LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

TITLE
COMPUTER SIMULATION OF SPACE STATION COMPUTER STEERED HIGH GAIN ANTENNA — FINAL REPORT SUBMITTED UNDER EFFECTIVE UNDER

MODEL __________________ APPROVED BY __________________

PREPARED BY S. W. Beach APPROVED BY John B. Damonte, Manager Antenna Systems
S. W. Beach Guidance & Control Systems

CHECKED BY D. G. Simcox APPROVED BY J. J. Rodden, Manager Guidance & Control Systems

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APPENDIX B - BRIEF DESCRIPTION OF THE DEADAM PACKAGE B-1
APPENDIX C - TRADE-OFF STUDY SIMULATION RESULTS C-1
1.0 INTRODUCTION

The purpose of this final report is to summarize the mathematical modeling and programming of the complete simulation program. Much of the material included is taken from earlier reports (Task 1 through Task 4) but is repeated here in order to provide a complete description in a single document.

Appendix A — Deck Setup and Input Variables — is also nearly identical to the separate document — Space Station Antenna Simulation Digital Computer Program Operating Requirements — and is included here both for completeness and to show the input parameter values used in the program run of Appendix C — Trade-off Study Simulation Results.
2.0 BASIC PROGRAM STRUCTURE

The simulation program described in this report is an application of a general purpose simulation package (DEADAM) maintained by Dept. 62-11, LMSCI, Sunnyvale, Calif. This foundation program provides for reading input data cards, numerically integrating up to 50 first order differential equations (not necessarily linear or continuous), and monitoring up to 48 variables on printed output and on plots.

For constructing a particular simulation program communication with the DEADAM package is accomplished through the subroutine SETUP in which the details of the differential equations and output variables are defined, usually with the aid of additional subroutines called from SETUP.

The computations done by or called for by the SETUP subroutine for the "Computer Steered High Gain Antenna Simulation" are indicated in Figure A-1 and are described in detail in the following sections of this report.

For efficient computation of pointing requirements (gimbal angles), a simplified simulation program is included which uses a different version of the SETUP subroutine (SETUP/POINT). The computations called for by this program are a subset of those illustrated in Figure A-1 and are indicated in Figure A-2.
3.0 SIMULATED SYSTEM MODELLING

The system being simulated by the "Computer Steered High Gain Antenna Simulation" program consists of 1) a high gain antenna, 2) an antenna gimbal control system, 3) an on board computer, and 4) the environment in which 1), 2), and 3) are to operate. The interconnection of the mathematical models of these four subsystems is indicated in Figure 3.0-1.

3.1.1 Antenna Model

This section describes the mathematical model used by the simulation program for the radiating system (antenna) and has been extracted from the Task 1 Report - Math Modeling of High Gain Antenna - dated 1 March 1972.

The programming of this modeling is contained in the subroutines M3NPLS and THERMD which are called by SETUP to compute gain along the actual line of sight, monopulse system output signals, and shift in the line of sight due to solar heating deformations; and in the subroutines GAIN, AXIS, and MODEL which are called by the antenna initialization routine ANTIN only once (per case) to determine parameters used by M3NPLS and THERMD.
Figure 3.0-1 Interconnection of Subsystems
3.1.2 AN OVERVIEW

A simplified schematic diagram of the radiating system model is shown in Fig. A-2.1. Each of the elements in this figure will be discussed separately in later sections. In this section we shall present an overview of the radiating system model and the interrelationship of the basic elements.

The input portion of the program takes all of the input data needed for the calculation of gain except for the coordinate angles $\theta$ and $\phi$ and the coordinates of the sun with respect to the reflector. It has been assumed, in setting the input up this way, that the computer program will be used primarily in a "simulation" mode -- that is, to simulate the operation of an actual or proposed system. This means that all the adjustable design parameters are introduced in the input block of the program and represent one particular system. All these input parameters will remain fixed throughout a run. The most rapidly varying coordinates then will be the LOS coordinate angles and the coordinates of the sun. Thus, with one input block of data we should be able to simulate the operation of the system throughout an orbit or an operational situation, but making parametric variations of certain design parameters (such as reflector diameter) for a fixed orientation of the LOS would require re-inputting the basic data.

In addition to the basic design parameters, the input data base will contain a number of flags to select various options available within the program.

One of the flags contained in the input data base is SMP which selects either the simple gain and beamwidth calculation or the more complex computation. If SMP=1, then the peak gain and beamwidth will be calculated from simple formulas. If SMP=0, then the peak gain of the antenna along its nominal boresight axis and the beamwidth are calculated using the current distribution method. The latter option will have several feed options and reflector options associated with it.

The output of either of these calculations is the peak gain of the antenna and the half-power beamwidth with the beam direction defined as being along the nominal boresight axis of the antenna. This output is then corrected for thermal effects. The angular position of the sun relative to the reflector is fed into a correction calculation block. Based on this sun position, the direction of the peak of the antenna beam will be shifted from its nominal position, using a table of values based on ATS F and G experience. The maximum gain value will also be reduced in the same way.
Following this correction, a pair of coordinate values $\theta$ and $\phi$ representing the LOS to the relay satellite will be entered. The computation of these coordinate angles will take into account any movement of the reflector boresight that results from steering -- that is, the angles $\theta$ and $\phi$ represent the true position of the LOS with respect to the nominal boresight axis of the reflector. Using these coordinates, the gain in the direction $\theta$ and $\phi$ will be calculated using a simple approximation formula for the peak of the main beam. This gain is that associated with a single feed located at the focal point of the reflector. For either the non-monopulse option or the five-horn monopulse option, this would be the gain of the communications channel in the LOS direction.

Another of the flags contained in the input data base is MON, which sets up the calculation of monopulse sum and difference signals where desired. For MON=0, no monopulse signals are calculated and the gain value already determined is simply read out. Then the next values of $\theta$ and $\phi$ and sun angle are read and the calculation is continued. For MON=4, a four-horn monopulse system is assumed. Using design parameters contained in the input data base, sum and difference signal gain values are calculated. The sum channel gain value is also the communications channel gain value. After output, the program goes on to the next LOS position. For MON=5, the calculation is the same as for the 4 horn system, except that the communication channel gain value is the same as it would be for MON=0.

One very important point should be noted here. Even if the complicated form of gain calculation is selected, this computation is performed only once to determine the peak gain of the antenna and the half-power beamwidth. Once this computation is made, it is not repeated as new values of $\theta$ and $\phi$ are entered. The complex computation simply determines the maximum gain of the antenna and the relative gain at any angle is found using this peak gain value and an approximation formula. The gain at the actual position of the LOS could be determined directly from the complicated form of the computation, but the error in using an approximation is comparable to (and probably less than) the computational accuracy of the complicated computation itself. The accuracy is certainly good enough for engineering purposes at any rate, and so it was not deemed prudent to use the complicated computation more than once per run as it requires a large amount of computer time compared with that required by the approximation. There are some limitations to the foregoing statements, so we shall present the rationale here in detail.
3.1.3 ACCURACY OF THE GAUSSIAN PATTERN APPROXIMATION

The current distribution method will be used (when desired) to calculate the peak gain on axis and the gain at four symmetrically located points off axis (in the vicinity of the half-power level). From these data an elliptical paraboloid will be fitted to the peak of the main beam. For the case of a symmetrical main beam aligned with the nominal boresight axis, the current distribution method will determine $G_m$ and $\beta$, where $2\beta$ is the half-power beamwidth of the antenna pattern. Then the main beam within the half-power contour will be approximated by the formula

$$G(a) = G_m \exp \left( -p \frac{a}{\beta} \right)^2 \tag{3.1}$$

where $G(a)$ is the gain in a direction which makes an angle $a$ with respect to the boresight axis. In the above $p$ is a constant.

The pattern shape given by Eq. (3.1) is a Gaussian curve and this approximation is sometimes called the Gaussian approximation. When converted to decibels, the equation becomes that of a parabola.

$$10 \log_{10} G(a) = 10 \log_{10} G_m - 3.010 \left( \frac{a}{\beta} \right)^2 \tag{3.2}$$

For this reason, the approximation is often called the parabolic approximation. For the more general case where the pattern beamwidths in two orthogonal planes are not equal, Eq. (3.2) must be generalized to the form of an elliptical paraboloid.

A study was made of the accuracy of Eq. (3.2) compared to some typical theoretical pattern shapes. Specifically, the gain pattern functions chosen were

$$g(a) = \left( 2^n \frac{n!}{u^n} J_n(u) \right)^2 G_m \tag{3.3}$$

where $u = \left( \frac{\pi D}{\lambda} \right) \sin a$, $D$ is the aperture diameter and $\lambda$ is the wavelength. These are the pattern shapes that result from circular apertures of uniform phase having an amplitude distribution of the form

$$A(r) = (1 - r^2)^{n-1} \tag{3.4}$$
where \( r (\leq 1) \) is the normalized radius of the aperture.

When \( G(\alpha)/G_m \) as given by Eq. (3.1) is matched to Eq. (3.3) at the peak \( (\alpha = 0) \) and at the half power point \( (\alpha = \beta) \), the error curve shown in Figure A-3.1 is the result. This is a plot of the equation

\[
\Delta G = -3.010 \left( \frac{\alpha}{\beta} \right)^2 - 10 \log_{10} \left( \frac{G(\alpha)}{G_m} \right)
\]

(3.5)

for \( n = 1 \) and \( n = 4 \). Although in Fig. 3.2 \( D/\lambda \) was 200, there was no significant difference for \( 20 \leq D/\lambda \leq 500 \). From the figure it can be seen that the Gaussian approximation gives a gain not more than 0.05 dB too low within the half-power contour, although it deteriorates rapidly when \( \alpha > \beta \).

As we shall mention later, the computational accuracy of the current distribution method is about 0.07 dB. While the Gaussian approximation would not properly represent specially shaped beams, such as those having flat tops, it should be an accurate representation of normal pencil beam patterns applicable to communications problems. The accuracy of this representation is better than 0.05 dB within the half-power contour and improves as we approach the peak of the beam.

Beyond the half-power contour the Gaussian approximation begins to produce erroneous results. But for the computer-steered system, a misalignment of more than half a half-power beamwidth would cause serious doubts concerning the efficacy of the computer-steering method since the misalignment loss would exceed 3 dB.

The Gaussian approximation will also be used in the monopulse case, not only for the data or communication channel, but also to form the monopulse error signals. Although initial misalignment during acquisition may be greater than \( \beta \), giving some error in gain, the monopulse will track toward the beam peak to reduce the error to within acceptable limits when the acquisition phase ends and the self-tracking phase begins.

The approximation will be used to save computer time since the current distribution integration process is quite costly compared to the simpler approximation. The approximation is considered sufficiently accurate for practical engineering purposes. Beamwidth and the angle between the LOS and the beam axis will be read out to flag situations where the approximation begins to deteriorate.
Figure A-3.1 Gain Error of Gaussian Approximation
The radiating system model receives data for calculation from four different sources: the built-in data files, external data files, the input subroutine, and other elements of the simulation program.

The built-in data files are as follows:

1. Standard Feed Gain Function. This is an experimental feed gain function data file which can be used in the program to calculate the reflector gain. This data file will represent a typical experimental feed designed to provide a tapered aperture illumination with approximately a -10 dB edge taper.

2. Thermal Gain Degradation Data File. This is a data file representing the peak gain degradation of a typical unfurlable reflector antenna as a function of sun position. It is used, as explained in Section A-7, to provide correction for thermal distortion effects.

3. Thermal Beamshift Data File. This is a data file representing the beamshift of a typical unfurlable reflector antenna as a function of sun position. It is used to provide for correction for thermal distortion effects.

Any of the built-in data files may be updated as required to reflect a current design case.

The one external data file is an experimental feed gain function data file which the user must provide.

The only data that the model receives from other elements of the simulation program are the coordinates of the LOS and the coordinates of the sun in reflector reference coordinates. These data are the independent variables for each single run. When the model is run by itself without the balance of the simulation master program, these data must be supplied on cards.

All of the remaining parameters necessary for the calculations performed by the radiating system model are supplied by the user on cards through the input subroutine. Some of the input parameters act as flags for selecting various options which may be exercised. The important input parameters are:
BMW.... This is the beamwidth factor. This is the product of the half-power beamwidth and the aperture size in wavelengths. See Eq. 5.3.

CSN.... This parameter flags the feed option to be used, as follows:

CSN < 0: Selects either the built-in or the external experimental feed data file. See Sections A-6.3.4 and A-6.3.5.

0 ≤ CSN ≤ 999: Uses analytical function for feed gain function. Value of CSN is used in the analytical gain function. See Sections A-6.3.2 and A-6.3.3.

CSN > 999: Uses function that provides uniform aperture illumination. See Section A-6.3.1.

DBK.... This is the diameter of an area that blocks the reflector aperture. See Section A-6.5. DBK is in inches.

DIA.... This is the reflector diameter in inches.

EFF.... This is the aperture efficiency in percent.

FTV.... This is the feed to vertex distance in inches. If FTV=0, the feed is placed at the nominal focal point of the reflector.

GFE.... This is normally the peak gain of the feed. GFE and CSN determine the exact feed option, as follows:

CSN < 0; GFE < 0: The built-in reference experimental feed pattern is used. See Section A-6.3.5.

CSN < 0; GFE ≥ 0: The external experimental feed pattern is selected. See Section A-6.3.4.

0 ≤ CSN ≤ 999; GFE ≤ 0: Uses analytical function for feed gain function with peak gain value for feed computed internally. See Section A-6.3.2.
$0 \leq \text{CSN} < 999; \ GFE > 0$: Uses analytical function for feed
gain function with GFE as the peak gain value for
the feed. See Section A-6.3.3.

GHZ....This is the frequency in GigaHertz.

HUB....This is the radius of the hub of the reflector in inches. By
hub is meant any portion of the reflector at the vertex which
is either a hole in the surface or a surface area not meant to
be part of the reflector (as, for example, a flat plate covering
a hole).

MON....This is the monopulse flag, as follows:

- MON=0: does not calculate monopulse error signals.
- MON=4: Assumes a four-horn monopulse system.
- MON=5: Assumes a five-horn monopulse system.

See Section 3.1.

PAN....Flags the choice surface.

- PAN $\leq 0$: Selects perfect paraboloid. See Section A-6.4.1.
- PAN $> 0$: Selects perfect Flex-Rib surface and sets the number
  of panels equal to PAN. See Section A-6.4.2.

POL....Selects polarization of the feed.

- POL = 1: dipole mode of linear polarization.
- POL = 2: slot mode of linear polarization.
- POL = 3: right hand circular polarization.
- POL = 4: left hand circular polarization.
PPW.... This stands for points per wavelength and determines the rate at which the aperture is sampled to calculate the integral for gain. A built-in trap will require at least 600 points to be used to evaluate the integral. See Section 3.1.

SMP.... This flags the simple or the complex model.

SMP=0: The gain is determined by the current distribution method. See Section 3.1.

SMP=1: The gain is determined by the simple model. See Section 3.1.

TDT(6,3).... This is a data array which defines the method of extrapolating the gain degradation and beamshift data for thermal distortion to other reflector diameters and frequencies. See Section 3.1.

XAP.... This is the cross over angle in the $\phi$ plane for either monopulse case.

XAT.... This is the cross over angle in the $\theta$ plane for either monopulse case.

XVP.... This is the cross over level in the $\phi$ plane for either monopulse case.

XVT.... This is the cross over level in the $\theta$ plane for either monopulse case.

(NOTE: At least one and no more than two of the parameters XAP, XAT, XVP, XVT will have a non-zero value whenever monopulse is called for. The monopulse may be specified by offset angles XAP and/or XAT or by cross over levels XVP and/or XVT (but not both). If only one non-zero value is given, the case is assumed to be symmetrical. Thus if XAP=0 and XAT=0 then the program sets XAT=XAP. See Section A-9.)
3.1.5 PEAK GAIN AND BEAMWIDTH CALCULATION - SIMPLE CASE

If SMP=1, the simple model is selected. This causes the peak gain to be calculated using the formula

\[ G = \eta \left( \frac{\pi D}{\lambda} \right)^2 \]  

(5.1)

where \( \eta \) = the overall antenna aperture efficiency, \( D \) = the aperture diameter and \( \lambda \) = the wavelength. The wavelength in inches is calculated from the equation

\[ \lambda = \frac{11.802854}{f} \]  

(5.2)

where \( f \) = the frequency in GigaHertz. The quantities \( \eta \), \( D \), and \( f \) are represented by EFF, DLA, and GHZ, respectively, in the input subroutine. If EFF=0, the EFF is set equal to 0.55 (considered to be a typical value).

The half-power beamwidth \( \beta_o \) is determined by

\[ \beta_o = \beta_r \frac{\lambda}{D} \text{ degrees} \]  

(5.3)

where \( \beta_r \) is the beamwidth factor represented by BMW in the input subroutine. If BMW=0, BMW is set equal to 70 (a typical value) in the simple case computation.

Note that in the simple case the beam is assumed to be rotationally symmetric.

There is no justification for the use of the simple case formulas given above on the basis of accuracy. These formulas have been accepted for years in the antenna design field as representing typical designs. Normally, they would be used because specific design information is lacking about the antenna to be used. On the other hand, the simple model will normally be quite satisfactory when parametric tradeoffs not related to the radiating system itself are being studied.

By making the proper use of input data the simple model can be used to represent an actual antenna having known characteristics. Thus, if we have measured the gain and beamwidth of a specific antenna, we may use Eq. 5.1 and Eq. 5.3 to calculate \( \eta \) and \( \beta_r \) (EFF and BMW) which may then be set as input quantities.
3.1.6 PEAK GAIN AND BEAMWIDTH CALCULATION - CURRENT DISTRIBUTION METHOD.

3.1.6.1 GENERAL EQUATIONS

The gain of the antenna will be calculated by the "current distribution" method. The reflector is assumed to be illuminated by a point source feed (one producing spherical phase fronts at the reflector). The feed produces a surface current distribution on the reflector, and to find the total radiation at any point in the far-zone of the reflector, we sum (integrate) the vector contributions of elements of surface current.

The current distribution method is a standard procedure in the antenna science. We shall omit the basic derivation which starts with the boundary conditions at the reflector surface, and instead will use the radiation integral given by Silver* as our starting point. In the following the notation $\vec{E}$ will be used to indicate that $E$ is a vector.

The total field at a point $(R, \theta, \phi)$ in the far-zone of the reflector is

$$\vec{E} = \frac{-j\kappa R}{R} \left[ \frac{P_{\text{rad}}}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \right]^{\frac{1}{2}} \left[ G(\phi) e^{i(\theta, \phi) - j \frac{\Omega_T}{\lambda}} \right]$$

where $\kappa = \frac{2\pi}{\lambda}$

$\lambda$ = wavelength

$P_{\text{rad}}$ = the total radiated power

$\mu$ and $\epsilon$ are the constitutive parameters of the medium

$G(\theta, \phi)$ = the (scalar) gain function of the feed.

$\vec{e}(\theta, \phi)$ is a unit vector everywhere defining the polarization of the feed pattern.

The vector $\mathbf{\bar{r}}_T$ is the component of the complex vector $\mathbf{\bar{r}}$ which is perpendicular to the direction of propagation. That is,

$$\mathbf{\bar{r}}_T = \frac{\mathbf{i}}{\mathbf{e}} \cdot (\mathbf{i} \cdot \mathbf{\bar{r}}) + \frac{\mathbf{i}}{\mathbf{\phi}} \cdot (\mathbf{\bar{r}} \cdot \mathbf{\bar{r}}) \quad (6.2)$$

The vector $\mathbf{\bar{r}}$ is given by

$$\mathbf{\bar{r}} = \int \frac{G_f(\psi, \xi)}{\rho} \left[ \mathbf{n} \times (\mathbf{\bar{r}}_\rho \times \mathbf{e}) \right] e^{-jk(\mathbf{1} - \mathbf{\bar{r}}_\rho \cdot \mathbf{1}_R)\rho} d\mathbf{s} \quad (6.3)$$

The coordinate systems are shown in Fig. A-6.1. The feed is located at the origin. Points on the reflector are located by spherical coordinates $(\rho, \psi, \xi)$ or by rectangular coordinates $(x, y, z)$. The variables of integration can be chosen from either of these two systems. The far-field observation point is located by the spherical coordinates $(R, \theta, \phi)$. The corresponding rectangular coordinates $(X, Y, Z)$ are also shown to aid in visualizing the transformations that follow.

In Eq. 6.3 $\mathbf{\bar{r}}_\rho$ is a unit vector in a direction toward a point on the reflector while $\mathbf{\bar{r}}_R$ is a unit vector in a direction toward the far field observation point. The quantities $G_f$ and $\mathbf{e}$ have already been defined. The vector $\mathbf{n}$ is a unit vector normal to the reflector surface.

In Eq. 6.1 the product $\sqrt{C_f \mathbf{e}}$ accounts for the back radiation of the feed in a direction toward the observation point. Normally in high gain antenna systems with well-designed, directive feeds, this contribution is negligible in comparison to the summed contributions of the reflector currents. Therefore, we shall neglect back radiation here.

Neglecting back radiation, we find that the gain function of the reflector system is

$$G(\phi, \theta) = \eta_r \frac{\mathbf{\bar{r}}_T \cdot \mathbf{\bar{r}}_T^*}{\lambda^2} \quad (6.4)$$
Figure A-6.1 COORDINATE SYSTEM
where $\eta_r$ is the radiation efficiency of the antenna. That is

$$\eta_r = \frac{P_{\text{rad}}}{P_{\text{in}}}$$  \hspace{1cm} (6.5)$$

where $P_{\text{in}}$ is the total input power. The radiation efficiency accounts for only the dissipative losses in the antenna.

The problem then reduces to the evaluation of the complex vector integral $\mathbf{I}$.

3.1.6.2 CALCULATION OF THE VECTOR $\mathbf{I}$

The vector $\mathbf{I}$ is evaluated by numerical methods on the computer. The general expression for $\mathbf{I}$ is given by Eq. 6.3. The integration is performed over $S$, the surface of the reflector. Either spherical or rectangular coordinates may be used as variables of integration; we shall use the latter here.

The quantity $\sqrt{G}$ in Eq. 6.3 is numerically proportional to the electric field strength of the feed as a function of direction. In this form there is an implication that only the main lobe of the feed radiation falls upon the reflector. The first factor in the integrand, $\sqrt{G} / \rho$, is the feed pattern adjusted for the relative space attenuation to various points on the reflector.

The bracketed expression in the integrand is the only vector part of the integral. This term accounts for the conditions of reflection at the reflector surface. The exponential term is the phase factor. For a perfect paraboloid the phase factor is reducible to $\exp(-2j\pi F)$, a constant.

The reflector influences the value of $\mathbf{I}$ through $\rho$, the distance from the feed phase center to a point on the surface, and through $\mathbf{n}$, the vector normal. We shall discuss feed and reflector surface options in following sections and confine our attention here to the remaining parts of the integrand.
The key element to be considered is the vector \( \vec{V} \) defined by

\[
\vec{V} = \vec{n} \times (\vec{1}_\rho \times \vec{e}) \tag{6.6}
\]

If we resolve \( \vec{V} \) into components parallel to the rectangular coordinate axes, the unit vectors \( \vec{1}_x, \vec{1}_y, \) and \( \vec{1}_z \) are invariant in direction and magnitude as we move across the reflector. Thus, we may remove the aforementioned vectors from under the integral sign and (when we take real and imaginary parts) reduce the complex vector integral \( \vec{I} \) to a set of six real integrals. Of course, we may resolve \( \vec{V} \) into rectangular coordinate components regardless of whether we choose spherical or rectangular coordinates as the variables of integration.

The vector \( \vec{e} \) describes the polarization of the feed pattern as a function of direction. Since the reflector is in the far zone of the feed, the longitudinal component of \( \vec{e} \) is zero. Even if this were not so, the longitudinal component of \( \vec{e} \) would make no contribution to the integral since

\[
\vec{1}_\rho \times \vec{1}_\rho \left( \vec{1}_\rho \cdot \vec{e} \right) = 0 \tag{6.7}
\]

Thus, without any loss of generality we may take the polarization vector to be

\[
\vec{e} = \vec{1}_\theta \left| B_\theta \right|^2 + \vec{1}_\phi \left| B_\phi \right|^2 \tag{6.8}
\]

with the constraint

\[
\left| B_\theta \right|^2 + \left| B_\phi \right|^2 = 1 \tag{6.9}
\]
We could have defined \( \mathbf{e} \) in terms of its rectangular coordinate components. But then even the simplest polarization would require using all three rectangular components. We might be tempted to let \( \mathbf{e} = \mathbf{1}_x \) (or \( \mathbf{1}_y \)) be a linear polarization, but this would mean that as the wave progresses toward the reflector, the electric field vector would remain parallel to the x (or y) axis and this is not typical of practical feeds. If we define \( \mathbf{e} \) in terms of the spherical coordinate components of the \( (\rho, \psi, \xi) \) system, the longitudinal component may be discarded, but this definition has the effect of specifying radial and circumferential components of polarization on the reflector surface.

Defining \( \mathbf{e} \) in terms of the far-field spherical coordinates \( (R, \theta, \phi) \) accomplishes two things. First, the relationship between the feed polarization and the polarization of the resultant far-zone field of the reflector is obvious. Secondly, the \( \theta \) and \( \phi \) components of feed radiation are easy to visualize and are typical of practical antennas.

When \( B_\theta = 1, B_\phi = 0 \), we have a linear polarization similar to that of a dipole antenna. We shall refer to this as the "dipole" mode of polarization. On the other hand when \( B_\phi = 1, B_\theta = 0 \), the linear polarization is similar to that of a slot antenna. Since \( B_\theta \) and \( B_\phi \) can be complex and can each be functions of \( \theta \) and \( \phi \), it is possible to construct any arbitrary polarization vector. For example, circular polarizations may be formed by setting \( B_\phi = \frac{1}{\sqrt{2}} \) and \( B_\theta = \pm j \frac{1}{\sqrt{2}} \).

Although we originally set up \( \mathbf{e} \) in terms of spherical coordinate components, we will eventually need to resolve \( \mathbf{e} \) into rectangular coordinate components to perform the indicated vector operations. Also we need to find the \( \theta \) and \( \phi \) components of the far field radiation to compute \( 1_T \). Thus we shall need unit vectors \( 1_R, 1_\phi \), and \( 1_\theta \) expressed in both reflector and far field coordinates.

\[
A = \sqrt{y^2 + z^2}
\]  
(6.10)
we have

\[ \mathbf{i}_R = \frac{\mathbf{i}_p}{\rho} = \frac{\mathbf{i}_x}{\rho} x + \frac{\mathbf{i}_y}{\rho} y + \frac{\mathbf{i}_z}{\rho} z \]  

(6.11)

\[ \mathbf{i}_\theta = -\frac{\mathbf{i}_x}{\rho} \frac{\rho_A}{\rho} + \frac{\mathbf{i}_y}{\rho} \frac{x}{\rho_A} + \frac{\mathbf{i}_z}{\rho} \frac{x}{\rho_A} \]  

(6.12)

\[ \mathbf{i}_\phi = \frac{\mathbf{i}_y}{\rho} \frac{z}{\rho_A} + \frac{\mathbf{i}_z}{\rho} \frac{y}{\rho_A} \]  

(6.13)

and

\[ \mathbf{i}_R = \frac{\mathbf{i}_x}{\rho} \cos \theta - \frac{\mathbf{i}_y}{\rho} \sin \theta \sin \phi - \frac{\mathbf{i}_z}{\rho} \sin \theta \sin \phi \]  

(6.14)

\[ \mathbf{i}_\theta = -\frac{\mathbf{i}_x}{\rho} \sin \theta - \frac{\mathbf{i}_y}{\rho} \cos \theta \cos \phi - \frac{\mathbf{i}_z}{\rho} \cos \theta \sin \phi \]  

(6.15)

\[ \mathbf{i}_\phi = +\frac{\mathbf{i}_y}{\rho} \sin \phi - \frac{\mathbf{i}_z}{\rho} \cos \phi \]  

(6.16)

Writing the vector \( \mathbf{n} \) in the form

\[ \mathbf{n} = \frac{\mathbf{i}_x}{\rho} n_x + \frac{\mathbf{i}_y}{\rho} n_y + \frac{\mathbf{i}_z}{\rho} n_z \]  

(6.17)
we have

\[ V = \vec{i}_x \left[ \frac{n_y}{A} (B_y A - B_r x) + \frac{n_z}{A} (z B_\varphi + xy \frac{B_\varphi}{\rho}) \right] \\
+ \vec{i}_y \left[ \frac{n_z}{A} \left( \frac{A B_\varphi}{\rho} \right) - \frac{n_x}{A} (y B_\varphi - xz \frac{B_\varphi}{\rho}) \right] \\
+ \vec{i}_z \left[ -\frac{n_x}{A} (z B_\varphi + xy \frac{B_\varphi}{\rho}) - \frac{n_y}{A} \left( \frac{A B_\varphi}{\rho} \right) \right] \]

(6.18)

The surface element \( \text{d}S \) is

\[ \text{d}S = \frac{dx \, dy}{-n_z} \quad (6.19) \]

Since the product \( \nabla \text{d}s \) contains components of \( \vec{n} \) in both the numerator and denominator, it is immaterial whether the normal is directed toward or away from the origin.

For the phase factor we must evaluate the expression \( \Gamma \) where

\[ \Gamma = \rho (1 - \vec{I}_P \cdot \vec{I}_R) \quad (6.20) \]

This turns out to be

\[ \Gamma = \rho - x \cos \theta + y \sin \theta \cos \phi + z \sin \theta \sin \phi \quad (6.21) \]
Thus

\[ I = - \int \int \frac{\sqrt{V} e^{-jk \rho}}{\rho n_2} \, dx \, dy \]  

(6.22)

where \( \sqrt{V} \) is given by Eq. 6.18 and \( \rho \) by Eq. 6.21.

We shall now consider feed and reflector options available in the model.

3.1.6.3 FEED OPTIONS

The feed pattern is represented in Eq. 6.3 by the product

\[ \sqrt{G_f} \psi \xi \mathbf{e} (\psi, \xi) \]

The factor \( \sqrt{G_f} \) represents the amplitude pattern (on a field strength basis) and the vector \( \mathbf{e} \) defines the polarization. The phase factor for the feed is unity. The feed radiation at the reflector surface is represented by

\[ \sqrt{G_f} \mathbf{e} \mathbf{e}^{-jk \rho/\rho} \]

which corresponds to a far-field representation of the feed radiation. The analysis assumes that the reflector surface is everywhere in the far zone of the feed.

Various input parameters permit us to select from five different feed options. These range from a simple theoretical feed gain function to an exact description of the feed pattern which has been determined by measurement. The use of any of these options will be dictated by the amount of information that is available about the feed and by the purpose of making the particular computer run.

3.1.6.3.1 Uniform Illumination

Uniform aperture illumination represents an important special case. This gives the upper bound of gain for in-phase aperture illumination and is the basis for defining 100 per cent aperture efficiency. There are two ways to calculate the maximum gain for uniform illumination. One is by the simple formula

\[ G_m = \left( \frac{\pi D}{\lambda} \right)^2 \]  

(6.23)
which is simply Eq. 5.1 with η = 1. This does not allow us to determine the losses due to aperture blockage or due to surface distortions. It assumes a perfect paraboloidal reflector of diameter D and an unblocked aperture.

The second method is to let

\[ G_f(\psi, \xi) = C \cdot \rho(\psi, \xi) \quad (6.24) \]

in Eq. 6.22, where C is a constant. When this equation is used, the current integration method may be used with any of the available reflector options. Also various aperture blockages may be used. Uniform illumination gives more weighting to the edge of the reflector and less to the reflector vertex than a tapered illumination does. Since blockage is assumed to occur at the center of the aperture, using uniform illumination will tend to de-emphasize the effects of blockage. Since reflector options tend to have maximum deviation from a perfect paraboloid at the reflector edge, using uniform illumination will tend to emphasize the effects of surface distortions.

Frankly, including the uniform illumination option in the current-distribution computation will be of limited value in the final program, but it is easy to include and may be of some value for diagnostic purposes. The use of uniform illumination with a perfect paraboloid and no blockage is an important reference case that can be used to check the computational accuracy of the computer program, for example. The result obtained can be compared with the value of \( G_m \) obtained from Eq. 6.23 and the accuracy thereby determined.

Thus the uniform illumination case will be included in the complex model. However, the gain function will not be that determined by Eq. 6.24 which would make the illumination uniform for the particular reflector model chosen. Instead the gain function will be that which provides uniform illumination for a perfect paraboloid with the feed at the focal point. For this case
\[ G_x (\psi, \xi) = \cot^2 \frac{\psi_m}{2} \sec^4 \left( \frac{\psi}{2} \right) \] \hspace{1cm} (6.25)

or

\[ G_x (\psi, \xi) = \frac{16 F^2}{b^2} \sec^4 \left( \frac{\psi}{2} \right) \] \hspace{1cm} (6.26)

The illumination function is then

\[ \frac{\sqrt{G_x}}{\rho} = \frac{4F}{D \rho} \sec^2 \left( \frac{\psi}{2} \right) \] \hspace{1cm} (6.27)

which for a perfect paraboloid reduces to

\[ \frac{\sqrt{G_x}}{\rho} = \frac{4}{D} \] \hspace{1cm} (6.28)

This option is called by setting CSN > 999 in the input subroutine.
3.1.6.3.2 Theoretical Feed Gain Functions

An analytical function may be used to represent the feed gain function. A typical function is given by

\[ G_f (\psi, \xi) = 2(m + 1) \cos^m \psi \]  \hspace{1cm} (6.29)

for \(0 < \psi < 90^\circ\) and

\[ G_f (\psi, \xi) = 0 \]  \hspace{1cm} (6.30)

for \(90^\circ < \psi < 180^\circ\).

Silver* uses this function in his treatment of reflector antenna properties. We have used this function extensively in deriving design curves for reflector systems. We have found that it gives good relative gain values when treating reflector antenna design problems parametrically. This would indicate that the pattern shapes are reasonable representations of typical feed patterns. Patterns for this gain function are shown in Fig. A-6.2.

The peak gain value obtained when using these functions is not correct. These functions produce gains which are higher than those obtained in practice. This is because a practical feed whose pattern shape matches the \(\cos^m \psi\) curve will have a lower gain than \(2(m + 1)\) for two reasons. First the theoretical feed has no radiation in the rear hemisphere \(\psi > 90^\circ\) while a practical feed will have some backradiation, however small. Second, the theoretical feed has no forward hemisphere side lobe structure. The practical feed, however, may have sidelobes or distortions of the main lobe skirt which will lower efficiency even though the distortions or sidelobes do not fall upon the reflector.

When the value of \(m\) is chosen to optimize the feed pattern for a particular reflector (a particular F/D ratio), the peak gain corresponds to an aperture efficiency of 83% or thereabouts for values of \(m\) up to 8. Typical practical values range from 55% to 65%. To be conservative the model will be set to adjust the gain of

*Op. Cit., p125

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Figure A-6.2 PATTERNS OF THEORETICAL FEED GAIN FUNCTION
the feed function to the low end of the range. Since $55/83$ is approximately $2/3$, Eq. 6.29 can be modified to be

$$G_f (\psi, \xi) = \frac{\Delta}{3} (m+1)^m \cos \psi.$$  \hspace{1cm} (6.31)

This option will be called by setting CSN in the range $0 \leq CSN \leq 999$ in the input subroutine, in which case $m$ will be set equal to CSN. The quantity $GFE$ must also be set $\leq 0$.

3.1.6.3.3 Modified Theoretical Gain Function

Another way of using the theoretical gain function and at the same time obtaining realistic gain values is to use the actual feed gain as determined by measurement. In this case

$$G_f (\psi, \xi) = G_F \cos^m \psi$$  \hspace{1cm} (6.32)

for $0 \leq \psi \leq 90^\circ$ and

$$G_f (\psi, \xi) = 0$$  \hspace{1cm} (6.33)

for $90^\circ < \psi < 180^\circ$. The quantity $G_F$ is the measured feed gain.

This option may be called by setting $0 \leq CSN \leq 999$ and setting $GFE > 0$. In the input subroutine $GFE$ is the measured feed gain corresponding to $G_F$ above.
3.1.6.3.4 Experimental Feed Patterns

We can improve the correlation between the predicted gain values which are computed by the program and experimental gain values that would be measured on the range by replacing the analytical function describing the feed gain function with the measured gain function of the feed. It is now relatively easy to determine the spherical coverage pattern of a feed in a form suitable for inclusion in the computer program.

A first order approximation might be to fit a suitable surface to the two principal plane patterns of the feed. Although this is generally better than an analytical function, it is not quite as good as using the complete pattern contour of the feed sampled at close intervals.

The experimental feed pattern data must be supplied to the computer in a format compatible with the program. The data file format to be described here is directly obtainable by measuring the feed pattern with Scientific Atlanta Radiation Distribution Equipment. If the feed pattern is measured another way, it will have to be converted to the standard format before it can be used with the computer program and no provisions for this conversion are included in the model.

The coordinate system used in measuring the feed patterns is shown in Fig. A-6.3. The feed axis is aligned with the $\psi = 0$ axis. The resulting coordinates ($\psi$, $\xi$) are the same coordinates defined in Fig. A-6.1. We have developed equations for other orientations of the feed axis, but so far we have never found occasion to use them. The difficulty in using the orientation shown in Fig. A-6.3 is that the polarization rotates during the measurement of the pattern. Therefore, when the feed is nominally linearly polarized, the patterns are measured with a circularly-polarized transmitting antenna and a constant 3 dB polarization loss is assumed. When the feed is nominally circularly-polarized, the appropriate circular polarization is used for the transmitting antenna. Then when the data file is used in the computer program, either dipole or slot polarization is used for the linear case or the appropriate circular polarization is used for the circularly-polarized case.
Figure A-6.3 FEED PATTERN COORDINATES
This procedure is admittedly an approximation with regard to the variation of polarization throughout the feed pattern. Equations have been developed for making a series of feed pattern measurements with different polarizations so that the vector \( \mathbf{e} \) may be determined point by point throughout the pattern. This requires an added cost of measurement and an increased amount of computer time for each run and thus far such a complication has not been found necessary.

With the set-up shown in Fig. A-6.3 the Scientific Atlanta equipment samples the feed pattern every 2 degrees in \( \Psi \) and in \( \xi \). Starting at \( \Psi = 0 \) and concluding at \( \Psi = 90^\circ \), the model tower is positioned in 2 degree increments. At each \( \Psi \) position a complete conical pattern is obtained by rotating in \( \xi \) and sampling every 2 degrees. The data file therefore consists of 91 \( \Psi \) scans each consisting of a start-of-scan marker and 180 data points corresponding to the sampling in \( \xi \). At the end of the 91st scan, a start-of-scan marker followed by an end-of-file marker occurs. The complete data file, therefore, consists of 16473 data points including markers.

The data file as measured represents only the relative gain pattern of the feed. Each value in the data file must be corrected so that it represents the actual gain of the feed in that particular direction. To do this, it is necessary to make a separate experimental measurement of the peak gain of the feed.

Having the complete feed pattern on a data file allows us to integrate the feed pattern to determine the feed directivity. This may then be compared with the measured gain value of the feed to determine the feed radiation efficiency. Also, it is possible to integrate the portion of the feed radiation intercepted by the reflector which may then be compared with the total radiation to determine the spillover efficiency.

The data points representing feed radiation are quantized to the nearest quarter dB and are limited to within the range of approximately 0 to 40 dB. The quantization gives an error of at worst \( \pm 0.125 \) dB for any particular value of the feed pattern, but on the average the error is much less.

Also, the feed pattern is sampled at 2 degree intervals in both angular coordinates and this does not agree with the sampling pattern used in the
integration process. Therefore, feed pattern values at the integration sampling points must be found by interpolation. Since the feed is generally a smooth, slowly varying function over the angle subtended by the reflector, the interpolation error is not significant.

The accuracy of feed representation will be discussed further in a later section.

The experimental feed pattern option may be called in the program by setting CSN < 0 and by setting GFE > 0 in the input subroutine.

3.1.6.3.5 Reference Experimental Feed Pattern

This option is the same as the experimental feed pattern option, except that an experimental feed pattern data file which is considered to be typical of practical horn feeds will be built into the program.

This option may be called by setting CSN < 0 and GFE < 0 in the input subroutine.

3.1.6.4 REFLECTOR OPTIONS

The reflector is represented in Eq. 6.3 by the scalar function and by the vector \( \mathbf{n} \). The function \( \rho = f(\psi, \xi) \) describes the variation of the distance from the origin (feed) to a particular point on the reflector surface as a function of the variables of integration. If the surface is defined in the form

\[
z = g(x, y)
\]

then

\[
\rho = \sqrt{x^2 + y^2 + (g(x, y))^2}
\]  

(6.34)

The vector \( \mathbf{n} \) represents the variation of a unit vector normal to the reflector surface as a function of position on the reflector. The vector \( \mathbf{n} \) can
be obtained by taking the gradient of any scalar equation equal to a constant which represents the reflector surface. Thus if

\[ H = \rho - f(\psi, \xi) = 0 \quad (6.35) \]

or if

\[ H = z - g(x, y) = 0 \quad (6.36) \]

(depending on how the surface is defined)

then

\[ \overline{n} = \frac{\nabla H}{|\nabla H|} \quad (6.37) \]

Included in the radiating system model are two analytical representations of special reflector surfaces. One is the paraboloid and the other is the flex-rib reflector. (The latter is applicable not only to the flex-rib unfurlable reflector but also to various "umbrella" type reflectors).

For any particular kind of antenna it is possible to develop a distortion theory embodied in an equation \( \rho = f(\psi, \xi) \) or \( z = g(x, y) \) to represent the actual distorted surface in the presence of orbital thermal and/or dynamic effects. Then \( \rho \) (or \( z \)) and the vector \( \overline{n} \) derived therefrom may be used directly in Eq. 6.3 to calculate gain as it is degraded by the orbital environment. This has been done for the flex-rib type of construction on the ATS F and G reflector project, for example.

The difficulty is that the form of the \( \rho \) or \( z \) equation depends explicitly on the distortion theory formulated for each particular type of reflector. The only type of general treatment possible is to expand the reflector surface in a general power series or similar expansion, but this becomes cumbersome when one attempts to relate it to a specific design for which a distortion theory has
been or can be developed.

Since the treatment of thermal effects has been limited in this study, we shall include only the perfect paraboloid and the perfect flex-rib surfaces. The effects of a thermally-distorted surface will be handled as we shall describe in a later section. The reader can be assured that if a particular reflector design is chosen and \( \rho \) or \( z \) equations can be derived representing the surface in the presence of the orbital environment, the basic model can be modified to include the effects of these distortions. It would also be necessary to modify the input subroutine to handle new input data.

3.1.6.14.1 The Perfect Paraboloid

The equation for a perfect paraboloid of focal length \( F \) with vertex located at \((x, y, z)\) coordinates of \((0, 0, z_D)\) is

\[
z = z_D - \frac{x^2 + y^2}{4 F}
\]

(6.38)

Thus \( \rho \) is given by

\[
\rho = \sqrt{x^2 + y^2 + \left(z_D - \frac{x^2 + y^2}{4 F}\right)^2}
\]

(6.39)

Since \( z_D \) is a constant

\[
\nabla H = \nabla z_D = \nabla \left(z + \frac{x^2 + y^2}{4 F}\right)
\]

(6.40)

and

\[
\nabla H = \frac{1}{x} \frac{x}{2 F} + \frac{1}{y} \frac{y}{2 F} + \frac{1}{z}
\]

(6.41)
and $\bar{n}$ can be found from Eq. 6.37 with

$$|\nabla H| = \frac{1}{2F} \sqrt{x^2 + y^2 + 4F^2}$$

(6.42)

This option can be called by setting PAN < 0 in the input routine.

### 3.1.6.4.2 The Perfect Flex-Rib Reflector

The Flex-Rib reflector may be called a sectoral approximation to a desired paraboloidal surface. The frontal view of this type of reflector is shown in Fig. A-6.4. In each wedge-shaped sector the surface is approximated by a parabolic cylinder.

The equation for a parabolic cylinder represented by the sector designated by $s = 0$ in Fig. A-6.4 is simply the equation of the x-z plane intercept, since the elements of this particular parabolic cylinder are parallel to the y axis. Thus for $s = 0$

$$z = z_D - \frac{x^2}{4F_C}$$

(6.43)

where $F_C$ is the focal distance of the parabolic cylinder.

If we rotate this panel through an angle $\xi = \xi_S$, we have the equation

$$z = z_D - \frac{(x \cos \xi_S + y \sin \xi_S)^2}{4F_C}$$

(6.44)

In particular if we have $N$ panels then Eq. 6.44 becomes

$$z = z_D - \frac{(x \cos \frac{2\pi s}{N} + y \sin \frac{2\pi s}{N})^2}{4F_C}$$

(6.45)
Figure A-6.4  FRONTAL VIEW FLEX RIB REFLECTOR

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and the $s$-th panel extends over the range

$$(2s-1) \frac{N}{N} \leq \xi \leq (2s + 1) \frac{N}{N}$$

We may define a parameter $W$ as

$$W = x \cos \frac{2\pi s}{N} + y \sin \frac{2\pi s}{N} \quad (6.46)$$

This has special significance since it is the distance of a particular point on the reflector from the center of the aperture as measured, not radially, but along the centerline of its own particular panel. In terms of this parameter

$$\rho = \sqrt{x^2 + y^2 + \left(z_D - \frac{W^2}{4F} \right)^2} \quad (6.47)$$

As in the previous section we may take $z_D$ as the constant defining the surface. Thus

$$\nabla H = \nabla (z + \frac{W^2}{4F}) \quad (6.48)$$

and

$$\nabla H = 1 \frac{W}{2F} \cos \frac{2\pi s}{N} + i \frac{W}{2F} \sin \frac{2\pi s}{N} + i \frac{2\pi}{z} \quad (6.49)$$

Then $\bar{n}$ can be found from Eq. 6.37 with

$$|\nabla H| = \frac{1}{2F} \sqrt{W^2 + 4F^2} \quad (6.50)$$
The quantity $F_C$ is the focal distance of the parabolic cylinder. We must determine the relationship of $F_C$ to $F$, the focal length of the "equivalent" paraboloid. To do this consider the intersection of a radial plane ($\xi = \text{a constant}$) with the reflector surface. Separating out the dependence on $\xi$ in Eq. 6.45, we have

$$z = z_D - \frac{r^2}{4F_C} \cos^2 \left( \xi - \frac{2\pi s}{N} \right)$$

(6.51)

where $r = \rho \sin \psi$ is the offset of a point from the $z$-axis. Comparing Eq. 6.51 with Eq. 6.43, we conclude that the intersection of a radial plane containing the $z$ axis and the reflector surface is a parabolic arc of focal length

$$F_1(\xi) = \frac{F_C}{\cos^2 \left( \xi - \frac{2\pi s}{N} \right)}$$

(6.52)

The focal length $F_R$ of the reflector rib (which is the boundary between two adjacent panels) is obtained by setting $\xi = (2s \pm 1) \pi/N$. Thus

$$F_R = F_O / \cos^2 \left( \frac{\pi}{N} \right)$$

(6.53)

We may conclude that the paraboloid which is a best fit to this surface must intersect the surface twice in each panel and will therefore have a focal length $F$ such that $F_R > F > F_C$. As the number of panels increases without bound, the Flex-Rib surface more closely approaches a paraboloid. Since $F_R \to F_C$ as $N \to \infty$, then in the limit $F_R = F = F_C$.

A mean value of the function $F_1(\xi)$ can be found by integrating $F_1$ over the aperture. There is, of course, no radial variation of $F_1$. This mean value is

$$F = F_C \left( 1 + \frac{1}{3} \tan^2 \frac{\pi}{N} \right)$$

(6.54)
or

\[ F = F_R \left( 1 - \frac{2}{3} \sin^2 \frac{\pi}{N} \right) \]  \hspace{1cm} (6.55)

We have chosen to let \( F \), the focal length of the "equivalent" paraboloid, be this mean value of the function \( R_1 \).

When \( z_D \) is set equal to \( F \) as defined above, the peak gain varies as a function of \( D/\lambda \) as shown in Fig. A-6.5. When the reflector is a good approximation to a perfect paraboloid, setting \( z_D \) to any value other than \( F \) does not improve the gain by a significant amount (something of the order of \( 10^{-3} \) dB). However, when the gain curve departs significantly from the perfect paraboloid gain curve, some of the lost gain can be recovered by moving the feed. This, however, is not a normal design region for this type of reflector since, even with refocussing, the gain degradation is severe. Thus, we can set \( z_D = F \) and conclude that \( F \) is the focal length of the equivalent paraboloid for all normal reflector designs.

The perfect Flex-Rib reflector case can be called by setting \( N > 0 \). The variable \( N \) is represented by PAN in the input routine. For this case \( \rho \) is found from Eq. 6.47 and the vector \( \Pi \) is found from Eq. 6.49 (normalized by Eq. 6.50). The focal lengths are related by Eq. 6.53 through Eq. 6.55.

3.1.6.5 ASSUMPTIONS AND ACCURACY

In this section we shall discuss the basic assumptions associated with using the current distribution method to calculate gain. We shall also mention some of the checks that have been made to determine the accuracy involved.

There are three basic theoretical assumptions involved in the original formulation of the general equations. First of all, the method is applicable to determining the far field radiation of the reflector antenna only. Secondly, the reflector is assumed to be in the far field of the feed. Third, direct radiation of the feed to the point of observation in the far zone is neglected.
The usual criterion for determining the far-zone of a directive antenna is that the distance $R$ from the antenna exceeds $2D^2/\lambda$. This will nearly always be true for orbital antennas. For example, at 100 nm altitude or at 100 nm distance between two space vehicles, it would require an antenna larger than 173 feet in diameter to fail to satisfy this criterion at X-band (10 GHz), clearly beyond the state of the art for the immediate future. The only conditions under which we might fail to satisfy the far-zone criterion are during the testing of orbital antennas on the ground on some ranges; during very close approaches of two space vehicles, as in rendezvous in some extremely large aperture systems intended for the transmission of power by microwave radiation. None of these situations are intended to be covered by the simulation of the antenna in this study.

When the distance from the antenna is exactly $2D^2/\lambda$, the gain loss is typically of the order of 0.05 dB. Since normally the distance will be much in excess of this minimum distance, the gain error will be reduced to an insignificant value.

The assumption that the reflector is everywhere in the far zone of the feed is not as easy to justify but normally it would be true. To illustrate, a typical horn type feed for a paraboloidal reflector would have an effective aperture of the order of 1 wavelength so as to illuminate the aperture properly. With $F/D$ ratios of the order of 0.5, this would mean that reflectors smaller than about 2 wavelengths would fail to meet the criterion. A $2\lambda$ reflector fed by a $1\lambda$ feed would suffer severe blocking and provide only a few dB gain. In fact, it probably would be better to turn the feed around and eliminate the reflector, perhaps adding aperture to the feed horn. Thus, for normal feeds we will probably not run into a situation where the reflector is not in the far zone of the feed.

The assumption that the reflector is in the far zone of the feed is made so we can apply geometrical optics when determining the amplitude of the feed radiation at the point where it strikes the reflector. Because of this assumption, there is no phase factor relating to the feed radiation in the basic formulation. The feed is assumed to be a point source with spherical phase fronts. There may be some cases where the feed radiation does not have equal phase across the angle subtended by the reflector and when this happens, the feed cannot be considered to have a single point phase center — thus the criterion would not be satisfied.
Normally the criterion that the reflector be in the far zone of the feed will be satisfied to a degree sufficient for all practical purposes. The user should be on the lookout for any unusual feed designs which might have a significant phase error throughout the angle subtended by the reflector. Should this occur, he may correct the results for the appropriate amount of gain degradation attributable to such phase error or he may elect to use the simple model.

The third assumption is that the back radiation of the feed can be neglected. If this is not so, the correction can be made as indicated in Eq. 6.1. Normally, well designed feeds will have a front-to-back ratio of at least 15 or 20 dB and very often considerably more. For typical feeds, the back radiation would normally be some 10 or more dB below isotropic and this would be insignificant in comparison with the peak gain of the reflector which normally would be 20 to 60 dB above isotropic. The back radiation usually would be further reduced in the normal design by obstructions behind the feed, such as feed support brackets, electronic boxes, or perhaps the space vehicle itself.

Of more importance are the practical approximations which have been made in constructing the model from the basic formulation. For some of these approximations we have not been able to obtain an estimate of the error directly attributable thereto, but we know what the overall accuracy seems to be.

We have made a basic assumption with regard to polarization. If the feed is linearly polarized, we have assumed that it is either a dipole or slot mode, as previously discussed. If the feed is circularly polarized, we assumed that the polarization is a quadrature combination of dipole and slot modes. No provision has been made for elliptically polarized feeds, since we normally try to achieve either linear or circular polarization.

The choice of the polarization modes is only important when we are using the experimental feed patterns. We have made calculations using the theoretical feed gain functions, including uniform illumination, and have found no significant difference in the results for each of the four basic polarizations.

When we are using experimental feed patterns, our assumptions regarding the polarization modes become of more importance. The difficulty is not whether the choice of dipole and slot modes is a correct one. We measure the gain function
of a linear antenna with a circularly polarized transmitting polarization and then
during the integration process, we assume that the polarization is in one of the two
standard linear modes. If instead the linear polarization has some other form, such
as always parallel to the x-axis, we would still expect to get the same result, based
on our experience with theoretical feed patterns referred to in the preceding paragraph.
Similarly, if the feed polarization is circular throughout the pattern, it is immaterial
what two linear polarizations are used to define circular polarization.

If the feed has elliptical polarization, we shall be disregarding a component
of its radiation either when we measure the feed pattern or when we use it in the
program, or both. The error that occurs is dependent on relative amplitudes of
the nominal polarization component and the omitted component. Since the reflector
would have integrated the discarded component just as it does the retained component
and would have then added the two in complex vector fashion, we can estimate bounds
on the error from the relative amplitudes of the two components.

Similarly, the four standard polarizations do not provide for the fact that
some feed patterns have polarization characteristics which vary throughout the angle
subtended by the reflector. This is most noticeable in frequency-independent type
feeds over some portions of their operating bands. This variation tends to occur
near the edge of the reflector, usually where the illumination taper tends to de-emphasize
its effect. Furthermore, in a well-designed feed this variation is usually held within
reasonable bounds.

Frankly, it is difficult to determine what part of the error is attributable
to the departure of the actual feed polarization from the assumed state. An investiga-
tion of this effect on accuracy would be a separate study all in itself. We know
that if it were a serious problem we could measure both amplitude and polarization
(and even phase) of the feed pattern and put these corrections into the program.
The result would be at least a four-fold increase in the test time required to measure
feed characteristics, a significant increase in program storage requirements on the
computer, and a significant increase in compute time for every case. The overall
accuracy of the computation without this refinement is satisfactory for engineering
purposes (as we shall see) so adding this complication does not seem justified.
The theoretical gain function option was primarily intended to be used as a means of evaluating parametric trade-offs. The relative accuracy for evaluating reflector designs is quite good and has been confirmed by experiment. In this test the gains of a high-precision 4 foot paraboloid and a 12 panel, 4 foot Flex-Rib reflector were compared at 4, 8, and 12 GHz. A direct substitution method was employed so that the same aperture illumination, focal distance, and frequency were used for both cases. The primary feed patterns were measured and fitted to the analytical feed functions. Then the relative gain values predicted by theory and experiment were compared. Agreement was within about 0.05 to 0.1 dB, even though the feed patterns were not exact fits to the analytical functions. This test confirmed the relative accuracy of the current integration method of gain calculation.

As mentioned before, use of the analytic function without modifying the peak gain value gives peak gain values that are unrealistic. The modification given in Eq. 6.31 should be more representative of typical antennas and should be within ± 1 dB for typical cases, though it may be in error by more than that amount for any particular case. When the analytic function is modified by using the actual peak gain of the feed, the error is estimated to be within ± 1 for the particular case considered. In these estimates, we have not included any allowance for transmission lines losses and have referenced the antenna gain to the feed terminals. The estimates in this paragraph relate to absolute accuracy -- that is, the accuracy of predicting the true gain of the antenna.

The basic radiation integral is approximated by numerical integration methods in the model. The sampling interval must be fine enough to sample accurately the illumination taper across the aperture, the reflector contour, and the electromagnetic wavelength. Electromagnetic theory would tell us that there should be one sampling point per half-wavelength across the reflector, but if this is used as a criterion, the reflector surface may not be adequately sampled when the reflector is small in terms of wavelengths. Thus a wavelength criterion is used, but a certain minimum number of points must be taken for the double summation to represent the integral.
For large reflectors, fewer points can be taken if the surface is smooth. The paraboloid, for example, requires fewer points than a many-pannelled Flex-Rib because the paraboloid is a smooth surface of revolution. In many cases when doing parametric studies we have found good relative accuracy with sampling rates as low as one point for every five wavelengths, but, of course, the absolute accuracy deteriorates somewhat.

The criterion we normally use is that one point should be taken per wavelength, except that in no case should fewer than about 600 points be taken. The accuracy for one point per wavelength sampling is almost as good as that obtained for one point per half-wavelength sampling, but the integration time is only one quarter as long. For exploratory parametric studies, fewer sampling points can be taken to reduce compute time while searching for the optimum values. The proper minimum sampling rate for a given problem can be determined by increasing the sampling rate and noting where the gain value begins to stabilize. There will be some oscillation of the gain value about the true gain value as the sampling rate is increased further due to basic inaccuracies in the calculation (computer arithmetic accuracy).

To check the computational accuracy, we have used the uniform illumination feed option and the perfect paraboloid reflector option and compared the resultant gain value with that obtained by using Eq. 6.23. For one point per wavelength sampling the agreement is about 0.07 dB. This is considered to be the computational accuracy of the program. (The machine used for this test is the SDS 940 time-sharing computer. The case considered was the ATS F and G reflector at 8.25 GHz).

When using the experimental feed option, two additional errors occur. First the feed gain values are quantized to the nearest quarter-dB. Second, since the sampling of the feed pattern in the data file is not coincident with the sampling of the aperture in the integration process, feed pattern data must be interpolated at the integration sampling points. Studies of the best method of interpolation showed that linear interpolation was adequate since the feed pattern generally is quite smooth for typical designs. Moreover, taking higher order differences eventually and/or occasionally results in poorer accuracy due to the quantization of the feed pattern data. The reason for this can be seen by comparing the following
difference tables for unquantized and quantized data.

<table>
<thead>
<tr>
<th>Actual Values</th>
<th>Quantized</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>4.6</td>
<td>4.5 .0</td>
</tr>
<tr>
<td>4.7</td>
<td>4.75 .25</td>
</tr>
<tr>
<td>4.8</td>
<td>4.75 .0</td>
</tr>
<tr>
<td>4.9</td>
<td>5.0 .25</td>
</tr>
<tr>
<td>5.0</td>
<td>5.0 .0</td>
</tr>
</tbody>
</table>

Due to the rounding off, higher order differences eventually will increase causing poorer accuracy of interpolation. If we used only first and second order differences we would occasionally get poorer accuracy (near where the values change).

To check the overall computational accuracy of the program, we constructed an artificial "experimental feed" data file simulating the feed gain function that provides uniform illumination of the aperture (Eq. 6.25). The feed data file was quantized to the nearest quarter-dB, as an experimental data file would be. In the integration process linear interpolation was used. At 8.25 GHz the gain program calculated a gain of 57.873 dB for a 30-foot reflector using this data file with sampling at one point per wavelength. The gain equation for uniform illumination (Eq. 6.23) gave a gain of 57.958 dB. The difference, 0.085 dB, represents the overall computational accuracy, including machine accuracy, the representation of the double integral by the double summation, linear interpolation of the feed data, and the effects of quantizing the feed data. In this check a 500 panel Flex-Rib reflector was used to simulate a paraboloid, so the minor effect of that approximation is also included. Thus the computational accuracy using the experimental feed option is almost the same as that obtained using the theoretical feed options.

Aperture blockage by the feed assembly or other structures is accounted for by not integrating the surface currents over the projection of the blockage on the surface of the reflector. That is, the limits of integration are adjusted so as to omit portions of the reflector radiation not contributing to the on-axis gain. This approach is accurate on axis and near the reflector axis. For observation
points at wide angles to the reflector axis, it is necessary to account for the fact that the blockage would not obscure the vertex area of the reflector but some other displaced part. However, since the model is normally used to predict gain values near the axis of high gain systems, the refinement applicable to wide angles has not been included.

Blockage is considered to be a circular blockage centered about the reflector axis. If the blockage is not circular, the best procedure is to equate the area represented by the blockage to a circular blockage area for use in the program. The blockage may not be centrally located, but normally it would be near the center of the aperture. If the blockage is off center, then the model tends to give conservative results.

The apparent gain of the reflector antenna will be modified by the impedance mismatch of the feed when mounted in the reflector. This mismatch may be thought of as having two components, one the inherent mismatch of the feed in free space and the other the reaction of the reflector on the feed. The theoretical gain of the reflector/feed can be corrected if the mismatch of the feed in the reflector is known. Often this is not available. Therefore, the model calculates the magnitude and phase of the interaction of the feed and the reflector. This can be used as a bound or tolerance on the gain values obtained from the model. Normally, in a well designed system this will not be a problem, since the feed should be reasonably well matched in free space and since, the normal aperture distributions for maximum gain do not provide a high degree of reflector feed interaction.

We shall cite an example to illustrate the reaction effect and indicate, at the same time, something of the overall absolute accuracy of the model. LMSC experienced a perturbation in a gain versus frequency curve of about 1.5 dB for two measurements 50 MHz apart at L-Band. Careful tests indicated this perturbation was not due to measurement error. The model was used to predict the gain at the two frequencies in question from experimentally determined feed patterns. The computed values were within 0.1 dB of the curve obtained by extrapolating smooth portions of the gain curve with no correction for mismatch. This represented an agreement of about 0.7 dB between theoretical and experimental values. When the reflection coefficient was calculated, it was found to be of the order of -11 dB with
a large phase change over the 50 MHz frequency interval. This reaction in combination
with a measured free space mismatch of the feed of about 2:1 was sufficient to account
for the observed gain perturbation. These were range instrumentation antennas with
-22 dB edge illumination for low sidelobes. The low edge illumination resulted in
relatively high concentration of energy near the center of the reflector causing more
interaction with the feed than would normally be encountered in a typical general
purpose antenna. The typical case where the illumination tapers to -10 or -11 dB
to maximize gain results in a reflection coefficient attributable to the reflector of
the order of -18 to -20 dB.

One effect which is not taken into account is the interaction of the feed
support struts with the feed. This is the effect the structure has in modifying the
amplitude or phase of the feed pattern (as distinguished from the blockage of the
aperture caused by the feed and other support structures). Normally, the antenna
designer will design the structure for minimum effect on the feed patterns, but
structural considerations nearly always limit the designers ability to achieve his
desires. This is probably the major factor limiting the accuracy of the model.
With well-designed and simple support structures we may neglect this consideration.
But the user should be on guard when complicated support structures are used (as
when large masses are supported with the feed). Where this effect is not negligible,
the feed pattern can be measured in the presence of the support structure to obtain
a better feed model.

We have previously cited tests of the relative accuracy of the model
(the tests with the 4-foot reflectors) and of the absolute accuracy of the model
(tests on the range instrumentation antennas). We have also checked the absolute
accuracy of the model using a feed designed for the ATS F and G verification
tests and a four-foot reflector. The agreement between the gain value predicted
by the model and that obtained by measurement was about 0.16 dB. The conditions
of test were such that we could expect very good experimental accuracy, so this
test seems to confirm the accuracy of the model.
3.1.7 CORRECTION FOR THERMAL EFFECTS

The scope of the effort in considering influence factors was limited in this study to be compatible with available funding. As a consequence, the effects of thermal distortions on the gain of the antenna along a particular LOS will be handled as a correction based on extrapolation of LMSC's experience with the ATS F and G reflector and with other systems.

The effect of a distorted reflector can be accurately handled by including in the current distribution integration model an option for a distorted reflector. The overall program sequence can be modified to calculate the actual gain of the reflector along the line of sight, rather than calculating peak gain and using the Gaussian approximation as described in Section A-3. All that is necessary to accomplish this is an analytical function which describes the distorted surface and which can be differentiated to determine the normal surface vector.

The problem of including the precise calculation of distorted surface effects is the complete lack of generality in any formulation that can be made. The description of the perfect paraboloid may apply to many types of reflector construction, such as honeycomb sandwiches or spun dishes. Similarly, the description of the perfect Flex-Rib surface also applies to the umbrella type of deployable reflector. But to include distortion effects requires developing a distortion theory for each possible method of realizing each type of surface. For example, the distortion equation of a Flex-Rib reflector would be different from that of an umbrella reflector which might have rigid ribs that fold up against the reflector axis. Similarly, there is a large amount of work involved in establishing the design parameters that optimize each type of reflector for the chosen orbit. Thus in a limited scope effort, only a correction-type treatment of thermal effects is possible.

The ATS F and G reflector designed for 8.25 GHz operation (30 foot diameter aperture) will be the primary initial basis for making a thermal correction. Beamshift and gain degradation data for this case will be extrapolated to other sizes and frequencies as required.

The peak gain and the on-axis gain of the ATS reflector at 8.25 GHz is shown as a function of orbit hour in Fig. A4-7.1. The beamshift is shown in Fig. A-7.2. Both these curves are for the configuration utilizing Chromel-R mesh. The orbit hour is directly relatable to sun angle in the xz plane of the reflector. (In far-zone coordinates this would be the ZY plane or the \( \phi = \pm \pi \) plane. See Fig. A-6.1). In the simple or the complicated gain calculation, the peak gain is
Figure A-7.1  GAIN DEGRADATION - ATS F&G REFLECTOR
Figure A-7.2 BEAMSHIFT - ATS F&G REFLECTOR
calculated and the beam position is defined as \( \theta = 90^\circ, \phi = 90^\circ \). The thermal correction will correct the peak gain value and provide for a new reference position for the beam. A coordinate transformation (a rotation about the reflector axis) will be used to handle the case where the sun is not in the aforementioned plane.

We shall denote the gain degradation for the reference case by \( \Delta G_o \) for diameter \( D_0 \) and frequency \( f_o \). Then for any diameter \( D \) and frequency \( f \), we will use the form

\[
10 \log_{10} G_m = 10 \log_{10} G_m - \Delta G \quad \text{dB}
\]  

(7.1)

where \( G_{mo} \) is the peak gain for the undistorted case and where

\[
\Delta G = \Delta G_0 \left[ a_0 + a_1 \frac{D}{D_0} + a_2 \frac{D^2}{D_0^2} \right] \left[ b_0 + b_1 \frac{f}{f_o} + b_2 \frac{f^2}{f_o^2} \right]
\]

(7.2)

In Eq. 7.2 the parameters \( a_n \) and \( b_n \) are input constants which fit the design case best. The form of Eq. 7.2 allows some flexibility of adjustment by making changes in the input constants. Generally, some of the input constants may be zero. The form used above does require some justification.

Since most of the systematic distortion errors are monotonic, increasing functions of radius, we would expect the surface error to increase as the diameter is increased. As the surface error increases, so does the gain degradation. Thus we can expect the magnitude of the gain degradation to increase as \( D/D_0 \) increases. Eq. 7.2 gives us the possibility of making a second-degree polynomial fit to the scaling effect. Similarly, frequency changes act in the same way because wavelength, which is inversely proportional to frequency, is the unit of measure in reflector antenna systems. (That is, all distances may be measured in wavelengths instead of inches).

To use the correction option, we must simply make some judgement about how the distortions of the case in hand would be extrapolated from the reference case and then assign appropriate constants. If the gain degradation data for the case at hand becomes available in some way, the reference file may be updated and then with an appropriate choice of constants no correction will be made.
The gain degradation will depend on other factors besides D and f. Amplitude distribution, focal length-to-diameter ratio, and various other parameters may all have a bearing on the actual gain degradation. But our intent here is to supply the best correction that can be made for thermal distortions consistent with the scope of the study. The manner in which this correction is made allows the program to be updated whenever distortion effects are analyzed in more detail.

Exactly the same philosophy is applied to the beamshift problem. When the sun is in the xz plane (Fig. A-6.1), the angular corrections to the position of the peak of the beam become

\[ \phi_n = \frac{\pi}{2} + d\phi \]

(7.3)

and

\[ \theta_n = \frac{\pi}{2} = d\theta \]

(7.4)

where

\[ d\phi = d\phi_0 \left[ c_0 + c_1 \frac{D}{D_0} + c_2 \left( \frac{D}{D_0} \right)^2 \right] \left[ s_0 + d_1 \frac{f}{f_0} + d_2 \left( \frac{f}{f_0} \right)^2 \right] \]

(7.5)

and

\[ d\theta = d\theta_0 \left[ e_0 + e_1 \frac{D}{D_0} + e_2 \left( \frac{D}{D_0} \right)^2 \right] \left[ s_0 + s_1 \frac{f}{f_0} + s_2 \left( \frac{f}{f_0} \right)^2 \right] \]

(7.6)

Using the same functional form for beamshift does not necessarily imply that the beamshift will be a function of diameter scaling ratio or of frequency scaling ratio. For example, a distortion mode corresponding to a simple tilt of the reflector, if scaled to a larger diameter, would still be a tilt of the same angle and thus would...
be independent of $D/D_0$. Also, we would not expect the displacement of the beam to be dependent on frequency when this displacement is measured in degrees or radians. That is because we tend to think of the displacement as the result of an "effective" rotation of the reflector. The importance of this rotation arises when we measure the rotation in beamwidths and not degrees. Thus while we have included provision for dependence on diameter and frequency, there may be many cases in which the beamshift would be independent of either variable or both.

The reference file for beamshift data can be updated just as we mentioned above for the gain degradation reference file.
For purposes of providing the input signal to the monopulse model (subroutine 
MONFLS) a distorted antenna reference frame (D-frame) is defined as the frame 
obtained from the undistorted antenna reference frame (A-frame) by applying 
the (small) rotation $\Delta \phi$ and $\Delta \theta$ about the appropriate axes (see definitions of 
$\Delta \phi$ & $\Delta \theta$ above). In this reference frame the peak gain of the antenna lies 
along the $-Z_D$ axis and the unit line of sight vector in this reference frame 
(LHATD) is the input to MONFLS.

The D-frame is obtained from the A-frame by an effective single rotation 
$$d\psi = \sqrt{(\Delta \phi)^2 + (\Delta \theta)^2}$$ 
about the $E_\psi$ axis (see Figure A.0.1) where 
$$\bar{E}_\psi = \frac{\Delta \phi}{\sin \theta} \bar{E}_\phi + \frac{\Delta \theta}{\sin \theta} \bar{E}_\theta$$.

The Euler parameters for the transformation from the A-frame to 
the D-frame are defined such that 
$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} \bar{E}_\psi \\ A_\phi \sin \frac{d\psi}{2} \\ A_\phi \cos \frac{d\psi}{2} \end{bmatrix}, \quad q_4 = \cos \frac{d\psi}{2}$$

or since $d\psi$ is small and $\bar{E}_\psi$ is a linear combination of $\bar{E}_\phi$ and $\bar{E}_\theta$,

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \frac{\Delta \phi}{2} \begin{bmatrix} \cos \Omega \\ \sin \Omega \\ 0 \end{bmatrix} + \frac{\Delta \theta}{2} \begin{bmatrix} -\sin \Omega \\ \cos \Omega \\ 0 \end{bmatrix} 
\Rightarrow

\begin{align*}
q_1 &= \frac{1}{2} (\Delta \phi \cos \Omega - \Delta \theta \sin \Omega) \\
q_2 &= \frac{1}{2} (\Delta \phi \sin \Omega + \Delta \theta \cos \Omega) \\
q_3 &= 0 \\
q_4 &= 1
\end{align*}$$

where $\Omega$ is the angle between the $X_A$ axis and the axis of the $\Delta \phi$ rotation 
(see Figure A.0.1). The transformation matrix ($T_{D/A}$) is obtained from these 
Euler parameters using the subroutine EPTD/D. 

LOCKHEED MISSILES & SPACE COMPANY
Distorted Axis of Peak Gain (-Z

Undistorted Axis of Peak Gain (-Z

\( S = \text{Sun Vector} \)

Figure A.0.1
3.1.8 GAIN CALCULATION ALONG THE LOS

The first step after the input subroutine is to calculate the antenna gain at five points. The pattern of these five points is shown in Fig. A-8.1. When the current distribution method is used to calculate the gain, the gain is calculated on axis and at four angles off axis as shown in the figure. When the simple method is used, we have the same result since we know the peak gain on axis and the half-power beamwidth. Thus we have the following table of values in either case:

<table>
<thead>
<tr>
<th>Gain</th>
<th>$\theta$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$</td>
<td>$\theta_n$</td>
<td>$\phi_n$</td>
</tr>
<tr>
<td>$G_2$</td>
<td>$\theta_n$</td>
<td>$\phi_n - \delta$</td>
</tr>
<tr>
<td>$G_3$</td>
<td>$\theta_n$</td>
<td>$\phi_n + \delta$</td>
</tr>
<tr>
<td>$G_4$</td>
<td>$\theta_n - \delta$</td>
<td>$\phi_n$</td>
</tr>
<tr>
<td>$G_5$</td>
<td>$\theta_n + \delta$</td>
<td>$\phi_n$</td>
</tr>
</tbody>
</table>

In the above table, $\theta_n, \phi_n$ are the coordinates of the reference axis (in this case the beam peak). When the method has been used to calculate gain, $G_2, G_3, G_4,$ and $G_5$ have the value $G_1 - 3$ dB and $\delta$ is the half-power beamwidth divided by 2. The gain values and angular coordinates may have been corrected for thermal effects.

These five gain values and their corresponding coordinates are used to fit an elliptic paraboloid to the peak of the beam. This paraboloid is then used to determine the gain along the LOS for varying coordinates of the LOS, thus saving much computer run time. The accuracy of this approximation has been discussed in Section 3.

In the vicinity of $\theta = \pi/2, \phi = \pi/2$, Eq. 3.2 may be generalized to the form:

$$10 \log_{10} G_m = 10 \log_{10} G(\theta, \phi) = T (\theta - \theta_0)^2 + P (\phi - \phi_0)^2$$

(8.1)

where $G_m$ is the peak gain value and where $\theta_0, \phi_0$ are the coordinates of the beam peak. It will happen that $G_m = G_1, \theta_0 = \theta_n,$ and $\phi_0 = \phi_n$ because the reference axis $\theta_n, \phi_n$ happens to be the beam peak in these calculations.
Figure A-8.1 LOCATION OF GAIN CALCULATION POINTS

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In general, however, it is not necessary that this be so, and when the current distribution is applied to distorted reflectors, the peak gain and the beam position can be found by using Eq. 8.1 and five gain values as indicated in the above table.

For convenience we shall use the notation $G'_x$ to indicate $10 \log_{10} G_x$ in the following.

In general, we find that

$$P = \frac{1}{4\delta^2} (2G'_1 - G'_2 - G'_3) \quad (8.2)$$

$$T = \frac{1}{4\delta^2} (2G'_1 - G'_4 - G'_5) \quad (8.3)$$

and that

$$\rho^*_o = \rho_n + \frac{G'_3 - G'_2}{4P \delta} \quad (8.4)$$

$$\varrho^*_o = \varrho_n + \frac{G'_5 - G'_4}{4T \delta} \quad (8.5)$$

When the beam peak lies along the reference axis then $G'_2 = G'_3$ and $G'_4 = G'_5$, so that

$$10 \log_{10} G(\phi, \varphi) = G'_1 - (G'_1 - G'_2) \left(\frac{\phi - \phi_o}{\delta}\right)^2 - (G'_1 - G'_5) \left(\frac{\varphi - \varphi_o}{\delta}\right)^2 \quad (8.6)$$

$$= G'_1 - P (\phi - \phi_o)^2 - T (\theta - \theta_o)^2$$
which for the calculations made in the simple model would be

\[ 10 \log_{10} G(\theta, \varphi) = 10 \log_{10} G_\perp - \frac{30.10}{(\beta')^2} \left[ (\varphi - \varphi_o)^2 + (\theta - \theta_o)^2 \right] \]  

(8.7)

where \(2 \beta\) is the half-power beamwidth. Equation 8.6 is used to represent the antenna pattern in all subsequent calculations. The parameter \(S\) is chosen in the current distribution calculation to be half the estimated half-power beamwidth to obtain good correlation over this region.
3.1.9 MONOPULSE MODEL

The monopulse system used on the high gain antenna could be either a four-horn or a five-horn configuration. In the five-horn configuration a single horn located at the focus of the reflector provides the communications channel signal; we shall denote this horn and its associated beam by the letter T. The error signals are formed from four offset feeds a, b, c, and d clustered about the focus. In the four-horn configuration the on-axis horn is omitted and the remaining horns are not displaced quite as far from the reflector axis. In this case the communications signal is the sum signal of the monopulse.

The choice between the two configurations is a tradeoff between communications channel gain and tracking capability. The sum signal of a four-horn monopulse, being the sum of four offset beams, has a lower peak gain that that provided by a single on-axis horn. Thus the five-horn configuration provides higher communications channel peak gain. On the other hand, because of the presence of the fifth horn, the remaining four horns must be displaced further from the axis of the reflector than they would be in the four-horn configuration. As a result, the four-horn approach can have higher beam crossover levels -- more nearly at the optimum level -- and provides better tracking.

The monopulse model will calculate four gain values for each position of the LOS. One of these, \( G_D \), is the gain available along the line of sight in the communications or service channel. Another, \( G_S \), is the gain available in the monopulse sum channel. The remaining gain values, \( G_0 \) and \( G_{90} \), are the monopulse error channel gains for the constant \( \theta \) and constant \( \phi \) "planes" respectively. The model allows the user to select a four-horn, or five-horn monopulse or no monopulse at all. The flag for this is MON in the input routine.

When MON=0, the model will not compute monopulse sum or difference signals. Then \( G_D \) is set equal to \( G(\theta, \phi) \) as discussed in the previous section. The remaining gain values \( G_S, G_0, \) and \( G_{90} \) are set to zero.

When MON=5, \( G_D \) is also set equal to \( G(\theta, \phi) \). The model then calculates \( G_S, G_0, \) and \( G_{90} \) as we shall discuss in the following paragraphs. When MON=4, the model computes \( G_S, G_0, \) and \( G_{90} \) and then sets \( G_D = G_S \).

Each of the five beams can be represented by an equation of the form of Eq. 8.6, except that \( \theta_0, \phi_0 \) must be adjusted to include the shift of...
each beam off the axis represented by $\theta_n$, $\phi_n$. The coordinates of the axes of the five beams in the model are

<table>
<thead>
<tr>
<th>Beams</th>
<th>$\theta_o$</th>
<th>$\phi_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>$\theta_n$</td>
<td>$\phi_n$</td>
</tr>
<tr>
<td>a</td>
<td>$\theta_n - U$</td>
<td>$\phi_n - V$</td>
</tr>
<tr>
<td>b</td>
<td>$\theta_n - U$</td>
<td>$\phi_n + V$</td>
</tr>
<tr>
<td>c</td>
<td>$\theta_n + U$</td>
<td>$\phi_n - V$</td>
</tr>
<tr>
<td>d</td>
<td>$\theta_n + U$</td>
<td>$\phi_n + V$</td>
</tr>
</tbody>
</table>

For the small offset angle used in a monopulse we would not expect the peak gain $G_1$ or the beamwidth to change.

(NOTE: In the previous presentation of the monopulse model in the progress reports a rotationally symmetric beam was assumed similar to Eq. 3.3. It was then necessary to find the angle between the LOS and each of the 5 beam axes. The approximation represented by Eq. 8.6 gives the gain in terms of $\theta$, $\phi$ of the LOS directly. In the vicinity of $\theta = 90^\circ$, $\phi = 90^\circ$ we can treat $\theta$ and $\phi$ much the same as we would treat rectangular coordinates. Thus with Eq. 8.6 as the model the geometrical problem is simplified).

In the direction $\theta, \phi$ we obtain $G_a$, $G_b$, $G_c$ and $G_d$. Since sum and difference signals must be obtained by adding and subtracting on a voltage basis, we have for the sum channel gain

$$G_s = A_s \left( \sqrt{G_a} + \sqrt{G_b} + \sqrt{G_c} + \sqrt{G_d} \right)^2$$  \hspace{1cm} (9.1)

where $A_s$ is a factor to account for the modification of the peak gain by the monopulse action.

Similarly

$$G_\phi = A_s \left( \sqrt{G_a} + \sqrt{G_b} - \sqrt{G_c} - \sqrt{G_d} \right)^2$$  \hspace{1cm} (9.2)
Quadrant can be determined by the phases of the difference signals compared to the sum (on a field strength basis).

If we let

\[ G_\phi = A_s \left( \sqrt{G_a} - \sqrt{G_b} + \sqrt{G_c} - \sqrt{G_d} \right)^2 \]  

(9.3)

where \( P \) and \( T \) are given by Eq. 8.2 and 8.3 and where

\[ v = \log_{10} e = 0.434294482 \]  

(9.5)

and if we let

\[ \varphi = \varphi_n + \Delta \varphi \]  

(9.6)

\[ \theta = \theta_n + \Delta \theta \]  

(9.7)

then

\[ G_s = A_s G_\phi \exp \left[ \frac{-P (\Delta \varphi)^2 - T (\Delta \theta)^2}{10w} \right] \left[ 4 \cosh \frac{P V \Delta \varphi}{10w} \sinh \frac{T U \Delta \theta}{10w} \right]^2 \]  

(9.8)
The only actual gain value needed is $G_D$. The tracking system will utilize the error signals normalized with respect to the monopulse sum signal. Thus the output of the monopulse model will be $G_D$, $G_S/G_S$, and $G_S/G_S$ (plus the quadrant information). The required error signal ratios are

\[
\frac{G_\theta}{G_S} = \tanh^2 \left( \frac{TU \Delta \theta}{10w} \right) \quad (9.12)
\]

and

\[
\frac{G_\phi}{G_S} = \tanh^2 \left( \frac{P \Delta \theta}{10w} \right) \quad (9.13)
\]

For the 4-horn case the sum channel of the monopulse is the service channel. For this case it is necessary to evaluate $A_S$ so that $G_D(\theta, \phi) = G_S(\theta, \phi)$ may be found. For the no monopulse or the 5 horn-monopulse we do not need to evaluate $A_S$. 

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The quantity $A_g$ may be found by performing the integration

$$\int_0^{2\pi} \int_0^\pi G_s(\theta, \phi) \sin \theta \, d\theta \, d\phi = 4\pi$$

Unfortunately, the model for $G_s(\theta, \phi)$ is not valid for all $\theta, \phi$. But the model is best near $\theta_n, \phi_n$ where its contribution to the integral is most important. A reasonably good value of $A_g$ can be obtained by limiting the range of integration to a small region around $\theta_n, \phi_n$ which we shall denote by $\tau$. Specifically,

$$16 A_g G_p = \frac{4\pi}{\int_\tau G_s(\theta, \phi) \sin \theta \, d\theta \, d\phi}$$

We already know $G_1$, the maximum value of $G_T(\theta, \phi)$ as given by Eq. 9.11. We can find the value $G_y$ that the above process would yield. Thus,

$$G_y = \frac{4\pi}{\int_\tau G_T(\theta, \phi) \sin \theta \, d\theta \, d\phi}$$

$$= \frac{4\pi}{\int_\tau \exp \left[-\frac{P (\Delta \phi)^2 + T (\Delta \phi)^2}{10w}\right] \sin \theta \, d\theta \, d\phi}$$

The ratio of Eq. 9.16 to Eq. 9.17 is the gain loss due to the monopulse action as compared to that that would be provided by a single horn on axis.

Thus, the maximum value of $G_s(\theta_n, \phi_n)$ is

$$G_s(\theta_n, \phi_n) = \frac{(16 A_g G_p)}{G_y} G_1$$
If the model were perfect, then $G_y$ would be equal to $G_1$ and $G_S(\theta_n, \phi_n)$ would be the value obtained from Eq. 9.16. By using the ratio $16 \frac{A_S G_P}{G_y}$ to modify $G_1$, we obtain a better model since some of the inaccuracies in Eq. 9.16 and Eq. 9.17 tend to cancel.

Finding the peak value of $G_S$ is only a problem in the four-horn case. When $MON=4$, the integrations indicated by Eq. 9.16 and Eq. 9.17 will be performed for the first set of values $\theta$, $\phi$. The peak value thus obtained for $G_S(\theta_n, \phi_n)$ from Eq. 9.18 will be retained for all subsequent LOS positions for the same case.

3.2.1 **Antenna Control System Model**

This section describes the mathematical model used by the simulation program for the antenna control system and has been extracted from the Task 1 Report - Math Modeling of High Gain Antenna - dated 1 March 1972.

The programming of this modeling is contained in subroutines CNTRL7 and SERVØ.
3.2.2.0 MODES OF OPERATION

3.2.2.1 REFERENCE FRAMES

In order to discuss the several modes of operation to be simulated, three of the orthogonal, righthand reference frames that will be used are described. The antenna reference frame (A) has, as two of its axes, the negative boresight axis and the inner most gimbal axis. The IMU reference frame is fixed with respect to the space station. The gimbal angles are Euler angles relating the angular position of the antenna reference frame to the IMU reference frame, assuming rigidity of all members. The outer gimbal angle (about the axis common to the boom and gimbal ring) is $\alpha$ and the inner gimbal angle is $\beta$. The IMU senses the angular position and angular velocity of the IMU reference frame with respect to an inertial reference frame (I).

3.2.2.2 COMPUTER COMMAND MODE

In the computer command mode the antenna angular position command is computed by the on-board digital processor as a function of the ephemeris of the relay satellite at which the antenna is to point and the position and attitude of the space station with respect to the inertial reference frame as determined by the inertial measurement unit (IMU) and the on-board space station ephemeris. A spiral search scan may be superimposed for acquisition of the relay satellite RF signal. For slewing to a relay satellite, limits will be placed on commanded angular rates commensurate with mechanical limitations. The antenna angular position command is converted from components in the IMU reference frame to gimbal (Euler) angles prior to being compared with the actual antenna position, as shown in Fig. B-1.

The rate stabilization shown as a block in Fig. B-1 and in detail in Fig. B-2 provides the rate feedback path. In order to reduce the disturbance input effect of space station attitude changes on the antenna angular position with respect to the inertial reference frame, the space station angular rate is added to the antenna angular rate in the IMU reference frame.
Figure B-1  MANUAL AND COMPUTER COMMAND MODES
3.2.2.3 MANUAL COMMAND MODE

It is assumed that the manual mode is used to bring the antenna to a fixed orientation relative to the inertial reference frame and that the manual command signals originate within the space station by someone making appropriate settings of input devices and then initiating motion. Only step angular position commands relative to the inertial reference frame will be simulated. The commands will be converted to gimbal angles and then compared with the sensed gimbal angles to form the position error signal as shown in Fig. B-1.

3.2.2.4 RF AUTOTRACK MODE

In the RF autotrack mode, using a sufficiently strong RF signal being received from the relay satellite, the angular position difference between the line-of-sight to the relay satellite and the antenna boresight axis is sensed by the monopulse system. The servo is automatically switched from the search scan computer command mode to the RF autotrack mode when the received signal strength exceeds a preset threshold level. Since the receiving antenna beam shape changes as a function of carrier frequency, a corresponding error signal gain adjustment must be made as indicated in Fig. B-3. Next, the error signals are converted from the antenna reference frame (the frame in which they are sensed) to the gimbal (Euler) angles.

When in the RF autotrack mode, the gimbal angle sensor outputs may be used to correct the on-board program which computes the gimbal angle commands required to point the antenna at the relay satellite, i.e., to update the computer command mode program.
3.2.3 CONTROL LAWS

3.2.3.1 OBSERVATION OF OUTPUT STATES

The control laws (more than one will be modeled and simulated) will use the angular position and rate of the antenna about the gimbals when in the computer command and manual command modes. When in the RF autotrack mode, the angular position error signal is developed within the monopulse system but the gimbals may still be used directly. Fig. B-4 indicates several alternate sources of information for the control law. When in the computer command mode, gimbals axis angular rate information may be sensed by a rate gyro or a tachometer, or estimated from the gimbals angular position sensor output.

3.2.3.2 STRUCTURE

Control law alternatives are shown in Fig. B-5 and include integral-error compensation, derivative-error compensation, and derivative-output compensation. The control law outputs, which are the compensated error signals for each gimbals axis, are the inputs to the motor drive electronics. As is indicated in the figure, the math model includes both linear and nonlinear control law alternatives. The control law selected is implemented within the three "gain and compensation" blocks shown in Figs. B-1, B-2, and B-3.

3.2.3.3 VISIBILITY

Possible obscuration of the relay satellite by the earth or by portions of the space station is monitored using visibility discretes. If the antenna servo system is operating in the monopulse autotrack mode and the line-of-sight to the relay satellite is obscured, it will be possible to automatically switch to the computer command mode.
3.2.4 DIGITAL PROCESSOR

The sampled-data effects of digital processing will not be simulated because the Adams-Bashforth integration package which will be used, has a variable integration step size. Simulation of a fixed sampling rate controller would introduce a discontinuity at each sampling instant which would require a re-initialization of the Adams-Bashforth integration package, thus substantially increasing the computer run time. This also precludes simulation of random effects using a random number generator. The entire servo simulation will be deterministic. All digital processing will be modeled as continuous signal processing.
3.3.1 On Board Computer Model

This section describes the mathematical model used by the simulation program for the on board computer and has been extracted from portions of the Task 2 Report - Mathematical Model for the Pointing Requirements of the Space Station High Gain Antenna - dated 28 Oct. 1972, and the Task 4 Report - Math Modeling of Interface Computer - dated 30 March 1972.

The programming of this modeling is contained in the subroutines ØBKNMT, ØBEPH3, ØBEPH1, ØBEPH2, INTSS1, INTSS2, ØBSTCL, ANTCOM, and CLERTN which are called by SETUP to compute the antenna gimbal angle commands predicted by the on board computer.
3.3.2 Computed Space Station Kinematics

The on board kinematics computations are simulated by the subroutine \( \phi_{KNMT} \). The function of these computations is to determine the space station attitude relative to the orbital reference frame from the initial attitude and the time history of the space station and orbital reference frame inertial rates.

Within the subroutine the relative space station attitude is specified by the euler parameters \((q_1, \ldots, q_4)\) of the rotation which would align the orbital reference frame \((0)\) with the space station reference frame \((C)\). When this rotation is by the angle \( \phi \) about the axis \( \hat{e} \), the euler parameters are defined as

\[
q_1 = \epsilon_x \sin (\phi/2) \\
q_2 = \epsilon_y \sin (\phi/2) \\
q_3 = \epsilon_z \sin (\phi/2) \\
q_4 = \cos (\phi/2)
\]

where

\[
\begin{bmatrix}
\epsilon_x \\
\epsilon_y \\
\epsilon_z 
\end{bmatrix} = [\hat{\epsilon}] = [\hat{\epsilon}]
\]
The time derivatives of these euler parameters may be expressed in terms of the components of the space station and orbital reference frame angular velocities ($\dot{\omega}_c^{-1}$ and $\dot{\omega}_o^{-1}$ respectively) as

$$
\begin{bmatrix}
\dot{q}_1 \\
\dot{q}_2 \\
\dot{q}_3 \\
\dot{q}_4
\end{bmatrix} = \frac{1}{2} \left( \Omega_c + \Omega_o \right) 
\begin{bmatrix}
q_1 \\
q_2 \\
q_3 \\
q_4
\end{bmatrix}
$$

where

$$
\Omega_c \Delta = 
\begin{bmatrix}
0 & \omega_3 & -\omega_2 & \omega_1 \\
-\omega_3 & 0 & \omega_1 & \omega_2 \\
\omega_2 & -\omega_1 & 0 & \omega_3 \\
-\omega_1 & -\omega_2 & -\omega_3 & 0
\end{bmatrix},
\left[ \dot{\omega}_c^{-1} \right]_o = 
\begin{bmatrix}
\omega_1 \\
\omega_2 \\
\omega_3
\end{bmatrix}
$$

$$
\Omega_o \Delta = 
\begin{bmatrix}
0 & \omega_3 & -\omega_2 & -\omega_1 \\
-\omega_3 & 0 & \omega_1 & -\omega_2 \\
\omega_2 & -\omega_1 & 0 & -\omega_3 \\
\omega_1 & \omega_2 & \omega_3 & 0
\end{bmatrix},
\left[ \dot{\omega}_o^{-1} \right]_o = 
\begin{bmatrix}
\omega_1 \\
\omega_2 \\
\omega_3
\end{bmatrix}
$$

and the direction cosine matrix for the orbit frame to platform frame transformation may be expressed in terms of the euler parameters as
These formulations are derived from the classical works of Euler, Rodrigues, Hamilton and others and are documented in a Lockheed internal report by E. F. Weiten.¹

The above differential equations for the four euler parameters are numerically integrated and used as indicated above to obtain the direction cosine matrix $[T_{c/o}]$ as a function of time.

¹ A Four-Vector Method of Describing the Rotational Motion of Rigid Bodies, E. F. Weiten, Feb. 1964.
3.3.3 Computed Ephemerides

The relay satellite ephemerides are computed by subroutines OBEPH1 & OBEPH2, and the space station ephemeris is computed by subroutine OBEPH3. The computations are identical in all three of these routines.

The on-board ephemeris subroutine OBEPH1 computes the position vector $\vec{R}$ and the inertial velocity vector $\vec{V}$ by means of the approximate formulae that would be used by an on-board computer. While there are several possibilities for on board ephemeris formulas this first version of OBEPH1 (OBEPH1/LAGRAN) uses 8 point lagrangian interpolation for each of the components of $\vec{R}$ and $\vec{V}$.

For each of the 8 time points, values are supplied at initialization for the time ($t_i$), the $X$, $Y$, $Z$ components of $\vec{R}$ ($Y_{11}$, $Y_{12}$, $Y_{13}$ respectively), and the $X$, $Y$, $Z$ components of $\vec{V}$ ($Y_{14}$, $Y_{15}$, $Y_{16}$ respectively).

The components of $\vec{R}$ and $\vec{V}$ are then computed as functions of time ($t$) according to

$$\begin{bmatrix} \vec{R} \\ \vec{V} \end{bmatrix}_E = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \end{bmatrix}$$

$$z_1 = \sum_{j=1}^{8} Q_j \ Y_{ji}, \quad z_4 = \sum_{j=1}^{8} t - t_j$$

For the space station the orbital reference rate ($\vec{\omega}_r$) and the earth frame to orbit frame transformation matrix ($[T_{0/E}]$) are computed from

$$\vec{\omega}_r = \frac{1}{|\vec{R}|} (\vec{R} \times \vec{V})$$
This expression for $\hat{\omega}_T$ is an approximation which neglects the very small component along the orbital z-axis due to gravitational acceleration along the orbital y-axis (an earth oblateness effect). The expression for $[T_{0/E}]$ in terms of $\hat{R}$ and $\hat{V}$ is however exact, with $\hat{\omega}_T$ being used as an intermediate function of $\hat{R}$ and $\hat{V}$. 
3.3.4 Earth Occultation of LOS (OBSTCL)

Figure 8.1 Earth Occultation Geometry

The object (relay satellite or ground station) located at \( \mathbf{R}_o \) is considered to be visible from the station located at \( \mathbf{R}_s \) if the line of sight between the station and the object does not pass through the sphere of radius \( \text{REQ} + 150,000 \text{ ft} \) centered at the center of the earth. This model neglects the oblate shape of the earth (a variation of about 70,000 ft) and assumes no effect upon the line of sight above an altitude of 150,000 ft.

The computations are performed as follows: the angle \( \alpha_o \) between \( \mathbf{R}_s \) and \( \mathbf{R}_D \) is compared with the angle \( \alpha_m \) defined by

\[
\alpha_m = \sin^{-1} \left( \frac{\text{REQ} + 150,000}{|\mathbf{R}_s|} \right)
\]
and if $\alpha_o > \alpha_m$ then the object must be visible and no further computations are required. If $\alpha_o < \alpha_m$ then the object will not be visible if it is on the opposite side of the horizon from the station, i.e., if the projection of $\vec{R}_o \cdot \vec{R}_s$ is less than $P_o$.

$$\vec{R}_o \cdot \vec{R}_s < P_o$$

$$P_o = (\text{REQ} + 150000) \sin \alpha_m = \frac{(\text{REQ} + 150000)^2}{\left| \vec{R}_s \right|}$$

$$\vec{R}_o \cdot \vec{R}_s < (\text{REQ} + 150000)^2$$

The condition for line of sight intersection with the earth (approximation) is then

$$\alpha_o < \alpha_m \text{ and } \vec{R}_o \cdot \vec{R}_s < (\text{REQ} + 150000)^2$$
3.3.5 Space Station Occultation of LGS (INTSS-1 & 2)

Discussion

The objective of this function is to determine whether the line of sight (specified by the unit vector \( \hat{S} \)) originating from the antenna gimbal point (specified by the position vector \( \vec{R} \)) passes through the space station ellipsoid envelope (specified by the relation \( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \)).

The method used is to analytically determine the minimum value of the quantity

\[
Q = \frac{2}{2.2.2} \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right)
\]

along the line

\[
x = R_x + S_x d \\
y = R_y + S_y d \\
z = R_z + S_z d
\]

(where \( d \) is the forward distance along the line of sight from the antenna gimbal point), and then to observe whether or not the minimum is less than 1 and occurs at a positive value of \( d \). Both of these conditions being met indicates an intersection.

Setting the derivative of \( Q \) with respect to \( d \) equal to zero indicates that \( Q \) is minimum when \( d \) has the value

\[
d_{o} = \frac{-SR_x a^2 + SR_y b^2 + SR_z c^2}{(S_x/a)^2 + (S_y/b)^2 + (S_z/c)^2}
\]

and the minimum value of \( Q \) is

\[
Q_o = \left( \frac{R_x + S_x d_o}{a} \right)^2 + \left( \frac{R_y + S_y d_o}{b} \right)^2 + \left( \frac{R_z + S_z d_o}{c} \right)^2
\]
In terms of these quantities the condition for line of sight intersection with the space station envelope is

\[ d_o > 0 \text{ and } Q_o < 1 \]
3.3.6 Gimbal Angles and Rates (ANTCM)

Discussion

The equations which form the basis for ANTCM are given below. The gimbal angles are obtained from the line of sight (LOS) vector coordinatized in the earth frame (E) assuming a roll, pitch (R/P) rotation from the platform frame (C) to the antenna frame (H). The object is to find the gimbal angles (α and β) which cause the LOS to align with the negative z axis of the antenna frame.

\[ L = RR - RA = \text{LOS vector coordinatized in E frame} \]

\[ L = \left< L, L \right> = \text{Magnitude of the LOS vector} \]

\[ L = T_{C/E} L = \text{LOS vector coordinatized in C frame} \]

\[ T_{H/C} = [\beta]_2 [\alpha]_1 = \text{Transformation from C frame to H frame} \]

\[ [\alpha]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\alpha & s\alpha \\ 0 & -s\alpha & c\alpha \end{bmatrix} \]

\[ [\beta]_2 = \begin{bmatrix} c\beta & 0 & -s\beta \\ 0 & 1 & 0 \\ s\beta & 0 & c\beta \end{bmatrix} \]

\[ L = L_{H} = \text{LOS vector in H frame after the gimbal rotations} \]

Defining \[ L = \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} \]
\[
\begin{bmatrix}
0 \\
0 \\
-l
\end{bmatrix} =
\begin{bmatrix}
C\beta & S\beta & S\alpha \\
0 & C\alpha & S\alpha \\
S\beta & -C\beta & C\beta & C\alpha
\end{bmatrix}
\begin{bmatrix}
l_1 \\
l_2 \\
l_3
\end{bmatrix}
\]

Solving the above equations for \( \alpha \) and \( \beta \) results in

\[
\alpha = \tan^{-1}\left(\frac{l_2}{l_3}\right)
\]

\[
\beta = \tan^{-1}\left(\frac{-l_1}{l_3/C\alpha}\right)
\]

i.e.

\[
(c\alpha) l_2 = -(s\alpha) l_3
\]

\[
\tan \alpha = \left(\frac{l_2}{l_3}\right)
\]

Where the signs are chosen to align the negative \( z_H \) axis with the L0S vector for \( \beta = 0 \).

Similarly

\[
(c\beta) l_1 + (s\alpha s\beta) l_2 - (s\beta c\alpha) l_3 = 0
\]

and

\[
l_1 = [(s\alpha) l_2 - (c\alpha) l_3] \tan \beta
\]

Noting that \((s\alpha) l_2 - (c\alpha) l_3 = \frac{(s\alpha) (c\alpha) l_2 - (c\alpha)^2 l_3}{c\alpha}\)

\[
= \frac{(s\alpha)^2 l_3 - (c\alpha)^2 l_3}{c\alpha} = -\frac{l_3}{c\alpha}
\]
Hence

\[-l_1 = \left(\frac{-l_2}{C\alpha}\right) \tan \beta\]

or

\[\beta = \tan^{-1}\left(\frac{-l_1}{l_3/C\alpha}\right)\]

where the signs were chosen (for \(\alpha = 0\)) to align the negative \(z_H\) axis with the L\O S vector.

The determination of signs in this equation can also be arrived at from consideration of the third equation:

\[-l_1 = l_1 \cdot s\beta - l_2 \cdot C\beta \cdot s\alpha + l_3 \cdot C\beta \cdot C\alpha\]

The expressions for the gimbal angle rates \((\alpha, \beta)\) can be derived from the following starting point.

Assume that the following variables are known

\[\omega_{C-I} = \text{angular rate of the platform frame (C) with respect to an inertial frame (I)}\]

\[I\]

\[RR = \text{time derivative of the relay orbit radius vector with respect to an inertial frame}\]

\[I\]

\[RA = \text{time derivative of the platform orbit radius vector with respect to an inertial frame}\]

\[T_{C/E} = \text{transformation from earth frame (E) to platform frame (C)}\]

\[\alpha, \beta, T_{H/C} = \text{as defined previously}\]
Since \( L = (RR - RA) \)
\[
\begin{align*}
I &= (I) \\
L &= (RR - RA)
\end{align*}
\]
then
\[
L = -\left(\omega^{C-I} \times L\right) + L
\]
and
\[
H = C \left(\omega^{C-H} \times L\right)
\]
\[
L = C \left(\omega^{H-C} \times L\right)
\]

It is desirable to coordinatize the above equation in the antenna frame \((H)\) since both \(L\) and \(L\) have simple representations in that frame. Assuming the antenna to be tracking the LOS perfectly:

\[
L_H = \begin{bmatrix} 0 \\ 0 \\ -l \end{bmatrix} \quad l = \text{range}
\]
\[
H_L = \begin{bmatrix} 0 \\ 0 \\ l \end{bmatrix} \quad l = \text{range rate}
\]

Hence
\[
L_H = C \left(L_H - \left(\omega^{H-C} \times L_H\right)\right)
\]

where
\[
C_L = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \quad \text{(for convenience)}
\]
\[
\begin{align*}
\omega_{H-C}^H &= \begin{bmatrix} 0 \\
\beta \\
0 \end{bmatrix} + \begin{bmatrix} c\beta & 0 & -s\beta \\
0 & 1 & 0 \\
s\beta & 0 & c\beta \end{bmatrix} \begin{bmatrix} \alpha \\
\beta \\
s\beta \alpha \end{bmatrix} = \begin{bmatrix} c\beta \alpha \\
\beta \\
s\beta \alpha \end{bmatrix} \\
(\omega_{H-C}^H)_{x} \Delta &= \begin{bmatrix} 0 & -s\beta \alpha & \beta \\
\beta & 0 & -c\beta \alpha \\
\beta & c\beta \alpha & 0 \end{bmatrix}
\end{align*}
\]

Combining the above

\[
\begin{bmatrix} 0 \\
0 \\
-\ell \end{bmatrix} = \begin{bmatrix} d_1 \\
d_2 \\
d_3 \end{bmatrix} + \begin{bmatrix} \beta \\
-2c\beta \alpha \end{bmatrix} \ell
\]

Solving for \( \dot{\alpha} \) and \( \dot{\beta} \)

\[
\begin{align*}
\dot{\beta} &= -\frac{d_1}{\ell} \\
\dot{\alpha} &= \frac{d_2}{\ell + c\beta}
\end{align*}
\]

range rate \( \dot{\ell} \) = \(-d_3\)
3.3.7 Calibration Model (CLERTN)

The calibration model is a "best fit" of the error between the open loop generated gimbal angles and those gimble angle profiles which exist when the antenna is tracking via the monopulse RF link. The term "best fit" will be used in the sense of least square. The procedure for obtaining the best fit is described in the sequel.

When the antenna is tracking via the RF monopulse link the actual gimbal angles will be used as a reference. If the computer generated gimble angle commands were exactly correct there would be no difference between the generated command and the actual gimbal angles of the autotrack mode. However, due to misalignments, thermal distortions of the beam and other error sources, the computer generated commands will not be exactly correct. Hence, while in the autotrack mode the actual gimbal angles can be compared with the commanded to produce error data. This data can then be fitted to some selected model. See Figure 5.0-1.

![Figure 5.0-1 Comparison of Actual and Commanded Gimbal Angles During Autotrack Mode](image)

The model which will be used in the simulation to represent the gimbal angle error is

\[
\begin{align*}
\epsilon_\alpha &= A_\alpha + B_\alpha \sin \omega_o (t-t_o) + C_\alpha \cos \omega_o (t-t_o) \\
\epsilon_\beta &= A_\beta + B_\beta \sin \omega_o (t-t_o) + C_\beta \cos \omega_o (t-t_o)
\end{align*}
\]

where \( \omega_o \) is the average orbit rate \( \left( \frac{2\pi}{T} \right) \).
However, in order to illustrate the fitting procedure the following simple model will be used

\[ \epsilon_\alpha = A_\alpha + B_\alpha \sin \omega_o(t-t_o) \]

\[ \epsilon_\beta = A_\beta + B_\beta \sin \omega_o(t-t_o) \]

Defining \( \mathbf{x} = \begin{bmatrix} A_\alpha \\ B_\alpha \end{bmatrix} \) (treating the axes independently)

\[ \mathbf{y} = \begin{bmatrix} \epsilon_\alpha(t_1) \\ \epsilon_\alpha(t_2) \\ \vdots \\ \epsilon_\alpha(t_n) \end{bmatrix} \]

\[ \mathbf{H} = \begin{bmatrix} 1 & \sin \omega_o(t_1-t_o) \\ 1 & \sin \omega_o(t_2-t_o) \\ \vdots \\ 1 & \sin \omega_o(t_n-t_o) \end{bmatrix} \]

The object is to find an \( \mathbf{x} = \hat{\mathbf{x}} \) such that

\[ \frac{1}{2} \langle \mathbf{y} - \mathbf{H} \hat{\mathbf{x}}, \mathbf{y} - \mathbf{H} \hat{\mathbf{x}} \rangle \overset{\Delta}{=} \frac{1}{2} \langle \mathbf{z}, \mathbf{z} \rangle \overset{\Delta}{=} J \]

is a minimum.

i.e. \[ \frac{\partial J}{\partial \hat{\mathbf{x}}} = \mathbf{z}^T \frac{\partial \mathbf{x}}{\partial \hat{\mathbf{x}}} = (\mathbf{y} - \mathbf{H} \hat{\mathbf{x}})^T (-\mathbf{H}) = 0^T \]
The above equation implies

$$H^T y = H^T H \hat{x}$$

Therefore if \([H^T H]\) has rank two \([H^T H]^{-1}\) exists and

$$\hat{x} = [H^T H]^{-1} H^T y$$

It is suggested that during the actual calibration that the data vector \(y\) be filled by taking points equally spaced around the orbit.

The simulation will contain the capability of adding in the error model specified previously, but it will be up to the user to generate the coefficients for the best fit. The simulation can be used to generate the data from which the fit can be made once all the important error sources have been added to the program. Bias and thermal errors will be the error sources which will be mainly compensated.

By doing this type of calibration it should be possible to reduce the overall pointing errors of the computer steering mode of operation. It will also reduce down times, i.e., if the monopulse momentarily loses track and the computer steering is immediately initiated, a reacquisition search mode requirement will be less likely.

### 3.4.1 Actual Dynamics, Kinematics, and Geometry Model

This section describes the mathematical model used by the simulation program for the environment in which the antenna system is to operate. Portions have been extracted from the Task 2 Report - Mathematical Model for the Pointing Requirements of the Space Station High Gain Antenna - dated 28 Oct. 1972, and the Task 3 Report - Math Modeling of Influence Factors - dated 22 May 1972.

The programming of this modeling is contained in subroutines KINMAT, ANTDYN, EPHEM1, EPHEM2, EPHEM3, SUN, and MOON which are called by SETUP to determine the actual line of sight and sun vector directions.
3.4.2.0 *Antenna Mounting Dynamics and Deflections (ANTDYN)*

The antenna dynamics model has its origins in some work performed by G. Margulies*. This model was modified for further work at LMSC. The model at that stage was present in Appendix D of the original proposal for the "Computer Simulation of Space Station Computer Steered High Gain Antenna". The model contained within this section is a modification of those equations to meet the purpose and assumptions of this study. The resulting model is described in Section 3.1 of the Task 3 Report.

In order to include the effects of the antenna boom flexibility (and space station flexibility in general), the dynamics equations could not be separated from the flexibility equations. Hence a great deal of effort was required to obtain the equations describing the overall rigid body and flexibility model. To accomplish this most efficiently, the aid of G. Margulies and his associate J. Ho (of the R and D division of LMSC) was enlisted. The work presented is a condensation of the work done by J. Ho in May of 1972. It is felt that this resulting model correctly models the configuration of the space station gimbaled antenna. However, there may be some difficulty in actually arriving at the required parameters associated with the flexibility model.

---

3.4.2.1 Notations and Definitions

Square brackets ([ ]) are used here to indicate matrices with the symbol or symbols inside labelling the whole matrix (one symbol) or the individual elements (appropriate number of symbols) or partitioned submatrices (appropriate number of symbols separated by dashed lines). Vectors and diadics (operators) are indicated by symbols with one or two (respectively) bars over them. When a vector or diadic symbol appears inside of a set of square brackets with a subscript P, or A this indicates the matrix of coordinates of the vector or diadic in the space station (P for platform) or antenna (A) reference frame.

The symbols used here are defined in the following lists.

**Antenna Characteristics**

- $\mathbf{I}_A \triangleq$ inertia diadic of antenna
- $m_A \triangleq$ mass of antenna
- $\mathbf{R}_2 \triangleq$ displacement vector, antenna center of mass to hinge point
- $\mathbf{e}_\beta \triangleq$ unit vector in direction of antenna fixed gimbal axis

**Space Station Characteristics**

- $m_P \triangleq$ space station mass
- $\mathbf{R}_1 \triangleq$ displacement vector, undeformed space station center of mass to hinge point
- $\mathbf{e}_\alpha \triangleq$ unit vector in direction of space station fixed gimbal axis
- $\omega_q \triangleq$ bending mode frequency for free vibration of non-spinning space station in mode described by $\varphi$ (below)
- $\varphi \triangleq$ bending deformation mode shape, a vector function of spatial coordinates which is analytic, has zero value and zero curl at the hinge point.
In the following definitions \( \int_{\mathcal{P}} f( \cdot ) \, dm \) indicates integration over the mass distribution of the space station, and \( \vec{r}_1 \) is the displacement vector from the hinge point to the element \( dm \).

\[
\begin{align*}
\mathbf{\Phi} &\triangleq \frac{1}{m_{\mathcal{P}}} \int_{\mathcal{P}} \vec{\phi} \, dm \\
\vec{Y} &\triangleq \frac{1}{m_{\mathcal{P}}} \int_{\mathcal{P}} (\vec{r}_1 \times \vec{\phi}) \, dm \\
\overset{\frown}{\mathbf{E}}_{\phi} &\triangleq \frac{1}{m_{\mathcal{P}}} \int_{\mathcal{P}} \left\{ \phi^2 \mathbf{E} - \vec{\phi} \vec{\phi} \right\} \, dm, \quad \mathbf{E} \text{ is unit diadic} \\
\overset{\frown}{\mathbf{N}}^* &\triangleq \frac{1}{m_{\mathcal{P}}} \int_{\mathcal{P}} (\vec{\phi} \cdot \vec{r}_1) \mathbf{E} - \vec{\phi} \vec{r}_1 \, dm \\
\vec{\nu}_c &\triangleq \text{bending mode slope } \frac{1}{2} \vec{\nabla} \times \vec{\phi} \text{ at control position}
\end{align*}
\]

**Variables**

\( \vec{\omega} \triangleq \text{angular velocity of space station at hinge point} \)

\( \vec{\omega}_c \triangleq \text{angular velocity of space station at control position} \)

\( \alpha \triangleq \text{gimbal angle about } \vec{e}_\alpha \)

\( \beta \triangleq \text{gimbal angle about } \vec{e}_\beta \)

\( q \triangleq \text{bending coordinate in terms of which the translational and angular displacements of the space station due to bending are given respectively by } q \vec{\phi} \text{ and } q \frac{1}{2} \vec{\nabla} \times \vec{\phi} \)
Forces

\[ T_\alpha \triangleq \text{torque about gimbal axis } \vec{e}_\alpha \]
\[ T_\beta \triangleq \text{torque about gimbal axis } \vec{e}_\beta \]

Derived Quantities

\[ [\mathcal{Q}]_P \triangleq \begin{bmatrix} [\vec{e}_\alpha]_P \mid [\vec{e}_\beta]_P \end{bmatrix} \]
\[ m_T \triangleq m_A + m_P \]
\[ m_B \triangleq \frac{m_A}{m_T} \]
\[ \vec{R}_{22} \triangleq m_B \left\{ (\vec{R}_2 \cdot \vec{R}_2) \vec{R} - \vec{R}_2 \vec{R}_2 \right\} \]
\[ \vec{L} \triangleq \vec{R}_A + \vec{R}_{22} \]
\[ \vec{\eta} \triangleq \alpha \vec{e}_\alpha + \beta \vec{e}_\beta \]
\[ \hat{\vec{s}} \triangleq \alpha \beta (\vec{e}_\alpha \times \vec{e}_\beta) + (\vec{w} \times \vec{\eta}) \]
\[ \vec{R}'_1 \triangleq \vec{R}_1 - q \vec{\Phi} \]
\[ \vec{b} \triangleq 2q \vec{\Phi} - \vec{w} \times \vec{R}'_1 \]
\[ \vec{Q}' \triangleq -(\vec{w} + \vec{\eta}) \times \vec{L} \cdot (\vec{w} + \vec{\eta}) - \vec{L} \cdot \vec{a} - m_B \vec{R}_2 \times (\vec{w} \times \vec{b}) \]
\[ \vec{R}'_{12} \triangleq m_B \left\{ (\vec{R}'_1 \cdot \vec{R}_2) \vec{R} - \vec{R}'_1 \vec{R}_2 \right\} \]
\[ \vec{N}' \triangleq \vec{L} - \vec{R}'_{12} \]
\[ [\mathcal{X}]_P \triangleq m_B [\vec{R}_2 \times \vec{\Phi}]_P \]
\[ M \triangleq m_\phi - m_P \vec{\Phi}^2/m_T \]
\[ [\psi]_P \triangleq m_B \left[ \vec{R} + \left( \frac{m_P}{m_T} \vec{R}_1 - \frac{m_A}{m_T} \vec{R}_2 \right) \times \vec{\Phi} \right]_P \]
\[ K \triangleq (m_\phi - m_P \vec{\Phi}^2) \omega^2 \]
\[ \mathcal{J} \triangleq -Kq + m_P \vec{w} \cdot (\vec{N}_p + q \vec{E}_o) \cdot \vec{w} \]
\[ + (m_P^2/m_T) \vec{\Phi} \cdot (\vec{w} \times \vec{b}) + m_B \vec{\Phi} \cdot \left\{ \vec{R}_1 \times \vec{a} - \vec{w} \times (\vec{w} \times \vec{R}_1) \right\} \]
3.4.2.2 Antenna Dynamics Equations

For the special case in which the space station dynamics are not considered and the space station rate \( \vec{\omega} \), and acceleration \( \ddot{\vec{\omega}} \) are treated as known inputs, the antenna dynamics equations may be expressed as

\[
\begin{bmatrix}
[G]^T \begin{bmatrix}
L & [G]
\end{bmatrix}
+ [G]^T \begin{bmatrix}
\alpha
\end{bmatrix}
\end{bmatrix}
\begin{bmatrix}
\dot{\alpha}
\dot{\vec{\omega}}
\end{bmatrix}
= 
\begin{bmatrix}
0
M
\end{bmatrix}
\begin{bmatrix}
\ddot{\alpha}
\ddot{\vec{\omega}}
\end{bmatrix}
\]

Eq. 3.0.1

where the subscript \( P \) has been dropped from \([G]_P\), \([L]_P\), \([\alpha]_P\), \([\vec{\omega}]_P\), \([N']_P\), \([\psi]_P\), and \([\ddot{\vec{\omega}}]_P\) both for clarity and to emphasize the fact that the equations are independent of the reference frame chosen for coordinatization.

Equation 3.0.1 was obtained from Ref. 2 by straightforward translation to the notation of Ref. 1 followed by specialization to the antenna dynamics only case considered here.

Since the space station is not rigid its angular velocity is not unique. The \( \vec{\omega} \) which appears in Equation 3.0.1 is the space station angular velocity at the hinge point which is not in general the controlled part of the space station for which the angular velocity \( \vec{\omega}_c \) and acceleration \( \ddot{\vec{\omega}}_c \) are known. These quantities are related by characteristics of the bending mode shape:

\[
\vec{\omega}_c = \vec{\omega} + \dot{q} \vec{\nu}_c
\]

Eq. 3.0.2

\[
\ddot{\vec{\omega}}_c = \ddot{\vec{\omega}} + \dot{q} \ddot{\vec{\nu}}_c
\]

Eq. 3.0.3
Since \( q \) is a state variable Eq. 3.0.2 may be used to compute \( \dot{\omega} \) from the input \( \dot{\omega}_c \). However \( q \) is not a state variable and is not available for the analogous computation of \( \dot{\omega} \), hence Eq. 3.0.3 is combined with Eq. 3.0.1 to obtain

\[
\begin{bmatrix}
\begin{bmatrix} g \end{bmatrix}^T \begin{bmatrix} \begin{bmatrix} \alpha \end{bmatrix} \end{bmatrix} & \begin{bmatrix} g \end{bmatrix}^T \left( \bar{X} - \begin{bmatrix} \begin{bmatrix} \alpha \end{bmatrix} \end{bmatrix} \end{bmatrix} \\
\begin{bmatrix} \psi \end{bmatrix}^T \begin{bmatrix} \alpha \end{bmatrix} & M - \begin{bmatrix} \psi \end{bmatrix}^T \begin{bmatrix} \nu \end{bmatrix}
\end{bmatrix}
\begin{bmatrix}
\ddot{\alpha} \\
\ddot{\beta} \\
\ddot{\nu}
\end{bmatrix}
= \begin{bmatrix}
\begin{bmatrix} g \end{bmatrix}^T \begin{bmatrix} \begin{bmatrix} \alpha \end{bmatrix} \end{bmatrix} + \begin{bmatrix} T_\alpha \\ T_\beta \end{bmatrix} - \begin{bmatrix} g \end{bmatrix}^T \begin{bmatrix} \nu \end{bmatrix} \begin{bmatrix} \dot{\omega}_c \end{bmatrix} \\
\begin{bmatrix} \psi \end{bmatrix}^T \begin{bmatrix} \dot{\omega}_c \end{bmatrix}
\end{bmatrix}
\end{array}
\]

Eq. 3.0.4

These equations are used in the simulation program to compute the derivatives \( \dot{\alpha}, \dot{\beta}, \) and \( \dot{\nu} \) of the state variables \( \alpha, \beta, \) and \( \nu \) respectively from the state variables and the driving quantities \( T_\alpha, T_\beta, \dot{\omega}_c, \) and \( \ddot{\omega}_c \) supplied by other elements in the program.
3.4.2.3 Bending Inputs for Sample Mode Shape

As an example of a flexible S/S model consider the simple case of a rigid main body with a flexible antenna mounting boom depicted below.

If the flexible boom is taken to be of negligible mass then the modal displacement $\phi$ is only important for the main body, where it may be expressed as

$$\phi (r) = -a^j - \alpha Z_j + \alpha Y_k \Rightarrow$$

$$[\phi]_P = \begin{bmatrix} 0 \\ -\alpha Z \\ \alpha Y \end{bmatrix}$$

The bending inputs for this mode shape are evaluated as follows:

$$m_\phi \Delta \int_P \phi^2 dm = \int_P \left\{ (a + \alpha Z)^2 + (\alpha Y)^2 \right\} dm = ...$$

$$= m_P a^2 + \alpha^2 \int_{xx}^P$$
\[ \Phi_P = \frac{1}{m_P} \int_P \Phi_P \, dm = \frac{1}{m_P} \int_P \begin{bmatrix} 0 \\ -a - \alpha Z \\ \alpha Y \end{bmatrix} \, dm = \begin{bmatrix} 0 \\ -a \\ 0 \end{bmatrix} \]

\[ \Phi_P = \frac{m_P}{m_P} \begin{bmatrix} 0 & 0 & 0 \\ 0 & a^2 m_P + \alpha^2 I_z^P & \alpha^2 I_y^2 \\ 0 & \alpha^2 I_y^P & \alpha^2 I_y \end{bmatrix} = \ldots \]

\[ \Phi_P = \frac{m_P}{m_P} \begin{bmatrix} \frac{1}{\alpha^2} m_P a^2 + I_z^p & 0 & 0 \\ 0 & I_y^p & -I_y^Z \\ 0 & -I_y^Z & \frac{1}{\alpha^2} m_P a^2 + I_z^p \end{bmatrix} \]

\[ \Phi_P = \frac{1}{m_P} \int \{ (\Phi \cdot \mathbf{r}_l) \} \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{\alpha^2} m_P a^2 + I_z^p + m_P \frac{a^q}{\alpha} \\ \frac{1}{\alpha^2} m_P a^2 + I_z^p + m_P \frac{a^q}{\alpha} \end{bmatrix} \]

\[ \Phi_P = \frac{1}{m_P} \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{\alpha^2} m_P a^2 + I_z^p & -I_y^Z & I_y^Z \\ \frac{1}{\alpha^2} m_P a^2 + I_z^p & I_y^Z & I_y^Z \end{bmatrix} \]
\[
[Y]_P = \frac{1}{m_P} \int_P \left[ \mathbf{r}_l \times \mathbf{\phi} \right]_P \, dm = \ldots
\]

\[
\begin{bmatrix}
I_{xx}^P + m_P \frac{\alpha_l}{\alpha} \\
I_{xy}^P \\
I_{xz}^P
\end{bmatrix}
\]

\[
[V]_P = \begin{bmatrix}
\alpha \\
0 \\
0
\end{bmatrix}
\text{for control system on main body.}
\]

The mass distribution parameters (inertias) used in the above results are defined as:

\[
I_{xx}^P = \int_P x^2 \, dm, \text{ similarly for } Y \text{ & } Z
\]
\[
I_{xy}^P = \int_P x y \, dm, \text{ similarly for } XZ \text{ & } YZ
\]
\[
I_{xx}^P = I_{yy}^P + I_{zz}^P, \text{ similarly for } YY \text{ & } ZZ
\]

3.4.3 **Actual Kinematics (KINMAT)**

The mathematical model for obtaining the space station attitude from the space station angular rate and the orbital rate is identical to that used by the on board kinematics computations (Section 3.3.2).
### Mathematical Discussion

The equations used by subroutine EFHEM1 to compute the satellite ephemeris information are derived in the LMSC document *The Motion of a Satellite About an Oblate Earth*, H. W. Small, Nov. 10, 1961, LMSC/A086756, and are more clearly presented in the LMSC document *The Motion of a Satellite About an Oblate Earth — A Guide to the use of the Solution*, P. Norov, Nov. 29, 1962, LMSC/A340246. The statement of these equations without the derivation is presented here.

The position vector \( \vec{R} \) and the inertial velocity vector \( \vec{V} \) coordinatized in the earth reference frame are obtained from the instantaneous orbit elements \( P, A, B, i, \Omega, u \) by the relations

\[
\begin{align*}
\vec{R} &= \frac{P}{1 + A \cos u + B \sin u} \hat{e}_R \\
\vec{V} &= \sqrt{\frac{\mu}{P}} \left[ (1 + A \cos u + B \sin u) \hat{e}_L + (A \sin u - B \cos u) \hat{e}_R \right]
\end{align*}
\]

where \( \mu = 1.407675 \times 10^{16} \text{ ft}^3/\text{sec}^2 \),

\[
\begin{align*}
\hat{e}_R &= \begin{bmatrix} \cos u \cos \Omega - \sin u \cos i \sin \Omega \\ \cos u \sin \Omega + \sin u \cos i \cos \Omega \\ \sin u \sin i \end{bmatrix}, \quad \text{and} \\
\hat{e}_L &= \begin{bmatrix} \cos u \cos \Omega - \cos u \cos i \sin \Omega \\ - \sin u \sin \Omega + \cos u \cos i \sin \Omega \\ \cos u \sin i \end{bmatrix}
\end{align*}
\]
The first five of these instantaneous orbit elements are obtained from the mean orbit elements $P_B$, $e_B$, $\omega_B$, $i_B$, $\Omega_B$ (which are constants) and $u$ by the relations

\[ P = P_B (1 + \bar{J}_2 \alpha_1 \sin^2 i_B) \]

\[ A = A_o + B_o G - \bar{J}_2 [(1 - e_B^2) \cos u (P_2 + \sin^2 i_B \cos^2 u) + \]

\[ P_2 \psi_o (A_o + (1 + \psi_o) \cos u) \]

\[ B = B_o - A_o G - \bar{J}_2 [(1 - e_B^2) \sin u (P_2 - \sin^2 i_B \sin^2 u) + \]

\[ P_2 \psi_o (B_o + (1 + \psi_o) \sin u) \]

\[ i = i_B + \frac{1}{2} \bar{J}_2 \alpha_1 \sin i_B \cos i_B \]

\[ \Omega = \Omega_B - (\frac{3}{2} \bar{J}_2 \cos i_B) u + \bar{J}_2 \alpha_2 \cos i_B \]

where

\[ \bar{J}_2 = J_2 \left( \frac{R_E}{P} \right)^2 = 0.0010827 \left( \frac{20925741}{P} \right)^2 \]

\[ \alpha_1 = \frac{3}{2} (\cos^2 u - \sin^2 u) + 2 (A_o \cos^3 u - B_o \sin^3 u) \]

\[ \alpha_2 = \frac{3}{2} \sin u \cos u + 3 B_o \cos u - A_o \sin^3 u - B_o \cos^3 u \]

\[ A_o = e_B \cos [\omega_B + \frac{3}{2} \bar{J}_2 (2 - \frac{5}{2} \sin^2 i_B) u] \]

\[ B_o = e_B \sin [\omega_B + \frac{3}{2} \bar{J}_2 (2 - \frac{5}{2} \sin^2 i_B) u] \]

\[ G = \bar{J}_2 \alpha_2 (1 - \frac{5}{2} \sin^2 i_B) - \frac{3}{2} \bar{J}_2 (A_o \sin u - B_o \cos u) \]

\[ P_2 = \frac{3}{2} \sin^2 i_B \sin^2 u - \frac{1}{2} \]

\[ \psi_o = 1 + A_o \cos u + B_o \sin u \]

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while $u$ is obtained by numerically integrating the equation

$$u = \sqrt{\frac{\mu}{p^3}} \left( 1 + A \cos u + B \sin u \right)^2 \left[ 1 + 3 \frac{J_2}{p^2} \cos^2 i \sin^2 u \right] \left( 1 + A \cos u + B \sin u \right)$$

The transformation $T_{0/0}$ from the earth reference frame to the orbit reference frame and the inertial angular velocity of the orbit reference frame $\omega_{0-0}$ are obtained from a 3-1-3 euler angle transformation with angles $\Omega, i, u_m$ and rates $\dot{\Omega}, \dot{i}, \dot{u}$ where

$$\Omega = \Omega - \omega_E t, \quad \omega_E = \text{angular velocity of earth} = 72921321 \times 10^{-4} \text{ sec}^{-1}$$

$$i = i \text{ defined above}$$

$$u_m = u \text{ modulo } 2\pi$$

$$\dot{\Omega} = \left[ -3 J_2 \left( \frac{a}{p} \right)^4 \sqrt{\frac{\mu}{p^3}} \left( 1 + A \cos u + B \sin u \right)^3 \cos i \right] \sin^2 u$$

$$\dot{i} = \left[ 3 J_2 \left( \frac{a}{p} \right)^4 \sqrt{\frac{\mu}{p^3}} \left( 1 + A \cos u + B \sin u \right)^3 \cos i \right] \cos u \sin i$$

$$\dot{u} = u \text{ defined above}$$

followed by the interchange of axes given by the transformation

$$T_x = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & -1 \\
-1 & 0 & 0
\end{bmatrix}$$
3.4.5  Sun Ephemeris

Mathematical Discussion

In the initialization section, Subroutine SUN first converts the input date (e.g., 062767 for June 27, 1967) to Modified Julian Date (MJD), which is defined as

\[
\text{Modified Julian Date} = \text{Julian Day Number} - 2,400,000.5,
\]

where the Julian Day Number is the number of days which have elapsed from Greenwich mean noon on January 1, 4713 B.C. (Julian proleptic calendar), to Greenwich mean noon on the calendar date in question. (Thus, at noon June 27, 1967, \( JD = 2,439,662 \), and \( MJD = 39,661.5 \).) The MJD is thus a measure of the JD in which the "24" is dropped and the day advances one unit at midnight rather than at noon.

The mean orbit elements of the sun at midnight (0 UT) beginning the input date (or the following day if the seconds part of the base time is greater than 86,400) are computed from formulas referred to an epoch date of January 1.0, 1900 (midnight beginning January 1, 1900, MJD 15020) rather than January 0.5, 1900 (noon on December 31, 1899) as in Ref. 1, the Explanatory Supplement to the American Ephemeris and Nautical Almanac. The distinction between Greenwich Mean Time (or UT, Universal Time) and ephemeris time ET is ignored for these purposes. Let \( d \) be the number of ephemeris days which have elapsed from the epoch date to the base midnight date:

\[
d = MJD - 15,020. \quad \text{(NDAY (3))}
\]

also, let \( T \) be this time period measured in Julian centuries of 36525 ephemeris days:

\[
T = \frac{d}{36525} \quad \text{(TCNTRY)}
\]
Figure 6.1 The Inertial Coordinate System and Solar Angular Orbit Elements
Then the mean elements of the sun with respect to an inertial coordinate frame (Fig. 1) referred to the mean equator and equinox of the base midnight date are given by the following expressions (cf. Ref. 1, p. 98):

Mean anomaly $M_\theta$, measured from mean perigee of the sun's orbit, along the ecliptic to the mean sun:

$$M_\theta, B = \frac{358.96863013}{d} + \left(1^\circ - \frac{014399733}{d}\right) d$$

- $0.0015 T^2 - 0.000003 T^3$ (CM)

Mean eccentricity $e_\theta$:

$$e_\theta, B = 0.0167510394 - 0.00004180 T - 0.000000126 T^2$$ (ECC)

Mean obliquity of the ecliptic $\epsilon$:

$$\epsilon, B = 23^\circ 45229382 - 0130125 T - 0.00000164 T^2$$

+ $0.00000503 T^3$. (OBL)

Geometric mean longitude $L_\theta$, measured from the mean equinox of the base midnight date, along the ecliptic to the mean sun:

$$L_\theta, B = 280^\circ 18950367 + \left(1^\circ - \frac{0143526666}{d}\right) d$$

+ $0.00303 T^2$. (CL)

All of the angles are taken modulo 360° and converted to radians.

In addition to the base solar elements, the Greenwich mean sidereal time (GMST), also referred to as the right ascension of Greenwich $\alpha_U$ or (imprecisely) the Greenwich hour angle GHA is computed at the base midnight date:

$$\alpha_U, B = 100^\circ 18118494 + \left(1^\circ - \frac{0143526666}{d}\right) d.$$ (COMG)

$\alpha_U, B$ is also taken modulo 360° and converted to radians.
On subsequent calls, Subroutine SUN computes the inertial and earth-referenced direction cosines of the true sun at any time $T$ (in seconds) after the input base time of the run, or $\text{TIME} = \text{TIMERF} + T$ seconds after the base midnight date: starting from the mean angular elements at this time,

$$M_\theta = M_{\theta, B} + 1.9909687222 \times 10^{-7} \cdot \text{TIME} \quad \text{rad.} \quad \text{(AM)}$$

$$L_\theta = L_{\theta, B} + 1.991063804 \times 10^{-7} \cdot \text{TIME} \quad \text{rad.} \quad \text{(AL)}$$

the true longitude of the sun $\Lambda_\theta$ is found by computing the equation of the center $\xi_\theta$ from a series expansion in the mean anomaly (Ref. 2, p. 77):

$$\Lambda_\theta = L_\theta + \xi_\theta, \quad \text{rad.} \quad \text{(ARGS)}$$

where

$$\xi_\theta = (2e - \frac{1}{4} e^3) \sin M + (\frac{5}{4} e^2 - \frac{11}{24} e^4) \sin 2M$$

$$+ \frac{13}{12} e^3 \sin 3M + \frac{103}{96} e^4 \sin 4M \quad \text{(DARG)}$$

$$= \left[ (\frac{5}{2} + \frac{27}{8} e^2 \cos^2 M - \frac{125}{24} e^2 \sin^2 M) e \cos M \right.$$  

$$+ (2 + 3e^2 \cos^2 M - \frac{1}{3} e^2 \sin^2 M) \] \sin M,$$

and $e$ is written for $e_{\theta, B}$.

The error in truncating this series expansion at the $e^4$ term is of order $e^5$, or $1 \times 10^{-9}$ radians. The inertial direction cosines of the true sun are then

$$\begin{bmatrix}
\ell_{\theta, I} \\
m_{\theta, I} \\
n_{\theta, I}
\end{bmatrix} =
\begin{bmatrix}
\cos \Lambda_\theta \\
\sin \Lambda_\theta \cos \xi_B \\
\cos \Lambda_\theta \sin \xi_B
\end{bmatrix} \quad \text{(SI)}$$

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To find the direction cosines in the earth-fixed coordinate system, the earth-to-inertial transformation matrix $T_{EI}$ is used: At TIME seconds after the base midnight date, the GMST is

$$\alpha_{G} = \alpha_{G,B} + \Omega_{EI} \cdot \text{TIME} \quad \text{rad.},$$

where $\Omega_{EI}$ is the inertial rotation rate of the earth,

$$\Omega_{EI} = 7.292115147 \times 10^{-5} \text{ rad/sec.}$$

Neglecting precession and nutation effects, $T_{EI}$ may be written

$$T_{EI} = \begin{bmatrix} \cos \alpha_{G} & -\sin \alpha_{G} & 0 \\ \sin \alpha_{G} & \cos \alpha_{G} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

so that the earth-referenced direction cosines of the true sun are

$$\begin{bmatrix} \ell_{\theta,E} \\ m_{\theta,E} \\ n_{\theta,E} \end{bmatrix} = T_{EI} \begin{bmatrix} \ell_{\theta,I} \\ m_{\theta,I} \\ n_{\theta,I} \end{bmatrix}.$$  \hspace{1cm} (SE)

The magnitude of the radius vector from the earth to the sun is then calculated. In astronomical units, it is given by

$$R_{\theta} = \frac{(1 - e^{2})}{1 + e \cos (M_{\theta} + \Omega_{\theta})}.$$  \hspace{1cm} (PAU)

Subroutine SUN also determines whether the satellite is in sunlight or not. The conditions which must be satisfied for the satellite to lie in the (cylindrical) shadow of the earth are (Fig. 2)
Figure 6.2 Geometry for Satellite in Earth's Shadow

Figure 6.3 Orbit Beta Angle
\[
\cos \psi < 0
\]
\[
R \sin \psi < R_{EQ} ,
\]
where \( R_{EQ} \) is the earth's equatorial radius, \( R \) is the satellite radial distance, and \( \psi \) is the geocentric angle between the sun and the satellite. If \( \hat{u}_\psi \) is the earth-frame unit vector in the solar direction, then the above conditions can be written in the vector form
\[
\hat{R} \cdot \hat{u}_\psi < 0
\]
\[
|\hat{R} \times \hat{u}_\psi| < R_{EQ} .
\]
The integer NIGHT is set to 1 if the satellite is in shadow and 0 if it is in sunlight.

Finally, SUN calculates the "orbit beta angle" \( \beta \) (Fig. 3), which is the angle between the solar direction unit vector \( \hat{u}_\psi \) and its projection on the satellite orbital plane. If \( \zeta \) is the angle between \( \hat{u}_\psi \) and a vector normal to the orbit plane,
\[
\sin \zeta = |\hat{u}_\psi \times \hat{v}_{RXV}| ,
\]
then
\[
\beta = 90^\circ - \zeta .
\]
REFERENCES (For Section 3.4.5)


3.4.6 Moon Ephemeris

Mathematical Discussion

In the Initialization Section, Subroutine MOON computes the mean orbit
elements of the moon at the base midnight date (see SUN Mathematics Section).
If T is the time elapsed from an epoch date of January 0.5, 1900 (noon on
December 31, 1899),

\[ T = \frac{MJD - 15.019.5}{365.25} \]

then the mean elements with respect to the inertial coordinate system
described earlier (Fig. 1 of Subroutine SUN section) are given by the follow-
ing expressions (Ref.: Explanatory Supplement to the American Ephemeris and
Nautical Almanac):

Mean anomaly \( M_\mathcal{A} \), measured from the mean lunar perigee along the orbit to
the mean moon:

\[ M_\mathcal{A},B = 296.104608 + 477.198.849108 \ T 
+ .009190 \ T^2 + .0000032 \ T^3 \]  (AM1)

Longitude of the mean ascending node \( \Omega_\mathcal{A} \), measured from the mean equinox
of date along the ecliptic:

\[ \Omega_\mathcal{A},B = 259.185375 - 1934.11201 \ T 
+ .002077 \ T^2 + .000002 \ T^3 \]  (ΩM1)

Mean argument of perigee \( \omega_\mathcal{A} \), measured from the mean ascending node along the
lunar orbit:

\[ \omega_\mathcal{A},B = 75.116281 + 6003.176041 \ T 
- .012102 \ T^2 - .000015 \ T^3 \]  (WM1)
These angles are all taken modulo 360° and converted to radians. In addition, the following mean elements are considered as constants:

Mean eccentricity $e_\mathcal{M}$:

$$e_{\mathcal{M},B} = .054900489$$

Mean inclination $i_\mathcal{M}$:

$$\sin i_{\mathcal{M},B} = .089683448$$
$$\cos i_{\mathcal{M},B} = .99597032$$

Mean semi-latus rectum, $p_\mathcal{M} = a_\mathcal{M} (1 - e^2)$:

$$p_{\mathcal{M},B} = 1.257355 \times 10^9 \text{ ft.}$$

On subsequent calls, Subroutine MOON computes the distance and inertial coordinate frame components of the true moon at any time $T$ (in seconds) after the input base time of the run, or $\text{TIME} = \text{TIMERF} + T$ seconds after the base midnight date: starting from the mean angular elements at this time,

$$M_\mathcal{M} = M_{\mathcal{M},B} + .228027135 \cdot T \text{ rad.}$$ (AM)

$$\Omega_\mathcal{M} = \Omega_{\mathcal{M},B} - .000921422029 \cdot T \text{ rad.}$$ (ΩM)

$$\omega_\mathcal{M} = \omega_{\mathcal{M},B} + .0028685683 \cdot T \text{ rad.}$$

where

$$T = \frac{\text{TIME}}{86,400},$$ (TIME)

The true anomaly of the moon $\theta_\mathcal{M}$ is found by computing the equation of the center $\dot{\theta}_\mathcal{M}$ from a series expansion in the mean anomaly (see SUN Mathematics Section):

$$\theta_\mathcal{M} = M_\mathcal{M} + \ddot{\theta}_\mathcal{M}, \quad \text{rad}$$ (THM)
where
\[ \dot{\alpha} = 2e_{\alpha, B} \sin M_{\alpha} + \frac{5}{4} e_{\alpha, B}^2 \sin 2 M_{\alpha}. \]

The error in truncating this series expansion at the \( e^2 \) term is of order \( e^3 \), or .0002 radians.

The magnitude of the geocentric radius vector is then
\[ R_{\alpha} = \frac{P_{\alpha, B}}{1 + e_{\alpha, B} \cos \theta_{\alpha}}, \quad \text{(RMS)} \]

and its components in the inertial coordinate system are
\[
\begin{bmatrix}
  x_{\alpha, I} \\
y_{\alpha, I} \\
z_{\alpha, I}
\end{bmatrix}
= \begin{bmatrix}
  \cos \Omega_{\alpha} \cos u_{\alpha} - \cos i_{\alpha, B} \sin \Omega_{\alpha} \sin u_{\alpha} \\
- \sin \Omega_{\alpha} \cos u_{\alpha} - \cos i_{\alpha, B} \cos \Omega_{\alpha} \sin u_{\alpha} \cos \epsilon_{B} \\
- \sin i_{\alpha, B} \sin u_{\alpha} \sin \epsilon_{B} + \sin i_{\alpha, B} \sin u_{\alpha} \cos \epsilon_{B}
\end{bmatrix}
\]

where
\[ u_{\alpha} = \theta_{\alpha} + \omega_{\alpha}, \quad \text{(UM)} \]

and \( \epsilon_{B} \) is the mean obliquity of the ecliptic, calculated in Subroutine SUN.
This appendix describes the format and ordering of the data cards which are read by the program to enter the input data.

Data cards are placed in the deck immediately after the program execution card (V XQT LOOP for the complete simulation program or V XQT POINT for the pointing requirements program) and are arranged as follows:
If more than one case is to be run, one or more blocks of the following might be inserted between the blank card and the "3" card (at *).

( BLANK CARD )

PLUT CHANGES ( CANNOT DELETE PLOTS, ONLY MODIFY )

DATA TO CHANGE FROM CASE 1

TITLE CASE n

To change the "nominal" data, i.e. clear V-ARRAY and PREAD information before inputing the next set, place a "2" card, (a 2 in column one) before the desired title card.

CARD FORMATS

Title

Column 1 must be blank (see General Comments at end for extended feature)

Data for V-array

The data for the V-array is input in free field format:

\[
l_1 \ v_1 \ l_2 \ v_2 \ l_3 \ v_3 \ \cdots \ l_n \ v_n
\]

where \( l_i \) is a V-array position index and \( v_i \) is the data value associated with \( V(l_i) \). Blank(s) (at least one) must separate the \( l_i \) and \( v_i \), and \( l_i \) need not start in column one.

The \( l_i \) are in integer format with \textit{no} included blank(s) allowed since blank(s) are separators.
The $v_i$ may use any of the following formats:
- Integer - no decimal point in number
- Fixed point - value has a decimal point
- Exponential - number followed by the exponent as in floating point number.

All the following are valid and equivalent.

42.5, 4.25E+1, 4.25E1, 425E-1

Example:

```
|   42.1 | 16.1 |
```

*** DATA MUST BE PAIRED, i.e., EVERY $l_i$ MUST HAVE A $v_i$ ***

PLOT DATA

Plots from the DEADAM package are available in four forms (see Appendix A).

The first three are closely related since their formats are derived from the same array (FREAD). For discussion, they will be referred to as **Full frame**, **1/3 frame**, both produced on the FR-80, and **printer plots** plotted on the high speed printer.
These three plot forms are specified in the following manner.

Full and 1/3 frame -

\[
P_{p_1 d_1 p_2 d_2 \ldots p_1 d_1} \; ; i - 1, 10
\]

\(p_1\) is the plot number

\(d_i\) is the channel information for plotting on plot \(p_i\)

\(d_i\) may be any one of the following

- OXY or Y will plot output channel Y vs time
- XOO will plot time vs output channel X
- XY will plot X vs Y

X and Y must be 2 digits (i.e., 21, 02, etc.)

To designate that the first group of plots requested are to be 1/3 frame (three plots per frame) use

\[
P \; 1000 \; n
\]

where \(n\) is the number of plots to be plotted three to a frame. All plots numbered greater than \(n\) will be full frame. If \(n\) is not an integral multiple of 3, there will be blank 1/3 frame plots on the \((\lceil \frac{n}{3} \rceil + 1)\)th frame.

Printer plots are rough plots received as part of DEADAM printed output. To get printer plots in addition to FR80 plots, use the following data card:

\[
L \; n_1 \; n_2 \; n_3 \; \ldots \; n_i
\]

where \(n_i\) is a plot number specified on a "P" card that is to be print-plotted; the \(n_i\) need not be sequential.
Plot Scale Card

These cards are again associated with the plots specified on a "P" card and will therefore affect both FR80 and printer plots. They allow scaling to specified limits for these plots.

Format

\[ S \ n \ 0 \ l_1 \ v_1 \ldots \ l_i \ v_i \]

Where

- **S** specifies Plot scale card
- **n** number of plot to be scaled (corresponds to a "P" card specification)
- **0** dummy (not used)
- **l_i** limit being set (must be grouped: if X min set, X max must be set) according to following table.

<table>
<thead>
<tr>
<th>Limit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>X</td>
</tr>
<tr>
<td>max</td>
<td>Y</td>
</tr>
</tbody>
</table>

Data generated outside of specified limits will not be plotted.

\[ v_i \]

limit value. Pairs \((l_i, v_i)\) have the same format as \((V\text{-array position, data value})\) pairs.

Multiplot card

Multiplot allows the plotting of up to 10 channels vs the same abscissa; the plot is full frame. The multiplot card has the form

\[ M \ n \ k \ l_1 \ l_2 \ldots \ l_k \ l_{k+1} \]
where $M$ specifies multiplot card

$n$ multiplot #

$k$ number of ordinate channels

$l_i$ channels to be plotted on ordinate, $l = 1, \ldots, k$

$l_k + 1$ channel to be used as abscissa

(If $l_k + 1$ is 0 or blank, $l_k + 1$ is assumed to be time.)

Scaling is automatically set.

General Comments:

A (@) punch on a Data or Plot cards will cause the program to ignore those columns following the (@) punch on that card. At least one set of data information must have been set before the (@) punch.

Title card extension: If there is an "*" in column 80, that card will be listed immediately; and the program will read the next card to get the heading information. This will continue until the last Title card read has no "*" in column 80. This allows the user to append some comments before his V-ARRAY list out.

Entries in the V-ARRAY (entered via the above described data cards) are interpreted by the individual subroutines of the program according to the following input lists. The absolute location of an input variable is its V-ARRAY index. Relative locations are also given since the starting index for the input data of each routine (except ADAMS and ANTIN) may be changed (see input list for subroutine SETUP).
### Input List For Subroutine SETUP/LOOP and SETUP/POINT

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Relative Location</th>
<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
</tr>
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<td>ground station longitude</td>
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<td>N.M.</td>
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* — SETUP/LOOP only

** — SETUP/POINT only

---

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<th>Variable</th>
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<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<td>discontinuities at TDISC(I)</td>
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<tr>
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<td>INPADM + 6</td>
<td>406</td>
<td>- 1 to suppress output at disc.</td>
<td>-</td>
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<tr>
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<td>INPADM + 7</td>
<td>407</td>
<td>&gt; 0 to suppress output at disc. except for V(406) &lt; T &lt; V(407)</td>
<td>sec.</td>
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<tr>
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<td>output interval</td>
<td>sec.</td>
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<td>sec.</td>
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<td>EPC(_0)N</td>
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* values set internally if input is 0
### Input List For Subroutine ADAMS (internal integration routine) Continued

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<td>Description</td>
<td>Units</td>
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### Input List For Subroutine ANTIN

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<tr>
<th>Variable Name</th>
<th>Relative Location</th>
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<th>Description</th>
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<th>Nominal Value</th>
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<td>110</td>
<td>flag: if 0 ANTIN not called</td>
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<tr>
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<td>deg</td>
<td>70</td>
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<tr>
<td>CSN</td>
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<td>112</td>
<td>feed option parameter</td>
<td>-</td>
<td>2.5</td>
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<tr>
<td>DBK</td>
<td>IDXV + 3</td>
<td>113</td>
<td>dia. of aperture blockage</td>
<td>in</td>
<td>0</td>
</tr>
<tr>
<td>DIA</td>
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<td>114</td>
<td>reflector diameter</td>
<td>in</td>
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<td>aperture efficiency</td>
<td>%</td>
<td>55</td>
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<td>FTV</td>
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<td>peak gain of feed</td>
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<td>operating frequency</td>
<td>G Hz</td>
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<td>123</td>
<td>integration step(pts/wavelength)</td>
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<td>SIM</td>
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<td>124</td>
<td>flag: 0 for antenna study only</td>
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<td>POL</td>
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<td>polarization flag: 1 for linear dipole, 2 for linear slot mode, 3 for right hand circular, and 4 for left hand circular</td>
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A-11
### Input List For Subroutine ANTIN Continued

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<tr>
<th>Variable Name</th>
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<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<td>PHC</td>
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<td>131</td>
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<td>deg</td>
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<tr>
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<td>deg</td>
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<td>deg</td>
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For SIM = 0

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### Input List For Subroutine MØNHLS

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<tbody>
<tr>
<td>MØN</td>
<td>INDEXV</td>
<td>201</td>
<td>option index: 0 → no monopulse error signals, 1 → four horn system, 5 → five horn system</td>
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<td>4</td>
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<td>GDB</td>
<td>INDEXV + 1</td>
<td>202</td>
<td>peak antenna gain</td>
<td>db</td>
<td>0 *</td>
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<td>P</td>
<td>INDEXV + 2</td>
<td>203</td>
<td>beam shape parameters</td>
<td>db/deg²</td>
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<td>T</td>
<td>INDEXV + 3</td>
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<td>horn</td>
<td>db/deg²</td>
<td>3.0 *</td>
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<td>INDEXV + 4</td>
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*indicates values that may be computed by ANTIN*
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<td>E1</td>
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<td>IDXV + 20</td>
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<tr>
<td>CDPHI</td>
<td>IDXV + 21</td>
<td>271</td>
<td>constant (indep. of sun)</td>
<td>deg</td>
<td>0*</td>
</tr>
<tr>
<td>CDTHA</td>
<td>IDXV + 22</td>
<td>272</td>
<td>vector) beam shift angles</td>
<td>deg</td>
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*indicates values that may be computed by ANTIN
## Input List For Subroutine SSRATE

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<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<tr>
<td>K0PT</td>
<td>IDXV</td>
<td>330</td>
<td>option index</td>
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<td>0</td>
</tr>
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</table>

For K0PT = 0 S/S rate is set equal to orbit rate, no inputs

For K0PT = 1

| GMP1(1)       | IDXV + 1          | 331                | S/S X-axis rate (constant) deg/sec |       |               |
| GMP1(2)       | IDXV + 2          | 332                | S/S Y-axis rate (constant) deg/sec |       |               |
| GMP1(3)       | IDXV + 3          | 333                | S/S Z-axis rate (constant) deg/sec |       |               |

For K0PT = 2

| PMP1(1)       | IDXV + 1          | 331                | S/S X-axis accel. (constant) deg/sec^2 |       |               |
| PMP1(2)       | IDXV + 2          | 332                | S/S Y-axis accel. (constant) deg/sec^2 |       |               |
| PMP1(3)       | IDXV + 3          | 333                | S/S Z-axis accel. (constant) deg/sec^2 |       |               |
| R1            | IDXV + 4          | 334                | S/S X-axis rate (initial) deg/sec^2 |       |               |
| R2            | IDXV + 5          | 335                | S/S Y-axis rate (initial) deg/sec^2 |       |               |
| R3            | IDXV + 6          | 336                | S/S Z-axis rate (initial) deg/sec^2 |       |               |
## Input List For Subroutine KINMAT

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Relative Location</th>
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<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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</thead>
<tbody>
<tr>
<td>IRΩT</td>
<td>INDEXV</td>
<td>300</td>
<td>input rotation sequence</td>
<td>-</td>
<td>321</td>
</tr>
<tr>
<td>PHI(1)</td>
<td>INDEXV + 1</td>
<td>301</td>
<td>S/S X-axis rotation angle</td>
<td>deg</td>
<td>- 10</td>
</tr>
<tr>
<td>PHI(2)</td>
<td>INDEXV + 2</td>
<td>302</td>
<td>S/S Y-axis rotation angle</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>PHI(3)</td>
<td>INDEXV + 3</td>
<td>303</td>
<td>S/S Z-axis rotation angle</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>NØPRØT</td>
<td>INDEXV + 19</td>
<td>319</td>
<td># of optional output sequences</td>
<td>-</td>
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<tr>
<td>RCHNG</td>
<td>INDEXV + 20</td>
<td>320</td>
<td>optional output rotation sequence</td>
<td>-</td>
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</tr>
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<td>INDEXV + 21</td>
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Input List For Subroutine EHEM 3

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<th>Nominal Value</th>
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<tr>
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<td>input option index</td>
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<td>3</td>
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<tr>
<td>OMEGA0</td>
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<td>51</td>
<td>average orbit rate</td>
<td>rad/sec</td>
<td>-</td>
</tr>
<tr>
<td>EB</td>
<td>INDEXV + 2</td>
<td>52</td>
<td>orbit eccentricity</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CLINB</td>
<td>INDEXV + 3</td>
<td>53</td>
<td>orbit inclination</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>WB</td>
<td>INDEXV + 4</td>
<td>54</td>
<td>perigee argument</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>AMU</td>
<td>INDEXV + 5</td>
<td>55</td>
<td>initial true anomaly</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>CAIWB</td>
<td>INDEXV + 6</td>
<td>56</td>
<td>ascending node longitude</td>
<td>deg</td>
<td>-</td>
</tr>
</tbody>
</table>

For K0PT = 1

| PERIOD        | INDEXV + 1        | 51                | nodal period | sec    | -             |
| PRAD          | INDEXV + 2        | 52                | perigee radius | nm     | -             |
| CLINB         | INDEXV + 3        | 53                | orbit inclination | deg   | -             |
| WB            | INDEXV + 4        | 54                | perigee argument | deg   | -             |
| U             | INDEXV + 5        | 55                | initial satellite argument | deg | -             |
| CAIWB         | INDEXV + 6        | 56                | ascending node longitude | deg   | -             |

For K0PT = 2

<p>| R0MNAK        | INDEXV + 1        | 51                | orbit semi-major axis | nm | 381.3.1 |
| EB            | INDEXV + 2        | 52                | orbit eccentricity | -     | 0.         |
| CLINB         | INDEXV + 3        | 53                | orbit inclination | deg    | 90.          |
| WB            | INDEXV + 4        | 54                | perigee argument | deg    | 90.          |
| AMU           | INDEXV + 5        | 55                | initial true anomaly | deg   | - 90.        |
| CAIWB         | INDEXV + 6        | 56                | ascending node longitude | deg   | 90.          |</p>
<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Relative Location</th>
<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<td>input option index</td>
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<td>3</td>
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<tr>
<td>OMEGAø</td>
<td>INDEXV + 1</td>
<td>61</td>
<td>average orbit rate</td>
<td>rad/sec</td>
<td></td>
</tr>
<tr>
<td>EB</td>
<td>INDEXV + 2</td>
<td>62</td>
<td>orbit eccentricity</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CLINB</td>
<td>INDEXV + 3</td>
<td>63</td>
<td>orbit inclination</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>WB</td>
<td>INDEXV + 4</td>
<td>64</td>
<td>perigee argument</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>AMU</td>
<td>INDEXV + 5</td>
<td>65</td>
<td>initial true anomaly</td>
<td>deg</td>
<td></td>
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<td>CAFWB</td>
<td>INDEXV + 6</td>
<td>66</td>
<td>ascending node longitude</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>PERIOD</td>
<td>INDEXV + 1</td>
<td>61</td>
<td>nodal period</td>
<td>sec</td>
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<tr>
<td>PRAD</td>
<td>INDEXV + 2</td>
<td>62</td>
<td>perigee radius</td>
<td>nm</td>
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<tr>
<td>CLINB</td>
<td>INDEXV + 3</td>
<td>63</td>
<td>orbit inclination</td>
<td>deg</td>
<td></td>
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<td>WB</td>
<td>INDEXV + 4</td>
<td>64</td>
<td>perigee argument</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>INDEXV + 5</td>
<td>65</td>
<td>initial satellite argument</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>CAFWB</td>
<td>INDEXV + 6</td>
<td>66</td>
<td>ascending node longitude</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>RÔÔNÅK</td>
<td>INDEXV + 1</td>
<td>61</td>
<td>orbit semi-major axis</td>
<td>nm</td>
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</tr>
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<td>EB</td>
<td>INDEXV + 2</td>
<td>62</td>
<td>orbit eccentricity</td>
<td>-</td>
<td>0.00011</td>
</tr>
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<td>CLINB</td>
<td>INDEXV + 3</td>
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<td>orbit inclination</td>
<td>deg</td>
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<td>perigee argument</td>
<td>deg</td>
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<td>AMU</td>
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<td>initial true anomaly</td>
<td>deg</td>
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## Input List For Subroutine  EHEM 2

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**For K0FT = 1**

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<th>Description</th>
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<th>Nominal Value</th>
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</thead>
<tbody>
<tr>
<td>OMEGA0</td>
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<td>71</td>
<td>average orbit rate</td>
<td>rad/sec</td>
<td>-</td>
</tr>
<tr>
<td>EB</td>
<td>INDEXV + 2</td>
<td>72</td>
<td>orbit eccentricity</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CLINB</td>
<td>INDEXV + 3</td>
<td>73</td>
<td>orbit inclination</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>WB</td>
<td>INDEXV + 4</td>
<td>74</td>
<td>perigee argument</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>AMU</td>
<td>INDEXV + 5</td>
<td>75</td>
<td>initial true anomaly</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>CAPWB</td>
<td>INDEXV + 6</td>
<td>76</td>
<td>ascending node longitude</td>
<td>deg</td>
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**For K0FT = 2**

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<th>Description</th>
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<th>Nominal Value</th>
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<tbody>
<tr>
<td>PERIOD</td>
<td>INDEXV + 1</td>
<td>71</td>
<td>nodal period</td>
<td>sec</td>
<td>-</td>
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<tr>
<td>PRAD</td>
<td>INDEXV + 2</td>
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<td>perigee radius</td>
<td>nm</td>
<td>-</td>
</tr>
<tr>
<td>CLINB</td>
<td>INDEXV + 3</td>
<td>73</td>
<td>orbit inclination</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>WB</td>
<td>INDEXV + 4</td>
<td>74</td>
<td>perigee argument</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>U</td>
<td>INDEXV + 5</td>
<td>75</td>
<td>initial satellite argument</td>
<td>deg</td>
<td>-</td>
</tr>
<tr>
<td>CAPWB</td>
<td>INDEXV + 6</td>
<td>76</td>
<td>ascending node longitude</td>
<td>deg</td>
<td>-</td>
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**For K0FT = 3**

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<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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</thead>
<tbody>
<tr>
<td>R0INAK</td>
<td>INDEXV + 1</td>
<td>71</td>
<td>orbit semi-major axis</td>
<td>nm</td>
<td>22770.8</td>
</tr>
<tr>
<td>EB</td>
<td>INDEXV + 2</td>
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<td>orbit eccentricity</td>
<td>-</td>
<td>.00011</td>
</tr>
<tr>
<td>CLINB</td>
<td>INDEXV + 3</td>
<td>73</td>
<td>orbit inclination</td>
<td>deg</td>
<td>.01</td>
</tr>
<tr>
<td>WB</td>
<td>INDEXV + 4</td>
<td>74</td>
<td>perigee argument</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>AMU</td>
<td>INDEXV + 5</td>
<td>75</td>
<td>initial true anomaly</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>CAPWB</td>
<td>INDEXV + 6</td>
<td>76</td>
<td>ascending node longitude</td>
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### Input List For Subroutine SUN

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<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATE</td>
<td>INDEXV</td>
<td>80</td>
<td>date (month day year)</td>
<td>-</td>
<td>032172</td>
</tr>
<tr>
<td>TM0D</td>
<td>INDEXV + 1</td>
<td>81</td>
<td>initial time of day</td>
<td>sec</td>
<td>21600</td>
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</table>

(Greenwich)
<table>
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<th>Relative Location</th>
<th>Absolute Location</th>
<th>Units</th>
<th>Nominal Value</th>
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<tbody>
<tr>
<td>A</td>
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<td>ft</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>IDXV + 1</td>
<td>91</td>
<td>ft</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>IDXV + 2</td>
<td>92</td>
<td>ft</td>
<td>1</td>
</tr>
<tr>
<td>AP(1)</td>
<td>IDXV + 3</td>
<td>93</td>
<td>ft</td>
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<td>AP(2)</td>
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</tr>
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<td>IRΩT</td>
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<td>PHI(1)</td>
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<td>deg</td>
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<td>PHI(2)</td>
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<td>deg</td>
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</tr>
<tr>
<td>PHI(3)</td>
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</table>

Input List For Subroutine INTSSI
### Input List For Subroutine INTSS2

<table>
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<th>Variable Name</th>
<th>Relative Location</th>
<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>IDXV</td>
<td>100</td>
<td>X-semi axis of ellipsoid</td>
<td>ft</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>IDXV + 1</td>
<td>101</td>
<td>Y-semi axis of ellipsoid</td>
<td>ft</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>IDXV + 2</td>
<td>102</td>
<td>Z-semi axis of ellipsoid</td>
<td>ft</td>
<td>1</td>
</tr>
<tr>
<td>AP(1)</td>
<td>IDXV + 3</td>
<td>103</td>
<td>S/S frame position coordinates of antenna gimbal point</td>
<td>ft</td>
<td>0</td>
</tr>
<tr>
<td>AP(2)</td>
<td>IDXV + 4</td>
<td>104</td>
<td></td>
<td>ft</td>
<td>0</td>
</tr>
<tr>
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### Input List For Subroutine ANTDYN

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For FREQ < 0 no S/S flexibility is accounted for and no further inputs are required
## Input List For Subroutine ANTDYN

### Continued

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<tr>
<th>Variable Name</th>
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<td>Description</td>
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### Input List For Subroutine CNTRL7

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<td>141</td>
<td>attitude gain, pointing mode</td>
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<tr>
<td>K2A</td>
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<td>142</td>
<td>rate gain, pointing mode (deg/sec)⁻¹</td>
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<tr>
<td>K3A</td>
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<td>attitude gain, tracking mode</td>
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<td>rate gain, tracking mode (deg/sec)⁻¹</td>
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<td>bias</td>
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<td>attitude gain, tracking mode</td>
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<td>RESOLR</td>
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<tr>
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<td>sec</td>
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<td>RØ</td>
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<td>deg</td>
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<td>tangential scan rate</td>
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<td>DS</td>
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<td>radial scan rate</td>
<td>deg/rev</td>
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ALFA channel parameters:

BETA channel parameters:

resolver characteristics:

spiral scan parameters:

A-26
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<th>Variable Name</th>
<th>Relative Location</th>
<th>Absolute Location</th>
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<td># of bits in gimbal sensor output</td>
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<tr>
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<td>QUANTZ</td>
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<td># of bits in error signal output</td>
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<td>LSURCH</td>
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<td>flag: 0 to inhibit spiral scan</td>
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Initial conditions:
## Input List For Subroutine SERV0, FGEN

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<th>Relative Location</th>
<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<td>ALFA channel torque gain</td>
<td>ft-lbs</td>
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<td>KGB</td>
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<td>BETA channel torque gain</td>
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**Channel 1 of FGEN**

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<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<tbody>
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<td># of points</td>
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<tr>
<td>XP(1,1)</td>
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<td>input value, pt. 1</td>
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</tr>
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<td>YP(1,1)</td>
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<td>185</td>
<td>output value, pt. 1</td>
<td>ft-lbs</td>
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<td>XP(1,2)</td>
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<td>YP(1,2)</td>
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<td>output value, pt. 2</td>
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<td>XP(1,3)</td>
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<td>YP(1,3)</td>
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**Channel 2 of FGEN**

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<th>Nominal Value</th>
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<td>output value, pt. 2</td>
<td>ft-lbs</td>
<td>.08</td>
</tr>
<tr>
<td>XP(2,3)</td>
<td>INDEXV + 14</td>
<td>195</td>
<td>input value, pt. 3</td>
<td>rad/sec</td>
<td>10</td>
</tr>
<tr>
<td>YP(2,3)</td>
<td>INDEXV + 15</td>
<td>196</td>
<td>output value, pt. 3</td>
<td>ft-lbs</td>
<td>.08</td>
</tr>
<tr>
<td>Variable Name</td>
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<td>Absolute Location</td>
<td>Description</td>
<td>Units</td>
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<tr>
<td>IRøT</td>
<td>INDEXV</td>
<td>325</td>
<td>input rotation sequence</td>
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<td>321</td>
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<tr>
<td>PHI(1)</td>
<td>INDEXV + 1</td>
<td>326</td>
<td>S/S X-axis rotation angle</td>
<td>deg</td>
<td>-10.</td>
</tr>
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<td>PHI(2)</td>
<td>INDEXV + 2</td>
<td>327</td>
<td>S/S Y-axis rotation angle</td>
<td>deg</td>
<td>0</td>
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<tr>
<td>PHI(3)</td>
<td>INDEXV + 3</td>
<td>328</td>
<td>S/S Z-axis rotation angle</td>
<td>deg</td>
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### Input List For Subroutine ØEPH3

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<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<tr>
<td>KØPT</td>
<td>INDEXV</td>
<td>500</td>
<td>option index (not used)</td>
<td>-</td>
<td>-</td>
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<tr>
<td>XT(2)</td>
<td>INDEXV + 1</td>
<td>501</td>
<td>time at input point 1</td>
<td>sec</td>
<td>0</td>
</tr>
<tr>
<td>RV1(2)</td>
<td>INDEXV + 2</td>
<td>502</td>
<td>earth frame position coordinates of point 1</td>
<td>m.m.</td>
<td>0</td>
</tr>
<tr>
<td>RV2(2)</td>
<td>INDEXV + 3</td>
<td>503</td>
<td>earth frame position coordinates of point 1</td>
<td>m.m.</td>
<td>3844.7</td>
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<tr>
<td>RV3(2)</td>
<td>INDEXV + 4</td>
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<td>earth frame position coordinates of point 1</td>
<td>m.m.</td>
<td>0</td>
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<td>UVI(2)</td>
<td>INDEXV + 5</td>
<td>505</td>
<td>earth frame velocity components at point 1</td>
<td>ft/sec</td>
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<tr>
<td>UV2(2)</td>
<td>INDEXV + 6</td>
<td>506</td>
<td>earth frame velocity components at point 1</td>
<td>ft/sec</td>
<td>0</td>
</tr>
<tr>
<td>UVI(2)</td>
<td>INDEXV + 7</td>
<td>507</td>
<td>earth frame velocity components at point 1</td>
<td>ft/sec</td>
<td>21552.3</td>
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<tr>
<td>XT(3)</td>
<td>INDEXV + 11</td>
<td>511</td>
<td>time at input point 2</td>
<td>sec</td>
<td>1200.0</td>
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<tr>
<td>RV1(3)</td>
<td>INDEXV + 12</td>
<td>512</td>
<td>earth frame position coordinates of point 2</td>
<td>m.m.</td>
<td>102.41</td>
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<tr>
<td>RV2(3)</td>
<td>INDEXV + 13</td>
<td>513</td>
<td>earth frame position coordinates of point 2</td>
<td>m.m.</td>
<td>1167.31</td>
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<tr>
<td>RV3(3)</td>
<td>INDEXV + 14</td>
<td>514</td>
<td>earth frame position coordinates of point 2</td>
<td>m.m.</td>
<td>3660.26</td>
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<tr>
<td>UVI(3)</td>
<td>INDEXV + 15</td>
<td>515</td>
<td>earth frame velocity components at point 2</td>
<td>ft/sec</td>
<td>-2012.1</td>
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<tr>
<td>UV2(3)</td>
<td>INDEXV + 16</td>
<td>516</td>
<td>earth frame velocity components at point 2</td>
<td>ft/sec</td>
<td>-23277.3</td>
</tr>
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<td>UVI(3)</td>
<td>INDEXV + 17</td>
<td>517</td>
<td>earth frame velocity components at point 2</td>
<td>ft/sec</td>
<td>71474.1</td>
</tr>
<tr>
<td>XT(4)</td>
<td>INDEXV + 21</td>
<td>521</td>
<td>time at input point 3</td>
<td>sec</td>
<td>2400.0</td>
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<tr>
<td>RV1(4)</td>
<td>INDEXV + 22</td>
<td>522</td>
<td>earth frame position coordinates of point 3</td>
<td>m.m.</td>
<td>-514.82</td>
</tr>
<tr>
<td>RV2(4)</td>
<td>INDEXV + 23</td>
<td>523</td>
<td>earth frame position coordinates of point 3</td>
<td>m.m.</td>
<td>-3081.21</td>
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<tr>
<td>RV3(4)</td>
<td>INDEXV + 24</td>
<td>524</td>
<td>earth frame position coordinates of point 3</td>
<td>m.m.</td>
<td>2233.22</td>
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<tr>
<td>UVI(4)</td>
<td>INDEXV + 25</td>
<td>525</td>
<td>earth frame velocity components of point 3</td>
<td>ft/sec</td>
<td>-2184.2</td>
</tr>
<tr>
<td>UV2(4)</td>
<td>INDEXV + 26</td>
<td>526</td>
<td>earth frame velocity components of point 3</td>
<td>ft/sec</td>
<td>-14049.3</td>
</tr>
<tr>
<td>UVI(4)</td>
<td>INDEXV + 27</td>
<td>527</td>
<td>earth frame velocity components of point 3</td>
<td>ft/sec</td>
<td>-19972.7</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Relative Location</td>
<td>Absolute Location</td>
<td>Description</td>
<td>Units</td>
<td>Nominal Value</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------</td>
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<td>--------------------------------------</td>
<td>-------</td>
<td>---------------</td>
</tr>
<tr>
<td>XT(5)</td>
<td>INDXV + 31</td>
<td>531</td>
<td>time at input point 4</td>
<td>sec</td>
<td>3600.</td>
</tr>
<tr>
<td>RV1(5)</td>
<td>INDXV + 32</td>
<td>532</td>
<td>earth frame position coordinates of point 4</td>
<td>m.m.</td>
<td>-799.14</td>
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<tr>
<td>RV2(5)</td>
<td>INDXV + 33</td>
<td>533</td>
<td></td>
<td>m.m.</td>
<td>-2975.0</td>
</tr>
<tr>
<td>RV3(5)</td>
<td>INDXV + 34</td>
<td>534</td>
<td></td>
<td>m.m.</td>
<td>-2299.55</td>
</tr>
<tr>
<td>VV1(5)</td>
<td>INDXV + 35</td>
<td>535</td>
<td>earth frame velocity components at point 4</td>
<td>ft/sec</td>
<td>3812.4</td>
</tr>
<tr>
<td>VV2(5)</td>
<td>INDXV + 36</td>
<td>536</td>
<td></td>
<td>ft/sec</td>
<td>11787.3</td>
</tr>
<tr>
<td>VV3(5)</td>
<td>INDXV + 37</td>
<td>537</td>
<td></td>
<td>ft/sec</td>
<td>-19662.8</td>
</tr>
<tr>
<td>XT(6)</td>
<td>INDXV + 41</td>
<td>541</td>
<td>time at input point 5</td>
<td>sec</td>
<td>4800.</td>
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<tr>
<td>RV1(6)</td>
<td>INDXV + 42</td>
<td>542</td>
<td>earth frame position coordinates of point 5</td>
<td>m.m.</td>
<td>428.52</td>
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<tr>
<td>RV2(6)</td>
<td>INDXV + 43</td>
<td>543</td>
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<td>m.m.</td>
<td>1173.86</td>
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<tr>
<td>RV3(6)</td>
<td>INDXV + 44</td>
<td>544</td>
<td></td>
<td>m.m.</td>
<td>-3634.45</td>
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<tr>
<td>VV1(6)</td>
<td>INDXV + 45</td>
<td>545</td>
<td>earth frame velocity components at point 5</td>
<td>ft/sec</td>
<td>7965.5</td>
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<tr>
<td>VV2(6)</td>
<td>INDXV + 46</td>
<td>546</td>
<td></td>
<td>ft/sec</td>
<td>21795.4</td>
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<td>VV3(6)</td>
<td>INDXV + 47</td>
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<td>ft/sec</td>
<td>7970.7</td>
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<tr>
<td>XT(7)</td>
<td>INDXV + 51</td>
<td>551</td>
<td>time at input point 6</td>
<td>sec</td>
<td>6000.</td>
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<tr>
<td>RV1(7)</td>
<td>INDXV + 52</td>
<td>552</td>
<td>earth frame position coordinates of point 6</td>
<td>m.m.</td>
<td>1628.66</td>
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<tr>
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<tr>
<td>RV3(7)</td>
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<td>m.m.</td>
<td>82.13</td>
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<tr>
<td>VV1(7)</td>
<td>INDXV + 55</td>
<td>555</td>
<td>earth frame velocity components at point 6</td>
<td>ft/sec</td>
<td>-222.4</td>
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<tr>
<td>VV2(7)</td>
<td>INDXV + 56</td>
<td>556</td>
<td></td>
<td>ft/sec</td>
<td>-475.5</td>
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<td>VV3(7)</td>
<td>INDXV + 57</td>
<td>557</td>
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<td>ft/sec</td>
<td>21516.7</td>
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<tr>
<td>Variable Name</td>
<td>Relative Location</td>
<td>Absolute Location</td>
<td>Description</td>
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</tr>
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<td>-------------------</td>
<td>-------------------</td>
<td>--------------------------------------------------</td>
<td>--------</td>
<td>---------------</td>
</tr>
<tr>
<td>KOPT</td>
<td>INDXV</td>
<td>560</td>
<td>option index (not used)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RLØN</td>
<td>INDXV + 1</td>
<td>561</td>
<td>relay satellite longitude</td>
<td>deg</td>
<td>15</td>
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### Input List For Subroutine ØBEPH2/SYNCH

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<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<td>option index (not used)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RLØN</td>
<td>INDXV + 1</td>
<td>581</td>
<td>relay satellite longitude</td>
<td>deg</td>
<td>145</td>
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### Input List For Subroutine CLBRTN

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<th>Absolute Location</th>
<th>Description</th>
<th>Units</th>
<th>Nominal Value</th>
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<tr>
<td>K0FT</td>
<td>IDXV</td>
<td>340</td>
<td>option index (not used)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OMEGA</td>
<td>IDXV + 1</td>
<td>341</td>
<td>frequency of sinusoidal corrections</td>
<td>deg/sec</td>
<td>0</td>
</tr>
<tr>
<td>TREF</td>
<td>IDXV + 2</td>
<td>342</td>
<td>reference time</td>
<td>sec</td>
<td>0</td>
</tr>
<tr>
<td>AA</td>
<td>IDXV + 3</td>
<td>343</td>
<td>ALFA gimbal angle bias corrections</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>BA</td>
<td>IDXV + 4</td>
<td>344</td>
<td>Coeff. of sine correction term (ALFA)</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>CA</td>
<td>IDXV + 5</td>
<td>345</td>
<td>Coeff. of cosine correction term (ALFA)</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>AB</td>
<td>IDXV + 6</td>
<td>346</td>
<td>BETA gimbal angle bias correction</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>BB</td>
<td>IDXV + 7</td>
<td>347</td>
<td>Coeff. of sine correction term (BETA)</td>
<td>deg</td>
<td>0</td>
</tr>
<tr>
<td>CB</td>
<td>IDXV + 8</td>
<td>348</td>
<td>Coeff. of cosine correction term (BETA)</td>
<td>deg</td>
<td>0</td>
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</tbody>
</table>
Figure A-1  Functional Block Diagram of Setup/Loop
Figure A-2 Functional Block Diagram of SETUP/PDIRECT

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APPENDIX B

BRIEF DESCRIPTION OF THE DEADAM PACKAGE

A real-time simulation analysis can be accomplished with LMSC DEADAM simulation. Figure B-1 illustrates the basic structure of the program. The main program DEADAM acts as the overall executive program which controls the main integration package (ADAMS) and the primary I/O routines. The ADAMS subroutine contains the heart of the integration package. It performs numerical integration of the system of first order ordinary differential equations with piecewise continuous derivatives. The differential equations are usually non-linear and time varying and can be represented in the following form.

\[
\dot{x} = f(x, u(t))
\]

The above differential equations are defined by the user through the construction of the user executive (SETUP). The integration is performed using a third-order Adams-Bashforth predictor-corrector formula. The step size is adjusted automatically to stay within prescribed error bounds on the difference between predictor and corrector. Hence the step size will vary to allow efficient use of computer time without sacrificing accuracy. A self-starting procedure is used to form the first few differences.

The above features are standard for most Adams-Bashforth methods. In addition, a discontinuity prediction scheme has been incorporated into the DEADAM package. This allows the discontinuity point to be approached without iteration which results again in efficient use of computer time.
USER LIBRARY

MAIN BUILDING BLOCKS FOR ON ORBIT CONTROL SYSTEM SIMULATION (ALREADY DEVELOPED)

MAIN BUILDING BLOCKS USER PECULIAR TO BE WRITTEN BY USER

AUXILIARY SUBROUTINES FOR MATRIX AND VECTOR MANIPULATIONS, USER DEBUG OUTPUTS ETC. (ALREADY DEVELOPED)

USER SUBROUTINES ARE OUTSIDE THIS BLOCK:

THIS SYSTEM OF ROUTINES CONTROLS THE INTEGRATION (ADAMS) OF THE DIFFERENTIAL EQUATIONS DEFINED THROUGH THE USER EXECUTIVE (SETUP). IT ALSO CONTROLS THE DISCONTINUITY PREDICTION SCHEME (C0NTRO, DHYST) AND ALL STANDARD INPUT/OUTPUT (INPUT, OUTPUT, PLTVEH).

Figure B-1 DEADAM Program
APPENDIX B

The user executive (SETUP) must be written for each simulation by the user. It is the organizing subroutine through which the differential equations are defined. The prescription for writing SETUP is contained in the document:


Since many aerospace control system simulations have parts in common, a user library has been developed for rapid and easy construction of complicated simulations. Partial lists with brief descriptions of the existing library subroutines are contained in Tables B-2 and B-3. The standardization of these routines allows the construction of sophisticated simulations of highly complex systems in very short periods of time.

The ease in construction of a typical DEADAM simulation can best be illustrated via a simple example. Suppose a simulation was required for a rigid vehicle stabilized by a pitch and yaw wheel during a boost thrust along its x axis. Also suppose there exists a pitch and yaw torque on the rigid body. The problem is to observe the motion of the body and the change in the orbital states.

The user may write a SETUP routine taking advantage of the user library. Such a SETUP is listed on the next page. Note that other outputs which may be desired have not been defined.

There are many fixed input variables which are not shown explicitly in the context of the user executive (SETUP). These are defined indirectly from an input array through the initialization calls to ORBUDYN and KINDYN. Examples of such variables are inertias, initial rigid body orientation, initial rates, initial orbit states. Also initialized through the same input array are the fixed parameters needed by the integration package and those needed by the I/O routines. Examples of these are minimum step size, print interval, initial time, maximum time and number of output channels.
SUBROUTINE SETUP (KP)
COMMON/IO/OUT (50, L0)
COMMON/CONST/ENG, RAD, PI, TPI, PI2, REQ, RFL, GM, CMGE, FTNM
COMMON/SETOUT/ICANL(96)/S0D/INPAIM/MAIN/AID(13), V(300)
COMMON/KIND/TOE(3,3), JUNK(18), PHI(3), RATES(3), OMEGA(3)
COMMON/ORBIT/WREF(3), RMAG, RV(3), TOE(9) VMAG, VV(3), ALT, LAT, LON
REAL LAT, LON, TORQB(3), HWHEEL(3), FORCE(3), THRUST(3), TB0(3,3)
G = T0 (100, 200, 300, 400, 500, 600, 700, ) KP

100 L0 = 1 VIndex of initial state variable.
INPAIM = 100 VIndex for ADAMS input data
RETURN

200 NVORB = 1 VIndex for ORBDYN input data
NVKIN = 50 VIndex for KINDYN input data
IDXORB = 1 VORBDYN state index
CALL ORBDYN (1, NVORB, IDXORB, FORCE, SMUG) \ Initialization
IDXKIN = 8 VKINDYN state index
CALL KINDYN (1, NVKIN, IDXKIN, TORQB, HWHEEL, WREF, RMAG) \ Initialization
NND = 14 VIndex of final state variable
RETURN

300 CALL ORBDYN (2, NVORB, IDXORB, FORCE, SMUG) \ WRITE OUT
CALL KINDYN (2, NVKIN, IDXKIN, TORQB, HWHEEL, WREF, RMAG) \ WRITE OUT
ICANL(1) = 6H ROLL VAdditional output channels heading
ICANL(2) = 6H RATE Vcan be defined here
RETURN

400 CALL ORBDYN (3, NVORB, IDXORB, FORCE, SMUG) \ DEFINE OUTPUT
CALL KINDYN (3, NVKIN, IDXKIN, TORQB, HWHEEL, WREF, RMAG) \ DEFINE OUTPUT
THRUST(1) = 200. VThrust in lb.
SMUG = 100. VMass in slugs
CALL TRNPS(T0B, TB0)
CALL DDV(TB0, THRUST, FORCE)
CALL ORBDYN (4, NVORB, IDXORB, FORCE, SMUG) \ DEFINE DERIVATIVES
TORQB(2) = .5 VPitch torque in ft-lb
TORQB(3) = .6 VYaw torque in ft-lb
HWHEEL(2) = 50. VPitch wheel angular momentum ft-lb-sec
HWHEEL(3) = 50. VYaw wheel angular momentum ft-lb-sec
CALL KINDYN (4, NVKIN, IDXKIN, TORQB, HWHEEL, WREF, RMAG)
RETURN

500 CALL ORBDYN (5, NVORB, IDXORB, FORCE, SMUG) \ SPECIAL OUTPUTS
CALL KINDYN (5, NVKIN, IDXKIN, TORQB, HWHEEL, WREF, RMAG)
OOUT(LOUT, 1) = RATES(1) * DEG VAdditional outputs defined here
RETURN

600 RETURN

700 CALL ORBDYN (6, NVORB, IDXORB, FORCE, SMUG) \ DEBUG
CALL KINDYN (6, NVKIN, IDXKIN, TORQB, HWHEEL, WREF, RMAG) \ DEBUG
RETURN

Once the user executive (SETUP is written and compiled, the initiation of the
program is carried out by
XQT DEADAM
Following by appropriate
DATA CARDS

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LOCKHEED MISSILES & SPACE COMPANY
Figure B-2 Functional Block Diagram of Example Simulation
### TABLE B-2

**USER LIBRARY - AUXILIARY SUBROUTINES (AND FUNCTIONS)**

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGLE (X,Y)</td>
<td>Defines angle between X and Y</td>
</tr>
<tr>
<td>ANOMOD (X)</td>
<td>X module 2π in radians</td>
</tr>
<tr>
<td>ARCTAN (A, B)</td>
<td>Arc tangent function with 4 quadrant return (ATAN2)</td>
</tr>
<tr>
<td>ANGLET (A, IAX, D)</td>
<td>D = [A] IAX (transformation for rotation A about axis IAX)</td>
</tr>
<tr>
<td>AXEQB5(A,X,B)</td>
<td>Solves AX = B for X (5x1)</td>
</tr>
<tr>
<td>BOXPRD(X1,X2,X3)</td>
<td>Function = X1, X2, X3</td>
</tr>
<tr>
<td>DCTOEA (KS,LS,MS,E,A,B,C,IDEG)</td>
<td>Direction cosing matrix (E) to [ C ] [ B ] [ A ] [ K S ]</td>
</tr>
<tr>
<td>DCTOEP(D,EP,DMAG)</td>
<td>Direction cosing matrix to Euler parameters</td>
</tr>
<tr>
<td>DDD(D1,D2,D3)</td>
<td>D3 = D1*D2 Matrix product (see MAB)</td>
</tr>
<tr>
<td>DDI(V1,V2)</td>
<td>V2 = D1*V2 Linear transformation (3x3) of a vector</td>
</tr>
<tr>
<td>DIAD(R,S,RST)</td>
<td>RST = R &gt; &lt; S (Diadic)</td>
</tr>
<tr>
<td>DINV(D,DL)</td>
<td>DI = (D)</td>
</tr>
<tr>
<td>DOTPRD(X,Y)</td>
<td>Dot product of vectors X and Y</td>
</tr>
<tr>
<td>EATODC(KS,LS,MS,DC,AN,EN,CN,IDEG)</td>
<td>DC = [ C N ] [ B N ] [ C A N ] [ K S ] ((DEG = 0 rad.)</td>
</tr>
<tr>
<td>EPTODC(EP,D)</td>
<td>Euler parameters to direction cosines</td>
</tr>
<tr>
<td>EULER(IS,JS,KS,WBODY, WREF,A,R,DC,IDEG,EULER)</td>
<td>IDEG = 0, converts Euler angles (A) and rates (R) to body rates (WBODY) and dir. cos (DC)</td>
</tr>
<tr>
<td>EYRP(PSI,PHI,THETA,T)</td>
<td>Direction cosing matrix (T) to Euler angles [ [θ] [φ] [ψ] ]</td>
</tr>
<tr>
<td>EPRATE(EPD,EPW)</td>
<td>Rigid body rate (W) to Euler parameter rate (EPD)</td>
</tr>
<tr>
<td>EPWINI (Q,W,U,PSI,PHI,THETA,UB,PSID,PHID,THETAD)</td>
<td>Define inertial euler parameters (Q) and body rate (W)</td>
</tr>
<tr>
<td>EPZTB1 (TBI,Q)</td>
<td>Euler parameters (Q) to direction cosine matrix (TB1)</td>
</tr>
<tr>
<td>LENGTH (X)</td>
<td>Real function determines magnitude of vector X (3x1)</td>
</tr>
<tr>
<td>MAC (C,A,B)</td>
<td>C = A*B Matrix multiplication (see DDD)</td>
</tr>
<tr>
<td>MABC (D,A,B,C)</td>
<td>D = A * B * C</td>
</tr>
<tr>
<td>MABT (C,A,B)</td>
<td>C = A * B^T</td>
</tr>
<tr>
<td>MALAT (C,A,I)</td>
<td>C = A_I A^T</td>
</tr>
<tr>
<td>MATDA (C,D,A)</td>
<td>C = A_I B where B (I,J) = A(I,J) * D (I)</td>
</tr>
</tbody>
</table>
APPENDIX B

TABLE B-2 (Continued)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATIA (C,A,I)</td>
<td>C = A^T IA</td>
</tr>
<tr>
<td>MFILL (C,C11, C12, C13, C21, C22, C23, C31, C32, C33)</td>
<td>Fills (3 x 3) matrix</td>
</tr>
<tr>
<td>MINV (C,A)</td>
<td>C = (A) (see DINV)</td>
</tr>
<tr>
<td>MSUM2 (D,SA,A,SB,D)</td>
<td>D = SA * A + SB * B sums two matrices (SA, SB = scalars)</td>
</tr>
<tr>
<td>MSUM2 (D,SA,A,SB,B,SC,C)</td>
<td>D = SA * A + SB * B + SC * C sums three matrices (SA, SB, SC = scalors)</td>
</tr>
<tr>
<td>MTR (C,A)</td>
<td>C = A</td>
</tr>
</tbody>
</table>

PAGE Skips to new page

TFILL (A, NAXIS, ANGLE) A = [Angle] NAXIS (see ANGLET)

TF12 (A, ANGLE1, ANGLE2) FORMS Roll/Pitch or 1/2 rotation

TRNS (D,DT) DT = (D)^T (see MTR)

VABCTX (V,A,B,C,X) V = (A B C)^T X

VABX (V,A,B,X) V = (A B).X

VATX (V,A,X) V = A.X

VATXSY (V,A,X,S,T) V = A.X + S.Y (S = scaler)

VAX (V,A,X) V = AX (see DDV)

VAXSY (V,A,X,S,Y) V = AX + S . Y (S = scaler)

VCOPY (V,I,J,T) Copies row (I = row) or col. (I = col.) of T into V

VCROSS (Z,S,X,Y) Z = S . (X cross Y) cross product (S = scalor) (See VXV)

VDX (V,D,X) \( V(l) = D(l) \cdot X(l) \) I = 1,3

VFILL (Z,Z1,Z2,Z3) Fills (s x 1) vector

VMAG (X) Forms magnitude of X (function)

VSCALE (X,S) Rescales X to magnitude S

VSUM2 (Z,S1,X1,S2,X2) Z = S1 . X1 + S2 . X2 (S1, S2 = scalors) sums two vectors

VSUM3 (S,S1,X1,S2,X2,S3,X3) (see VSUM2)

VSUM4 (S,S1,X1,S2,X2,X3,S4,X4) (see VSUM2)

VUNIT (X) Rescales X to unit vector

VXKYSZ (V,X,Y,S,Z) V = X cross Y + S.Z (S = scalor)

VXDDV (V1,D,V2,V3) V3 = V1 cross D.V2

VXV (V1,W2,V3) V3 = V1 cross V2 (cross product) (see VCROSS)
# TABLE B-3 - SPECIAL OUTPUT ROUTINES

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLOOK1 (T1,A)</td>
<td>Prints out ((3 \times 3)) matrices ((A_1, A_2, A_3, A_4)) with associated titles ((T1, T2, T3, T4)), titles are 30 spaces long, numbers are in F10.3 format</td>
</tr>
<tr>
<td>MLOOK2 (T1,A1,T2,A2)</td>
<td>Same as MLOOK series except F10.6 format</td>
</tr>
<tr>
<td>MLOOK3 (T1,A1,T2,A2,T3,A3)</td>
<td>Prints out ((3 \times 1)) vectors with associated title (2I1 spaces long) format is F13.6 times 10 to the I1 power etc. (scaling)</td>
</tr>
<tr>
<td>MLOOK4 (T1,A1,T2,A2,T3,A3,T4,A4)</td>
<td>Prints out ((N \times 1)) vector with associated title (2I1 spaces long)</td>
</tr>
<tr>
<td>TLOOK1 (T1,A)</td>
<td>Function converting X to n bit word with resolution DELTA</td>
</tr>
<tr>
<td>TLOOK2 (T1,A1,T2,A2)</td>
<td>Same as BITS but output is ((0 - 100)) percent of full scale</td>
</tr>
<tr>
<td>TLOOK3 (T1,A1,T2,A2,T3,A3)</td>
<td>Function which converts 8 real variable discretes ((0,1)) to 3 octal bit word.</td>
</tr>
<tr>
<td>TLOOK4 (T1,A1,T2,A2,T3,A3,T4,A4)</td>
<td></td>
</tr>
<tr>
<td>VLOOK1 (T1,V1,I1)</td>
<td>Prints out ((3 \times 1)) vectors with associated title ((2I1 \times 10)) times 10 to the I1 power etc. (scaling)</td>
</tr>
<tr>
<td>VLOOK2 (T1,V1,I1,T2,V2,I2)</td>
<td></td>
</tr>
<tr>
<td>VLOOK3 (T1,V1,I1,T2,V2,I2,T3,V3,I3)</td>
<td></td>
</tr>
<tr>
<td>VLOOK4 (T1,V1,I1,T2,V2,I2,T3,V3,I3,T4,V4,I4)</td>
<td></td>
</tr>
<tr>
<td>VLOOKN (T,V,N)</td>
<td>Prints out ((N \times 1)) vector with associated title ((2I1 \times 10)) times 10 to the I1 power etc. (scaling)</td>
</tr>
<tr>
<td>BITS (N, DELTA, X)</td>
<td>Function converting X to n bit word with resolution DELTA</td>
</tr>
<tr>
<td>SCALE (N, DELTS, X)</td>
<td>Same as BITS but output is ((0 - 100)) percent of full scale</td>
</tr>
<tr>
<td>TRIGGR (D1,D2,D3,D4,D5,D6,D7,D8)</td>
<td>Function which converts 8 real variable discretes ((0,1)) to 3 octal bit word.</td>
</tr>
</tbody>
</table>
APPENDIX C
TRADE-OFF STUDY SIMULATION RESULTS

During the course of developing and debugging the simulation program described in this report numerous runs were made using typical values for the input parameters of the simulated system. The parameters which determine the response of the antenna pointing control system were adjusted in order to obtain stable, non-oscillatory, and rapidly converging antenna pointing control.

The plots and printed computer output included in this appendix show the behavior of a typical space station computer steered high gain antenna using "optimized" control system gains. The values for all of the input parameters used in the illustrated simulation run are included in the input lists of Appendix A.

The initial conditions were chosen to give a pointing error of about 10° in order to demonstrate the behavior of the controlled antenna during acquisition. When the gimbal angles get within 1.0° of the on board computed values the control system switches to its auto-track mode, using the monopulse error signals (at about 18 seconds in this case). Using an antenna with about a 1.0° half power beam width and monopulse horn separations of 1.0° (total) the antenna control system was able to track the relay satellite within about 0.3°.

The bending input data used in this run was computed from the expressions derived in Section 3.4.2.3 for a space station main body of cylindrical mass distribution (50 ft radius x 100 ft length) weighing 322,000 lbs (10,000 slugs) and with a boom antenna mount which deflects 1.0° angularly for each 1.0 ft translationally. The bending frequency was set at 1/10 Hz (.628 rad/sec) which is considered fairly low (corresponding to a not very stiff space station and boom).
The described bending mode is observed (Fig. C.4) to respond as expected to gimbal torques and space station orbital rate and to have insignificant ($10^{-4}$ deg) effect on pointing.
Figure C.1 Computed Gimbal Angle (ALFAC), Actual Gimbal Angle (ALFA), and Gimbal Rate (ALFAD) v.s. Time
Figure C.2 Gimbal Rate (ALFAD), Gimbal Torque (TALFA), and Monopulse Error Signal (VEL) vs. Time

C-4.
Figure C.3  Antenna Gain (GAIN), Antenna Pointing Error for Thermally Distorted (ERROR D) and Nominal (ERROR A) Antenna v.s. Time.
Figure C.4  Bending Mode Coordinate v.s. Derivative
Figure C-5  Computer Printed Output

The following six pages are reproduced from computer printout and show details of the data plotted in Figures C-1 through C-4.