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AN ANTENNA SYSTEM FOR THE MICROWAVE LIMB SOUNDER

Report No. TR077
Final Report
JPL Contract No. 954294

Prepared for:

JET PROPULSION LABORATORY
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ABSTRACT

This report describes the results of an initial design study to determine a suitable antenna system for the Microwave Limb Sounder experiment. The resulting antenna system consisting of a parabolic cylinder fed by a number of Gregorian subreflectors is described and estimates of achievable antenna beamwidths and beam efficiencies are made. A short analysis is presented which yields expressions for the subreflector coordinates which can be implemented into existing programs for future antenna design and evaluation.

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1.0 INTRODUCTION

1.1 Purpose and Scope

This report describes the results of an initial design study to determine a suitable millimeter wave antenna system for the Microwave Limb Sounder (MLS) experiment. The study was performed over a six-month period beginning in December 1975. The resulting design was coordinated with inputs from mechanical design personnel at JPL and technical personnel from Oxford University, Oxford, United Kingdom, and the University of Bern, Bern, Switzerland. Attempts were made to provide the most versatile system with a configuration suitable for the first Spacelab Mission.

The antenna system chosen in this study consists of a parabolic cylinder fed by a number of Gregorian subreflectors. Teh antenna is described in Section 2.0 and preliminary beam efficiency estimates are made in Section 2.1. A short analysis is presented in Section 3.0, which yields expressions for the subreflector coordinates which can be immediately implemented in existing programs which predict the exact far field behavior of the antenna.

1.2 The MLS Requirement

The basic requirement for the MLS antenna system is to provide a single polarization, extremely high efficiency antenna beam with the highest possible vertical resolution for low-noise radiometers operating simultaneously at the five millimeter frequencies of 63, 118, 167, 184 and 230 GHz. Besides vertical resolution the radiometer beams are required to scan slowly in elevation in a programmable manner. Provision must also be made to provide calibration signals for the radiometers.

Approximately one meter of verticle aperture is available in the orbiter and it is desired that this area be used most efficiently. Ongoing receiver development will probably give rise to higher frequency radiometers in the near future so that it is desirable that the MLS antenna system be adaptable to the possible utilization of these devices as well as possible modification of the present radiometers to other adjacent frequencies.

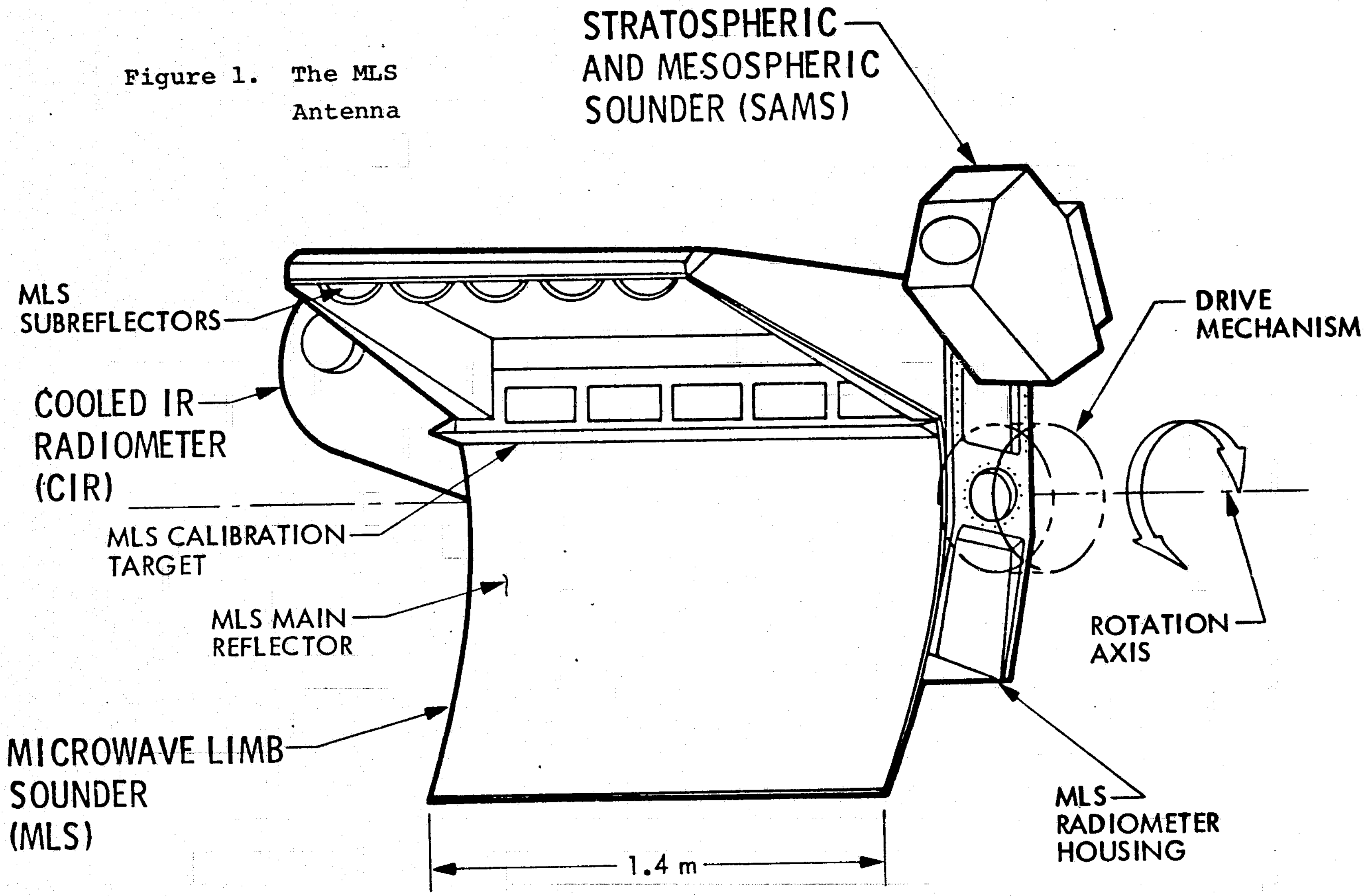
2.0 THE MLS ANTENNA

Figure 1 shows the antenna configuration selected for the MLS experiment. The antenna consists of a singly curved parabolic cylinder main reflector fed by individual subreflectors, one for each of the radiometer channels. Each subreflector collects energy from a portion of the main reflector and focusses it into the individual radiometers via an electromechanically tiltable input mirror. Because the main reflector is singly curved, very high reflector tolerances can be achieved at relatively low cost thus allowing operation at the highest possible frequencies. The modular configuration of the antenna system gives the most versatility in terms of independence and interchangeability of the radiometers. The antenna is scanned in elevation by mechanically tipping the entire antenna system by means of a stepping motor-gear drive. It is planned that the antenna will be scanned in programmable steps of $.003^{\circ}$.

The main and subreflectors and supporting structures will be constructed from laminated and machined graphite-epoxy in order to make thermal distortions negligible. The surfaces will be covered with a reflective coating and held within an rms tolerance of .03mm.

Figure 2 shows a detailed schematic of how each antenna channel operates. The MLS main reflector focusses energy from the limb down to a doubly curved Gregorian subreflecto

Figure 1. The MLS Antenna



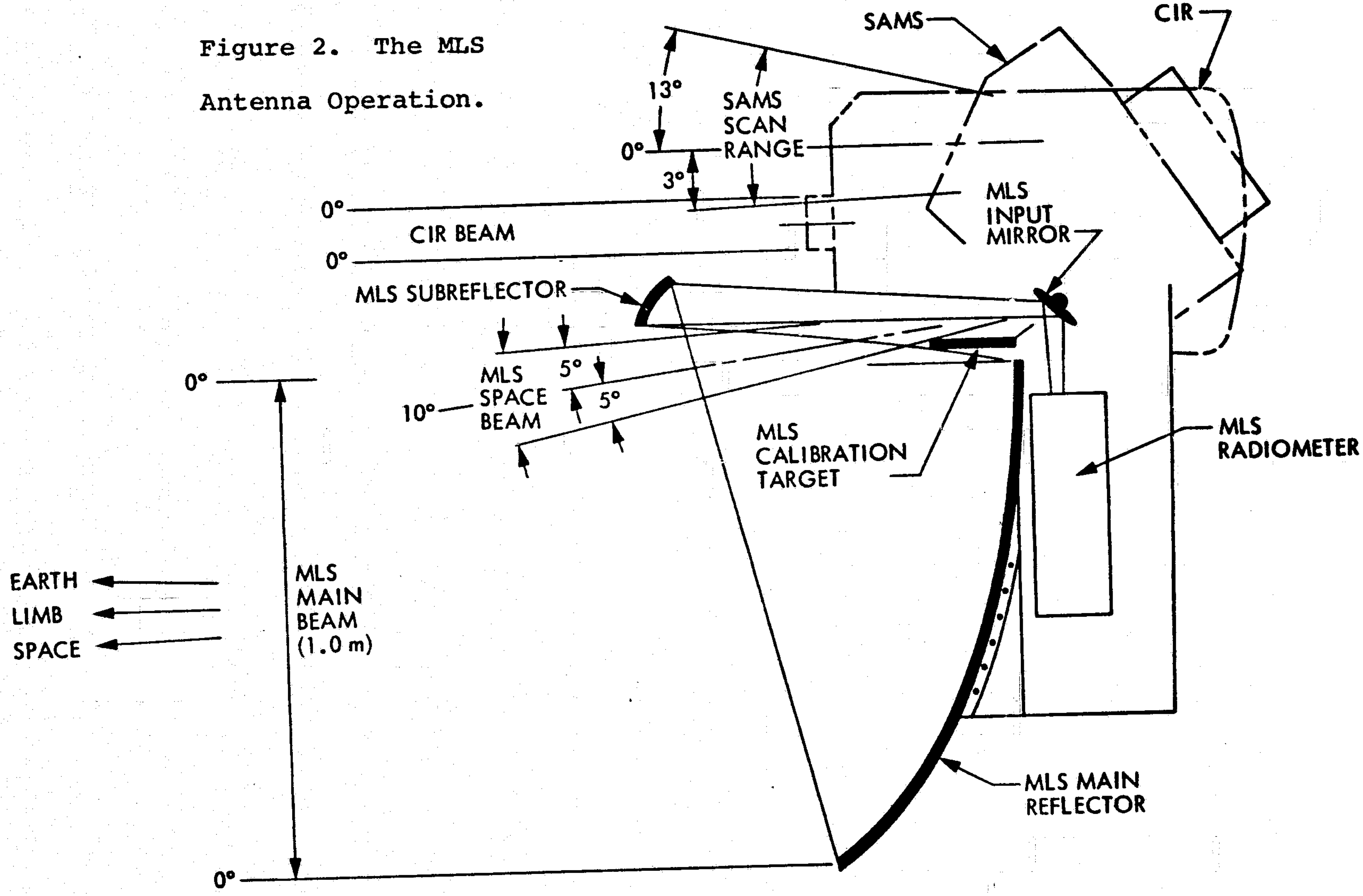


Figure 2. The MLS Antenna Operation.

about 0.2mm in diameter which subtends approximately 10° at the radiometer input. The radiometer will be provided with the appropriate optics to receive the subreflector beam with negligible spillover. As can be seen in the figure by tilting the MLS input mirror the radiometer beam can be switched from the subreflector to cold space or to a calibration target for the purposes of calibrating the radiometer. The main reflector has a one meter vertical aperture which collimates the subreflector energy in elevation. The azimuth beamwidth of the antenna system is entirely determined by the subreflector which collimates the energy in the azimuth plane. The resulting geometry will produce a fan beam in elevation with an aspect ratio of 5:1. Assuming a cosine illumination taper of the main reflector the calculated elevation beamwidths for the five channels are given in Table I.

TABLE I

Radiometer (frequency, GHz)	Beamwidth (degrees)
63	0.33
118	0.18
167	0.13
184	0.11
230	0.09

2.1 Beam Efficiency Estimation

An estimate was obtianed of the amount of spurious energy which the MLS antenna could receive from sidelobe reception of noise from the relatively hot earth. A calculation was made to determine what fraction of the antenna power is contained in the entire antenna pattern with the exception of the region just below the main beam which includes half the elevation sidelobes. For the purpose of this estimate the aperture distribution of the antenna is assumed to be a product function in elevation and azimuth with the elevation aperture field distribution given by

$$f(x) = \cos \frac{\pi}{2} x \qquad 0 < x < h \tag{1}$$

where x is the elevation coordinate of the aperture and h is the aperture height. The far zone electric field radiated by this aperture distribution is given by

$$F(u) = \frac{\cos u}{1 - \left(\frac{2u}{\pi}\right)^2} \tag{2}$$

where $u = \pi \frac{h}{2} \sin \theta$ and θ is the elevation angle measured off the antenna boresight. A plot of the antenna pattern as a function of u is shown in Figure 3 and although this is an assumed pattern it is believed to be representative of

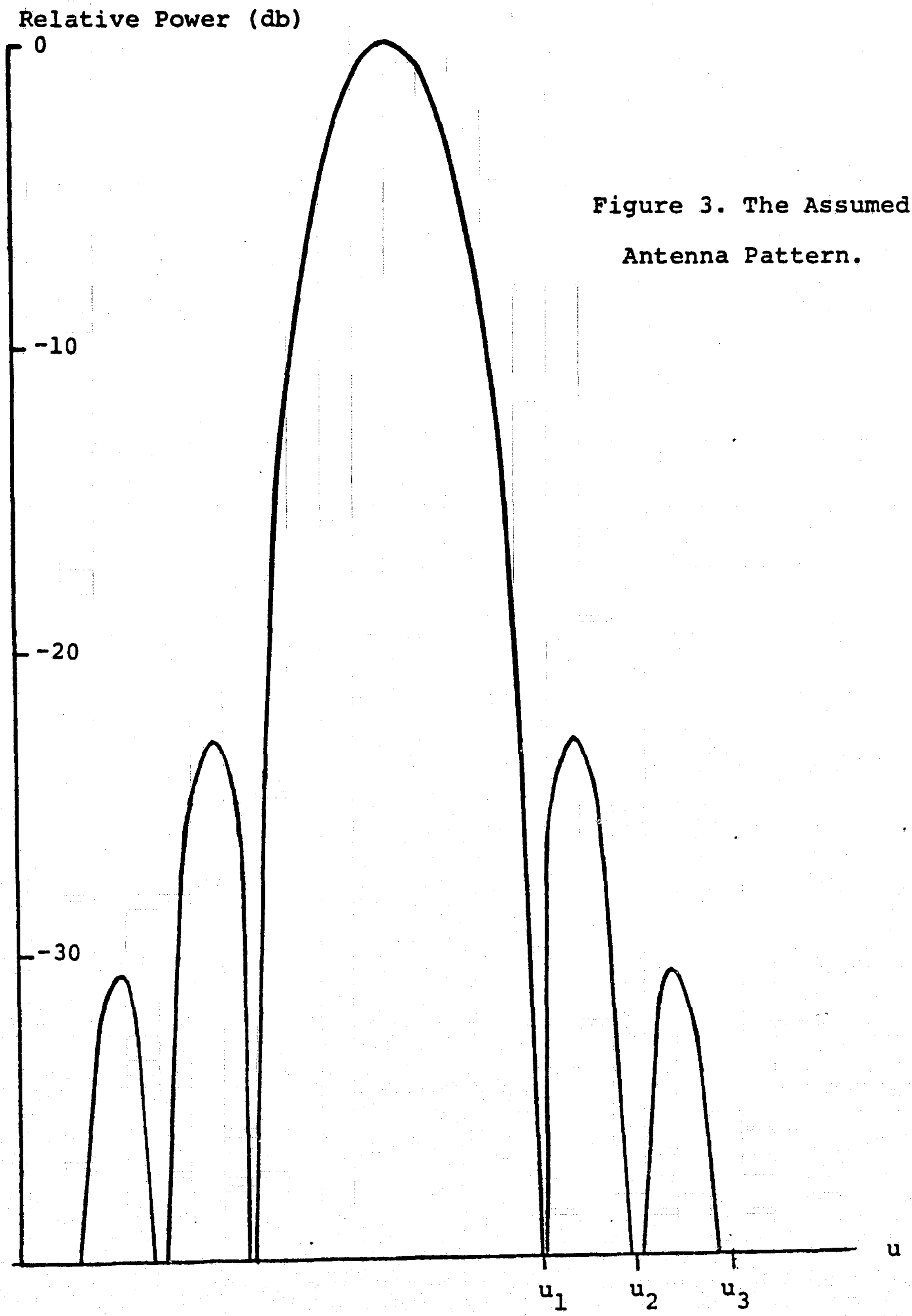


Figure 3. The Assumed Antenna Pattern.

radiation patterns achieveable with the unblocked offset fed antenna geometry. The fraction of power contained in the portion of the pattern to the left of a given angle u is given by

$$\mathrm{EFF}(u) = \frac{\int_{-\infty}^{u} F^2(u) \quad du}{\int_{-\infty}^{u} F^2(u) \quad du} \tag{3}$$

$$= \frac{1}{2} + \frac{1}{2}\left[\mathrm{Si}(2u+\pi) + \frac{\mathrm{Cin}}{\pi}(2u+\pi) + \mathrm{Si}(2u-\pi) - \frac{\mathrm{Cin}}{\pi}(2u-\pi) - \frac{2u\cos^2 u}{u^2 - \left(\frac{\pi}{2}\right)^2}\right]. \tag{4}$$

where

$$\mathrm{Si}(z) = \int_0^z \frac{\sin t}{t}\, dt \qquad \mathrm{Cin}(z) = \int_0^z \frac{1-\cos t}{t}\, dt$$

This antenna efficiency was computed for the antenna null angles u_1, u_2 and u_3 as shown in Figure 3. The results are shown in Table II.

TABLE II

n	Fraction of antenna energy contained in antenna pattern up to the nth null; $EFF(u_n)$
1st null	.9970
2nd null	.9995
3rd null	.9998

As can be seen from the table less than 1% of the power is contained in the lower antenna sidelobes.

3.0 CALCULATION OF THE SUBREFLECTOR COORDINATES

In this section an analysis is presented which will allow the computation of the antenna subreflector coordinates. The results of the following analysis can easily be adapted to existing computer programs[1] which compute the far field antenna patterns as a function of the antenna design parameters. Thus, the results of the analysis will allow a computer design of the actual antenna dimensions which optimize the antenna performance, a design study which is beyond the scope of this effort.

The geometry of the antenna for the analysis is shown in Figure 4. To simplify the analysis all distances are normalized to the height of the main reflector, h. As seen in the figure, an X,Y,Z coordinate system has been chosen with the Z-axis a unit distance from the back of the main reflector. This has been done to make the final results consistent with use in the aforementioned existing programs.[1] The top of the subreflector is located a distance S from the Z-axis. The X-Z plane is the radiating aperture plane of the antenna. The feed-point is located at the focus of the subreflector a distance F from the Z-axis and a distance H below the top of the subreflector. A second coordinate system XX, YY, ZZ is arranged at the subreflector focus in order to describe the coordinates of the subreflector. The objective of the analysis is as follows: given a point X,Z in the antenna aperture plane, and a specification of the design parameters of Table III.

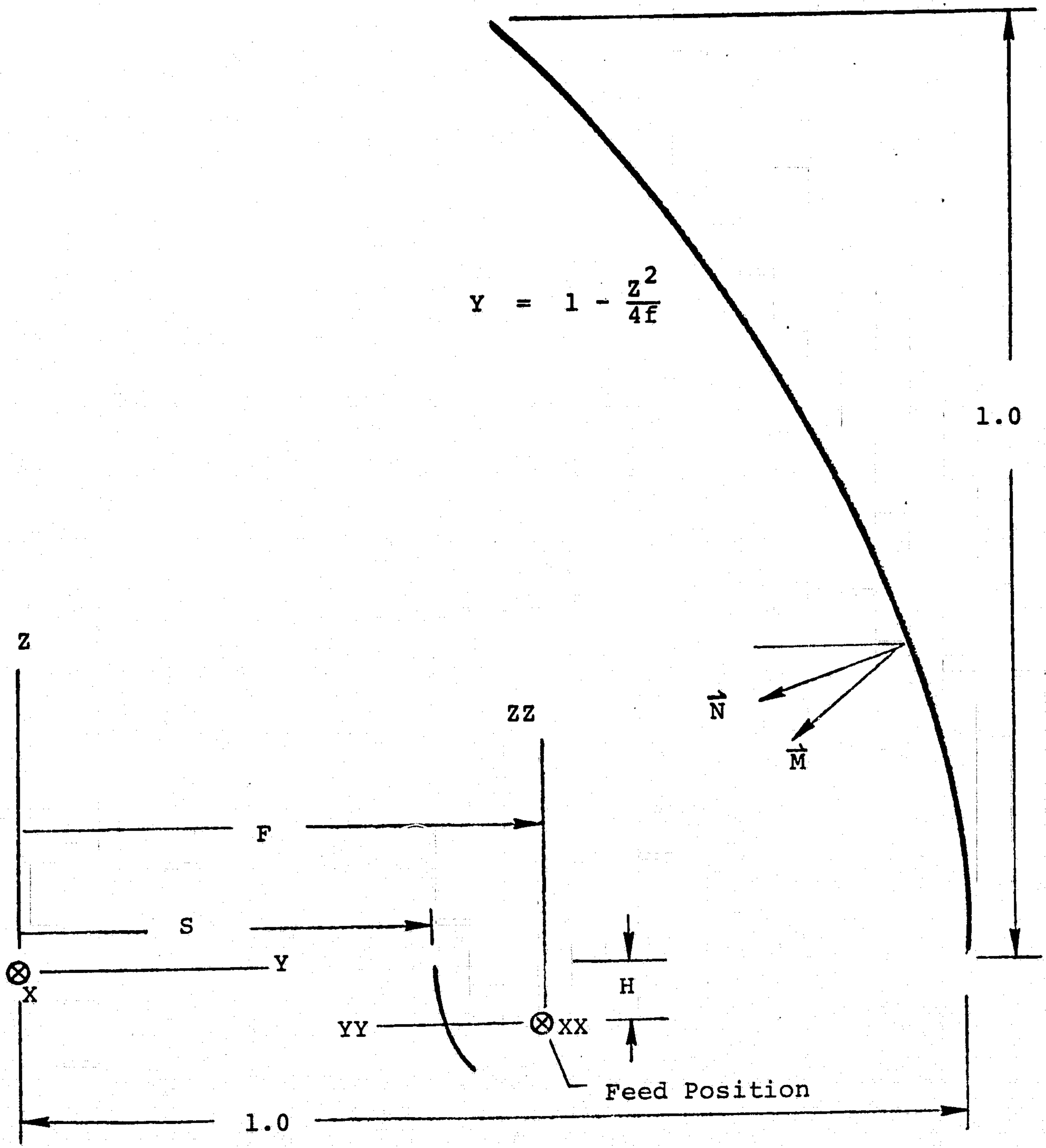


Figure 4. The Antenna Geometry

TABLE III

ANTENNA DESIGN PARAMETERS

F = Distance of the feed phase center from the Z-axis.

H = Distance of feed phase center from the bottom of the main reflector.

S = Distance of the subreflector top from the Z-axis.

f = Focal length of the main reflector.

Determine the coordinates XX,YY and ZZ of the point on the subreflector on which the received ray passing through X,Z impinges. Again all distances specified in Table III are normalized to the height of the aperture h.

PARABOLIC CYLINDER COORDINATES

For a point X and Z in the antenna aperture the projected point on the parabolic cylinder has a Y-coordinate given by

$$Y = 1 - \frac{Z^2}{4f} \tag{1}$$

SURFACE NORMAL

The parabolic cylinder is defined by the equation

$$f(X,Y,Z) = Y + \frac{Z^2}{4f} = 1$$

The surface normal is in the direction of the negative gradient of this function or

$$-\text{grad } f = -\vec{a}_y - \frac{Z}{2f}\,\vec{a}_z$$

The magnitude of this vector is

$$|\text{grad } f| = \sqrt{1 + \left(\frac{Z}{2f}\right)^2}$$

Thus, the three components of the surface normal are

$$NX = 0 \tag{2}$$

$$NY = -1/\sqrt{1 + \left(\frac{Z}{2f}\right)^2} \tag{3}$$

$$NZ = -\left(\frac{Z}{2f}\right) / \sqrt{1 + \left(\frac{Z}{2f}\right)^2} \tag{4}$$

REFLECTED RAY

Upon reflection the component of the incident ray in the direction of the surface normal is reversed. Thus, for an incident ray in the direction $\vec{a}_y$ the direction of the ray scattered from the reflector is given by

$$\vec{M} = \vec{a}_y - 2NY*\vec{N}$$

The three components of the ray from the reflector are then given by

$$MX = -2NY*NX \qquad (5)$$

$$MY = 1 - 2NY \qquad (6)$$

$$MZ = -2NY*NZ \qquad (7)$$

SUBREFLECTOR COORDINATES

The vector extending from the subreflector feed to the illuminated point on the torus is given by

$$\vec{RF} = X\,\vec{a}_x + (Y-F)\,\vec{a}_y + (Z+H)\,\vec{a}_z \qquad (8)$$

The vector from the feed to the illuminated point on the subreflector is given by

$$\vec{RR} = -XX\,\vec{a}_x - YY\,\vec{a}_y + ZZ\,\vec{a}_z \qquad (9)$$

From the geometry it is clear that

$$\vec{RR} = \vec{RF} + \vec{M}\;C(X,Z) \qquad (10)$$

For phase coherence the scalar function C(X,Z) must be such that

$$Y + C + |\vec{RR}| = \text{constant} = K \tag{11}$$

where K is the total path length from the feed to the X-Z plane

$$K = \sqrt{H^2 + (F - S)^2 + 2} - S \tag{12}$$

From Eqs. (10) and (11),

$$|RR|^2 = (K - Y)^2 - 2C \quad (K - Y) \quad + C^2$$
$$|RR|^2 \qquad |RF|^2 \quad +2C\ M \cdot RF \quad + C^2$$

which can be solved to yield

$$C(X,Z) = \frac{(K - Y)^2 - X^2 - (Y - F)^2 - (Z + H)^2}{2\left[K - Y + MX*X + MY*(Y - F) + MZ*(Z + H)\right]} \tag{13}$$

and the reflector coordinates are then given by Eqs. (10), (12) and (13) as follows

$$XX = -X - C*MX \tag{14}$$

$$YY = F - Y - C*MY \tag{15}$$

$$ZZ = Z + H + C*MZ \tag{16}$$

4.0 CONCLUSIONS AND RECOMMENDATIONS

A viable antenna concept for the MLS experiment has been obtained which is consistent with the electrical requirements and mechanical and interface constraints imposed by the orbiter vehicle and the collaborative nature of the experiment. It is recommended that the next step in the antenna development program consist of numerical studies using the results of Section 3.0 of this report to accurately determine the expected antenna performance levels and a specific physical design of the antenna subreflector geometry.

5.0 NEW TECHNOLOGY

No reportable items of new technology have been identified in the work described in this report.

6.0 REFERENCES

1. Gustincic, J.J., "Design of an Offset Fed Scanning Antenna for the Shuttle Imaging Microwave System," JPL Contract No. 954145 Report No. TR070, 14 April 1975, pp. 40-55.