13. HOW THE PROGRAM WORKS

This ray tracing program consists of various subroutines that perform specific tasks in calculating ray paths. This division of labor facilitates modifying the program to solve specific problems. Often it may be necessary to change only one or two subroutines to convert the program to a different use.

The main program (NITIAL) sets up the initial conditions (transmitter location, wave frequency, and direction of transmission) for each ray trace. In setting up the initial conditions for each ray trace, the main program (NITIAL) steps frequency, azimuth angle of transmission, and elevation angle of transmission. The details of the workings of NITIAL can be found in the flow chart in figure 5. Then subroutine TRACE calculates one ray path for the requested number of crossings of the specified receiver height. Subroutine TRACE is the heart of the ray tracing program. It is the most complicated subroutine included, but also the most important to understand. The flow chart in figure 6 should help to explain TRACE.

Subroutine RKAM integrates the differential equations numerically using an Adams-Moulton predictor-corrector method with a Runge-Kutta starter. Subroutine HAMLTN evaluates the differential equations to be integrated. Subroutine RINDEX calculates the phase refractive index and its gradients, the group refractive index, and the polarization. (Eight versions of subroutine RINDEX are included.) Subroutines ELECTX, ELECT1, MAGY, and COLFRZ calculate the ionospheric electron density, perturbations to the electron density (irregularities), the earth's magnetic field, and the electron collision frequency, respectively. Several versions of these four subroutines are included and it is easy to add more. Subroutine REACH calculates a straight-line segment of a ray path in free space between the earth and the

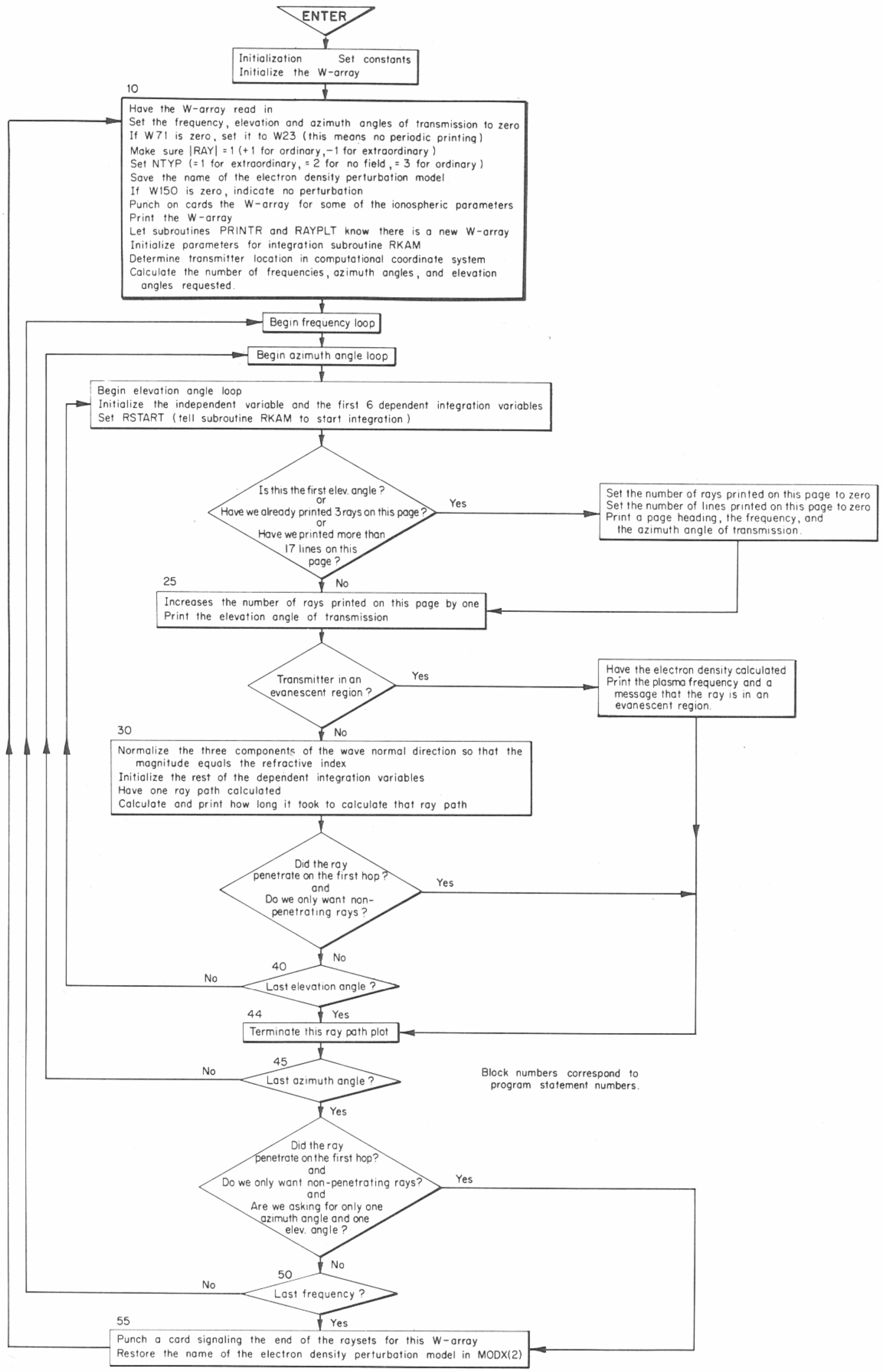

Figure 5. Flow chart for program NITIAL.

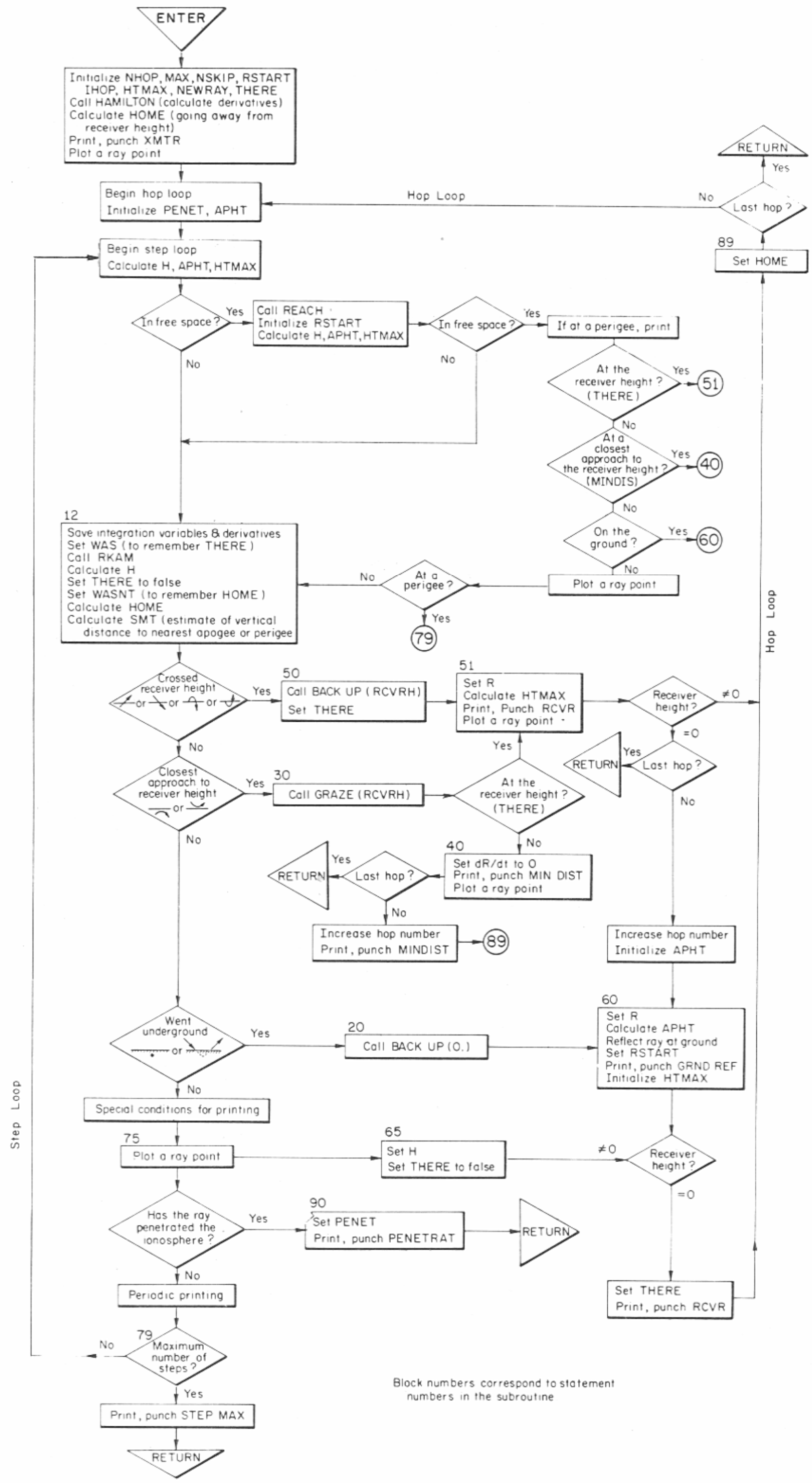

Figure 6. Flow chart for subroutine TRACE.

The ray graphics illustrate the path of a ray during a single step.

ionosphere or between ionospheric layers. Subroutine BACK UP finds an intersection of the ray with the receiver height or with the ground. Subroutine PRINTR prints information describing the ray path and punches the results on cards (raysets). Subroutine RAYPLT plots the ray path. The block diagram in figure 7 shows the relationship among these (and other) subroutines.

The listings of most of the subroutines have comments that should help in understanding how they work. In addition, Tables 3 through 14 define the variables in the common blocks.

14. ACKNOWLEDGMENTS

Part of the organization of this program into subroutines follows that of the program of Dudziak (1961), in particular for subroutines RKAM, HAMLTN , RINDEX, ELECTX, MAGY, and COLFRZ. Also, the coordinate transformation in subroutine PRINTR and the method for data input via the W array are taken from the program of Dudziak (1961). The term "rayset," the idea of punching results of each hop for each ray trace onto cards, and the idea of automatically plotting ray paths come from the program of Croft and Gregory (1963). The quasi-parabolic layer electron density model QPARAB is taken from the paper by Croft and Hoogasian (1968). Notice that the quasi-parabolic layer that is now in the program is slightly different from the one in the program of Jones (1966). Subroutine RKAM is a modification of subroutine RKAMSUB, which was written by G. J. Lastman and is available through the CDC CO-OP library (the CO-OP identification is D2 UTEX RKAMSUB). Subroutine GAUSEL was written by L. David Lewis, Space Environment Laboratory, National Oceanic and Atmospheric Administration. Subroutine FSW was written in conjunction with Helmut Kopka of the Max-Planck-Institut für Aeronomie, Lindau/Harz, Germany.

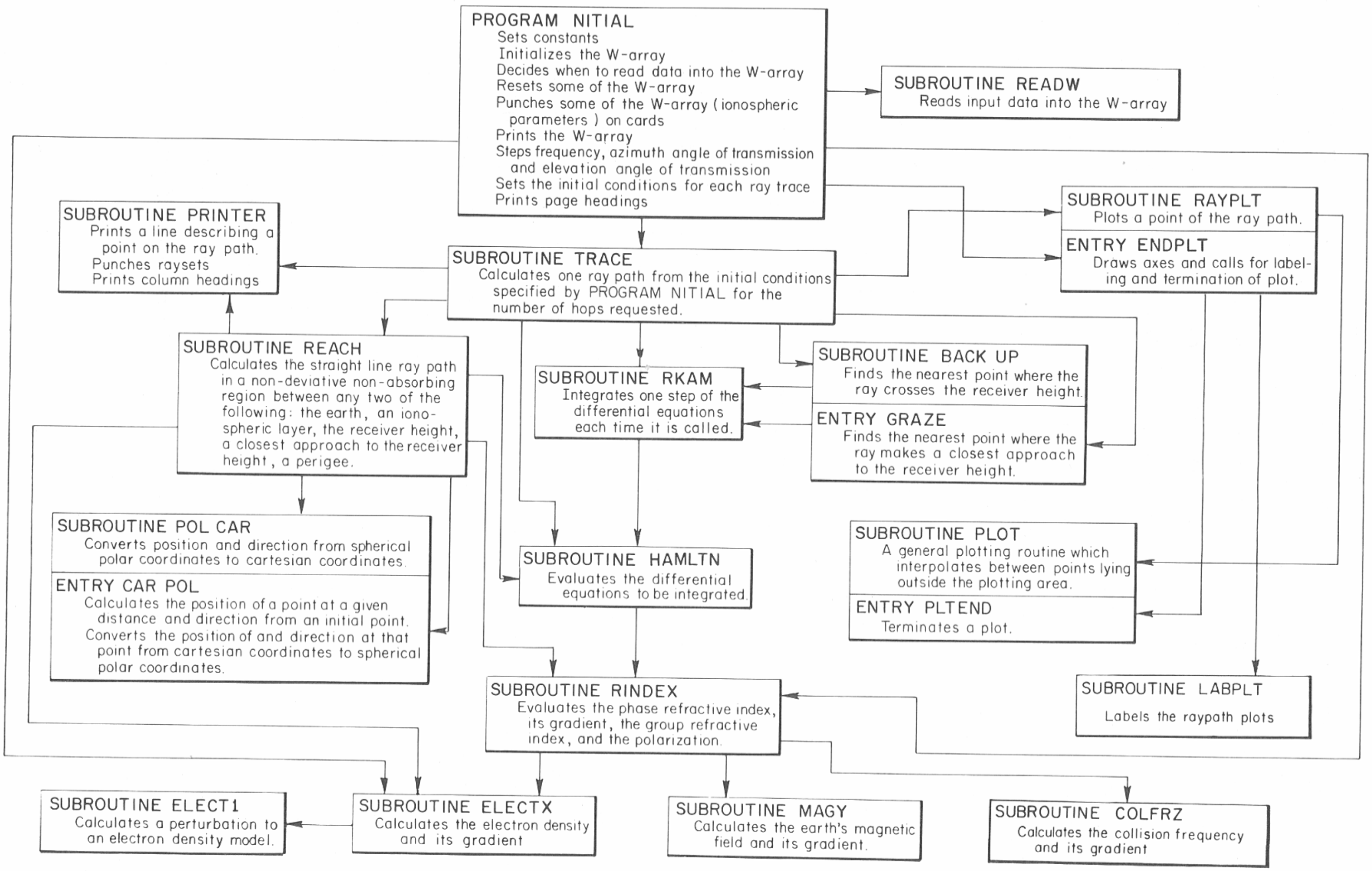

Figure 7. Block diagram for the ray tracing program.

Table 3. Definitions of the Parameters in Blank Common

Position in Common	Variable Name	Definition
1-20	R	The dependent variables in the differential equations being integrated--the definitions of the first six are fixed, but the others may be varied by the program user.
1	R(1)	r
2	R(2)	θ
3	R(3)	φ
4	R(4)	k_r
5	R(5)	k_θ
6	R(6)	k_φ
7-12	R(7)-R(12)	Those variables the user has chosen to integrate, taken in the following order: P -phase path in kilometers A -absorption in decibels Δf -Doppler shift in hertz s -geometrical path length in kilometers
13-20	R(13)-R(20)	Reserved for future expansion.
21	T	Group path in kilometers (the independent variable in the differential equations).
22	STP	Step length in group path.
23-42	DRDT	The derivatives of the dependent variables with respect to the independent variable T.

R and T are initialized in program NITIAL and changed in subroutines RKAM, REACH, and BACK UP.

STP is calculated in subroutine RKAM.

DRDT is calculated in subroutine HAMLTN and used in subroutine RKAM.

Table 4. Definitions of the Parameters in Common Block /CONST/

Position in Common	Variable Name	Definition
1	PI	π
2	PIT2	2π
3	PID2	$\pi/2$
4	DEGS	$180.0/\pi$
5	RAD	$\pi/180.0$
6	K	Ratio of the square of the plasma frequency to the electron density in $MHz^2 cm^3 = r_o c^2/\pi = e^2/(4\pi^2 \varepsilon_o m)$, where r_o is the classical electron radius, c is the free space speed of light, e is the charge on the electron, m is the mass of the electron, and ε_o is the capacitivity of a vacuum.
7	C	Free space speed of light in km/sec.
8	LOGTEN	$\log_e 10$

These parameters are set in program NITIAL.

Table 5. Definitions of the Parameters in Common Block /RK/

Position in Common	Variable Name	Definition
1	N	The number of equations being integrated.
2	STEP	The initial step in group path in kilometers.
3	MODE	Defines type of integration used (same as W41), see Table 2.
4	E1MAX	Maximum allowable single step error (same as W42).
5	E1MIN	Minimum allowable single step error (= W42/W43).
6	E2MAX	Maximum step length (same as W45).
7	E2MIN	Minimum step length (same as W46).
8	FACT	Factor by which to increase or decrease step length (same as W47).
9	RSTART	Nonzero to initialize numerical integration, zero to continue integration.

These parameters are calculated in program NITIAL (some are temporarily reset in subroutine BACK UP) and are used in subroutine RKAM.

Table 6. Definition of the Parameters in Common Block /RIN/

Postion in Common	Variable Name	Definition
1, 2, 3	MODRIN	Description of version of RINDEX in BCD.
4	COLL	= 1 if this version of RINDEX includes collisions, = 0 otherwise.
5	FIELD	= 1 if this version of RINDEX includes the earth's magnetic field, = 0 otherwise.
6	SPACE	TRUE, if the ray is in a nondeviative, nonabsorbing medium.
7, 8	KAY2	k^2, square of the complex phase refractive index times ω^2/c^2.
9, 10	H	Hamiltonian (complex)
11, 12	PHPT	$\partial H/\partial t$ (complex)
13, 14	PHPR	$\partial H/\partial r$ (complex)
15, 16	PHPTH	$\partial H/\partial \theta$ (complex)
17, 18	PHPPH	$\partial H/\partial \varphi$ (complex)
19, 20	PHPOM	$\partial H/\partial \omega$ (complex)
21, 22	PHPKR	$\partial H/\partial k_r$ (complex)
23, 24	PHPKTH	$\partial H/\partial k_\theta$ (complex)
25, 26	PHPKPH	$\partial H/\partial k_\varphi$ (complex)
27, 28	KPHPK	$\vec{k} \cdot \partial H/\partial \vec{k}$ (complex) $= k_r \partial H/\partial k_r + k_\theta \partial H/\partial k_\theta + k_\varphi \partial H/\partial k_\varphi$
29, 30	POLAR	Characteristic polarization of the wave; equal to the ratio of the component of the electric field perpendicular with the earth's magnetic field to the transverse component of the electric field parallel with the earth's magnetic field (complex) (Budden, 1961, p. 49, eq. (5.13)).

Table 6. (Continued)

Position in Common	Variable Name	Definition
31, 32	LPOLAR	Characteristic longitudinal polarization of the wave; equal to the ratio of the longitudinal component of the electric field to the component of the electric field perpendicular with the earth's magnetic field. (complex) Budden, 1961, p. 54, eq. (5. 38)).
33	SGN	= +1 or -1; used for ray tracing in complex space.

These parameters are calculated in subroutine RINDEX and used in subroutine HAMLTN.

Note: In some subroutines, the real and imaginary parts of the complex variables have separate names.

Table 7. Definitions of the Parameters in Common Block /FLG/
(See Subroutine TRACE)

Position in Common	Variable Name	Definition
1	NTYP	= 1 for extraordinary, = 2 for no field, = 3 for ordinary
2	NEWWR	Set equal to . TRUE. to tell subroutine RAYPLT there is a new W array.
3	NEWWP	Set equal to . TRUE. to tell subroutine PRINTR there is a new W array.
4	PENET	Set equal to . TRUE. if the ray just penetrated.
5	LINES	Number of lines printed on the current page.
6	IHOP	Hop number (at the beginning of each ray, subroutine TRACE sets this parameter to zero so that subroutine RAYPLT will begin a new line in plotting the ray path and subroutine PRINTR will print column headings and punch a transmitter rayset).
7	HPUNCH	The height to be punched on the raysets.

Table 8. Definitions of the Parameters in Common Block /XX/

Position in Common	Variable Name	Definition
1	MODX(1)	BCD name of the electron density subroutine.
2	MODX(2)	BCD name of the subroutine defining a perturbation to the electron density model.
3	X	X in Appleton-Hartree formula, square of the ratio of the plasma frequency to the wave frequency.
4	PXPR	$\frac{\partial X}{\partial r}$
5	PXPTH	$\frac{\partial X}{\partial \theta}$
6	PXPPH	$\frac{\partial X}{\partial \varphi}$
7	PXPT	$\frac{\partial X}{\partial t}$, where t is time; used for calculating Doppler shifts.
8	HMAX	Height of maximum electron density.

These parameters are calculated in subroutine ELECTX, possibly modified in subroutine ELECT1, and are mainly used in subroutine RINDEX.

Table 9. Definitions of the Parameters in Common Block /YY/

Position in Common	Variable Name	Definition
1	MODY	BCD name of the subroutine defining the earth's magnetic field.
2	Y	Y in the Appleton-Hartree formula, ratio of the electron gyrofrequency to the wave frequency.
3	PYPR	$\frac{\partial Y}{\partial r}$
4	PYPTH	$\frac{\partial Y}{\partial \theta}$
5	PYPPH	$\frac{\partial Y}{\partial \varphi}$
6	YR	Y_r, proportional to the component of the earth's magnetic field in the r direction.
7	PYRPR	$\frac{\partial Y_r}{\partial r}$
8	PYRPT	$\frac{\partial Y_r}{\partial \theta}$
9	PYRPP	$\frac{\partial Y_r}{\partial \varphi}$
10	YTH	Y_θ
11	PYTPR	$\frac{\partial Y_\theta}{\partial r}$
12	PYTPT	$\frac{\partial Y_\theta}{\partial \theta}$

Table 9. (Continued)

Position in Common	Variable Name	Definition
13	PYTPP	$\frac{\partial Y_\theta}{\partial \varphi}$
14	YPH	Y_φ
15	PYPPR	$\frac{\partial Y_\varphi}{\partial r}$
16	PYPPT	$\frac{\partial Y_\varphi}{\partial \theta}$
17	PYPPP	$\frac{\partial Y_\varphi}{\partial \varphi}$

These parameters are calculated in subroutine MAGY and are mainly used in subroutine RINDEX.

Table 10. Definitions of the Parameters in Common Block /ZZ/

Position in Common	Variable Name	Definition
1	MODZ	BCD name of the collision frequency subroutine.
2	Z	Z in the Appleton-Hartree formula, ratio of the electron-neutral collision frequency to the angular wave frequency.
3	PZPR	$\frac{\partial Z}{\partial r}$
4	PZPTH	$\frac{\partial Z}{\partial \theta}$
5	PZPPH	$\frac{\partial Z}{\partial \varphi}$

These parameters are calculated in subroutine COLFRZ and are mainly used in subroutine RINDEX.

Table 11. Definitions of the Parameters in Common Block /TRAC/

Position in Common	Variable Name	Definition
1	GROUND	.TRUE. if the ray is on the surface of the earth.
2	PERIGE	.TRUE. if the ray has just made a perigee.
3	THERE	.TRUE. if the ray is at the receiver height.
4	MINDIS	.TRUE. if the ray has just made a closest approach to the receiver height.
5	NEWRAY	Set equal to .TRUE. to tell subroutine REACH that this is a new ray.
6	SMT	An estimation of the vertical distance to an apogee or perigee of the ray.

These parameters are used for communication between subroutine TRACE and subroutines REACH and BACK UP.

Table 12. Definition of the Parameter in Common Block /COORD/

Position in Common	Variable Name	Definition
1	S	The straight line distance along the ray from the position of the ray where REACH was called to the present position.

This parameter is used for communication between subroutine REACH and subroutine POL CAR.

Table 13. Definitions of the Parameters in Common Block /PLT/

Position in Common	Variable Name	Definition
1	XMIN0, XL	The x coordinate of the left side of the plotting area in kilometers.
2	XMAX0, XR	The x coordinate of the right side of the plotting area in kilometers.
3	XMIN0, YB	The y coordinate of the bottom of the plotting area in kilometers.
4	YMAX0, YT	The y coordinate of the top of the plotting area in kilometers.
5	RESET	Set equal to one whenever the plotting area is changed.

These parameters are used for communication between subroutine RAYPLT and subroutine PLOT.

Table 14. Definitions of the Parameters in Common Block /DD/

Position in Common	Variable Name	Definition
1	IN	Intensity. IN = 0 specifies normal intensity. IN = 1 specifies high intensity.
2	IOR	Orientation. IOR = 0 specifies upright orientation. IOR = 1 specifies rotated orientation (90° counterclockwise).
3	IT	Italics (Font). IT = 0 specifies non-Italic (Roman) symbols. IT = 1 specifies Italic symbols.
4	IS	Symbol size. IS = 0 specifies miniature size. IS = 1 specifies small size. IS = 2 specifies medium size. IS = 3 specifies large size.
5	IC	Symbol case. IC = 0 specifies upper case. IC = 1 specifies lower case.
6	ICC	Character code, 0-63 (R1 format). ICC and IC together specify the symbol plotted.
7	IX	X-coordinate, 0-1023.
8	IY	Y-coordinate, 0-1023.

We also want to thank those who have used our program and have pointed out errors or made suggestions. In particular, we are grateful to Dr. T. M. Georges of the Wave Propagation Laboratory, National Oceanic and Atmospheric Administration, for his suggestions resulting from extensive use of the program, for development of some of the ionospheric models (DCHAPT, DTORUS, WAVE, WAVE2), and for financing part of the development of ray tracing through a spitze.

Examples of use of the ray tracing program are shown in the reports by Stephenson and Georges (1969) and Georges (1971).

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