NATIONAL RADIO ASTRONOMY OBSERVATORY
2015 IVY ROAD
CHARLOTTESVILLE, VIRGINIA 22903
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June 17, 1982

12 METER MILLIMETER WAVE TELESCOPE
MEMO No. 174

Dr. William Ward (C270)
MIT/Lincoln Labs
P. O. Box 73
Lexington, Massachusetts 02173

Dear Dr. Ward:

The National Radio Astronomy Observatory (NRAO) is presently in the midst of a program to rebuild the surface of its millimeter radio telescope on Kitt Peak, Arizona. We would like to measure the new 12-meter diameter surface using the LES-8 or LES-9 satellite in CW mode at K-band as a source for an interferometric measurement. The enclosed report details the technique to be employed and outlines other technical considerations.

We have budgeted to build a two-channel LES-8/9 receiver in FY 1982 employing ambient mixers with a 1200 Kelvin SSB noise temperature. We are anxious to learn if the LES-8 or LES-9 satellite can be made available to us so that we can proceed with component procurement.

Our satellite time requirements are quite modest. We envision two four-hour sessions separated by several weeks about one year from now for system orientation and initial measurement. Several months after that, we envision an eight to ten hour session in order to evaluate the 12-meter surface at several elevation angles. A single four to five hour session once a year after that would probably be required for surface maintenance.

The NRAO is operated by Associated Universities, Inc. under contract No. NSF AST-79-08925 with the National Science Foundation (NSF). The Acting Section Head of the NSF Division of Astronomical Sciences is Dr. Vernon Pankonin (telephone (202) 357-9857). The NRAO is engaged in basic scientific research in radio astronomy and performs research and development in electronics to support its various scientific programs.

We would appreciate your efforts in obtaining permission for us to schedule time on the LES-8 or LES-9 satellite. Correspondence or technical questions can be directed to Craig Moore at Green Bank, West Virginia. Mr. Moore can be reached by telephone at (304) 456-2127/2011.

Sincerely,

Michael Balister
Head
Electronics Division

Enclosures

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NATIONAL RADIO ASTRONOMY OBSERVATORY

TECHNICAL CONSIDERATIONS FOR HOLOGRAPHIC MEASUREMENT OF THE NRAO 12-METER SURFACE

Craig R. Moore

15 June 1982

Introduction

Microwave holography is emerging as a useful technique for measuring surface irregularities in parabolic reflector antenna. Several groups have made successful measurements using the radio continuum source 3C 84 (Scott and Ryle, Mullard, 15.4 GHz; Rogers, Haystack, 8.4 GHz; Napier, VLA, 6 cm) or a geosynchronous satellite (Wu, Algonquin, 12 GHz, ANIK-B). Each of these measurements utilized a second nearby steerable parabola as a reference element which was either regularly used and instrumented as an interferometer pair or was set up as a VLBI experiment. At least one group has made a millimeter frequency measurement with a ground based far field reference signal (Davis, U. of Texas, 86.1 GHz). In this measurement the received signal was strong enough to use a simple "sky horn" receiver mounted on the main antenna as the reference channel, thus eliminating the need for a separate interferometer antenna element. This approach is of interest to us because we do not want to bear the expense of erecting a steerable dish near the 12-m antenna nor is there sufficient space at our Kitt Peak site to allow one of any appreciable size. However, the 12-m mount does not permit viewing a ground based transmitter either in the far field or near field. Thus, a geosynchronous satellite combined with the "sky horn" reference receiver appears to be a practical solution. A "snapshot" of the surface could be taken periodically to determine if any changes in the surface have occurred.

Measurement Specifications

The new 12-meter surface for the NRAO Kitt Peak antenna is predicted to have a 70 μm RMS surface accuracy which would make it useful to 1.2 mm wavelength, or 250 GHz. The individual panels have been measured to have an RMS deviation of 25 to 40 μm. A mechanical template method of measurement is being developed in order to set the panels on the back-up structure. This method will measure 12 points on a radius and 144 radii for a total of 1728 points. It is hoped that these measurements will have a resolution of 30 μm. To be of value a holographic measurement should have comparable resolution in both surface height and number of data points.

Scott and Ryle (1977) relate the RMS surface measurement error to the number of sample points per diameter, the wavelength of the measurement signal, and the on-axis signal-to-noise ratio. This relationship is given as:

$$\Delta\sigma = \frac{n\lambda}{4\pi \mathrm{SNR}} \tag{1}$$

In order for each data point to be independent of the adjacent ones, the angular spacing between points must be at least one beamwidth. Thus, the antenna must be scanned ± n/2 beam widths in azimuth and elevation while the reference channel remains on axis. To provide resolution comparable to the mechanical measurement we propose achieving an RMS surface error ($\Delta\sigma$) of 20 μm over an n x n grid of 2500 data points, which requires scanning the antenna ± 25 beamwidths. The SNR required then depends on the shortest wavelength satellite transmission that can be found.

Satellite Selection

The literature was searched in an effort to identify satellites with a down-link frequency above 20 GHz, preferably a CW beacon. A number of

Japanese domestic satellites have been launched with frequencies between 19.5 GHz (CS) and 34.5 GHz (ECS and ETSII). These have spot beam earth coverage over Japan and are thus not visible from Kitt Peak. The ATS-6 satellite had 20 GHz and 30 GHz beacons for propagation experiments, but this satellite has been turned off due to old age. It is noted in passing that this was the satellite that interfered with the Green Bank interferometer at 2695 MHz some years ago. The four Comstar satellites have propagation experiment beacons of 19.04 GHz and 28.56 GHz. The D3 satellite was used about 12 months ago in an attempt at a holographic measurement of the NRAO 140-ft antenna. Dr. Peter Arnold of Bell Laboratories (201-949-5293) informed us that the beacons on all four satellites have been turned off due to deteriorating DC power on the satellites. Since these birds are used for commercial communications, there is no chance of the beacons being activated and thus jeaprodizing commerical operations.

The LES-8 and LES-9 military satellites each have a spot beam down link covering North America of 38.04 GHz and 36.84 GHz, respectively. These satellites were built by Lincoln Laboratories for the USAF and are used for military communications. However, it is possible for non-DOD U.S. Government-sponsored agencies to obtain time on these satellites for scientific purposes. Read Predmore of U. Massachusetts has used LES-8 for beam shape measurements of the Five College Radio Observatory antenna. Dr. William Ward of Lincoln Labs (617-862-5500, x7236) is the contact person for these requests. He advises us that there has been no degradation in performance in either of these satellites over the past several years and that none is expected over the next several years. The DC power is derived from a radio isotope thermoelectric generator instead of the conventional solar cell panels. Three axis stabilization is by a gimballed momentum wheel instead of the usual hydrogen peroxide control jets.

For these reasons the design life is indefinitely long. In order to obtain time on these satellites Dr. Ward suggested that we write a letter to him detailing our interest, scientific purpose and relationship with the NSF. He would then write to the military scheduling office outlining our need and qualifications. Following approval of our application we could then deal directly with the scheduling office when we wanted time. Dr. Ward further stated that they like to do this kind of thing on an occasional basis as it broadens the scope of the satellite program. There is no charge for any services as we are a U.S. Government-sponsored organization. This appears to be a good long-term signal source for holographic measurements and is also the highest frequency satellite down link that the author has been able to identify.

The LES-8 and LES-9 Parameters

The LES-8 and -9 satellites combine UHF and K-band transmit/receive capabilities for earth/space/earth and earth/space/space/earth communications links. The K-band down link is available on a 9.5° beamwidth horn or a 1.2° beamwidth steerable dish. The latter provides about 18 dB more effective isotropically radiated power (EIRP) and is updated in pointing every 20 minutes; but this can be done more often if needed. The LES-8 antenna has been easier to get time on up to now, but we should provide enough flexibility in our design to receive either satellite. The important parameters for the dish antenna are:

	LES-8	LES-9
Frequency	38.04 GHz	36.84 GHz
Polarization ...	LHCP	RHCP
EIRP	38.8 dBW	36.6 dBW
Longitude	109° West	106° West

The frequency is derived from an ovenized crystal oscillator having a stability of $\pm 1 \times 10^{-11}$ per day. The spectrum of the unmodulated K-band carrier is thought to be less than 200 Hz wide.

The orbit of both satellites is circular, synchronous with a 25° inclination near the ecliptic plane. Details for the LES-8 orbit are shown in Figure 1. Pointing from Kitt Peak (31° 57' 15" N and 111° 36' 51" W) for LES-8 ranges from 175° to 181° in azimuth and 28° to 78° in elevation. This large satellite motion causes a Doppler shift at 38 GHz of approximately ± 20 kHz with a maximum rate of nearly 600 Hz/5 minutes. An ephimeris is normally provided which gives the pointing values and Dopper shift in 5 minute intervals.

A Possible Configuration

In the following discussion we will assume a receive frequency of 36.84 GHz or 38.04 GHz depending on which places the more severe requirement on the particular parameter concerned. Thus, we assume that the 12-m antenna has the following performance at the satellite down-link frequency:

Gain	70 dB at 45% efficiency.
Beamwidth	2.7'
± Beamwidth scan angle ...	2.25° total angle.

We envision a mechanical configuration similar to that shown in Figure 2. The reference channel horn should be half a beamwidth of ∿ 3° in order to keep the satellite signal in the beam over the 2.25° antenna scan angle. The antenna gain of the reference channel is then taken as 34 dB. From equation 1 for $\Delta\sigma = 20\ \mu\text{m}$, $n = 50$ and $\lambda = 8.2$ mm (36.8 GHz), we find the required signal-to-ratio noise is 1622.

The link budget for LES-9 and the above receiver configuration is given in Table I. Ambient mixer front-ends and reasonably clear weather conditions are assumed. The product column is for a correlator output which makes more efficient use of SNR than amplitude detection of each channel. The final value is the carrier-to-noise ratio in a 1 Hz noise bandwidth.

TABLE I

Satellite → Earth Link Budget for Receive Antenna Peaked on LES-9 at 36.84 GHz

Item		Signal	Ref.	$\sqrt{\text{Signal x Ref}}$
Satellite EIRP (dish)	dBW	36.6	36.6	
Pointing Loss, Satellite	dB	-1.0	-1.0	
Pointing Loss, Earth Receiver	dB	--	--	
Polarization Loss	dB	-0.5	-0.5	
Path Loss (EL = 28°)	dB	-214.9	-214.9	
Atmospheric Absorption (EL = 28°)	dB	-1.5	-1.5	
Receiver Antenna Gain (on axis)	dB_i	70	34	
Received Signal	dBW	-111.3	-147.3	-129.3
Receiver KT_S (T_S = 1200 K SSB)	dBW/Hz	-197.8	-197.8	-197.8
C/No	dB Hz	86.5	50.5	68.5

Obtaining the SNR from the carrier-to-noise density ratio requires a bit of thought as we are dealing with a large SNR and consequently a carrier-to-noise ratio much greater than unity. This constraint as well as the signal being an unmodulated CW carrier is quite a bit different than the radio astronomy case. However, from Kraus, 1966 (with a little help from Schwartz, Bennett and Stein, 1966), I think we can show that for a correlation interferometer with $C/N = C/No\ B_{IF} \gg 1$ the correlator output SNR is:

$$\text{SNR} = \frac{C}{No}\frac{\tau}{4}\cos^2\phi = \frac{C}{N}\frac{B_{IF}\,\tau}{4}\cos^2\phi \qquad (2)$$

where $\frac{C}{No}$ is the root product of the C/No of each channel and ϕ is the phase angle difference. The only restriction is that $1/\tau \le B_{IF}/2$.

Thus for an SNR of 2000 with ϕ set to zero and both channels on-axis, an integration time of 1 millisecond is required. The IF bandwidth must be at least 2 kHz but not larger than 100 kHz in order to keep C/N >> 1 when measuring the sidelobes off-axis (25 dB down). The total integration time for n^2 data points would then be $n^2\tau = 2.5$ seconds. If we scan the antenna in elevation at a 2.7'/second rate (i.e., 1 beamwidth/sec) and sample for a few milliseconds every second, then it takes 50 seconds per scan and we have ∿ 1/500th beamwidth movement during each integration period. Fifty scans (50 x 50) grid would take 0.7 hours plus time to index in azimuth and and return to on-axis once each scan to calibrate the receiver. A complete 50 x 50 grid could then be done in approximately 2 hours.

One problem with the above scheme is that we assume that the satellite transmitted power, the transmission path, and the receiver gain are stable between calibrations. Receiver instabilities can be removed with a pilot tone calibration signal injected into each feed. If we must detect the signal power in the reference channel in order to normalize the correlator output for received signal variations, then a much more severe requirement is placed on τ/B_{IF} to achieve an SNR of 2000 in the normalized data. This is because the C/No is limited to the reference channel value which does not have the improvement due to the 12-m reflector gain. If we can neglect the dc component of the noise in the square law detector, then for C/N >> 1 the SNR becomes:

$$\text{SNR} = \frac{C}{No}\frac{\tau}{4} = \frac{C}{N}\frac{B_{IF}\,\tau}{4} \qquad (3)$$

For C/No = 50.5 dB in the reference channel and SNR = 2000, we require an integration time of 70 millisecond and an IF bandwidth between 28 Hz and 11 kHz. This latter constraint is to keep C/N > 10.

A block diagram for an appropriate receiver is shown in Figure 3. The type of backend employed will determine some aspects of this receiver. It is felt that an analog correlator—double balanced mixer or quarter square multiplier (hybrid and square law detectors)— cannot handle the signal dynamic range without some form of AGC in the signal input. We have shown instead a receiver which assumes a digital type correlator, possibly off line if only the A/D output is recorded on tape. A pilot tone for receiver calibration is shown. This would be offset from the satellite frequency by a small amount and the final LO could be frequency switched to move the pilot tone into and out of the IF passband. The final LO could also provide the Doppler correction. This implies that the gain and phase response of the receiver prior to this mixer has no fine grain structure which could distort the data. Otherwise, the Doppler correction would have to be made in the first LO. If the received satellite signal proves too variable, the digitized reference channel signal could be integrated for several tenths of a second and the resulting value used to normalize the correlator data once each second. Care must be taken to keep out correlated noise, i.e., LO noise and channel cross coupling through LO power splitters. Liberal use of isolators in LO lines is contemplated.

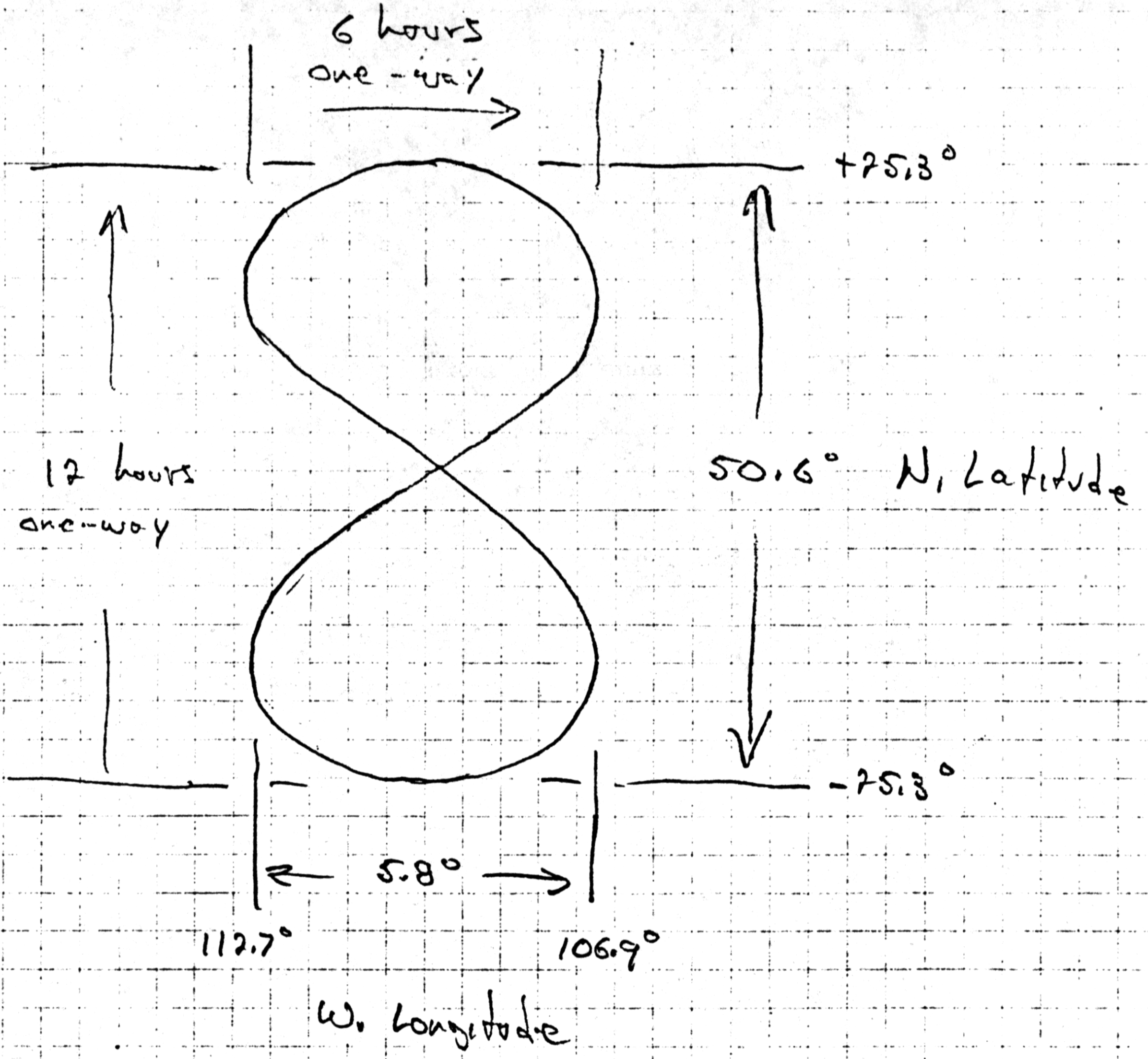
Sources of Error

There are a number of sources of error in the system just described. These need to be analyzed to determine if the effects are large enough to cause significant error and, if so, what can be done to offset or correct for these errors. We list some sources here which have come to mind. I am sure there are others not mentioned:

1) Satellite received power variations.
2) Satellite Doppler frequency shift and the resulting phase change due to unequal path lengths ahead of the Doppler correction.
3) Reference channel feed horn amplitude and phase response variations with pointing.
4) Signal channel feed phase variations across the illumination angle.
5) Receiver differential gain and phase variations.
6) Satellite orbit track superimposed on antenna grid scan.

BIBLIOGRAPHY

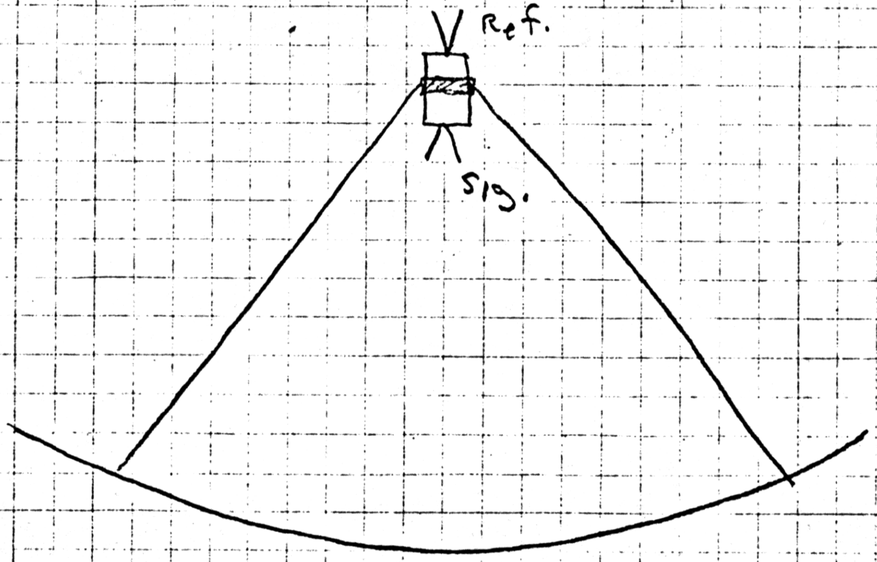
1) Scott and Ryle, Mon. Not. Roy. Astron. Soc., Vol. 178, p. 539, 1977.
2) Kraus, Radio Astronomy, Ch. 7, McGraw-Hill, 1966.
3) Schwartz, Bennett and Stein, Comm. Sys. and Tech., Ch. 3, McGraw-Hill, 1966.



Radius of orbit ~ 42,166 km , ΔR = 24.5 km

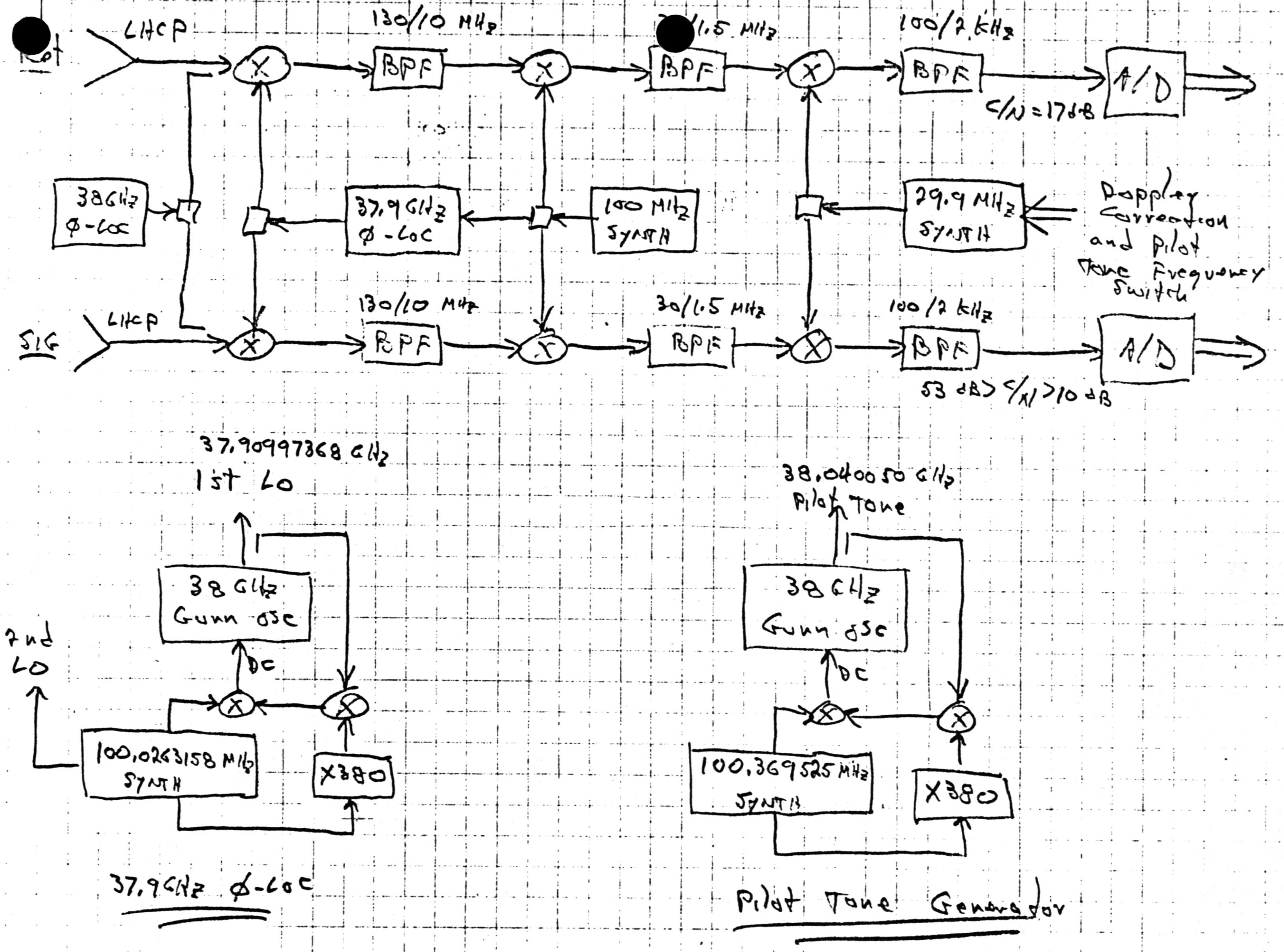
LES-8 Orbital Track
for 1/25-26/80

Figure 1



Possible Mechanical Configuration for Holographic Surface Measurement

Figure 2



37.9GHz φ-Loc

Pilot Tone Generator

Figure 3 Receiver block diagram for LES-8, satellite holographic antenna measurement