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LIMITATIONS ON Ku- BAND COMMUNICATIONS DUE TO MULTIPATH

August 1977

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

NAS 9-14960

Task Order No. B0703

Shuttle Tracking and Communication Support
Antenna and Propagation Evaluation

Design Note
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1.0 SUMMARY

The purpose of this design note is to evaluate the Earth and Orbiter body reflections involving the Tracking Data Relay Satellite (TDRS)/Orbiter communications link. Recommendations address operational conditions in order to avoid critical multipath impacts, modulation preferences during acquisition, and preferred scan limit implementation.

This detailed analysis employs the use of the baselined 36-inch diameter dish and triple channel monopulse system. The Orbiter is assumed to be in a nominal orbiting altitude of 237.57 n.mi. This evaluation shows that the scan limitations for grazing angles relative to Orbiter reflections for the sum and difference radiation patterns are 3.5 and 2.0 degrees respectively. The results show a zero peak shift in the sum pattern at an offset (grazing) angle of 3.5 degrees, and a zero null shift in the difference pattern at an offset (grazing) angle of 2.0 degrees. The results in this design note indicate a possibility of false lock-on when the Orbiter grazing angle is less than 3.5 degrees. Results from the Earth reflections are minimal and not expected to cause any critical variations in the received power of the TDRS/Orbiter r.f. communications link for positive grazing angles. The recommended modulation for the multipath environment is the spread spectrum because a smaller percentage of power would be lost by cancellation.
2.0 INTRODUCTION

The purpose of this design note is to evaluate the effects of multipath from both the Orbiter and the Earth and make recommendations for tracker implementation for the Space Shuttle Orbiter Ku-Band Communications Antenna System. First, background information is given to orient the reader to the definition of multipath and related parameters. This is followed by a discussion pertaining to the factors required to analyze the multipath phenomena which include: geometrical configuration, electrical characteristics, scattering and reflection factors, and path difference. These factors are compiled into two math tools which were developed in References A and B for the analysis of Earth and Orbiter multipath respectively.

The remaining sections of this design note are related to evaluation of multipath on the sum and difference patterns including recommended performance limitations imposed by the Earth and Orbiter. The results of the output from the two math tools are interrelated in the results section to show the rationale for pertinent recommendations. The last section in this design note summarizes the recommendations for proper tracker scan implementation.
3.0 BACKGROUND

The basis for this Earth and Orbiter multipath study had its origin from a general multipath study (Reference C) that indicated some concern on this subject, and recommended further investigation. This initial study indicated that the amplitude of the multipath factor had its null points nearly coinciding with the Pseudo Noise (PN) sideband spacing which was 5.486 kHz. The present spacing is 2.9599 kHz.

The multipath phenomenon is the result of a signal reflected off an object or protrusion in the vicinity of the direct signal causing enhancement or cancellation of part or all of the resultant signal that is transmitted from the Tracking and Data Relay Satellite (TDRS) to the Orbiter. The multipath factor which represents multipath is broken up into a specular and diffuse component. The specular reflected wave is the worst case from a uniform surface, such as the relatively smooth surface of the Orbiter and uniform areas of the Earth. The diffuse wave is scattered over a broad angle greatly reducing the possibility of direct signal perturbation.

Two math tools were developed, which are found in Appendix B; one is related to Earth multipath which is designed to aid in the study of multipath as a function of grazing angle and frequency; the second program is concerned with Orbiter multipath using similar aspects as in the Earth multipath program.

The skin of the Orbiter is covered with a thermal protection system
(TPS) with various-thicknesses to accommodate the different heating loads anticipated on the orbiter's surface during mission operation. The purpose of the TPS is to dissipate external surface heat buildup on the Orbiter. The TPS consists of five layers of material which was analyzed for reflective properties (Reference B). The results of this analysis show that only the outside layer contributes significantly to the reflection coefficient at low grazing angles. The outside layer of the TPS has a thickness of 0.10".

The Ku-Band Communications Antenna is a parabolic dish type antenna with right hand circular polarization (RHCP) having a thirty-six inch diameter. Antennas are deployed from the orbiter's right and left side and will be used only during on-orbit activities. The antenna mountings are located in the forward section of the payload bay. The right antenna may also be used for radar purposes.

The region where multipath will have the most impact for communications is near the line-of-sight where the grazing angles of the signals from the TDRS are small. In this region the reflected signal has a phase shift which approaches 180° causing either a gain or loss of signal strength at the Shuttle Orbiter depending on the path difference between the direct and indirect signal.
4.0 DISCUSSION

The discussion section is divided into seven subsections, in which the rationale for the multipath parameters is developed and incorporated into a computer program that aids in the evaluation of multipath on the Ku-Band Communications Antenna System. The recommended operational limitations will also be discussed to obtain optimum implementation of this antenna system. The first section deals with the two geometrical configurations used to determine the Earth and Orbiter math models and its respective parameters. The electrical properties of the different Earth, in and Orbiter surfaces are also shown in this section. The second section, 4.2, deals with the development of the reflective and scattering parameters for the respective math models. The third section, 4.3, is concerned with the development of the path difference between a direct and indirect signal which may indicate whether enhancement or cancellation will occur. The incorporation and modifications of the multipath parameters are combined into an equation for both Earth and Orbiter multipath in Section 4.4. The multipath equation is expressed in dB which is called "multipath factor". The Fortran programs written for this multipath evaluation are discussed in Section 4.5. In this section, the modifications made to the basic multipath factor equation are explained relative to the Earth, the Orbiter, and the sum and difference pattern sensitivity to multipath. In Section 4.6, evaluation of the multipath phenomenon is discussed in relation to the sum and difference channels. This evaluation uses a Bessel function to produce the sum radiation pattern.
found in Reference D. The difference channel radiation pattern is produced using a sine function approximation which is found in Reference E. These patterns are combined in a computer program with the multipath factor to show the sensitivity of the Ku-Band sum and difference patterns to multipath relative to the Earth and Orbiter. In Section 4.7, the results from the multipath program written as a function of frequency and grazing angle are discussed for both the Earth and Orbiter. The recommended functional implementation of the Ku-Band antenna is made in this section and also documented in the results section for convenience.

The data obtained in this analysis is shown in graphical form and is used to indicate the limitations of the tracking capabilities of the Ku-Band Communication System. From these results, optimum implementation for the Ku-Band antenna is recommended.

4.1 Geometric Configuration

The geometries that are used to analyze multipath relative to the Earth and Orbiter utilize a geometrical optics approach for a sphere and cylinder. The sphere represents the shape of the Earth and the cylinder represents the orbiter's shape. The geometrical configurations for Earth and Orbiter multipath are shown in Figures 1 and 2, respectively. The region of interest for multipath is near the line-of-sight (LOS) or interference region. This is a region with small grazing angles and path differences, resulting in relatively small r.f. phase shifts between the direct and indirect signals. These geometries are
shown in Figures 1 and 2.

4.1.1 Geometrical Bodies

The geometry of the Earth multipath shown in Figure 1 considers the atmospheric effects and spherical effects on the signal from the TDRS. The atmospheric effects are due to refractive and diffractive bending of the incident wave and reflected wave off the Earth. The effect of the atmosphere is to take 4/3 of the earth's radius which is referred to as the effective radius of the Earth. Figure 1 also shows the pertinent angles and arc distances used to determine the amount of movement of the Orbiter in a fixed orbit traversing around the earth's center while holding the TDRS in a fixed position. The curved surface of the Earth is accounted for by the divergence factor which approaches zero as the grazing angle is encountered making the received field the same as that of free space. The grazing angle, $\psi_1$, in Figure 1 is encountered when the Orbiter/TDRS line of site passes thru the point of wave impingement on the earth's surface (apex of grazing angle).

The geometry for Orbiter multipath is illustrated in Figure 2; the Orbiter is assumed to be a smooth cylinder rotating in a circular orbit around the Earth approaching the point for acquisition of the TDRS signal. The approach taken for this aspect is to consider the TDRS to be in the far field, therefore implying that the direct and indirect paths are parallel upon incidence to the orbiter's thermal protection system. The effect of the TPS on the reflected signal was evaluated
in Reference C. Results indicated that the top layer of the TPS has the major effect compared to the other four layers of the TPS at near grazing angles.

4.1.2 Electrical Characteristics

The electrical properties of the objects from which the TDRS signal is reflected should be considered in order to have a meaningful result relative to the scattering and reflection of the signal. The Earth and Orbiter multipath were considered from a number of surfaces which are listed in Table I with the conductivity in Siemens/meter and relative dielectric constant.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CONDUCTIVITY (Siemens/meter)</th>
<th>COMPLEX DIELECTRIC CONSTANT (εr) at 13.775 GHz</th>
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<tr>
<td>Top Layer TPS</td>
<td>1.102x10^-2</td>
<td>4.8-j1.44x10^-2</td>
</tr>
<tr>
<td>Sandy Soil</td>
<td>10^-5</td>
<td>3-j1.31x10^-5</td>
</tr>
<tr>
<td>Wet Soil</td>
<td>10^-3</td>
<td>80.-j1.31x10^-3</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>10^-2</td>
<td>80.-j1.31x10^-3</td>
</tr>
<tr>
<td>Salt Water</td>
<td>4</td>
<td>80.-j5.24</td>
</tr>
<tr>
<td>Ice</td>
<td>5x10^-3</td>
<td>2.92-j6.532x10^-9</td>
</tr>
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TABLE I ELECTRICAL PROPERTIES OF ORBITER/EARTH SURFACES
4.2 Scattering and Reflection Parameters Relative to Earth and Orbiter Multipath

The scattering coefficient for the specularly reflected wave off the Orbiter is calculated using equation (1) Reference F, which is used for both the Earth/Orbiter surfaces listed in Table 1.

\[ |\rho_s| = \exp - \left( \frac{4\pi}{\lambda} \sigma_{\text{rms}} \sin \psi_1 \right) \]  \hspace{1cm} (1)

- $|\rho_s|$ is the scattering coefficient magnitude (no units)
- $\sigma_{\text{rms}}$ is the root-mean-square roughness height in meters
- $\psi_1$ is the grazing angle in radians
- $\lambda$ is the wavelength in meters
- $\pi$ is 3.14159265358979324

The specular scattering coefficient is considered to have a value of unity for the Orbiter surface multipath calculations. The unity scattering factor indicates that the Orbiter is assumed to have a smooth surface.

The scattering coefficient will alter the reflection coefficient in such a way that the resultant specular reflection component will be $|\hat{R}_s| = |\rho_s| |\hat{R}_e|$. The baselined polarization for the Ku-Band Communication Antenna is circular. The circular reflection coefficient, $|\hat{R}_e|$, consists of two components, vertical and horizontal as shown in equation (2).
\[ |\hat{R}_c| = \frac{|\hat{R}_v + \hat{R}_h|}{2} \] (Reference G) \hspace{1cm} (2)

\( \hat{R}_v \) is the vertical reflection coefficient (Reference H) (no units)

\( \hat{R}_h \) is the horizontal reflection coefficient (Reference H) (no units)

The respective vertical and horizontal components in equation (2) are calculated by the following equations (Reference H).

\[ |\hat{R}_v| = \sqrt{1 + \frac{b_v}{2}(1 - \cos 2\psi) - m_v \sin \psi} \] \hspace{1cm} (3)

\[ |\hat{R}_h| = \sqrt{1 + \frac{b_h}{2}(1 - \cos 2\psi) - m_h \sin \psi} \] \hspace{1cm} (4)

\( \psi \) is the grazing angle in radians

\( b_v, b_h, m_v, \) and \( m_h \) are complex parameters used to calculate the vertical and horizontal reflection components (Equations 5a-5d)

\[ b_v = \frac{\varepsilon_f + \chi^2}{S^2 + q} \] \hspace{1cm} (5a)

\[ b_h = \frac{1}{S^2 + q} \] \hspace{1cm} (5b)
\[ m_v = \frac{2(S\varepsilon_r + qX)}{S^2 + q^2} \]  

\[ m_h = \frac{2S}{S^2 + q^2} \]  

\( \varepsilon_r \) is the relative dielectric constant of either the Earth or Orbiter surface (no units)

\( S \) is a function of grazing angle and complex dielectric constant (equation 6a)

\( X \) is the imaginary component of relative dielectric constant (equation 6b)

\( q \) is a function of \( S \) and \( X \) (equation 6c)

\[
S = \sqrt{\left[ (\varepsilon_r - \cos^2 \psi_1)^2 + X \right]^{1/2} + (\varepsilon_r - \cos \psi_1)^2 / 2} 
\]  

\[ X = 1.80 \times 10^{10} \left( \frac{S}{F} \right) \]  

\[ q = \frac{X}{2S} \]  

\( \sigma \) is the conductivity of the respective reflecting surface in Siemens/meter

\( F \) is the frequency in Hz

The reflection coefficient approaches unity for small grazing
angles and decreases as the grazing angle increases. Along with the circular reflection coefficient there is also the circular phase lag, $\phi_c$, which has a vertical and horizontal phase component. The simplified form for the calculation of the circular phase lag is written in equation (7) as

$$\phi_c = \frac{\phi_v + \phi_H}{2}$$  \hspace{1cm} (7)

$\phi_v$ is the vertical phase lag in radians

$\phi_H$ is the horizontal phase lag in radians

The horizontal and vertical phase lag components are given in equations (8) and (9) (Reference H) as

$$\phi_v = \tan^{-1}\left(\frac{X \sin \psi - q}{\varepsilon_r \sin \psi_1 - S}\right) - \tan^{-1}\left(\frac{X \sin \psi_1 + q}{\varepsilon_r \sin \psi_1 + S}\right)$$ \hspace{1cm} (8)

$$\phi_H = \tan^{-1}\left(\frac{-q}{\sin \psi_1 - S}\right) - \tan^{-1}\left(\frac{q}{\sin \psi_1 + S}\right)$$ \hspace{1cm} (9)

The phase lag is a function of the dielectric and conductive properties of the reflective surface, grazing angle, and frequency of the transmitted signal from the TDRS.
4.2.1 Earth Reflective Characteristics

The reflective characteristics of Earth refer to the shape of the reflecting surface and the atmospheric environment. The spherical shape of the Earth is taken into account by the spherical divergence factor, $D_e$. The spherical divergence factor is an abstract measure of the reflected field off the Earth received at the Ku-Band Antenna on the Orbiter as it approaches the TDRS in its circular orbit about the Earth. The divergence factor approaches zero as the grazing angle, $\varphi_1$, approaches zero making the received field the same as that of free space. The grazing angle is that angle between the path made by the incident component of the indirect signal and a plane tangent at the point of wave impingement on the surface of the Earth. The spherical divergence factor for Earth is calculated by equation (10) found in Reference I as:

$$D_e = \frac{a_e (r_1 + r_2) \sin \tau_2 \cos \tau_2}{\sqrt{[(a_e + z_2) r_1 \cos \tau_3 + (a_e + z_1) r_1 \cos \tau_1] (a_e + z_1)(a_e + z_2) \sin \theta}}$$

- $a_e$ is the effective radius of the Earth in meters ($8.986333333 \times 10^6$ meters)
- $r_1$ & $r_2$ are the distance components of the indirect wave in meters
- $z_2$ is the altitude of the TDRS in meters
- $z_1$ is the altitude of the Orbiter in meters
- $\tau_1$ is the angle between a line from earth's center to the Orbiter and the selected wave moving towards the Orbiter in radians
- $\tau_2$ is the complement of the grazing angle, the angle between the normal on the tangent at the point of reflection and the incident wave of the indirect
signal in radians

is the angle between a line from the earth's center to the TDRS and the incident component of the indirect signal in radians

is the angle made by the arc distance between the Orbiter and TDRS relative to the earth's center in radians

4.2.2 Orbiter Reflective Characteristics

The reflective properties of the orbiter's surface, which is assumed to be a cylinder, is accounted for by the cylindrical divergence factor which has been found to be the square root of the spherical divergence. The radius of the orbiter's cylindrical fuselage is 2.992 meters. The cylindrical divergence is a function of the grazing angle, Orbiter radius, and the height of the Ku-Band antenna from the orbiter's surface. The TDRS is assumed to be in the far field which will result in incident parallel wave paths for the direct and indirect signals. The cylindrical divergence is calculated by use of equation (11).

\[ D_{cy} = \frac{4}{\sqrt{\frac{a \sin \psi_1 + 2r_2}{\left(1 + \frac{z_2}{a}\right) \sin \left(\cos^{-1} \frac{a^2 (a + z_1)^2 - r_2^2}{2a(a + z_1)}\right)}}} \]

is the radius of the orbiter's fuselage in meters (a = 2.9921005843281686563 m.)

is the grazing angle made by the incident wave of the indirect signal and tangent at the reflection point in radians (Reference—Figure 2)

is the Ku-Band antenna height from the orbiter's surface in meters

is the reflected distance component of the indirect signal in meters
The cylindrical divergence factor for the Orbiter has been shown to be the square root of the spherical divergence that is found in Reference 1. The effective radius parameter, $a_e$, is replaced by the orbiter's radius, $a$, in equation (11) because operation of the Ku-Band Communications will only occur during on-orbit activities where there are no refractive and diffractive effects from an atmosphere.

4.3 Path Difference Relative to Earth and Orbiter

The final factor required to compose an equation to calculate a reasonable value for the magnitude of multipath due to the Earth and Orbiter is the path difference. Two path difference equations will be discussed in this section, one for the Earth geometry and one for the Orbiter geometrical configuration.

The Earth path difference, $\Delta r$, is a function of altitude and path traveled by the Orbiter and TDRS relative to the Earth's center. There are three components required to calculate the Earth path difference, the incident and reflected path distances of the indirect signal, and the path distance of the direct signal. The two components of the indirect signal are calculated by equations (12) and (13) in meters found in Reference 1.

\[
r_1 = \sqrt{a_e^2 + (a_e + z_2)^2 - 2a_e(a_e + z_2) \cos \frac{d_1}{a_e}} \quad (12)
\]

\[
r_2 = \sqrt{a_e^2 + (a_e + z_1)^2 - 2a_e(a_e + z_1) \cos \frac{d_2}{a_e}} \quad (13)
\]
ae is the effective earth's radius in meters (8.986333333 \times 10^6 \text{ meters})

z_1 \text{ is the altitude of the Orbiter in meters}

z_2 \text{ is the altitude of the TDRS in meters}

d_1 \text{ and } d_2 \text{ are the arc distances for the incident and reflected signal of the indirect wave in meters (reference figure 1)}

The path of the direct signal between the TDRS and Orbiter is calculated by equation (14) in meters.

\[
r = \frac{z_1^2}{ae} \sqrt{\left( \frac{1}{ae} + \frac{z_2}{ae} \right)^2 - 2\left( \frac{1}{ae} \right)\left( \frac{z_2}{ae} \right) + 2\left[ 1 + \frac{z_1}{ae} + \frac{z_2}{ae} + \left( \frac{1}{ae} \right)^2 \right] \left[ 1 - \cos\left( \frac{d_1}{ae} \right) \right]} \tag{14}
\]

d \text{ is the arc distance of the direct signal relative to the spherical surface of the Earth in meters}

The Orbiter path difference, \( \Delta r_0 \), is a function of the grazing angle and antenna height above the orbiter's surface. The path difference is calculated using equation (15) found in Reference J as

\[
\Delta r_0 = 2z_1 \tan \psi_1 \tag{15}
\]

since \( z_2 \gg z_1 \)

\[
\tan \psi_1 = \frac{z_1 - z_2}{d_2} = \frac{z_2}{d_2}
\]

\( z_2 \) is the altitude of the TDRS in meters

\( z_1 \) is the height of the Ku-Band antenna above the orbiter's surface in meters

\( \psi_1 \) is the grazing angle in radians
4.4 Earth and Orbiter Multipath Factors

The Earth and Orbiter multipath factors which represent a direct and indirect component compose the received signal (field) at the Ku-Band Communications Antenna on the Orbiter. This field is a result of the transmitted signal from the TDRS. The resultant multipath factor for both Earth and Orbiter encompasses the five factors outlined in Sections 4.1-4.3 which are the electrical properties of the reflecting surface, the geometrical shape of the reflecting object, reflection properties of the reflective surfaces, surface roughness, and the path difference of the direct and indirect signal. The multipath factor representing the multipath phenomena is a voltage ratio parameter. Equation (16) is used to represent Earth multipath.

\[
L_{MP}(dB) = 20 \log \left| 1 + \rho_s \left( \frac{r}{r_1 + r_2} \right) D_e \left| \hat{R}_c \right| e^{-j \left( \frac{2\pi}{\lambda} \Delta r + \phi_c \right)} \right| (16)
\]

- \( \rho_s \) is the scattering coefficient (no units)
- \( r \) is the differential loss factor between the direct and indirect signal (no units)
- \( r_1 + r_2 \) is the spherical divergence factor (no units)
- \( \hat{R}_c \) is the circular polarized reflection coefficient magnitude (no units)
- \( \Delta r \) is the path difference of the direct and indirect wave in meters relative to the Earth in meters
- \( \phi_c \) is the phase lag of a circular polarized wave in radians
- \( \pi \) is 3.14159265358979324
- \( \lambda \) is the wavelength in meters
Equation (16) is used to account for the multipath impact on the sum and difference radiation patterns as will be shown in section 4.6. This equation is also used to account for the variation of frequency and grazing angle to evaluate the limitations of the tracking subsystem of the Ku-Band Communications Antenna relative to the Earth.

The same factors that apply for Earth multipath will also apply for Orbiter multipath with some modification. These factors that are modified include the scattering coefficient, the differential loss factor between the direct and indirect signal, path difference, and the divergence factor. The remaining factors, reflection coefficient and electrical surface properties, still must be considered. The surface of the Orbiter is assumed to be smooth having a scattering coefficient equal to unity. Another modification is the differential loss factor between the direct and indirect signal which is negated considering the TDRS to be in the far field. The approach taken is to consider the direct and indirect traveling waves to have parallel paths incident to the surface of the Orbiter. The path difference, therefore, will be a function of grazing angle and the height of the Ku-Band antenna above the surface of the Orbiter. The only other major modification for Orbiter multipath relative to Earth multipath is the divergence factor which requires the divergence to be from the cylindrical surface of the Orbiter. The cylindrical divergence has been proven to be the square root of the spherical divergence factor. This multipath parameter is calculated assuming the TDRS to
be in the far field. After incorporation of these modifications, the Orbiter multipath equation used in the computer program is shown as equation (17), which is a voltage calculation.

\[
L_{MP} (dB) = 20 \log \left| 1 + \rho_s D_{cy} \right| R_c \left| e^{-\jmath \left( \frac{2\pi}{\lambda} \Delta r_o + \phi_c \right)} \right| \quad (17)
\]

- \( L_{MP} \) is the multipath factor in dB
- \( \rho_s \) is the scattering coefficient equal to one (no units)
- \( D_{cy} \) is the cylindrical divergence factor (no units)
- \( R_c \) is the circular reflection coefficient magnitude for a circular polarized wave (no units)
- \( \Delta r_o \) is the path difference between the direct and indirect signal relative to the Orbiter in meters
- \( \phi_c \) is the reflection coefficient circular phase lag in radians
- \( \lambda \) is the wavelength in meters
- \( \pi \) is 3.14159265358979324

The factors in these multipath equations, 16 & 17, which are varied to evaluate the multipath phenomena include frequency, grazing angle, and electrical surface properties pertaining to the Earth and Orbiter.

4.5 Fortran Programs

The computer programs developed for this analysis are designed for the 1108 EXEC II system. The programs can be adapted to the 1110 EXEC VIII system by making control card changes. The subprograms that were used to complete this multipath analysis
include a plot program, Bessel Function program used to analyze the multipath impact on the sum pattern, a difference pattern function to evaluate multipath impact on the difference channel, and a computer program concerning the reflective effect on a signal in a multi-layer dielectric. The multiple-layer dielectric program was used to study the effect of the TPS on the reflected signal (indirect signal).

The programs developed for this analysis are contained in Appendix B which all use a double precision format to avoid errors due to round-off of the output data. The first two programs listed and flowcharted in the appendix (Figures 18-21) are used to give the results of Earth and Orbiter multipath as a function of either grazing angle or frequency. The remaining two programs (Figures 22-25) are used to show the effect of Earth and Orbiter multipath on the sum and difference channels for multiple offset angles as a function of grazing angle and frequency.

The components previously discussed that make up the multipath programs for this evaluation are incorporated into two general computer programs relative to the Earth and Orbiter. The two programs are then adapted to study the multipath impact on the sum and difference channels of the tracking system of the Ku-Band Communications Antenna.
4.6 Multipath Impact on Radiation Patterns for Sum and Difference Channels

The multipath effect on the sum and difference channels of the Ku-Band tracking system has been evaluated by combining the individual radiation pattern and the multipath factor into their respective electric field equations. The electric field of the direct and indirect signals relative to the sum pattern are written as a function grazing angle, \( \psi_1 \), frequency, and offset angle, \( \phi \).

The geometry used to evaluate the impact of multipath on the sum and difference tracking channels is illustrated in Figure 3A. This geometry is utilized for both the Earth and Orbiter related multipath math models. The dotted line illustrates the path of the signal relative to the Earth multipath math model.

In Figure 3A the indirect signal is only illustrated to prevent possible confusion with a line representing the direct signal. The antenna radiation patterns are calculated for offset angles from the horizontal denoted by \( \phi \) in Figure 3B between zero and ten degrees. The negative offset \( (-\phi) \) would refer to the Ku-Band Communications antenna being pointed towards the Earth or Orbiter surface. The electric field equations for the direct and indirect signals that are used to illustrate the Earth and Orbiter multipath impact on the sum pattern are shown in equations (18) and (19), respectively.

\[
E(\psi_1 - \phi) = \left| \frac{2\lambda}{\pi D} \left[ \frac{\csc \left( \frac{\pi D}{\lambda} \sin \left( \psi_1 \right) \right)}{\sin (\psi_1 - \phi)} \right] \right| 
\]  
(18)
\[ E(\psi_1 - \phi) = \left| \frac{2}{\pi D} \frac{J_1 \left( \frac{\pi D}{\lambda} \sin (-\psi_1 - \phi) \right)}{\sin (-\psi_1 - \phi)} \right| \]  \hspace{1cm} (19)

\( D \) is the diameter of the Ku-Band antenna in meters

\( \psi_1 \) is the grazing angle in radians

\( \phi \) is the offset with respect to the horizontal of the antenna in radians

\( J_1 \) is the first order Bessel function (Reference J)

\( J_1 \left[ \left( \frac{\pi D}{\lambda} \right) \sin (\psi_1 - \phi) \right] \) is the Bessel function argument for the direct signal

\( J_1 \left[ \left( \frac{\pi D}{\lambda} \right) \sin (-\psi_1 - \phi) \right] \) is the Bessel function argument for the indirect signal

Equations (18) and (19) are combined with the multipath equations (16) and (17) to evaluate the multipath impact on the sum radiation pattern relative to the Earth and Orbiter. The resultant modified multipath equation for Orbiter multipath is shown in equation (20).

\[ L_{\text{MP}}' \ (\text{dB}) = 20 \log \left| E(\psi_1 - \phi) + E(-\psi_1 - \phi) (\rho S D_C G \hat{r}_C) e^{-j \left( \frac{2\pi}{\lambda} \Delta r_o + \theta_C \right)} \right| \]  \hspace{1cm} (20)

\( E(\psi_1 - \phi) \) is the electric field of the direct signal in volts/meter

\( E(-\psi_1 - \phi) \) is the electric field of the indirect signal in volts/meter

Equation (20) accounts for the combined effect of the direct and indirect components of the resultant signal received at the Orbiter from the TDRS. The indirect signal field includes the effect of multipath off the Orbiter.
The result of Orbiter multipath impact on the sum radiation pattern is shown in Figure 4. This radiation pattern illustrates the results of a signal being received at a grazing angle of 1.5° and the antenna at an offset angle of 1.5° in a multipath environment. The radiation pattern is isotropic as all the patterns are in the design note. The error or peak shift of this pattern is shown to be 0.08° from the 1.5° point on the grazing angle coordinate. Sum channel radiation patterns were also evaluated for offset angles between ±5° within a 0-10° grazing angle spectrum.

The Earth multipath impact on the sum radiation pattern is calculated using equation (16). The resultant modified Earth multipath equation relative to the sum channel is shown in equation (21) as

\[
L_{MP}'' (dB) = 20 \log \left| E(\psi_1 - \phi) + E(-\psi_1 - \phi)(\rho_s \left( \frac{-\pi}{r_{1+r_{2}}} \right) D_{1}\Delta r \ e^{-j \left( \frac{2\pi}{\lambda} \Delta r + \phi_c \right)} \right| \quad (21)
\]

The equations used to calculate the direct and indirect signals in order to show the impact on the difference channel employs a sine function as shown in equations (22-23) which were derived from Reference E.

\[
E' (\psi_1 - \phi) = \sin \left( \pi \left( \frac{\psi_1 - \phi}{HPBW} \right) + \pi \right) - \sin \left( \pi \left( \frac{\psi_1 - \phi}{HPBW} \right) \right) \quad (22)
\]
\[ E''(\psi_1 - \phi) = \sin \left( \pi \left( \frac{\psi_1 - \phi}{\text{HPBW}} \right) + \pi \right) - \sin \left( \pi \left( \frac{-\psi - \phi}{\text{HPBW}} \right) \right) \] (23)

\[
\begin{align*}
\psi_1 & \quad \text{is the grazing angle in radians} \\
\phi & \quad \text{is the offset angle with respect to the horizontal of the antenna in radians} \\
\pi & \quad \text{is 3.14159265358979324} \\
\text{HPBW} & \quad \text{is the half-power beamwidth (1.30°)}
\end{align*}
\]

To account for the multipath impact on the difference channel from the Orbiter and Earth, \( E(\psi_1 - \phi) \) and \( E(-\psi_1 - \phi) \) are replaced by \( E'(\psi_1 - \phi) \) and \( E''(-\psi_1 - \phi) \) in equations (20) and (21). The results from the difference channel function is repetitious which means the graphs are interpreted in a localized manner i.e. for a particular offset angle (grazing angle) on the coordinate axis within ± X degrees the null shift may be read directly. An example is shown in Figure 5 for the Orbiter multipath impact on the difference channel where the offset is 3.5 degrees having a null shift of .18 degrees. The modified Earth and Orbiter multipath equations (20 and 21) pertaining to the sum and difference channels are incorporated into the multipath programs shown in Appendix B, Figures 44 and 46, as a function of grazing angle and frequency.

### 4.7 Evaluation of the Multipath Effects

A general computer program has been written to evaluate the impact of multipath on the Ku-Band Communications Antenna performance. The program has many modifications that were written for the
1108 Executive II system. These modifications were written to show the impact of multipath on the received signal from the TDRS to the Orbiter. The different modifications aid the evaluation of multipath from the Earth and Orbiter as a function of grazing angle and frequency. Another modification has been written to evaluate the multipath impact on the sum and difference radiation patterns to determine the antenna limits of the Ku-Band tracking for the communications system.

4.7.1 Evaluation and Recommended Implementation for the Ku-Band Antenna Referenced to Earth Multipath

The five different surfaces chosen to represent the earth's composition are: sandy soil, wet soil, fresh and salt water, and ice. The results showed minimal multipath magnitudes of $10^{-3}$ and $10^{-13}$ between 0 and .2 degree grazing as a function of grazing angle. Frequency also shows a minimal effect relative to Earth multipath at a grazing angle of .20 for the five respective Earth surfaces. Figure 6 shows the Earth multipath magnitude from sandy soil which is also representative of the other four Earth surfaces as a function of frequency.

The Earth multipath impact to the sum and difference patterns as a function of grazing angle shows a minimal effect as illustrated in Figures 7-8 from sandy soil. The peak and null shifts are very minimal in the radiation patterns of Figures 7 and 8. This impact is also representative of the other four Earth surfaces.
The Earth multipath impact to the sum and difference pattern as a function of frequency had the same minimal impact for small grazing angles from the five respective surfaces considered on the earth's surface as shown in Figures 9 and 10, respectively. The curves shown in Figures 9-10 show no scalloping of the pattern indicating that there may not be any interference within the frequency bandwidth of the TDRS/Orbiter communications link. Therefore, the impact of Earth multipath as a function of frequency shows that there is no effect as shown in Figures 9 and 10.

The multipath from the earth's surface will have a minimal effect on the signal transmitted from the TDRS at a carrier frequency of 13.775 GHz. Also, the pointing error or peak and null shifts are at a minimum for the sum and difference patterns of the TDRS carrier frequency producing a good tracking signal.

In relation to the Earth multipath, the modulation of the carrier signal from the Tracking Data Relay Satellite (TDRS) may be a despread signal due to the results shown in this paragraph. Recommended implementation of the Ku-Band Antenna is not restricted due to Earth multipath and therefore may function with very little interference from the earth's reflections.

4.7.2 Evaluations and Recommended Implementation for the Ku-Band Antenna Referenced to Orbiter Multipath

The Orbiter multipath factor shown in Figure 11 as a function of grazing angle indicates that it is a cyclic function with increasing magnitude and angle. When integrated with a signal
degradation or enhancement may result. The Orbiter multipath factor as a function of frequency illustrated in Figure 12 shows that the multipath nulls do not occur within the r.f. bandwidth of the TDRS/Orbiter signal for grazing angles less than 3.5 degrees.

The Orbiter multipath math model was used to show the peak and null shifts of the sum and difference patterns for grazing angles between 0° and 10° at offset angles between ±5°. Table 2 contains a tabulation of these respective shifts or pointing errors for corresponding offset angles within the grazing angle spectrum. Table 2 shows that minimum pointing error for the sum pattern occurred at 3.5° offset (grazing angle) and 2.0° offset (grazing angle) for the difference pattern.

The Orbiter multipath results shown in Figure 13 as a function of grazing angle shows that the minimum peak shift of the sum pattern occurred at a grazing angle of 3.5 degrees. Therefore, it may be concluded that the worst case tracking due to multipath interference will occur when the grazing angle is 0-3.5 degrees in relation to the sum pattern. There are still some minor perturbations in the sidelobes which are at a level of -17 dB down from the main lobe.

The minimum null displacement of the difference pattern was found to be at a grazing angle of two degrees as shown in Figure 14. The difference pattern is the signal from which the elevation and azimuth difference tracking channel is derived. Figure 14 shows that there are possibilities for false lock-on at lower
<table>
<thead>
<tr>
<th>Offset Angle, $\theta$ (degrees)</th>
<th>Sum Pattern Pointing Error (degrees)</th>
<th>Difference Pattern (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.0</td>
<td>0.18</td>
<td>0.185</td>
</tr>
<tr>
<td>-1.5</td>
<td>0.02</td>
<td>0.52</td>
</tr>
<tr>
<td>-1.0</td>
<td>0.23</td>
<td>0.60</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>0</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>0.5</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>1.0</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>1.5</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
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<td>0.50</td>
<td>0.01</td>
</tr>
<tr>
<td>2.5</td>
<td>0.50</td>
<td>0.02</td>
</tr>
<tr>
<td>3.0</td>
<td>0.50</td>
<td>0.20</td>
</tr>
<tr>
<td>3.5</td>
<td>0.00</td>
<td>0.18</td>
</tr>
<tr>
<td>4.0</td>
<td>0.00</td>
<td>1.10</td>
</tr>
<tr>
<td>4.5</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>5.0</td>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 2: Pointing Errors Due To Orbiter Multipath For Sum And Difference Radiation Patterns.
grazing angles shown by the small glitch or false null in the pattern just before the main null. There are a number of false nulls in Figure 14 which accounts for the repetitious sine function used to produce this pattern. With this false null being close to the actual null which is characteristic in a multipath environment a spread modulation is recommended to avoid as little power loss as possible in the signal. In a spread spectrum modulation or pseudo noise modulation the power bandwidth is large decreasing the possibility of total signal cancellation.

The impact of Orbiter multipath on the sum and difference pattern as a function of frequency shows a possibility of interference. The center frequency of the carrier, 13.775 GHz, is shifted close to the null between the mainlobe and first sidelobe of the sum pattern for an offset of -2.00 and +3.00 at small grazing angles (0-1.320) as shown in Figures 15-16. Therefore, the multipath interference may occur at these respective offsets with the center frequency of the carrier being shifted close to the null between the mainlobe and sidelobe of the sum pattern.

The difference channel is affected by multipath in relation to frequency in that the TDRS carrier frequency bandwidth is at the top of the difference lobe for offset angles greater than 2.5 degrees and lower in the null for offset angles of less than 2.50 at small grazing angles (0-1.320). Therefore, tracking of an object would be better at +2.50 off the horizontal of the beam. This result is shown in Figures 17 for offset angles of +2.50 relative to the difference pattern.
In relation to Orbiter multipath, there is a possibility for cancellation of the TDRS signal as explained in this paragraph. Therefore the recommended modulation to use is pseudo noise (PN) for the orbiter multipath environment.
5.0 RESULTS

The purpose of this section is to summarize the factors from the previous discussion to define the rationale for pertinent recommendations for operation of the Ku-Band tracking in a multipath environment.

The first three discussion sections (4.1-4.3) reviewed the factors and geometries used to build the math models to analyze multipath relative to either the Earth or Orbiter. The r.f. bandwidth (13.75-13.80 GHz) analyzed was the Ku-Band TDRS/Orbiter communications link which operates at a center frequency of 13.775 GHz. The calculations performed considered the geometrical shapes of a sphere and cylinder for the Earth and Orbiter. The factors that are considered in these math models are grouped into three areas which include: the electrical characteristics of the reflecting surfaces, reflective surface characteristics, and the path differences between the direct and indirect signal from the TDRS. Equations 16-17 represent the multipath factor relative to the Earth and Orbiter, respectively. These equations may be adaptable to numerous surface conditions on the Earth or Orbiter.

Multipath at small grazing angles can have an impact on the operation of the Ku-Band tracking system. The multipath phenomena may impact the system by shifting and scalloping of the sum and difference signals which could result in a false lock-on of the TDRS signal as shown in Figure 37, and also a r.f. phase variation which could result in partial or total cancellation within the spectrum of the TDRS signal.
The received signal on the TORS/Orbiter link (Forward Link) may be enhanced or degraded by the multipath factor dependent on the r.f. phase variation between the direct and indirect signal, and also the electrical characteristics of the reflecting surface. The sum and difference curves shown in Figures 37 and 38 show a minimum peak shift of zero degrees for an offset of $3.5^\circ$ and a minimum null shift of $.001^\circ$. The sum pattern will not have maximum tracking for grazing angles of $3.5^\circ$ or less. The difference pattern showed a minimum shift for grazing angles of 2 degrees or less. The difference between the peak shift and null shift which has the maximum difference will yield the best tracking signal.

The most favorable modulation for a multipath environment is considered to be a spread spectrum or pseudo noise type of modulation. This fact has been shown to be true in past history. The spread spectrum spacing for Ku-Band is 2.9599 kHz over a 6.056 MHz bandwidth. The spread spectrum requires a small beamwidth, as is baselined, in order to operate properly. The spread spectrum has a very good advantage over other modulations such as the despread modulation where, if cancellation does occur, the cancellation may be very slight in comparison with the despread modulation.
6.0 CONCLUSIONS AND RECOMMENDATIONS

As a result of this multipath study relative to the Earth and Orbiter, the following communication oriented recommendations are made for the Ku-Band Communications Antenna tracking system.

(1) The multipath effects from the earth's surface will have a very minimal impact on the TDRS/Orbiter communications link (13.75-13.80 GHz). As a result communication may be maintained when the TDRS is within the line of site of the Orbiter.

(2) The Orbiter reflections will impact the sum and difference patterns limiting the antenna scan of the Ku-Band tracking system. Grazing angles of 3.5 degrees or less will generate an impact on the received signal by scalloping of the radiation patterns and may also result in a false lock-on. The recommended scan limit for Orbiter multipath corresponds to a minimum grazing angle of 3.5 degrees.

(3) Use of the spread spectrum (pseudo noise modulation) is recommended to create minimum cancellation impact and may be used during acquisition if the signal-to-noise ratio is adequate.

(4) Further use of this math tool may be applied to radar problems and changes in the baseline antenna patterns.
7.0 REFERENCES


\[ \tau_1 = \sin^{-1} \left( \frac{a_e \sin \left( \frac{d_2}{r_2} \right)}{r_2} \right) \text{ (radians)} \]

\[ \tau_2 = \cos^{-1} \left( \frac{a_e + z_2}{a_e} \cos \tau_3 \cos \tau_1 \right) \text{ (radians)} \]

\[ \tau_3 = \sin^{-1} \left( \frac{a_e \sin \left( \frac{d_1}{r_1} \right)}{r_1} \right) \text{ (radians)} \]

\[ \psi_1 = 90^0 - \tau_2 \text{ (radians)} \]

\[ \psi_2 = \psi_1 \text{ (radians)} \]

**WHERE:**

\[ d = \frac{\pi a e \theta}{180^0} \text{ (meters)} \]

\[ d_1 = \frac{d}{\theta_e} + p \cos \left( \frac{\phi + \pi}{3} \right) \text{ (meters)} \]

\[ p = \frac{2}{\sqrt{3}} \sqrt{\frac{a_e}{p^2}} (z_1 + z_2) + \left( \frac{d}{2} \right)^2 \text{ (meters)} \]

\[ \phi = \cos^{-1} \left( \frac{2a_e}{z_1 + z_2} \right) \text{ (meters)} \]

\[ d_2 = d - d_1 \]

\[ \theta_{\text{max.}} = \cos^{-1} \left( \frac{a_e}{z_1 + a_e} \right) + \cos^{-1} \left( \frac{a_e}{z_2 + a_e} \right) \text{ (radians)} \]

\[ \theta = \cos^{-1} \left( \frac{(z_1 + a_e)^2 + (z_2 + a_e)^2 - r^2}{2 (z_1 + a_e) (z_2 + a_e)} \right) \text{ (radians)} \]

**FIGURE 1 EARTH MULTIPATH GEOMETRY**
Ku-BAND ANTENNA

SHUTTLE ORBITER (FRONT VIEW)

\[ \phi' = \Omega + \frac{\pi}{2} \text{ (radians)} \]

\[ \psi_2 = \psi_1 \text{ (radians)} \]

\[ r_1 = \sqrt{a^2 + (a + z_2)^2 - 2a(a + z_2)\cos\frac{d_1}{a}} \text{ (meters)} \]  \text{(Reference I)}

\[ r_2 = \sqrt{a^2 + (a + z_1)^2 - 2a(a + z_1)\cos\frac{d_2}{a}} \text{ (meters)} \]  \text{(References I)}

WHERE:

\[ d = \frac{\pi a \theta}{180^\circ} \text{ (meters)} \]

\[ d_2^1 = a \theta_2 \text{ (90° grazing) (meters)} \]

\[ d_2 = d_2^1 - 1.1 \times 10^{-4} \text{ (meters)} \]

\[ d_1 = d - d_2 \text{ (meters)} \]

\[ \theta = \cos^{-1} \left( \frac{(z_1 + a)^2 + (z_2 + a)^2 - r^2}{2(z_1 + a)(z_2 + a)} \right) \]

FIGURE 2 ORBITER MULTIPATH GEOMETRY
FIGURE 3A GENERAL RADIATION PATTERN GEOMETRY

FIGURE 3B SUM RADIATION PATTERN GEOMETRY
MULTIPATH EFFECT FROM THE ORBITER VEHICLE

\[ \theta = 1.5^\circ \]

\[ F = 13.775 \text{GHz} \]

\[ \alpha = \pi \]

**Figure 4** MULTIPLE EFFECT FROM THE ORBITER VEHICLE (SUM PATTERN IMPACT)
FIGURE 5  MULTIPATH EFFECT FROM THE ORBITER VEHICLE
MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH

FIGURE 6  MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH'S SURFACE (FREQUENCY)
MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH

\[ F = 13.775 \text{GHz} \]

**Figure 7** MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH'S SURFACE (SUM PATTERN IMPACT, GRAZING ANGLE)
MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH

FIGURE 8  MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH'S SURFACE (DIFFERENCE PATTERN IMPACT, GRAZING ANGLE)

F = 13.775 GHz

GRAZING ANGLE (DEGREES)

OFFSET = 2.0 DEGREES
MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH

Figure 9: Multipath effect from sandy soil of the Earth's surface (sun pattern impact frequency)
MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH

FIGURE 10 MULTIPATH EFFECT FROM SANDY SOIL OF THE EARTH'S SURFACE (DIFFERENCE PATTERN IMPACT FREQUENCY)
FIGURE 11  MULTIPATH EFFECT FROM THE ORBITER VEHICLE
(GRAZING ANGLE)
Figure 13 Multipath Effect from the Orbiter Vehicle (Sum Pattern Impact, Grazing Angle)
FIGURE 14  MULTIPATH EFFECT FROM THE ORBITER VEHICLE
(DIFFERENCE PATTERN IMPACT, GRAZING ANGLE)
MULTIPATH EFFECT FROM THE ORBITER VEHICLE

FIGURE 15  MULTIPATH EFFECT FROM THE ORBITER VEHICLE
MULTIPATH EFFECT FROM THE ORBITER VEHICLE

FIGURE 17  MULTIPATH EFFECT FROM THE ORBITER VEHICLE
(DIFFERENCE PATTERN IMPACT, FREQUENCY)
APPENDIX B
MULTIPATH PROGRAMS (FORTRAN)
<table>
<thead>
<tr>
<th>COMMON</th>
<th>PREL(111D)</th>
<th>AFPL(111D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00100</td>
<td>10</td>
<td>COMMON</td>
</tr>
</tbody>
</table>

**Figure 13** EARTH MULTIPATH AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
1. CONDUCTIVITY OF TYPE OF EARTH SURFACE
2. RELATIVE DIELECTRIC CONSTANT OF TYPE OF EARTH SURFACE
3. ARC DISTANCE INCREMENT
4. FREQUENCY OF TRANSMITTED SIGNAL FROM TORUS TO ORBITER

READ(S,26,END=41)CON,RQ,E,INC,FREO

FORMAT(4016.9)
C ARC DISTANCE LIMITATION
READ(S,67)K

FORMAT(1016.9)
C ROUGHNESS FACTOR
H=2.

C DISTANCE FROM EARTH'S SURFACE TO ORBITER
Z1=4.399798405

C DISTANCE FROM EARTH'S SURFACE TO TORUS
Z2=3.578607
\[ I=1 \]
\[ J=1 \]
FI=3.141592653589793238

C DEGREE TO Radian CONVERSION
X=FI/180.

C RADIUS OF THE EARTH
A=.848933333307

C ANGLE BETWEEN LINE FROM ORBITER AND NORMAL TO EARTH'S TANGENT RELATIVE TO THE CENTER OF THE EARTH

CONT. ON PG. 2

FIGURE 19 FLOWCHART FOR EARTH MULTIPATH AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
ANGLE BETWEEN LINE FROM TORS AND NORMAL TO EARTH'S TANGENT RELATIVE TO THE CENTER OF THE EARTH

\[ \theta = \arccos \left( \frac{1}{r} \right) \]

\[ t = \theta \times \left( \frac{L}{X} \right) \]

\[ s = \theta \times \left( \frac{L}{X} \right) \]

MAXIMUM ANGLE Theta AT GROUND

\[ \theta = t + s \]

CONTINUE

TOTAL ARC DISTANCE BETWEEN TORS AND ORBITER

\[ D = \left( \frac{P}{x} \times \theta \right) \times 180 \]

\[ P = \left( \frac{2}{\sqrt{1+\theta}} \right) \times \theta \]

\[ \phi = \arccos \left( \frac{L}{D} \right) \]

ARC DISTANCE BETWEEN THE REFLECTION POINT ON THE SURFACE OF THE EARTH AND THE ORBITER

\[ D_2 = D / 2 + P \times \cos \left( \frac{\phi + \theta}{2} \right) \]

ARC DISTANCE BETWEEN TORS AND REFLECTION POINT OFF THE SURFACE OF THE EARTH

\[ D_1 = D - D_2 \]

TWO DISTANCE COMPONENTS OF INDIRECT SIGNAL

\[ R_{NG1} = \sqrt{\left( \frac{Z_1}{A} \right)^2 - \left( \frac{Z_2}{A} \right)^2 - 2 \times \left( \frac{Z_1}{A} \times \frac{Z_2}{A} \right) + 2 \times \left( \frac{1}{A} \right)} \]

\[ R_{NG2} = \sqrt{\left( \frac{Z_1}{A} \right)^2 - \left( \frac{Z_2}{A} \right)^2 - 2 \times \left( \frac{Z_1}{A} \times \frac{Z_2}{A} \right) + 2 \times \left( \frac{1}{A} \right)} \]

DISTANCE TRAVELED BY DIRECT SIGNAL

\[ R_{NG} = \sqrt{\left( \frac{Z_1}{A} \right)^2 - \left( \frac{Z_2}{A} \right)^2 - 2 \times \left( \frac{Z_1}{A} \times \frac{Z_2}{A} \right) + 2 \times \left( \frac{1}{A} \right)} \]

CONT. ON PG 3

FIGURE 19 CONTINUED
PATH DIFFERENCE FROM DIRECT AND INDIRECT SIGNAL

\[ \text{PDIFF} = \text{RANG1} + \text{RANG2} - \text{RANG} \]

ANGLE BETWEEN REFLECTED SIGNAL PATH AND LINE FROM EARTH'S CENTER TO THE ORBITER

\[ \text{TAU1} = \arcsin \left( \frac{A \times \sin (O2/A)}{R \times \sin (O2/A)} \right) / \text{RANG2} \]

ANGLE BETWEEN SIGNAL PATH OF INDIRECT SIGNAL FROM THE IDORS AND LINE FROM THE CENTER OF THE EARTH TO THE IDORS

\[ \text{TAU3} = \arcsin \left( \frac{A \times \sin (O1/A)}{R \times \sin (O1/A)} \right) / \text{RANG1} \]

COMPLEMENT OF GRAZING ANGLE

\[ \text{TAU2} = \arccos \left( \frac{\left( A + R^2 \right) \times \cos (\text{TAU3}) - \text{RANG1}}{\text{RANG1}} \right) / A \]

IF \((\text{TAU2} - \pi/2) = 23,23,22\)

- \text{GAMMA2} = \pi/2 - \text{TAU2}

IF \((\text{TAU2} - \pi/2) = 23,23,24\)

- \text{DIV1} = \text{RA} \times (\text{RANG1} + \text{RANG2} \times \text{OSA}) \times (\sin (\text{TAU2}) \times \cos (\text{TAU2}))

- \text{DIV2} = \text{OSORT} \left( \left( A + R^2 \right) \times \text{RANG1} \times \text{OSA} \times (\sin (\text{TAU3}) \times (A + R^2) \times \text{RANG2} \times \cos (\text{TAU3})) \right) \times (A + R^2) \times (A + R^2)

CONT. ON FIG. 4.  EARMU  PG. 3 OF 6

FIGURE 19 CONTINUED
FIGURE 19 CONTINUED

\[ F = \frac{1}{(Q - 2) \times 0.1} \times \sin(\theta) \times \gamma \times \beta \]

\[ G = \left( \frac{D}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ H = \left( \frac{E}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ I = \left( \frac{F}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ J = \left( \frac{G}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ K = \left( \frac{H}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ L = \left( \frac{I}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ M = \left( \frac{J}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ N = \left( \frac{K}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ O = \left( \frac{L}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ P = \left( \frac{M}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ Q = \left( \frac{N}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ R = \left( \frac{O}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ S = \left( \frac{P}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ T = \left( \frac{Q}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ U = \left( \frac{R}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ V = \left( \frac{S}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ W = \left( \frac{T}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ X = \left( \frac{U}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ Y = \left( \frac{V}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]

\[ Z = \left( \frac{W}{S} \right) \times \frac{1}{\sin(\theta)} \times \gamma \times \beta \]
C PHASE ANGLE CHANGE FOR A HORIZONTAL POLARIZED WAVE

\[ \text{PHAH} = \text{OATAN}(-0/(\text{OSIN(GAMAI(I))}-1)-\text{OATAN}(-0/(\text{OSIN(GAMAI(I)+1)}+1)+\text{PI} \]

C CIRCULAR REFLECTION COEFFICIENT

\[ \text{RC} = \text{DABS(FVH+RHH)}/2.1 \]

C PHASE ANGLE CHANGE FOR A CIRCULAR POLARIZED WAVE

\[ \text{PHAC} = (\text{PHAH}+\text{PHAH})/2. \]

C SCATTERING REFLECTION COEFFICIENT

\[ \text{SCAT} = \text{OSAT}(\text{DEXP}(-((4.*\text{PI}/\text{WAVE})*\text{H}*\text{OSIN(GAMAI(I))})*0.2)) \]

C MULTIPATH FIELD STRENGTH

\[ \text{FIELD} = 1. + ((\text{RANG}/(\text{RANG1}+\text{RANG2}))*\text{DIV})*\text{DABS(AC)}*\text{SCAT}*4.2 + 2.((\text{RANG}/(\text{RANG1}+\text{RANG2}))*\text{DIV})*\text{DABS(AC)}*\text{SCAT}*(\text{COS}(((2.*\text{PI}/\text{WAVE})*\text{RAD(F)}+\text{PHAC}) \]

C MULTIPATH FACTOR

\[ \text{RELP}(\text{J}) = \text{20.*DLOG}10(\text{DABS(FIELD)}) \]
\[ \text{GAMAI(\text{J})} = \text{GAMAI(I)}+(L./X) \]
\[ \text{GRAZE(\text{J})} = \text{SNGL}1(\text{GAMAI(J)}) \]
\[ \text{AMP}(\text{J}) = \text{SNGL}(\text{RELP(J)}) \]
\[ U = \text{THET1}-K \]
\[ I = \text{+L} \]
\[ J = \text{+L} \]
\[ \text{THET} = \text{THET}-\text{INC} \]

IF(BTHET.GT.U)

\[ T \]

GO TO 21

NAMELIST/FATIS/RELP,GAMAI

WRITE(6,FATIS)
NAMELIST/FATIS/AMP,GRAZE
WRITE(6,FATIS)

CONT. ON PG 6

C PAMMU

PG. 5 OF 6

FIGURE 19 CONTINUED
FIGURE 20  ORBITER MULTIPATH AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
<table>
<thead>
<tr>
<th>Parameter Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The grazing angle is defined as the angle between the line from the DORIS center to the reflection point on the surface of the target and the line from the target center to the reflection point on the surface of the orbit.</td>
</tr>
<tr>
<td>The angle of incidence for computing the reflection coefficient is 2(1 - cos(GAMA))/sin(GAMA).</td>
</tr>
<tr>
<td>The frequency for computation of the reflection coefficient is f = 1 GHz.</td>
</tr>
<tr>
<td>The parameters used to calculate the vertical polarization reflection coefficient are as follows:</td>
</tr>
<tr>
<td>- The electric constant used for computing the reflection coefficient is ( \epsilon_r ).</td>
</tr>
<tr>
<td>- The constant used for computing the reflection coefficient is ( F_{\text{ref}} ).</td>
</tr>
<tr>
<td>- The length of the transmitted signal from the DORIS center to the orbit is ( L ).</td>
</tr>
<tr>
<td>- The reflection point on the surface of the target is ( P ).</td>
</tr>
<tr>
<td>- The plane used to compute the reflection coefficient is ( P_{\text{el}} ).</td>
</tr>
<tr>
<td>- The center of the orbit is ( P_{\text{o}} ).</td>
</tr>
<tr>
<td>- The center of the target is ( P_{\text{tar}} ).</td>
</tr>
<tr>
<td>- The polarization angle is ( \theta ).</td>
</tr>
<tr>
<td>- The direction angle is ( \phi ).</td>
</tr>
<tr>
<td>- The range of the target is ( R ).</td>
</tr>
<tr>
<td>- The radius of curvature of the orbit is ( R_o ).</td>
</tr>
<tr>
<td>- The radius of the target is ( R_t ).</td>
</tr>
<tr>
<td>- The distance between the orbit center and the target center is ( D ).</td>
</tr>
<tr>
<td>- The direction angle is measured from the orbit center to the target center.</td>
</tr>
<tr>
<td>- The polarization angle is measured from the orbit center to the target center.</td>
</tr>
<tr>
<td>- The direction angle is measured from the orbit center to the target center.</td>
</tr>
</tbody>
</table>

**Figure 20 Continued**
### Parameters Used to Calculate Horizontal Polarization Reflection Coefficient

- \( \text{Phase Angle Change for a Horizontal Polarized Wave} \)
- \( \text{Horizontal Reflection Coefficient} \)
- \( \text{Circular Reflection Coefficient} \)
- \( \text{Scattering Reflection Coefficient} \)
- \( \text{Multipath Field Strength} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

### Phase Angle Change for a Vertical Polarized Wave

- \( \text{Phase Angle Change for a Vertical Polarized Wave} \)
- \( \text{Vertical Reflection Coefficient} \)
- \( \text{Circular Reflection Coefficient} \)
- \( \text{Scattering Reflection Coefficient} \)
- \( \text{Multipath Field Strength} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

### Vertical Reflection Coefficient

- \( \text{Multipath Path 2} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

### Circular Reflection Coefficient

- \( \text{Multipath Path 2} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

### Scattering Reflection Coefficient

- \( \text{Multipath Path 2} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

### Multipath Field Strength

- \( \text{Multipath Path 2} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

### Vertical Polarized Wave

- \( \text{Phase Angle Change for a Vertical Polarized Wave} \)
- \( \text{Vertical Reflection Coefficient} \)
- \( \text{Circular Reflection Coefficient} \)
- \( \text{Scattering Reflection Coefficient} \)
- \( \text{Multipath Field Strength} \)
- \( \text{Waiting for Path Field} \)
- \( \text{Multipath Path 1} \)

---

**END OF COMPILED; NO DIAGNOSTICS**

---

**FIGURE 20 CONTINUED**
CONDUCTIVITY OF THE ORBITER SKIN
RELATIVE DIELECTRIC CONSTANT OF THE ORBITER SKIN
FREQUENCY OF TRANSMITTED SIGNAL FROM TORS TO ORBITER
ACQUISITIONINCREMENT
LOOP DIMENSION

30
READ(S,26,END=41)CGN.ANIE,INC,FREQ,K

26
FORMAT(UD16.9,13)
C DISTANCE BETWEEN TORS AND ORBITER
Z2=3.53460203607
C DISTANCE BETWEEN ORBITER SKIN AND KU-BAND ANTENNA
Z1=1.0
C RMS ROUGHNESS IN METERS
H=0.0
I=1
PI=3.14159265358979
C DEGREE TO RADIAN CONVERSION
θ=PI/180.
C RADIUS OF THE ORBITER FUSELAGE
A=2.992100564328168
C ANGLE BETWEEN LINE FROM ANTENNA AND NORMAL TO ORBITER'S TANGENT RELATIVE TO ORBITER'S CENTER
SIN(Θ)=COS(A/(Z1+A))
C ANGLE BETWEEN LINE FROM TORS AND NORMAL TO ORBITER'S TANGENT RELATIVE TO THE ORBITER'S CENTER
C OS(Θ)=COS(A/(Z2+A))
C ARC DISTANCE BETWEEN THE REFLECTION POINT ON THE SURFACE OF THE ORBITER AND THE KU-BAND ANTENNA
CONT. ON PG 2

PG 1 OF 5

FIGURE 21 FLOWCHART FOR ORBITER MULTIPATH AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
\begin{align*}
C &= \text{TOTAL ARC DISTANCE BETWEEN ANTENNA AND TORS} \\
D &= A \times (\text{THETI} - \text{STHEI}) \\
B &= \text{THETI} - \text{DATAN}(21/02) \\
C &= \text{GRAZING ANGLE} \\
C &= \text{ARC DISTANCE BETWEEN TORS AND REFLECTION POINT OFF THE SURFACE OF THE ORBITER} \\
O &= 0 - D2 \\
C &= \text{COMPLEMENT OF GRAZING ANGLE} \\
\phi &= (\pi/2) - \text{GAMAL(1)} \\
B &= \text{THETL} - \pi/2 + \phi \\
C &= \text{TWO DISTANCE COMPONENTS OF INDIRECT SIGNAL} \\
\text{RANG2 - OSORT} &= (A \times 2 + (A + 21)) \times 2 - ((2 \times A \times (A + 21)) \times \cos(02/A1)) \\
\text{RANCl - OSORT} &= (A \times 2 + (A + 21)) \times 2 - ((2 \times A \times (A + 21)) \times \cos(01/A1)) \\
C &= \text{PATH DIFFERENCE FROM DIRECT AND INDIRECT SIGNAL} \\
P &= 2 \times ZL \times \tan \text{GAMAL(1)} \\
C &= \text{DIFFERENCE FROM DIRECT AND INDIRECT SIGNAL} \\
\text{ACOS} &= ((A \times 2 + (A + 21)) \times 2 - \text{RANG2} \times 2)/(2 \times A \times (A + 21)) \\
\text{DIS} &= \text{OSORT}((A \times \sin \text{GAMAL(1)}))/((A \times \sin \text{GAMAL(1)} + 2 \times \text{RANG2}) \times (1 + (2/(1/A1)) \times \sin(\text{SICK}))) \\
D &= \text{OSORT(DIS)} \\
C &= \text{WAVELENGTH OF TRANSMITTED SIGNAL FROM THE TORS TO THE ORBITER} \\
\text{WAVE} &= 3.008/\text{FREQ} \\
C &= \text{FUNCTION OF DIELECTRIC CONSTANT USED FOR COMPUTING REFLECTION COEF} \\
\text{CONT. ON PG 3}
\end{align*}
C FUNCTION OF DIELECTRIC CONSTANT AND FREQUENCY FOR COMPUTATION OF A REFLECTION COEFFICIENT

\[ Q = \frac{Y}{(2 \times S)} \]

C PARAMETERS USED TO CALCULATE VERTICAL POLARIZATION REFLECTION COEFFICIENT

\[ BV = (A0 \times 2 \times Y \times 2,1) / (S \times 2,1 \times D \times 2,1) \]
\[ PV = (2 \times (S \times A0 \times D \times Y)) / (S \times 2,1 \times D \times 2,1) \]

C VERTICAL POLARIZATION REFLECTION COEFFICIENT

\[ RV = DSORT((1 + BV / 2,1) \times (1 - \cos(2 \times \text{GAMAL}[1])) \times PV \times \sin(\text{GAMAL}[1])) / (1 + (BV / 2,1) \times (1 - \cos(2 \times \text{GAMAL}[1])) \times PV \times \sin(\text{GAMAL}[1])) \]

C PHASE ANGLE CHANGE FOR A VERTICAL POLARIZED WAVE

\[ \Phi V = \text{Datan}((Y \times \cos(\text{GAMAL}[1] - Q) / (A0 \times \sin(\text{GAMAL}[1] - S))) - \text{Datan}(Y \times \cos(\text{GAMAL}[1] + Q) / (A0 \times \sin(\text{GAMAL}[1] + S))) \]
\[ \Phi V = \Phi V + \Phi I \]

C PARAMETERS USED TO CALCULATE HORIZONTAL POLARIZATION REFLECTION COEFFICIENT

\[ BH = 1 / (S \times 2,1 \times D \times 2,1) \]
\[ PH = (2 \times S) / (S \times 2,1 \times D \times 2,1) \]

C HORIZONTAL REFLECTION COEFFICIENT

\[ RH = DSORT((1 + (BH / 2,1) \times (1 - \cos(2 \times \text{GAMAL}[1])) \times PH \cos(\text{GAMAL}[1]) / (1 + (BH / 2,1) \times (1 - \cos(2 \times \text{GAMAL}[1])) \times PH \cos(\text{GAMAL}[1])) \]

C PHASE ANGLE CHANGE FOR A HORIZONTAL POLARIZED WAVE

\[ \Phi H = \text{Datan}(-Q / (D \times \sin(\text{GAMAL}[1] - S)) - \text{Datan}(0 / (D \times \sin(\text{GAMAL}[1] + S))) \]
\[ \Phi H = \Phi H + \Phi I \]

C CIRCULAR REFLECTION COEFFICIENT

CONT. ON PG 4 OAHMU
EQ. 3 OF 5

FIGURE 21 CONTINUED
C PHASE ANGLE CHANGE FOR A CIRCULAR POLARIZED WAVE

PHAC = (PHA1 + PHA2)/2.

C SCATTERING REFLECTION COEFFICIENT

SCAT = QOSORT(0EXP(-((4.*PI)/WAVE)*K*USIN(GAMAL(I)**2))

C MULTIPATH FIELD STRENGTH

FIELD = 1. + (QIV*OABS(RC)*SCAT)**2 + 2. * (QIV*OABS(RC)*SCAT)*(DCOS(((2.*PI)/WAVE)*PADF1 + PHAC))

NAMELIST PATH6/FIELD
WRITE(6, PATH6)

C MULTIPATH FACTOR

RELP(I) = 20. * LOG10(OABS(FIELD))
GAMAL(I) = GAMAL(I)**x/X
AMP(I) = SNGL(RELP(J))
GRAZE(I) = SNGL(GAMAL(J))
WRITE(6, AMP(I), GRAZE(I)

IF(I.EQ.K)
F
T
GO TO 36
R3
I = I + 1
J = J + 1
D2 = D2 - INC
GAMAL(I) = QATAN(Z1/D2) - BTHE1

IF(I.LE.K)
F
T
CONT. ON PG 5

FIGURE 21 CONTINUED
FIGURE 21 CONTINUED
FIGURE 22 EARTH MULTIPATH IMPACT ON SUM AND DIFFERENCE CHANNEL AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
FIGURE 22 CONTINUED
FIGURE 22 CONTINUED
FIGURE 23  FLOWCHART FOR ORBITER MULTIPATH IMPACT ON SUM AND DIFFERENCE CHANNELS AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
C BESSEL FUNCTION CONSTANT

\[ m = 1 \]
\[ \pi = 3.14159265358979 \]

C DEGREE TO RADIANS CONVERSION

\[ x = \pi / 180. \]

C RADIUS OF THE ORBITER FUSELAGE

\[ R = 2.99200586328168 \]

C ANGLE BETWEEN LINE FROM ANTENNA AND NORMAL TO ORBITER'S TANGENT RELATIVE TO ORBITER'S CENTER

\[ \theta_1 = \arccos (A / (Z_1 + A)) \]

C ANGLE BETWEEN LINE FROM TORS AND NORMAL TO ORBITER'S TANGENT RELATIVE TO ORBITER'S CENTER

\[ \theta_2 = \arccos (A / (Z_2 + A)) \]

C ARC DISTANCE BETWEEN THE REFLECTION POINT ON THE SURFACE OF THE ORBITER AND THE KU-BAND ANTENNA

\[ d_2 = a \times \theta_1 \]

C TOTAL ARC DISTANCE BETWEEN ANTENNA AND TORS

\[ d = a (\theta_1 + \theta_2) \]

C GRAZING ANGLE

\[ \gamma = \arctan (Z_1 / d_2) \]

C ARC DISTANCE BETWEEN TORS AND REFLECTION POINT OFF THE SURFACE OF THE ORBITER

\[ d_1 = d - d_2 \]

C COMPLEMENT OF GRAZING ANGLE

\[ \gamma = \arcsin (Z_1 / d_2) \]

CONT. ON PG 3

FIGURE 23 CONTINUED
\[
\begin{align*}
\text{FIGURE 23 CONTINUED} & \\
\text{TWO DISTANCE COMPONENTS OF INDIRECT SIGNAL} & \\
RNG2 &= \text{OSORT}(A \times 2 + (A+Z1) \times 2 - (2. \times A) \times (A+Z1) \times \cos(D1/A1)) \\
RNG1 &= \text{OSORT}(A \times 2 + (A+Z2) \times 2 - (2. \times A) \times (A+Z2) \times \cos(D1/A1)) \\
\text{PATH DIFFERENCE FROM DIRECT AND INDIRECT SIGNAL} & \\
\text{PROF} &= 2. \times Z1 \times \text{TAN}(|\text{GAMAL}|) \\
\text{DIVERGENCE FACTOR} & \\
SICK &= 0. \cos((A \times 2 + (A+Z1) \times 2 - RANG2 \times 2) / (2. \times A \times (A+Z1))) \\
\text{WAVELENGTH OF TRANSMITTED SIGNAL FROM THE TORUS TO THE ORBITER} & \\
WAVE &= 3.008 / \text{FREQ} \\
\text{FUNCTION OF DIELECTRIC CONSTANT USED FOR COMPUTING REFLECTION COEFFICIENT} & \\
Y &= 1.80010 \times (\text{CON/FREQ}) \\
\text{PARAMETER USED TO CALCULATE REFLECTION COEFFICIENT} & \\
S &= \text{OSORT}(\text{OSORT}((\text{DIE} - (1./2.) \times (1. + \text{OCOS}((2. \times \text{GAMAL}(1) || 2. \times Y || 2.1) + (R \times \text{DIE} - (1./2.) \times (L. + \text{OCOS}((2. \times \text{GAMAL}(1) || 1./2.) \times \text{OSIN}(|\text{SICK}|)) \\
\text{FUNCTION OF DIELECTRIC CONSTANT AND FREQUENCY FOR COMPUTATION OF REFLECTION COEFFICIENT} & \\
O &= Y / (2. \times S) \\
\text{PARAMETERS USED TO CALCULATE VERTICAL POLARIZATION REFLECTION COEFFICIENT} & \\
B Vin &= (R \times D(E \times 2.) \times Y \times 2.1) / (S \times 2.) + Q \times 2.1) \\
P Vin &= (2. \times S \times D(E \times Q \times Y) / (S \times 2.) + Q \times 2.1) \\
V Vin &= \text{OSORT}((1. \times (B Vin / 2.) \times (L. - \text{OCOS}((2. \times \text{GAMAL}(1) || \text{PV} \times \text{OSIN}((2. \times \text{GAMAL}(1)| / (1. \\
\text{CONT. ON PG 4} & \\
\text{FIGURE 23 CONTINUED} & \\
\text{ORASDO} & \\
\text{PG 3 OF 10} & \\
\end{align*}
\]
C PHASE ANGLE CHANGE FOR A VERTICAL POLARIZED WAVE

\[ \text{PHV} = \text{ATAN} \left( \frac{Y \times \text{OSIN}(\text{GAMAL(I)}) - D}{R \times \text{EIN}(\text{GAMAL(I)}) - S} \right) - \text{ATAN} \left( \frac{Y \times \text{OSIN}(\text{GAMAL(I)}) + D}{R \times \text{EIN}(\text{GAMAL(I)}) + S} \right) \]

\[ \text{PHV} = \text{PHV} + \pi \]

C PARAMETERS USED TO CALCULATE HORIZONTAL POLARIZATION REFLECTION COEFFICIENT

\[ \text{BH} = \frac{L}{(S \times 2 + O \times 2)} \]
\[ \text{PH} = \frac{2 \times S}{(S \times 2 + O \times 2)} \]

C HORIZONTAL REFLECTION COEFFICIENT

\[ \text{RH} = \text{OSQRT} \left( \frac{(L + (BH/2.1) \times (1 - \text{OCOS}(2 \times \text{GAMAL(I)})) - PH \times \text{OSIN}(\text{GAMAL(I)}) \times (L + (BH/2.1) \times (1 - \text{OCOS}(2 \times \text{GAMAL(I)})) + PH \times \text{OSIN}(\text{GAMAL(I)}))}{(L + (BH/2.1) \times (1 - \text{OCOS}(2 \times \text{GAMAL(I)})) + PH \times \text{OSIN}(\text{GAMAL(I)}) \times (L + (BH/2.1) \times (1 - \text{OCOS}(2 \times \text{GAMAL(I)})) - PH \times \text{OSIN}(\text{GAMAL(I)}) \times (L + (BH/2.1) \times (1 - \text{OCOS}(2 \times \text{GAMAL(I)})) + PH \times \text{OSIN}(\text{GAMAL(I)}))} \right) \]

C PHASE ANGLE CHANGE FOR A HORIZONTAL POLARIZED WAVE

\[ \text{PHAH} = \text{ATAN} \left( \frac{-Q}{(\text{OSIN}(\text{GAMAL(I)}) - S)} \right) - \text{ATAN} \left( \frac{Q}{(\text{OSIN}(\text{GAMAL(I)}) + S)} \right) \]

C CIRCULAR REFLECTION COEFFICIENT

\[ \text{RC} = \text{OSQRT} \left( \frac{(\text{AV} + \text{RH})}{2.1} \right) \]

C PHASE ANGLE CHANGE FOR A CIRCULAR POLARIZED WAVE

\[ \text{PHAC} = (\text{PHAH} + \text{PHAC} + \pi) / 2 \]

C SCATTERING REFLECTION COEFFICIENT

\[ \text{SCAT} = \text{OSQRT} \left( \text{DEXP}(\frac{(1 - \text{PI} / \text{WAVE}) \times \text{OSIN}(\text{GAMAL(I)})}{2} \right) \]

C MULTIPATH FIELD STRENGTH (INDIRECT SIGNAL)

\[ \text{FIELD} = \text{DIV} \times \text{ABS} \times \text{SCAT} \times 2 + 2 \times \text{DIV} \times \text{ABS} \times \text{SCAT} \times \text{OCOS} \left( \frac{2 \times \text{PI}}{\text{WAVE}} \right) \times \text{PRO} +\text{PHAC} \]

C BESSEL FUNCTION SUBPROGRAM (SUM PATTERN)

\[ \text{X2} = ((\text{PI} \times O \times \text{AV} / \text{WAVE}) \times \text{OSIN}(\text{GAMAL(I)}) \times (\text{PI} \times O \times \text{AV} / \text{WAVE}) \times \text{OSIN}(\text{GAMAL(I)})) \]

C BESSEL FUNCTION LIMITATION

CONT. ON PG 5

FIGURE 23 CONTINUED
I

P

TTY

B-29

Y1-Y1+2

I

NT= (M+}!2)12 .

6E1'R=2.0* [NT+Y l

I6E1"A=BE1A+.001

RFL,G=0.0

E1FLG:-O. [l

FCLG=0.0

OFLG::0.0

EFLG=L.O

Z=1.0

FFLG=OCOS((1gETA-2.1*(P1/2.1))'

CONTINUE

IF(IBETA—M)S0.6L.60

CFLG=EFLG

60

CONTINUE

IF(IBETA.EQ.0)

T

GO TO 62

F

IF(F6FLG.GT.0000001)

F

CONT. ON PG 6

FIGURE 23 CONTINUED
BETA=2.0*(INT+1)
IBETG=BETA+.001
AFLG=0.0
BFLG=0.0

EFLG=0.0
OFLG=0.0
EFLC=1.0
Z=1.0
FFLG=0.0 (IBETG-2.1)*PI/2.)

CONTINUE

IF (IBETG-M) 72, 71, 72

71

CFLG=EFLG

CONTINUE

72

IF (IBETG.EQ.0)

T

GO TO 77

F

IF (BFLG .GT. 0.000001)

F

CONT. ON FG 8

FIGURE 23 CONTINUED
\[
\text{DIFF}=\sin(\text{PT} \times (\text{GAMAL}[I] - \text{PT}[L])/\text{HPSW}) + \text{PT} \times \sin(\text{PT} \times (\text{GAMAL}[I] - \text{PT}[L])/\text{HPSW})
\]

\[
\text{YLMP}[I]=\text{DAABS(\text{DIFF}+(\text{DIFF} \times \text{FIELD}))}
\]

\[
C \quad \text{DIFFERENCE PATTERN FIELD}
\]

\[
\text{DP}[I]=20 \times \text{LOG10} (\text{YLMP}[I])
\]

\[
\text{GAMAL}[I]=\text{GAMAL}[I] \times (L./X)
\]

\[
\text{PT}[L]=\text{PT}[L] \times (L./X)
\]

\[
\text{LSP}[I]=\text{SP}(I)
\]

\[
\text{LOP}[I]=\text{DP}[I]
\]

\[
\text{MLSP}[I]=\text{SNQL} (\text{LSP}[I])
\]

\[
\text{NLDP}[I]=\text{SNQL} (\text{LOP}[I])
\]

\[
\text{GRAF} = \text{SNQL} (\text{GAMAL}[I])
\]

\[
\text{PT}[L]=\text{PT}[L] \times X
\]

\[
[i=I+L]
\]

\[
[j=J+1]
\]

\[
C \quad \text{ARCODISTANCE INCREMENT}
\]

\[
O2=O2-\text{INC}
\]

\[
\text{IF}(I, \text{EQ}, 184)
\]

\[
T \quad \text{GO TO 84}
\]

\[
F \quad \text{CONTINUE}
\]

\[
\text{GRAF}[I]=\text{DTRAN} (Z1/O2) - \text{BTHET}
\]

\[
\text{IF}(I, \text{LT}, K)
\]

\[
T \quad \text{GO TO 21}
\]

\[
F \quad \text{GO TO 21}
\]

\[
\text{GO TO 21}
\]

\[
\text{CONTINUE}
\]

\[
\text{CONT. ON FIG 10}
\]

\[
\text{CONT. ON FIG 10}
\]

\[
\text{FIGURE 23 CONTINUED}
\]
NAMELIST/OCEP/PT
WRITE(G,OCEP)
NAMELIST/PATH2/GRAZE
WRITE(G,PATH2)
NAMELIST/MULTI/LSP,LDP
WRITE(G,MULTI)

DO 90 I=1,L83

WRITE(BIMLSP(I),GRAZE(I),NLOP(I))

90 CONTINUE
ENDFILES

C OFFSET INCREMENT

PT(L+1)=PT(L)+2.22222222-2
L=L+1

IF(L.LT.21)

T

GO TO 80

F

GO TO 30

CONTINUE
END

FIGURE 23 CONTINUED
Figure 24  ORBITER MULTIPATH IMPACT ON SUM AND DIFFERENCE CHANNELS AS A FUNCTION OF GRAZING ANGLE OR FREQUENCY
FIGURE 24 CONTINUED
FIGURE 24 CONTINUED
FIGURE 24 CONTINUED
FIGURE 24 CONTINUED
FIGURE 24 CONTINUED
Figure 25: Flowchart for Earth multipath impact on sum and difference channels as a function of grazing angle or frequency.
K=1
PI=3.141592653589793238

C DEGREE TO RADIANS CONVERSION
X=PI/180.

C RADIUS OF THE EARTH
A=.668933333337

C ANGLE BETWEEN LINE FROM ORBITER AND NORMAL TO EARTH'S TANGENT RELATIVE TO THE CENTER OF THE EARTH
THET1=ACOS(A/(22-A))

C ANGLE BETWEEN LINE FROM TORS AND NORMAL TO EARTH'S TANGENT RELATIVE TO THE CENTER OF THE EARTH
STHET=ACOS(A/(21-A))
T1=THET1*(1./X)
ST=STHET*(1./X)

C MAXIMUM ANGLE THETA AT GRASSING
BTC1=THET1+ST

A2=
CONTINUE

C TOTAL ARC DISTANCE BETWEEN TORS AND ORBITER
0=(PI*K*A*BTC1)/180.
P=(2./OSQRT(3.11)*(OSQRT(A*(21+22))+(0/2.1)**2.1)
PHI=ACOS((2.*A)*(21-22)*0/P**3.)

C ARC DISTANCE BETWEEN REFLECTION POINT ON THE SURFACE OF THE EARTH AND THE ORBITER
Q2=Q2/2+P*COS((PHI+PI)/3.1)

C ARC DISTANCE BETWEEN TORS AND REFLECTION POINT OFF THE SURFACE OF THE EARTH
Q1=Q1-Q2

C TWO DISTANCE COMPONENTS OF INDIRECT SIGNAL

CONT. ON PG 3

FIGURE 25 CONTINUED
\[
\begin{align*}
\text{RANG1} &= \text{SORT}(A \times 2 + (A + Z2) \times 2 - \frac{(1 + (Z2 / A)) \times (Z2 / A)}{2}) \times \text{COS}(Z1 / A) \\
\text{RANG2} &= \text{SORT}(A \times 2 + (A + Z2) \times 2 - \frac{(1 + (Z2 / A)) \times (Z2 / A)}{2}) \times \text{COS}(Z2 / A) \\
\text{C} &= \text{DISTANCE TRAVELED BY DIRECT SIGNAL} \\
\text{RANG} &= A \times \text{SORT}(2L / A) \times 2 + (Z2 / A) \times 2 - \frac{(1 + (Z2 / A)) \times (Z2 / A)}{2} \times (1 + (Z2 / A)) + (22 / A) \times (Z2 / A) \times (Z2 / A) \times (1 - \text{COS}(Z2 / A)) \\
\text{C} &= \text{PATH DIFFERENCE FROM DIRECT AND INDIRECT SIGNAL} \\
\text{PADIF} &= \text{RANG1} + \text{RANG2} - \text{RANG} \\
\text{C} &= \text{ANGLE BETWEEN REFLECTED SIGNAL PATH AND LINE FROM EARTH'S CENTER} \\
\text{TAU1} &= \text{ASIN}(A \times \text{COS}(Z2 / A) / \text{RANG2}) \\
\text{C} &= \text{ANGLE BETWEEN SIGNAL PATH OF INDIRECT SIGNAL FROM THE TORS AND LINE FROM THE CENTER OF THE EARTH TO THE TORS} \\
\text{TAU3} &= \text{ASIN}(A \times \text{COS}(Z2 / A) / \text{RANGL}) \\
\text{C} &= \text{COMPLEMENT OF GRAZING ANGLE} \\
\text{TAU2} &= \text{ACOS}((A + Z2) \times \text{COS}(\text{TAU3}) - \text{RANGL} / A) \\
\text{IF} (\text{TAU2-COMP}) &< 23.23.22 \\
\text{THET} &= \text{THET} - 1 \\
\text{IF} (\text{TAU2-COMP}) &> 23.23.24 \\
\text{CONTINUE} \\
\text{C} &= \text{GRAZING ANGLE} \\
\text{CONT. ON PG 4.}
\end{align*}
\]
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B-44

GRMFIL=PI/2

DIVL=A*(RANG1+RANG2)*OSORAT(DSIN(TAU2)*DCOS(TAU2))

DIV2=OSORAT(((A+Z2)*RANG1*DCOS(TAU3)+(A+Z1)*RANG2*DCOS(TAU11)*(A+Z1)

*O2)*OSIN(BTHE1*X1))

DIV=DIVL/DIV2

C FREQUENCY OF TRANSMITTED SIGNAL FROM TORS TO ORBITER

| I | FREQ(I)=13.000000009 |
| N=M-1 |

DO 50 I=1,N

FREQ(I+1)=FREQ(I)+24.545406

= 50 CONTINUE

DO 40 I=1,M,L

C WAVELENGTH OF TRANSMITTED SIGNAL FROM THE TORS TO THE ORBITER

WAVE=3.006/FREQ(I)

C FUNCTION OF DIELECTRIC CONSTANT USED FOR COMPUTING REFLECTION COEFFICIENT

Y=1.80010*(CON/FREQ(I))

C PARAMETER USED TO CALCULATE REFLECTION COEFFICIENT

S=OSORAT((OSORAT((D0IE-(1./2.)*(1.+DCOS(2.*GAMAL)))**2.+Y**2.1+(D0IE

-(1./2.)*(1.+DCOS(2.*GAMAL)))**2.1

C FUNCTION OF DIELECTRIC CONSTANT AND FREQUENCY, FOR COMPUTING REFLECTION COEFFICIENT

Q=Y/(2.*S)

C PARAMETERS USED TO CALCULATE VERTICAL POLARIZATION REFLECTION COEFFICIENT

CONT. ON PG 5

FIGURE 25 CONTINUED
\[
BY = (\text{ADGF} + 2. + \text{GRF} + 2.1)/(\text{SHGF} + 2. + \text{GRF} + 2.1)
\]
\[
PV = (2.\times(\text{S}\times\text{GRF} + \text{Y}))/(\text{SHGF} + 2. + \text{GRF} + 2.1)
\]

C \hspace{1cm} \text{VERTICAL POLARIZATION REFLECTION COEFFICIENT}

\[
RV = \text{DOSORT}(1. + (BY/2.1\times(1. - \text{OCOS}(GRF) + \text{GMAL})) - PV\times\text{OSIN(GMAL)})/(1. + (BY/2.1\times(1. - \text{OCOS}(GRF) + \text{GMAL})) + PV\times\text{OSIN(GMAL)})
\]

C \hspace{1cm} \text{PHASE ANGLE CHANGE FOR A VERTICAL POLARIZED WAVE}

\[
\text{PHAV} = \text{DQATAN}((\text{Y}\times\text{OSIN(GMAL)} - 0.)/(\text{ADGF}\times\text{OSIN(GMAL)} - 0.)) - \text{DQATAN}((\text{Y}\times\text{OSIN(GMAL)} + 0.)/(\text{ADGF}\times\text{OSIN(GMAL)} + 0.)) + \pi
\]

C \hspace{1cm} \text{PARAMETERS USED TO CALCULATE HORIZONTAL POLARIZATION REFLECTION COEFFICIENT}

\[
BH = 1. + (SGF2. + QGF2.1)
\]
\[
PH = (2.\times S1.)/(SGF2. + QGF2.1)
\]

C \hspace{1cm} \text{HORIZONTAL REFLECTION COEFFICIENT}

\[
RH = \text{DOSORT}(1. + (BH/2.1\times(1. - \text{OCOS}(GRF) + \text{GMAL})) - PH\times\text{OSIN(GMAL)})/(1. + (BH/2.1\times(1. - \text{OCOS}(GRF) + \text{GMAL})) + PH\times\text{OSIN(GMAL)})
\]

C \hspace{1cm} \text{PHASE ANGLE CHANGE FOR A HORIZONTAL POLARIZED WAVE}

\[
\text{PHAH} = \text{DQATAN}(-Q/(\text{OSIN(GMAL)} - S)) - \text{DQATAN}(Q/(\text{OSIN(GMAL)} + S)) + \pi
\]

C \hspace{1cm} \text{CIRCULAR REFLECTION COEFFICIENT}

\[
AC = (\text{DABS}(RV + RH)/2.1)
\]

C \hspace{1cm} \text{PHASE ANGLE CHANGE FOR A CIRCULAR POLARIZED WAVE}

\[
\text{PHAC} = (\text{PHAV} + \text{PHAH})/2.
\]

C \hspace{1cm} \text{SCATTERING REFLECTION COEFFICIENT}

\[
\text{SCAT} = \text{DOSORT}(\text{DEXP}(-(1.\times\pi)/\text{WAVE})\times\text{HOSIN(GMAL)}))\times2)
\]

C \hspace{1cm} \text{MULTIPATH FIELD STRENGTH (INDIRECT SIGNAL)}

\[
\text{FIELD} = ((\text{RANG} + \text{RANG} + \text{RANG})\times\text{DVSABS(AC)\timesSCAT})\times2. + 2. + ((\text{RANG} + \text{RANG} + \text{RANG})\times\text{DVSABS(AC)\timesSCAT})\times\text{OCOS((2.\times\pi)/\text{WAVE}\times\text{ADGF} + \text{PHAC}))
\]

C \hspace{1cm} \text{BESSEL FUNCTION ARGUMENT}

\[
X2 = ((\pi\times\text{O1A})/\text{WAVE}\times\text{OSIN(GMAL - FT1)})
\]

CONT. ON PG 6

FIGURE 25 CONTINUED
IF (BFLG=0) GOTO 65

63
BFLG=1.0
AFLG=AFLG+EFLG
GO TO 65

64
BFLG=0.0

65
CONTINUE

Z=((2.*BETA)*(EFLG+((-1.)*DFLG*X2)/(2.*BETA)))/X2
DFLG=EFLG
EFLG=2
BETA=BETA-1.0

GO TO 66

66
AFLG

Z=(2.*AFLG1+EFLEC
AFLG=CFLG/2

C DIRECT SIGNAL FIELD (SUM PATTERN)
SMF=(2.*WAVE*AFLG1)/(PI*DA*OSIN(CAM9L-PT(L)))

C BESSEL FUNCTION SUBPROGRAM
X3=((PI*DA/WAVE)*OSIN(-GAM9L-FT(L))

C BESSEL FUNCTION ARGUMENT
Y1=50

CONT. ON PG 8.
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0 = 0, 0
Y = Y + Z
INT = (K + X3)/2
BETA = 2.0 * INT + Y
AFLG = 0.0
BFLG = 0.0
CFLG = 0.0

DFLG = 0.0
EFLG = 1.0
Z = 1.0
FFLG = DCOS((BETA - 2.1) * (PI/2.1))

A5

70 CONTINUE

IF (BETA - K) 72, 71, 72

71 CFLG = EFLG

72 CONTINUE

R = 0

IF (BETA - R) 73, 72, 73

73 CONTINUE

CONT. ON PG 9

FIGURE 25 CONTINUED
IF (BFLG < 74, 74.75)

74
BFLG = 1.0

AFLG = AFLG + EFLG

GO TO 76

75
BFLG = 0.0

76
CONTINUE

76

z = (2BETA) * (EFLG + (-1) * DFLG * X3) / (2BETA) / X3

DFLG = EFLG

EFLG = z

BETA = BETA - 1.0

GO TO 70

70

2 = (2 * AFLG) * EFLG

AFLG = CFLG / z

C INDIRECT SIGNAL FIELD (SUM PATTERN)

SMP1 = (2 * WAVE * AFLG) / (PI * DI * OSIN(-GAMAL - PI * (L)))

IND = SMP1

XLMP[I] = DABS(SMP + (IND * FIELD))

C SUM PATTERN FIELD

SP[I] = 20 * OLOG10(XLMP[I])

C DIFFERENCE PATTERN FUNCTION

C DIRECT SIGNAL

CONT. ON PG -10

FIGURE 25 CONTINUED
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R-50

FIGURE 25 CONTINUED