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A Ray Trace Program for Line-of-Sight Microwave Communication Links
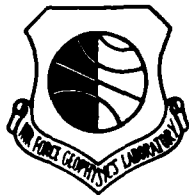
JAMES F. MORRISSEY

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ATMOSPHERIC SCIENCES DIVISION   PROJECT 6670

AIR FORCE GEOPHYSICS LABORATORY

HANSCOM AFB, MA 01731

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A ray trace program tailored to Line-of-Sight (LOS) communication links is described. The principal products of the program are the following: (1) a ray trace diagram, (2) a time of arrival plot, and (3) an angle of arrival plot. The ray trace allows for a complex terrain, multiple meteorological profiles, and has options for the type of reflection to be used.

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Preface

I thank Ms. Joan Freni of the Systems and Applied Sciences Corporation who is solely responsible for the programming. I also thank Mrs. Helen Connell for typing the manuscript.

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A Ray Trace Program for Line-of-Sight
Microwave Communication Links

1. INTRODUCTION

An effort was initiated in September 1981 to obtain high resolution vertical pro-
files of the microwave index of refraction contemporaneously with link delay
measurements on line-of-sight (LOS) communication links. The vertical profiles of
the index of refraction were obtained using a portable balloon borne radiosonde
system. These systems are capable of measuring the refractive index of about every
5 sec which in our application means about 10 m in altitude. These soundings could
be taken as close in time as 30 min and at more than one location along the link.

An atmospheric propagation model was sought that would take into account
complex terrain and horizontal gradients in refractivity. These constraints together
with the high frequencies (10-15 GHz) made a ray trace model seem the most attrac-
tive alternative. Although we used an existing ray trace model for some early in-
sights, [1] it was evident we needed a model tailored to our specific needs. This
report discusses the capabilities and mechanics of the model developed.

1. Wasky, R.P. (1977) A Geometric Optics Model for Calculating the Field
Strength of Electromagnetic Waves in the Presence of a Tropospheric Duct,
MSEE Thesis, University of Dayton, Ohio.

2. RAY TRACE MODEL DESCRIPTION

The computer program developed was written in Fortran/V for use on the AFGL Cyber 750 computer. Because it is modular, it is easily modified for application to other ray trace problems. It is written specifically for line-of-sight communication links and uses meteorological data from radiosonde measurements.

One version accepts meteorological soundings at several locations. It requires information on the vertical profile of refractive index, the height of the antennas, and the earth contour directly under the transmission beam. The refractive data are provided at "significant" levels determined in the same general manner that standard radiosonde data "significant" levels are selected. The earth contour data are presented as a sequence of points (2-dimensional) where the earth's surface slope changes significantly. These points are nodes. The program uses the refractive index data to calculate ray trajectories and the earth contour to determine shielding effects or reflections.

The model has two basic versions. One is designed to have a single vertical profile of refractive index that assumes the atmosphere is horizontally homogeneous. The other can accept several profiles along the link and then interpolates refractive structure between profiles. If the antennas are outside the last radiosonde, the model assumes horizontal homogeneity in the end portions. There are several control parameters, including the maximum and minimum initial ray angle, the angular spacing of the rays, and whether the operator wants no earth reflection, wants specular earth reflection, or wants all reflected rays directed to the receiving antenna.

The calculated trajectories are plotted on a flat earth profile with a vertical scale enlarged 58 times relative to the horizontal scale. The time of arrival of those rays that reach the end of path are presented in a second graph as a function of altitude. The time of arrival graph shows the times relative to the time of arrival of the ray with the shortest propagation time. A third graph gives the angle of arrival of these rays.

Figures 1 through 4 are presented to demonstrate the various options and versions of the model available to the operator. Data from a communication link in Germany over the Rhine River on 4 Nov 1981 were used for this example.

Figure 1a shows the version of the program designed for one refractive index input profile. This refractive structure profile is shown by the pair of lines at a distance of about 67 km along the path. The line that is exactly vertical indicates the location on the link where the radiosonde was released. The second line is the refractive index data profile (in m units) derived from that radiosonde (see Appendix A for m unit definition). The m scale is shown at the top of the plot. The altitude is given in meters, the distance in km. All rays emanate from the antenna

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on the left hand end of the link. Only the maximum and minimum rays are plotted near the antenna because the density of the rays would cause the plotting paper to saturate and tear. This example is for the case where no reflection has been selected so all rays that strike the ground are truncated. The ground is represented by the height profile at the bottom of the plot.

Figure 1b shows the relative arrival times (delays) of those rays that arrive at the end of the link and have neither struck the ground nor gone above the maximum plotting height. Figure 1c shows the angle of arrival of the same set of rays as those in Figure 1b. Both the arrival time and angle are shown at the altitude of the ray at end end of the link. If a horizontal line is drawn from 1b and 1c to 1a the ray corresponding to the plotted arrival time and delay can be identified. This is done with a dashed line at a height of 800 m for illustrative purposes.

Figure 2 shows the same case as shown in Figure 1, using the option that allows specular reflection. To keep the plot (Figure 2a) from getting too confusing, plotting of the following rays have been suppressed: reflected rays that go out of the plotted area at the top, rays that have a reflection angle of greater than 5°, and rays that re-intersect the earth (that is, a second reflection) are suppressed at the original intersection. In the time delay plot (Figure 2b) and the angle plot (Figure 2c) the reflected rays that reach the end of the link are indicated by the hexagonal symbols.

Figure 3 shows the same case using the option that directs all reflected rays toward the receiving antenna. This option adds additional rays over the number determined by the maximum and minimum angle and angular increment. These additional rays are chosen by directing rays toward the inflection points used to describe the earth's contour, which are then reflected toward the receiver. Only those rays that are unshielded in both legs of the journey are plotted. This type of reflected ray is depicted with a triangle symbol in the delay (Figure 3b) and angle (Figure 3c) plots.

Figure 4 illustrates the version of the profile designed for input from more than one radiosonde. In this case two soundings have been used, one at 42 km and one at 67 km. The ray trajectory is computed using only the 42 km sounding (horizontal homogeneity) up to 42 km, refractive data between 42 and 67 km are compiled by linear interpolation, and beyond 67 km only the sounding at 67 km is used. An earlier version using extrapolation in the outside zones was tried but resulted in very unrealistic refractive gradients and, consequently, ray traces. This version also has the reflection options shown for the single profile case.
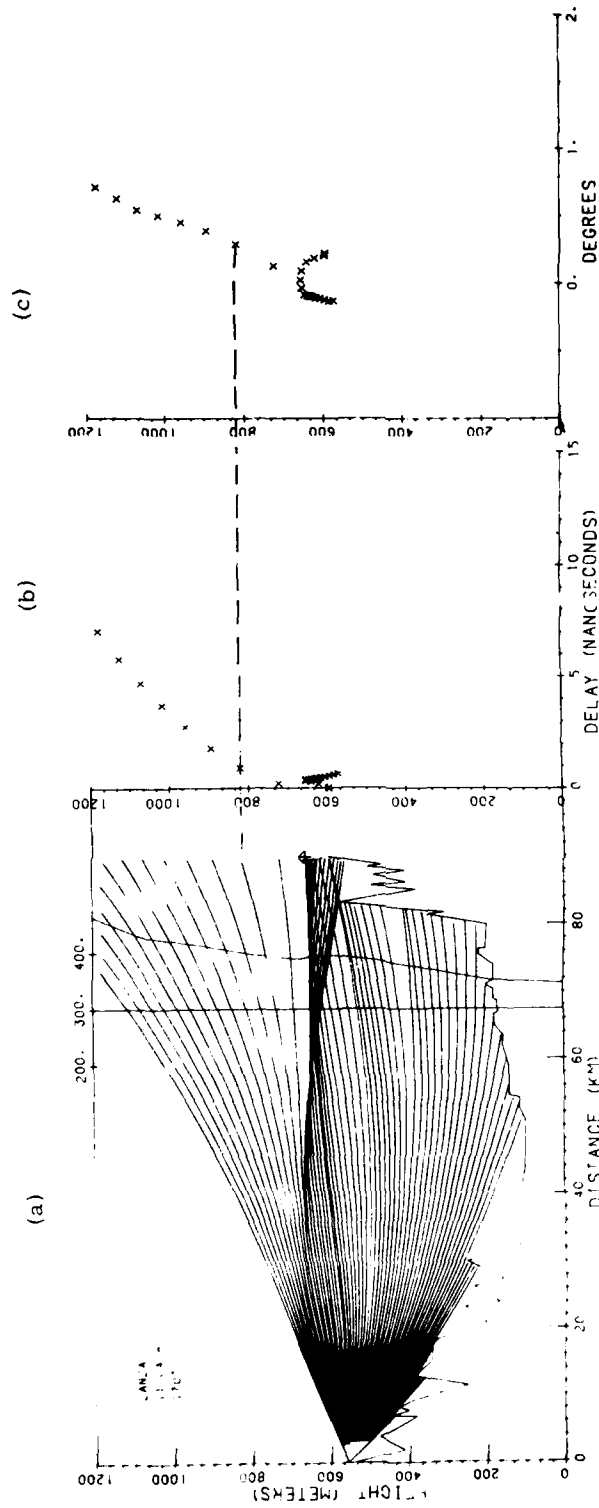
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Figure 1. Ray Trace for Langerkopf-Friolzheim Link on 4 Nov 1981 Without Reflections
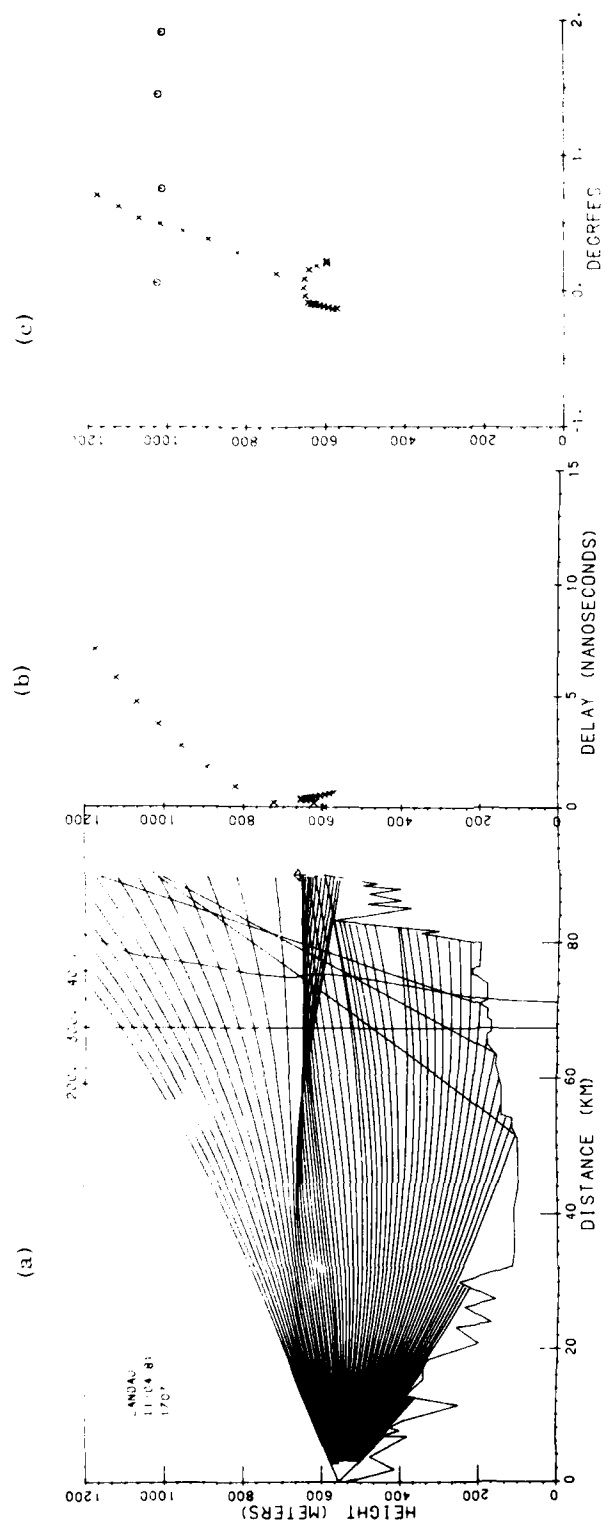
Figure 2. Ray Trace for Langerkopf-Friolzheim Link on 4 Nov 1981 With Specular Reflection From Earth
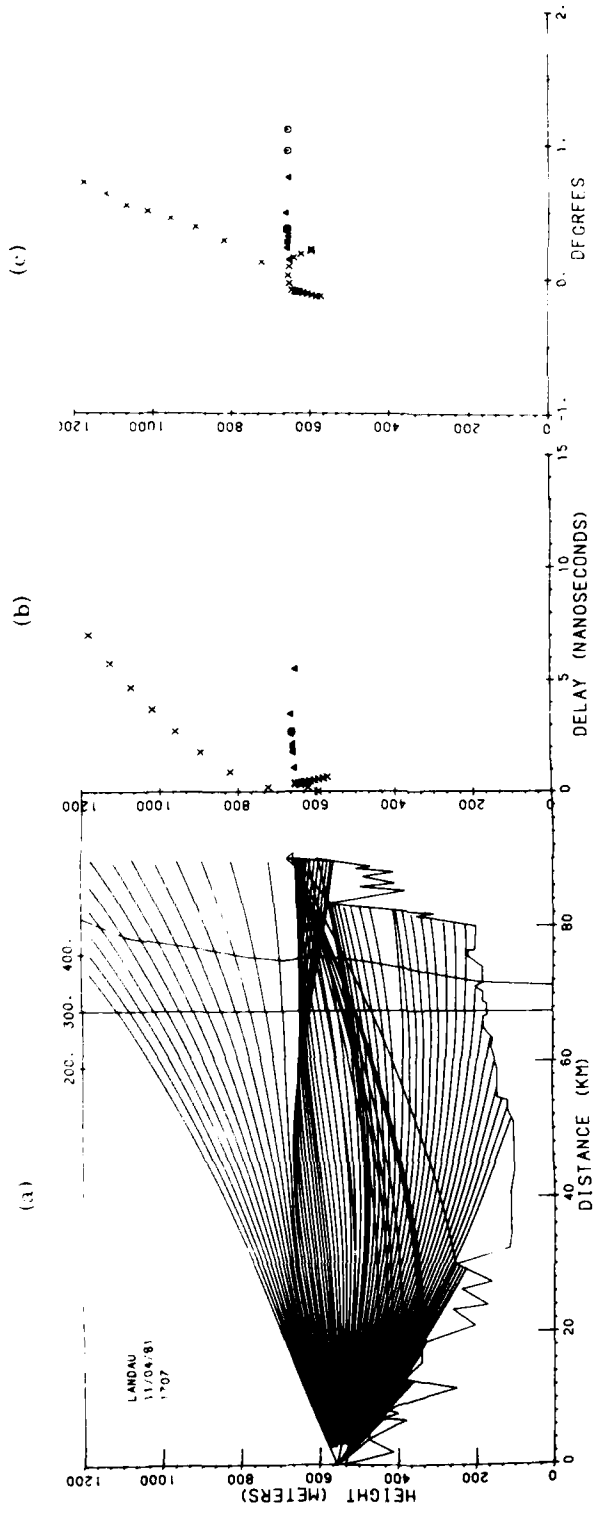
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Figure 3. Ray Trace for Langerkopf-Friolzheim Link on 4 Nov 1981 With Reflections Directed to Receiving Antenna
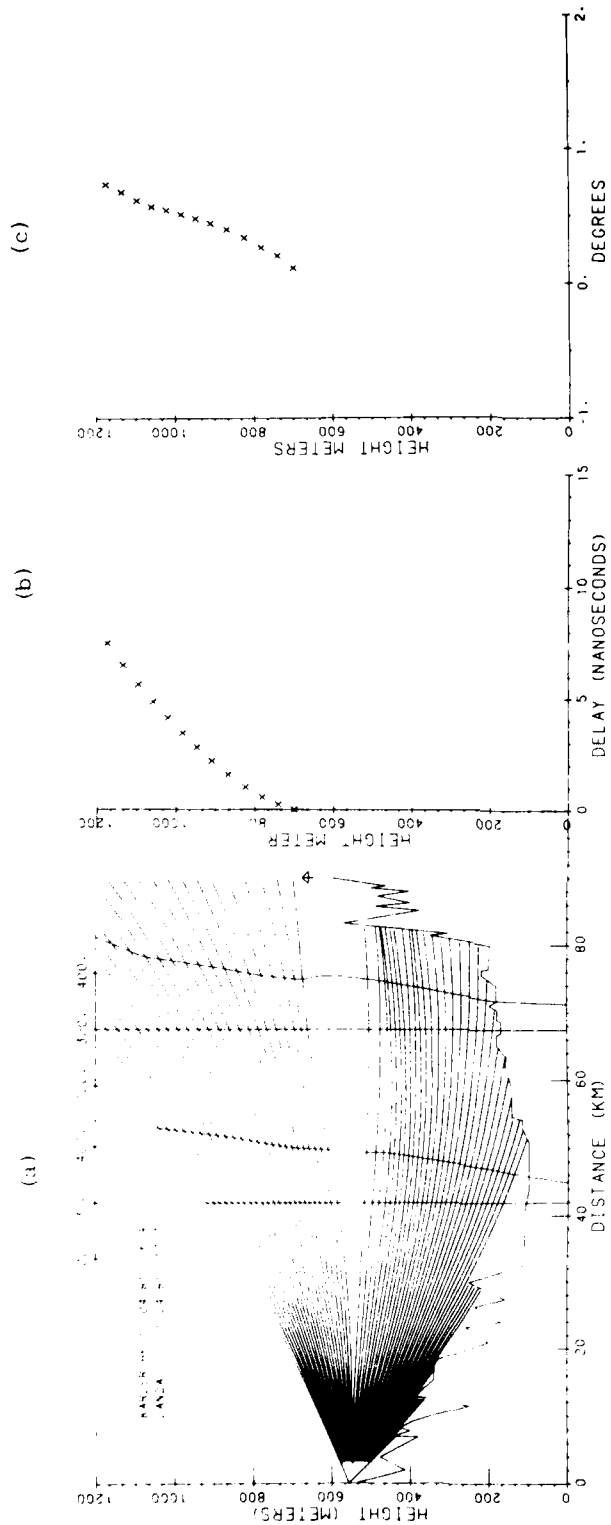
Figure 4. Ray Trace for Langerkopf-Friolzheim Link on 4 Nov 1981 Using Multiple Soundings for Refractive Index Values

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3. PROGRAM DESCRIPTION

A general flow diagram of the program is shown in Figures 5a, 5b, 5c, and 5d. Figure 5a shows the main part of the program RAYSUB. Figure 5b shows the subroutine RAYTRACE. Figure 5c shows the subroutine SEARCH. Figure 5d shows the subroutine RAYINC.

The main program, RAYSUB, does most of the housekeeping chores and has two principal parts. The first takes care of the evenly spaced fan of rays emanating from the transmitter. The second, when selected, directs rays at each of the nodes used to describe the earth profile and then redirects them to the receiver. The first task is accomplished by computing the initial angle and elevation for each ray and calling the RAYTRACE subroutine. The second task is accomplished by using the SEARCH routine to calculate the initial angle to hit the earth at a node, then RAYTRACE to get there, then SEARCH again for the initial angle to hit the receiver and finally RAYTRACE again to get there. Other functions of RAYSUB are house-keeping tasks. It reads the input refractive data, converts it to m units and extrapolates it down and up to make sure refractivity is defined in the complete space. It deletes reflected rays that are shielded and provides the plotting routines.

The RAYTRACE subroutine (Figure 5b) oversees each individual raytrace. It requires the starting increment index, the type reflection desired (KBNCE), the ray index, (I), whether to ignore the earth (ISWICH), and the position along the link to terminate the ray (XPOS2).

RAYTRACE selects the incremental distance to be used in computing the trajectory. It uses the lesser of one two-hundreth of the complete path length or the distance to the next surface node (in the multiple sounding version it also considers the distance to the next sounding). It uses RAYINC to do each increment of the trajectory and provides RAYINC with starting angle, height, increment, and whether to ignore the earth surface. If the return from RAYINC shows the ray to intersect the earth, RAYTRACE terminates the ray (KBNCE 0), or calculates the angle for specular reflection (KBNCE 1) and continues, or calculates the angle needed to reflect to the antenna (KBNCE 2) using SEARCH and continues.

The SEARCH (Figure 5c) subroutine is an iterative program for aiming rays from one point to another. It estimates the initial angle from the geometry, uses RAYINC to calculate the path, then corrects the initial angle estimate using the error (distance ray missed antenna). It ignores intersection with the earth (ISWICH -1) since it is only used to calculate an initial angle. Since not all paths are possible, (for example, there may be a radio hole), it aborts after nine attempts if the ray is more than 3 m from the intended target.

The RAYINC (Figure 5d) subroutine computes the incremental ray trajectories (Appendix A). This routine receives a height and an angle at the beginning of the increment and calculates the height and angle at the end of the increment. If this second height indicates it has passed a refractively significant altitude it determines the height and distance of the intersection of the ray with that altitude. After this, if selected, it tests to see if it would intersect the earth's surface. If it would it finds the point of intersection. RAYINC returns the height, angle and horizontal distance to the nearest intersection, if any, inside the original increment. It also informs the RAYTRACE of the type of termination (KTYPE: 1-normal; 2-intersect significant altitude; 3-intersect earth).

The ray trace model described is being used together with fine scale meteorological profile data to analyze performance on active LOS communication links. These tests were performed in conjunction with channel probe measurements of time of arrival, and in some cases, angle of arrival measurements. The model generates the time of arrival and angle of arrival plots, which allow direct comparison to both of the direct channel measurements. Because of the modular structure of the computer program used, it is easy to adapt it to do special tasks. It has, for example, been used to see the effect of coupling into a duct that is too high for "normal" ducting and is being adapted to analyze troposcatter radio propagation.
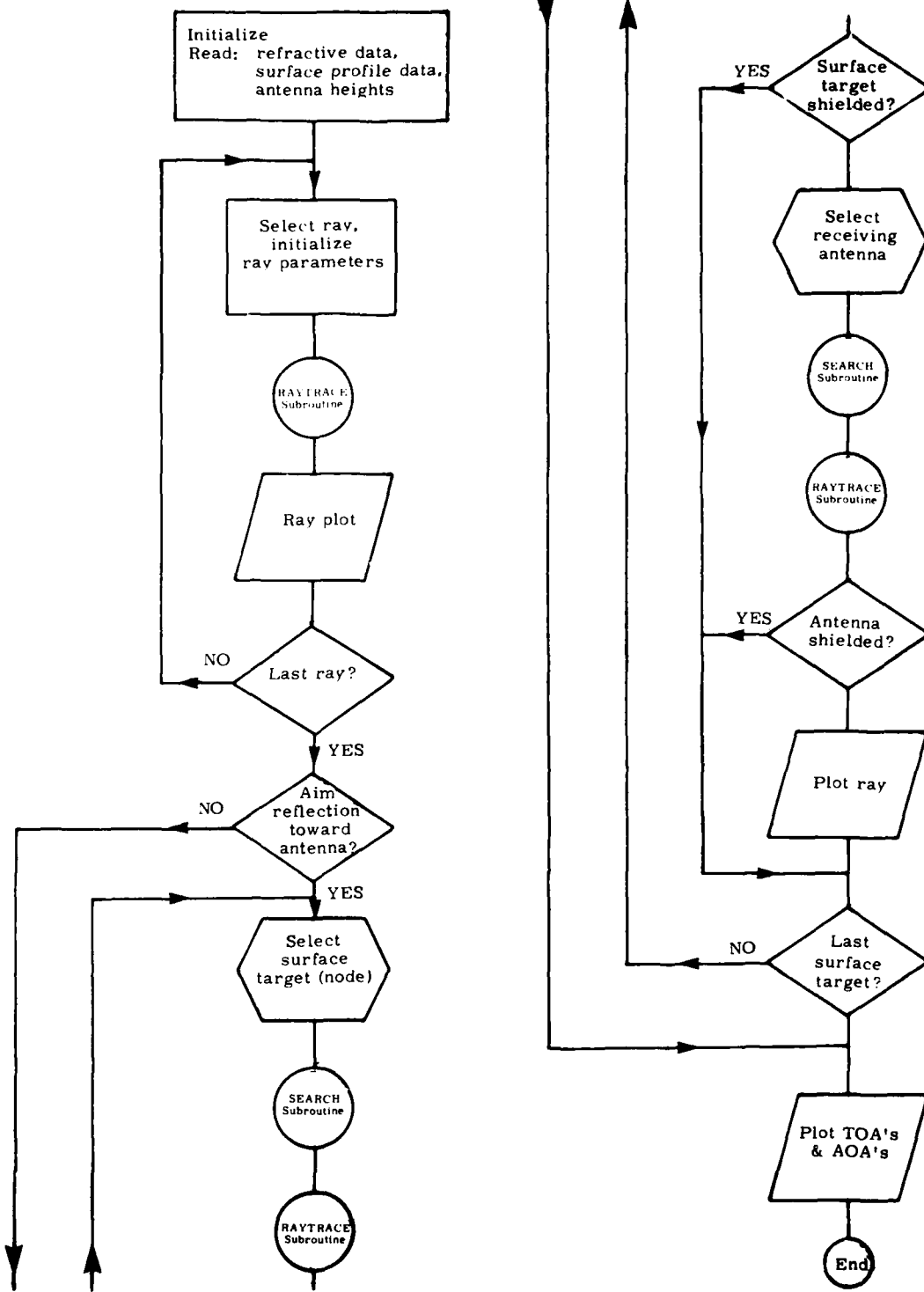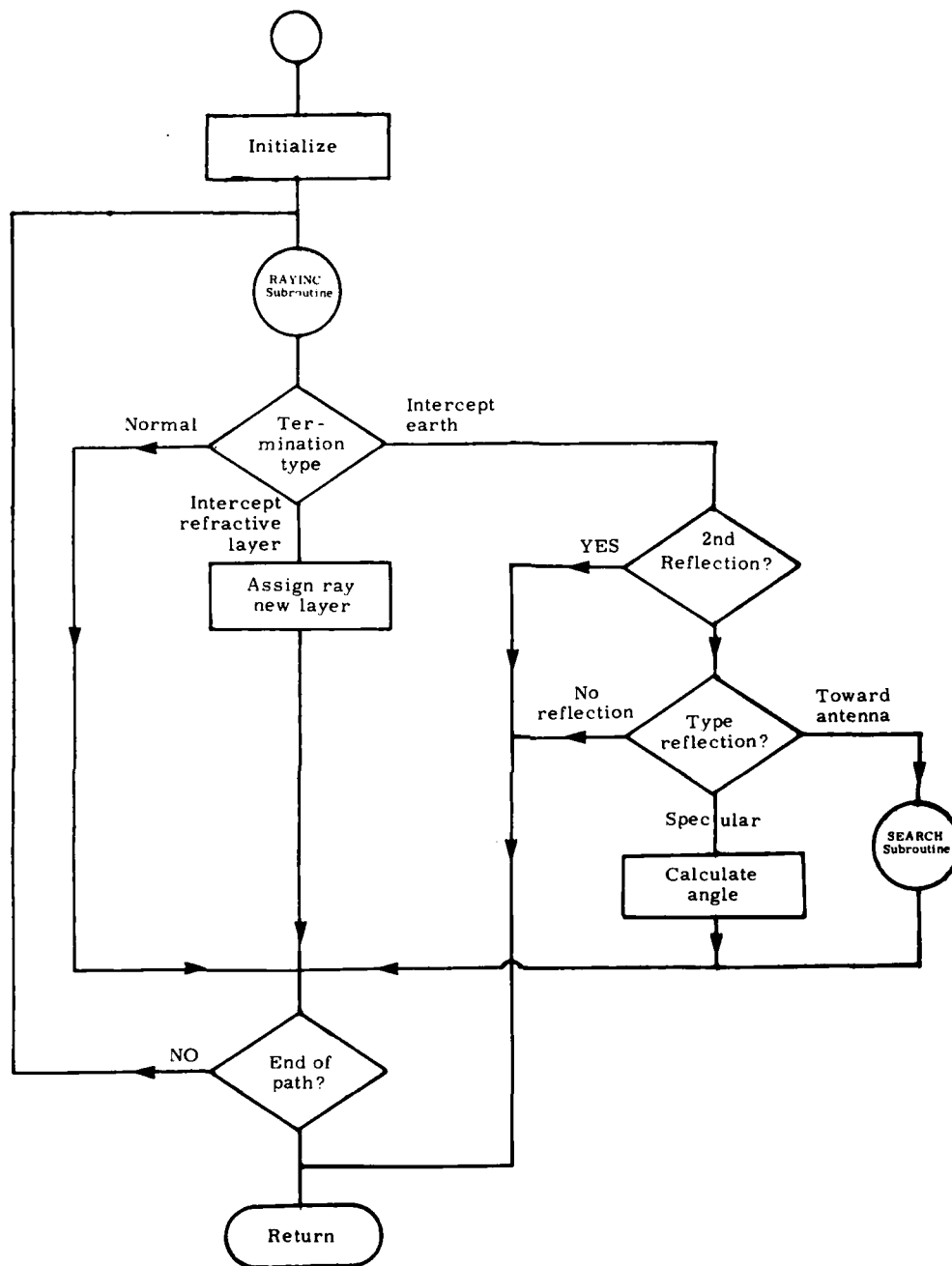
Figure 5a. RAYSUB Program
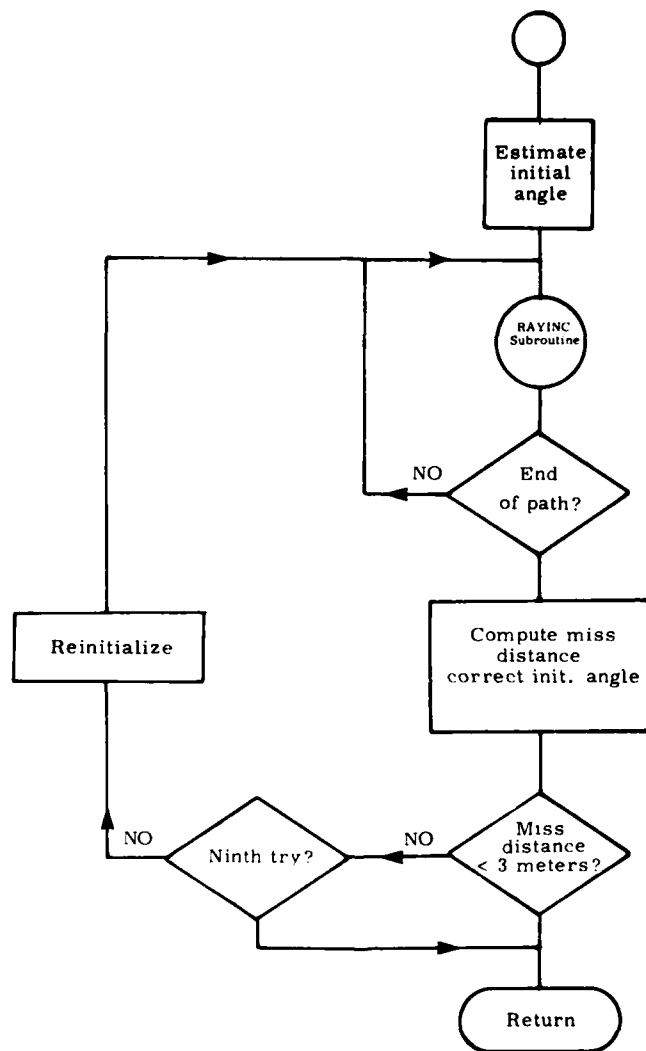
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Figure 5b. RAYTRACE Subroutine

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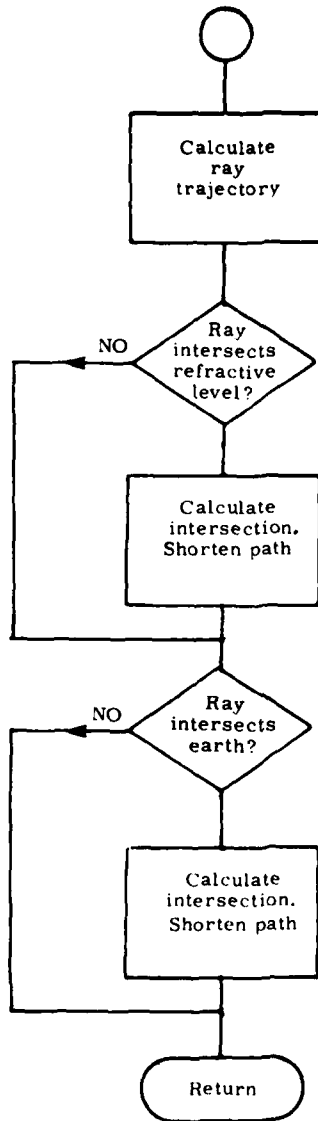Figure 5c.   SEARCH Subroutine

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Figure 5d.   RAYINC Subroutine

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Appendix A

Computation of Ray Trajectories

The angle that a straight line (ray) makes with any line normal to the local vertical in a circular coordinate system (Figure A1) can be described by

$$\theta_1 = \theta_0 + d\gamma$$

$$= \theta_0 + \tan^{-1} \frac{\Delta x}{r_e} .$$

Using the approximation $\tan^{-1} \frac{\Delta x}{r_e} \approx \frac{\Delta x}{r_e}$

$$\theta_1 = \theta_0 + \frac{\Delta x}{r_e} . \tag{A1}$$

The law of refraction for a nonhomogeneous dielectric[A1] states that the rays will be curved according to

$$\frac{1}{R} = -\frac{1}{n} \frac{dn}{dR} \tag{A2}$$

A1. Kern, D.E. (1951) <u>Propagation of Short Radio Waves</u>, McGraw Hill, New York.

where R is the radius of curvature, n is the refractivity of the dielectric (air) and $\frac{dn}{dR}$ the gradient of refractivity normal to the ray trajectory. The result of this curvature on θ is analogous to the effect of the curvature of the earth, with the opposite sense, that is, a positive R results in a reduction in the angle. Hence, if we use the same small angle approximation, $|R|$ is of the same order as r_e or greater, we can write

$$\theta_1 = \theta_0 + \left(\frac{1}{r_e} - \frac{1}{R} \right) \Delta x$$

or using Eq. (A2)

$$\theta_1 = \theta_0 + \left(\frac{1}{r_e} + \frac{1}{n} \frac{dn}{dR} \right) \Delta x$$

then using $n \approx 1$ and $\frac{dn}{dR} = \frac{1}{10^6} \frac{dN}{dZ} \cos \theta_0$

where $N \cong (n-1) \, 10^6$ and $\cos \theta_0 \approx 1$

$$\theta_1 = \theta_0 + \frac{1}{r_e} \left(1 + \frac{1}{157} \frac{dN}{dZ} \right) \Delta x$$

thus

$$\theta_1 = \theta_0 + 10^{-6} \frac{dM}{dZ} \Delta x \qquad \text{(A3)}$$

where M is the modified index of refraction given by

$$M \equiv N + 157 \, z \, .$$

An analytical expression for the height z_1 of the ray above the surface of the earth can be obtained from the MacLaurin series expansion and Eq. (A3)

$$Z_1 = Z_0 + Z_0' \Delta x + Z_0'' \frac{\Delta x^2}{2!} \qquad \text{(A4)}$$

but

$$Z' = \tan \theta \approx \theta$$

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and

$$Z'' \approx \theta' = 10^{-6} \frac{dM}{dZ}$$

then

$$Z_1 = Z_0 + \theta_0 \Delta x + 10^{-6} \frac{dM}{dZ} \frac{\Delta x^2}{2}. \tag{A5}$$

Equations (A3) and (A5) are sufficient to calculate the ray's trajectory given the initial angle and the gradient of the refractive index. It should be noted that small angle approximations were used in several places. The intended use of this technique is for line-of-sight communication links where the maximum angles are about 0.3 deg. The product using this technique has been checked against other ray trace techniques that do not make these approximations and no significant differences have been noted in angle, height, or relative propagation times. Similar treatment can be found in Millington[A2] and a more rigorous development in Dougherty.[A3]
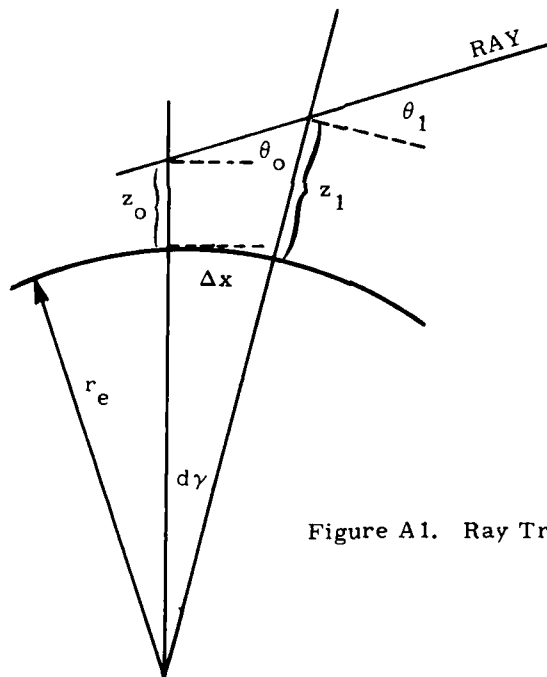

Figure A1. Ray Trace Geometry

A2. Millington, G. (1957) The concept of constant radius of the earth in tropospheric propagation, Marconi Rev., 20(No. 1):79-93.

A3. Dougherty, H. T. (1981) Electromagnetic Wave Trajectories at VHF and Higher Frequencies, NTIA-CR-81-14.

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