6. IONOSPHERIC MODELS

When using the program, one must specify ionospheric models which define electron density, collision frequency (if the effect of collisions is being considered), and the earth's magnetic field (if its effects are being taken into account) as a function of position in space. Each of these three characteristics of the ionosphere is defined by a separate subroutine.

Appendices 3, 4, 5, and 6 contain descriptions, input parameter forms and listings of ionospheric models that now exist. These ionospheric models are not likely to cover the needs of everyone who wants to use the program. Anticipating this when we wrote the program, we made it possible to add models easily. The user may make up his own ionospheric models by simply writing subroutines to define electron density, collision frequency, and the earth's magnetic field (and their gradients) as a function of position in space in spherical polar coordinates, following the form of the subroutines in appendices 3, 4, 5, and 6.

Appendix 3 contains electron density models; appendix 4 contains models of irregularities which may be applied as perturbations to any of the electron density models; appendix 5 contains models of the earth's magnetic field; and appendix 6 contains collision frequency models.

Having several versions of the subroutines for refractive index, electron density, collision frequency, and the earth's magnetic field gives the user not only a wide choice among ionospheric models, but also a variety of compromises between cost and an accurate description of the ionosphere, while still keeping the program simple.

7. FINDING THE RAY PATHS THAT CONNECT A TRANSMITTER AND RECEIVER

The reason for using a ray tracing program is to find all important ray paths that connect a given transmitter and receiver (either or both of which may be on a satellite) on a particular frequency and such properties of these ray paths as group time delay, phase time delay, and absorption of the wave. "All important" ray paths include those that reflect from the various ionospheric layers (including multiple reflections) and that propagate off the great circle path.

Since basically all that a ray tracing program can do is to calculate the path of a ray when given the transmitter location, frequency, and direction of transmission, it cannot directly calculate those ray paths that arrive at a specified receiver. The problem is to know, before tracing the ray, in which directions to transmit the ray so that it will arrive at the receiver. Since there are no general solutions to this problem, the user of a ray tracing program must rely on some sort of trial and error technique to find those ray paths that connect the transmitter and receiver. This involves varying the direction of transmission until a ray is found that reaches the receiver. If a ray tracing program does this automatically, we say that it has a homing feature. This program does not have such a feature. To find all the paths connecting the transmitter with the receiver requires a very elaborate homing routine because "homing in" on a receiver takes more judgment and common sense than speed in performing massive calculations. Therefore, the person using the program is more fitted to this task than is the computer program itself.

As an aid, however, the program allows the user to specify the receiver height, the number of hops, and a range of azimuth and elevation angles-of-transmission that he thinks will include those rays that will arrive at the receiver. The program then calculates a ray path for each of the azimuth and elevation angles-of-transmission specified in the range. Usually only in the case of ionospheres with large horizontal gradients will the azimuth angle-of-transmission have to be varied. The program will calculate each ray path far enough to intersect or make a closest approach to the receiver height for the requested number of hops. The user can then interpolate between those rays which surround the receiver.

We define the point of "closest approach" as the point on the ray path where the wave normal direction is horizontal. It approximates an apogee if the receiver is above the apogee height and it approximates a perigee if the receiver is below the perigee height. The approximation is good for oblique propagation. When the earth's magnetic field is neglected, a point of "closest approach" is exactly an apogee or perigee.

We count one hop every time the ray crosses the receiver height. If the receiver is on the ground, a ground reflection counts as one hop for the downcoming ray before the ground reflection, and another hop for the upgoing ray after the ground reflection. We count two hops every time the ray passes through a point of "closest approach" to the receiver height. This procedure helps make rays that have the same hop number have a ground range that is a continuous function of the direction of transmission.

8. OUTPUT

8.1 Printout

Periodically and at selected points during a ray trace, the program will print information giving the position of the current ray path point, the direction of the wave normal, and the cumulative values of quantities being integrated along the ray path such as group path, phase path, absorption, and Doppler shift. Appendix 8c contains a sample of the printout.

8.2 Punched Cards

The program will punch a card at the beginning of each ray, a card at each ground reflection, a card at each crossing of the receiver height, two cards for each closest approach to the receiver height, and a card at the end of each ray to summarize the main results of the ray path calculations. These cards are explained in figures 1 and 2.

These cards are very useful as input data to other computer programs and for plotting the results of the ray tracing. In fact, these cards represent the most useful form of output for production ray path calculations. This method, called the rayset information-storage technique, was developed by Dr. T. A. Croft (Croft and Gregory, 1963) of Stanford University.

8.3 Plots of the Ray Path

A plot of the actual ray path, especially for very irregular ionospheres, can be helpful in understanding what sometimes seems like strange results in light of the input data. Thus, the program has an option for plotting, providing, of course, that the user has a plotter and plotting subroutines such as those described in appendix 7. The program can plot the projection of the ray path on any vertical plane or on the ground. The input parameter forms for plots of the ray path (appendix 1i) give more details. Appendix 8e contains sample plots of the raypath.

9. DECK SET UP

The versatility gained by having several versions of some of the subroutines is somewhat offset because the user must learn the deck set up in order to make necessary substitutions. Figure 3 shows the deck setup, including the subroutines that make up the main deck and those which are frequently exchanged with alternate versions. The order of the subroutines is unimportant.

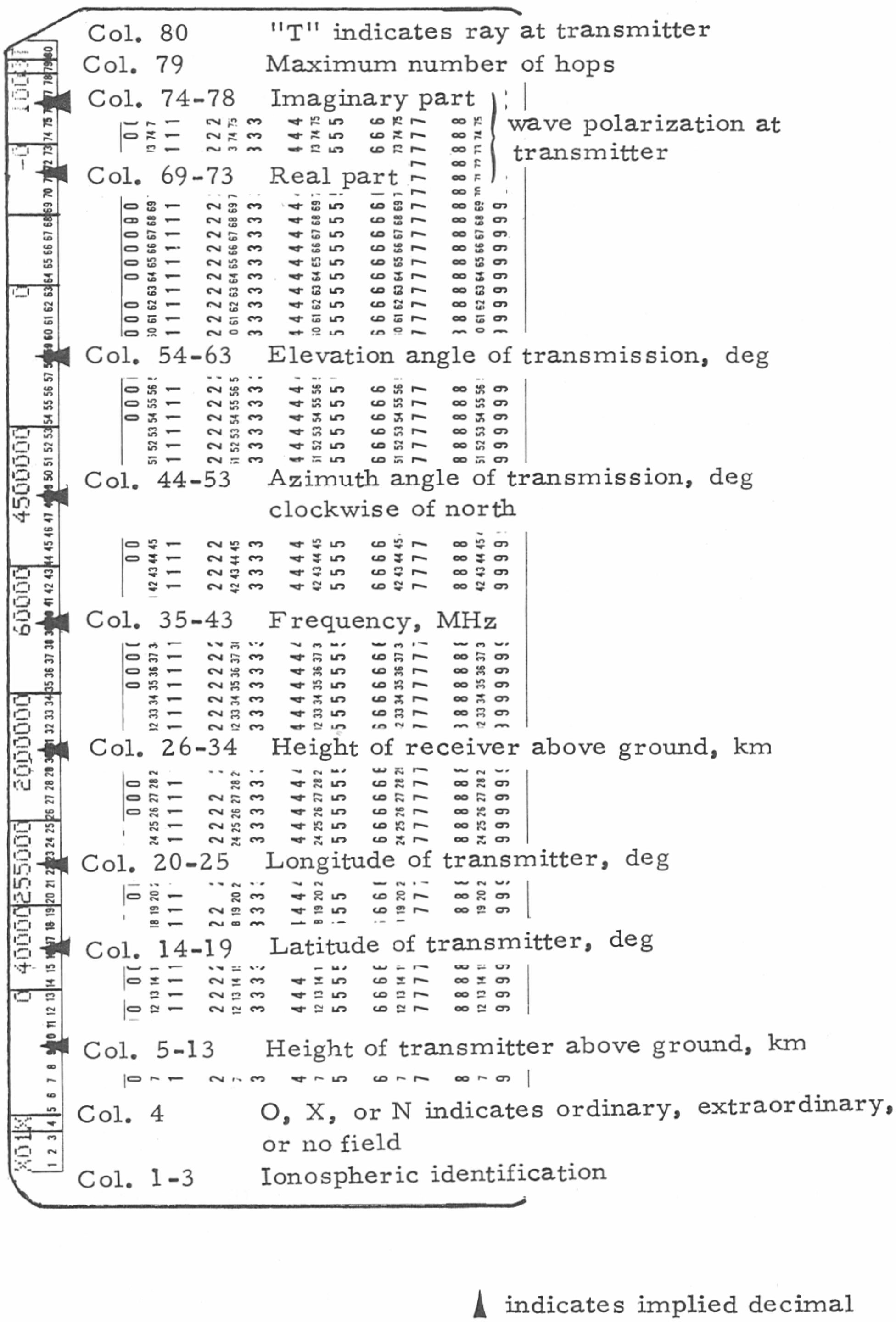
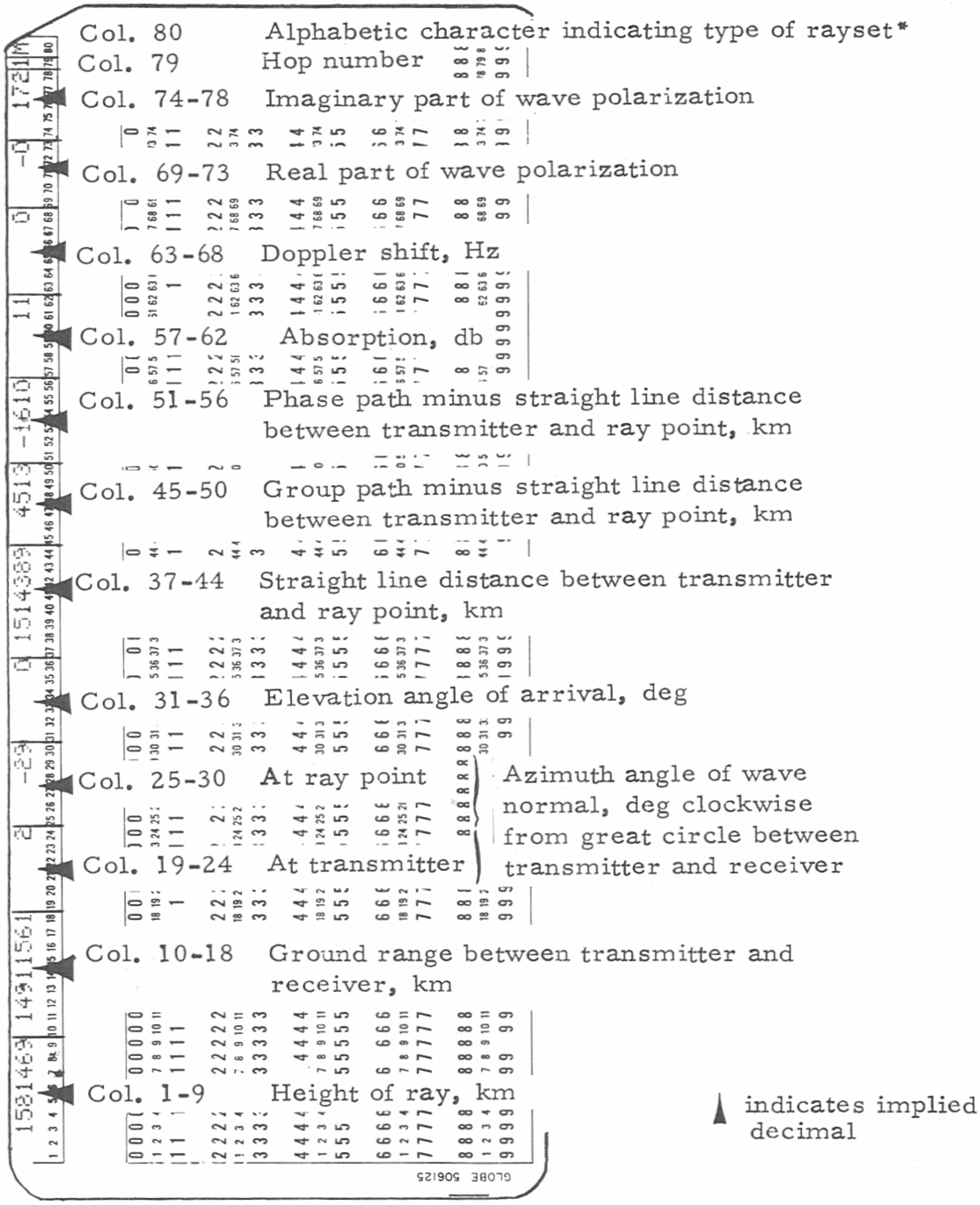


Figure 1. Sample transmitter rayset.



*G ray ground reflected. The height punched out is the apogee height since the last ground reflect.

M ray made a closest approach to the receiver height

P ray penetrated

R ray at the receiver height. The height punched out is the height of the ray farthest from receiver height since last crossing of receiver height

S program reached maximum number of steps

Figure 2. Sample minimum distance rayset.

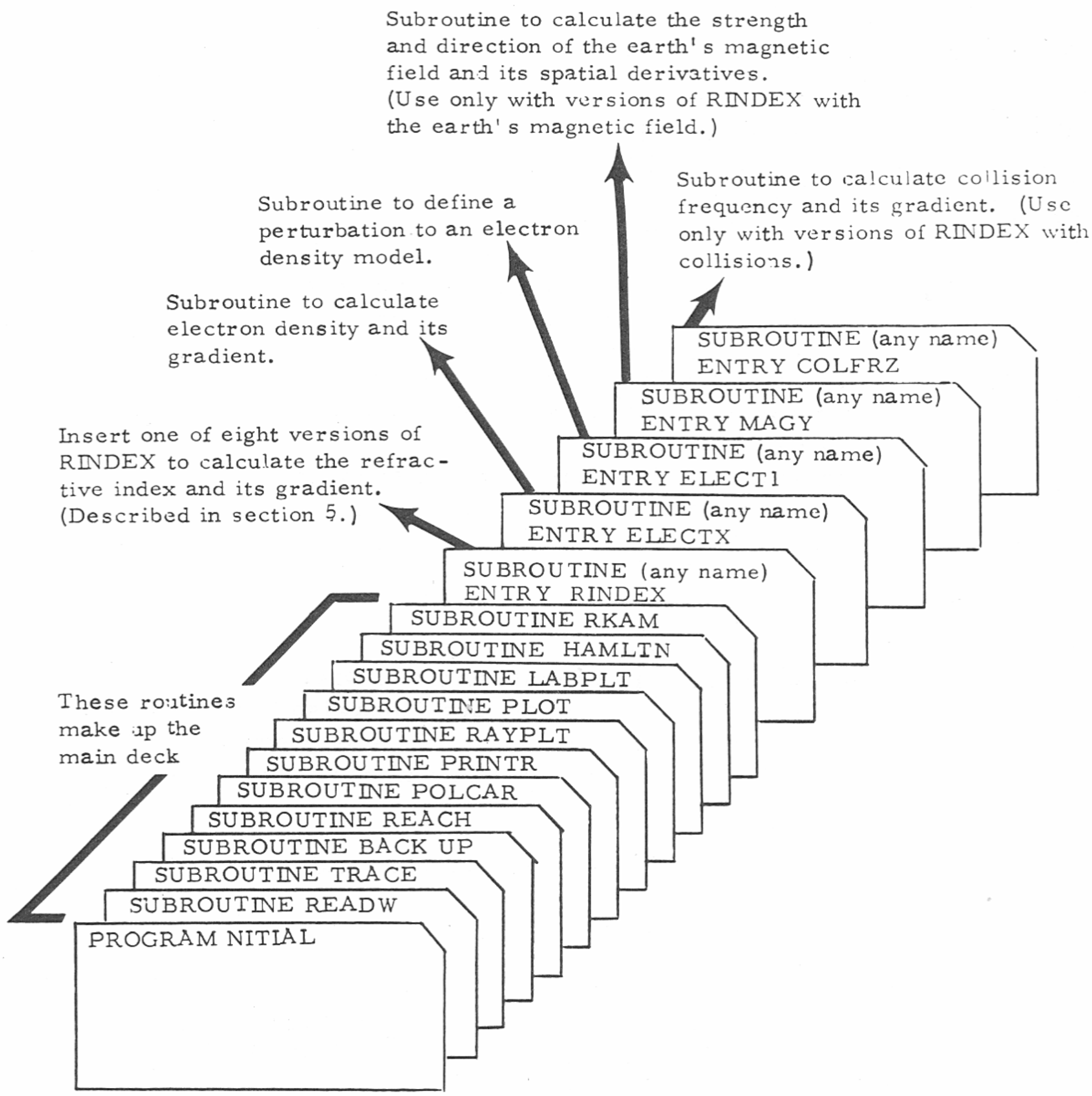


Figure 3. Program deck set-up

10. INPUT

The input data for a ray tracing program divide themselves naturally into two groups:

First, data that control the type of ray trace requested, such as the transmitter location and frequency, plus parameters describing analytic models of the ionosphere. Since there are few of these, efficiency in packing such data can be exchanged for versatility and ease of data handling. Therefore, by putting only one piece of data on each card, we gain the conveniences of reading in these data in any order and of having the program read in only those data that are different from those of the previous case. A number in the first three columns of each card identifies the data being read in. Table 2 defines the identifying numbers that are subscripts for a linear array, W. The last 56 columns of the card are available for comments.

We have also provided a method for conversion of units for input. The computer program needs angles in radians, whereas people usually like to use angles in degrees. The program is set up for angles in radians, but putting a "1" in column 18 allows the user to enter the angle in degrees and have the program make the conversion. A "1" in column 19 allows the user to enter central earth angles as the great circle distance along the ground in kilometers. (The program will calculate the latitude of a transmitter which is 500 km north of the equator, for instance.) The program expects distances in kilometers. A "1" in column 20 indicates a distance in nautical miles, and a "1" in column 21 indicates a distance in feet.

Appendix 8b contains a sample of how the cards are to be punched. If two or more cards have the same identifying number, the last one dominates. A card with the first three columns blank indicates the end of this type of data cards.

Table 2. Description of the Input Data for the W Array

W1	= 1. for ordinary ray = -1. for extraordinary ray
W2*	Radius of the earth in km
W3	Height of transmitter above the earth in km
W4	North geographic latitude of the transmitter
W5	East geographic longitude of the transmitter
W7	Initial frequency in MHz
W8	Final frequency in MHz
W9	Step in frequency in MHz (zero for a fixed frequency)
W11	Initial azimuth angle of transmission
W12	Final azimuth angle of transmission
W13	Step in azimuth angle of transmission (zero for a fixed azimuth)
W15	Initial elevation angle of transmission
W16	Final elevation angle of transmission
W17	Step in elevation angle of transmission (zero for a fixed elevation)
W20	Receiver height above the earth in km
W21	Nonzero to skip to the next frequency after the ray has penetrated the ionosphere
W22*	Maximum number of hops
W23*	Maximum number of steps per hop
W24*	North geographic latitude of the north geomagnetic pole
W25*	East geographic longitude of north geomagnetic pole
W41*	=1. for Runge-Kutta integration =2. for Adams-Moulton integration without error checking =3. for Adams-Moulton integration with relative error check =4. for Adams-Moulton integration with absolute error check
W42*	Maximum allowable single step error
W43*	Ratio of maximum single step error to minimum single step error
W44*	Initial integration step size in km (step in group path)
W45*	Maximum step length in km
W46*	Minimum step length in km
W47*	Factor by which to increase or decrease step length
W57	=1. to integrate, =2. to integrate and print phase path
W58	=1. to integrate, =2. to integrate and print absorption
W59	=1. to integrate, =2. to integrate and print doppler shift
W60	=1. to integrate, =2. to integrate and print path length
W71	Number of steps between periodic printout
W72	Nonzero to punch raysets on cards
W81	=0. to not plot ray path =1. to plot projection of ray path on a vertical plane =2. to plot projection of ray path on the ground
W82-88	Parameters used when plotting
W100-149	Parameters for analytic electron density models
W150-199	Parameters for perturbations to electron density models
W200-249	Parameters for analytic magnetic field models
W250-299	Parameters for analytic collision frequency models

*These values have been initialized in the main program but may be reset by reading them in. See Appendix 1b for the initial values.

A second group of input data cards are necessary if nonanalytic ionospheric models such as the electron density profile defined by subroutine TABLEX or the collision frequency profile defined by subroutine TABLEZ are used. Each subroutine defining a nonanalytic ionospheric model reads in data cards according to a format defined in that subroutine. An element in the W array controls the reading of these cards. (See table 2.) Figure 4 shows the order in which these data cards should be arranged.

11. ACCURACY

The numerical integration subroutine has a built-in mechanism to check errors and adjust the integration step length accordingly. If the errors get larger than a maximum specified by the user, the routine will decrease the step length in order to maintain the accuracy. On the other hand, if the accuracy is greater than that required by the user, the routine will increase the step length in order to reduce the computing cost. The user specifies the desired accuracy in W42 (see table 2). W42 is the maximum allowable relative error in any single step for any of the equations being integrated. To get a very accurate (but expensive) ray trace, one can use a small W42 (about 10^{-5} or 10^{-6}). For a cheap, approximate ray trace, one should use a large W42 (10^{-3} or even 10^{-2}). For cases in which all of the variables being integrated increase monotonically, the total relative error can be guaranteed to be less than W42. Otherwise, the total relative error cannot be easily estimated.

The far left column of the printout from the ray path calculation gives an indication of the integration error in the magnitude of the vector which points in the wave normal direction. Although the calculation of this error is made independently of the error calculation in the numerical integration routine, we have found that except near reflection for vertical or near vertical incidence this error is usually of the same order

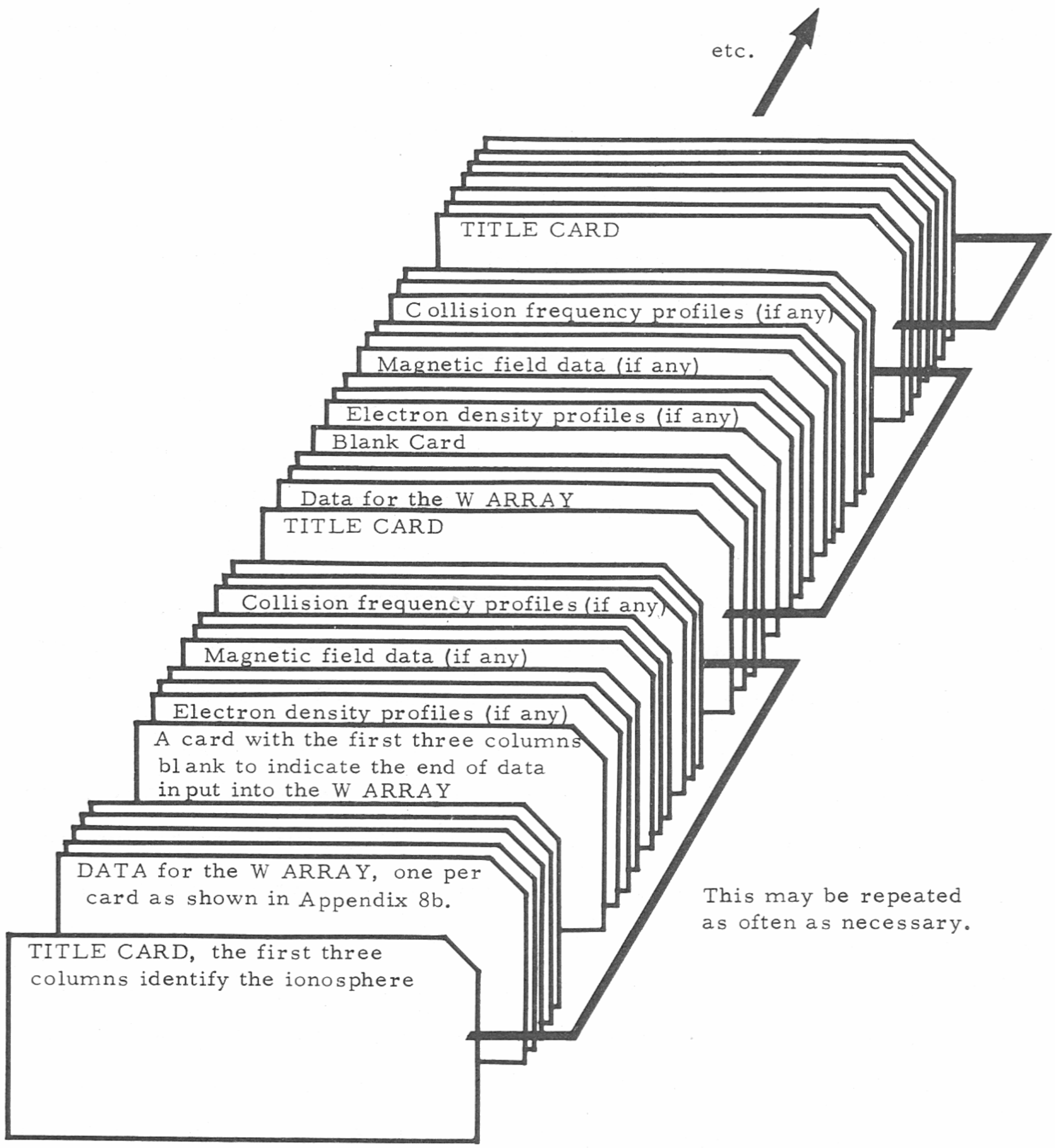


Figure 4. Data deck set-up.

of magnitude as that specified in W42. We have found that whenever this error has exceeded W42 by several orders of magnitude, the electron density subroutine we had written was calculating a gradient of electron density inconsistent with the spatial variation of electron density being calculated. See the general description of electron density models in Appendix 3a for more information.

12. COORDINATE SYSTEMS

The program uses two different spherical polar coordinate systems, namely, a geographic and a computational coordinate system. Input data for the coordinates of the transmitter (W4 and W5) and input data for the coordinates of the north pole of the computational coordinate system (W24 and W25) are entered in geographic coordinates. (Putting W25 equal to 0° and W24 equal to 90° would superimpose the two north poles and equate the two coordinate systems.)

When the two coordinate systems do not coincide, the three types of ionospheric models calculate electron density, the earth's magnetic field, and collision frequency in terms of the computational coordinate system. In particular, the dipole model of the earth's magnetic field uses the axis of the computational coordinate system as the axis for the dipole field. Thus, when using this dipole model, the computational coordinate system is a geomagnetic coordinate system, and both electron density and collision frequency must be defined in geomagnetic coordinates. Dudziak (1961) describes the transformations between these coordinate systems.