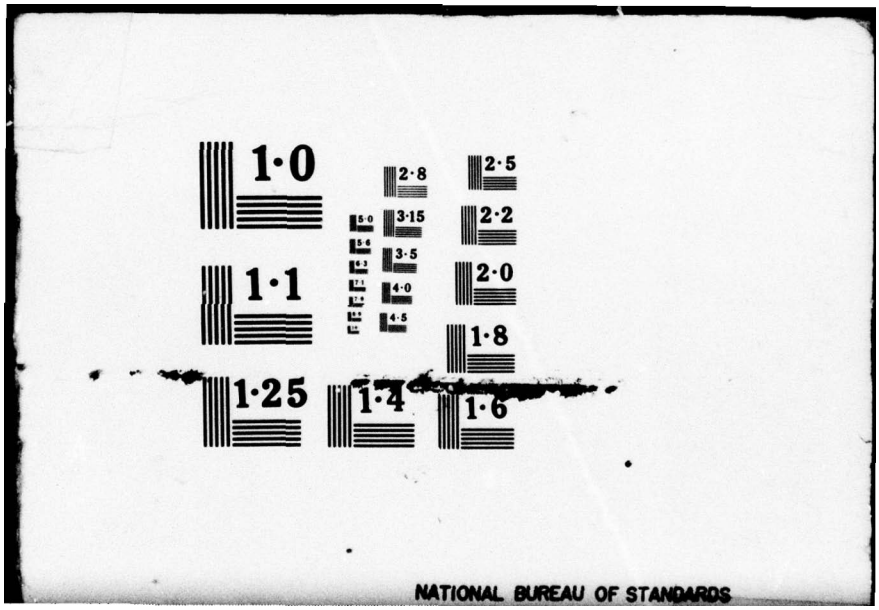
AD-A057 274 ILLINOIS UNIV AT URBANA-CHAMPAIGN DEPT OF ELECTRICAL --ETC F/G 4/1
BACKSCATTER IONOGRAM INVERSION BY RAY TRACING METHODS.(U)
APR 78 R E DUBROFF, N N RAO, R C YEH F19628-77-C-0108
UNCLASSIFIED UILU-ENG-78-2538 RADC-TR-78-86 NL

1 OF 2
ADA
057274


1·0
1·1
1·25
1·4
1·6
2·8
3·15
3·5
4·0
4·5
2·5
2·2
2·0
1·8
NATIONAL BUREAU OF STANDARDS

LEVEL II

RADC-TR-78-86
Final Technical Report
April 1978

BACKSCATTER IONOGRAM INVERSION BY RAY TRACING METHODS

Ionosphere Radio Laboratory
Department of Electrical Engineering
University of Illinois at Urbana-Champaign

Approved for public release;
distribution unlimited.

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFIS AIR FORCE BASE, NEW YORK 13441

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-78-86 has been reviewed and is approved for publication.

APPROVED: Ming S Wong

MING S. WONG
Project Engineer

APPROVED: Terrence J. Elkins

TERRENCE J. ELKINS, Assistant Chief
Propagation Branch
Electromagnetic Sciences Division

APPROVED: Walter Rotman

WALTER ROTMAN, Acting Chief
Electromagnetic Sciences Division

FOR THE COMMANDER: John P. Huss

JOHN P. HUSS
Acting Chief, Plans Office

If your address has changed or if you wish to be removed from the RADC mailing list, or if the addressee is no longer employed by your organization, please notify RADC (EEP), Hanscom AFB MA 01731. This will assist us in maintaining a current mailing list.

Do not return this copy. Retain or destroy.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: RADC-TR-78-86	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): BACKSCATTER IONOGRAM INVERSION BY RAY TRACING METHODS	5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report, 1 Jan [redacted] - 31 Dec [redacted] 77
	6. PERFORMING ORG. REPORT NUMBER: UILU-ENG-78-2538 Tech.Rep.62
7. AUTHOR(s): R. E. DuBroff, N. N. Rao, R. C. Yeh	8. CONTRACT OR GRANT NUMBER(s): F19628-77-C-0108
9. PERFORMING ORGANIZATION NAME AND ADDRESS: University of Illinois at Urbana-Champaign, Department of Electrical Engineering, Urbana IL 61801	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F, 2305J223, J2
11. CONTROLLING OFFICE NAME AND ADDRESS: Deputy for Electronic Technology (RADC), Hanscom AFB MA 01731, Monitor/Ming S. Wong/EEP	12. REPORT DATE: April 1978 / 13. NUMBER OF PAGES: 106
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): UILU-ENG-78-2538, TR-62	15. SECURITY CLASS. (of this report): UNCLASSIFIED / 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

RADC Project Engineer: Ming S. Wong (EEP)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Backscatter Ionogram
Group Path
Mean Squared Error Minimization
Inversion
Ionostate
Ray Tracing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a computerized method for deducing ionospheric parameters from the measurement of backscatter leading edge ionograms. A number of test cases are presented to demonstrate this technique. The technique is documented through the use of a complete program listing, a sample output, and a set of flow charts for the major computer subroutines.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

176 009

EVALUATION

This report is the final technical report on the contract. It covers research done on inversion of backscatter-radar ionograms during the 12-month period from 1 January through 31 December 1977. The objective of the research is to infer useful information on the ionosphere from observed HF backscatter ionograms, so that the effects of the ionosphere on the performance of backscatter radar systems, used for over-the-horizon detection, and of HF communication can be predicted.

The above work is relevant to the Technical Program Objective R1C (Surveillance Sensor Techniques) and is of value in that it provides a reasonably efficient method for determining the parameters of an ionospheric layer when the critical frequency, height and thickness of the layer varies linearly with distance. The method is applicable under situations where the ionosphere does not change sharply with distance.

Ming S Wong

MING S. WONG
Project Engineer

TABLE OF CONTENTS

1. INTRODUCTION 1

1.1 RAY TRACING & MINIMUM GROUP PATHS. 1
1.2 LQP MODEL & IONOSTATES 5
1.3 METHOD OF SOLUTION 7

2. RESULTS. 9

2.1 TWO VARIABLE CASE. 9
2.2 SIMULTANEOUS DETERMINATION OF 3 GRADIENTS. 10
2.3 THE EFFECT OF UNDERLYING IONIZATION. . . . 18
2.4 QUADRATIC GRADIENT 27

3. PROGRAM DOCUMENTATION. 37

3.1 OVERVIEW OF PROGRAM OPERATION. 37
3.2 FLOW OF MAJOR SUBROUTINES. 40
3.3 PROGRAM LISTING. 61
3.4 SAMPLE OUTPUT. 84
3.5 DATA FILE STRUCTURE. 90
3.6 CRASH CODES. 95

4. CONCLUSION 96

REFERENCES. 98

LIST OF FIGURES

Figure		Page
1	Two-dimensional ray tracing geometry	3
2	Two component (GFC&RB) convergence of MSE. . .	11
3	Level curves of an MSE surface	12
4	Two component (GFC&RM) convergence of MSE. . .	13
5	Combined effects of three simultaneous gradients upon ionosphere model.	15
6	Three component (GRB,GRM,&GRC) convergence of MSE with a small initial error.	17
7	Three component (GRB,GRM,&GFC) convergence of MSE with a large initial error.	19
8	Combined electron density model (with underlying layer).	20
9	RMS error introduced by underlying layer . . .	22
10	Error introduced by underlying layer at each sounding frequency.	24
11	Two component (GFC&RB) convergence of MSE in presence of underlying layer.	26
12	Four component (GFC,G2FC,GRB,&GRM) convergence of MSE	30
13	Backscatter leading edges for two different ionostates	31
14	Difference in backscatter leading edges for two different ionostates	32
15	Critical frequency variation for two different ionostates	33
16	Two component (G2FC&RM) convergence of MSE . .	36
17	Synthesis program flow chart	38
18	Inversion program flow chart	39
19	Flowchart for subroutine RAYT.	41-44

LIST OF FIGURES CONT.

Figure		Page
20	Flowchart for subroutine STAR.	46-50
21	Flatness test.	53
22	Flow chart for subroutine STEEP.	55-57
23	To illustrate the determination of a search direction for a new ionostate.	58

LIST OF TABLES

Table		Page
1	MINOR SUBROUTINES	60
2	CRASH CODE SUMMARY.	95

1. INTRODUCTION

1.1 RAY TRACING & MINIMUM GROUP PATHS:

One of the standard techniques for the study of electromagnetic wave propagation in inhomogeneous media is ray tracing, which is based upon the geometrical optics formulation. (For reviews of ray theory especially applied to the ionosphere, see Kelso, 1964; Yeh and Liu, 1972). This technique allows us to treat the wave propagation problem as a problem in mechanics in which our objective is, essentially, to calculate the trajectory of a fictitious point (or particle) that travels in space with a velocity equal the local group velocity of the electromagnetic wave. The knowledge of the ray trajectory also enables us to calculate other parameters (such as group path, phase path, and ground range) which may or may not be relevant to a particular problem in electromagnetic wave propagation.

While the form of the equations which govern the ray trajectory (i.e. the ray equations) are fairly general most of the ionospheric applications of the ray equations are based upon a spherical co-ordinate system in which case the ray equations are usually written in a form referred to as Haselegrove's equations (Haselegrove, 1957; Yeh and Liu, 1972). In the present work, we have restricted our attention to a two dimensional case in which the rays are assumed to propagate in one member of a family of vertical planes containing the straight azimuthal lines directed outward from the source. Furthermore it is assumed that the medium in which the rays propagate (that is, the ionosphere) has

properties which vary in only the radial and angular coordinates (see Figure 1). In other words, the ray propagation equations become two dimensional. It is furthermore assumed that the geomagnetic field may be neglected in which case the dispersion surface of the rays becomes isotropic (or, equivalently the wave-normal and group velocity vectors are parallel). With these conditions in mind, the ray equations may be written in the form of a set of coupled ordinary first order differential equations (i.e. Yeh and Liu, 1972):

$$\frac{dr}{d\tau} = \frac{\sigma_r}{n^2} \tag{1}$$

$$\frac{d\theta}{d\tau} = \frac{\sigma_\theta}{rn^2} \tag{2}$$

$$\frac{d\sigma_r}{d\tau} = \frac{1}{n}\frac{\partial n}{\partial r} + \sigma_\theta \frac{d\theta}{d\tau} = \frac{1}{n\partial r} + \frac{\sigma_\theta^2}{rn^2} \tag{3}$$

$$\frac{d\sigma_\theta}{d\tau} = \frac{1}{rn}\frac{\partial n}{\partial \theta} - \frac{\sigma_\theta}{r}\frac{dr}{d\tau} = \frac{1}{rn}\frac{\partial n}{\partial \theta} - \frac{\sigma_\theta \sigma_r}{rn^2} \tag{4}$$

with

n = phase refractive index

$\sigma_r = n\hat{k}\cdot\hat{r}$

$\sigma_\theta = n\hat{k}\cdot\hat{\theta}$

and with $d\tau$ representing the differential element of phase path. Two additional equations have also been used in order to allow us to keep track of the cumulative group and phase paths as the ray progresses. These additional

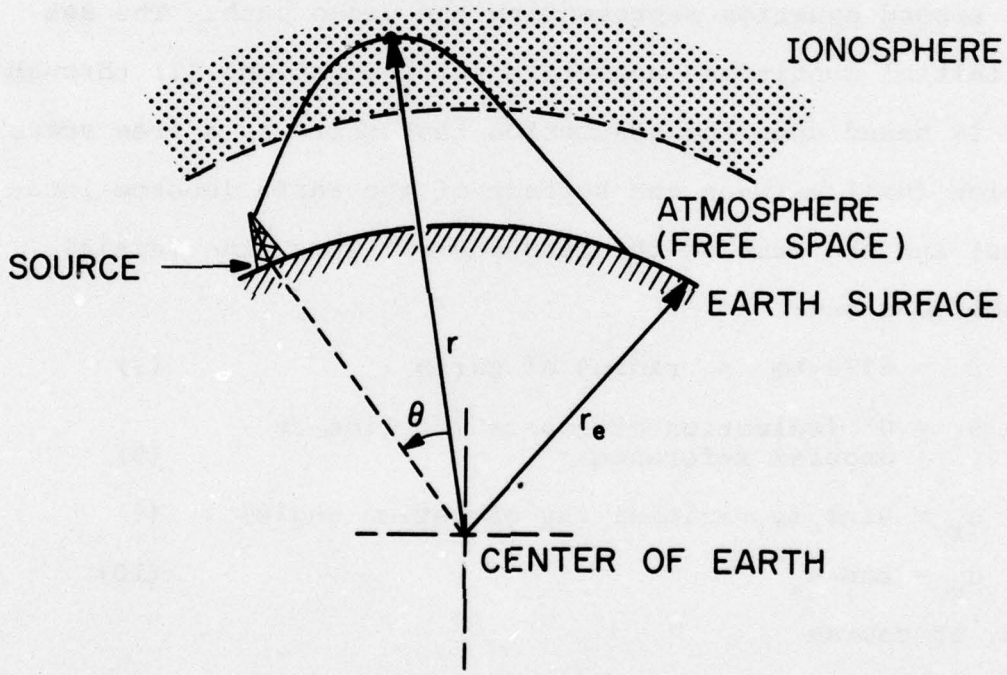


Figure 1. Two-dimensional ray tracing geometry.

equations are:

$$\frac{dP}{d\tau} = 1 \tag{5}$$

and

$$\frac{dP'}{d\tau} = \frac{1}{n^2} \tag{6}$$

with the first equation representing the phase path and the second equation representing the group path. The set of initial conditions associated with equations (5) through (6) is based upon the assumption that there is a free space region (n=1) between the surface of the Earth (source location) and the base of the ionosphere. Thus, the initial conditions are:

r = 6370 km = radius of Earth (7)

θ = 0^{o} (selection of source location as angular reference) (8)

$\sigma_r = \sin\phi_0$ (ϕ_0=initial ray elevation angle) (9)

$\sigma_\theta = \cos\phi_0$ (10)

and, of course

$P = P' = 0$ (11)

The net result of using these initial conditions in connection with a given model for the phase refractive index, n, is that the only remaining degree of freedom for a ray of some specified frequency is provided by the initial elevation angle of the ray (ϕ_0) and consequently the value of group path, P', which is computed when the ray has left

the source, reflected from the ionosphere, and returned back to the surface of the Earth is determined by ϕ_0. Of course, certain choices of ϕ_0 may result in the ray penetrating the ionosphere. Nevertheless, for those values of ϕ_0 which result in rays returning to the surface of the Earth there will be some value of ϕ_0 which results in a minimum group path. The physical significance of minimum group path rays is that they constitute the leading edge of backscatter ionograms (as discussed by Rao et al., 1976). This particular curve, in turn, forms the basis for the selection of the ionosphere model parameters.

1.2 LQP MODEL & IONOSTATES

In earlier work (Rao et al., 1976) we used the quasi-parabolic model to represent the ionospheric electron density profile (Croft and Hoogasian, 1968) in accordance with:

$$N_e(r) = N_m\left[1 - \left(\frac{r-r_m}{y_m}\right)^2 \left(\frac{r_b}{r}\right)^2\right] \quad r_b < r < r_m\left(\frac{r_b}{r_b - y_m}\right) \tag{12}$$

where

N_m = maximum electron density

r_m = radius to peak of ionosphere

y_m = layer semi-thickness = $r_m - r_b$

r_b = base radius

$N_e(r)$ = electron density at a geocentric distance of r

Equation (12) may also, however, be used in order to obtain an expression for the phase refractive index, n, since

$$n^2 = 1 - \frac{80.6N_e}{f^2} \tag{13}$$

In this case, it becomes more convenient to use the critical frequency (f_c) parameter instead of the maximum electron density parameter (N_m). These parameters are related, in the international system of units, by

$$f_c^2 = 80.6N_m \tag{14}$$

Thus, the refractive index at some given geocentric distance, r, may be computed by specifying the three parameters r_b, r_m and f_c.

In the present work, however, we have attempted to extend the quasi-parabolic model to allow the values of r_b, r_m, and f_c to vary with the angular co-ordinate, θ. Formally, the electron density may then be written as

$$N_e(r,\theta) = N_m(\theta)\{1 - [\frac{r-r_m(\theta)}{y_m(\theta)}]^2 [\frac{r_b(\theta)}{r}]^2\} \tag{15}$$

which introduces a corresponding angular dependence in the phase refractive index. Such an angular dependence is desirable in situations, for example, of simulating ionospheres in the trough region. Nevertheless, for a fixed value of θ, equation (15) has the form of an ordinary quasi-parabolic model of electron density and we have accordingly decided to designate this model as the LQP (or locally quasi-parabolic) model.

In most of the cases we will present it will be assumed that the angular dependence of the model parameters consists of a nominal value which is given by the value of the parameter directly above the source (θ=0) plus a constant gradient in the θ direction multiplied by the angular displacement away from the source (e.g. $r_b(\theta) = r_{bo} + \frac{dr_b}{d\theta} \cdot \theta = r_{bo} + GRB \cdot \theta$). Since there are three parameters, r_{bo}, r_{mo}, and f_{co}, as well as three gradients (one in each parameter), there is a total of six parameters needed to describe the LQP model. These six parameters may be considered to define a basis for a six dimensional space in which a simultaneous set of the six parameters may be thought of as constituting a vector (the ionostate) which we may define as:

$$\vec{\xi} = [RB, RM, FC, GRB, GRM, GFC] \qquad (16)$$

with

$RB = r_{bo}$

$RM = r_{mo}$

$FC = f_{co}$

$GRB = dr_b/d\theta$

$GRM = dr_m/d\theta$

$GFC = df_c/d\theta$

1.3 METHOD OF SOLUTION

Having defined the ionostate above (equation 16) the problem, stated in its simplest terms, becomes how to determine the six components of the ionostate in some optimum sense. The criterion which we have selected is that the

backscatter leading edge which would be observed if the ionosphere were LQP should match, as closely as possible, the backscatter leading edge as experimentally measured by the ionospheric sounder operating at the same set of frequencies and observing the actual ionosphere. More precisely, if we denote the set of sounding frequencies by f_i (for i=1 to N) and denote the measured backscatter leading edge by $P'(f_i)$, while denoting the LQP model backscatter leading edge as $\hat{P}'(\vec{\xi},f_i)$, the problem may be stated as:

Find $\vec{\xi}$ such that

$$e^2(\vec{\xi}) \equiv \frac{1}{N} \sum_{i=1}^{N} [P'(f_i)-\hat{P}'(\vec{\xi},f_i)]^2 \qquad (17)$$

is a minimum. A discussion of the mechanics of computing the appropriate ionostate, $\vec{\xi}$, will be deferred until section 3.

2. RESULTS

2.1 TWO VARIABLE CASE

While the ionostate as previously defined has six components, our present computer program has the capability of distinguishing between "fixed" and "variable" ionostate components. A fixed ionostate component implies that the reduction in the mean squared error (e^2) as defined by equation (17) may not be accomplished through any change in this particular component. Instead, the program may only reduce the mean squared error by adjusting the variable ionostate components. In this section we will be considering two simultaneous "variable" components.

Furthermore, in order to provide a reference by which to determine the efficacy of the program it is necessary to simulate the measurement of the backscatter leading edge in an ionosphere of known refractive index. For this purpose, we assumed that the ionosphere was locally quasi-parabolic and was completely specified by the ionostate, $\vec{\xi}_0$ where

$$\vec{\xi}_0 = [\text{RB; RM; FC, GRB; GRM; GFC}] = [6570 \text{ km; } 6720 \text{ km; } 5 \text{ MHz; } 0 \text{ km/rad; } 0 \text{ km/rad; } 2\text{MHz/rad.}] \quad (18)$$

Based upon this $\vec{\xi}_0$, we then proceeded to calculate the minimum group paths, $\hat{P}'_0(f_i)$, corresponding to a backscatter ionogram at discrete sounding frequencies. We then "estimated" an initial ionostate $\vec{\xi}_1$ which was found to result in minimum group paths, $\hat{P}'_1(f_i)$. The estimation of $\vec{\xi}_1$, however,

is not always a simple matter and the reader may wish to refer to section 4 for a more thorough discussion. Using the mean squared error e^2, defined in equation (17) as a criterion of optimality, we attempted to reconstruct the original ionostate, $\vec{\xi}_0$.

As an example, the cases illustrated in Figure 2 result from specifying the RM, FC, GRB, and GRM components of $\vec{\xi}_1$ as "fixed", thereby reducing the problem to a two dimensional minimization. In all these cases the fixed components were set to their correct values (i.e. the values of the corresponding components of $\vec{\xi}_0$). Using three different sets of starting values (marked by x's in Figure 2) for the remaining components (RB and GFC), the program was allowed to continue in an iterative manner until the mean squared error became less than 1 km^2. The underlined numbers in this figure represent the mean squared error, and the dotted curve corresponds roughly to the contour curve along which the mean squared error is approximately 7. A somewhat more complete set of contour curves is shown in Figure 3. As can be seen in comparing Figures 2 and 3, the trajectory of the point (RB, GFC) proceeds primarily along the direction of a narrow valley in the mean squared error surface.

Figure 4 shows a similar convergence when RM & GFC are used as variable ionostate components.

2.2 SIMULTANEOUS DETERMINATION OF 3 GRADIENTS

In this section, we assume that the overhead electron density profile is known. Therefore, the values of RB, RM,

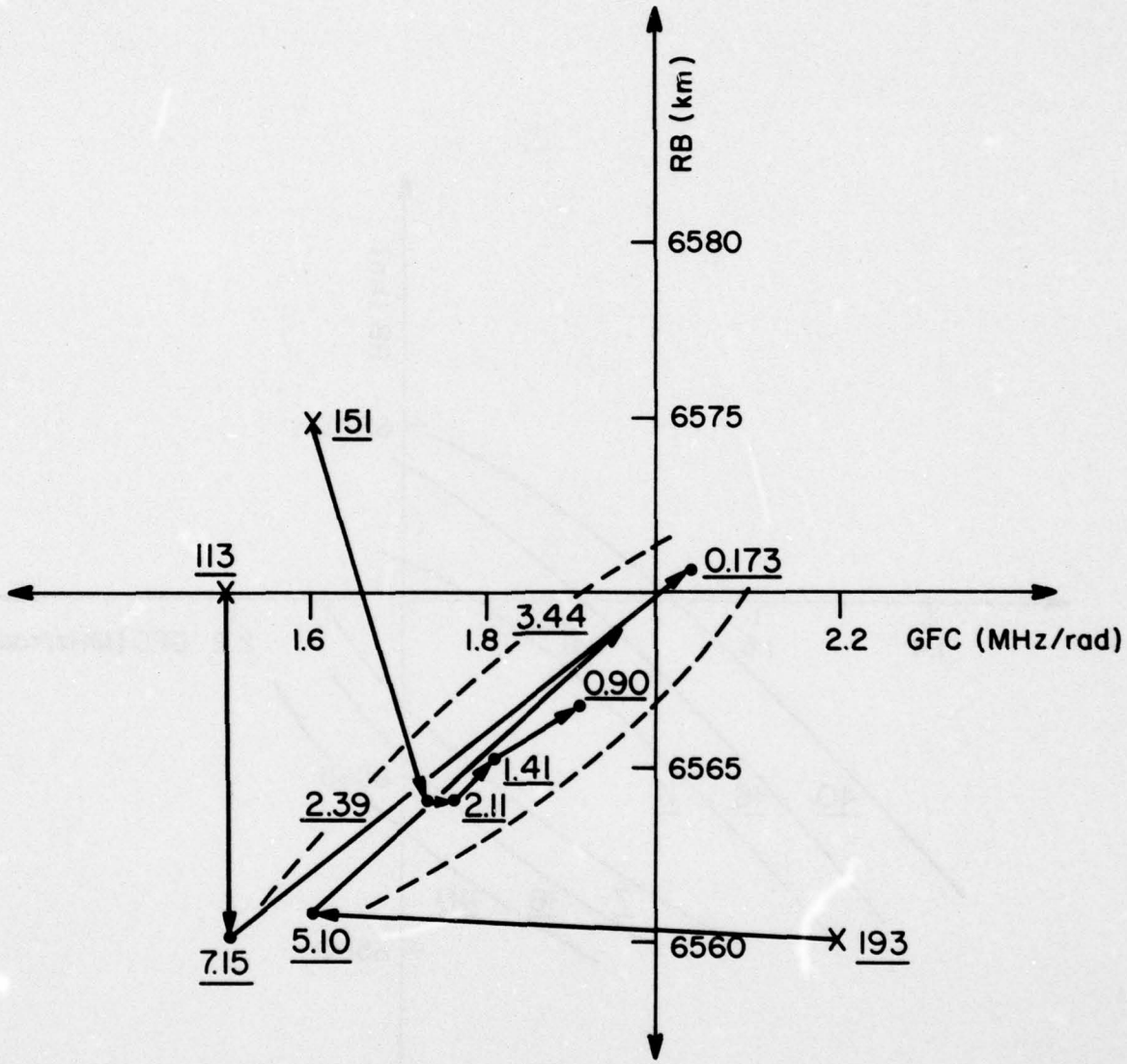


Figure 2. Two component (GFC&RB) convergence of MSE.

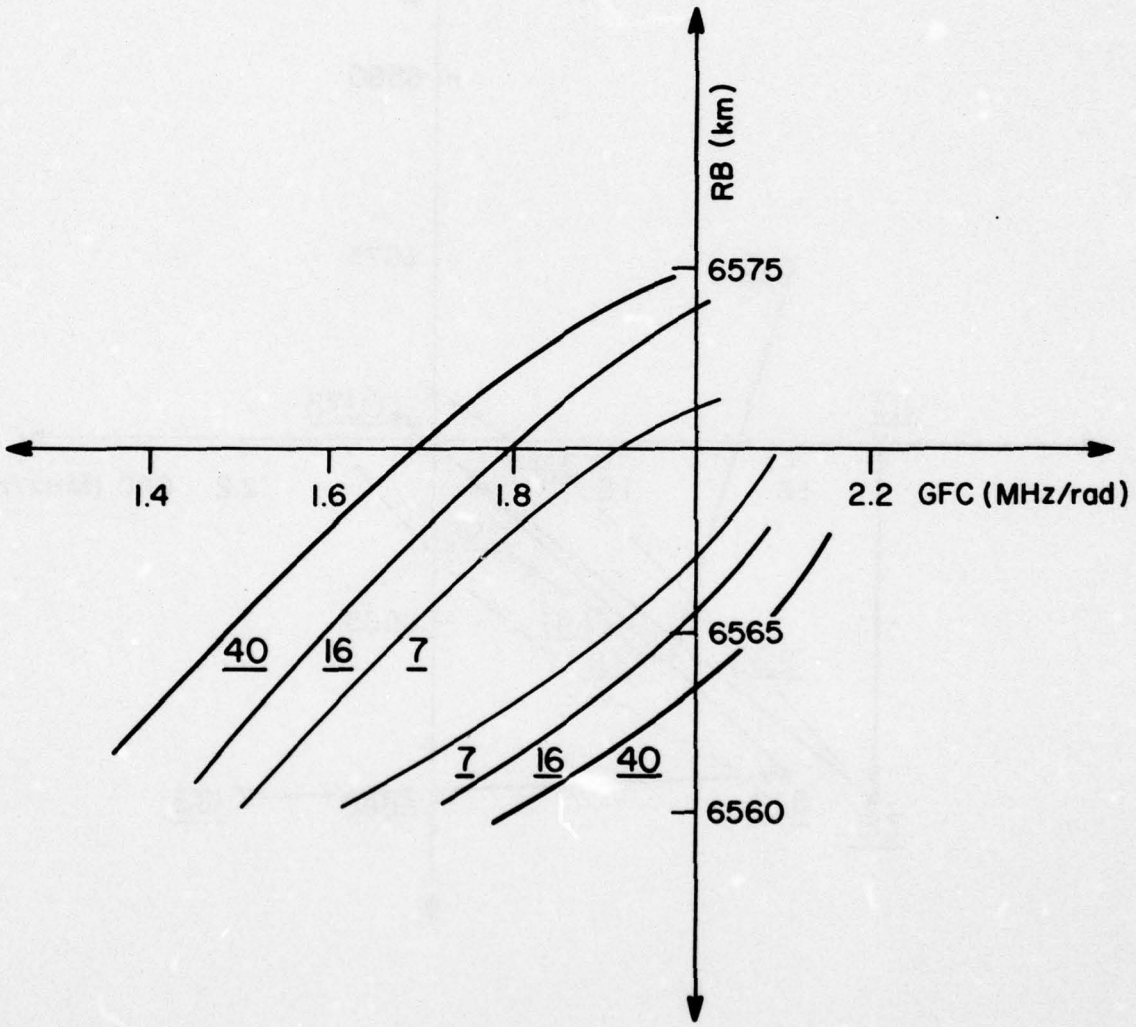


Figure 3. Level curves of an MSE surface.

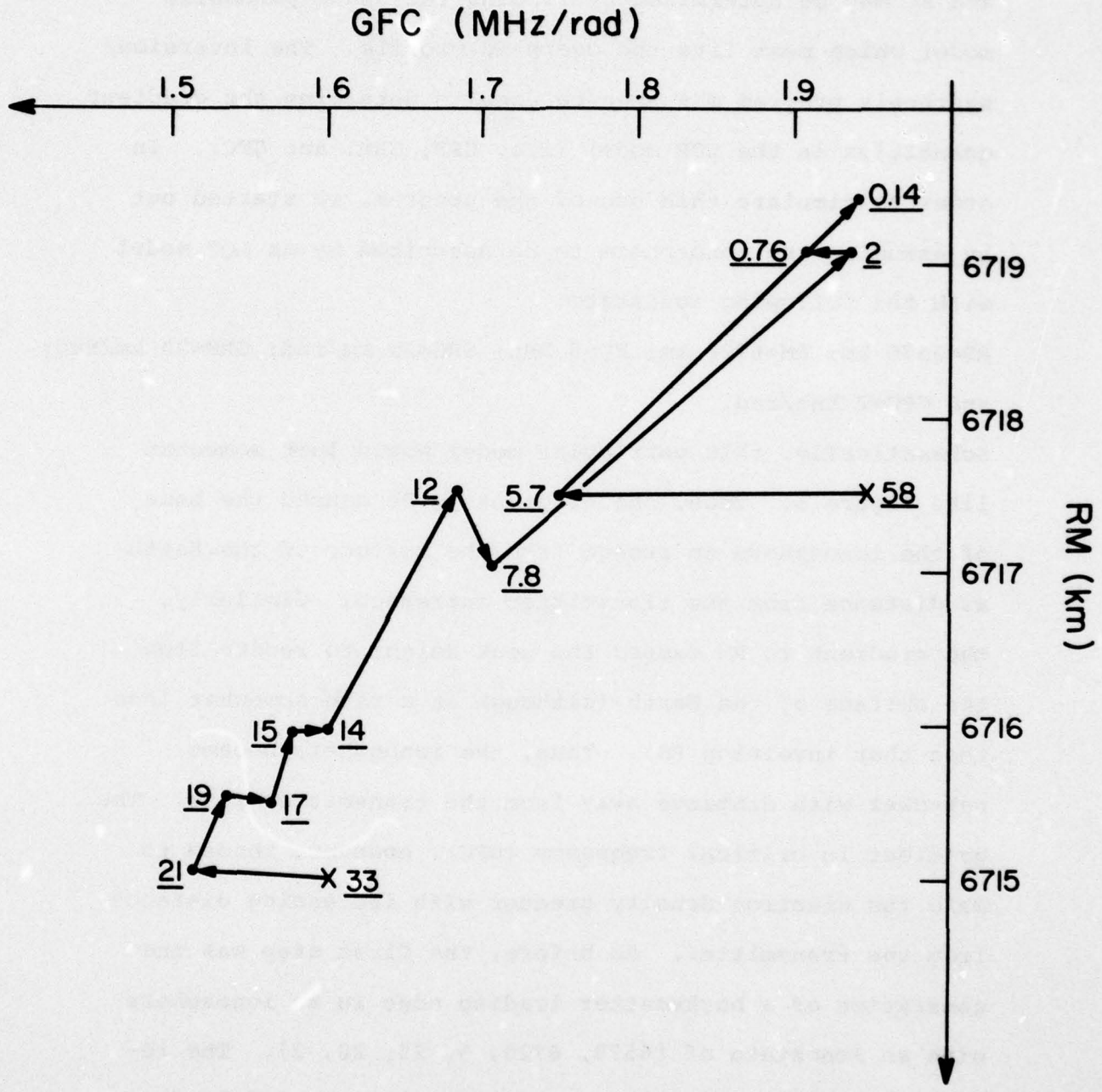


Figure 4. Two component (GFC&RM) convergence of MSE.

and FC may be determined by finding the quasi-parabolic model which best fits the overhead profile. The inversion/ synthesis program may then be used to determine the gradient quantities in the LQP model (i.e. GRB, GRM, and GFC). In order to simulate this use of the program, we started out by assuming the ionosphere to be described by an LQP model with the following ionostate:

RB=6570 km; RM=6720 km; FC=5 MHz; GRB=25 km/rad; GRM=20 km/rad; and GFC=2 MHz/rad.

Schematically, this particular model would look somewhat like Figure 5. Thus, the gradient in RB caused the base of the ionosphere to recede from the surface of the Earth as distance from the transmitter increased. Similarly, the gradient in RM caused the peak height to recede from the surface of the Earth (although at a rate somewhat less than that involving RB). Thus, the ionosphere became narrower with distance away from the transmitter site. The gradient in critical frequency (GFC), however, tended to make the electron density greater with increasing distance from the transmitter. As before, the first step was the generation of a backscatter leading edge in an ionosphere with an ionostate of {6570, 6720, 5, 25, 20, 2}. The results were computed for sounding frequencies of 6.5, 7.0, and 7.5 MHz, and are summarized below:

FREQUENCY (MHz)	MINIMUM GROUP PATH (KM)
6.5	1081.2
7.0	1172.3
7.5	1265.4

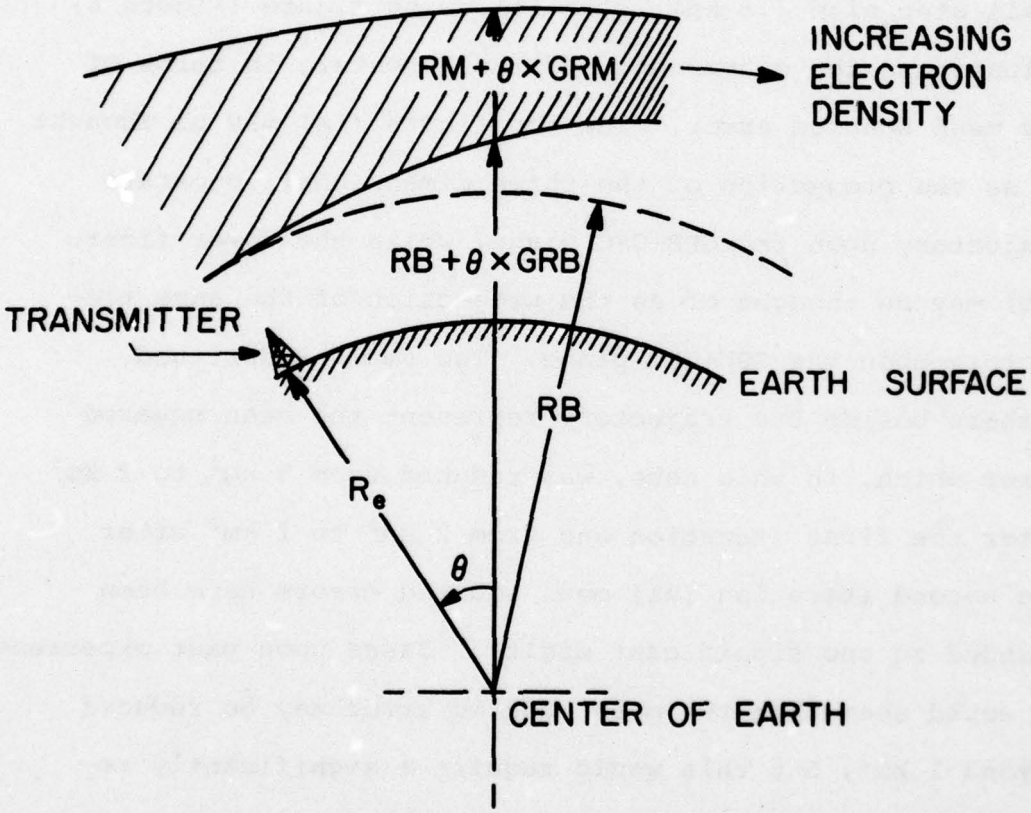
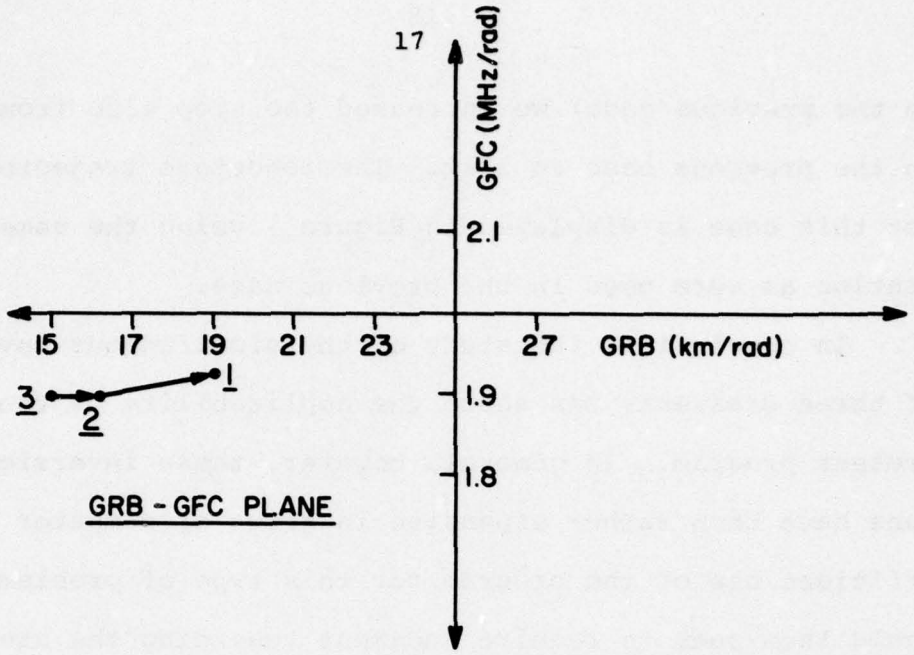


Figure 5. Combined effects of three simultaneous gradients upon ionosphere model.

The inversion/synthesis program was then run in the inversion mode for two separate cases. In the first case an initial ionostate of {6570, 6720, 5, 15, 10, 1.9} was selected with the last three components specified as variable ionostate components. The mean squared error resulting from this particular ionostate was found to be rather small (3 km^2) and thus the ray tracing was performed with a fairly small step size (.5 km). The following figure (Figure 6) illustrates the convergence of the ionostate in terms of the mean squared error. The top figure (6a) may be thought of as the projection of the three dimensional ionostate trajectory upon the GRB-GFC plane, while the lower figure (6b) may be thought of as the projection of the same trajectory upon the GRM-GFC plane. The small underlined numbers beside the trajectory represent the mean squared error which, in this case, was reduced from 3 km^2 to 2 km^2 after the first iteration and from 2 km^2 to 1 km^2 after the second iteration (all mean squared errors have been rounded to one significant digit). Based upon past experience, it would seem that the mean squared error may be reduced beyond 1 km^2, but this would require a significantly reduced step size in the ray tracing subroutine.

A somewhat more convincing demonstration of the simultaneous determination of the three gradients is provided by a second case. In this instance, we selected an initial ionostate of {6570, 6720, 5, 40, 30, 1.8}, and found an initial mean squared error of 43 km^2. As a result of the relatively large mean squared error (when compared



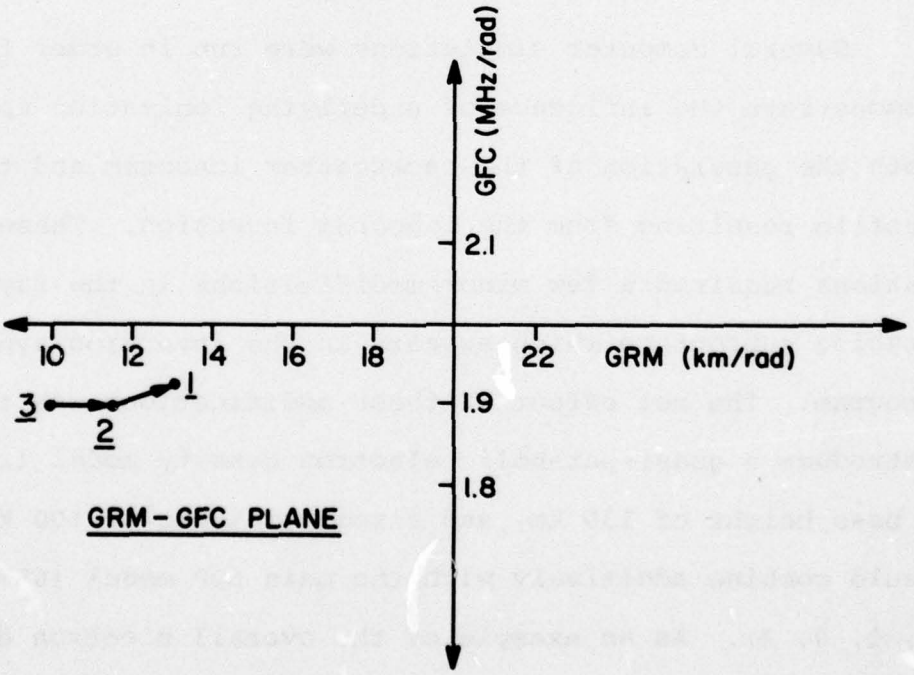


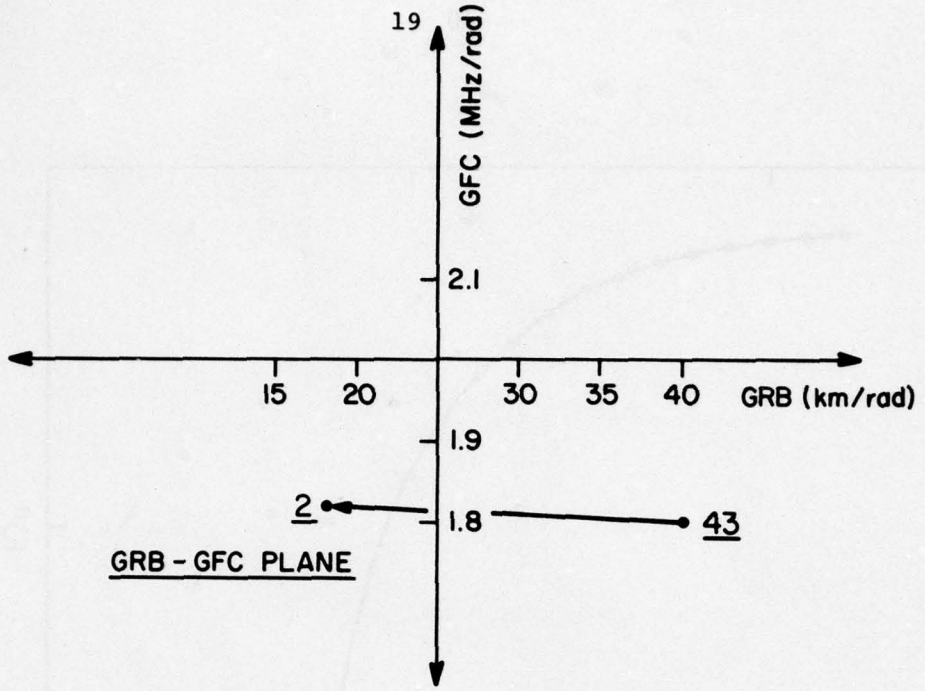
Figure 6. Three component (GRB, GRM,&GFC) convergence of MSE with a small initial error.

to the previous case) we increased the step size from .5 km in the previous case to 2 km. The ionostate trajectory for this case is displayed in Figure 7 using the same convention as were used in the previous case.

In conclusion, the study of the simultaneous inversion of three gradients has shown the applicability of the present program. In general, however, these inversion runs have been rather expensive in terms of computer time. Efficient use of the program for this type of problem would then seem to require judgment regarding the step size in the ray tracing program.

2.3 THE EFFECT OF UNDERLYING IONIZATION

Several computer simulations were run in order to demonstrate the influence of underlying ionization upon both the generation of the backscatter ionogram and the profile resulting from the ionogram inversion. These simulations required a few minor modifications in the ray tracing subroutine which appears in the inversion/synthesis program. The net effect of these modifications was to introduce a quasi-parabolic electron density model (with a base height of 130 km, and a semithickness of 100 km) which would combine additively with the main LQP model (6570, 6720, 5, 0, 0, 2). As an example of the overall electron density model which results when the critical frequency of the underlying ionization is set at .75 MHz, the following graph (Figure 8) may be considered. This graph, of course, corresponds to the profile which would exist above the



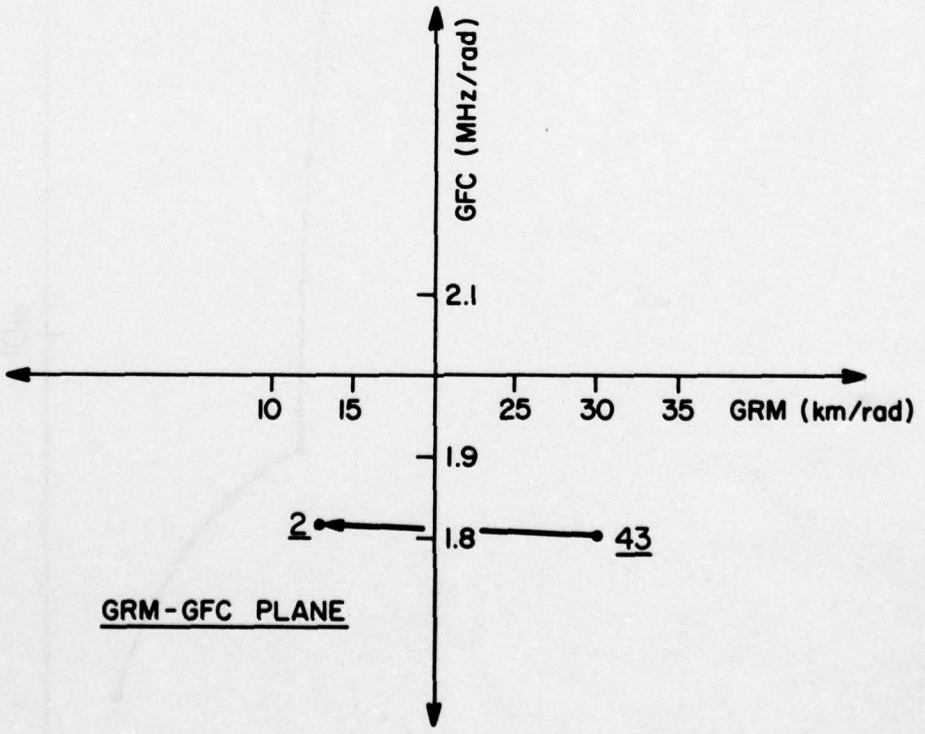


Figure 7. Three component (GRB,GRM,&GFC) convergence of MSE with a large initial error.

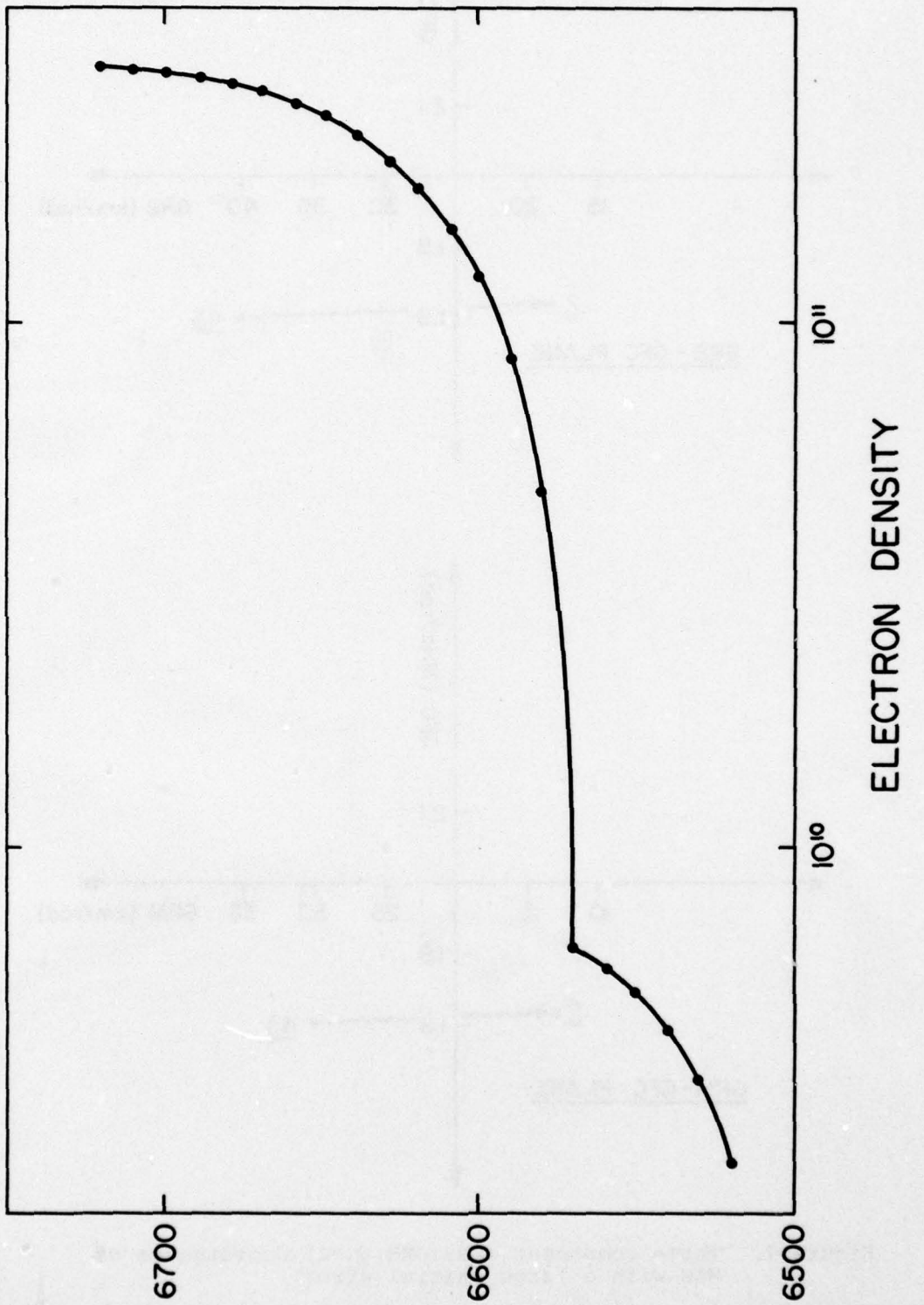


Figure 8. Combined electron density model (with underlying layer).

sounder. This distinction is necessary since the main LQP model contains a gradient in critical frequency, while the underlying layer is, in essence, a spherically symmetric electron density model.

In order to determine the effects of the underlying layer upon the present problem, we compared the results of simulated ionogram generation (synthesis) in both the presence and absence of the underlying layer. The minimum group paths as measured at 6.5, 7.0, and 7.5 MHz, in the absence of the underlying layer, provided a suitable reference, and, in fact, the values of minimum group path as measured at these three frequencies were 1076.3 km, 1165.4 km and 1256.3 km, respectively. Using the previously described model for the underlying ionization, various values of the critical frequency of this layer were used in order to simulate various degrees of intensity of the underlying ionization. For each such value of critical frequency, simulated ionogram generation (synthesis) was used to compute the values of minimum group paths, again at frequencies of 6.5, 7.0, and 7.5 MHz. Denoting these values by P'(6.5), P'(7.0), and P'(7.5), it was then possible to demonstrate (as shown in Figure 9) the significance of underlying ionization upon the measurement of minimum group path through the use of an RMS error defined as:

$$\text{RMS error}=\sqrt{\{[P'(6.5)-1076.3]^2+[P'(7.0)-1165.4]^2+[P'(7.5)-1256.3]^2\}/3}. \quad (19)$$

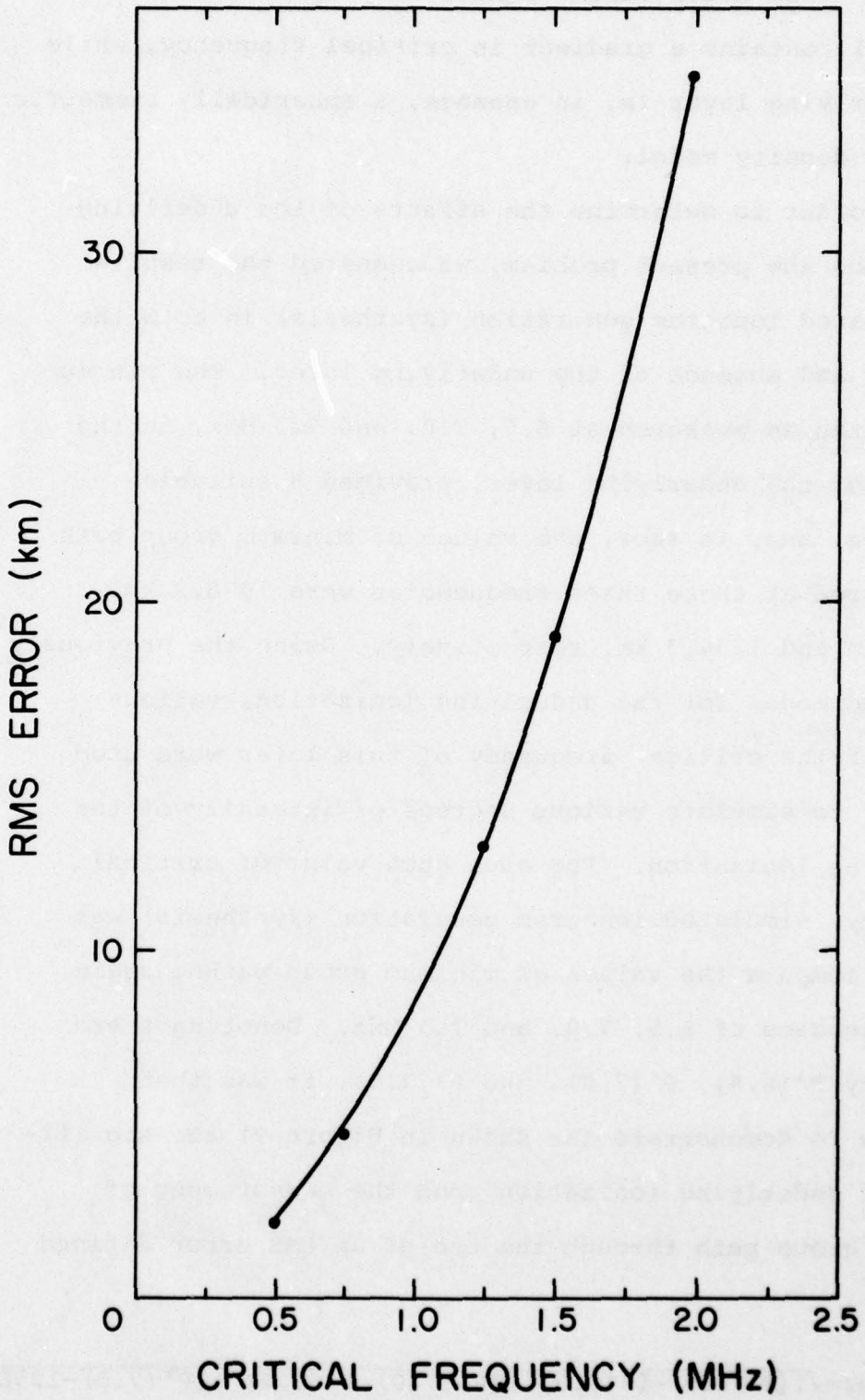


Figure 9. RMS error introduced by underlying layer.

As would be expected, the larger values of critical frequency in the underlying layer were associated with larger RMS errors. Furthermore, when the error at each individual frequency is plotted (as shown in Figure 10) it can be seen that the effects of underlying ionization, at each of the sounding frequencies, is quite similar to the composite effect shown in Figure 9.

In conclusion, therefore, our example demonstrates that the presence of an underlying layer can, indeed, affect the measurement of minimum group path, and that the degree to which the measurement is affected depends upon the "strength" of the underlying layer. While this conclusion is hardly surprising, it is significant to note that even when realistic estimates were used to model the underlying ionization, the measured values of minimum group path were substantially altered from the values which would be measured in the absence of such ionization.

A related problem, then, is to determine how this alteration in the group path will affect the ionostate which is computed by the inversion program. Again, we have proceeded to study this problem through the use of a particular example in which the ionosphere was assumed to consist of two layers -- an LQP model layer and a layer of underlying ionization. The LQP model, as before, was specified by the ionostate {6570, 6720, 5, 0, 0, 2}, while the underlying layer was set to have a critical frequency of .75 MHz. Actually, the electron density profile in

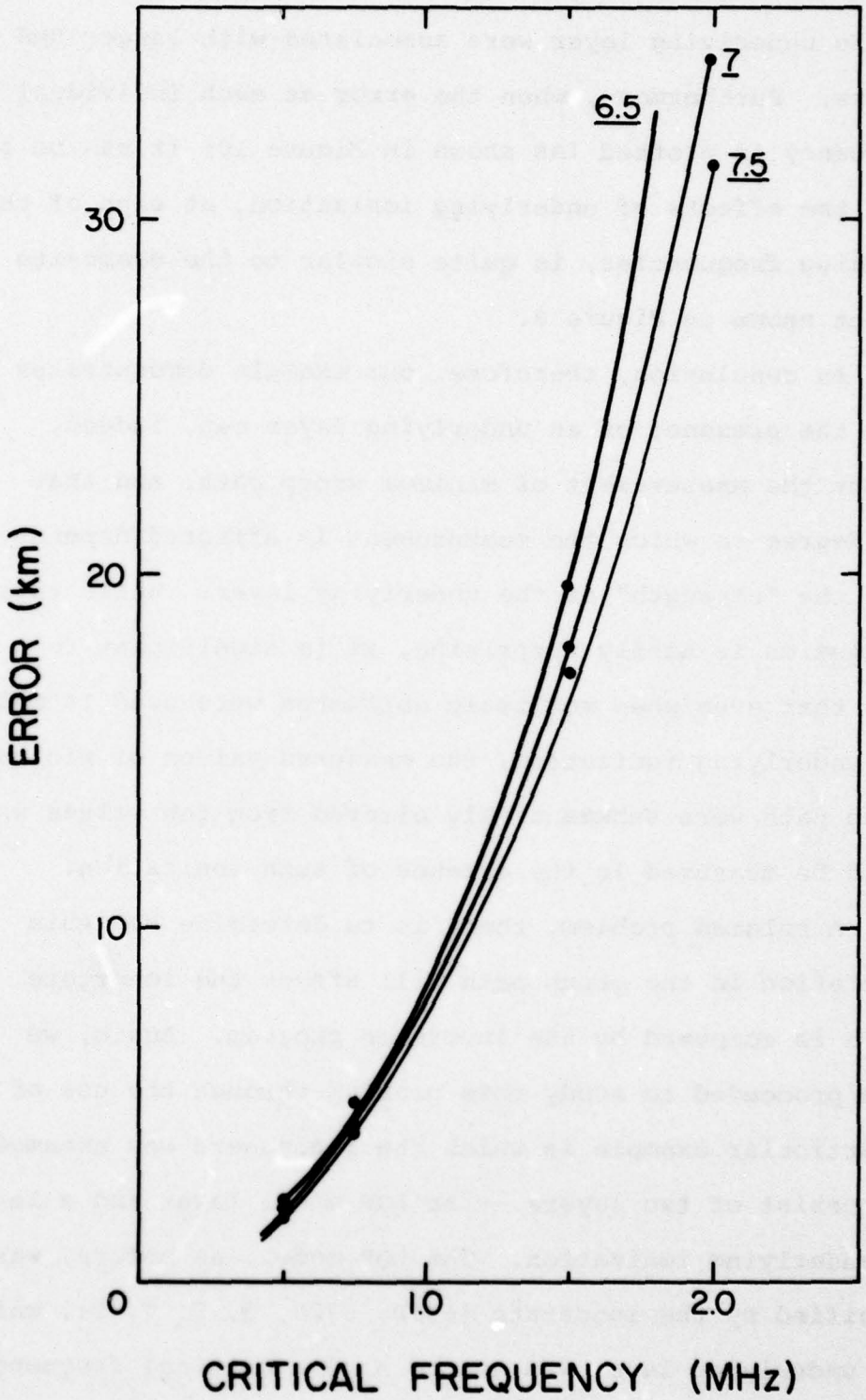


Figure 10. Error introduced by underlying layer at each sounding frequency.

this case is given by Figure 8. Our next step was to obtain the results of the simulated backscatter ionogram generation. Again, these results were available from some of the previous runs which were used in the construction of Figures 9 & 10, and are summarized below

frequency	elevation (degrees)	min. group path (km)
6.5	33.89	1081.4
7.5	28.08	1260.5

The next step, of course, was to use the values of minimum group path, given in the table above, as input for the inversion program. For the purpose of comparison, it is worthwhile to reconsider Figure 9, at this point. We know that the correct ionostate for the main (LQP) layer was {6570, 6720, 5, 0, 0, 2}. However, when the underlying ionization is present, we can see that this ionostate will result in a RMS error of about 5 km (or a mean squared error of 25 km^2). This error then provides somewhat of a "tidemark" in the sense that when a lower mean squared error is produced in the course of running the inversion program for this particular case, it would seem feasible that the program is attempting to construct a composite (or compromise) ionosphere model to simulate the effects of <u>both</u> the main and underlying layers of ionization. Indeed, this situation was found to occur. The following graph illustrates the convergence of the mean squared error

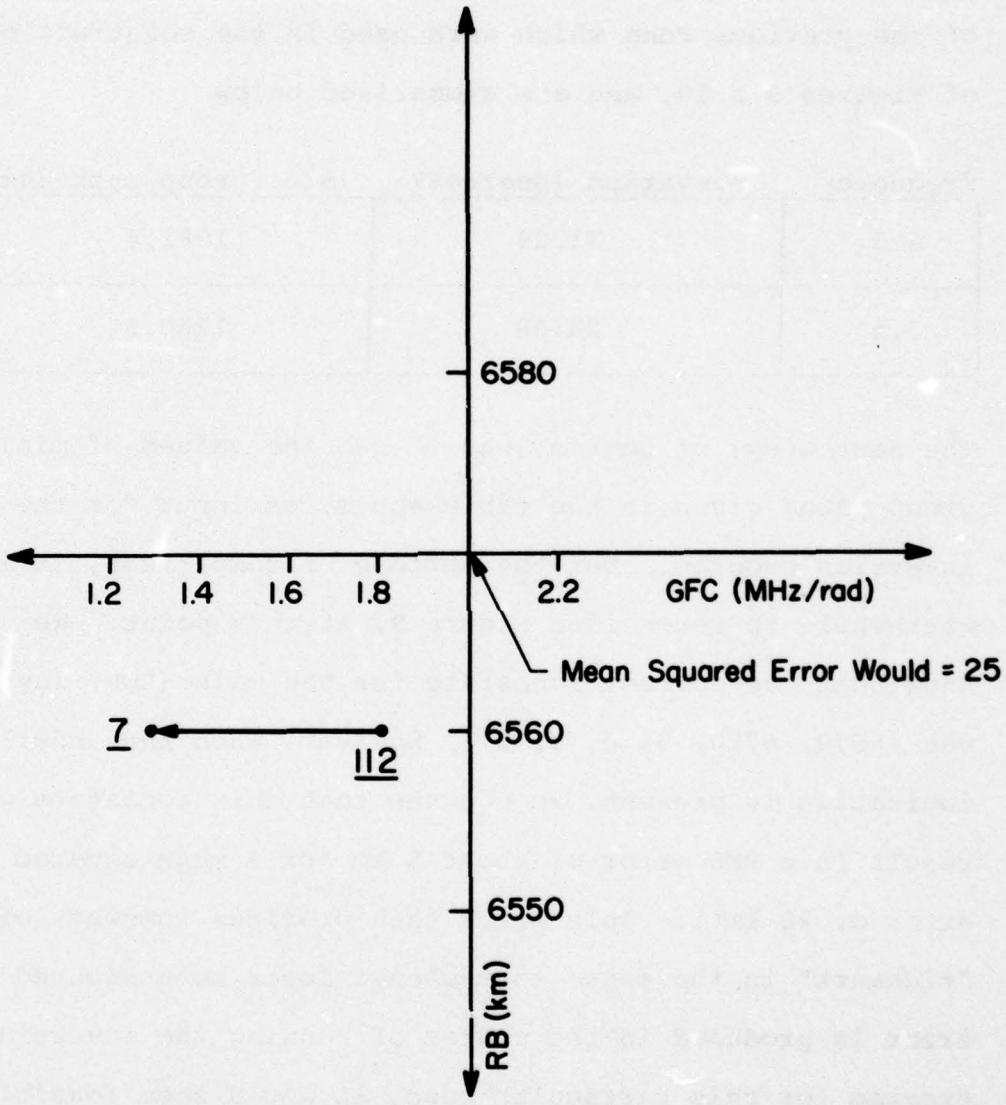


Figure 11. Two component (GFC&RB) convergence of MSE in presence of underlying layer.

when RB and GFC are specified as variable ionostate components. The mean squared error after one iteration is approximately 7 km^2, as opposed to the 25 km^2 error which would be obtained for the apparently correct ionostate of {6570, 6720, 5, 0, 0, 2}. A second iteration was also used, but failed to provide a significant change in either the ionostate or the mean squared error.

2.4 QUADRATIC GRADIENT

In this section, an additional ionostate component is introduced in order to allow for the possibility of a "quadratic gradient" in the critical frequency. While the resulting model may still be regarded as locally quasi-parabolic (LQP), the dependence of the critical frequency upon the geocentric angle subtended by the ray trajectory is now of the form:

$$f_c(\theta) = FC + GFC\times\theta + G2FC\times\theta^2 \qquad (20)$$

with GFC and G2FC as constants. The other quasi-parabolic parameters contain a "linear gradient", i.e.

$$r_b(\theta) = RB + GRB\times\theta$$

$$r_m(\theta) = RM + GRM\times\theta$$

Thus if we assume, as was previously done, that the overhead values of the quasi-parabolic parameters are known, the present section is intended to consider the simultaneous determination of four remaining ionostate components (i.e. GRB, GRM, GFC, and G2FC). In order to test this capability in the program we proceeded, as in previous cases, by selecting ionostate component values of:

RB = 6570 km

RM = 6720 km

FC = 5 MHz

GRB= 25 km/rad.

GRM= 20 km/rad.

GFC= 2 MHz/rad.

G2FC= 16 MHz/rad.^{2}

and simulating the measurement of a backscatter ionogram in an LQP model ionosphere at sounding frequencies of 6.5, 7.0, 7.5, and 8.0 MHz. The results of this simulation are summarized in the table below:

SOUNDING FREQUENCY (MHz.)	MINIMUM GROUP PATH (km)
6.5	1065.2
7.0	1149.8
7.5	1234.6
8.0	1322.0

These values of minimum group path were then used as part of the data input file for the inversion program. In addition, an initial ionostate of

RB = 6570 km

RM = 6720 km

FC = 5 MHz

GRB = 30 km/rad.

GRM = 28 km/rad.

GFC = 1.8 MHz/rad.

G2FC = 13 MHz/rad.^{2}

was specified. Allowing the inversion program to run on the basis of this data resulted in the generation of new estimates for the values of the variable ionostate components, as shown in Figure 12. Referring to this particular figure, it can be seen that the final set of variable ionostate components is still rather far away from the correct value, despite the fact that the mean squared error is reduced to .4 km^2. There are two possible explanations for this paradoxical result. The final set of ionostate components may represent an additional local minimum in the mean squared error hypersurface. Alternatively, the small value of mean squared error at the final set of ionostate components may represent the offsetting effects of certain combinations of variable ionostate components. More specifically, if a backscatter ionogram leading edge is synthesized in both the correct LQP model ionosphere and the final LQP model ionosphere, the results as shown in Figure 13 are virtually indistinguishable. That there is any deviation at all becomes apparent when the difference in minimum group paths is plotted as a function of frequency (Figure 14). In order to demonstrate why we believe that mutually offsetting effects may be responsible for the small value of mean squared error at the final set of ionostate components, we have plotted (in Figure 15) the over-head

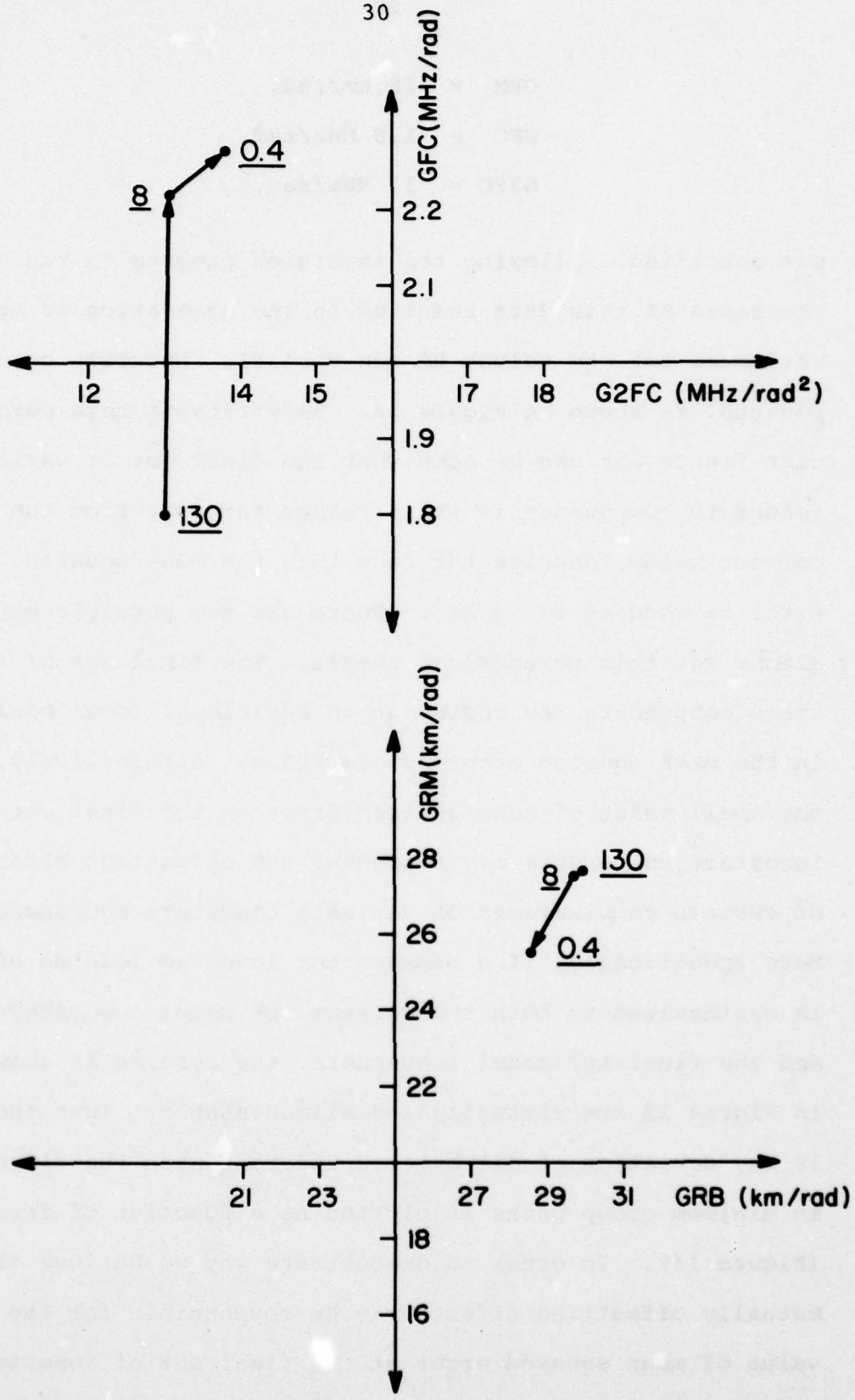


Figure 12. Four component (GFC,G2FC,GRB,&GRM) convergence of MSE.

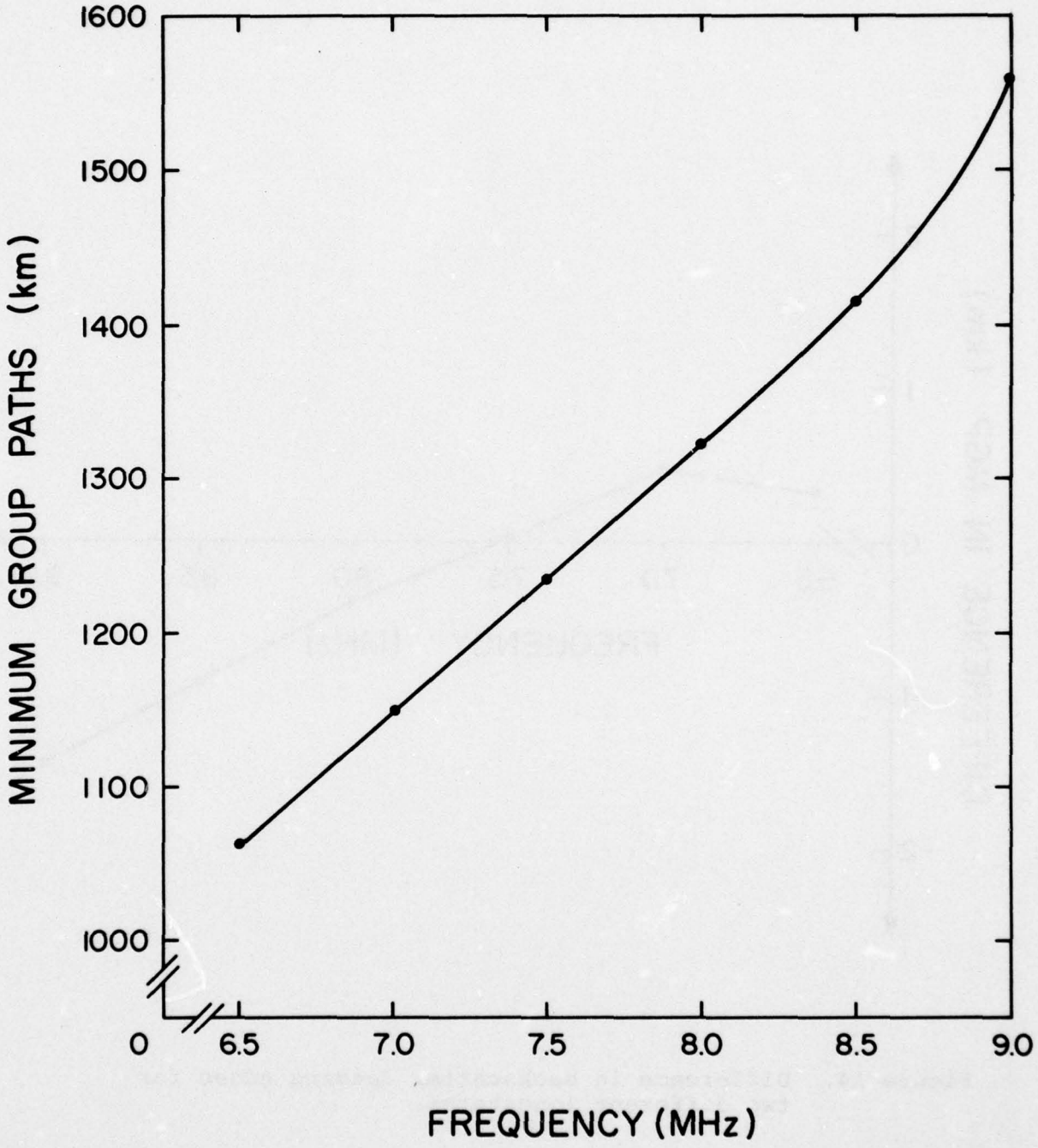


Figure 13. Backscatter leading edges for two different ionostates.

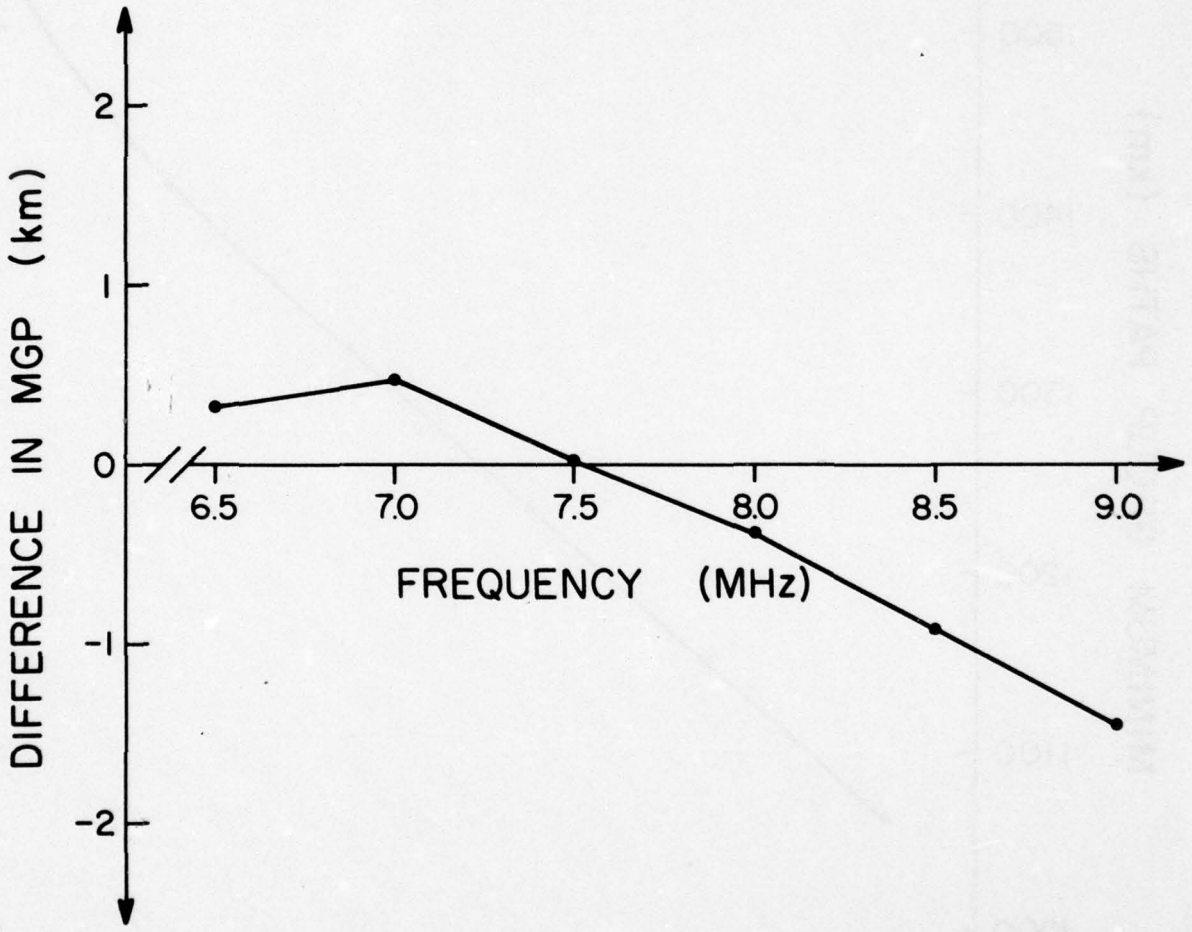


Figure 14. Difference in backscatter leading edges for two different ionostates.

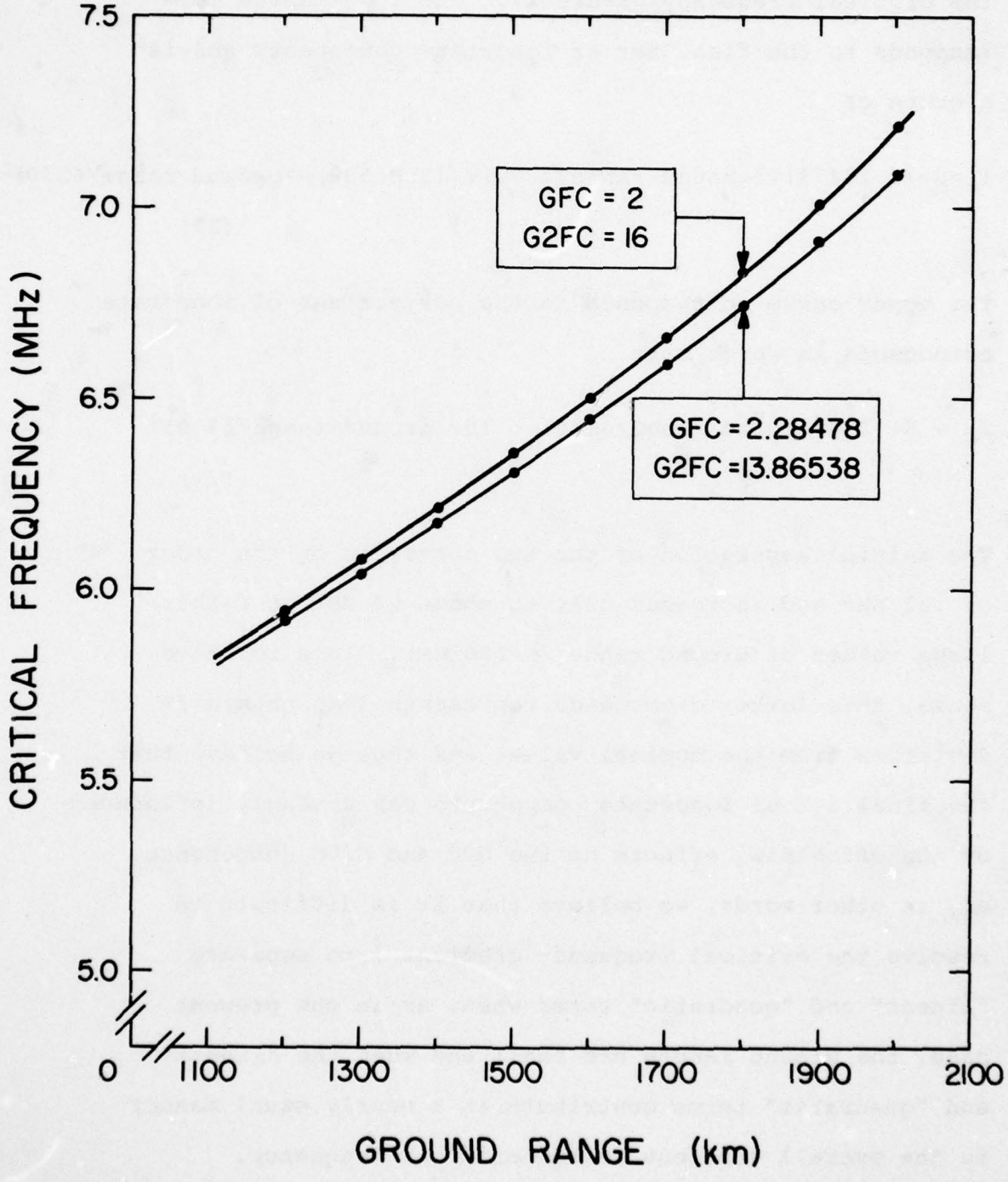


Figure 15. Critical frequency variation for two different ionostates.

values of critical frequency as a function of ground range distance from the sounder location (in the direction of the critical frequency gradient). The lower curve corresponds to the final set of ionostate components and is a graph of

$$f_c = 5 + (2.28478) \times (\text{ground range}/6370) + (13.86538) \times (\text{ground range}/6370)^2 \quad (21)$$

The upper curve corresponds to the correct set of ionostate components in which case

$$f_c = 5 + (2) \times (\text{ground range}/6370) + 16 \times (\text{ground range}/6370)^2 \quad (22)$$

The initial separation of the two curves is on the order of .02 MHz and increases only to about .1 MHz at rather large values of ground range ($\sim$2000 km). In a relative sense, this latter divergence represents less than a 2% deviation from the nominal value, and thus we believe that the final set of ionostate components was strongly influenced by the offsetting effects of the GFC and G2FC components, or, in other words, we believe that it is difficult to resolve the critical frequency gradient into separate "linear" and "quadratic" terms when, as in the present case, the ground ranges are small and when the "linear" and "quadratic" terms contribute in a nearly equal manner to the overall gradient in the critical frequency.

We did, however, consider the possibility of detecting a "quadratic" component in the absence of a "linear" term.

In this case, the correct ionostate was assumed to consist of

RB = 6570 km.

RM = 6720 km.

FC = 5 MHz

GRB = 25 km/rad.

GRM = 20 km/rad.

GFC = 0 MHz/rad.

G2FC= 16 MHz/rad.

The synthesis program was then run in order to compute the minimum group paths occuring at 6.5 and 7.0 MHz. These results were then used in the inversion program with estimated initial values for RM and G2FC. The convergence of these parameters is shown in Figure 16 for two sets of initial estimates. It can be seen that a rather substantial reduction in the mean squared error has occured.

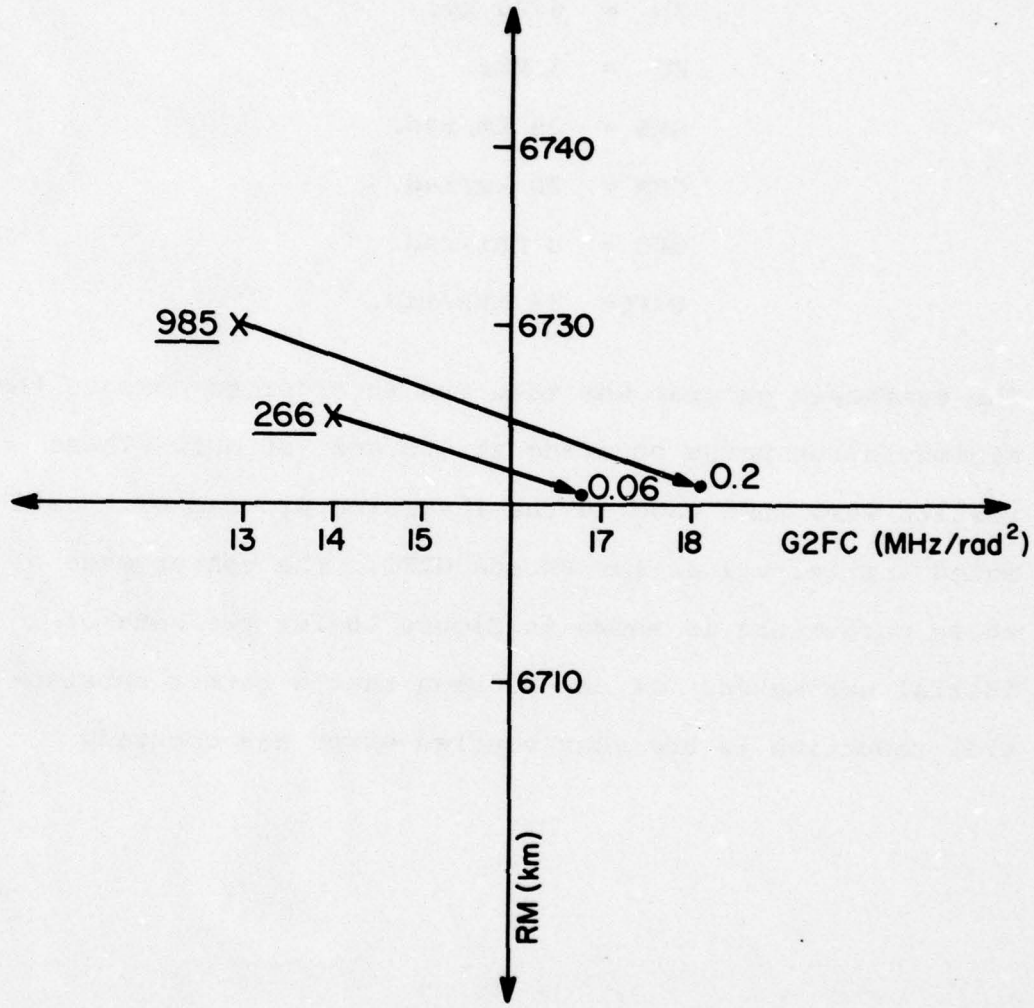


Figure 16. Two component (G2FC&RM) convergence of MSE.

3. PROGRAM DOCUMENTATION

3.1 OVERVIEW OF PROGRAM OPERATION

The purpose of this section is to provide an overall view of the operation of the backscatter ionogram inversion and synthesis programs. Figure 17 demonstrates how the synthesis portion of the program is accomplished. Since the program automatically assumes that the ionospheric electron density profile follows the LQP model, only the values of the six ionostate components, the sounding frequencies, and a few control parameters (which will be discussed later) need to be entered. The program then computes the minimum group paths for each of the sounding frequencies.

The inversion operation, as shown in Figure 18 is somewhat more complicated. In this case, the input consists of an estimated ionostate, a set of sounding frequencies, the corresponding minimum group paths which were observed at each sounding frequency, and some control parameters. In its simplest terms, the program then attempts to modify the estimated ionostate in a manner which results in the minimization of the mean squared error. It should be noted, however, that while Figures 17 and 18 illustrate the function of the program, the actual details of the program flow are considerably more complex. It is, therefore, our intention to provide a more detailed discussion at this time. This discussion will be limited to the inversion program since the synthesis program is actually contained in the inversion program, and will also be limited to the major subroutines.

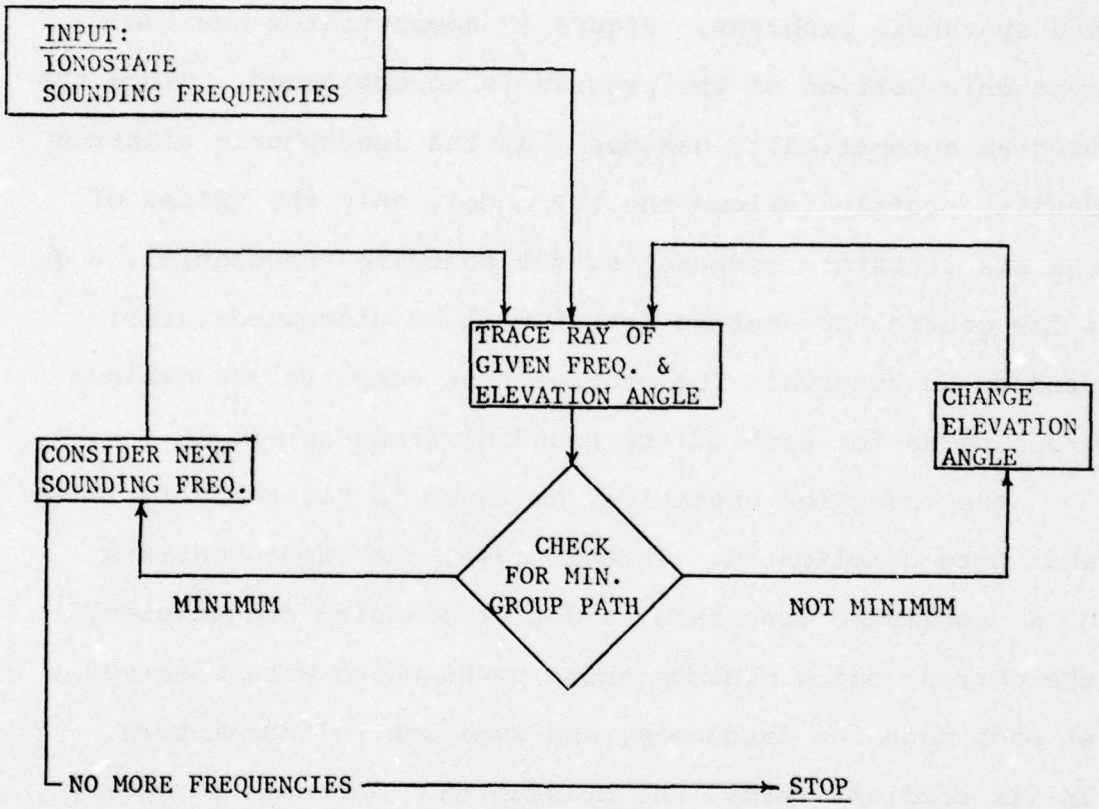


Figure 17. Synthesis program flow chart.

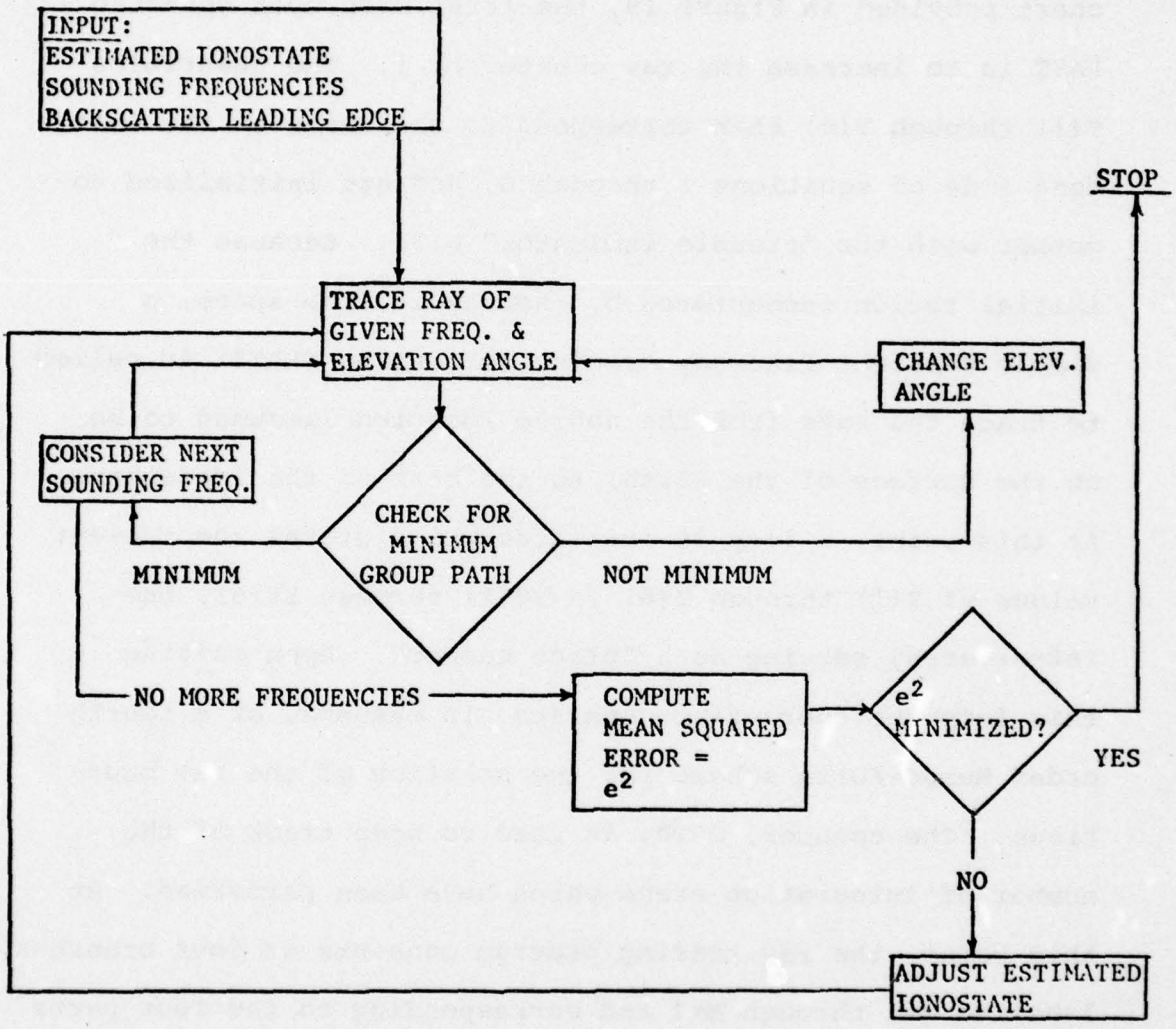


Figure 18. Inversion program flow chart.

3.2 FLOW OF MAJOR SUBROUTINES

The most fundamental part of the inversion program is the ray tracing subroutine, RAYT. Referring to the flow chart provided in Figure 19, the first step upon entering RAYT is to increase the ray counter by 1. The quantities Y(1) through Y(6) then correspond to the terms on the left hand side of equations 1 through 6, and are initialized together with the "trouble indicator" N(3). Because the initial region encountered by the ray is free space, a simple straight line ray tracing subroutine (RAYS) is called to trace the rays from the source location (assumed to be on the surface of the Earth) to the base of the ionosphere. At this point, a loop is initiated which stores the present values of Y(1) through Y(6) in YY(1) through YY(6), the latter array serving as a "place keeper". Upon exiting this loop the subroutine consists, in essence, of a fourth order Runge-Kutta scheme for the solution of the ray equations. The counter, NSTP, is used to keep track of the number of integration steps which have been performed. At this point, the ray tracing program consists of four branches, labelled M=1 through M=4 and corresponding to the four parts of an integration step in the 4th order Runge-Kutta solution. At statement 200 a test is performed to guarantee that the ray point lies within the spatial domain of the LQP model i.e. $r_b \leq r \leq r_m$. If $r<r_b$ the ray is assumed to be returning to Earth in which case the free space ray tracing subroutine RAYS is called. If $r>r_m$, it is assumed that the ray will

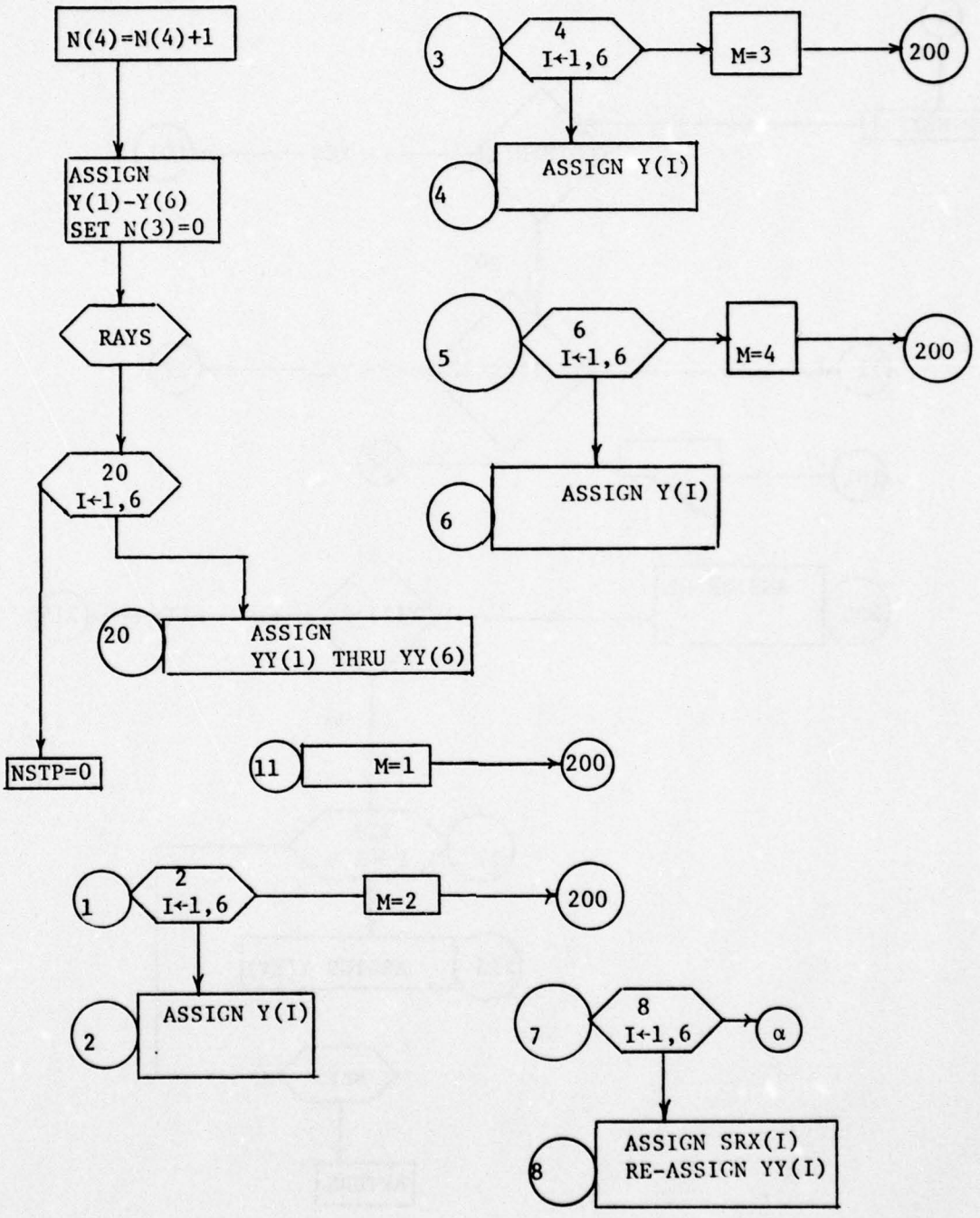


Figure 19. Flowchart for subroutine RAYT.

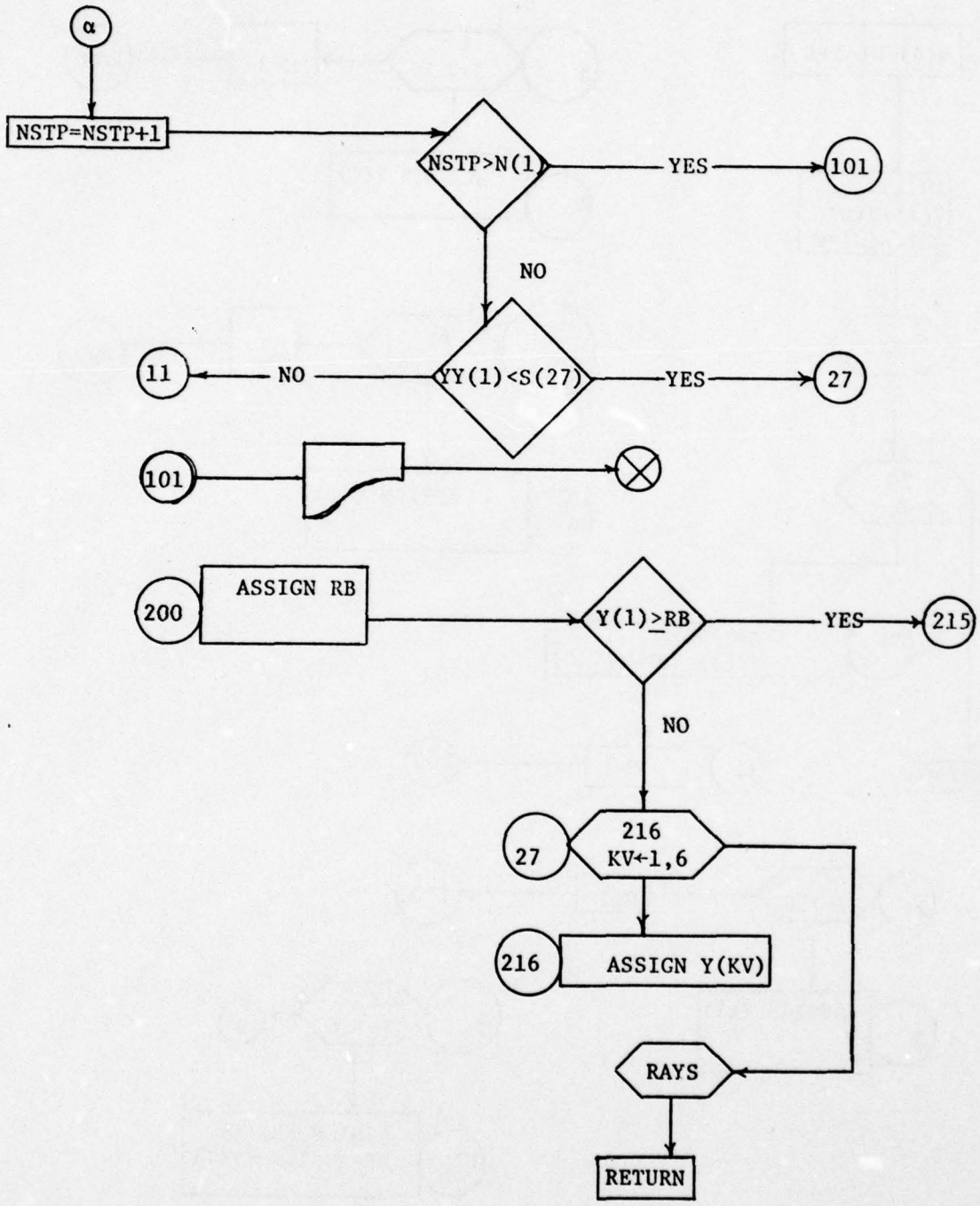


Figure 19 continued.

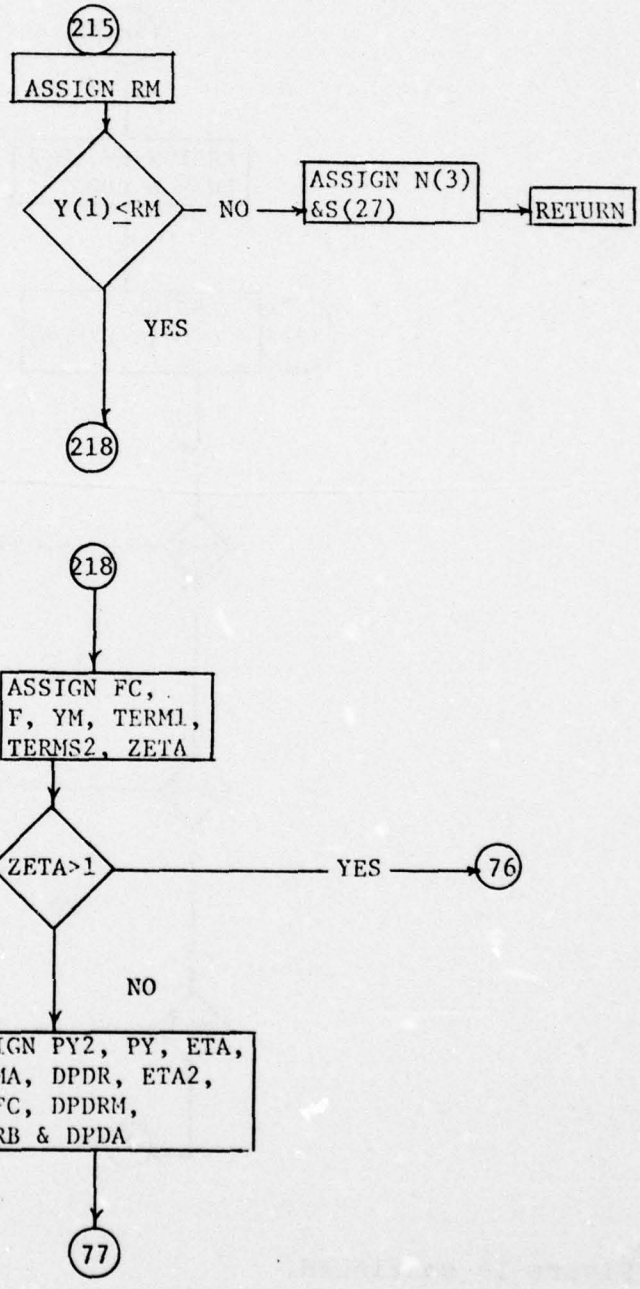


Figure 19 continued.

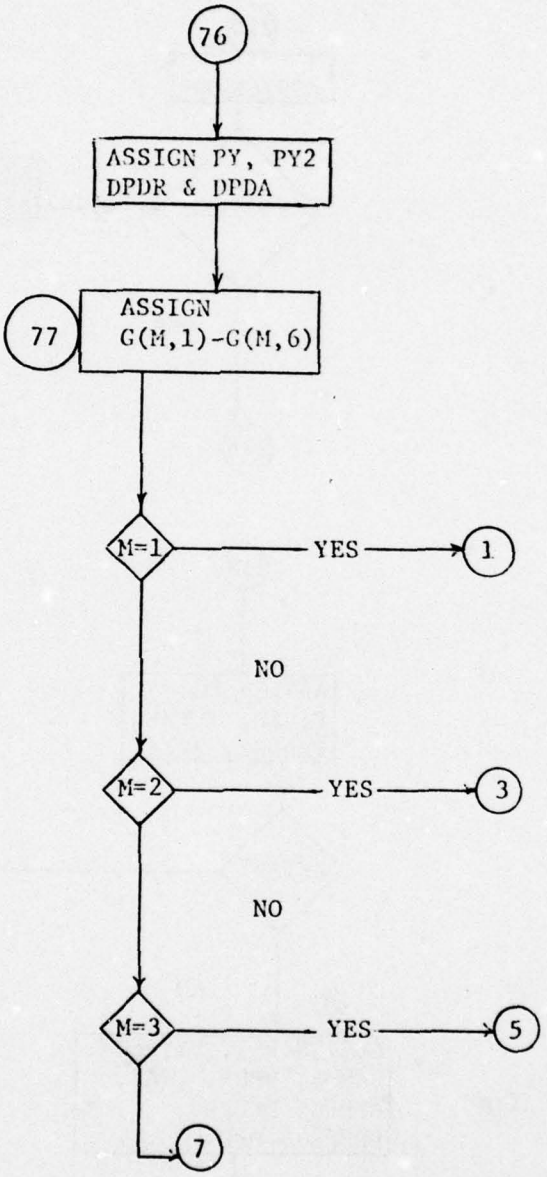


Figure 19 continued.

never return to Earth and therefore the trouble indicator N(3) is set to 1. Most of the time, however, the ray will be in the spatial domain of the LQP model and therefore the right hand sides of the ray equations 1 through 6 will be evaluated and stored in G(M,1) through G(M,6). When all four branches of this process have been completed (M=1 through M=4) one complete integration step will have been completed at which time the program will check again to see if it should continue. Upon returning from subroutine RAYT the program will either have a trouble indicator N(3) set to 1 or else it will have the group path corresponding to the input frequency and elevation angle.

This information, however, is not sufficient since we are interested only in rays which have the minimum group paths for a given frequency. For this reason, subroutine RAYT is nested inside another subroutine (STAR) which varies the initial ray elevation angle until a minimum group path is obtained.

Subroutine STAR was written to compute the minimum group path for a ray (with a given frequency) traced through an ionosphere with given parameters. The only parameter which may be varied in order to compute this minimum is the elevation angle of the ray.

Referring to the flow chart, an initial elevation angle is part of the input to this subroutine. Subroutine RAYT is then called in order to ensure that a ray with the initial elevation angle will, in fact, reflect back to the surface of the Earth. If this situation does not occur,

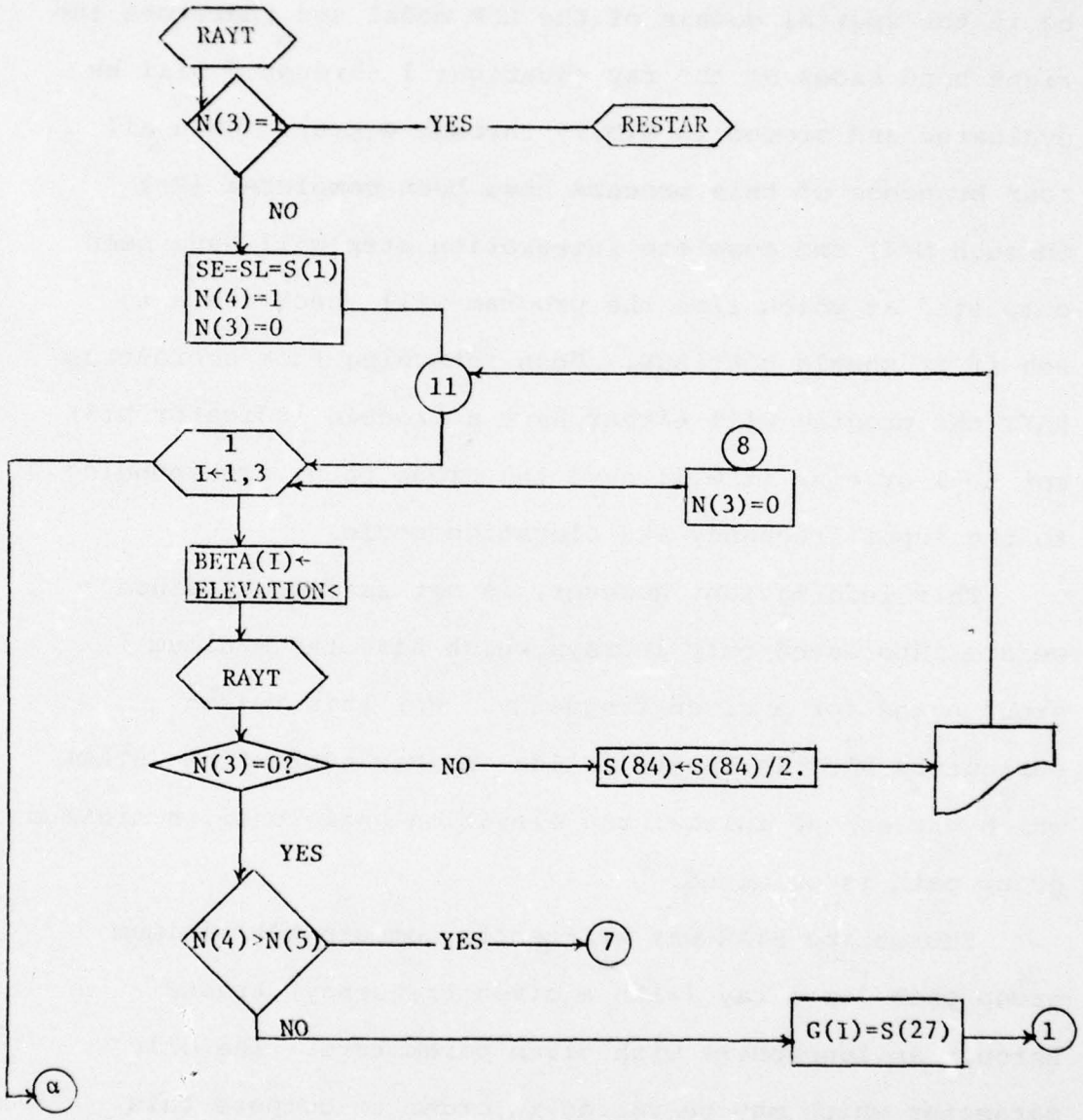


Figure 20. Flowchart for subroutine STAR.

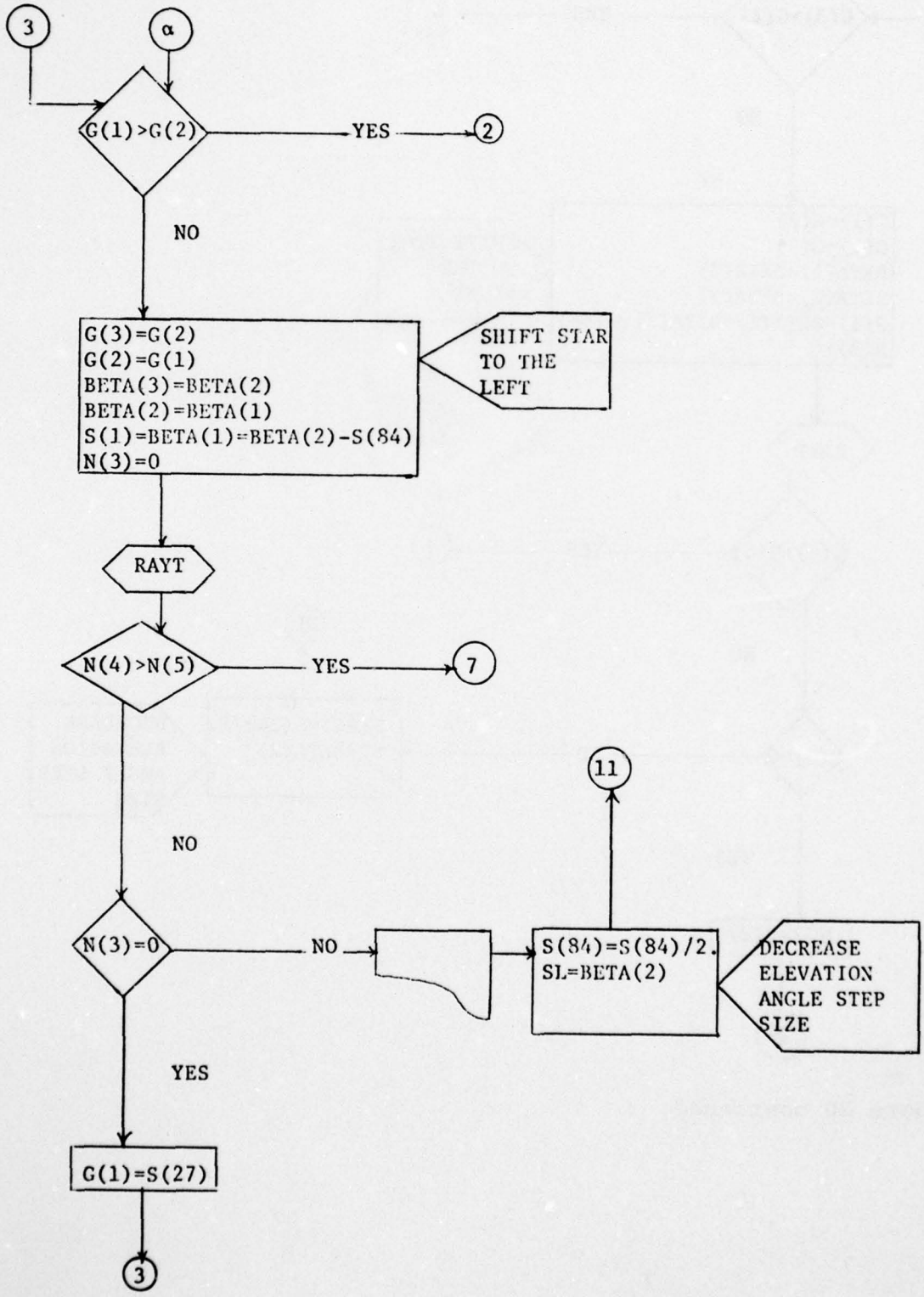


Figure 20 continued.

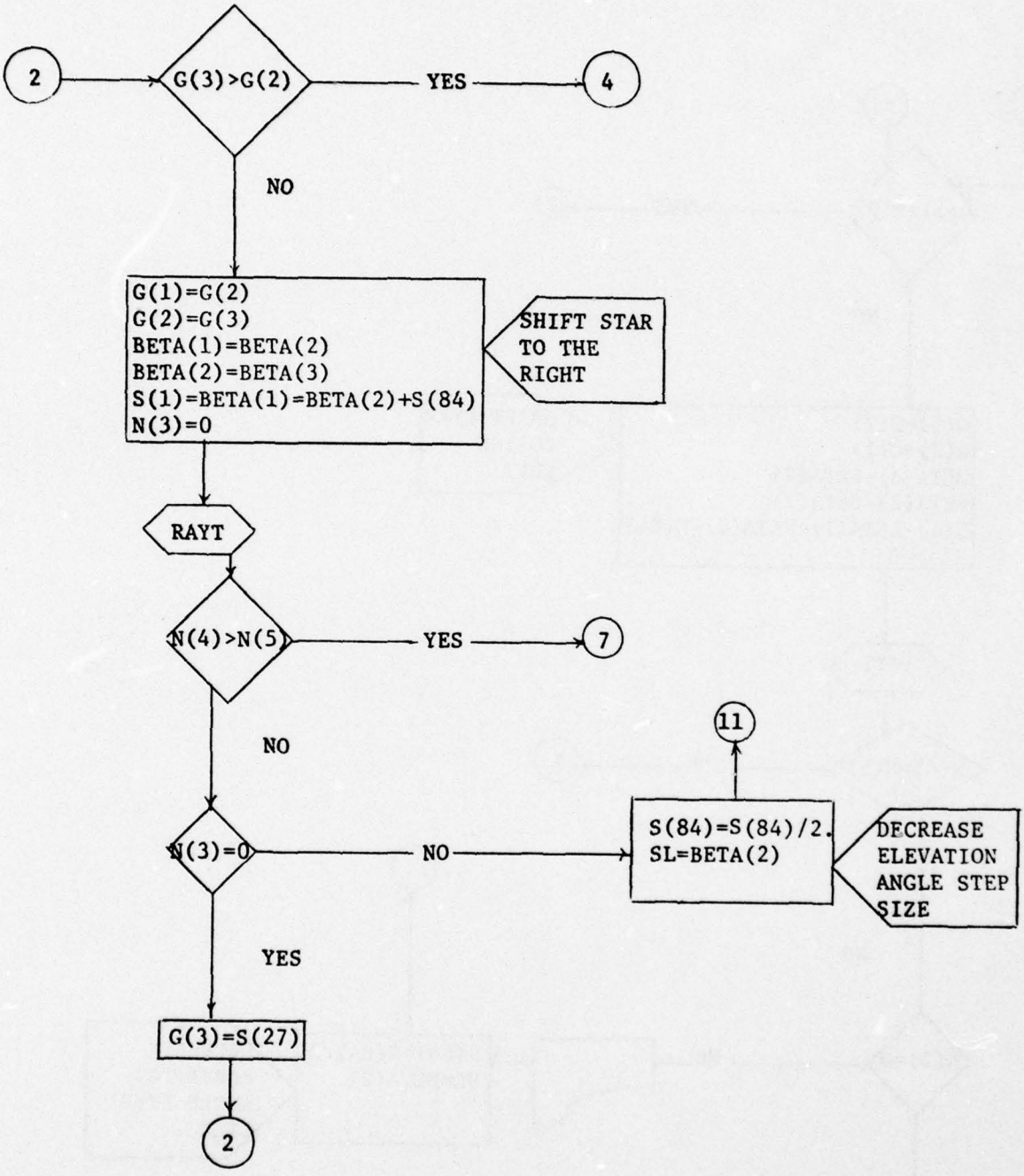


Figure 20 continued.

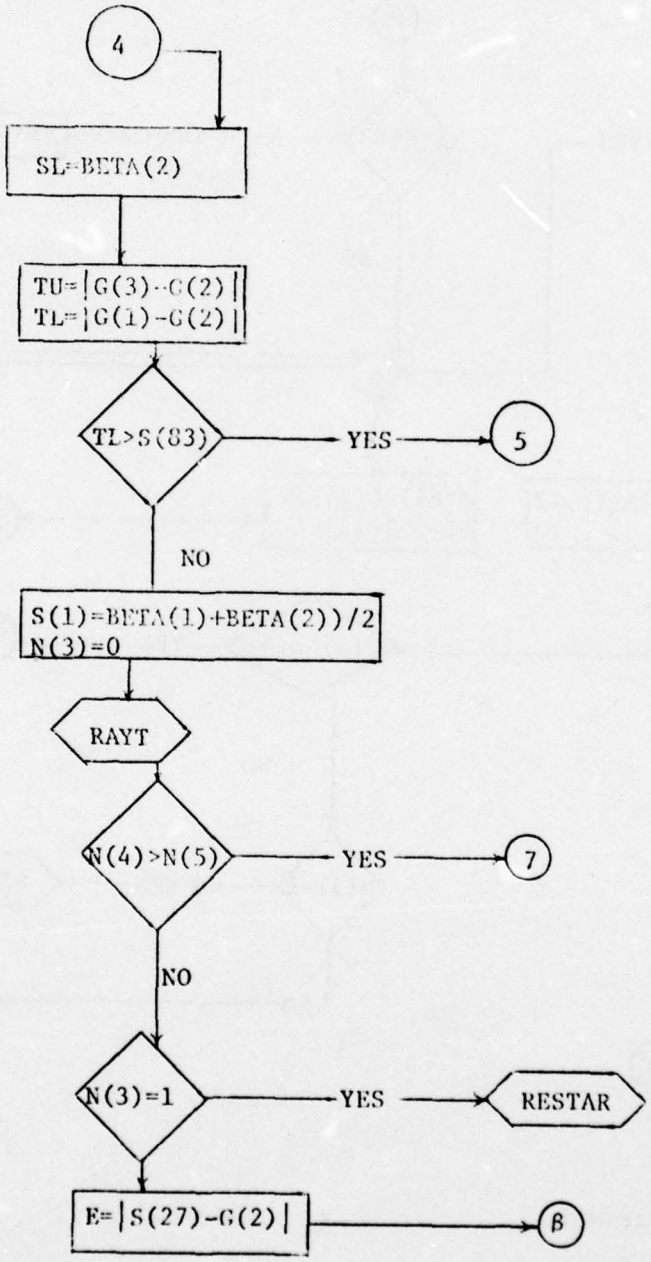


Figure 20 continued.

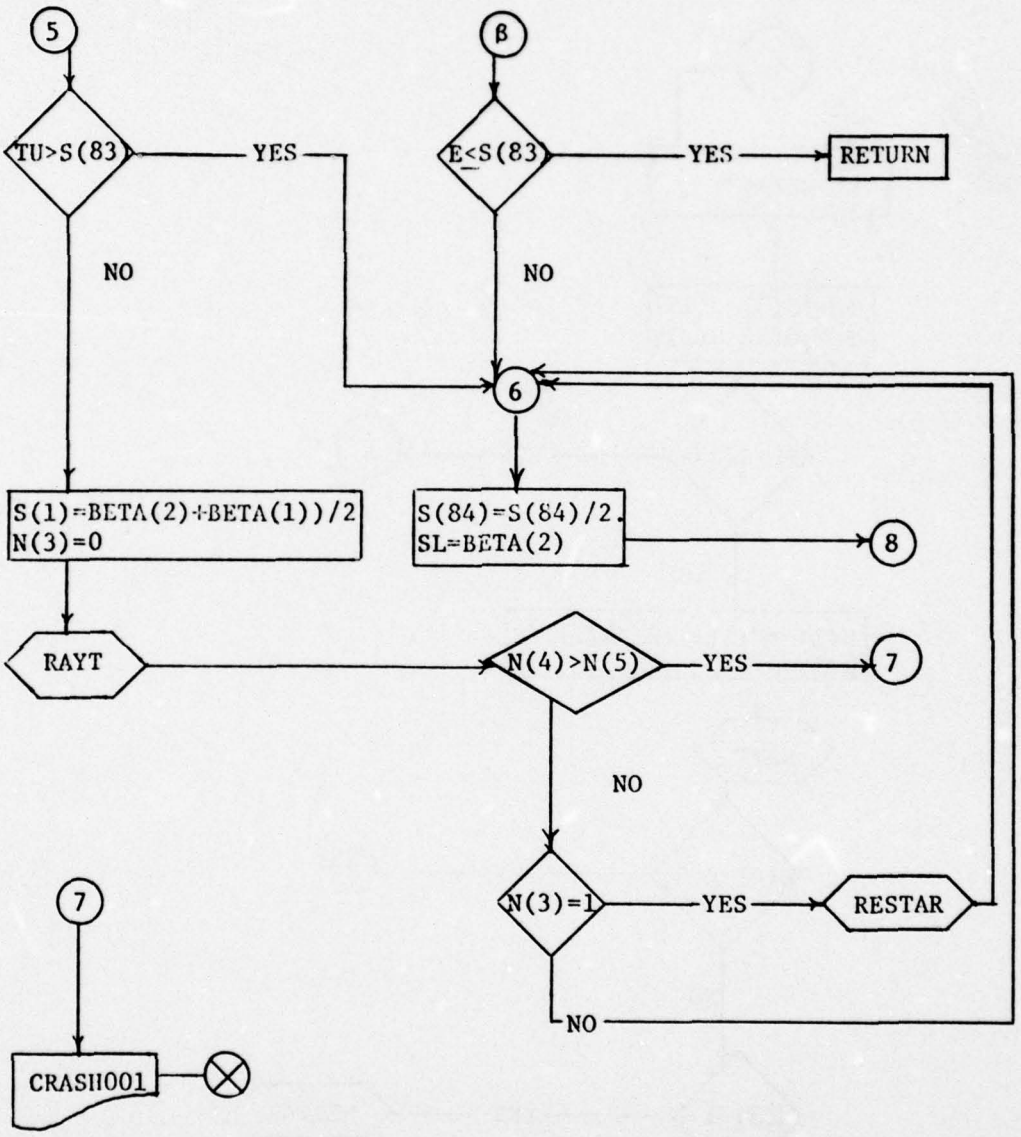


Figure 20 continued.

RAYT will set the flag "N(3)=1" and thus cause RESTAR to be called.

At this point, assuming that RESTAR has not been called, the initial elevation angle is saved, the ray counter N(4) is initialized, and the N(3) flag is set to zero. The program then constructs a "star" or "cluster" which consists of 3 equi-spaced elevation angles (denoted by $\beta(1)$, $\beta(2)$ and $\beta(3)$) (see Fig. 21). The center of the star is the initial elevation angle. For each of the 3 elevation angles in the star, a corresponding group path is computed. In the event that one (or more) of the elevation angles will not produce an Earth-striking ray, the width of the star is decreased by 50% and the process is repeated.

Assuming that all 3 rays will land on the Earth's surface, and assuming that the ray counter N(4) is less than N(5), the next task of the subroutine is to determine if the value of group path at the center of the star is less than the group path at the extremities. When this situation occurs (i.e. G(1)>G(2) and G(3)>G(2)) the minimum group path has been "localized". Program flow is then sent to statement 4 on the flow chart. This action initiates a two stage "flatness test". The first stage consists of determining if either

$$|G(3) - G(2)| < S(83)$$

or

$$|G(1) - G(2)| < S(83)$$

is satisfied. If neither inequality is satisfied, the star size is decreased by 50% and the program flow is sent back to statement 8. However, when either of the inequalities is satisfied, the second stage flatness test is initiated. In beginning this process, the subroutine "realizes" that the minimum group path occurs in either the interval [$\beta(1)$, $\beta(2)$] or [$\beta(2)$, $\beta(3)$] because it is assumed that the group delay vs. elevation angle curve is concave. It is also true, at this point in the subroutine, that the difference in group path values corresponding to the end points of the interval is less than S(83). This, however, is not always sufficient to establish the minimum value of group path, as can be seen from the following example:

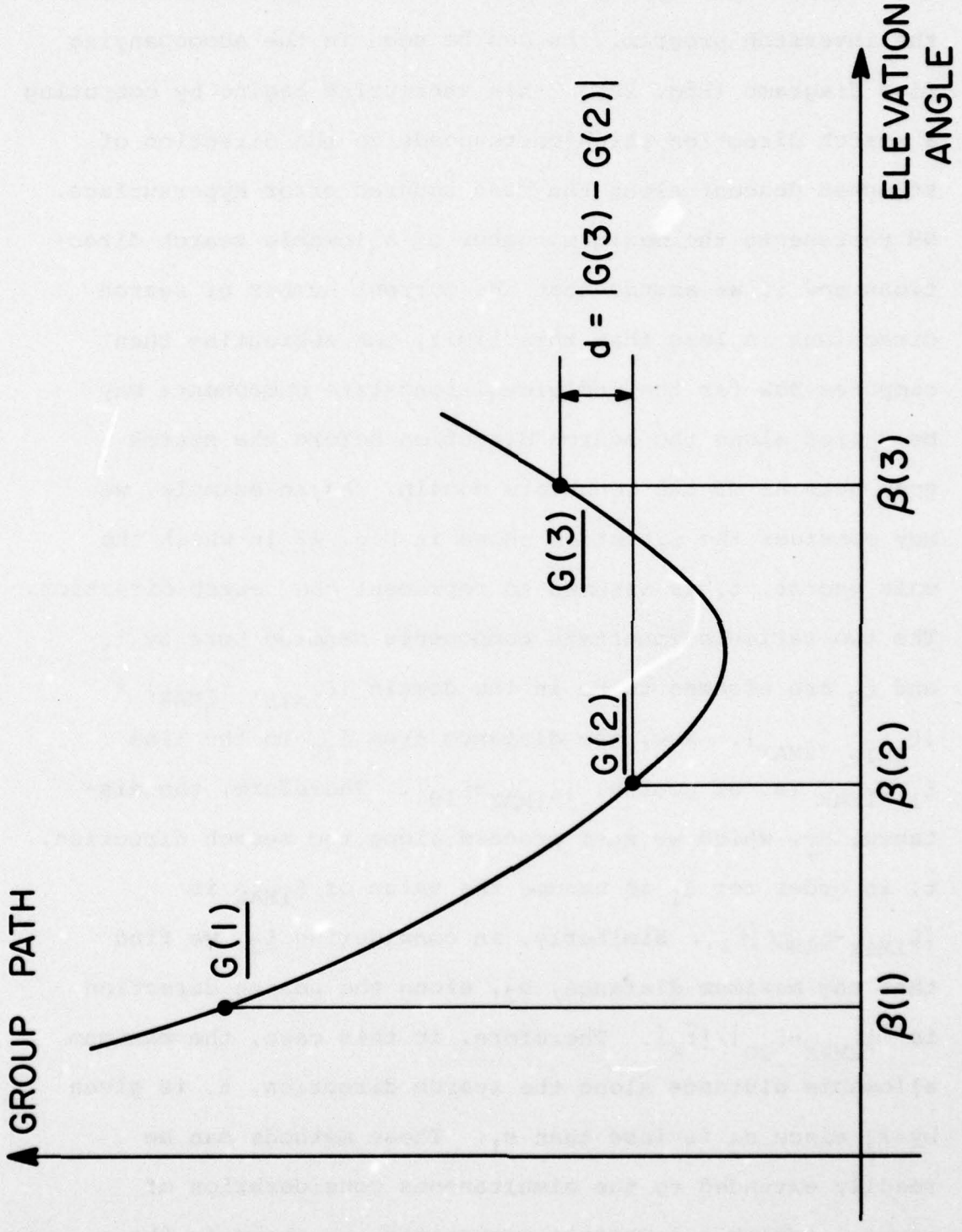


Figure 21. Flatness test.

Subroutine steep is the most important subroutine in the inversion program. As can be seen in the accompanying flow diagrams (Fig. 22), this subroutine begins by computing a search direction which corresponds to the direction of steepest descent along the mean squared error hypersurface. NM represents the maximum number of allowable search directions and if we assume that the current number of search directions is less than this limit, the subroutine then computes how far the individual ionostate components may be varied along the search direction before the search goes outside of the ionostate domain. As an example, we may consider the situation shown in Fig. 23 in which the unit vector, $\hat{t}$, is assumed to represent the search direction. The two variable ionostate components denoted here by ξ_1 and ξ_2 are assumed to be in the domain $[\xi_{1MIN}, \xi_{1MAX}] \times [\xi_{2MIN}\ \xi_{2MAX}]$. Now, the distance from ξ_{10} to the line $\xi_1=\xi_{1MAX}$ is, of course, $|\xi_{1MAX}-\xi_{10}|$. Therefore, the distance, s_1, which we must proceed along the search direction, $\hat{t}$, in order for ξ_1 to assume the value of ξ_{1MAX} is $|\xi_{1MAX}-\xi_{10}|/|\vec{t}_1|$. Similarly, in considering ξ_2, we find that the maximum distance, s_2, along the search direction is $|\xi_{2MAX}-\xi_{20}|/|\vec{t}_2|$. Therefore, in this case, the maximum allowable distance along the search direction, $\hat{t}$, is given by s_2 since s_2 is less than s_1. These methods can be readily extended to the simultaneous consideration of several variable ionostate components, as shown in the accompanying flow chart. Once the search direction and

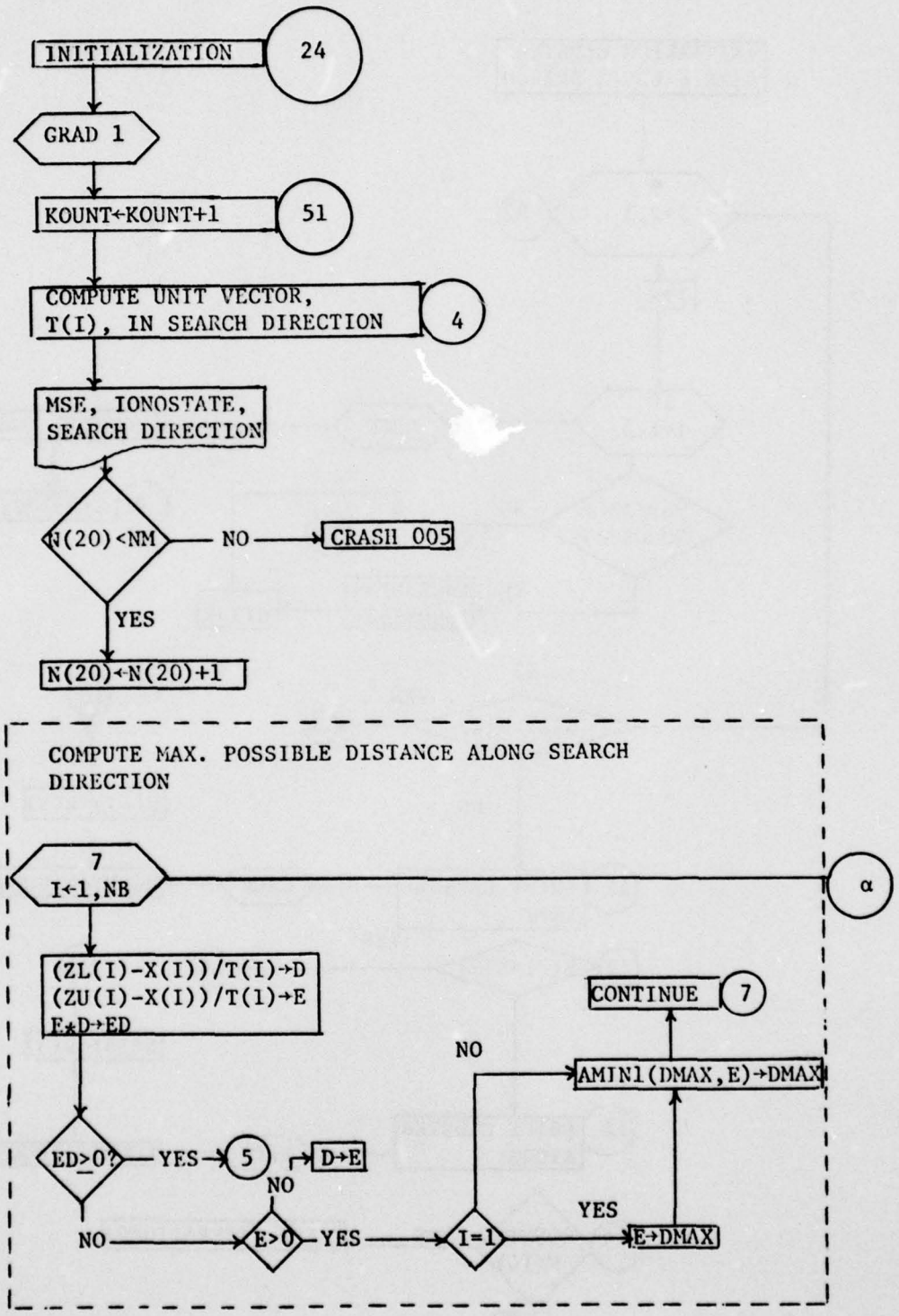


Figure 22. Flow chart for subroutine STEEP.

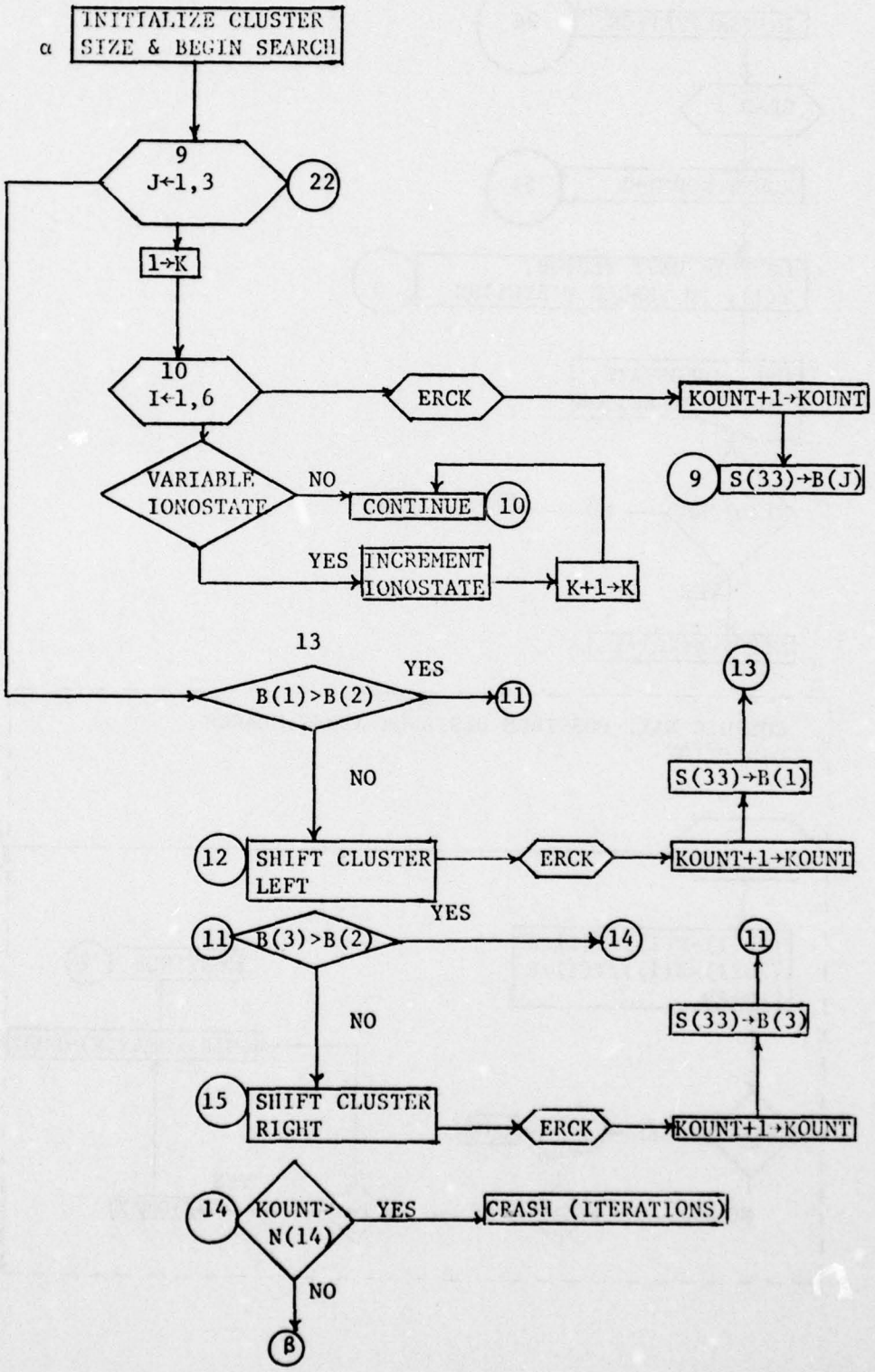


Figure 22 continued.

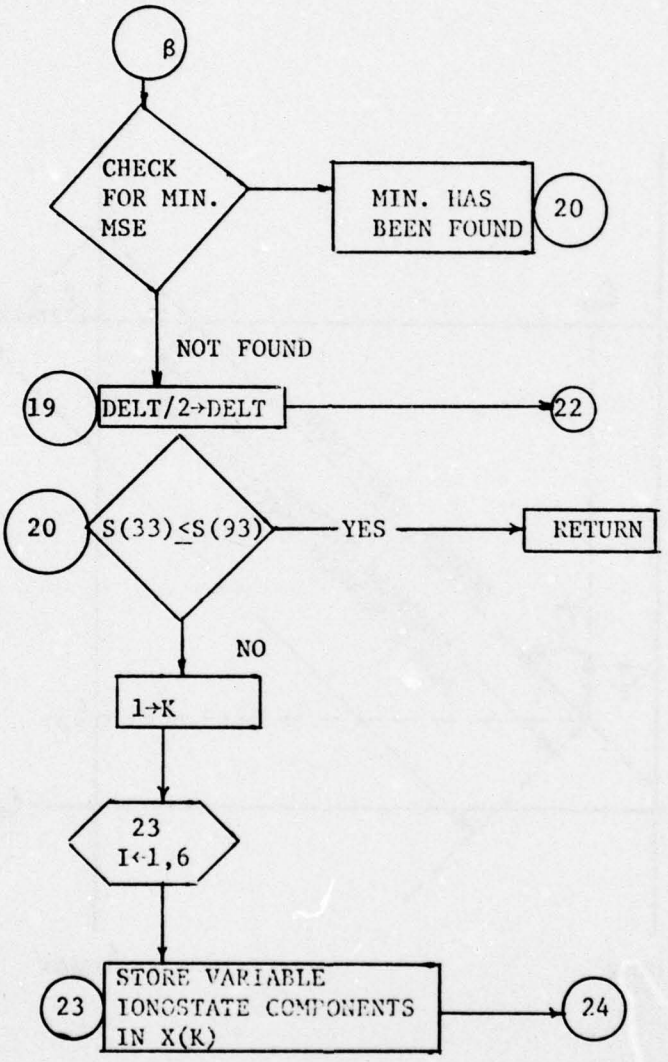


Figure 22 continued.

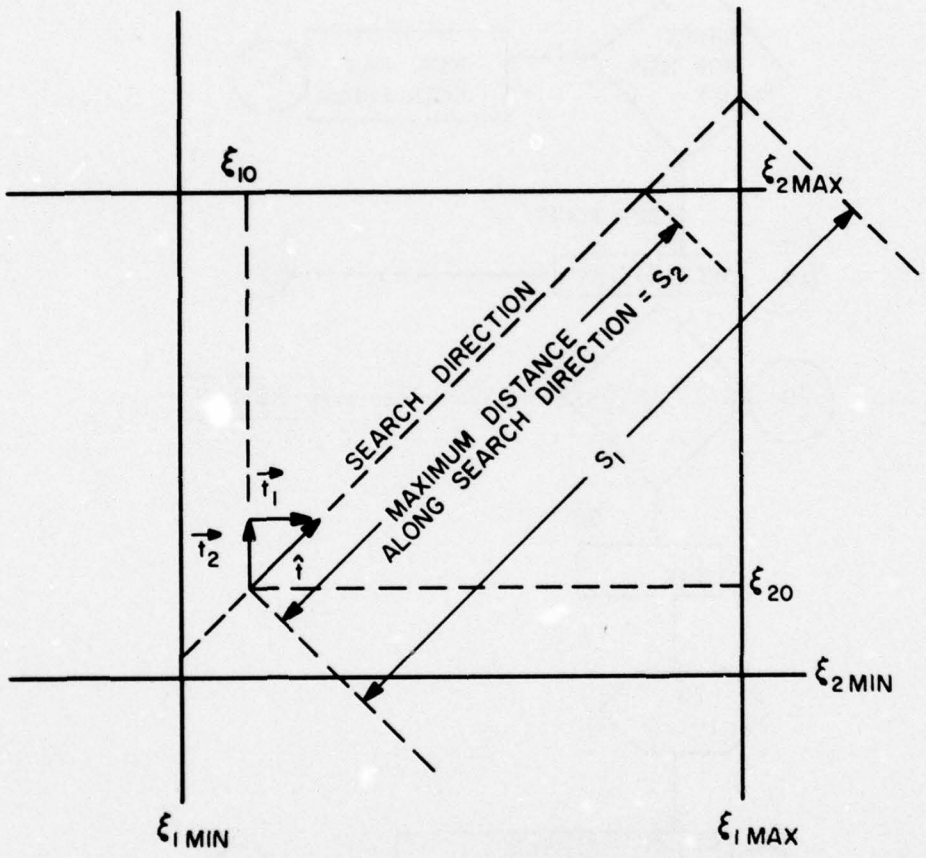


Figure 23. To illustrate the determination of a search direction for a new ionostate.

maximum distance have been established, the minimization procedure becomes a one dimensional problem in which our immediate objective is to find an ionostate which is on the search line and results in minimum mean squared error. This one dimensional minimization uses the same scheme as was used in subroutine STAR, including the same sort of tests which were used for termination of the minimization. In the present subroutine, however, the fact that a minimum has been found does not necessarily mean that the subroutine has finished its task. In particular, if the mean squared error is still larger than a value specified in the input file, the subroutine will go back and compute a new search direction corresponding to the local properties of the mean squared error hypersurface in the neighborhood of the present ionostate.

This completes the discussion of the major subroutines. The minor subroutines are much simpler and are summarized in the following table.

Table 1: MINOR SUBROUTINES

SUBROUTINE	CALLED FROM	CALLS TO	PURPOSE
SUPER	MAIN	SETD, STEEP, SYNTH, ERCK	supervisory
SYNTH	SUPER	STAR	simulation of backscatter sounding data
SETD	SUPER	———	Reads data file
RAYS	RAYT	———	Free space ray tracing
RESTAR	STAR	RAYT	Restart minimum group path search
ERCK	SUPER,STEEP, GRAD1	STAR	Compute MSE
GRAD1	STEEP	ERCK	Compute gradient of MSE

3.3 PROGRAM LISTING

The following pages provide a listing of the present version of the program. The file, DF, is the data file.

```
     PROGRAM F1          74/74   OPT=1 TRACE                    FTN 4.6+439

1                 PROGRAM F1(INPUT,OUTPUT,DF,TAPE10=DF)
                  COMMON S,Y,N
                  DIMENSION S(200),Y(6),N(200)
                  CALL SUPER
5                 STOP
                  END
```

```
C
C
C
C
      SUBROUTINE RAYT
      COMMON S,Y,N
      DIMENSION S(200),Y(6),N(200)
      DIMENSION YY(6),G(4,6),SRX(6)
      RL=S(108)
      N(4)=N(4)+1
C
C     THE PURPOSE OF THIS SUBROUTINE IS TO TRACE
C     A RAY OF GIVEN FREQUENCY & ELEVATION ANGLE.
C     WHEN RAY IS IN FREE SPACE SUBROUTINE RAYS
C     IS CALLED.
C
      Y(1)=6370.
      Y(2)=0.0
      Y(3)=SIN(S(1))
      Y(4)=COS(S(1))
      Y(5)=0.
      Y(6)=0.
      N(3)=0
C
C     INITIALIZATION COMPLETE, RAY IS PRESUMABLY IN
C     FREE SPACE.  THEREFORE, RAYS WILL BE USED
C
      CALL RAYS
      DO 20 I=1,6
   20 YY(I)=Y(I)
      NSTP=0
C
C     THE FOLLOWING IS A FOURTH ORDER RUNGE
C     KUTTA INTEGRATION
C
   11 M=1
      GO TO 200
    1 DO 2 I=1,6
    2 Y(I)=YY(I)+(S(20)/2.)*G(M,I)
C
C     1ST RUNGE KUTTA STEP COMPLETED.
C
      M=2
      GO TO 200
    3 DO 4 I=1,6
    4 Y(I)=YY(I)+(S(20)/2.)*G(M,I)
C
C     2ND RUNGE KUTTA STEP COMPLETED
C
      M=3
      GO TO 200
    5 DO 6 I=1,6
    6 Y(I)=YY(I)+S(20)*G(M,I)
C
C     3RD RUNGE KUTTA STEP COMPLETED
C
      M=4
```

```
                GO TO 200
              7 DO 8 I=1,6
60              SRX(I)=YY(I)
              8 YY(I)=YY(I)+(S(20)/6.)*(G(1,I)+2.*G(2,I)+2.*G(3,I)+G(4,I))
          C
          C     FINAL RUNGE KUTTA STEP COMPLETED
          C
65              NSTP=NSTP+1
          C
          C     CHECK FOR NUMBER OF STEPS
          C
                IF(NSTP.GT.N(1)) GO TO 101
70        C
          C     CHECK FOR FREE SPACE
                RB=S(21)+YY(2)*S(24)
                IF(YY(1).LT.S(108)) GO TO 27
                GO TO 11
75            101 CONTINUE
                PRINT 102
              102 FORMAT(1H ,9HNSTP>N(1))
                STOP
          C
80        C     THIS COMPLETES THE RUNGE KUTTA
          C     PART OF SUBROUTINE.  THE FOLLOWING PROCEDURE
          C     IS USED TO EVALUATE RIGHT HAND SIDE
          C     OF RAY EQUATIONS.
          C
85            200 RB=S(21)+Y(2)*S(24)
                IF(Y(1).GE.RL) GO TO 215
               27 DO 216 KV=1,6
          C
          C     BACK UP RAY TRAJECTORY BY ONE
90        C     STEP TO INITIALIZE FREE SPACE
          C     RAY TRACING SUBROUTINE.
          C
              216 Y(KV)=SRX(KV)
                CALL RAYS
95              RETURN
              215 CONTINUE
                RM=S(22)+Y(2)*S(25)
                IF(Y(1).LE.RM) GO TO 218
          C
100       C     CHECK FOR PENETRATING RAY
          C
                N(3)=1
                S(27)=1000.
                RETURN
105           218 FC=S(23)+Y(2)*S(26)
          C
          C     THE FOLLOWING STATEMENTS
          C     ARE USED TO EVALUATE "FORCING FUNCTION"
          C     TERMS ON THE RIGHT SIDE OF THE
110       C     RAY EQUATION.
          C
                F=S(28)/FC
                YM=RM-RB
                TERM1=1.-(1./(F**2))
```

```
   SUBROUTINE RAYT        74/74    OPT=1 TRACE                    FTN 4.6+439

115                TERM2=((RM-Y(1))/(F*YM))*(RB/Y(1))
                   TERM2=TERM2**2
                   ZETA=TERM1+TERM2
                   IF(ZETA.GT.1.00)  GO TO 76
                   PY2=ZETA
120                PY=SQRT(ZETA)
                   ETA=(RM-Y(1))/(F*YM)
                   GAMMA=(RB/Y(1))**2
                   DPDR=(-2.*ETA*GAMMA/(F*YM))-2.*(ETA**2/Y(1))*GAMMA
                   DPDR=DPDR/(2.*PY)
125                ETA2=ETA**2
                   DPDFC=(1./PY)*((-FC/(S(28)**2))+ETA2*GAMMA/FC)
                   DPDRM=(1./PY)*(GAMMA*ETA*((GAMMA/(RM-Y(1)))-GAMMA/YM))
                   DPDRB=(1./PY)*((GAMMA*ETA2/YM)+(GAMMA*ETA2/RB))
                   DPDA=DPDRB*S(24)+DPDRM*S(25)+DPDFC*(S(26))
130                GO TO 77
                76 PY=1.0
                   PY2=1.0
                   DPDR=DPDA=0.0
                77 G(M,1)=Y(3)/PY2
135                G(M,2)=Y(4)/(Y(1)*PY2)
                   G(M,3)=(DPDR/PY)+(Y(4)**2)/(Y(1)*PY2)
                   G(M,4)=(DPDA/(Y(1)*PY))-((Y(4)*Y(3))/(Y(1)*PY2))
                   G(M,5)=1./PY2
                   G(M,6)=1.0
140                IF(M.EQ.1) GO TO 1
                   IF(M.EQ.2) GO TO 3
                   IF(M.EQ.3) GO TO 5
                   GO TO 7
                   END
```

```
  SUBROUTINE SETD        74/74   OPT=1 TRACE          FTN 4.6+439

1           C
            C
            C
            C
5                 SUBROUTINE SETD
                  COMMON S,Y,N
                  DIMENSION S(200),Y(6),N(200)
            C
            C     NULL OUT S & N ARRAYS
10          C
                  DO 1 I=1,200
                  S(I)=0.0
                1 N(I)=0
            C
15          C     NOW READ S & N ARRAYS
            C
               20 CONTINUE
                  READ (10,3) K,Z
                3 FORMAT(13,1X,E20.7)
20                IF(K.LE.0) GO TO 4
                  S(K)=Z
                  GO TO 20
                4 CONTINUE
                  READ(10,6) K,M
25              6 FORMAT(13,15)
                  IF(K.LE.0) GO TO 7
                  N(K)=M
                  GO TO 4
                7 RETURN
30                END
```

SUBROUTINE RAYS 74/74 OPT=1 TRACE FTN 4.6+439

```
      C
      C
      C
      C
      SUBROUTINE RAYS
      COMMON S,Y,N
      DIMENSION S(200),Y(6),N(200)
      HPPI=3.14159/2.
      PHI=S(1)
      RE=S(31)
  333 FORMAT(1H ,3(E20.7,1X))
      C
      C     THIS SUBROUTINE IS CALLED
      C     ONLY WHEN THE RAY IS IN
      C     FREE SPACE.  THIS SUBROUTINE
      C     COMPUTES A STRAIGHT LINE
      C     TRAJECTORY.
      C
      IF(Y(3).LE.0.0) GO TO 4
      C
      C     THIS DETERMINES IF RAY IS
      C    GOING UP OR DOWN
      C
      GO TO 3
    3 RX=S(108)
      C
      C     RAY IS GOING UP, BUT
      C     RE IS CONSTANT
      C
      Z1=RE*Y(4)/RX
      TH1=ASIN(Z1)
      THETA=HPPI-PHI-TH1
      STEST=(RE/Z1)*SIN(THETA)
      C
      C     THIS COMPLETES THE UPGOING
      C     PART OF THE SUBROUTINE
      C
    1 Y(1)=RX
      Y(2)=THETA
      TH1=HPPI-TH1
      Y(3)=SIN(TH1)
      Y(4)=COS(TH1)
      Y(5)=Y(6)=STEST
      RETURN
    4 CONTINUE
      C
      C     THIS PART IS FOR DOWN GOING
      C     RAYS.
      C
      PHOOEY=ACOS(RE/Y(1))
      ZETA=ABS(Y(4))
      ABPHI=ACOS(ZETA)
      IF(ABPHI.LT.PHOOEY) GO TO 5
      C
      C     THIS CHECK IS FOR RAYS WHICH
      C     DO NOT DESCEND
      C     STEEPLY ENOUGH TO TOUCH THE
```

```
  SUBROUTINE RAYS        74/74   OPT=1 TRACE          FTN 4.6+439

                C       SURFACE OF THE EARTH.
                C
60                      ARE=HFPI-ABPHI
                        AY1=ASIN(Y(1)*SIN(ARE)/RE)
                        AY1=2.0*HFPI-AY1
                        ASTEST=(2.*HFPI)-AY1-ARE
                        STEST=SIN(ASTEST)*Y(1)/SIN(AY1)
65                      Y(5)=Y(5)+STEST
                        Y(6)=Y(6)+STEST
                        Y(2)=Y(2)+ASTEST
                        Y(1)=RE
                        S(27)=Y(5)
70                      RETURN
                      5 N(3)=1
                        Y(5)=Y(6)=1.0E+03
                        S(27)=Y(5)
                        RETURN
75                      END
```

```
SUBROUTINE ERCK        74/74   OPT=1 TRACE        FTN 4.6+439

 1          C
            C
            C
            C
 5                SUBROUTINE ERCK
                  COMMON S,Y,N
                  DIMENSION S(200),Y(6),N(200)
                  PRINT 333
              333 FORMAT(1H ,4HERCK)
10          C
            C     THIS SUBROUTINE COMPUTES THE
            C     MEAN SQUARED ERROR.
            C
                  NF=N(2)
15                S(33)=0.
                  DO 1 I=1,NF
            C
            C     FREQUENCY LOOP
            C
20                I1=I+7
                  I2=I+1
                  I3=I+13
                  S(1)=S(I3)
                  S(28)=S(I2)
25          C
            C     SET FREQUENCY & INITIAL ELEVATION ANGLE,
            C     CALL STAR TO FIND MINIMUM GROUP PATH.
            C
                  CALL STAR
30                S(I3)=S(1)
                  ANG=180.0*S(1)/3.14159
                1 S(33)=S(33)+(((S(27)-S(I1))**2)/NF)
                  IF(N(21).EQ.0) GO TO 2
                  PRINT 3,(S(L),L=21,26)
35                3 FORMAT(1H ,E20.7)
                  PRINT 4,S(33)
                4 FORMAT(1H ,4HMSE=,1X,E20.7)
                  STOP
                2 RETURN
40                END
```

SUBROUTINE STAR 74/74 OPT=1 TRACE FTN 4.6+439

```
      C
      C
      C
      C
      SUBROUTINE STAR
      COMMON S,Y,N
      DIMENSION S(200),Y(6),N(200)
      C
      C     THIS SUBROUTINE FINDS THE ELEVATION
      C     ANGLE WHICH RESULTS IN MINIMUM
      C     GROUP PATH AT A GIVEN FREQUENCY.
      C     IT ALSO EVALUATES THE MINIMUM GROUP
      C     PATH.
      C
      DIMENSION BETA(3),G(3)
      C
      C     CHECK ACCEPTABILITY OF INITIAL
      C     ELEVATION ANGLE.
      C
      CALL RAYT
      IF(N(3).EQ.1) CALL RESTAR
      C
      C     INITIALIZE ENTRY VALUE OF S(1)
      C
      SE=SL=S(1)
      N(4)=1
    8 N(3)=0
      C
      C     SET UP STAR & EVALUATE
      C     GROUP PATHS
      C
   11 CONTINUE
      DO 1 I=1,3
      BETA(I)=SL+(I-1)*S(84)
      S(1)=BETA(I)
      CALL RAYT
      IF(N(3).EQ.0) GO TO 12
      PRINT 13
   13 FORMAT(1H ,80X,13H*STAR SHRINK1)
      S(84)=S(84)/2.0
      GO TO 11
   12 CONTINUE
      IF(N(4).GT.N(5)) GO TO 7
    1 G(I)=S(27)
      C
      C     NOW CHECK FOR MINIMUM GROUP
      C     PATH AT CENTER OF CLUSTER
      C
    3 IF(G(1).GT.G(2)) GO TO 2
      C
      C     SHIFT STAR TO SMALLER ELEVATION
      C     ANGLES.
      C
      G(3)=G(2)
      G(2)=G(1)
      BETA(3)=BETA(2)
      BETA(2)=BETA(1)
```

SUBROUTINE STAR 74/74 OPT=1 TRACE

```
                S(1)=BETA(1)=BETA(2)-S(84)          FTN 4.6+439
                N(3)=0
60              CALL RAYT
                IF(N(4).GT.N(5)) GO TO 7
                IF(N(3).EQ.0) GO TO 14
                PRINT 15
             15 FORMAT(1H ,80X,13H*STAR SHRINK2)
65              S(84)=S(84)/2.0
                SL=BETA(2)
                GO TO 11
             14 CONTINUE
                G(1)=S(27)
70              GO TO 3
              2 IF(G(3).GT.G(2)) GO TO 4
          C
          C     SHIFT STAR TO LARGER
          C     ELEVATION ANGLES.
75        C
                G(1)=G(2)
                G(2)=G(3)
                BETA(1)=BETA(2)
                BETA(2)=BETA(3)
80              S(1)=BETA(3)=BETA(2)+S(84)
                N(3)=0
                CALL RAYT
                IF(N(4).GT.N(5)) GO TO 7
                IF(N(3).EQ.0) GO TO 16
85              PRINT 17
             17 FORMAT(1H ,80X,13H*STAR SHRINK3)
                S(84)=S(84)/2.0
                SL=BETA(2)
                GO TO 11
90           16 CONTINUE
                G(3)=S(27)
                GO TO 2
              4 SL=BETA(2)
          C
95        C     THE LEAST GROUP PATH NOW
          C     OCCURS AT THE CENTER OF
          C     THE CLUSTER.  NOW THIS
          C     MINIMUM VALUE WILL BE TESTED.
          C
100             TU=ABS(G(3)-G(2))
                TL=ABS(G(1)-G(2))
                IF(TL.GT.S(83)) GO TO 5
          C
          C     NOW TEST MIDPOINT BETWEEN
105       C     BETA(1) & BETA(2)
          C
                S(1)=(BETA(1)+BETA(2))/2.0
                N(3)=0
                CALL RAYT
110             IF(N(4).GT.N(5)) GO TO 7
                IF(N(3).EQ.1) CALL RESTAR
                E=ABS(S(27)-G(2))
                IF(E.LE.S(83)) RETURN
                GO TO 6
```

```
   SUBROUTINE STAR        74/74    OPT=1 TRACE          FTN 4.6+439

115                5 IF(TU.GT.S(83)) GO TO 6
                   C
                   C      NOW TEST MIDPOINT BETWEEN
                   C      BETA(2) & BETA(3)
                   C
120                      S(1)=(BETA(3)+BETA(2))/2.
                         N(3)=0
                         CALL RAYT
                         IF(N(4).GT.N(5)) GO TO 7
                         IF(N(3).EQ.1) CALL RESTAR
125                      E=ABS(S(27)-G(2))
                         IF(E.LE.S(83)) RETURN
                       6 S(84)=S(84)/2.0
                         SL=BETA(2)
                         GO TO 8
130                    7 CONTINUE
                         PRINT 333
                     333 FORMAT(1H ,3HD,E)
                   C
                   C      TOO MANY CALLS TO RAYT.
135                C      TERMINATE PROGRAM
                   C
                         PRINT 21
                      21 FORMAT(1H ,80X,16H*LAST ICNOSTATE:)
                         PRINT 22,(S(L),L=21,26)
140                   22 FORMAT(1H ,80X,2H**,E15.7)
                         PRINT 23
                      23 FORMAT(1H ,80X,18H**FREQUENCY (MHZ):)
                         PRINT 22,S(28)
                         PRINT 24
145                   24 FORMAT(1H ,80X,10H**CRASH001)
                         STOP
                         END
```

SUBROUTINE RESTAR 74/74 OPT=1 TRACE FTN 4.6+439

```
      C
      C
      C
      C
      SUBROUTINE RESTAR
      COMMON S,Y,N
      DIMENSION S(200),Y(6),N(200)
      PRINT 1
    1 FORMAT(1H ,17H*RESTART REQUIRED)
      KB=0
      KMIN=0
      HPI=3.14159/2.0
      S1MAX=HPI-1.0E-06
      S1MIN=1.0E-06
      GMIN=1.0E+06
      C
      C     INITIALIZATION FOR FIRST SEARCH
      C     IS COMPLETE.
      C
    3 DS=(S1MAX-S1MIN)/30.0
      DO 2 I=1,29
      S(1)=I*DS
      CALL RAYT
      C
      C     WAS RAY SUCCESSFULLY TRACED?
      C
      IF(N(3).EQ.1) GO TO 2
      C
      C     IS GROUP PATH > GMIN?
      C
      IF(S(27).GT.GMIN) GO TO 2
      GMIN=S(27)
      KMIN=1
      S1STAR=S(1)
    2 CONTINUE
      C
      C     HAS A ROUGH MINIMUM BEEN FOUND??
      C
      IF(KMIN.EQ.0) GO TO 5
      C
      C     IS SECOND SEARCH COMPLETE?
      IF(KB.EQ.1) GO TO 4
      S1MAX=S1STAR+DS-1.0E-06
      S1MIN=S1STAR-DS+1.0E-06
      KB=1
      GO TO 3
    4 S(1)=S1STAR
      RETURN
    5 CONTINUE
      PRINT 21
   21 FORMAT(1H ,80X,17H**LAST IONOSTATE:)
      PRINT 22,(S(L),L=21,26)
   22 FORMAT(1H ,80X,2H**,E15.7)
      PRINT 23
   23 FORMAT(1H ,80X,18H**FREQUENCY (MHZ):)
      PRINT 22,S(28)
      PRINT 24
```

```
      SUBROUTINE RESTAR      74/74    OPT=1 TRACE          FTN 4.6+439

                    24 FORMAT(1H ,80X,10H**CRASH002)
                       STOP
   60                  END
```

SUBRCUTINE GRAD1 74/74 OPT=1 TRACE FTN 4.6+439

```
      C
      C
      C
      C
      SUBROUTINE GRAD1
      COMMON S,Y,N
      DIMENSION S(200),Y(6),N(200)
      DIMENSION P2(200)
      C
      C     THIS SUBROUTINE COMPUTES
      C     THE GRADIENT OF THE
      C     MEAN SQUARED ERROR.
      C     FIRST, THE INITIAL MEAN SQUARED ERROR
      C     IS STORED IN A SEPARATE LOCATION.
      C
      CALL ERCK
      S(86)=S(33)
      PRINT 386,(S(LL),LL=14,16)
  386 FORMAT(1H ,3(E20.7,1X))
      EPS1=10.0*S(94)
      EPS2=1000.0*S(94)
      C
      C     SET GRADIENT INDEX, IG.
      C
      IG=41
      C
      C     ENTER SEARCH LOOP FOR
      C     VARIABLE IONOSTATE COMPONENT.
      C
      NTEST=0
      DO 3 I=1,6
      IN=I+5
      ID=I+86
      IS=I+20
      IF(N(IN).EQ.0) GO TO 3
    9 DS=S(ID)
      IF(DS.EQ.0) GO TO 4
      C
      C     A VARIABLE IONOSTATE COMPONENT
      C     HAS BEEN FOUND.  THE PARTIAL
      C     DERIVATIVE OF MSE WITH RESPECT
      C     TO THIS COMPONENT WILL NOW BE
      C     CALCULATED.
      C
      SOLD=S(IS)
   13 S(IS)=S(IS)+DS
      CALL ERCK
      E1=S(33)
      S(IS)=S(IS)-(2.0*DS)
      CALL ERCK
      E2=S(33)
      EAB=ABS(E1-E2)
      C
      C     CHECK THE DIFFERENCE IN MSE.
      C     IF IT IS TOO SMALL, IT IS
      C     VULNERABLE TO NUMERICAL ERROR.
      C     IF IT IS TOO LARGE, IT IS NOT
```

SUBROUTINE GRAD1 74/74 OPT=1 TRACE FTN 4.6+439

```
C     REPRESENTATIVE OF LOCAL PROPERTIES.
C
      IF(EAB.LT.EPS1) GO TO 10
      IF(EAB.GT.EPS2) GO TO 11
C
C     NOW RESET S(IS), PACK
C     THE GRADIENT VECTOR
C     AND CONTINUE THE SEARCH
C     LOOP.
C
      S(IS)=SOLD
      S(IG)=(E1-E2)/(2.0*DS)
      P2(IG)=(E1+E2-2.0*S(86))/(4.*DS*DS)
C
C     CHECK FOR LOCAL CONCAVITY
C
      IF(P2(IG).LE.0.0) NTEST=1
      IG=IG+1
    3 CONTINUE
      NN=41+N(12)-1
      IF(NTEST.EQ.0) GO TO 26
      PRINT 28
   28 FORMAT(1H ,80X,7H*CONVEX)
      RETURN
   26 DO 27 K=41,NN
   27 S(K)=S(K)/P2(K)
      PRINT 29
   29 FORMAT(1H ,80X,8H*CONCAVE)
      RETURN
C
C     FATAL ERRORS
C
   21 FORMAT(1H ,80X,17H**LAST IONOSTATE:)
   22 FORMAT(1H ,80X,2H**,E15.7)
   23 FORMAT(1H ,80X,17H**MEAN SQ. ERROR:)
    4 CONTINUE
      PRINT 21
      PRINT 22,(S(L),L=21,26)
      PRINT 23
      PRINT 22,S(86)
      PRINT 25
   25 FORMAT(1H ,80X,10H**CRASH004)
      STOP
   10 DS=2.0*DS
      PRINT 12,DS
   12 FORMAT(1H ,80X,4H*DS=,E20.7)
      PRINT 14,I
   14 FORMAT(1H ,80X,9H*STATE #=,I3)
      GO TO 13
   11 DS=DS/2.0
      PRINT 12,DS
      PRINT 14,I
      GO TO 13
      END
```

```
SUBROUTINE SUPER      74/74   OPT=1 TRACE                FTN 4.6+439

 1          C
            C
            C
            C
 5                SUBROUTINE SUPER
                  COMMON S,Y,N
                  DIMENSION S(200),Y(6),N(200)
                  DIMENSION X(6),G(6),H(40)
            C
10          C     THIS IS A SUPERVISORY SUBROUTINE
            C
                  CALL SETD
                  IF(N(16).EQ.1) GO TO 8
                  IF(N(21).EQ.1) GO TO 12
15                CALL STEEP
                  DO 2 I=21,26
                  PRINT 3, S(I)
                3 FORMAT(1H ,E20.7)
                2 CONTINUE
20                PRINT 100,S(33)
              100 FORMAT(1H ,4HMSE=,1X,E20.7)
                  STOP
                8 CALL SYNTH
                  STOP
25               12 CALL ERCK
                  PRINT 101,S(33)
              101 FORMAT(1H ,4HMSE=,E20.7)
                  STOP
                  END
```

```
SUBRCUTINE SYNTH      74/74   OPT=1 TRACE        FTN 4.6+439

 1          C
            C
            C
            C
 5                SUBROUTINE SYNTH
                  COMMON S,Y,N
                  DIMENSION S(200),Y(6),N(200)
            C
            C     THE PURPOSE OF THIS SUBROUTINE
10          C     IS TO SYNTHESIZE A BACKSCATTER
            C     IONOGRAM.
            C
                  NB=N(2)
                  DO 1 I=1,NB
15                S(1)=S(I+13)
                  S(28)=S(I+1)
                  CALL STAR
                  ANG=S(1)*180./3.14159
                  PRINT 2,S(28),ANG,S(27)
20                2 FORMAT(1H ,5HFREQ=,1X,F10.4,1X,5HELEV=,1X,F10.4,1X,
                   14HMGP=,1X,E20.7)
                  1 CONTINUE
                    RETURN
                    END
```

```
  SUBROUTINE STEEP      74/74   OPT=1 TRACE          FTN 4.6+439

 1          C
            C
            C
            C
 5                SUBROUTINE STEEP
            C
            C     THIS IS A SPECIAL STEEPEST
            C     DESCENT SEARCH SUBROUTINE TO
            C     DETERMINE OPTIMUM IONOSTATE.
10          C     SEARCH IS CONSTRAINED TO DOMAIN
            C     DEFINED BY THE INTERVAL (ZL(I),ZU(I))
            C     FOR I=1,6 WHICH MUST CONTAIN THE
            C     ORIGINAL ESTIMATED IONOSTATE.
            C     SEARCH WILL BE TERMINATED WHEN ONE
15          C     OF THE FOLLOWING CONDITIONS IS FOUND
            C     TO OCCUR:
            C           1.# CALLS TO ERCK.GT.N(14)
            C           2.MSE.LT.S(93)
            C           3.# SEARCH DIRECTIONS=N(20)
20          C
                 COMMON S,Y,N
                 DIMENSION S(200),Y(6),N(200)
                 DIMENSION X(6),ZL(6),ZU(6),T(6),B(6),H(6)
                 KOUNT=0
25               NM=N(20)
                 NB=N(12)
                 N(20)=0
                 K=1
            C
30          C     DETERMINE SEARCH DOMAIN
            C     STORE IONOSTATE IN X
            C
                 DO 1 I=1,6
                 IN=I+5
35               IF(N(IN).NE.1) GO TO 1
                 ZL(K)=S(I+94)
                 ZU(K)=S(I+100)
                 X(K)=S(I+20)
                 K=K+1
40             1 CONTINUE
              24 CONTINUE
              50 CALL GRAD1
              51 KOUNT=KOUNT+1
                 GNORM=0.0
45               DO 2 I=1,NB
               2 GNORM=GNORM+(S(I+40)**2)
                 GNORM=SQRT(GNORM)
                 DO 4 I=1,NB
               4 T(I)=-S(I+40)/GNORM
50               PRINT 3
               3 FORMAT(1H ,80X,10H*STATUS OK)
                 PRINT 100,N(20)
             100 FORMAT(1H ,80X,9HITERATION,I3)
                 PRINT 101
55           101 FORMAT(1H ,80X,18HPRESENT IONOSTATE:)
                 PRINT 102,(S(L),L=21,26)
             102 FORMAT(1H ,80X,E20.7)
```

```
      PRINT 103
  103 FORMAT(1H ,80X,17HSEARCH DIRECTION:)
      PRINT 102,(T(I),I=1,6)
      PRINT 104,S(86)
  104 FORMAT(1H ,80X,4HMSE=,E20.7)
      IF(N(20).LT.NM) GO TO 105
      PRINT 106
  106 FORMAT(1H ,80X,10H**CRASH005)
      STOP
  105 N(20)=N(20)+1
C
C     NOW DETERMINE MAXIMUM POSSIBLE
C     DISTANCE ALONG THIS DIRECTION.
C
      D=(ZL(1)-X(1))/T(1)
      E=(ZU(1)-X(1))/T(1)
      ED=D*E
      IF(ED.GE.0.) GO TO 5
      IF(E.GT.0.) GO TO 6
      E=D
    6 DMAX=E
C
C     NOW PERFORM SAME COMPUTATION FOR
C     REMAINING DIMENSIONS.
C
      DO 7 I=2,NB
      D=(ZL(I)-X(I))/T(I)
      E=(ZU(I)-X(I))/T(I)
      ED=E*D
      IF(ED.GE.0.) GO TO 5
      IF(E.GT.0.) GO TO 8
      E=D
    8 DMAX=AMIN1(DMAX,E)
    7 CONTINUE
C
C     INITIALIZE STAR SIZE
C     AND BEGIN SEARCH
C
   44 DELT=DMAX/3.0
      H(1)=0.
      DX0=H(2)=DELT
      H(3)=2.0*DX0
   22 DO 9 J=1,3
      K=1
      DO 10 I=1,6
      IN=I+5
      IF(N(IN).NE.1) GO TO 10
      IS=I+20
      S(IS)=X(K)+H(J)*T(K)
      K=K+1
   10 CONTINUE
      CALL ERCK
      KOUNT=KOUNT+1
    9 B(J)=S(33)
   13 IF(B(1).GT.B(2)) GO TO 11
      B(3)=B(2)
      B(2)=B(1)
```

```
      H(3)=H(2)
      DX0=H(2)=H(1)
      IF(DX0.LT.0.) GO TO 5
      IF(DX0.GT.DMAX) GO TO 5
      H(1)=DX0-DELT
      K=1
      DO 12 I=1,6
      IN=I+5
      IF(N(IN).NE.1) GO TO 12
      IS=I+20
      S(IS)=X(K)+H(1)*T(K)
      K=K+1
   12 CONTINUE
      CALL ERCK
      KOUNT=KOUNT+1
      B(1)=S(33)
      GO TO 13
   11 IF(B(3).GT.B(2)) GO TO 14
      B(1)=B(2)
      B(2)=B(3)
      H(1)=H(2)
      DX0=H(2)=H(3)
      IF(DX0.LT.0.0) GO TO 5
      IF(DX0.GT.DMAX) GO TO 5
      H(3)=DX0+DELT
      K=1
      DO 15 I=1,6
      IN=I+5
      IF(N(IN).NE.1) GO TO 15
      IS=I+20
      S(IS)=X(K)+H(3)*T(K)
      K=K+1
   15 CONTINUE
      CALL ERCK
      KOUNT=KOUNT+1
      B(3)=S(33)
      GO TO 11
C
C     NOW CHECK FOR TERMINATION
C
   14 IF(KOUNT.GT.N(14)) GO TO 16
C
C     CHECK TO SEE IF MINIMUM
C     HAS OCCURED IN PRESENT
C     DIRECTION
C
      HL=H(2)
      TU=ABS(B(3)-B(2))
      TL=ABS(B(2)-B(1))
      IF(TL.GT.S(107)) GO TO 17
      HM=(H(2)+H(1))/2.0
      K=1
      DO 18 I=1,6
      IN=I+5
      IF(N(IN).NE.1) GO TO 18
      IS=I+20
      S(IS)=X(K)+HM*T(K)
```

SUBROUTINE STEEP 74/74 OPT=1 TRACE FTN 4.6+439

```
                  K=K+1
               18 CONTINUE
                  CALL ERCK
175               KOUNT=KOUNT+1
                  E=ABS(S(33)-B(2))
                  IF(E.LE.S(107)) GO TO 20
                  GO TO 19
               17 IF(TU.GT.S(107)) GO TO 19
180               HM=(H(3)+H(2))/2.0
                  K=1
                  DO 21 I=1,6
                  IN=I+5
                  IF(N(IN).NE.1) GO TO 21
185               IS=I+20
                  S(IS)=X(K)+HM*T(K)
                  K=K+1
               21 CONTINUE
                  CALL ERCK
190               KOUNT=KOUNT+1
                  E=ABS(S(33)-B(2))
                  IF(E.LT.S(107)) GO TO 20
               19 DELT=DELT/2.
            C
195         C     THE MINIMUM HAS NOT YET
            C     BEEN FOUND IN THIS DIRECTION.
            C     REDUCE CLUSTER SIZE BY HALF
            C     & CONTINUE SEARCH.
            C
200               DX0=H(2)
                  H(1)=DX0-DELT
                  H(3)=DX0+DELT
                  GO TO 22
               20 CONTINUE
205         C
            C     THE MEAN SQUARED ERROR HAS BEEN
            C     SUFFICIENTLY REDUCED IN THIS
            C     DIRECTION.  IF THIS ERROR IS
            C     SMALL ENOUGH THE SUBROUTINE
210         C     WILL RETURN.  IF NOT,
            C     THE SUBROUTINE WILL CONTINUE
            C     SEARCH IN A NEW DIRECTION.
            C
                  IF(S(33).LE.S(93)) RETURN
215               K=1
                  DO 23 I=1,6
                  IN=I+5
                  IF(N(IN).NE.1) GO TO 23
                  X(K)=S(I+20)
220               K=K+1
               23 CONTINUE
                  GO TO 24
                5 CONTINUE
                  PRINT 25
225            25 FORMAT(1H ,8HOUTRANGE)
                  STOP
               16 DO 26 I=1,6
                  IS=I+20
```

```
   SUBROUTINE STEEP       74/74   OPT=1 TRACE          FTN 4.6+439

                     PRINT 27,S(IS)
230                  27 FORMAT(1H ,E20.7)
                     26 CONTINUE
                        PRINT 28
                     28 FORMAT(1H ,9HITERATION)
                        STOP
235                     END
```

3.4 SAMPLE OUTPUT

The following pages provide a sample output (as run in the time sharing mode). The input data file is also provided, although the data file structure will be discussed more thoroughly in section 3.5. Referring to the actual output, the message ERCK is printed to show that the program is actually running (as opposed to being entangled in an infinite loop). The first three printed values are the elevation angles for minimum group delays at the first three sounding frequencies. Several ERCK messages are then printed again to show that the program is still running. The message "*TIME LIMIT*" is generated by the time sharing terminal to show that a specified amount of computer time has been used, and that unless additional time is allocated, the terminal will log off. The command "T,20", therefore, is entered from the terminal in order to allow the program to continue. The next block of information is a summary of the results computed by the 0^{th} iteration. The message "*CONCAVE*" indicates that certain necessary conditions for the concavity of the MSE surface have been satisfied. The present ionostate (which, in this case, is the initial ionostate) is then printed, followed by a listing of the components of the unit vector along the search direction. Since there are three variable ionostate components in this case (GRB, GRM, and GFC), there are 3 non-zero components. Finally, the value of the mean squared error (MSE) is printed. The next set of "ERCK"

This is the sample output run. First the data file, D1, will be listed.

```
  2          6.5000E+000 BSI FREQ
  3          7.0000E+000 BSI FREQ
  4          7.5000E+000 BSI FREQ
  8          1.0812E+003 MGP @ 6.5
  9          1.1723E+003 MGP @ 7.0
 10          1.2654E+003 MGP @ 7.5
 14          5.9611E-001 EL @ 6.5
 15          5.4268E-001 EL @ 7.0
 16          5.1064E-001 EL @ 7.5
 20          2.0000E-000 R-K STEP
 21          6.5700E+003 RB EST
 22          6.7200E+003 RM EST
 23          5.0000E+000 FC EST
 24          4.0000E+001 GRB EST
 25          3.0000E+001 GRM EST
 26          1.8000E+000 GFC EST
 31          6.3700E+003 RE
 83          1.0000E-001 MGP RESOLUTION
 84          3.0000E-002 INTL STAR
 87          2.0000E-002 DIFF,N STEP RB
 88          2.0000E-002 DIFF,N STEP RM
 89          1.0000E-003 DIFF,N STEP FC
 90          3.0000E+000 DIFF'N STEP GRB
 91          3.0000E+000 DIFF'N STEP GRM
 92          1.0000E-002 DIFF'N STEP GFC
 93          1.0000E+000 EST MIN MSE
 94          1.0000E-001 EST MIN GRAD MSE
 95          6.5600E+003 MIN RB
 96          6.6900E+003 MIN RM
 97          4.0000E+000 MIN FC
 98          5.0000E+000 MIN GRB
 99          5.0000E-001 MIN GRM
100         -1.0000E+000 MIN GFC
101          6.6000E+003 MAX RB
102          6.8000E+003 MAX RM
103          6.0000E+000 MAX FC
104          5.0000E+001 MAX GRB
105          5.0000E+001 MAX GRM
106          3.0000E+000 MAX GFC
107          2.0000E-000 FLATNESS
108          6.5600E+003 RL
000                      ****
  1 8000 MAX # R-K STEPS
```

```
  2 0003 # FREQUENCIES
  5 0800 MAX ITERATIONS/STAR
  9 0001 GRB FLAG
 10 0001 GRM FLAG
 11 0001 GFC FLAG
 12 0003 # FLAGGED COMPONENTS
 14 0050 # FMFP ITERATIONS
 20 0001 # SEARCH DIRECTIONS
000      ****
READY.
```

Now the program will be run.

```
 ERCK
         .6210709E+00          .5420941E+00          .5102884E+00
 ERCK
 ERCK
 ERCK
 ERCK
 ERCK

*TIME LIMIT*

T=20

 ERCK
```

```
*CONCAVE
*STATUS OK
ITERATION  0
PRESENT IONOSTATE:
         .6570000E+04
         .6720000E+04
         .5000000E+01
         .4000000E+02
         .3000000E+02
         .1800000E+01
SEARCH DIRECTION:
        -.7894537E+00
        -.6138099E+00
         .4344753E-03
        0.
        0.
        0.
MSE=          .4316307E+02
```

```
 ERCK
 ERCK
 ERCK
 ERCK
```

messages imply that the program is looking for a minimum MSE by varying the variable ionostate components in a manner consistent with the previously determined search direction.

Finally, a local minimum is found and the elevation angles are for the minimum group paths at the three sounding frequencies are printed. The "*DS=" messages indicate that some difficulty was experienced in computing the derivatives which are necessary in the determination of the next search direction. These difficulties arise when the finite difference method, which is employed to approximate the derivative, finds that the difference in minimum group paths is about the same size as the uncertainty in the minimum group path (which we believe is on the order of a few tenths of a kilometer for integration step sizes ranging from a few hundred meters to a few kilometers). In this case the derivative may be very unreliable because of the relatively large influence of "noise". On the other hand, a difference in minimum group paths which is many orders of magnitude larger than this uncertainty is objectionable because it suggests that the finite difference approximation may be too crude. Therefore occasional adjustment of the differentiation step size, as seen in this example, is performed automatically.

The final block of information is the result of the first complete iteration. It can be seen that the variable

```
 ERCK
 ERCK
 ERCK
 ERCK
 ERCK
 ERCK

*TIME LIMIT*

T,20

 ERCK
 ERCK
         .6090006E+00          .5299066E+00          .5023783E+00
 ERCK
 ERCK
 ERCK
 ERCK
 ERCK
 ERCK


 ERCK
 ERCK


 ERCK
 ERCK


 ERCK
 ERCK

*TIME LIMIT*

T,20
```

```
*DS=          .2000000E-01
*STATE #=  6


*DS=          .4000000E-01
*STATE #=  6


*DS=          .8000000E-01
*STATE #=  6
```

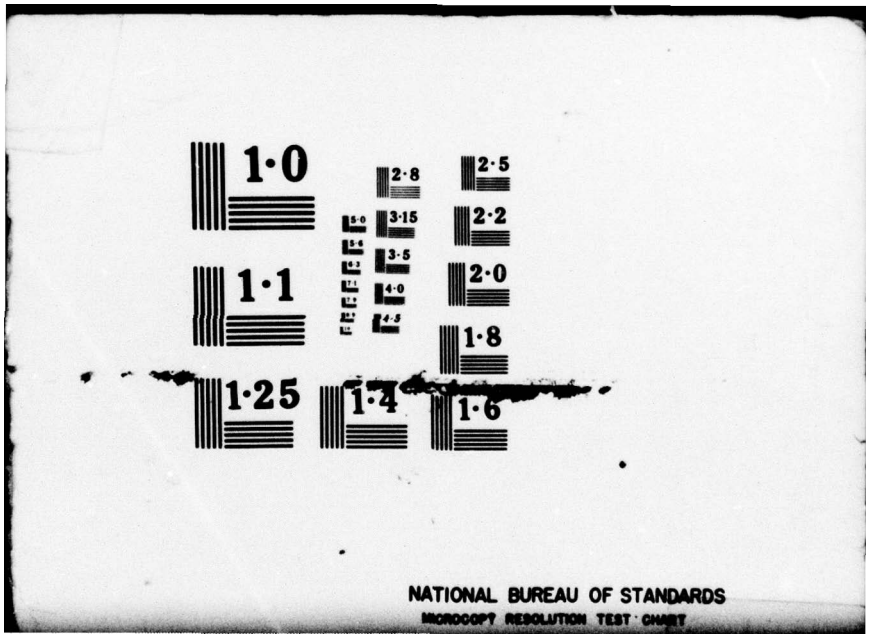
```
*CONCAVE
*STATUS OK
ITERATION  1
PRESENT IONOSTATE:
        .6570000E+04
        .6720000E+04
        .5000000E+01
        .1812500E+02
        .1299192E+02
        .1812039E+01
SEARCH DIRECTION:
       -.6671752E+00
        .7448048E+00
        .1196163E-01
```

AD-A057 274 ILLINOIS UNIV AT URBANA-CHAMPAIGN DEPT OF ELECTRICAL --ETC F/G 4/1
BACKSCATTER IONOGRAM INVERSION BY RAY TRACING METHODS.(U)
APR 78 R E DUBROFF, N N RAO, R C YEH F19628-77-C-0108

UNCLASSIFIED UILU-ENG-78-2538 RADC-TR-78-86 NL

2 OF 2
ADA
057274

END
DATE
FILMED
9-78
DDC


1·0
1·1
1·25
1·4
1·6
1·8
2·0
2·2
2·5
2·8
3·15
3·5
4·0
4·5
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

```
 0.
 0.
 0.
MSE=      .1571674E+01
**CRASH005

READY.
```

ionostate components have been adjusted and a new search direction has been computed. The mean squared error is now much smaller and the final message "**CRASH005" indicates that the program was terminated because the number of search directions was specified as 1 in the input file.

3.5 DATA FILE STRUCTURE

Although the data file provided in section 3.4 suggests an indication of some typical values for the data parameters, a more detailed discussion may be beneficial to the user of this program. The following page, therefore, consists of a computer print out of an information file (71) which provides an overview of the allocations of the S and N arrays. These two arrays serve the dual purposes of providing both the data input to the program and acting as common arrays to be passed between the various subroutines. Accordingly, the array elements which are used as data input are denoted by the usage symbol E (external) and the elements used for transferring information between subroutines are denoted by the symbol I (internal).

In the following discussion, however, we will be concerned only with the external elements of the S and N arrays. In particular, it is our intention to mention some of the specific considerations which must be made in the assignment of values to these elements. Elements S(2)-S(7), for example, are self-explanatory although the user should be aware that when less than the maximum number of sounding

S ARRAY ALLOCATIONS

NUMBER	DESCRIPTION	USAGE
1	CURRENT ELEVATION ANGLE (RAD)	I
2-7	IONOGRAM SOUNDING FREQUENCIES (MHZ)	E
8-13	IONOGRAM MIN GROUP PATHS (KM)	E
14-19	IONOGRAM MGP ELEVATION ANGLES (RAD)	E
20	RUNGE-KUTTA INTEG. STEP (KM)	E
21-26	IONOSTATE	EI
27	CURRENT GROUP PATH (KM)	I
28	CURRENT FREQUENCY (MHZ)	I
29-30	NOT USED	
31	RADIUS OF EARTH (KM)	F
32	NOT USED	
33	MSE	I
34-40	NOT USED	
41-46	GRADIENT OF MSE	I
47-82	NOT USED	
83	MGP RESOLUTION (KM)	E
84	INITIAL STAR SIZE (RAD)	E
85	INITIAL VALUE OF MSE (KM**2)	I
86	REFERENCE MSE (KM**2)	I
87	DIFF'N STEP IN RB (KM)	EI
88	DIFF'N STEP IN RM (KM)	EI
89	DIFF'N STEP IN FC (MHZ)	EI
90	DIFF'N STEP IN GRB (KM/RAD)	EI
91	DIFF'N STEP IN GRM (KM/RAD)	EI
92	DIFF'N STEP IN GFC (MHZ/RAD)	EI
93	ACCEPTABLE MIN FOR MSE (KM**2)	E
94	NOT USED	
95	LOWER BOUND ON RB (KM)	E
96	LOWER BOUND ON RM (KM)	E
97	LOWER BOUND ON FC (MHZ)	E
98	LOWER BOUND ON GRB (KM/RAD)	E
99	LOWER BOUND ON GRM (KM/RAD)	E
100	LOWER BOUND ON GFC (MHZ/RAD)	E
101	UPPER BOUND ON RB (KM)	E
102	UPPER BOUND ON RM (KM)	E
103	UPPER BOUND ON FC (MHZ)	E
104	UPPER BOUND ON GRB (KM/RAD)	E
105	UPPER BOUND ON GRM (KM/RAD)	E
106	UPPER BOUND ON GFC (MHZ/RAD)	E
107	FLATNESS FOR SUBRTN. STEEP (KM)	E
108	TRANSITION RADIUS (KM)	E

N ARRAY ALLOCATIONS

NUMBER	DESCRIPTION	USAGE
1	MAX # RUNGE KUTTA STEPS	E
2	# SOUNDING FREQUENCIES	E
3	TROUBLE FLAG	I
4	COUNTER	I
5	MAX # ITERATIONS/STAR CALL	E
6	RB FLAG	E
7	RM FLAG	E
8	FC FLAG	E
9	GRB FLAG	E
10	GRM FLAG	E
11	GFC FLAG	E
12	# VARIABLE IONOSTATE COMPONENTS	E
13	NOT USED	
14	MAX # ITERATIONS/STEEP CALL	E
15	NOT USED	
16	SYNTHESIS FLAG	E
17-19	NOT USED	
20	MAX # SEARCH DIRECTIONS	EI
21	MSE FLAG	E

TABS 6,16,56

frequencies (6) are used, the values should be entered in consecutive elements, starting from S(2). The next group of elements, S(8)-S(13), are minimum group paths, and while these elements are entered in the same order as S(2)-S(7), they are neither required nor used in the synthesis mode of the program. S(14)-S(19) are then the corresponding elevation angles which produce the minimum group paths in S(8)-S(13). In general these angles are unknown, but are used only as starting values for subroutine STAR. It has been our practice to use the synthesis mode to obtain this information, but any reasonable "guesses" should be sufficient. The Runge-Kutta step size, S(20), however, is rather critical since an excessively large value will cause significant errors in the ray tracing subroutine, RAYT, while an excessively small value will cause the expenditure of substantial amounts of computer time. Typical values for this parameter would be in the approximate range of .1 to 5 km. The ionostate is entered in the order: RB, RM, FC, GRB, GRM, GFC. In the inversion mode, this ionostate corresponds to the initial guess of the correct ionostate, while in the synthesis mode these parameters describe the ionosphere in which the backscatter leading edge is simulated. The elements S(83) and S(84) are used in subroutine STAR. S(83) determines when the minimum group path has been found (see discussion of subroutine STAR). For obvious reasons, S(83), must not be too much smaller than the uncertainty in ray tracing. The initial star size, S(84), was also discussed in connection

with subroutine STAR. S(87)-S(92) are differentiation step sizes which are used in approximating the gradient of the MSE by the finite difference method. Only those elements corresponding to variable ionostate components need to be specified. It should also be mentioned that these elements may be adjusted by the program if, based upon certain criteria, it would appear that the derivatives may be unreliable, as discussed previously in connection with the sample output. S(93) provides one of the termination criteria for subroutine STEEP and its value is somewhat subjective. Our typical value of 1 km^2 is sufficient because we have used simulated data in an LQP model ionosphere and thus have known that some ionostate, at least in theory, would result in an MSE of 0 km^2. In a more realistic case, a final MSE of 1 km^2 or less may not be attainable and thus a larger value for S(93) may be used. However, it should be emphasized that even if S(93) is too small, other parameters will eventually cause program termination and therefore there is no real danger of performing an infinite search for an unrealizable MSE. S(95)-S(106) define a finite domain in ionostate space over which the search for the optimum ionostate is to be performed. Again, only the bounds on variable ionostate components need to be specified. It is, of course, necessary that the initial ionostate be contained in this domain. In the event that the program begins to use ionostates outside of this domain a termination will occur which usually implies

that the domain is too small. S(107) is analogous in purpose to S(93). Finally, S(108) is the transition radius between free space and the ionosphere. For computational efficiency S(108) should be as large as possible, but must never exceed the local value of RB at any point on the ray trajectory. The end of the S array is signified by a blank card.

The N array is reasonably self-explanatory with the exception of flagged elements. Flags are set to either 1 or 0. In the case of N(6)-N(11) a flag of 1 denotes a variable ionostate. A flag of 1 in N(16) denotes that the program is to be run in the synthesis mode (0, of course, signifies inversion). A flag of 1 in N(21) signifies that the program is to terminate immediately after determining the MSE. The end of the N array is signified by a blank card. S array format is I3, 1X, E20.7 while N array format is I3,I5.

For the case of quadratic gradients, as discussed in section 2.4, the quantities involving RB in the S and N arrays can be replaced by corresponding values for G2FC. The only internal modifications which this necessitates in the program occur in subroutine RAYT. In particular, every RB= statement in this subroutine should be replaced with the fixed value of RB(6570 in our case). The assignment of FC (statement 218) must then be changed by adding the term S(21)*(Y(2)**2) and the assignment of DPDA must be corrected by the addition of 2*DPDFC*S(21)*Y(2).

3.6 CRASH CODES

The following codes are used to indicate the reason for program termination

TABLE 2: CRASH CODE SUMMARY

CODE	IMPLICATION
NSTP>N(1)	Too many iterations in RAYT. Try larger value of N(1)
CRASH001	Too many calls to RAYT. Try large value for N(5)
CRASH002	No minimum group path could be found for the given sounding frequency. Check data input file for mistakes. If file is correct, different sounding frequencies may be necessary.
CRASH004	No differentiation step size specified. Check data input file to make sure that for every variable ionostate component there is a differentiation step size in S(87)-S(92)
CRASH005	Program terminated upon reaching specified number of search directions without finding specified minimum mean squared error.
OUTRANGE	Ionostate is outside of specified domain. This domain may have to be made larger, and/or a different starting ionostate may be required.
ITERATION	Too many iterations in subroutine STEEP. Try increasing N(14).

4. CONCLUSION

As a result of our emphasis on applications, examples, and documentation in the previous sections, there are a few considerations of a general nature which still remain to be discussed. In addition, we would like to make some specific recommendations for possible improvements in the program.

The most persistent problem which we have considered is the problem of uniqueness in computing an optimum ionostate. The question of whether or not two different ionostates could result in identical backscatter leading edges is still unresolved. On a qualitative basis, we have discussed (see section 2.4) the possibility of various ionostate components having a mutually offsetting effect and it would, at least, therefore seem plausible that there is not a one-to-one mapping between the backscatter leading edge and a corresponding ionostate. However, even if there were such a one-to-one mapping it could still be possible that the mean squared error hypersurface would have more than one local minimum as a function of ionostate. In this case, the values at each of the local minima would be different and the objective, of course, would be to find the local minimum corresponding to the least mean squared error. Using the present form of this program in order to find the smallest local minimum would then require running the inversion mode for many different starting

values for the initial ionostate. This problem (i.e. sensitivity to starting values) is one that is common to all of the standard minimization procedures that we are presently acquainted with. We believe, however, that the choice of a starting value would be facilitated by the generation of a library of the backscatter leading edges produced by ray tracing in LQP model ionospheres based upon various ionostates. The selection of a particular starting value for the ionostate may also be facilitated through the use of the N(21) flag (see section 3.5). We have used this procedure to our advantage in obtaining a number of the results presented in section 2. In particular, setting N(21)=1 and using various ionostates in S(21)-S(26) can provide a rough picture of the MSE hypersurface.

Another problem, which was previously discussed, is the selection of the Runge-Kutta step size. The present ray tracing subroutine (RAYT) uses a fixed value, S(20), for the step size. A more efficient procedure would be to approximate both the truncation and round-off errors in each integration step, and adjust the step size accordingly. There is, however, some utilization of this idea in the present program through the incorporation of separate subroutines for free space and ionospheric ray tracing.

In spite of these problems, a number of successful computer runs have confirmed the feasibility of this procedure, and resulted in ionostates which were correct to within the tolerances specified in the data input file.

REFERENCES

Croft, T. A. and H. Hoogasian, Exact ray calculation in a quasi-parabolic ionosphere with no magnetic field, Radio Sci. 3, 69-74, 1968.

Haselegrove, J., Oblique ray paths in the ionosphere, Proc. Phys. Soc. London, Sect. B 70, 1957.

Kelso, J. M., "Radio Ray Propagation in the Ionosphere", McGraw-Hill, New York, 1964.

Rao, N. Narayana, Yeh, K. C., Youakim, M. Y. Hoover, K. E., Parhami, P., and R. E. DuBroff, Techniques of determining ionospheric structures from oblique radio propagation measurements. Technical Report RADC-TR-76-701 for Rome Air Development Center, Griffis Air Force Base, N.Y., 1976.

Yeh, K. C. and C. H. Liu, "Theory of Ionospheric Waves", Academic Press, New York, 1972.

MISSION
of
Rome Air Development Center

RADC plans and conducts research, exploratory and advanced development programs in command, control, and communications (C^3) activities, and in the C^3 areas of information sciences and intelligence. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

Printed by
United States Air Force
Hanscom AFB, Mass. 01731