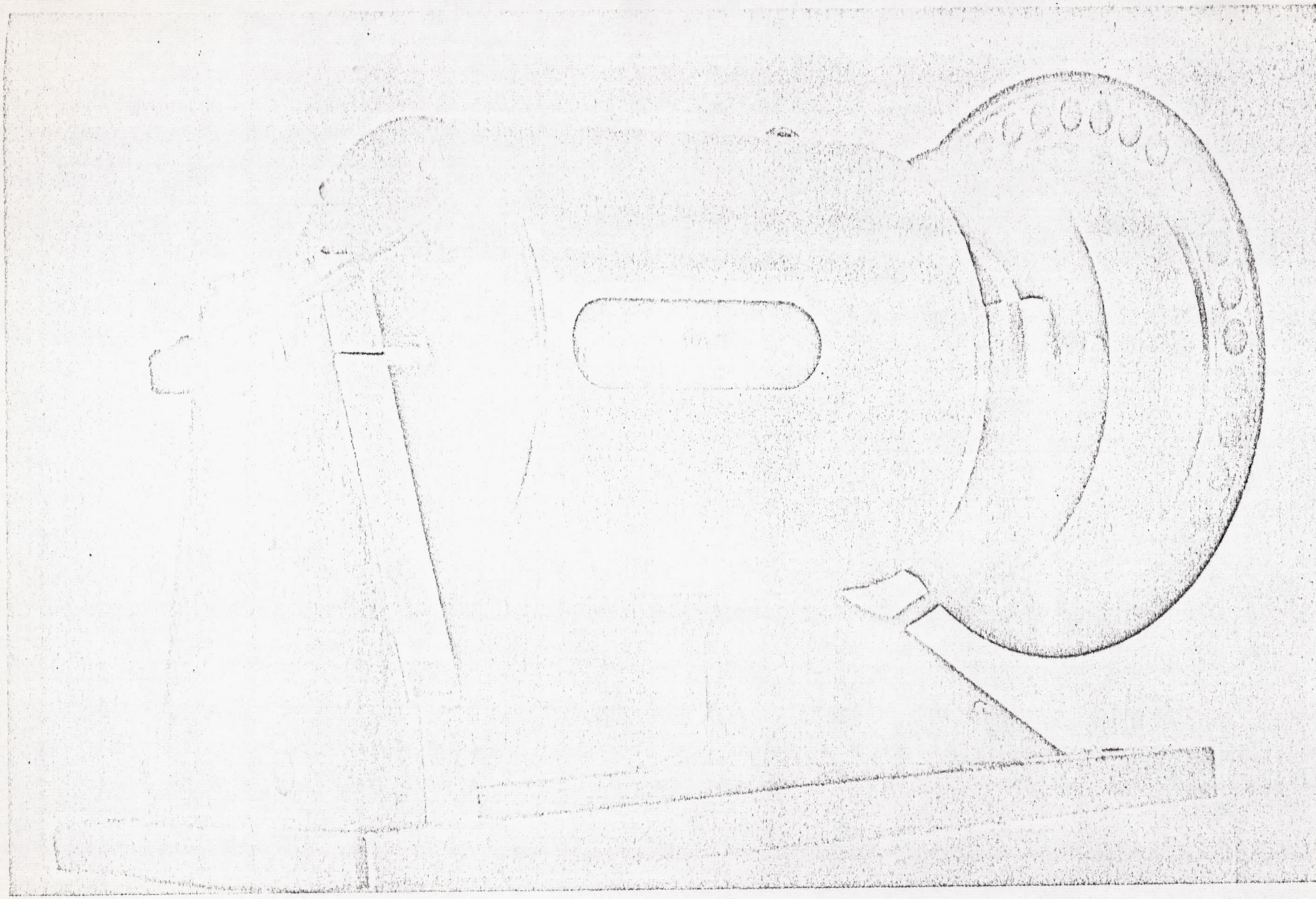


Figure II-6. Subreflector Assembly with Weather Cover.

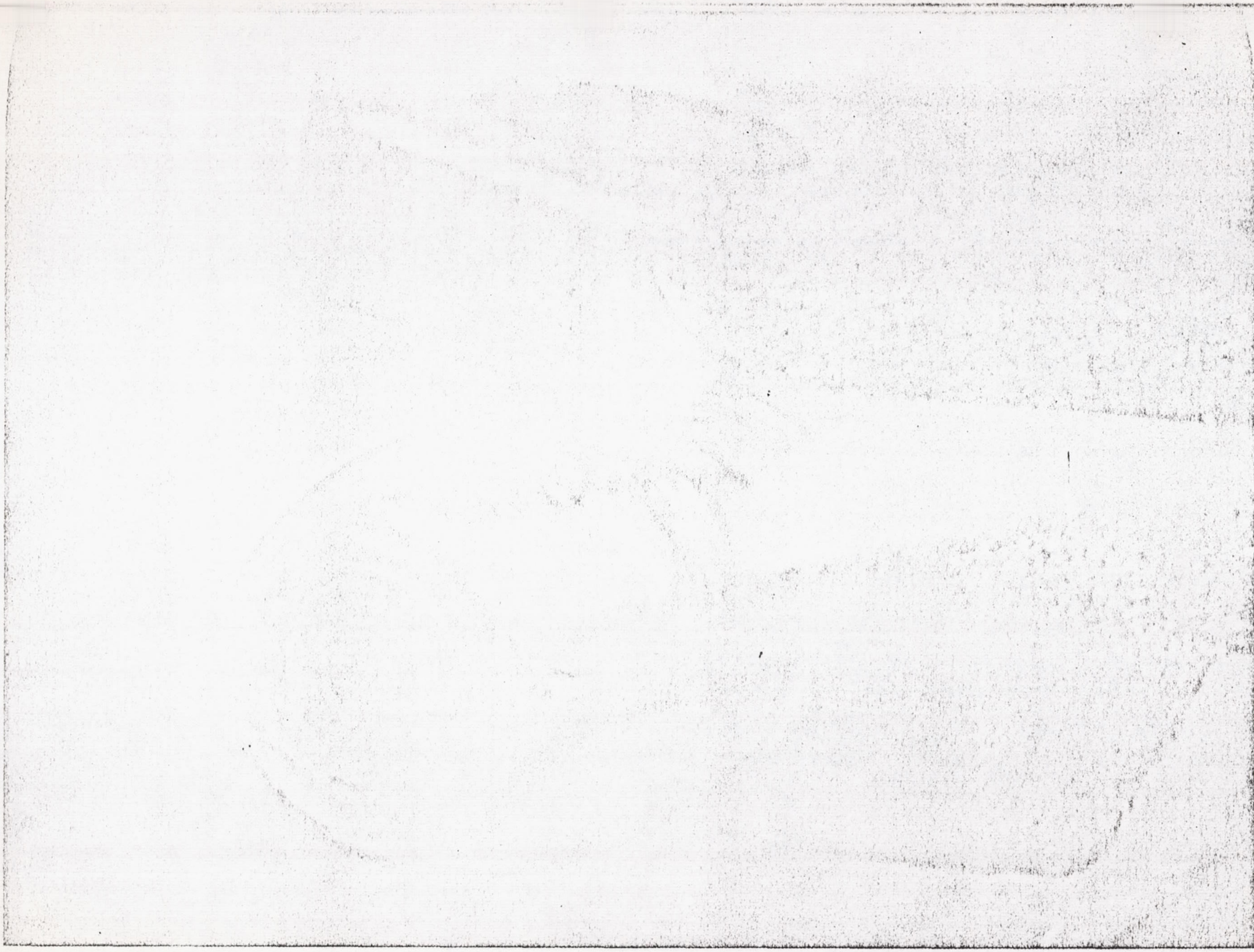


Figure II-7. Reflector Cam-Follower After Use.

Figure II-8. Counterweight Cam-Follower After Use.

III. DETERMINATION OF THE PHASE CENTER OF THE SCATTERED FIELD FOR AN ASYMMETRIC CASSEGRAINIAN FEED SYSTEM

As an extension of work done on the last contract (JPL 951756) and reported in an interim publication (USCEE 321), computations of phase center position for the tilted hyperboloid geometry were made. Originally, phase center determinations were made for hyperboloid D/λ values of 59.54, 24, and 10; the additional determinations were made for D/λ ratios of 7, 4, and 2. The complete set of results are shown in Table III-1, where a and ψ specify coordinates in the coordinate system symmetric with respect to the paraboloid. The physical-optics approximations for the current distribution are not expected to be valid for diameter/wavelength ratios that are not large compared to unity. Nevertheless, it has been experimentally verified under many different conditions that the calculated far-zone field based on the physical-optics currents is quite accurate for D/λ as small as four or five.[5,6] On the basis of this experimental justification small diameters have also been included in the analysis, although the two-wavelength result may indeed be questioned.

A determination of RMS phase deviation around the best-fit phase centers was determined for the D/λ ratios ranging from 59.54 down to 2. The results are shown in Table III-2. It is seen from this table that the RMS phase deviation around the best-fit center is less in each case than around the origin of the symmetric coordinate system (phase center for the non-tilted geometry.

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5. Rusch, W. V. T., "Scattering of a Spherical Wave by an Arbitrary Truncated Surface of Revolution", TR 32-434, Jet Propulsion Laboratory, Pasadena, California, May 27, 1963.

6. Brunstein, S. A., Private Communication.

D/λ	λ(mm)	a(λ)	a(mm)	Ψ(deg)
59.54	3.33 mm	1.707 λ	5.684 mm	88.11 deg
24	8.26 mm	0.689 λ	5.691 mm	89.37 deg
10	19.83 mm	0.289 λ	5.731 mm	94.04 deg
7	28.30 mm	0.204 λ	5.766 mm	95.17 deg
4	49.53 mm	0.117 λ	5.818 mm	88.58 deg
2	99.06 mm	0.062 λ	6.147 mm	111.15 deg

TABLE III-1

Phase center coordinates for various hyperboloid D/λ ratios. The diameter is held constant.

D/λ	Around	Radius (mm)	Radius (λ)	γ (angular deg.)	RMS Phase Deviation (electrical deg.)
59.54 λ=3.333 mm	Best-Fit Origin	5.684 mm 0.000 mm	1.707 λ 0.000 λ	88.11 deg	17.634 deg 344.44 deg
24 λ= 8.26 mm	Best-Fit Origin	5.691 mm 0.000 mm	0.689 λ 0.000 λ	89.37 deg	6.736 deg 138.23 deg
10 λ= 19.83 mm	Best-Fit Origin	5.731 mm 0.000 mm	0.289 λ 0.000 λ	94.04 deg	4.655 deg 56.751 deg
7 λ= 28.30	Best-Fit Origin	5.766 mm 0.000 mm	0.204 λ 0.000 λ	95.17 deg	5.122 deg 39.493 deg
4 λ= 49.53 mm	Best-Fit Origin	5.818 mm 0.000 mm	0.117 λ 0.000 λ	88.58 deg	6.420 deg 22.410 deg
2 λ = 99.06 mm	Best-Fit Origin	6.147 mm 0.000 mm	0.062 λ 0.000 λ	111.15 deg	7.403 deg 11.792 deg

TABLE III-2

Comparison of phase function characteristics for various hyperboloid D/λ ratios.

IV. SUN TRACKING SYSTEM

Millimeter-wave radio observations of a celestial source of radio energy provide a useful measure of the effective integrated attenuation of the atmosphere in this wavelength range. This information is particularly significant for the design of near-space and deep-space communications at millimeter wavelengths. The Bell Telephone Laboratories have established an automatic sun tracker to obtain atmospheric data at frequencies of 16 and 30 GHz (Figure IV-1).[7] A primary task of this contract period was to establish a similar sun tracking system with the existing 90-GHz radio telescope and nodding-subdish system.

A. Microwave Sun Tracker. A block diagram for a microwave sun tracker was analyzed by Mr. Charles Abronson, who was working on his Master's thesis during the period of this contract. Preliminary calculations indicated that an L-band or S-band system with adequate temperature and angular resolution to provide a sufficiently large control signal to maintain the 90-GHz beam on the sun would require prohibitively large antennas. Consequently, further analyses were carried out only for an X-band (10-12 GHz) system. Although atmospheric attenuation begins to become a problem at these higher frequencies, a document received from C. T. Stelzried indicated that X-band system degradation is only about 3 dB in a 1.0 inch/hour rain for angles within 50 degrees of zenith.

A computer program belonging to the Aerospace Corporation was used to estimate the antenna temperatures available for a potential microwave control signal. However, for a six-inch horn operating at X-band, a

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[7] News Release: 'Sun Used as 'Satellite' in Bell Laboratories Experiment", Bell Telephone Laboratories, Inc.

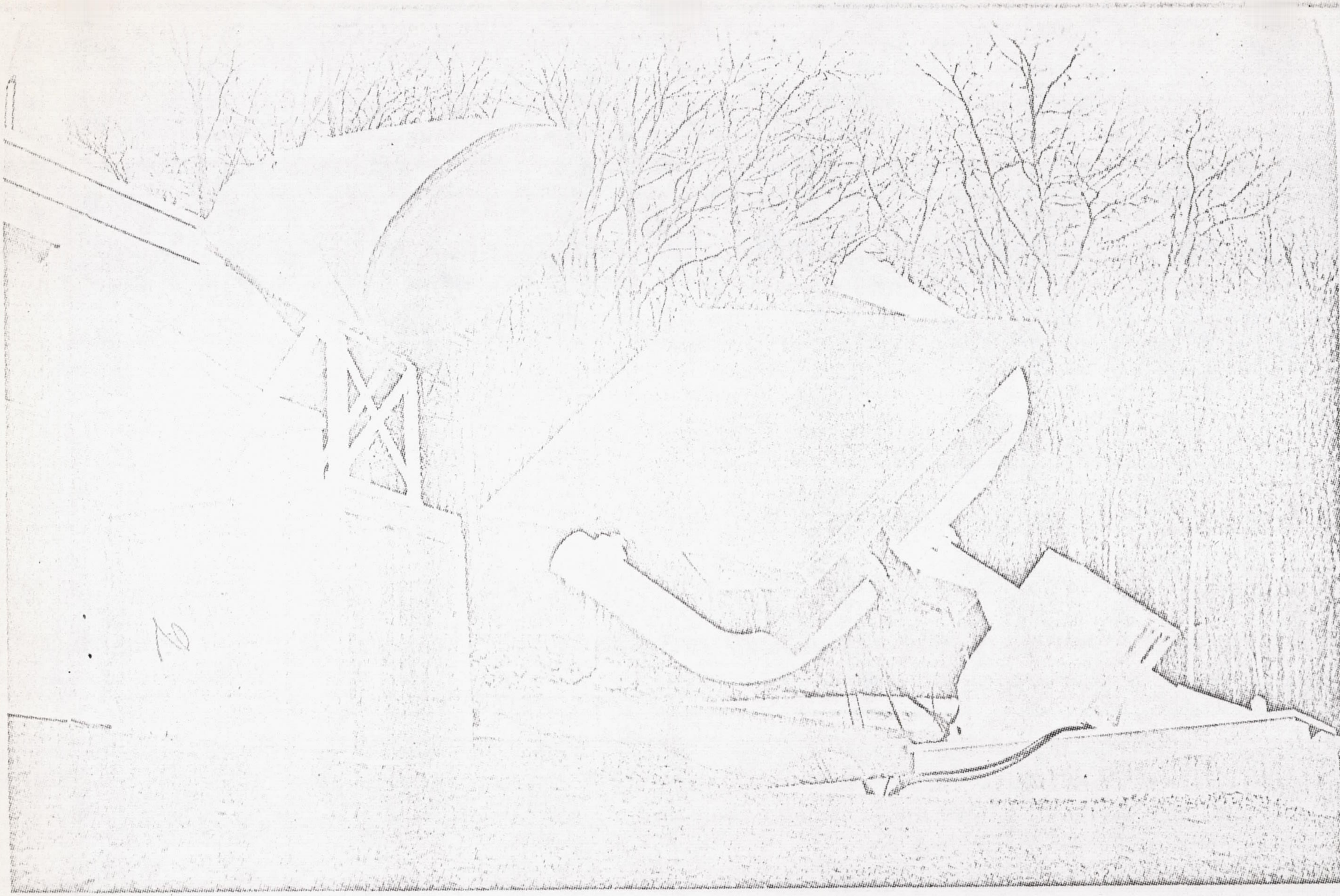


Figure IV-1. Bell Telephone Laboratories Sun Tracker.

tracking error of one minute (about the limit of error that could be tolerated by the 90-GHz beam) would cause a change of antenna temperature less than 0.1 degree Kelvin. Since this value was smaller than the probable RMS jitter of the radiometer with some reasonable time-constant, a decision was made to abandon plans for a microwave sun tracker and to fabricate an optical tracker instead.

B. Optical Sun Tracker: The optical sun tracker was designed to keep the antenna pointed at the sun with a miximum pointing error of one minute of arc in any direction. The error sensing device consisted of an optical telescope and four photoconductive cells to provide error signals for the feedback loop. The electronic circuitry consisted of two identical channels (Figure IV-2): one for the right-ascension axis and one for the declination axis. Each channel consisted of a detector, a logic circuit, and a power circuit. The power circuits controlled the stepping motors which drove the antenna. The logic circuits determined the correct sequence of voltages to be supplied to the stepping motors, and the detector circuits converted the analog signals from the photoconductive cells into appropriate inputs to the logic circuits.

1. Guide Telescope. The guide telescope (Figure IV-3) was manufactured by Optech Instruments in Monterey Park. It consisted of a 30-inch steel tube, a two-inch diameter achromatic objective lens, and an achromatic Barlow lens suitable to provide an effective focal length of 120 inches. An iris diaphram was mounted in front of the objective lens. The Barlow lens

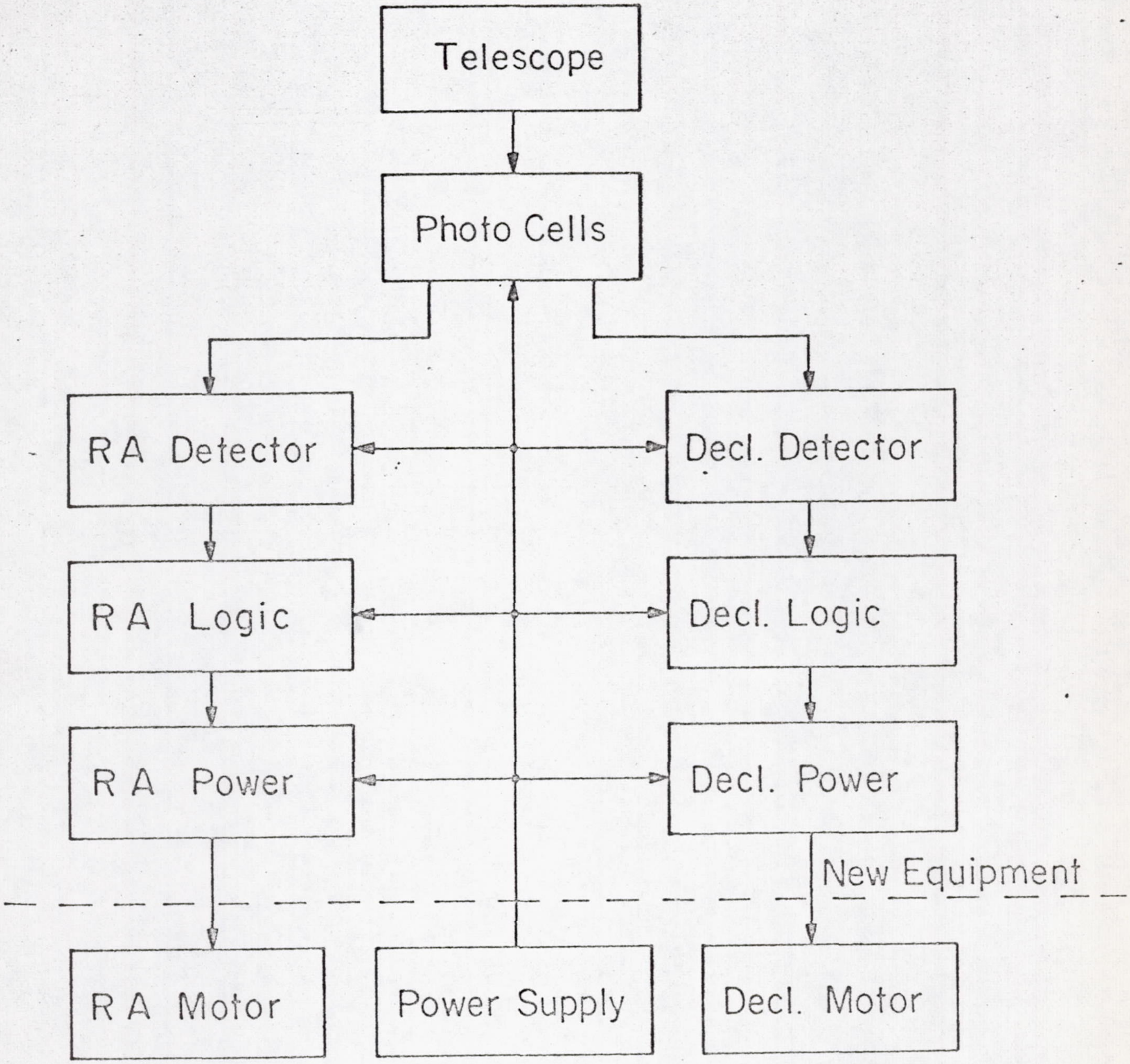
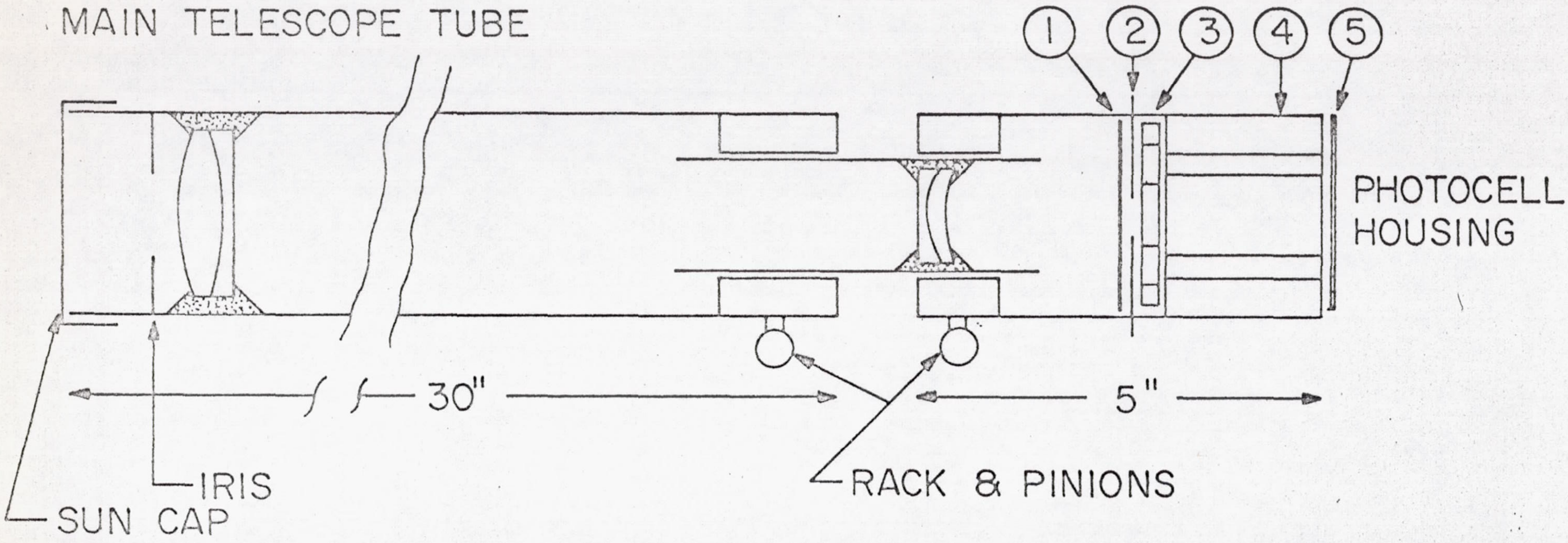


Figure IV-2. Block Diagram of Optical Sun Tracker.



1 Front Retaining Plate
2 Slides
3 Lens Spacer
4 Cell Holder
5 Rear Retaining Plate

1/2 Scale

Indicated Dimensions are Approximate.

Figure IV-3. Schematic Diagram of Guide Telescope.

was mounted in a 1.25-inch diameter draw tube which could be adjusted with respect to the main telescope tube with a rack and pinion. The photocell housing was attached to this draw tube. The optical system formed a real image, about 1.125 inches in diameter, on the photocell retaining plate. Behind the retaining plate four metal slides, each of which had a pinhole, were used to select light from each quarter of the limb of the solar image for the four photocells. Four concave lenses were then used to focus the light from each pinhole on one of the four photocells. A photograph of the guide telescope is seen in Figure IV-4, a closeup of the photocell housing in Figure IV-5, and an overall view of the entire telescope system in Figure IV-6.

2. Detector Circuits. The detector circuit received analog signals from the photocells. These signals, consisting of voltages between -10 and +10 volts, were then converted into four binary output signals x_1, x_2, x_1', and x_2', to drive the logic circuits. A photograph of the detector circuit board is seen in Figure IV-7.

3. Logic Circuits. The logic circuit received inputs x_1, x_2, x_1', and x_2' from the detector circuits. A high voltage for x_1 indicated that the R.A stepping motor should move one step east. A high voltage for x_1' indicated that the R.A. stepping motor should move one step west. x_2 and x_2' controlled the declination stepping motor in a similar fashion. x_1' was low whenever x_1 was high and x_2' was low whenever x_2 was high. The stepping motors

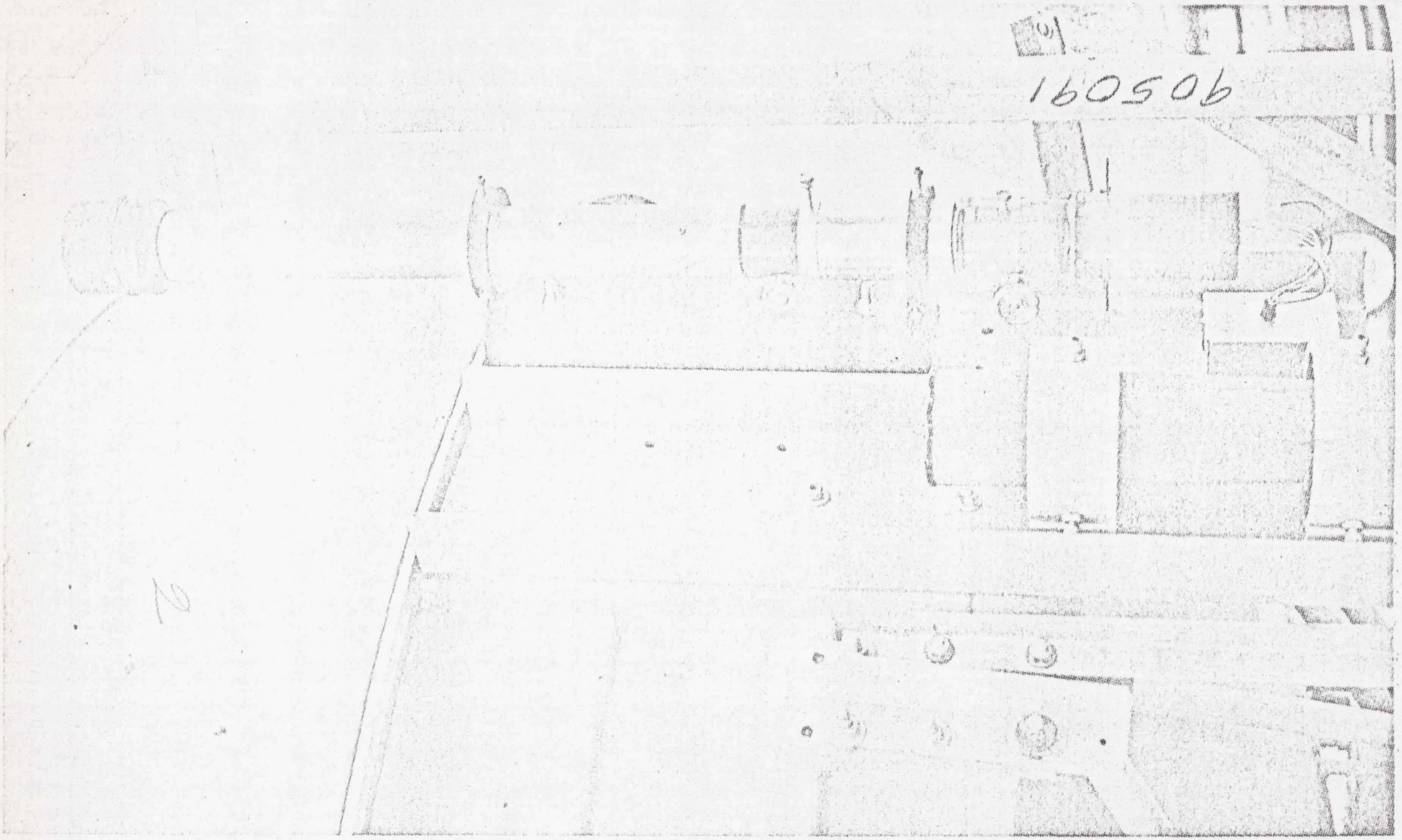


Figure IV-4. Guide Telescope.

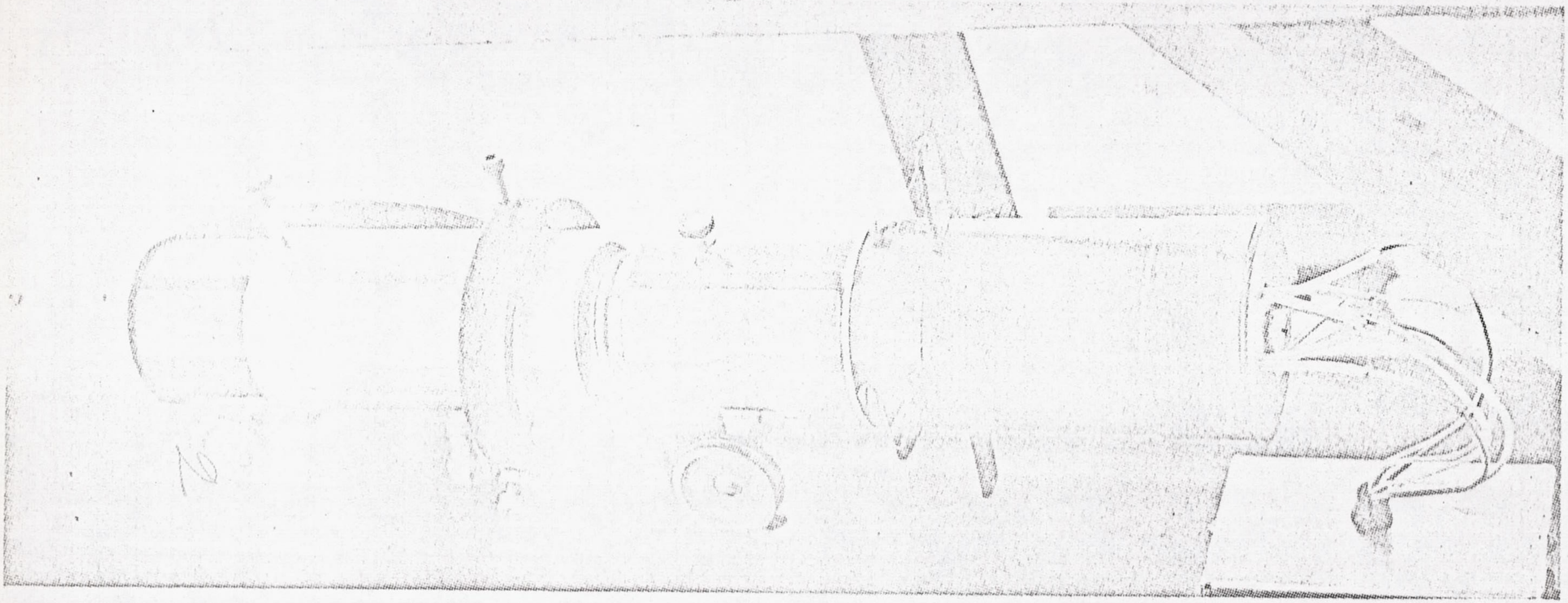


Figure IV-5. Photocell Housing of Guide Telescope.

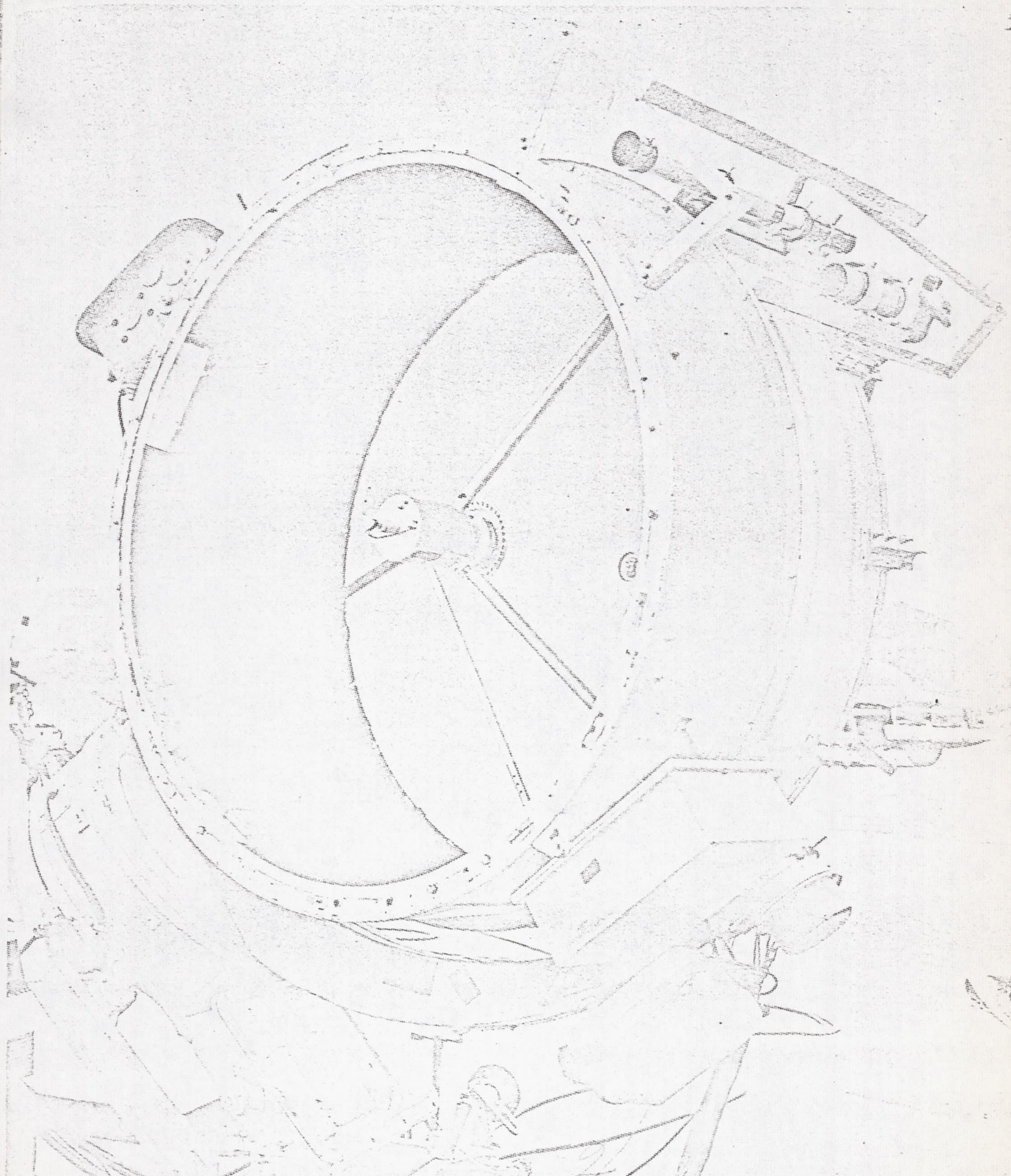


Figure IV-6. Sun-Tracking Radio Telescope.

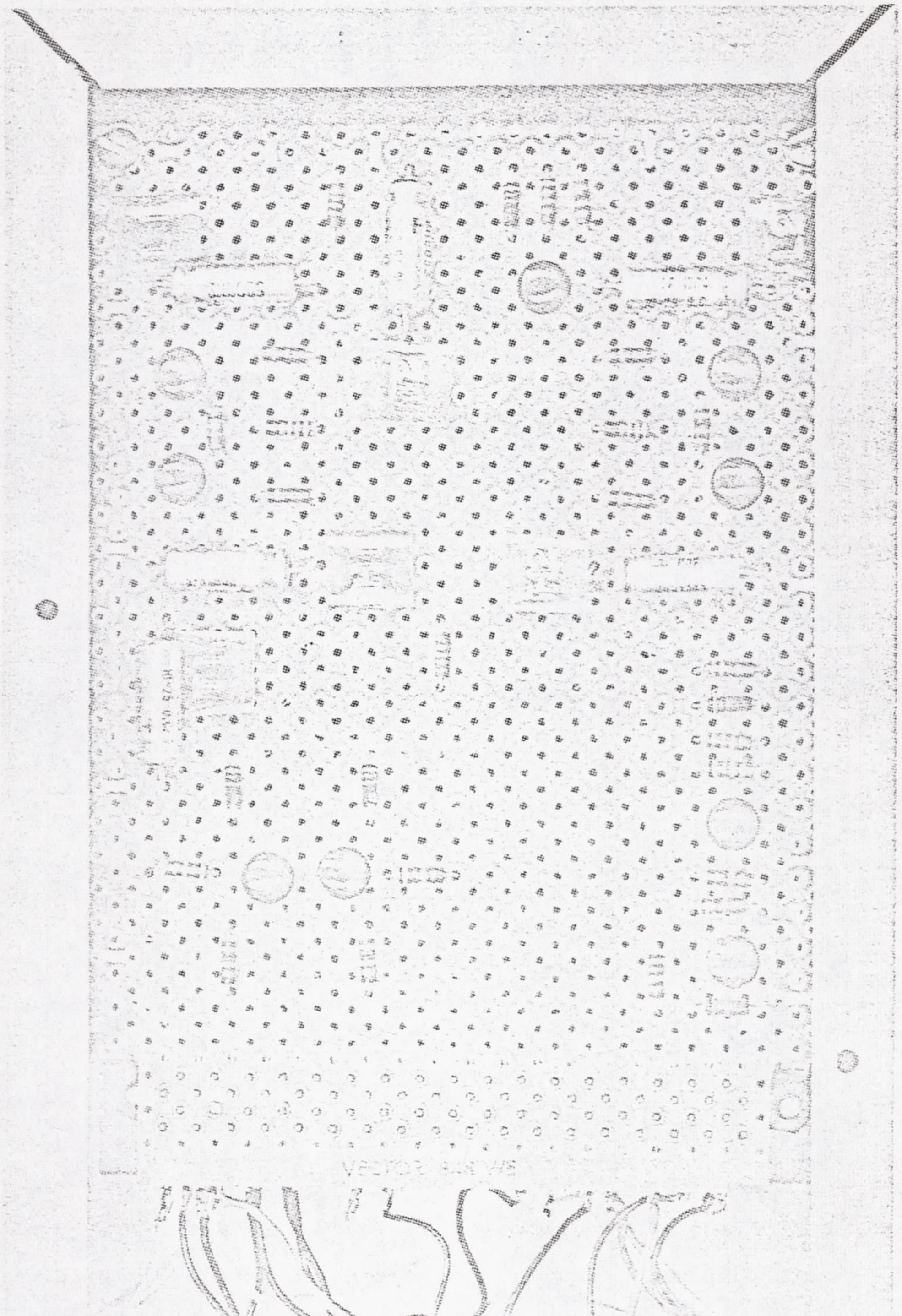


Figure IV-7. Detector Circuit Board.

operated as follows: either a +10 vdc or -10 vdc signal could be applied to each of the two motor windings. Thus there were four input combinations: (+, +), (+, -), (-, -), and (-, +). The basic job of the logic circuits was to decide the polarities of these voltages based upon the information supplied by x_1 and x_2. A photograph of the logic circuit board is seen in Figure IV-8.

4. Power Circuits. The power circuits received inputs w_1 and w_2 from the logic circuits. These signals were used to determine the position of a relay (see schematic diagram in Figure IV-9) which selected the polarity of the voltage supplied to the motor windings from the high-power supply. The diodes across the relay prevented contact arcing. A photograph of the power circuit board is seen in Figure IV-10.

5. Performance of the System. The optical sun tracker was found to perform within the design requirements of one-arcminute tracking error; and 15 days of tracking data were obtained in accordance with the contract task statement. It was found that the system worked with a clear sky or with a light haze, but that patches of clouds would cause the system to lose its lock on the sun whenever any portion of the sun's limb was obscured. Under such circumstances a semi-automatic tracking mode was implemented, during which manual corrections were applied to the sidereal tracking rate.

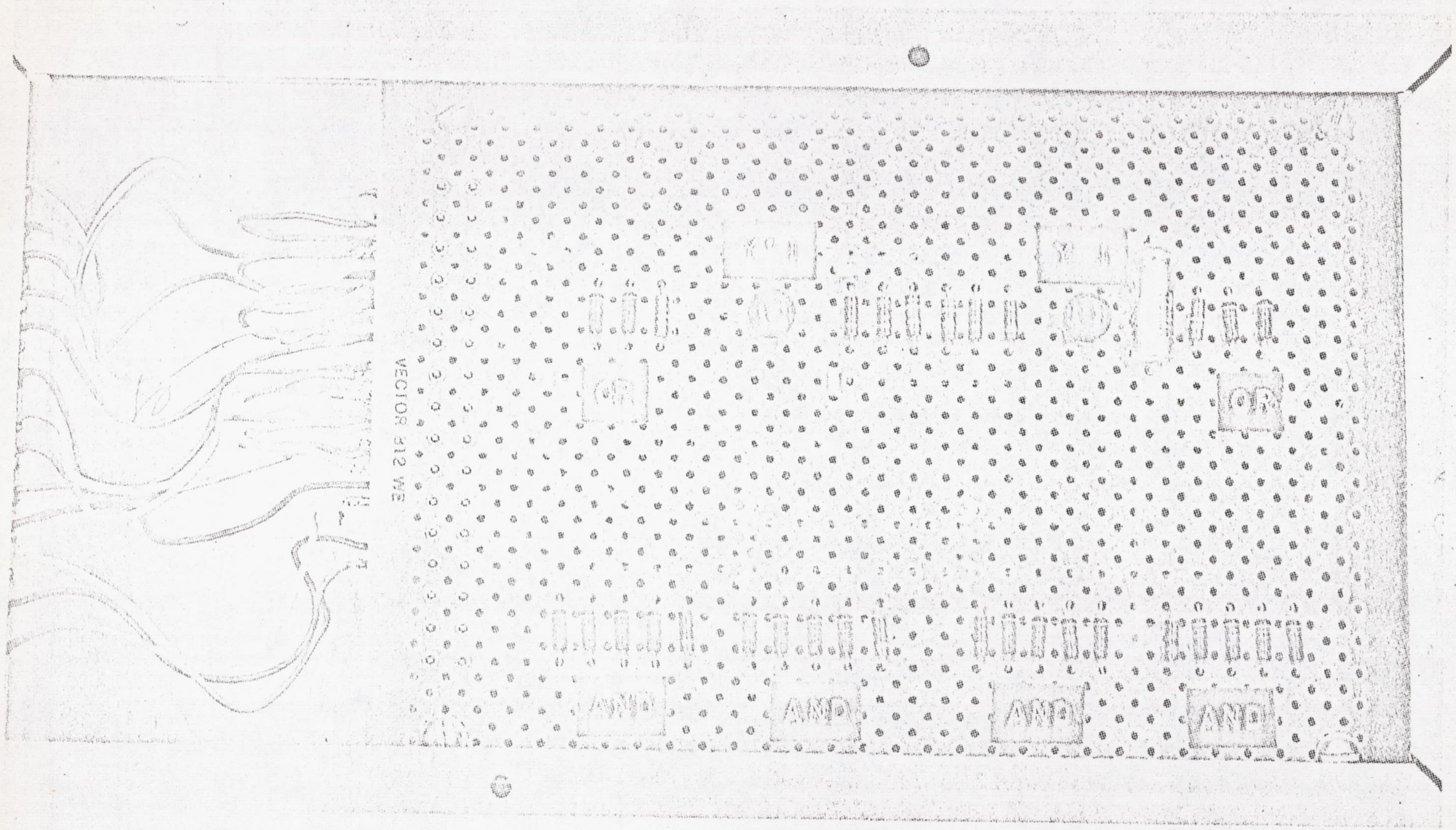


Figure IV-8. Logic Circuit Board.

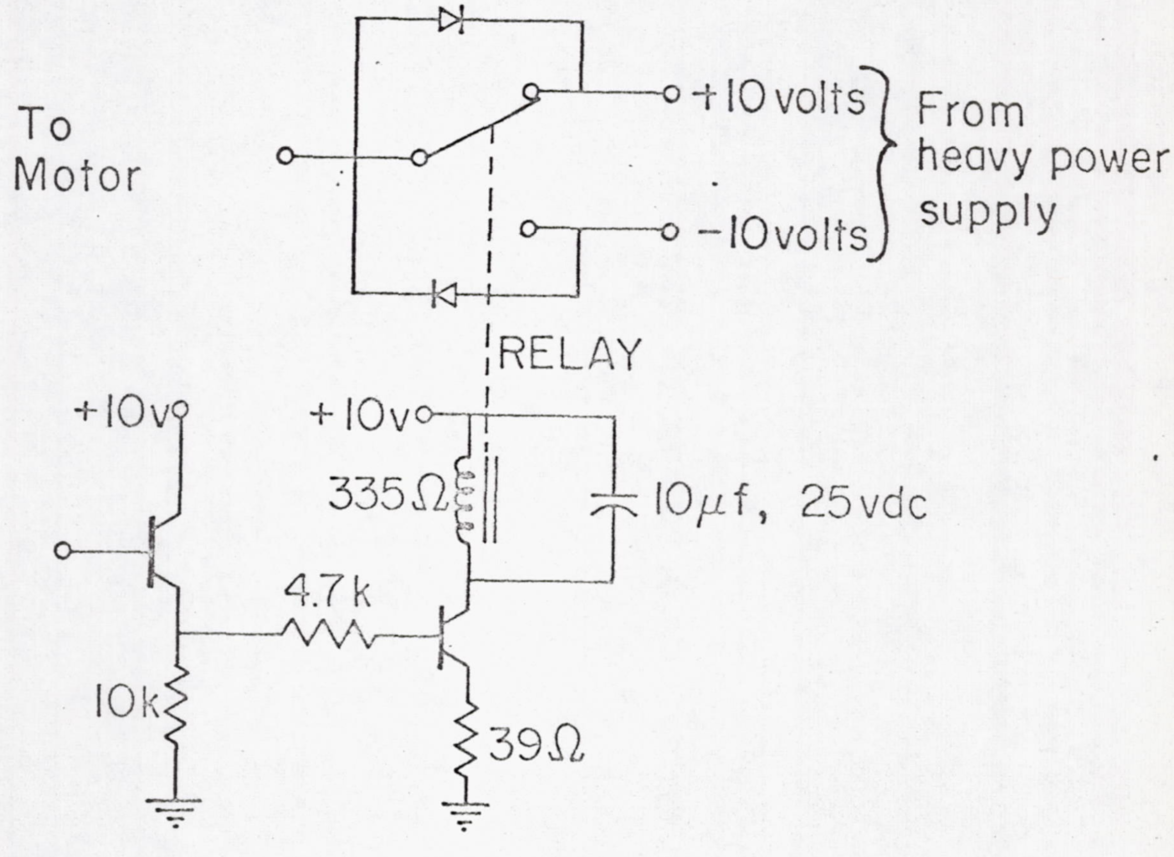


Figure IV-9. Power Circuit Schematic.

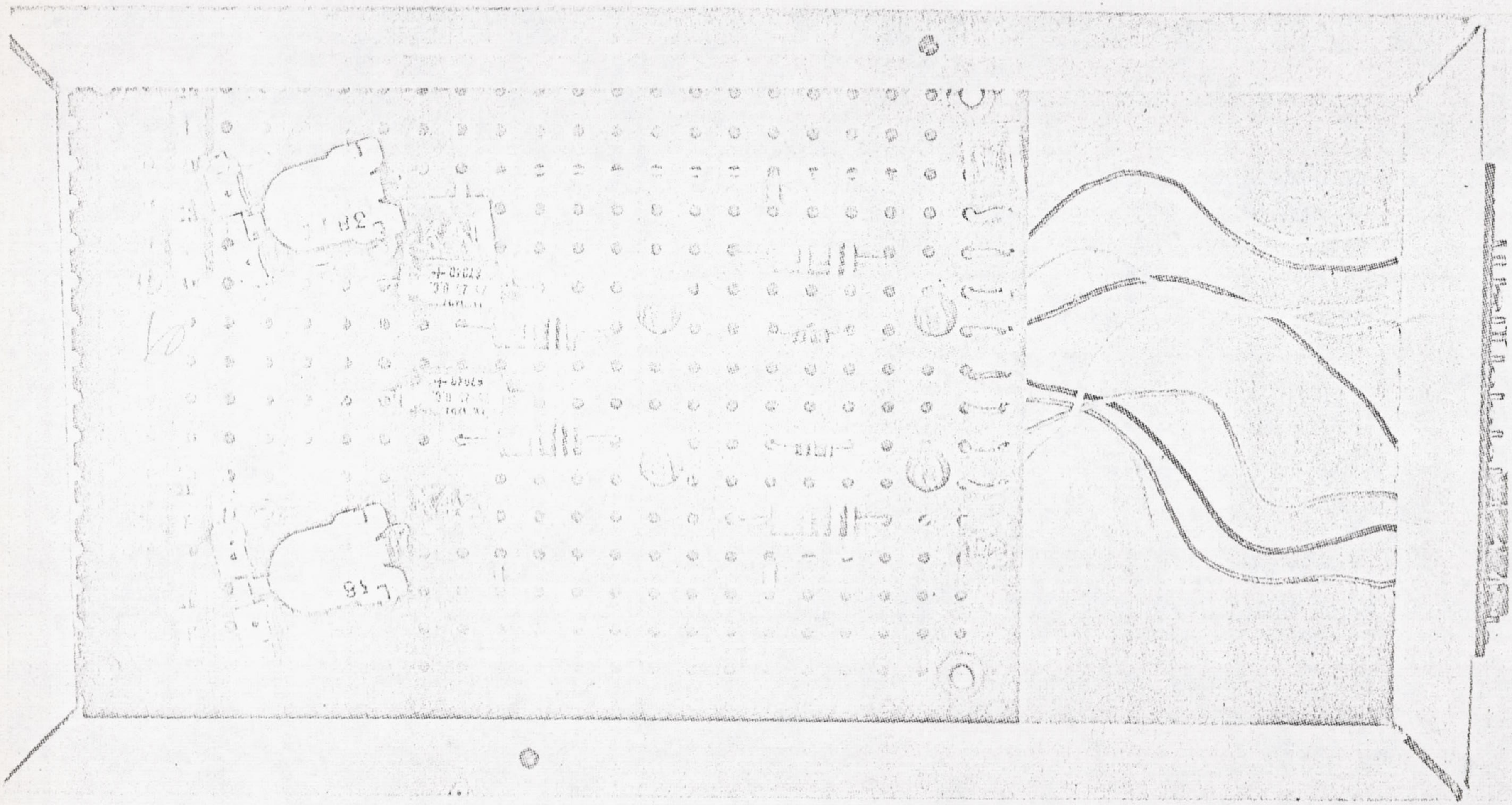


Figure IV-10. Power Circuit Board.

V. OBSERVATIONAL PROGRAM

A. Total Lunar Eclipse of 12 April, 1968. The radio telescope was moved from the Goldstone site to the Mesa Antenna Range at JPL in early December, 1967. However, the system was not restored to its operating condition until early in April, 1968. The moon was observed by S. Slobin and D. Oltmans on several nights prior to the eclipse, and the system sensitivity was found to have returned to the excellent level it had attained the previous October. Unfortunately, on April 12, the skies were extremenly overcast in the Los Angeles area, making visible tracking impossible. Consequently, the observations could not be carried out.

B. Solar Observations - January to April, 1969. In accordance with the requirements of the contract, the optical sun tracker was used to obtain atmospheric absorption data during fifteen days in the first three months of 1969. Because of unseasonably heavy rains, this program was considerably delayed from its original schedule. As reported in the previous sections, the sun tracker operated well within the design requirements. The data from these observations are reduced and correlated with atmospheric parameters in the following section.

VI. DATA REDUCTION

A. Zenith-Angle Program. In past observational programs, the zenith angle of the celestial object under observation was determined directly by measuring it with a transit. However, since the zenith angle is a function of celestial coordinates, time, and local latitude and longitude of the radio telescope, and since there was a shortage of manpower for the observations, a computer program was written to compute the zenith angle of the sun from the time of the observation and the solar coordinates as obtained from the Nautical Almanac. This program is reproduced in the Appendix.

B. Reduction of Solar Data. The solar data from fifteen days of observations was reduced using a technique developed by Stelzried and Rusch[8]. The resulting atmospheric loss for each day is tabulated in Table VI-1, together with the ground-level temperature and relative humidity at the time of the measurement.

C. Atmospheric Loss Study. Stelzried[9] has developed a theory which may be used to relate the 90-Ghz zenith loss with ground-level temperature and humidity. It may be assumed that the zenith atmospheric loss A in dB is separable into A_o, due to the total integrated oxygen content, and A_w, due to the total integrated water-vapor content.

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8 Stelzried, C. T. and W. V. T. Rusch, "Improved Determination of Atmospheric Opacity from Radio Astronomy Measurements", Journal of Geophysical Research, Vo. 72, No. 9, May 1, 1967, pp. 2445-2447.

9 Stelzried, C. T., Private Communication

DATE	ZENITH ATMOSPHERIC LOSS	PE	GROUND TEMPERATURE	GROUND HUMIDITY
1/4	0.513 dB	.013 dB	83° F	34%
1/11	1.157	.007	61	61
1/18	0.776	.111	54	70
1/30	0.619	.094	57	33
2/1	0.265	.016	64	38
2/8	0.586	.005	68	22
2/27	0.239	.164	62	51
3/1	0.300	.003	64	31
3/6	0.660	.018	58	27
3/13	0.410	.010	55	37
3/15	0.415	.005	70	22
3/20	0.678	.014	67	60
3/22	0.567	.005	72	36
3/27	0.545	.008	85	10
3/29	0.376	.024	84	38

TABLE VI-1

Atmospheric Data from 90-GHz Solar Observations.

Thus:

$$A = A_o + A_w \tag{VI-1}$$

The oxygen loss has been determined to be about 0.28 dB[10]. It may then be assumed that the water-vapor loss is related to the density of water vapor at ground level by the relation

$$A_w = A_{wr} \left(\frac{\rho}{\rho_r}\right)^{\alpha} \tag{VI-2}$$

where A_{wr} is the water-vapor loss of a reference atmosphere of temperature T_r and humidity H_r.

ρ is the actual ground-level density of water vapor, g/m^3

ρ_r is the ground-level density of water vapor of the reference atmosphere.

α is a parameter relating the loss to the water-vapor content in accordance with the above equation.

Stelzried has empirically determined that in the range from 32 to 100°F the water density in saturated air is related to the temperature by

$$\rho_s = 1.8722 + 7.4970 \times 10^{-3} T + 2.7799 \times 10^{-3} T^2 - 1.2069 \times 10^{-5} T^3 + 2.7390 \times 10^{-7} T^4 \tag{VI-3}$$

where the temperature is given in degrees Fahrenheit. The water-vapor content ρ and ρ_r are related to the content in saturated air by the relation

$$\rho = \frac{H}{100} \rho_s \tag{VI-4}$$

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[10] Shimabukuro, F.I., "Propagation Through the Atmosphere at a Wavelength of 3.3 Mm", IEEE Transactions on Antennas and Propagation, Vol. AP-14, No. 2, March 1966, p. 228.

where H is the humidity in percent. Equations (VI-3) and (VI-4) are then used to determine $\rho(T, H)$ and $\rho_r(T_r, H_r)$ for inclusion in equation (VI-2).

The remaining parameters in equation (VI-2), A_{wr} and α, may be determined by minimizing the variance between the theoretical and measured values. This has been done for the 15-days of solar data tabulated in Table VI-1 with the result that

$$A = 0.28 + 0.24 \left(\frac{\rho}{\rho_r}\right)^{0.4} \text{ dB} \qquad \text{(VI-5)}$$

where the temperature of the reference atmosphere has been chosen to be 60°F and the humidity to be 40 percent. The variance obtained in the statistical determination of the above equation was 0.05 dB.

The advantage of the above result is that it does not require information concerning the water-vapor content (or temperature and humidity) above ground level. The ground-level values are easily determined with conventional instruments. It should be emphasized that equation (VI-5), or an equivalent equation based upon considerably more data, is only valid for one particular season and geographical location and should not be expected to provide accurate information at other seasons and/or sites. However, once such an equation has been accurately determined for a particular site, considerable advantage can be derived from its use rather than the conventional extinction-curve technique.

VII: PERSONNEL

A. Principal Investigator: W. V. T. Rusch

B. Graduate Students:

1. C. Abronson
2. S. D. Slobin
3. C. A. Cooper

C. Undergraduate Students:

1. J. Breen
2. G. Craig
3. T. Donahue
4. B. Mayer
5. J. Potosky
6. P. Shoals

D. Professional Consultants:

1. R. A. Gardner - Radiometer
2. A. Giandomenico - Mechanical Design

VIII. PUBLICATIONS

A. U.S. Patent No. 3,417,399: "Millimeter-Wave Radiometer for Radio-Astronomy", December 17, 1968.

B. Slobin, S. D., "A Study of an Asymmetric Cassegrainian-Antenna Feed System and Its Applications to Millimeter-Wave Radio-Astronomical Observations", USCEE Report 321, University of Southern California, Los Angeles, December, 1968.

C. Rusch, W. V. T., Slobin, S. D., Stelzried, C. T., and Sato, T., "Observations of the Total Lunar Eclipse of October 18, 1967, at a Wavelength of 3.33 Millimeters", Astrophysical Journal, Vol. 155, March 1969, pp. 1017-1021.

D. Slobin, S. D. and Rusch, W. V. T., "A Case Study of Phase-Center Relationships in an Asymmetric Cassegrainian Feed System", IEEE Transactions on Antennas and Propagation, November, 1969.

E. JPL New Technology Report, Case #1781, "Improved Mm-Wave Rasiometer for Radio Astronomy".

F. Shoals, P. G., "Measurement of Atmospheric Loss at 3.33 Mm with an Automatic Sun Tracking System", winning paper for Sigma Xi Undergraduate Research Award, University of Southern California, May, 1969.

APPENDIX

FORTRAN IV COMPUTER PROGRAM TO COMPUTE ZENITH ANGLE

```
C
C THE DATA INPUT SHOULD BE IN THE FOLLOWING ORDER . . .
C NUMERICAL DATE, GREENWICH MEAN TIME IN HOURS, MINUTES AND SECONDS,
C THE GHA OF PREV HOUR, THE GHA OF NEXT HOUR, THE DEC. OF PREV HOUR,
C AND THE DEC. OF THE NEXT HOUR. ALL INPUT IS IN FLOATING POINT, AND A
CARD SIMILAR TO THE ONE WHICH FOLLOWS MAY BE USED ON THE KEYPUNCH DRUM.
C1AAAA-1AA-1AA-1AA--1AAA-1AAA-1AAA-1AAA-1AAA-1AAA-1AAA-1AAAAAAAAAAAAAAAAAAAAAAAAA
C DECLINATION NORTH IS POSITIVE, DECLINATION SOUTH IS NEGATIVE
C
C
C       ASSIGNED CONSTANTS
C       SINE OF LATITUDE 34 DEG. 12.34 MIN.
        S=.56221
C       COSINE OF LATITUDE 34 DEG. 12.34 MIN.
        C=.826987
C       DEGREE TO RADIAN CONVERSION FACTOR
        PIF=3.1415926/180.0
C       LONGITUDE  IN RADIANS
        LONG=118.17289
C
        WRITE(6,300)
300     FORMAT('1')
        READ(5,101)J
101     FORMAT(I2)
        DO999I=1,J
        WRITE(6,222)I
222     FORMAT('-DATA SET NUMBER ', I2/)
        READ(5,100)DAT,GH,GM,GS,GPA,GPB,GNA,GNB,DPA,DPB,DNA,DNB
100     FORMAT(F6.0,3F4.0,1X,8F5.0)
C
C       DECIMAL MINUTES
        GMD=GM/60.
C       DECIMAL SECONDS (CONSTANT OF 50 SECONDS HAS BEEN ADDED)
        GSD=(GS+50.)/3600.
        GMT=GH+GMD+GSD
C
```

```
C       CONVERT PARAMETERS TO DECIMAL
        DELTA=GMD+GSD
        P=GPB/60.
        X=GNB/60.
        CP=DPB/60.
        CN=DNB/60.
        GP=GPA+P
        GN=GNA+X
        IF(DPA-0.0)1,2,2
1       DP=DPA-CP
        GO TO 3
2       DP=DPA+CP
3       CONTINUE
        IF(DNA-0.0)4,5,5
4       DN=DNA-CN
        GO TO 6
5       DN=DNA+CN
6       CONTINUE
C
C       INTERPOLATE
        GIF=GN-GP
        DIF=DN-DP
        GINT=DELTA*GIF+GP
        DINT=DELTA*DIF+DP
        RD=DINT*PIF
        RGL=ABS(GINT-LONG)*PIF
C
C       FIND THE COSINE OF THE Z ANGLE
        COSZ=S*(SIN(RD))+C*(COS(RD))*(COS(RGL))
        TANZ=(SQRT(1-COSZ**2))/COSZ
        Z=ATAN(TANZ)
        Z=Z/PIF
C
        WRITE(6,200)DAT,GMT,GINT,DINT,Z
200     FORMAT(' THE NUMERICAL DATE IS        ',F5.0,/' THE GREENWICH MEAN T
       2IME IS  ',F6.2,/' THE GREENWICH HOUR ANGLE IS ',F6.2,/' THE DECLIN
       3 TION IS          ',F9.5,/' THE SUN HAS ZENITH ANGLE    ',F6.2)
999     CONTINUE
        WRITE(6,400)
400     FORMAT('1')
        END
```