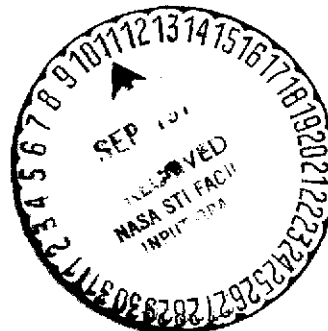UNIVERSITY OF ILLINOIS
URBANA

AERONOMY REPORT

NO. 60

DIGITAL-IONOSONDE STUDIES
OF F-REGION WAVES

by
R. M. Harper
S. A. Bowhill

July 1, 1974

Aeronomy Laboratory
Department of Electrical Engineering
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ABSTRACT

Accurate fixed-frequency virtual height data collected on a digital ionosonde is analyzed to measure speed and direction of traveling ionospheric disturbances by matching the experimental data with virtual height and echo amplitude obtained from a simple model of the disturbed ionosphere. Several data records analyzed in this manner indicate speeds of 400 to 680 msec^{-1} and a direction of propagation from north to south. The digital ionosonde collects virtual height data with a time resolution of 10 sec and a height resolution of less than 300 m.

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1. INTRODUCTION

Virtual height recorders were among the first instruments used to study traveling ionospheric disturbances. Virtual height data are generally recorded on photographic film with a height resolution on the order of a few km. With the availability of high speed computers for real time data collection, better resolution can be obtained by digitizing the output of a virtual height recorder and analyzing the data with a computer. Besides better height resolution, computer algorithms provide noise reduction and greater flexibility in collecting and recording the data.

1.1 *Statement of the Problem*

The purpose of this work is to study traveling ionospheric disturbances (TIDs) in the F region by comparing accurate fixed-frequency virtual-height data from a digital ionosonde with virtual heights calculated from simple models of the disturbances.

Horizontal speed, wavelength and direction of the disturbances are calculated from virtual-height data. The ionosphere is modeled as a curved reflector of radio waves. Virtual height and focusing effects for a reflector are calculated and compared with experimental data. The shape and size of the reflector are varied until the calculated height and amplitude match the experimental data. The horizontal wavelength of the disturbance is the horizontal size of the reflector and the speed of the disturbance is the wavelength divided by the period of the disturbance.

To determine the direction in which the disturbance is moving, the separation between the ordinary and extraordinary

wave reflection points is calculated. The time delay between
the appearance of prominent features of the disturbance at the
two reflection points is measured to determine the component of
speed projected in the N-S direction. The angle at which the
disturbance is propagating relative to North is the arc-cosine of the
N-S projection of the velocity divided by the speed of the disturbance.
The direction measured is either east or west of North. The
ambiguity cannot be resolved with the present equipment.

1.2 *Outline of the Thesis*

Chapter 2 reviews gravity wave and radio wave propagation
theory and describes how radio waves reflected from the ionosphere
are used to study gravity waves.

Chapter 3 describes the data collection system and contains
an analysis of the accuracy of the algorithm used to determine
virtual height.

Chapter 4 discusses the results of the analysis of data
by methods described in Chapter 2.

Chapter 5 contains the conclusions and suggestions for further
work.

Operating procedures and listings of the programs for collecting
and analyzing virtual height data are given in the appendices.

2. ANALYSIS OF TRAVELING IONOSPHERIC DISTURBANCES BY VIRTUAL-HEIGHT MEASUREMENTS

Traveling disturbances in the F region have been observed for more than 20 years. *Munro* [1950] used fixed-frequency virtual-height measurements to determine speed, direction and extent of these disturbances. *Hines* [1959] developed a theory of gravity waves to explain the disturbances observed by Munro and others.

In this chapter the effects of gravity waves on the propagation of radio waves are discussed and also how radio waves are used to measure the properties of traveling ionospheric distrubances.

In Section 2.1 the properties of gravity waves and their effects on the ionosphere are discussed.

In Section 2.2 the propagation of radio waves which retrace their path after reflection from a disturbed ionosphere is discussed.

In the following sections, techniques are developed to measure the speed and direction of the disturbance from properties of radio propagation in an ionosphere disturbed by gravity waves.

2.1 *Gravity Waves*

Sound waves propagating through the ionosphere are called gravity waves because of the effect gravity has on them. Gravity causes the density of the atmosphere to decrease with height. This horizontal stratification causes the propagation to be anisotropic.

A derivation of the wave equations can be found in *Yeh and Liu* [1972]. The dispersion relation for a gravity wave in an isothermal atmosphere is given by

$$\frac{n_x}{\{1-\omega_a^2/\omega^2\}/\{1-\omega_b^2/\omega^2\}} + \frac{n_z}{(1-\omega_a^2/\omega^2)} = 1 \qquad (2.1)$$

where $n_x = k_x/k_o$

$n_z = k_z/k_o$

c_s = speed of sound

$\omega_a = \gamma g/2c_s$ acoustic cutoff frequency

$\omega_b = (\gamma-1)^{1/2} g/c_s$ buoyant or Brunt frequency.

The coordinates are set up with z vertical, and with $\overline{k}_o$ in the x-z plane

$k_o = \omega/c_s = |\overline{k}_o|$ = the wave number

k_x and k_z are the components of $\overline{k}_o$ in the x and z directions respectively.

γ = the ratio of specific heats

g = the gravitational acceleration

For frequencies less than the Brunt frequency, the refractive index curve is shown in Figure 2.1. For these waves, called internal gravity waves, the phase velocity is directed downward when the waves are traveling upward.

Waves with frequencies greater than the acoustic cutoff frequency are called acoustic gravity waves and have an elliptical refractive index curve as shown in Figure 2.2.

For frequencies between the Brunt and acoustic cutoff frequencies, either k_x or k_z is imaginary. Freely propagating waves cannot have frequencies in this range, called the cutoff region.
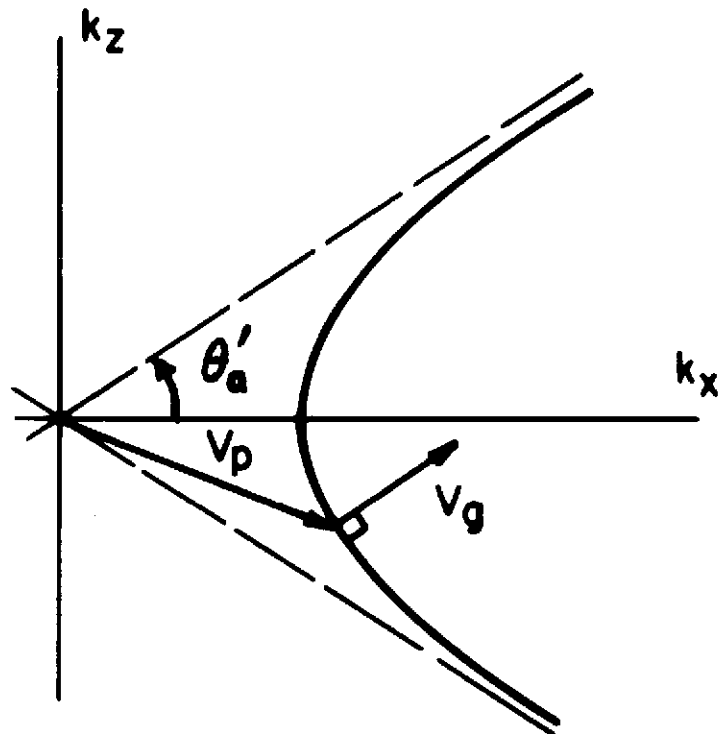
INTERNAL GRAVITY WAVES

Figure 2.1 Refractive index curve for an internal gravity wave from *Georges* [1967].
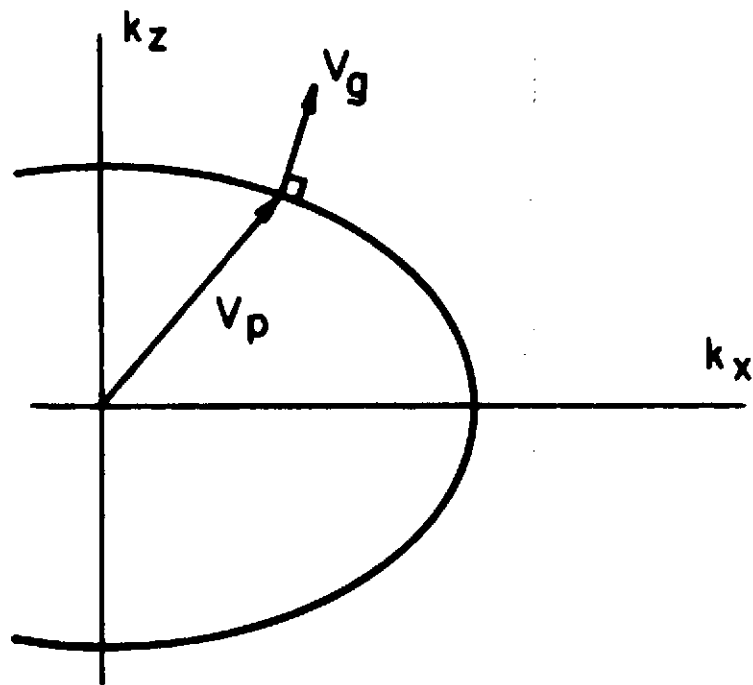
ACOUSTIC   WAVES

Figure 2.2   Refractive index curve for an acoustic gravity
wave from *Georges* [1967].

Typical values for ω_a and ω_b at 250 km are .483 and .436 rad sec^{-1} corresponding to periods of 13 and 14.4 min respectively.

Associated with the propagation of a gravity wave is the motion of small air parcels which move in elliptical orbits. Above the dynamo region, a force applied on the ions by collisions with neutral particles tends to drag them along with the air parcel but because of the earth's magnetic field, the ions are constrained to move in a spiral path along the field lines. Neglecting diffusion, the resulting ion velocity is equal to the component of the air parcel velocity parallel to the magnetic field. Electrons move with the ions to maintain neutrality.

Figure 2.3 shows the iso-ionic contours for a traveling ionospheric disturbance observed at Arecibo by *Harper* [1972]. In the next section, the propagation of radio waves in a disturbed ionosphere such as shown in Figure 2.3 is discussed.

2.2 *Radio Waves as a Tool for Studying Traveling Ionospheric Disturbances*

Almost all data on traveling ionospheric disturbances comes from radio propagation experiments. The earliest techniques relied on the time delay of waves reflected from the ionosphere. A description of wave propagation in a horizontally stratified ionosphere is given in *Budden* [1961].

For radio waves in the F region with frequencies greater than 1 MHz, the refractive index is given by

$$\mu = \left[1 - \frac{X}{1-T \pm (T^2+Y_L^2)^{1/2}} \right]^{1/2} \tag{2.2}$$

The axis are set up with z vertical and the magnetic intensity vector $\vec{B}$ in the x-z plane. ℓ and n are the x and z direction cosines of $\vec{B}$.
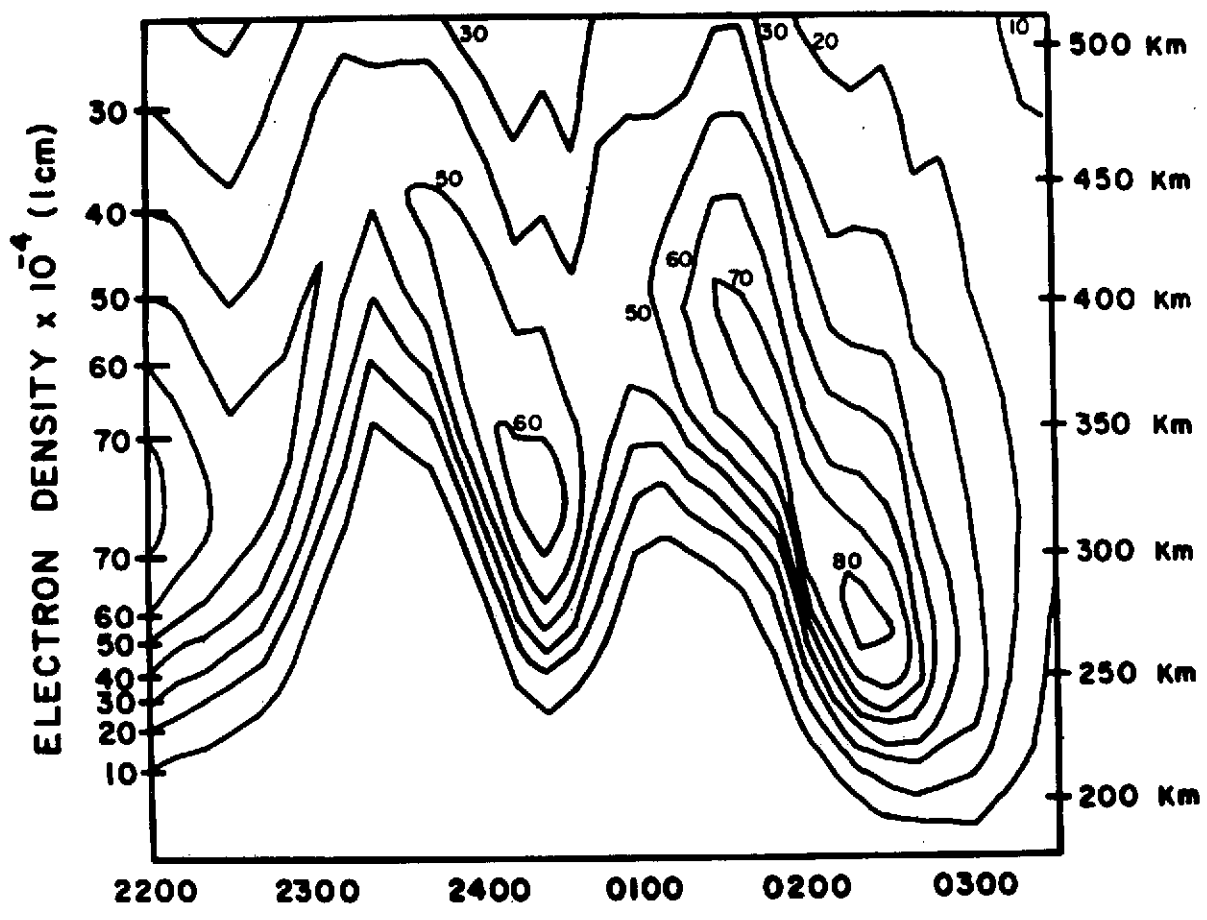
Figure 2.3 Iso-ionic contours in the presence of a gravity wave
from *Harper* [1972].

$$T = Y_T^2/2(1-X)$$
$$Y_L = nY$$
$$Y_T = \ell Y$$
$$Y = \omega_H/\omega \qquad \omega_H = |Be/m_e| \quad \text{gyrofrequency}$$
$$X = (\omega_n/\omega)^2 \qquad \omega_n^2 = Ne^2/\varepsilon_o m_e \quad \text{plasma frequency}$$

ε_o is the permittivity of free space

N is the electron density

e is the charge on an electron

m_e is the mass of an electron

The refractive index has two values corresponding to the ordinary and extraordinary polarizations. For a horizontally stratified ionosphere, a wave transmitted vertically and reflected from the ionosphere will re-trace its path and return to the ground at the point where it originated. Reflection occurs where $\mu = 0$. The ordinary wave path is deflected towards the magnetic pole and reflected when $X = 1$ or $N = \varepsilon_o m_e \omega^2/e^2$. The extra-ordinary wave path is deflected towards the equator and reflected when $X = 1 - Y$.

Gravity waves cause the ionosphere to be nonhorizontally stratified and waves which retrace their path are not vertically incident on the iono-sphere. Under these conditions, the reflection conditions $X = 1$ and $X = 1 - Y$ for the two polarizations still hold, but the path is deflected in the x and y directions from the path it would take in a horizontally strat-ified ionosphere.

The most convenient quantity to measure, relating to disturbances in the ionosphere, is virtual height h', the equivalent height of the reflec-tion point if the wave traveled at the speed of light c. If the time delay between the transmission of a wave and its reception at the same point after being reflected from the ionosphere is T, the virtual height is $h' = cT/2$.

For the purpose of studying gravity waves, the ionosphere is modeled
as a curved reflector with radio waves that retrace their path reflecting
at right angles to the surface as shown in Figure 2.4. The reflector
moves horizontally with the same velocity as the gravity wave. The shape is
assumed to be constant with time and not to vary in the y direction. The
virtual height of a wave reflected from point A is the slant height from the
ground to point B on the reflector. The virtual height measured from a
fixed location will vary as the reflector moves horizontally with velocity v.
To calculate virtual height for a reflector, it is easier to think of the
reflector remaining stationary and the transmitter and receiver moving along
the ground with velocity $-v$.

Virtual height measurements from the digital ionosonde provide the
period and a measure of the amplitude of the disturbance directly. Several
methods for determining horizontal wavelength, speed and direction are dis-
cussed in the following sections.

2.3 *Focusing of Radio Waves due to Ionospheric Irregularities*

One property of a curved reflector is to focus or defocus the waves re-
flected from it. The intensity of the radio waves reflected back to the
receiver is related to the curvature of the reflecting surface. *Whitehead*
[1956] derives a formula to relate the amplitude of the received wave to
the curvature of the reflector using the approximation that the transmitter
illuminates the reflector with constant power per unit area. The following
derivation is similar but drops that assumption. Figure 2.5 shows the geo-
metric relation between the reflector and the transmitter. At the point of
reflection, the reflector has a one dimensional radius of curvature R. The
amount of power illuminating the reflector over an area of length J and
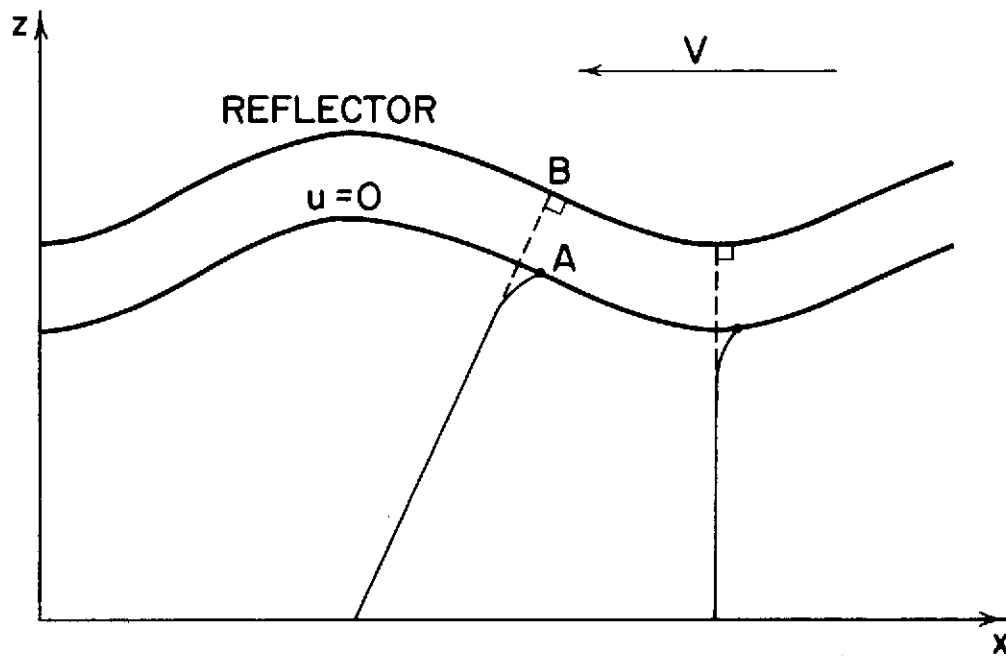
Figure 2.4   Ionosphere modeled as a curved reflector.
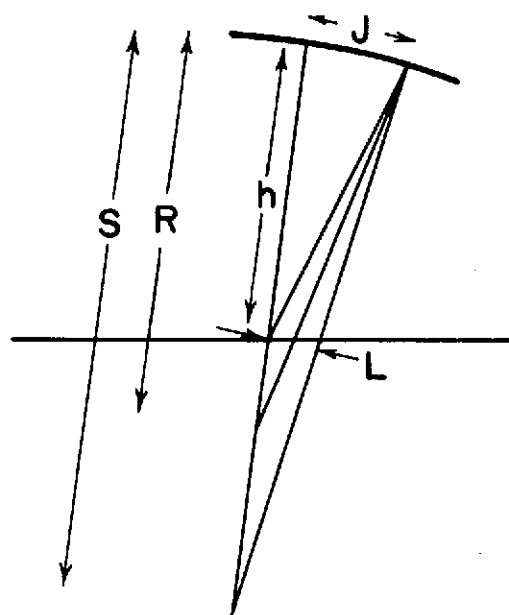
Figure 2.5 Focusing of radio waves by a curved reflector.

unit width is focused onto an area of length L and two units wide. The amount of power illuminating the reflector per unit area is proportional to h^2. The mirror formula is $1/h + 1/s = 2/R$. By similar triangles $J/L = s/(s-h) = R/2(R-h)$. The amplitude squared of the returning wave is proportional to the power per unit area at the ground which is equal to the power per unit area at the reflector times the focusing factor $R/2(R-h)$.

$$A^2 \; \alpha \; \frac{1}{h^2} \; \frac{R}{R-h} \tag{2.3}$$

If the shape of the reflector is given by $H(x)$, the radius of curvature R is given by

$$R = \left[1 + \frac{dH(x)}{dx}^2 \right]^{3/2} \frac{d^2H(x)}{dx^2} \tag{2.4}$$

Focusing depends on the horizontal structure of the reflector so the amount of focusing can be used to determine the reflector shape. This is discussed further in the next section.

2.4 *Effects of More Than One Reflection Point*

When the center of curvature of the reflector is above the ground, three rays reflected from the dome-shaped reflector retrace their paths back to their source simultaneously as shown in Figure 2.6.

For an assumed reflector shape $H(x)$, the virtual height of a ray reflected from a point x_o on the reflector is given by

$$h' = H(x_o) \; (1+m^2)^{1/2} \tag{2.5}$$
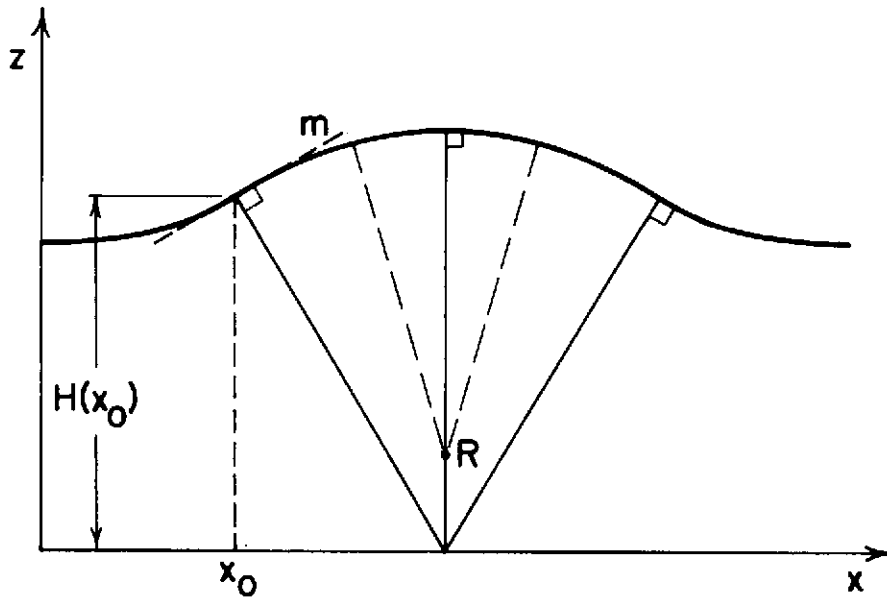
Figure 2.6   Three ray paths exist when the center of curvature is
above the ground.

where m is the slope of the reflector at the reflection point and the point on the ground where the ray originated is given by

$$x = x_o + H(x_o)m \tag{2.6}$$

A program for a Hewlett-Packard Model 9830 calculator plots virtual height and amplitude variations caused by focusing for any reflector shape. Operation of the program is discussed in Appendix III. The average height, peak-to-peak amplitude, horizontal size and shape of the reflector are adjustable. The reflector shape, virtual height and amplitude are plotted on a Hewlett-Packard Model 9862 plotter. An example is shown in Figure 2.7. The horizontal axis is in km. The graph can be thought of as the height and amplitude for a stationary reflector as the transmitter and receiver are moved in the horizontal direction. If the reflector is moving and the transmitter and receiver are stationary, the horizontal axis is proportional to time. The proportionality factor is the speed of the reflector.

If the virtual height and amplitude calculated from an assumed reflector shape matches the experimental data, the horizontal length of the gravity wave is equal to the length of the reflector. The horizontal phase speed of the disturbance is the wavelength divided by the period of the disturbance.

2.5 *Second Reflections*

A ray which travels from the ground to the ionosphere and back twice is called a second reflection or a two-hop ray. The simplest two-hop ray path is shown in Figure 2.8. The two-hop ray is not incident at right angles on the reflector and does not retrace its path after being reflected
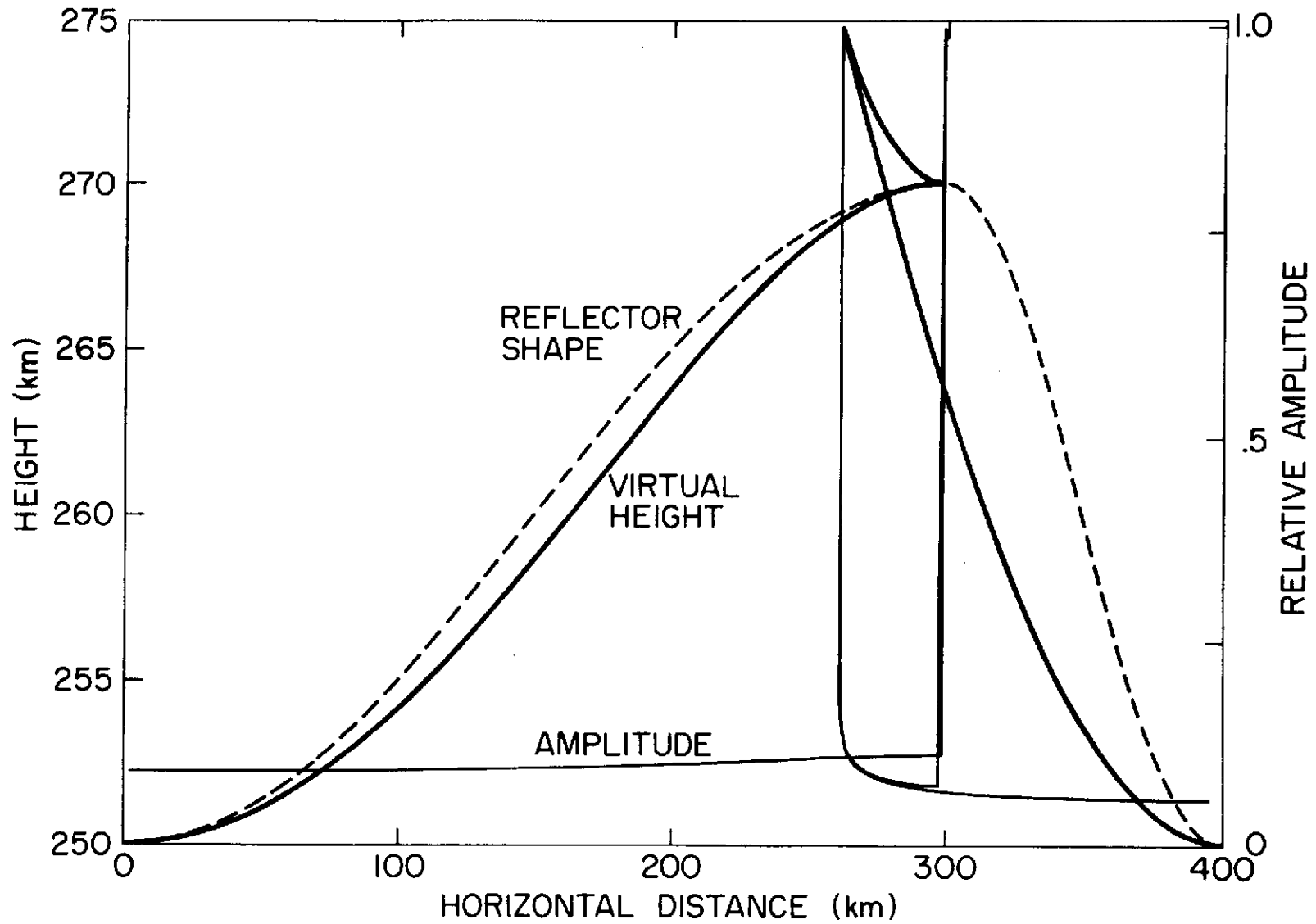
Figure 2.7   Virtual height and amplitude calculated from a reflector.
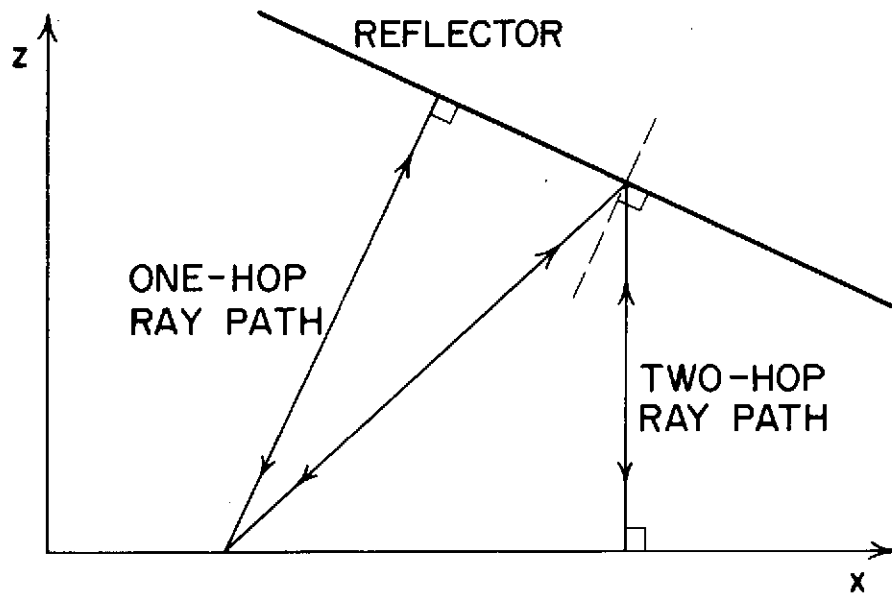
Figure 2.8 One- and two-hop ray paths.

from the ionosphere as the one-hop ray does. Because of this, the two-hop ray is reflected below the height where $X = 1$ and $X = 1 - Y$ for the ordinary and extraordinary polarizations respectively. For the reflector slopes of less than 20 degrees normally found in the ionosphere, the two-hop ray is nearly incident at right angles to the reflector and the one-hop reflector is used as an approximation of the reflection height of the two-hop ray.

The virtual height and amplitude for a two-hop ray can be calculated for a known reflector $H(x)$ in the same manner as for the one-hop ray. The virtual height for a ray which is reflected at x_o is

$$h' = H(x_o) \; (1+1/\cos(2 \; \tan^{-1} \; (m)))$$
(2.7)

where m is the slope of the reflector at x_o. The ray originates at

$$x = x_o + H(x_o) \; \tan(2 \; \tan^{-1}(m))$$
(2.8)

Focusing is calculated from the geometry shown in Figure 2.9. For simplicity, instead of being reflected at the ground, the ray passes through and is reflected from a mirror ionosphere on the other side of the ground line. From the mirror equation $1/s + 1/w = 2/R$ and $1/t + 1/(2H(x_o)-w) = 2/R$. By similar triangles $K/J = (2H(x_o)-w)/w$ and $L/R = (t-s)/t$. The amplitude of the ray as recieved is equal to the power per unit area along J times the focusing factor J/L.

$$A^2 = \frac{1}{s^2} \; \frac{w}{2H(x_o)-w} \; \frac{t}{t-s}$$
(2.9)

REFLECTOR

$$s = \frac{H(x_0)}{\cos(2\tan^{-1}(m))}$$
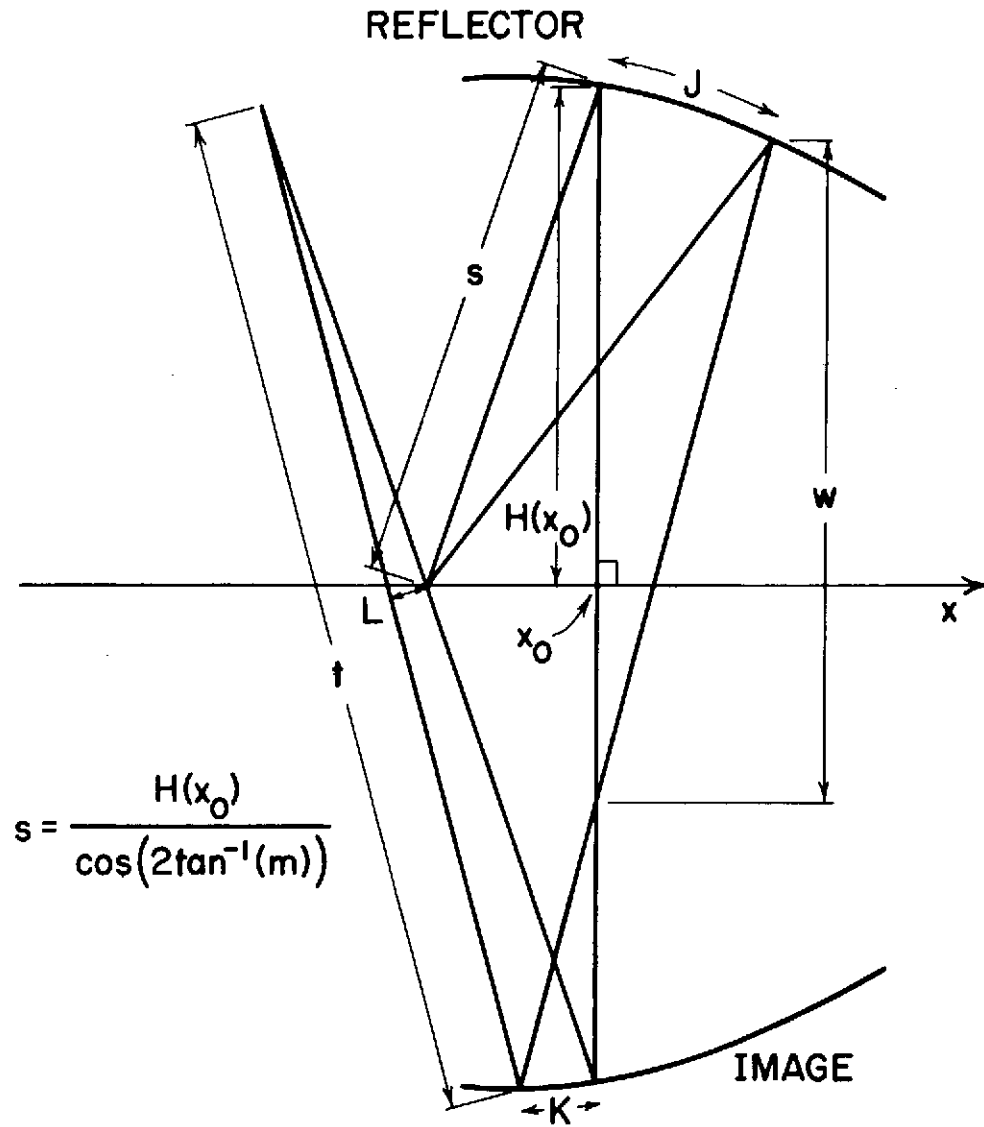
Figure 2.9 Geometry of two-hop focusing.

The program which calculates the height and amplitude for a one-hop ray path, also calculates the two-hop virtual height and amplitude. Figure 2.10 shows the two-hop virtual height and amplitude for the reflector shape used in Figure 2.7. The two-hop ray path data are used in the same manner as the one-hop data to determine the shape and size of the reflector.

A method of determining the direction of the disturbances is discussed in the next section.

2.6 *Lateral Deviation*

For a horizontally stratified ionosphere, the deviation of the wave path from vertical, the lateral deviation, is given by *Budden* [1961] as

$$\frac{dx}{dz} = \frac{+}{-} \frac{\ell\,n\,Y^2(1-\mu)^2}{(4Y_L^2(1-X)^2 + Y_T^4)^{1/2}} \qquad (2.10)$$

The − sign applies to the ordinary polarization and the + sign applies to the extraordinary polarization. The equation is integrated numerically to give lateral deviation. Table 2.1 gives the lateral deviation versus height above the bottom of the ionosphere for the two polarizations. For this calculation the F region of the ionosphere is modeled as a parabola with a width of 400 km and a maximum electron density of 10^{12} m^{-3}.

For an ionosphere disturbed by a gravity wave, the reflection points oscillate around the points for an undisturbed ionosphere and the separations calculated are average separations.

Since the reflection points are separated in the horizontal and vertical direction, the time delay between the appearance of prominent features of the disturbance at the two reflection points depends on the vertical phase variation and the horizontal velocity of the disturbance. The phase
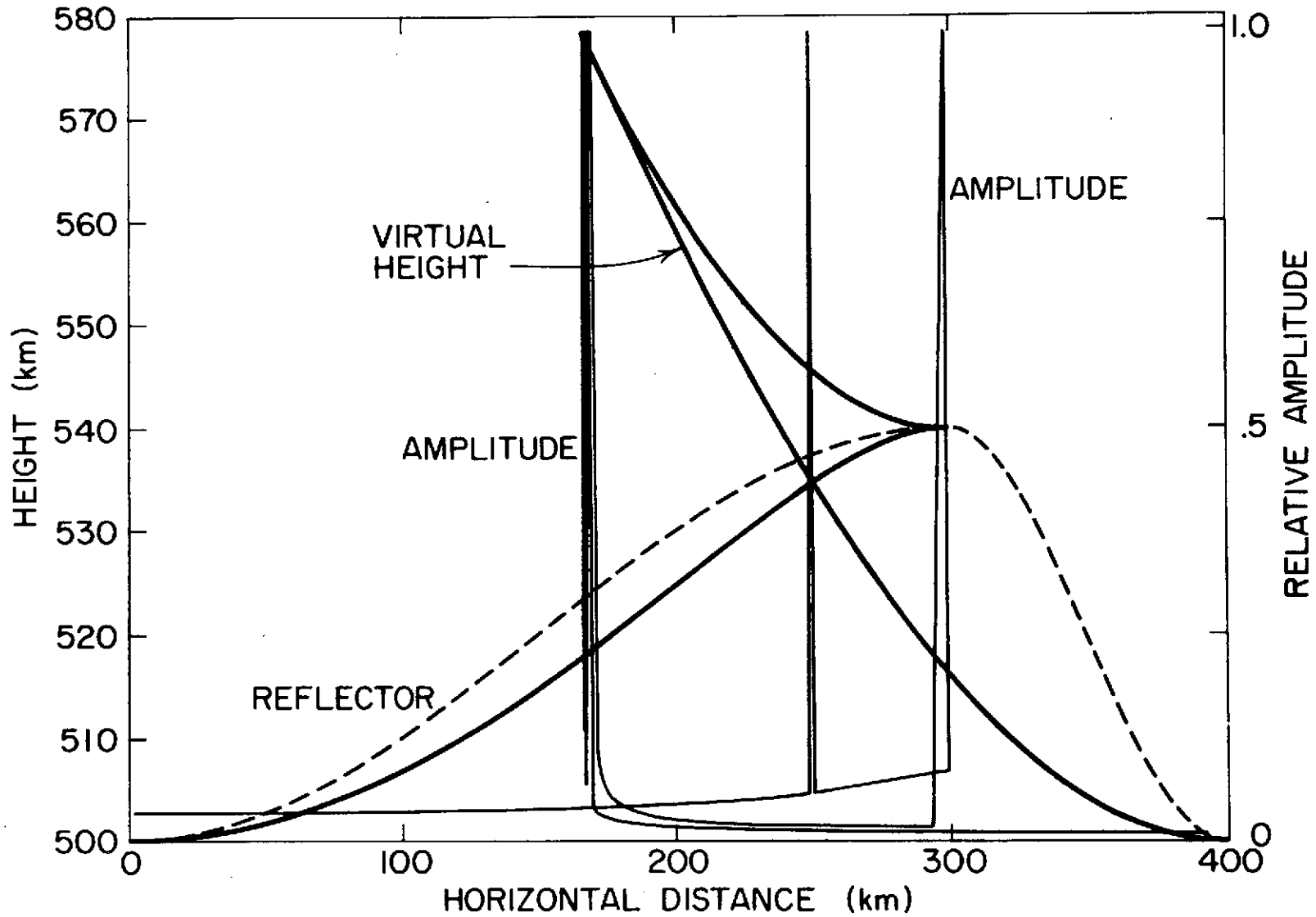
Figure 2.10 Virtual height and amplitude for the two-hop ray calculated for the reflector in Figure 2.7.

TABLE 2.1

Lateral deviation of ordinary and extraordinary wave polarizations.

```
OPERATING FREQUENCY = 4.1000
CRITICAL FREQUENCY = 9.0000
         LATERAL DEVIATION        DX/DZ        Y= 0.3824      1-Y= 0.6176
  Z(KM)     X         O          X         O         N          X
   1.00   -0.0021    0.0010    -0.0041    0.0019   1.00E+10    0.0481
   2.00   -0.0096    0.0040    -0.0087    0.0040   2.00E+10    0.0959
   3.00   -0.0199    0.0091    -0.0137    0.0063   2.99E+10    0.1435
   4.00   -0.0365    0.0168    -0.0193    0.0089   3.98E+10    0.1908
   5.00   -0.0591    0.0271    -0.0256    0.0117   4.96E+10    0.2379
   6.00   -0.0883    0.0405    -0.0327    0.0150   5.94E+10    0.2848
   7.00   -0.1252    0.0574    -0.0407    0.0186   6.91E+10    0.3314
   8.00   -0.1706    0.0782    -0.0499    0.0229   7.88E+10    0.3778
   9.00   -0.2260    0.1035    -0.0606    0.0277   8.84E+10    0.4239
  10.00   -0.2929    0.1341    -0.0730    0.0334   9.80E+10    0.4698
  11.00   -0.3735    0.1709    -0.0878    0.0401   1.08E+11    0.5155
  12.00   -0.4704    0.2152    -0.1056    0.0482   1.17E+11    0.5609
  13.00   -0.5871    0.2684    -0.1275    0.0581   1.26E+11    0.6061
  13.30   -0.6199    0.2833    -0.1338    0.0609   1.29E+11    0.6172
  14.00    0.0000    0.3327     0.0000    0.0705   1.36E+11    0.6510
  15.00    0.0000    0.4113     0.0000    0.0865   1.45E+11    0.6957
  16.00    0.0000    0.5085     0.0000    0.1080   1.54E+11    0.7401
  17.00    0.0000    0.6314     0.0000    0.1382   1.64E+11    0.7842
  18.00    0.0000    0.7918     0.0000    0.1838   1.73E+11    0.8283
  19.00    0.0000    1.0123     0.0000    0.2608   1.82E+11    0.8720
  20.00    0.0000    1.3446     0.0000    0.4173   1.91E+11    0.9155
  21.00    0.0000    1.9574     0.0000    0.8916   2.00E+11    0.9588
  22.00    0.0000    3.8295     0.0000    3.5805   2.09E+11    0.9996

LATERAL SEPARATION IS  4.449KM    VERTICAL SEPARATION IS  8.700KM
```

progression for disturbances with periods greater than 25 min is downward. *Georges* [1967] measured the angle of the phase front for a disturbance with a period of 40 min at 83° from vertical. For shorter periods the angle of the phase front decreases to 45°.

Figures 2.11a, b, and c indicate the reflection points and the phase front of the distrubance looking west, down and perpendicular to the velocity vector of the disturbance respectively. If the maximum for the ordinary reflector is at the ordinary reflection point, the maximum for the extra-ordinary reflector has a distance of $D_x + D_z \tan\phi$ to go to reach the extra-ordinary reflection point. If the time it takes for this to happen is τ, the projection of the velocity in the southerly direction is $V_s = (D_x + D_z \tan\phi \sec\theta)/\tau$. The cosine of the angle θ is the speed of the reflector v divided by the velocity projection in the southerly direction.

$$\cos\theta = V/V_s = V\tau/(D_x + D_z \tan\phi \sec\theta) \tag{2.11}$$

This can be solved for θ

$$\theta = \cos^{-1} \frac{V\tau - D_z \tan\phi}{D_x} \tag{2.12}$$

The angle θ is measured either east or west of north. The ambiguity cannot be resolved with the present equipment.

The velocity v is determined by methods described in the last three sections. Chapter 4 contains the results of applying the methods of this chapter to data collected by the digital ionosonde described in Chapter 3.
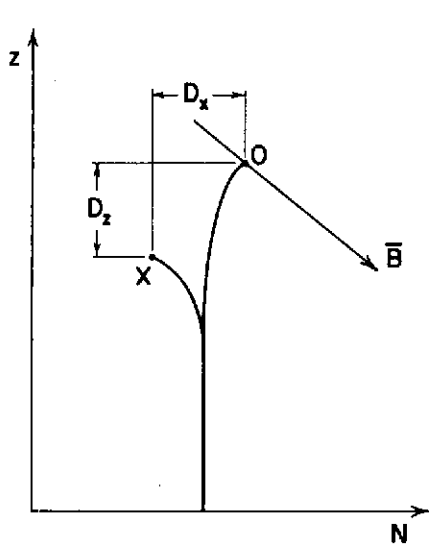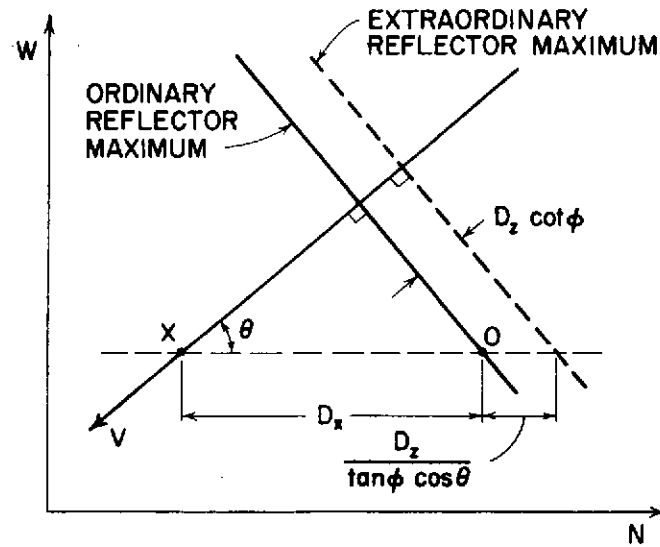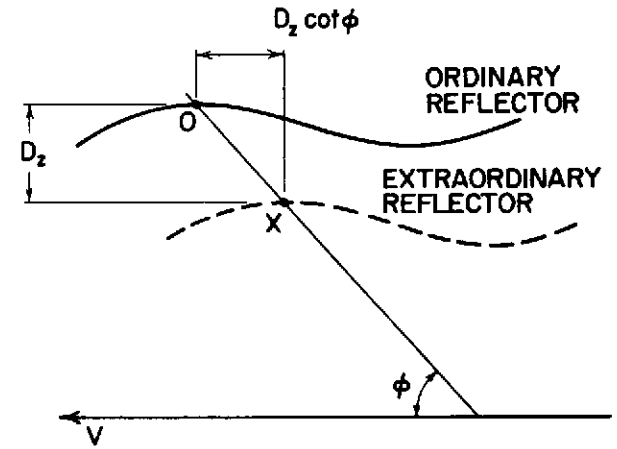
Figure 2.11   Three views of the ordinary and extraordinary reflection points and the phase front of a gravity wave.

3. DATA COLLECTION AND PROCESSING

The digital ionosonde, used to provide virtual height data for this work is formed by connecting a J5W ionosonde to a PDP-15 computer through a Hewlett-Packard Model 5610A analog-to-digital converter (ADC). A block diagram of the digital ionosonde is shown in Figure 3.1.

This chapter describes the operation of the system. The next section describes the basic hardware. Section 3.2 describes the algorithm used to provide accurate virtual height data and the accuracy of the algorithm is discussed in Section 3.3. Sections 3.4 and 3.5 discuss the PDP-15 programs. Section 3.6 describes a digital frequency counter for the ionosonde and the ways it is used.

3.1 Hardware Interconnections and Timing

The ionosonde contains a 20 kw pulse transmitter, a receiver and oscilloscopes and cameras to record virtual height data. A pulse generator synchronizes the transmitter pulse to the 60 Hz power line and is used to synchronize the ADC to the ionosonde.

The ionosonde transmits a 70 µsec pulse every 16.6 msec. The frequency of the pulse is adjustable from 250 kHz to 20.25 MHz. The bandpass of the ionosonde reciever is set by a switch at 10, 20, 35, or 70 kHz. The 20 kHz setting, which gives a received pulse width of approximately 30 µsec at 3 dB points, is normally used. The demodulated or video output is connected to the ADC through a line driver and a coaxial cable. The ionosonde sync pulse triggers the encode gate generator which generates the encode gate signal. 300 µsec after a pulse is transmitted, the encode gate line goes to a logical 1(5 V) for 6 msec as shown in Figure 3.2. While the encode gate signal is at "1" the ADC, if enabled by the computer,
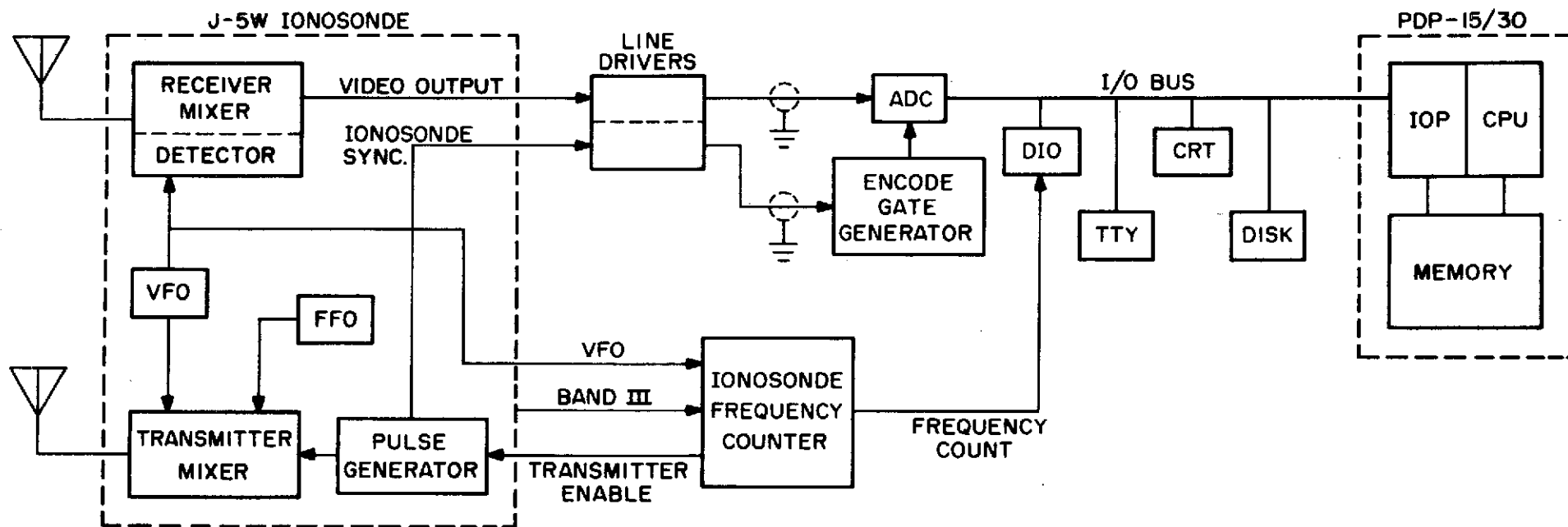
Figure 3.1   Block diagram of the digital ionosonde.
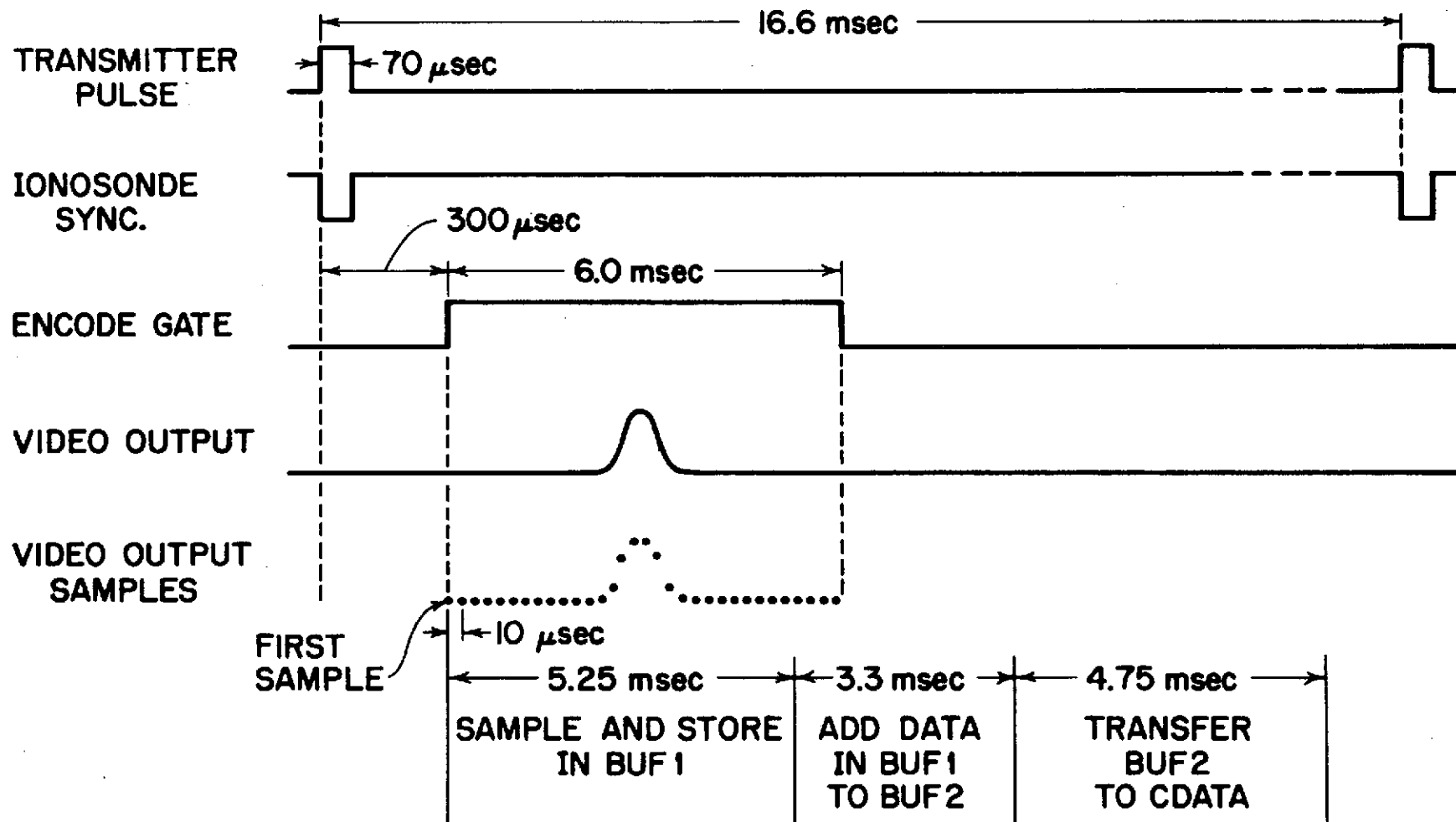
Figure 3.2 Timing diagram for the digital ionosonde.

samples the video output of the ionosonde at 10 µsec intervals, converts the analog voltage to a binary value and stores the values in consecutive locations in the PDP-15 core memory. The series of samples of the receiver output are called a frame of data.

A program on the PDP-15 identifies the echoes and prints their height and amplitude. The basic techniques for identifying echoes and measuring their virtual height are discussed in the next section. The data collection programs are discussed in Section 3.4.

3.2 Data Processing Techniques

A simple method of identifying echoes and determining their height is to set a threshold and to call a series of samples greater than the threshold an echo. The location of the largest sample in the echo determines the time delay of the echo and its virtual height. If the Ith sample in a frame is the peak of an echo, the time delay is $T = 300 + 10 \cdot (I-1)$ µsec.

There are several problems with this method. Noise sometimes exceeds the echo amplitude and, depending on the threshold level, either noise is detected as an echo or the echo is not detected. To reduce the effects of noise, a number of frames are averaged together.

The received amplitude at a fixed time delay after the transmission of a pulse contains both a noise and echo signal. Over a short period of time, the signal amplitude is constant but the noise varies in a random manner. If the signal exceeds the noise, the average amplitude over a number of frames approaches the signal amplitude. The signal-to-noise ratio is increased by a factor of the square root of the number of frames averaged. If too many frames are averaged, however, rapid changes in virtual height are not detected. As a compromise, 600 frames are averaged, which reduces

the noise by a factor of $\sqrt{600}$ or 27.6 dB and provides a determination of the virtual height every 10 sec. It is preferable to measure the average power or average amplitude squared rather than the average amplitude but the PDP-15 is not fast enough to square each sample and still have time to detect echoes and print out data.

The resolution to which the time delay is measured is $\pm$ 5 μsec which gives a height resolution of only $\pm$ 750' m. To increase height resolution, the shape of the received echo is interpolated from its samples and the center is determined more accurately. Figure 3.3 shows a typical received echo shape and the 10 μsec sampling points. A parabola is used to approximate the shape of the peak of the received echo which is approximately Gaussian. Using the coordinate system in Figure 3.3, the formula for a parabola is $Y = Ax^2 + Bx + C$. The parabola is fitted to the largest sample and the sample on each side of the largest.

at $X = 0$, $Y = Y_2 = C$

at $X = 1$, $Y = Y_3 = A + B + C$

at $X = -1$, $Y = Y_1 = A - B + C$

$$A = \frac{Y_1 - 2Y_2 + Y_3}{2}$$

$$B = \frac{Y_3 - Y_1}{2}$$

$$C = Y_2$$

The maximum amplitude of the parabola is offset from $x = 0$ by a distance P and at this point the derivative of the equation for the parabola is 0.

$$2AP + B = 0$$
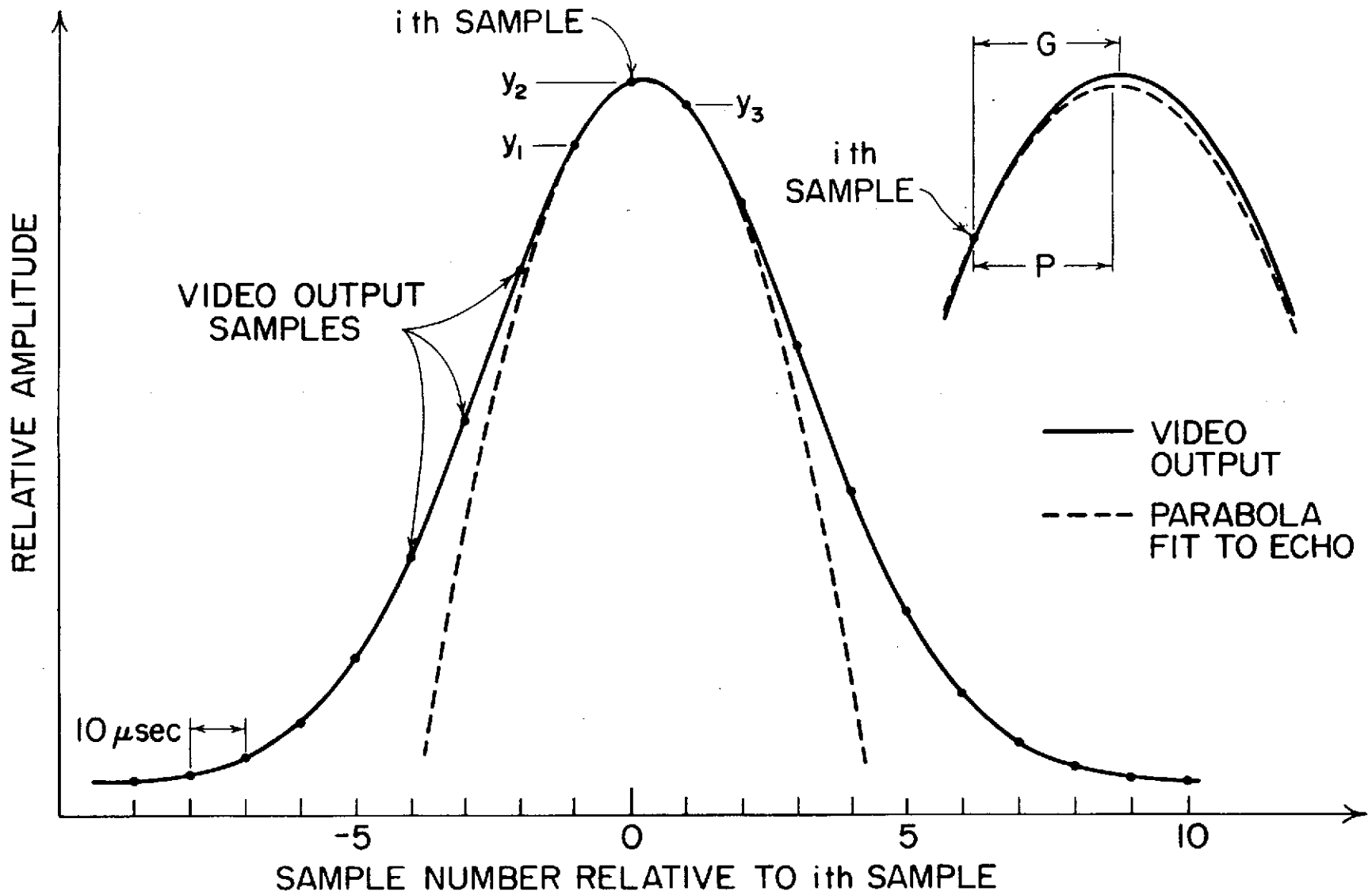
Figure 3.3 Parabola fitted to three samples of the received echo.

$$P = \frac{-B}{2A} + \frac{Y_1 - Y_3}{2(Y_1 - 2Y_2 + Y_3)}$$

The echo delay can now be determined more accurately as

$$T = 300 + 10(I-1+P) \; \mu sec$$

The accuracy of this formula depends on how close a parabola approximates the received echo shape and how much noise distorts the shape of the echo. This is discussed in the next section.

3.3 *Error Analysis*

The following analysis of the accuracy of the height algorithm assumes that if there are more than one echo, they do not overlap.

If the center of the echo is offset from the largest sample by a distance of G, the error in determining the virtual height of the echo is $P-G$. Figure 3.4 shows the error as a function of the echo offset G for various echo widths. For the 30 μsec wide echo, the maximum error is .125 μsec corresponding to a virtual height error of 18.75 m. The error decreases with increasing pulse width but, because the wider the echo, the closer the three samples are to being the same amplitude, noise causes larger errors for wider echoes than for narrow echoes.

To simulate the error under different noise conditions, a Monte Carlo approach is used. Random noise with a Gaussian distribution is added to a Gaussian shaped echo. A parabola is fitted to the largest sample and the sample on either side and the offset P is calculated. The process is repeated many times to get an RMS error. Figure 3.5 shows how the error varies with offset for a 30 μsec wide echo under conditions of no noise, 50 dB and 30 dB signal-to-noise ratio. The error for less than 50 dB
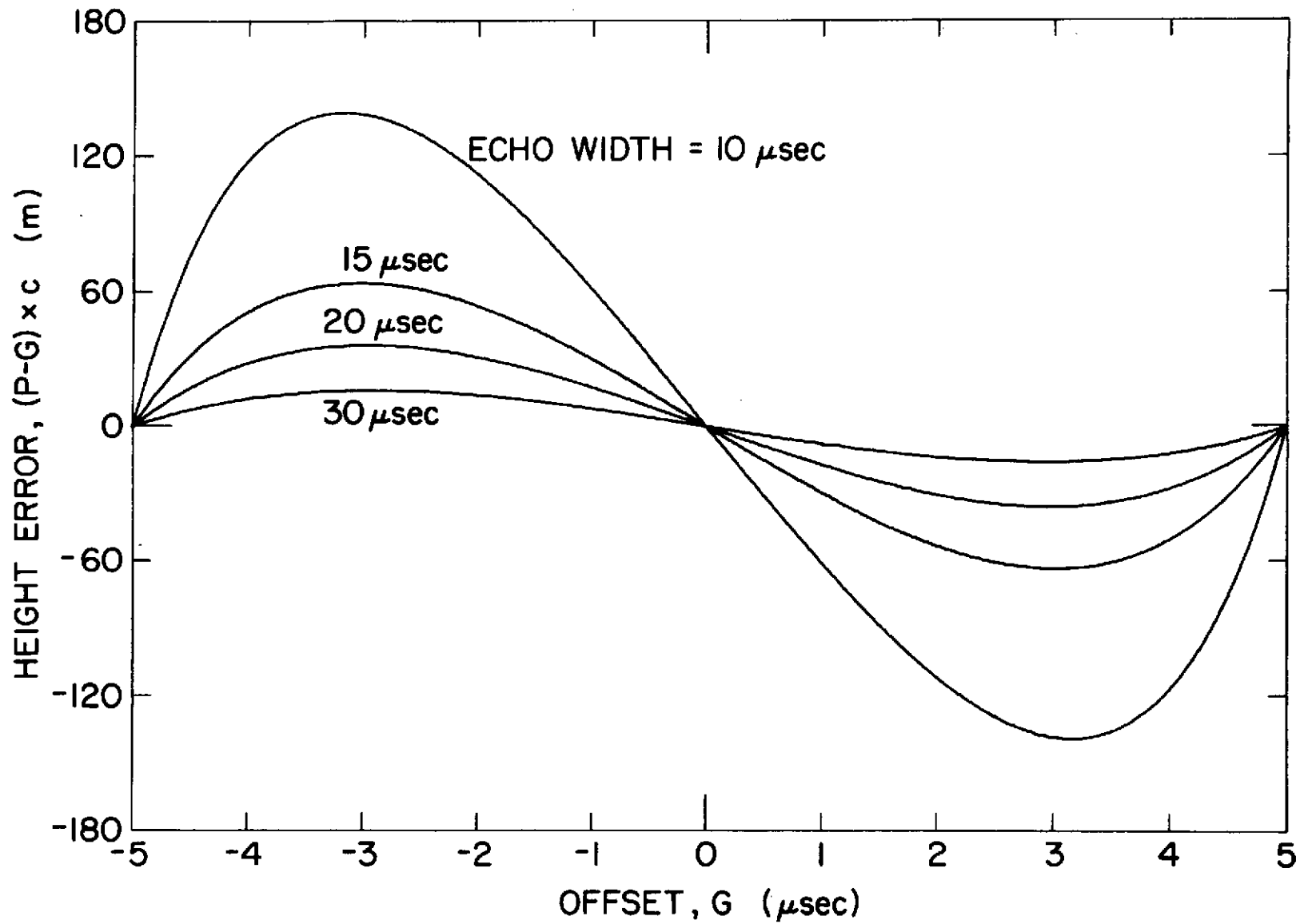
Figure 3.4 Height error as a function of G for various echo widths and no noise.
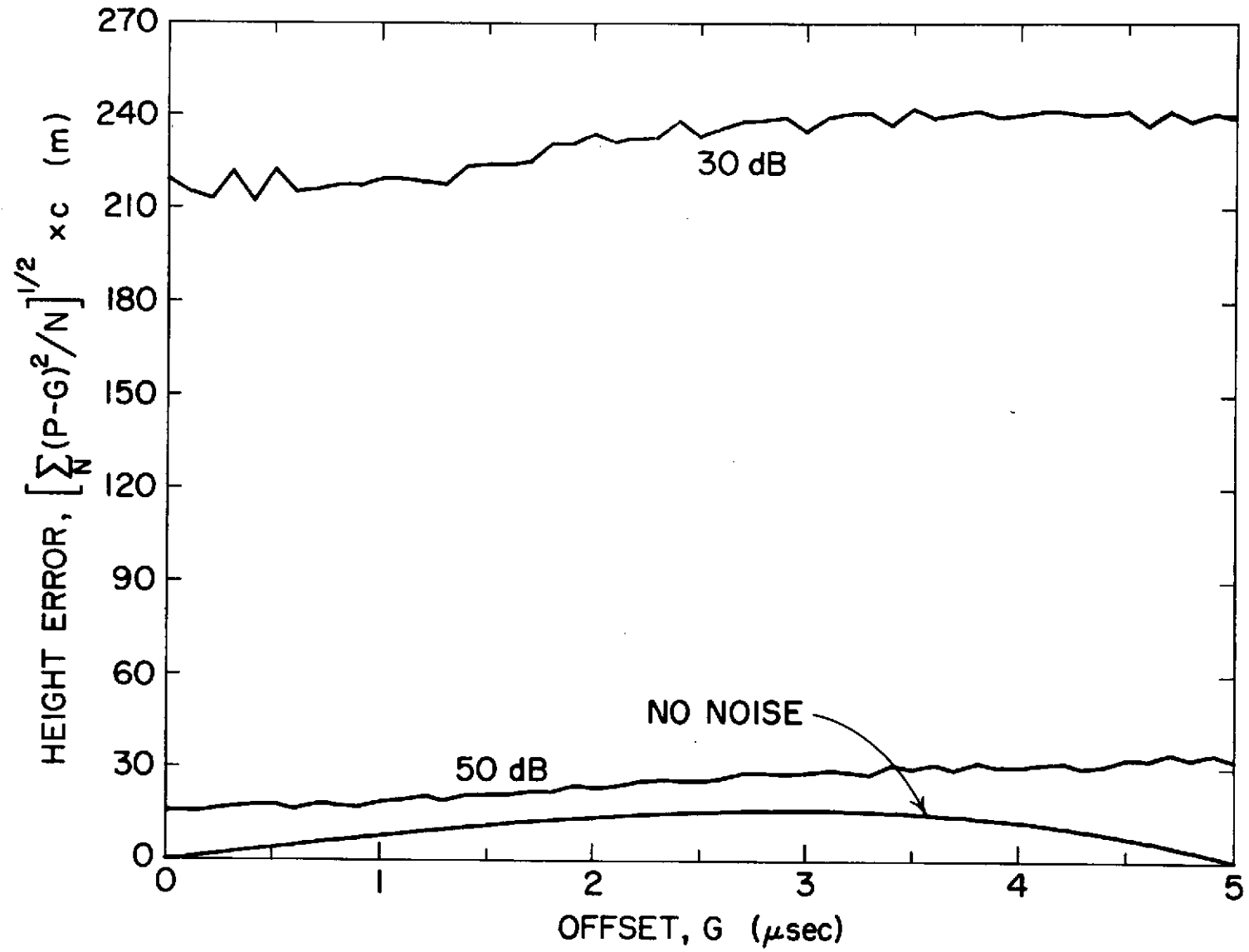
Figure 3.5 Height error as a function of G for a 30 μsec wide echo and various noise conditions.

signal-to-noise ratio is approximately independent of the offset G. Figure 3.6 shows the error as a function of the received pulse width for an offset of 2.5 µsec and various signal conditions. For a fixed signal-to-noise ratio, the error has a minimum value for some range of pulse width.

Noise conditions for the ionosonde vary with frequency, time of day and weather. Typical signal-to-noise ratios are from 0 to 30 dB. Averaging over 600 samples adds about 30 dB to the signal-to-noise ratio. Figure 3.6 indicates that the 30 µsec pulse width is near the minimum error for signal-to-noise ratios in the range of 30 to 60 dB. The error varies from $\pm$ 300 m in noisy conditions to $\pm$ 50 m for good signal conditions.

The phase of the returning echo relative to the transmitted signal and the time delay for the echo depend on the height of the reflector. When two echoes are received from different parts of the reflector but with nearly equal virtual heights, the amplitudes of the two echoes add vectorially and both echo shapes are distorted slightly. The apparent height and amplitude of each echo are different from the actual height and amplitude if the echoes did not interfere. The amount of change depends on the phase difference between the two echoes, their separation and their relative amplitudes. The maximum changes occur when the two echoes are in phase and 180° out of phase.

For the lower of the two echoes, the apparent height and amplitude increases when they are in phase and decreases when they are 180° out of phase. For the higher echo, the apparent height decreases and the amplitude increases when they are in phase. The height increases and the amplitude decreases when they are 180° out of phase. The changes in echo shape are shown in Figure 3.7. The maximum height and amplitude changes as a
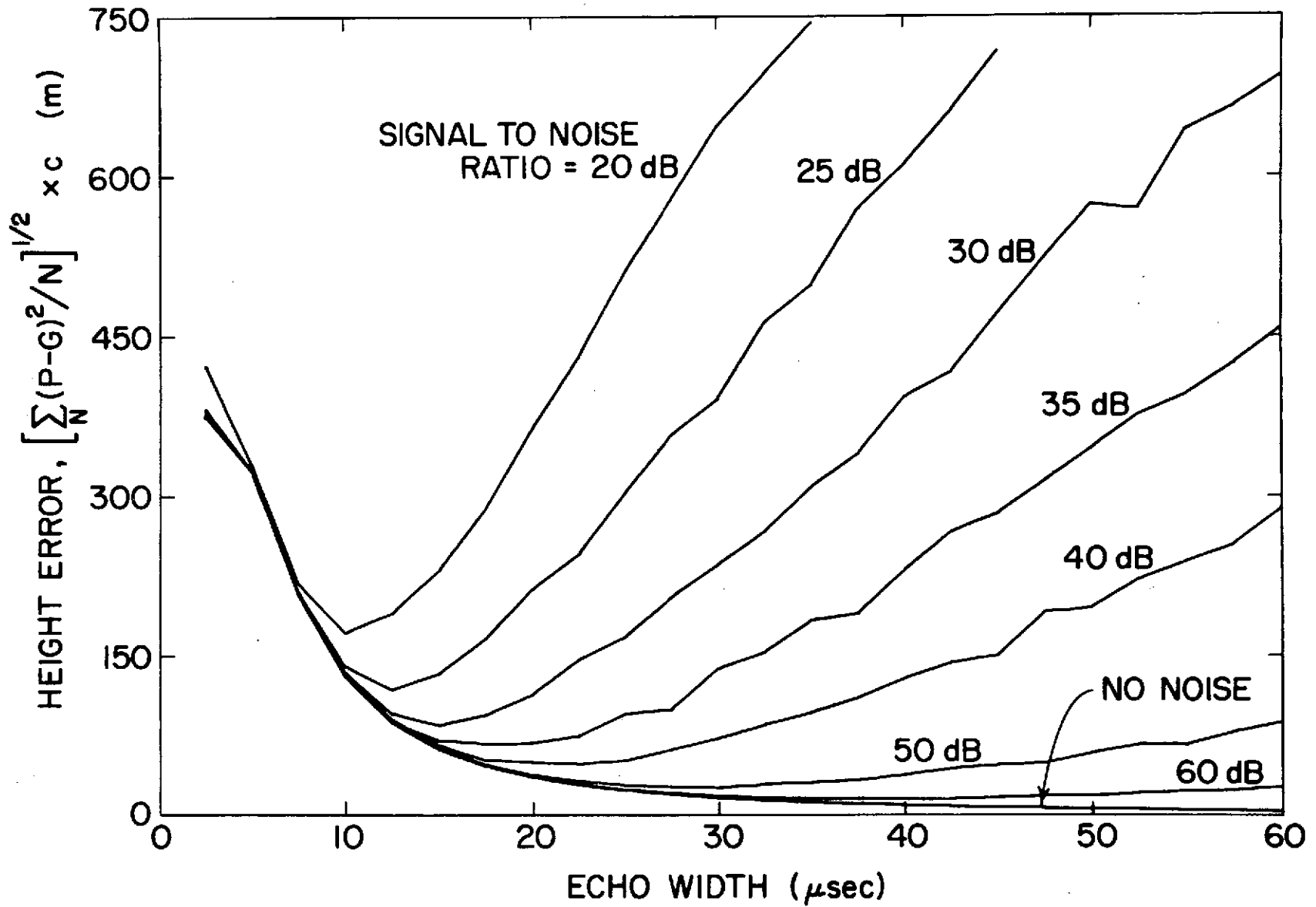
Figure 3.6 Height error as a function of echo width with G=2.5 μsec and various noise conditions.
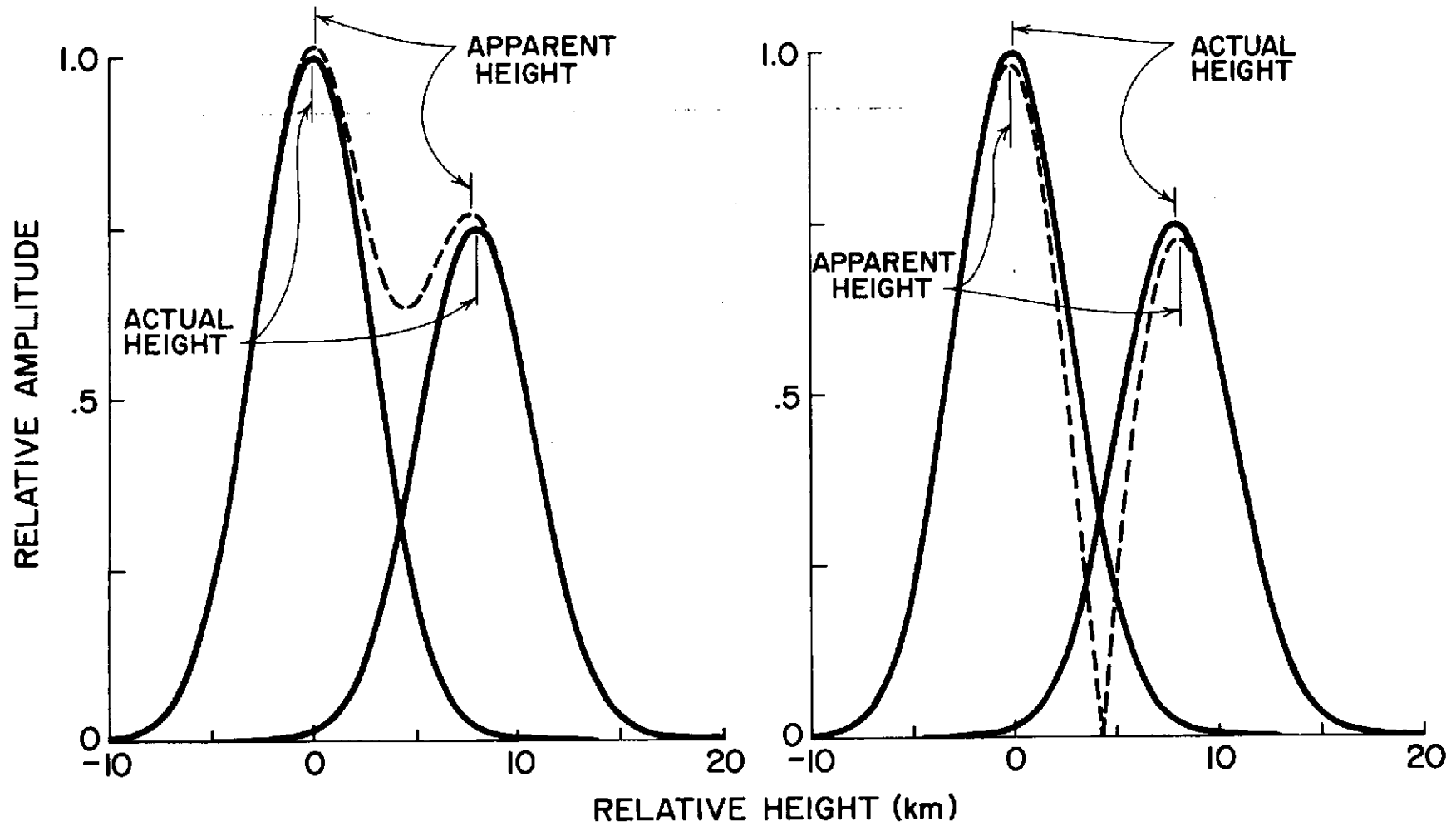
Figure 3.7 Distortion of echo shape due to two overlapping echoes.

function of the separation between the echoes for several values of relative amplitude are shown in Figure 3.8.

3.4 *Collection Programs*

A set of programs RPROC, HDATA, ECHO and PCK are used to collect and print out virtual height data on the digital ionosonde. An overall flow chart of the collection process is given in Figure 3.9.

RPROC is the main program which calls other subroutines. HDATA is a collection of subroutines which are written in assembly language because their functions cannot be done in FORTRAN. HDATA contains the following subroutines.

Subroutine GO reads console switch 0 which determines whether collection continues or restarts.

Subroutine ADGET sets up the ADC to put 530 samples in array BUF1. When the frame of data is in BUF1, an interrupt generated by the ADC starts the interrupt service routine ADINT at the highest priority level. Figure 3.10 contains a flow chart of the interrupt service routine. ADINT checks for a timing error in the ADC and starts the real-time subroutine RTS at a lower priority level. Additional operations done by RTS are not done in ADINT because the disks need to interrupt on the highest priority level but cannot while ADINT is running.

If a timing error occurs in the ADC or if the first sample in BUF1 is above a fixed level indicating a noisy frame, the data on that frame is ignored, otherwise the elements in BUF1 are added to the elements in array BUF2. After 600 frames, minus those ignored, are added together in this manner, the data in BUF2 is transferred to array CDATA and BUF2 is zeroed out to prepare for averaging the next 600 frames. The code used to add the
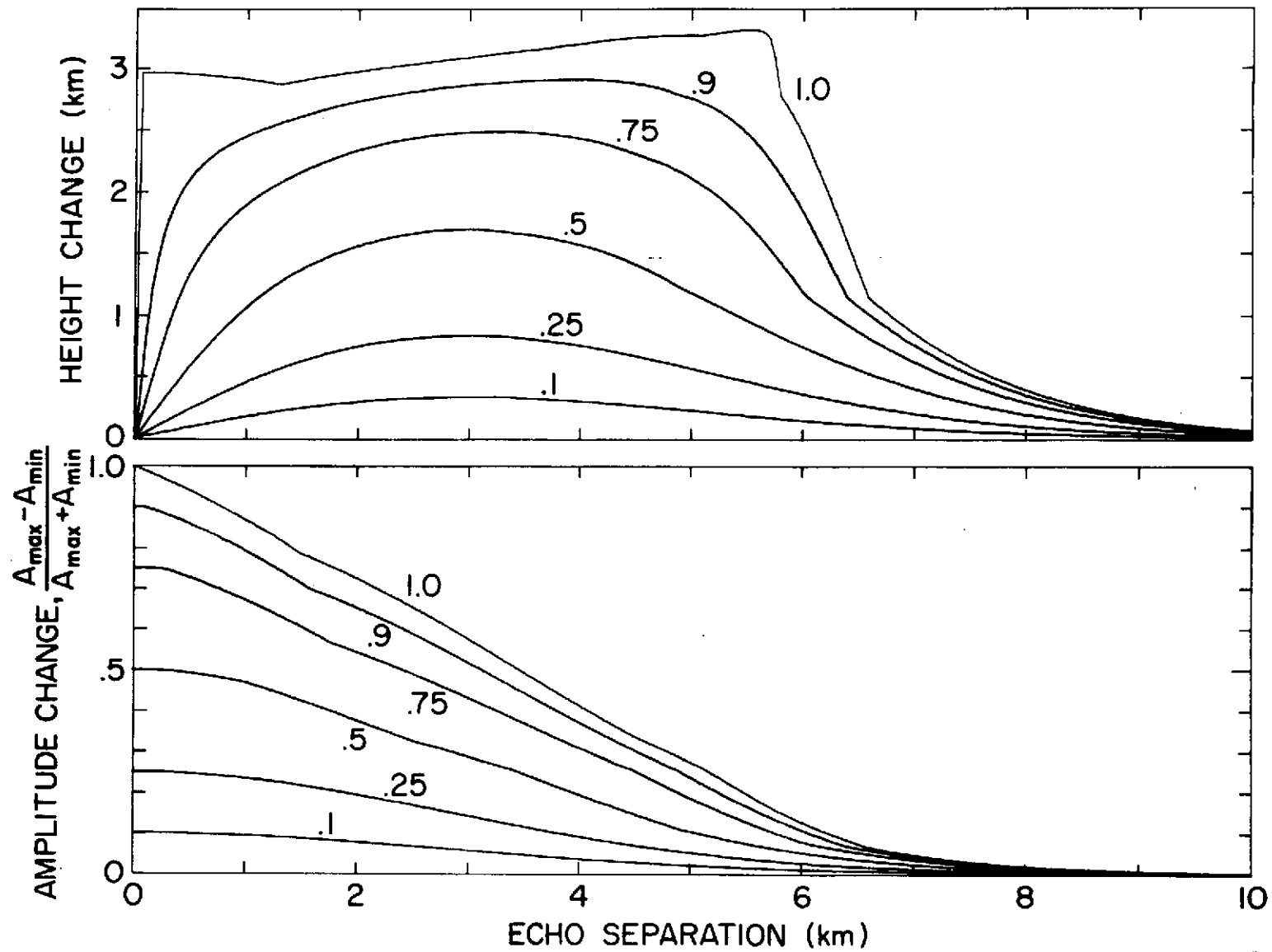
Figure 3.8 Height and amplitude change as a function of echo separation for several
values of relative amplitude.

PROGRAM RPROC | SUBROUTINE PACKAGE HDATA

START

INITIALIZE

INPUT TIME, DATE, HEIGHT XHT, FILE NAME

RDAT ← ADGET

BGDATA

START COLLECTION

GO

SWITCH

RDATA

IF ADC FAILED TO START

INTERRUPT

ADINT

RTS

PRINT TIME, FRAMES

ECHO — SEARCH NEAR XHT

PCR

PRINT ONE-HOP ECHOES

ECHO — SEARCH NEAR 2·XHT

PRINT TWO-HOP ECHOES

PUT DATA IN COMPACT FORM

WRITE DATA ON DISK
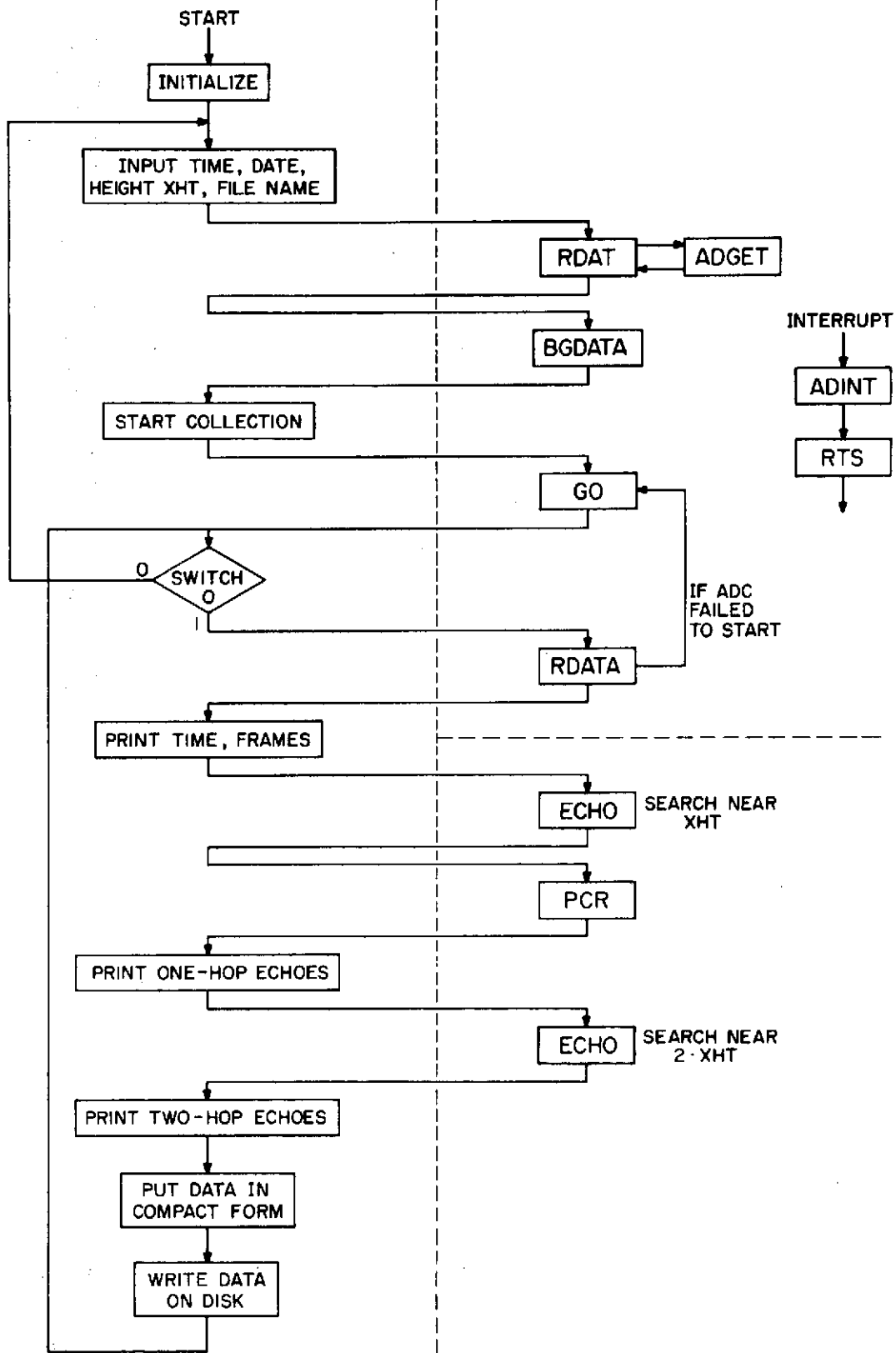
Figure 3.9 Overall flowchart of data collection and processing programs.

ADC INTERRUPT

- -

CHECK FOR PROPER
ADC OPERATION   ADINT

- -

RTS

IS FRAME
NOISY OR DID TIMING   YES
ERROR OCCUR ?

NO

ADD DATA IN
BUF1 TO BUF2

NUMBER
OF FRAMES ADDED   < 600
SO FAR ?

600

TRANSFER BUF2 TO CDATA
AND ZERO OUT BUF2

CONSOLE   I
SWITCH 0 ?   ADGET

O

EXIT   EXIT
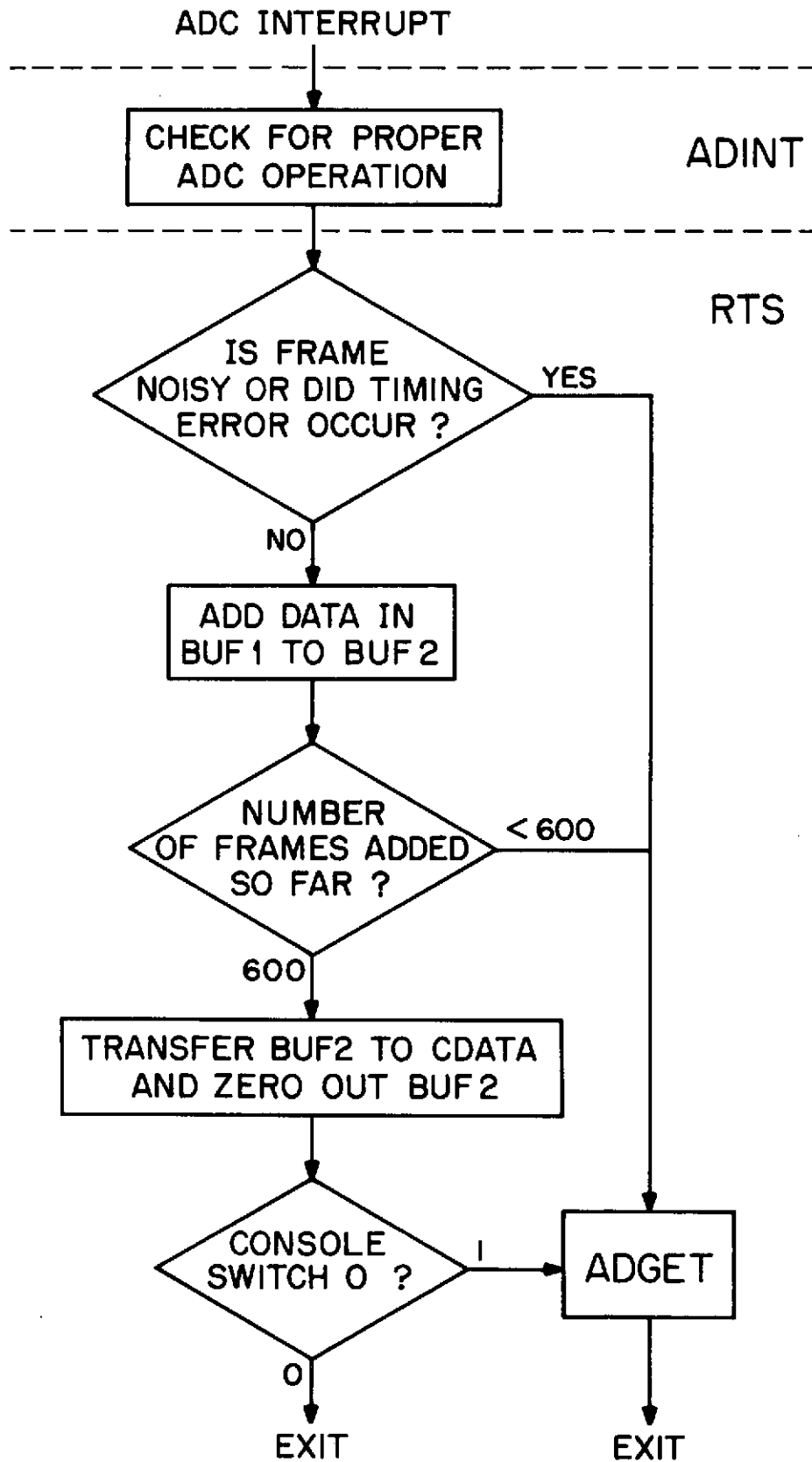
Figure 3.10 Flowchart of the interrupt service routine.

600th frame to BUF2 and transfer BUF2 to CDATA is executed in less than 11.4 msec in order to start the ADC in time to catch the next frame of data as shown in Figure 3.2. The code to add BUF1 to BUF2 is in straight line form to minimize its execution time. Since this code is executed once for each frame, minimizing its execution time provides more time for processing.

Subroutine RDATA is used to transfer control to the background until 600 frames have been added together, then data processing by RPROC continues. A flowchart of subroutine RDATA is given in Figure 3.11. Occasionally the ADC does not start when requested to by ADGET. RDATA checks for this condition and restarts the collection process if it has stopped. If the data processing by RPROC takes longer than 10 sec, the data collection and processing get out of synchronization. RDATA checks for this condition also and prints a warning if it occurs.

Subroutine RDAT sets up the inline code used to add BUF1 to BUF2, zeros out BUF2 and starts the ADC at the beginning of a collection run.

Subroutine BGDAT sets up a series of words which contain pointers to data used by the background display programs discussed in Section 3.5.

The remaining programs, PROC, ECHO and PCK, are written in FORTRAN.

Subroutine ECHO searches a copy of part of CDATA for echoes. A flowchart of ECHO is given in Figure 3.12. ECHO searches a region from 75 km below to 75 km above a specified height. The region searched is wide enough to include the ordinary and extraordinary echoes under most conditions. An echo is defined as 4 or more continuous samples above a threshold and noise is defined as all samples below the threshold. A threshold is set initially and a new threshold is computed for each 10 sec of data. Because of the offset in the amplifiers between the ionosonde and the ADC,
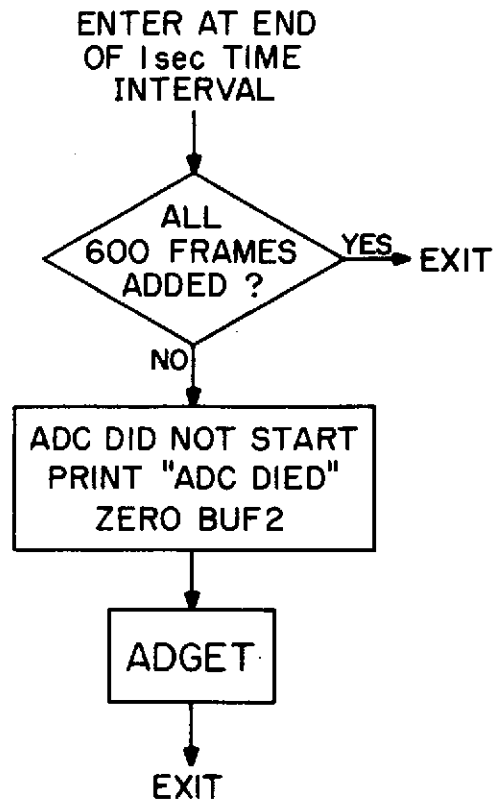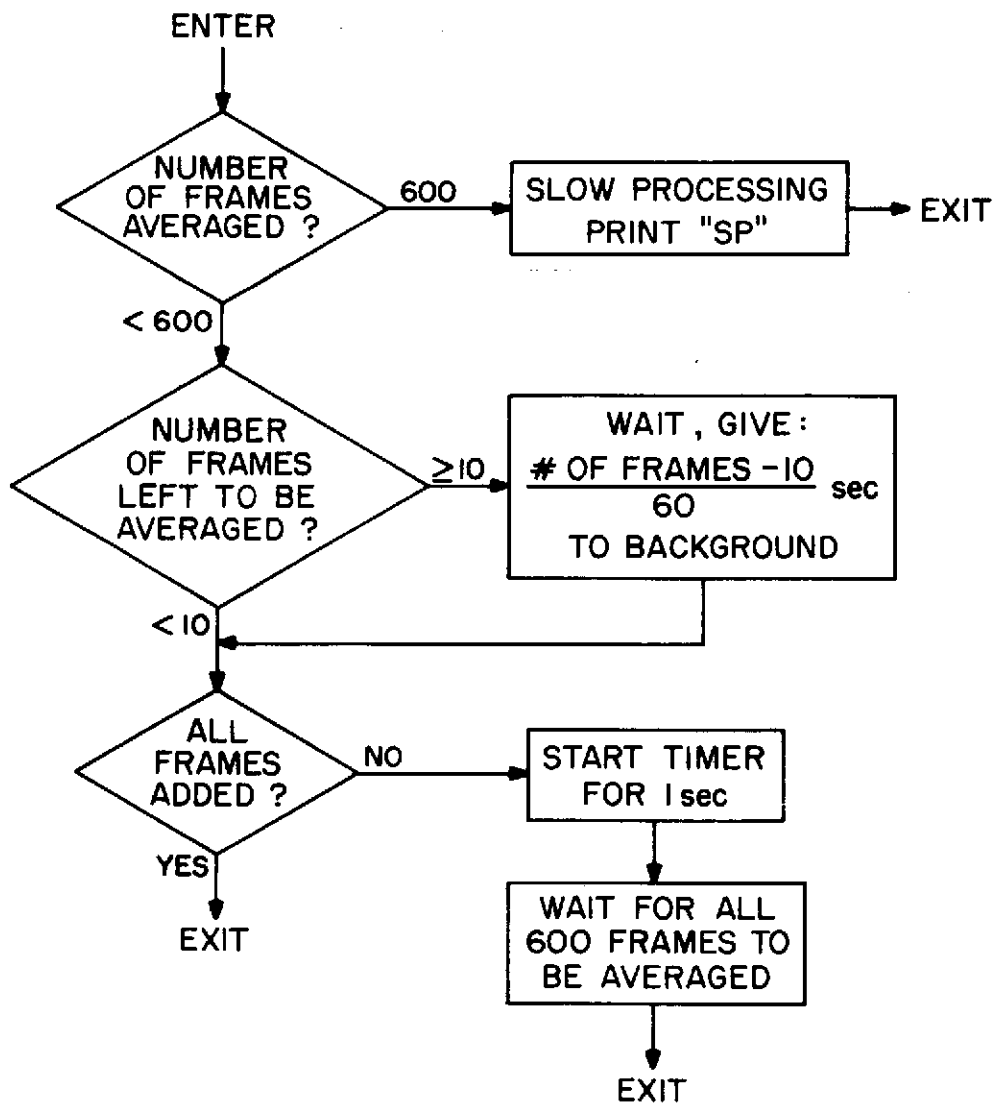
Figure 3.11   Flowchart of subroutine RDATA.

ENTER

CALCULATE
AVERAGE NOISE

NUMBER
OF NOISE
SAMPLES ?

≤50 → RESET THRESHOLD
AT .25 V

>50

CALCULATE
AVERAGE NOISE

CALCULATE
NEW THRESHOLD

SEARCH
FOR ECHO

END OF
SEARCH
RANGE
→ EXIT

NUMBER
OF NOISE
SAMPLES ?

>50

<50

EXIT

ECHO FOUND

REMEMBER
STARTING LOCATION
OF ECHO

RECORD HEIGHT
AND AMPLITUDE

SUBTRACT ASSUMED
ECHO SHAPE

START SEARCH BELOW
START OF LAST ECHO
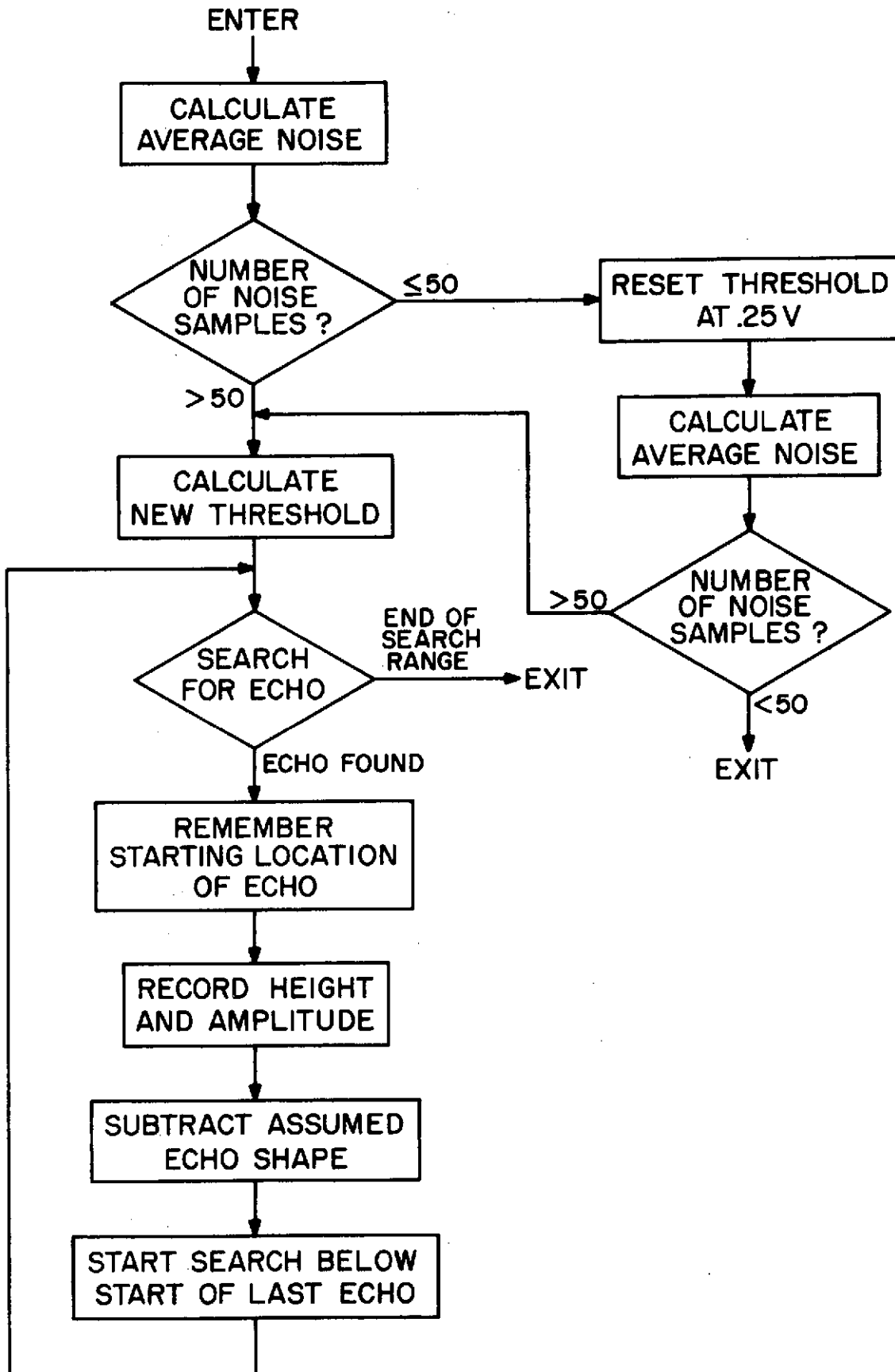
Figure 3.12   Flowchart of subroutine ECHO.

the true zero level is not known. The sample with the smallest value is assumed to be the zero level. The average of the noise samples is calculated and a new threshold is set at 5 times the average noise level. The threshold adjusts to changing noise and signal conditions. If the noise level suddenly increases above the threshold between one 10 sec period and the next, when the average noise is calculated, no samples will be below the threshold and an improper noise level is obtained. If too few samples are below the threshold, the threshold is set at a high level and another attempt is made to determine the noise and compute a new threshold.

Once an echo has been found, a parabola is fitted and the amplitude and height are recorded. Then a modified parabola shape shown in Figure 3.13 is subtracted from the actual echo shape and the search starts again below the location where the last echo started. This allows echoes which are close together to be resolved.

When RPROC is started, an initial height XHT is typed in. ECHO searches for echoes near this height and again at twice this height for second reflections. RPROC prints out data on 3 echoes at the lower height and 2 echoes at the higher height. The data are also put in a compact form and stored on the disk. After the echoes near XHT are located, subroutine PCK is called.

Subroutine PCK looks for an echo within 20 km of XHT. If there is at least one, the height of the closest echo to XHT is used as the new value of XHT. This is done so that ECHO is always searching a region centered on the location of the last echo.

3.5 *Display Programs*

In February 1973, a Hazeltine 2000 cathode-ray terminal replaced the model 33 teletype as the background control device. The Hazeltine terminal

TWO ECHOES OVERLAPPED

ASSUMED SHAPE OF LARGER ECHO

RESOLVED SHAPE OF SMALLER ECHO

RELATIVE AMPLITUDE

PARABOLA FIT

INVERTED PARABOLA

RELATIVE HEIGHT (km)
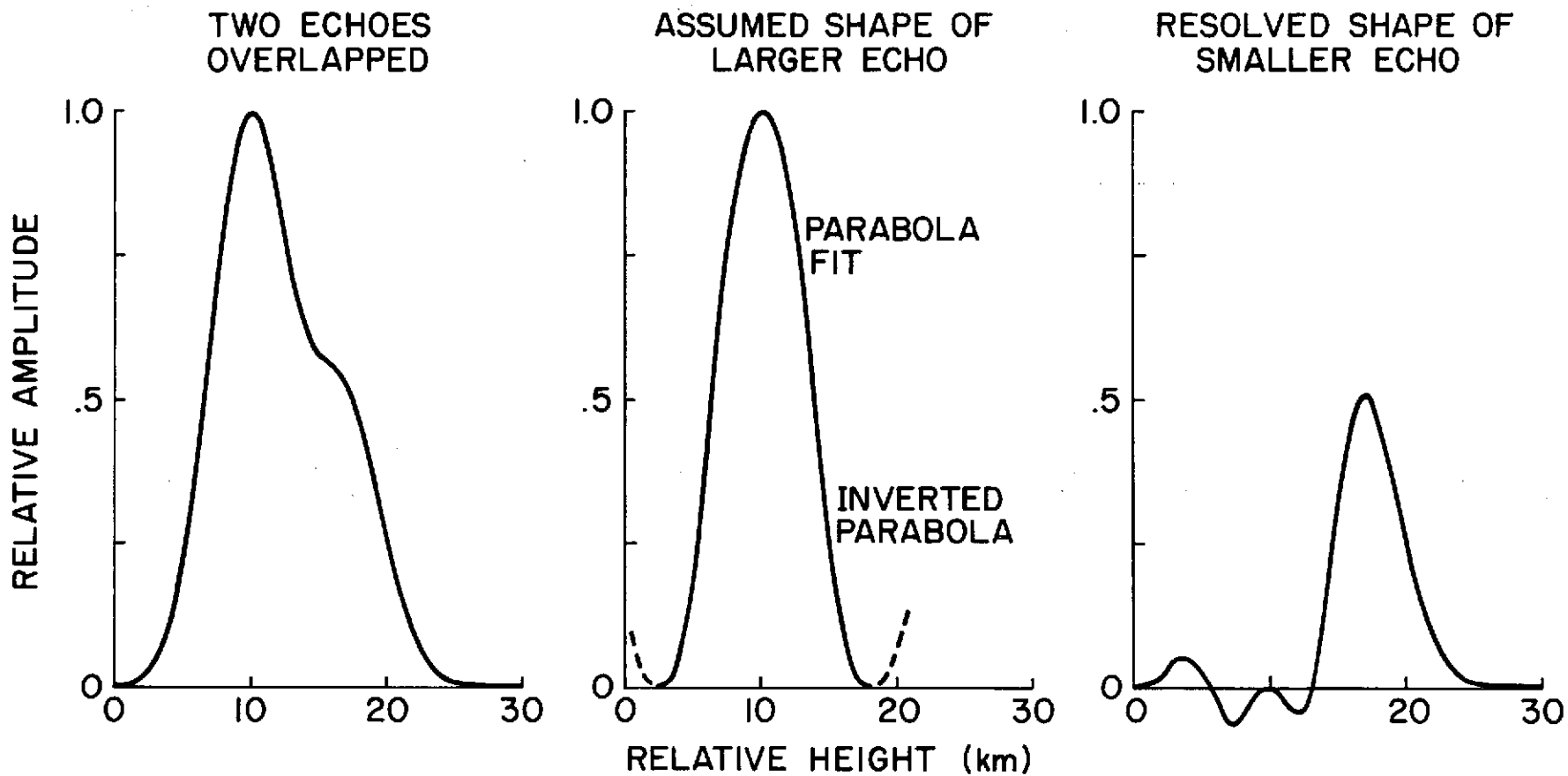
Figure 3.13   Subtract assumed echo shape from received echo to resolve second echo.

operates on a serial current loop interface and is compatible with the interface for a teletype. The Hazeltine terminal operates at a maximum speed of 9600 baud or 873 characters per second as compared to the teletype which operates at 110 baud or 10 characters per second. The substitution required only minor modifications to the PDP-15 hardware to use the full speed of the Hazeltine terminal.

The background clock board M452 is shown in Figure 3.14. The oscillator generates an 800 Hz signal which is divided to provide 110 Hz. Capacitor C5 is decreased to .01 μf and resistor R3 is adjusted to give 76800 Hz for the required baud rate of 9600. The TTY connector W078A does not operate at this rate because of a 1 μf filter capacitor. After changing this capacitor to .022 μf the Hazeltine terminal worked properly.

The Hazeltine terminal writes 5 full 74 character lines per second. The entire screen of 26 lines can be filled in approximately 5 sec. The Hazeltine terminal is used to provide real-time information on the operation of the data collection process and on the data being collected. Figure 3.15 contains a flowchart of the background display programs BGRAPH, BDATA, PARA and GRAPH. Depending on the setting of console switch 17, either a graph of 11 minutes of virtual height data or a graph of the echo shape is produced. An example of the virtual height graph is shown in Figure 3.16. A starting time in minutes is typed in and then the height of the echo picked by PCK is displayed. This graph provides a quick method of determining what the reflecting layer is doing and whether collection should continue or not.

An example of the echo-shape graph is given in Figure 3.17. The height and time for the one-hop echo in the center of the screen is given

Figure 3.14   Schematic diagram of background clock board M452.
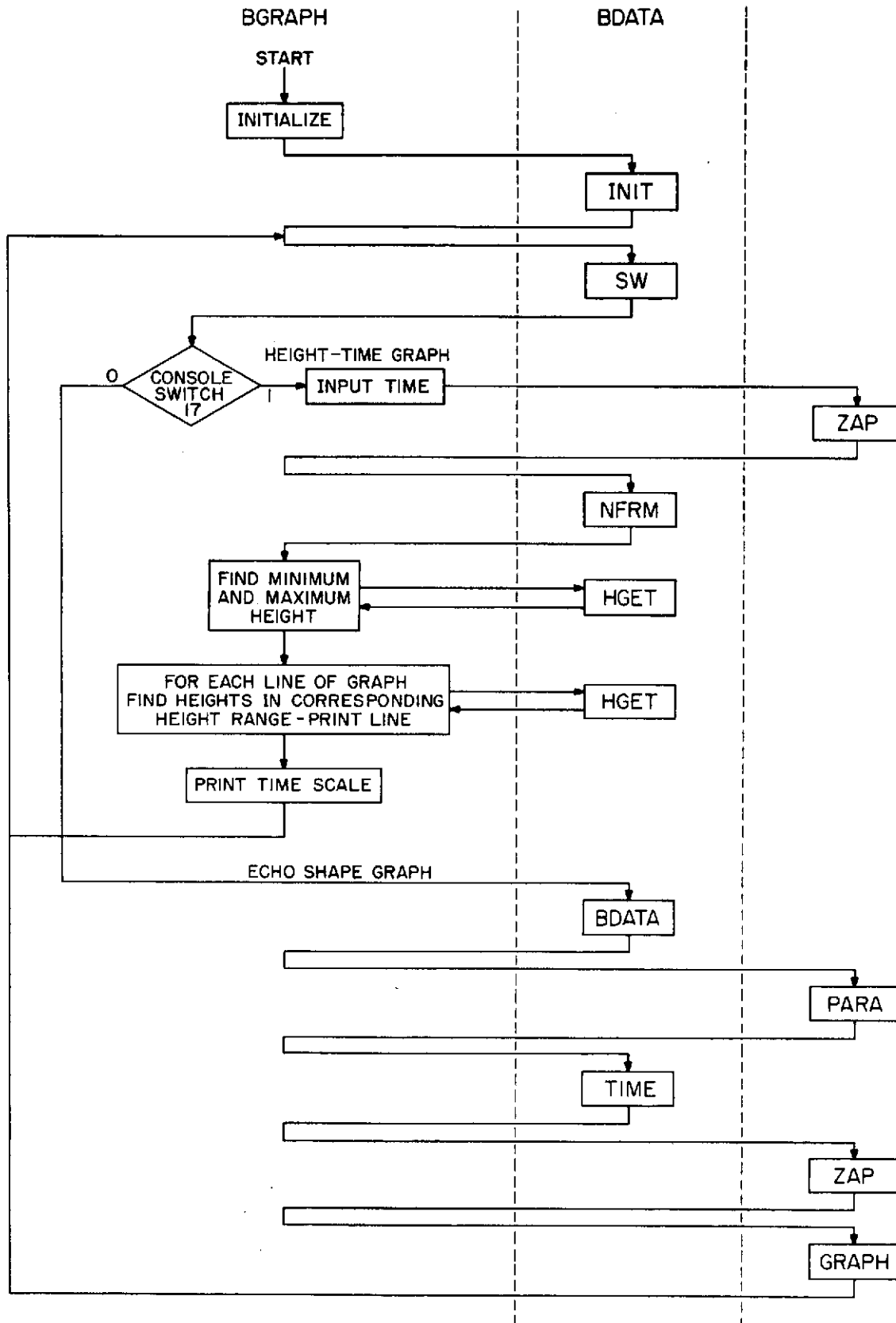
Figure 3.15   Flowchart of the background display programs.

VIRTUAL HEIGHT (km)

```
50
340.3                                    ***
340.2                                   *   *
340.1                                 *    **
340.0                               *  *      *
339.9                             *            
339.8                                      *   
339.7                          *           *   
339.6                                          
339.5                        *                 
339.4                                  *       
339.3                      *           *       
339.2                    *                     
339.1                                 *        
339.0                                *         
338.9            **                            
338.8                                          
338.7          *                   **          
338.6         *                                
338.5                           *         *  * 
338.4        *              ** **       *       
338.3      **            *            *        
338.2    **                        **          
338.1*                                          
338.1  *     *                                 
338.0  * *                                     
```

```
   50    51    52    53    54    55    56    57    58    59    60    61
```

TIME (min)
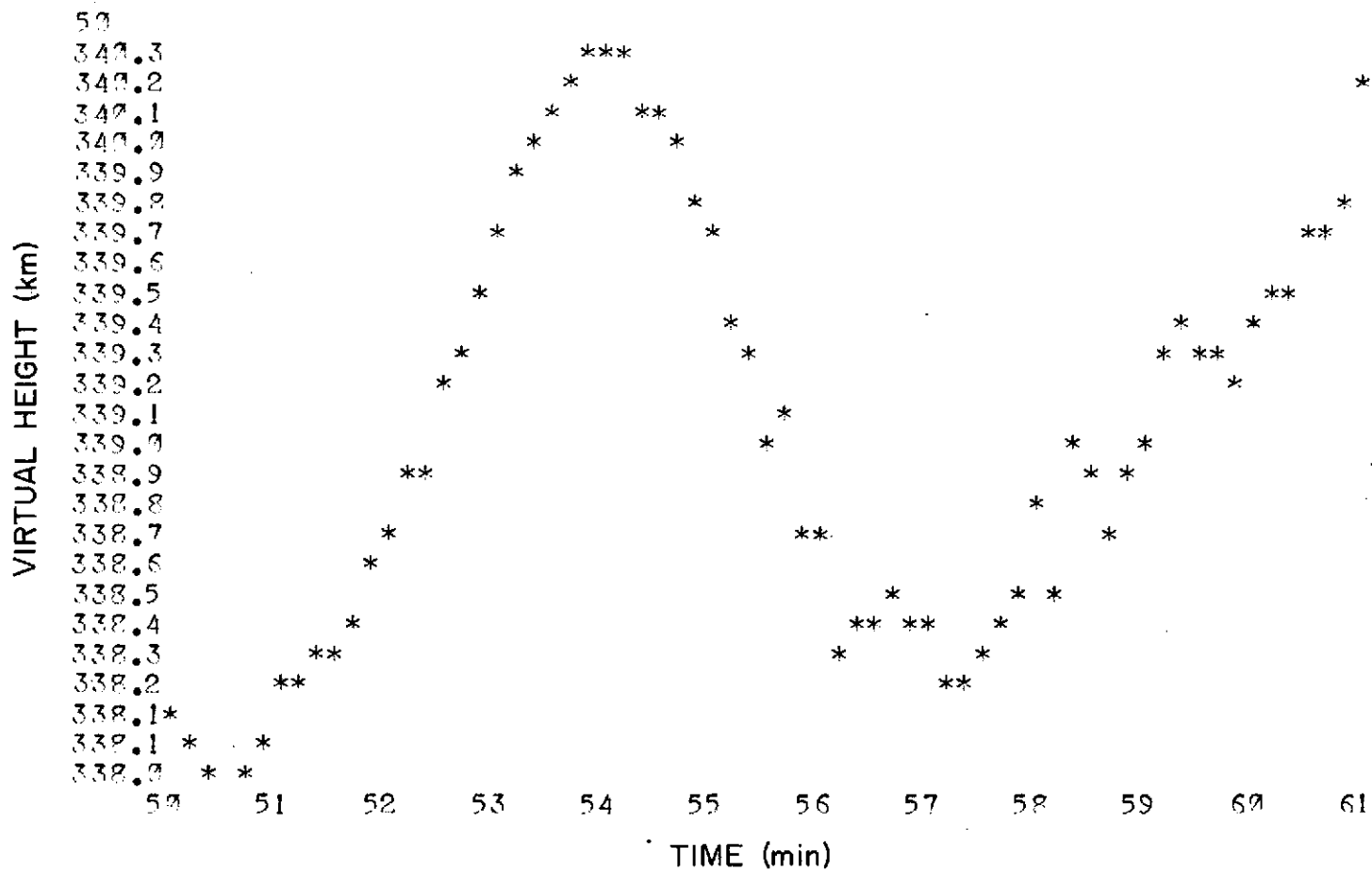
Figure 3.16 Example of height versus time graph.

```
H(KT)   AMP  O--------I--------I--------I--------I    ):50   I 211.258 I
229.5    28  I                  #O    T
228.0    29  I                  *
226.5    31  I                  #O
225.0    33  I                  #  O
223.5    34  I                  #    O
222.0    35  I                  #+   O
220.5    38  I                  #      +O
219.0    46  I                  #          O+
217.5    61  I                 #              O +
216.0    73  I                #                  O    +
214.5    95  I                #                     O    +
213.0   109  I                #                        O+
211.5   115  I                #                           *
210.0   112  I                #                        O+
208.5   101  I               #                      O   +
207.0    88  I              #                    O   +
205.5    77  I             #                *
204.0    69  I             #           +       O
202.5    62  I             #        +       J
201.0    59  I             #   +         O
199.5    62  I            #            O
198.0    66  I            #          O
196.5    70  I            #           O
195.0    77  I            #             O
193.5    87  I            #                 O
```
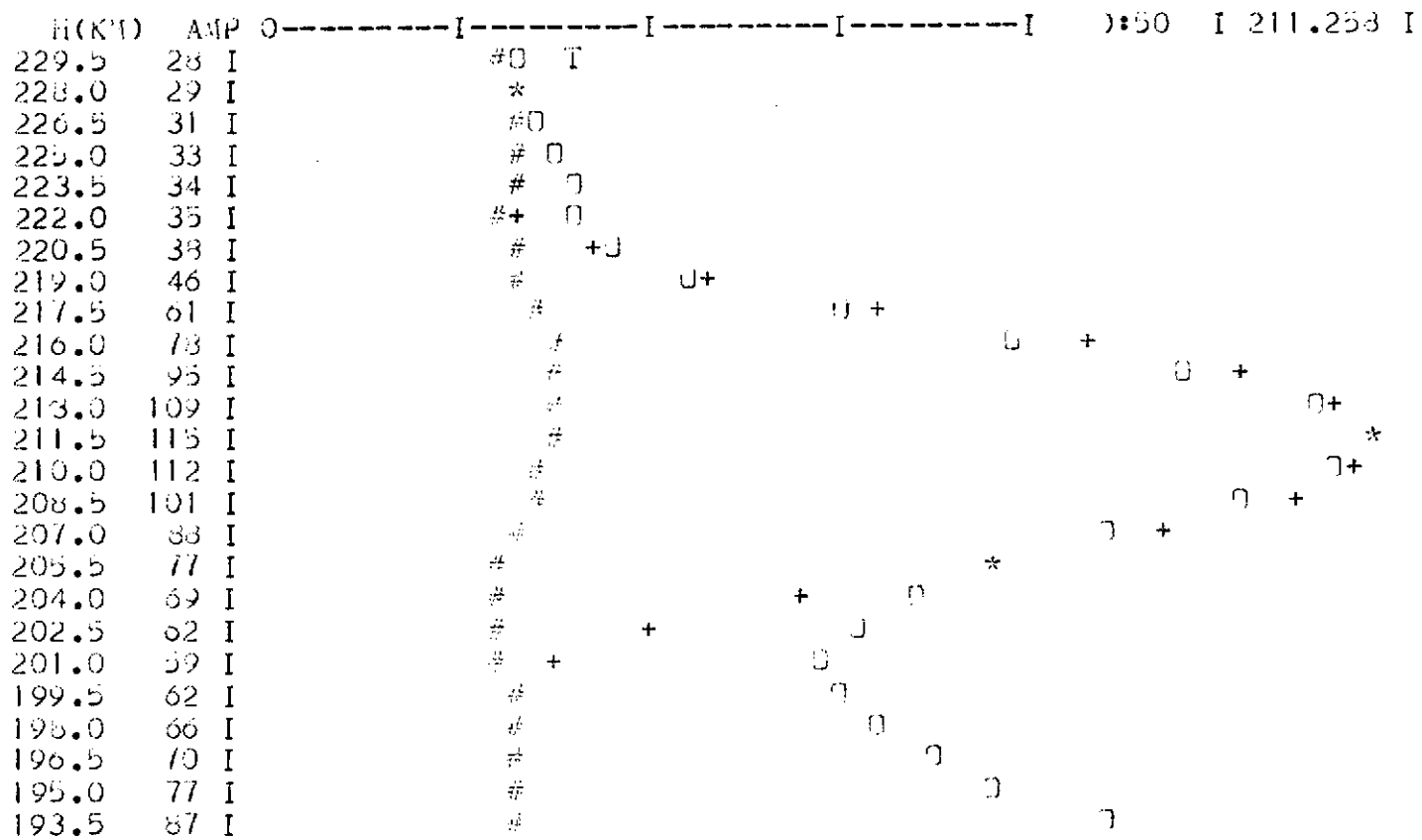
Figure 3.17   Example of echo shape graph.

50

at the top on the graph. The O's represent the one-hop echo, the +'s represent a parabola fit to the one-hop echo and the #'s represent the two-hop echo. The left-hand side of the screen has the height and amplitude of the averaged data near the one-hop echo. If any of the symbols overlap, an * is printed. The one-hop threshold is indicated by a T on the third line of the graph. This graph is useful in determining whether the algorithms in ECHO are functioning properly. It is also useful to check that ECHO is detecting all the echoes and not detecting noise as echoes. In conditions of high noise and low-signal strength, echoes can be seen on the graph that cannot be seen on an oscilloscope monitoring the video signal from the ionosonde.

3.6 *Ionosonde Frequency Counter*

A frequency counter was designed and built to measure the ionosonde transmitter frequency. The ionosonde is licensed to operate only on the ten frequency bands listed in Table 3.1. The frequency counter keeps the operation of the ionosonde legal by turning the transmitter off while the ionosonde is sweeping through frequencies not listed in Table 3.1. A digital display of the ionosonde frequency is provided in the computer room and, with remote ionosonde controls, the ionosonde can be operated from the computer room. With the digital input port to the PDP-15, the computer reads the ionosonde frequency and by using the digital output port, the computer can control the ionosonde frequency.

The ionosonde frequency range, 250 KHz to 20.25 MHz, is divided into four bands, 250 kHz to 750 kHz, 750 kHz to 2.25 MHz, 2.25 MHz to 6.75 MHz and 6.75 MHz to 20.25 MHz, called Band I, II, III and IV respectively. The transmitter frequency is formed in a mixer which subtracts a 4 MHz

Table 3.1 Frequency bands on which the
ionosonde is licensed to operate

420	-	1800 kHz
2000	-	2170 kHz
2194	-	2495 kHz
2505	-	3500 kHz
4000	-	4995 kHz
5005	-	7000 kHz
7300	-	8362 kHz
8366	-	9995 kHz
10005	-	14000 kHz
14350	-	14990 kHz
15010	-	19990 kHz

signal on Bands I, II and IV or 8 MHz on Band III from a variable fre-
quency oscillator (VFO) signal. The mixer operates in a pulsed mode so
the transmitter frequency is not continuously available and cannot be
counted directly. The counter measures the VFO frequency minus 4 or 8 MHz.
This is done by presetting the counter to - 4 MHZ (- 8 MHz on Band III)
before counting starts.

The circuit diagram for the frequency counter is given in Figures 3.18,
3.19 and 3.20. A 1 MHz crystal oscillator is divided by 400 to provide the
time base. The VFO signal is converted to TTL levels and counted for a
period of 200 μsec which provides a frequency resolution of 5 kHz. The
counter is 12 bits long, giving a maximum frequency count of 20.48 MHz.
The timing diagram in Figure 3.21 shows the relation between the preset
period and the counting period. During the preset period the counter is
preset to 6340_8 (4700_8 on Band III) and the SRFF formed by two cross-coupled
NANDs is set.

If the VFO input signal is not present, during the clear period the
counter is set to 0. If this were not done, when the ionosonde is off, the
counter would indicate 6340_8. When the computer reads a frequency of 6340_8,
it cannot tell whether the ionosonde is operating at 16.48 MHz or turned
off. A reading of 0 is unambiguous. If a VFO signal is present, the
counter will count during the count period, the SRFF is reset and the
counter is not cleared during the clear period. At the end of the count
period, the counter is allowed to settle for 50 μsec, then the Data-Ready
signal is true for 50 μsec. During this time, the count is transferred to
12 latches. The data in the latches are read by the computer through the
digital input port.
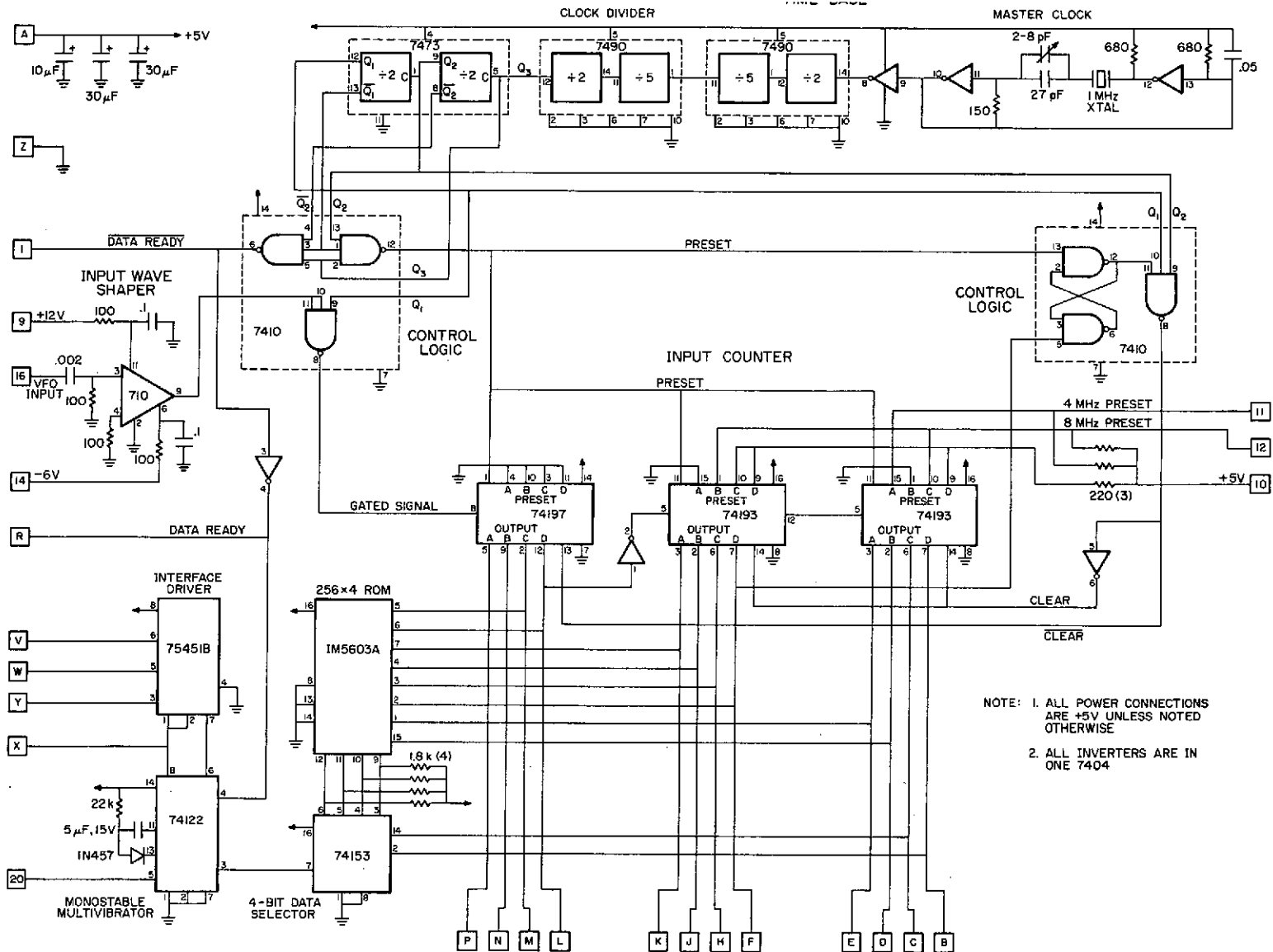
Figure 3.18 Schematic of ionosonde frequency counter time base, counter and frequency deleter board.
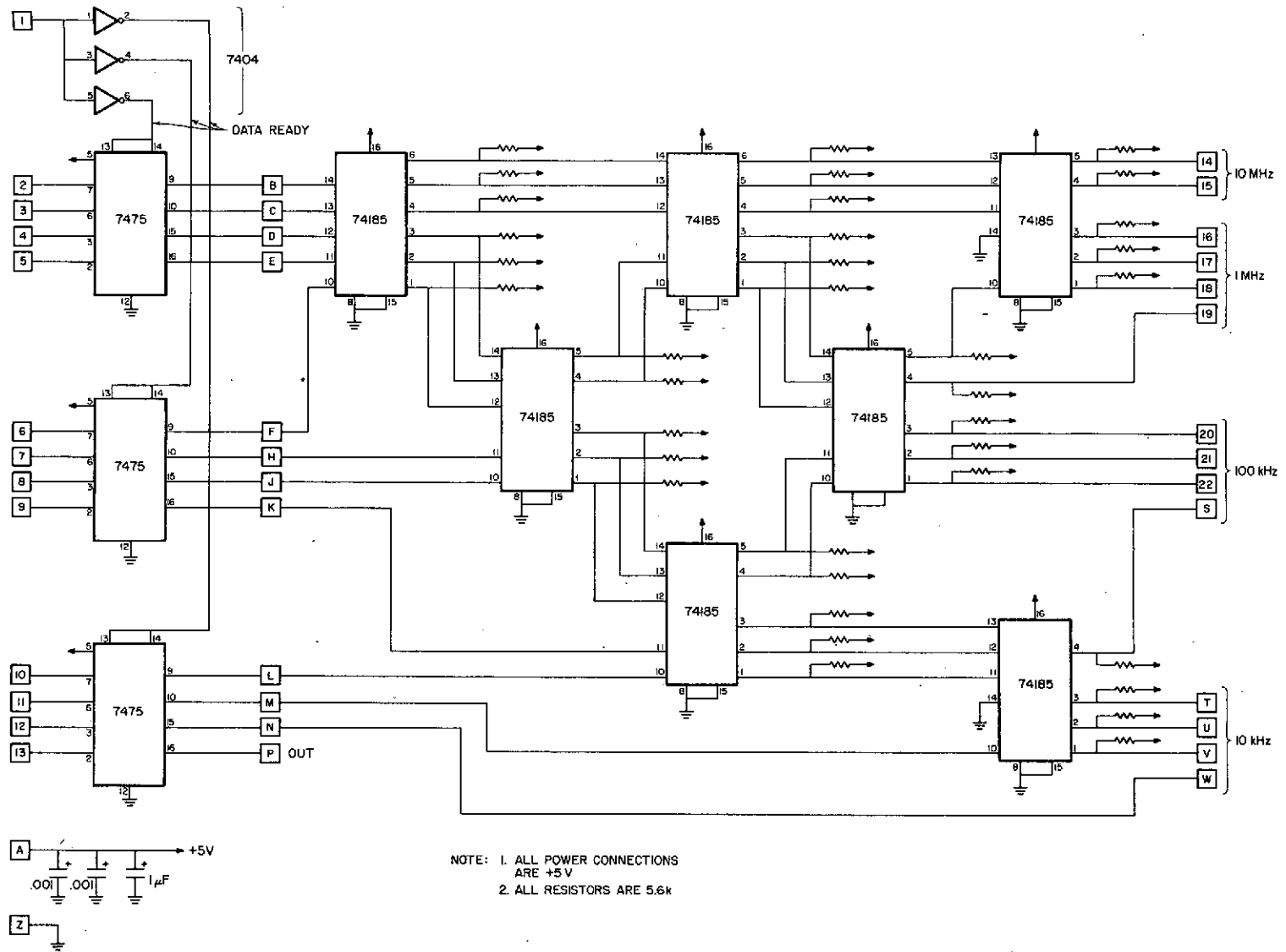
Figure 3.19 Schematic of ionosonde frequency counter data latch and binary to BCD converter board.
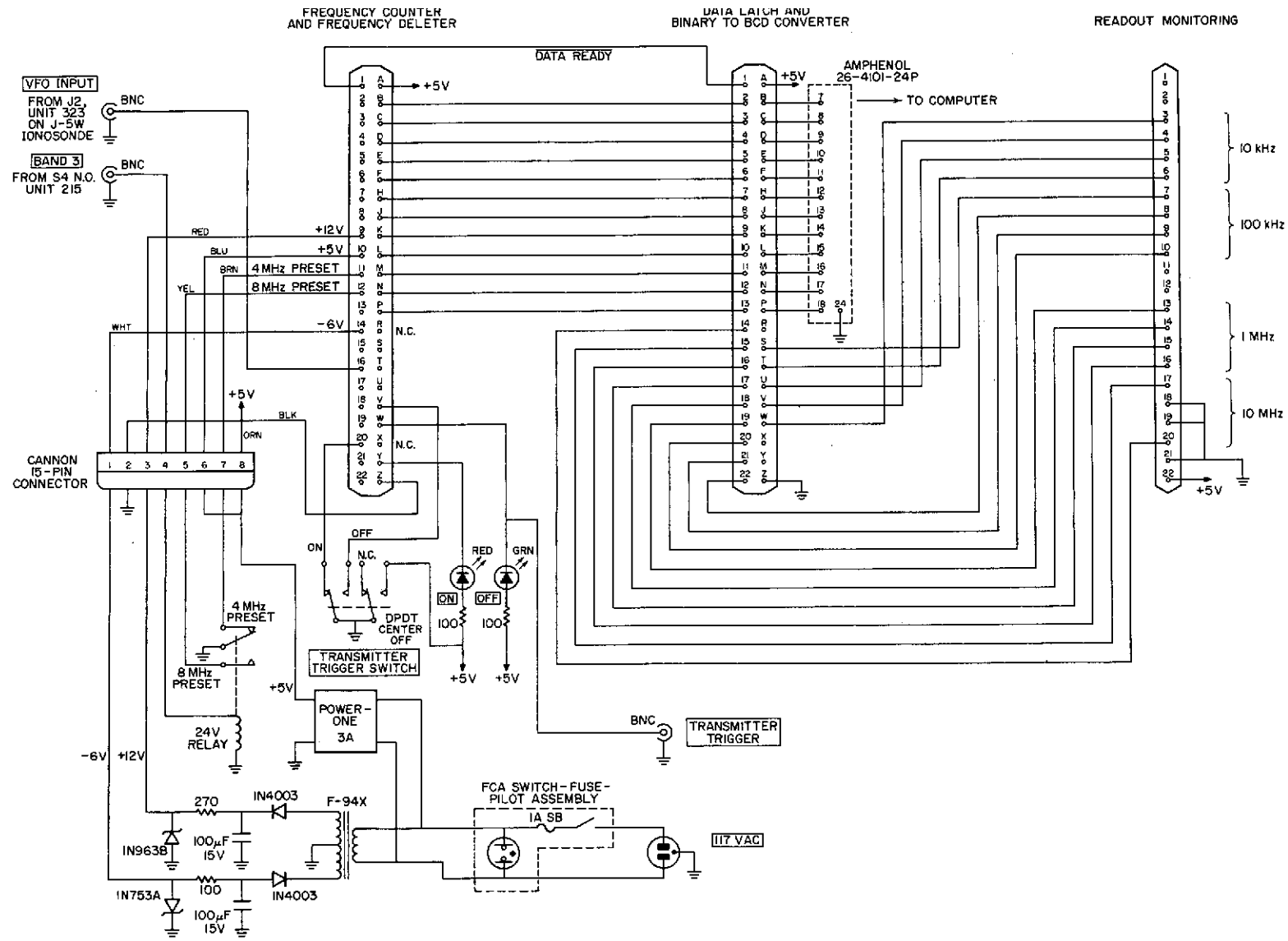
Figure 3.20 Schematic of ionosonde frequency counter power supply and board interconnections.
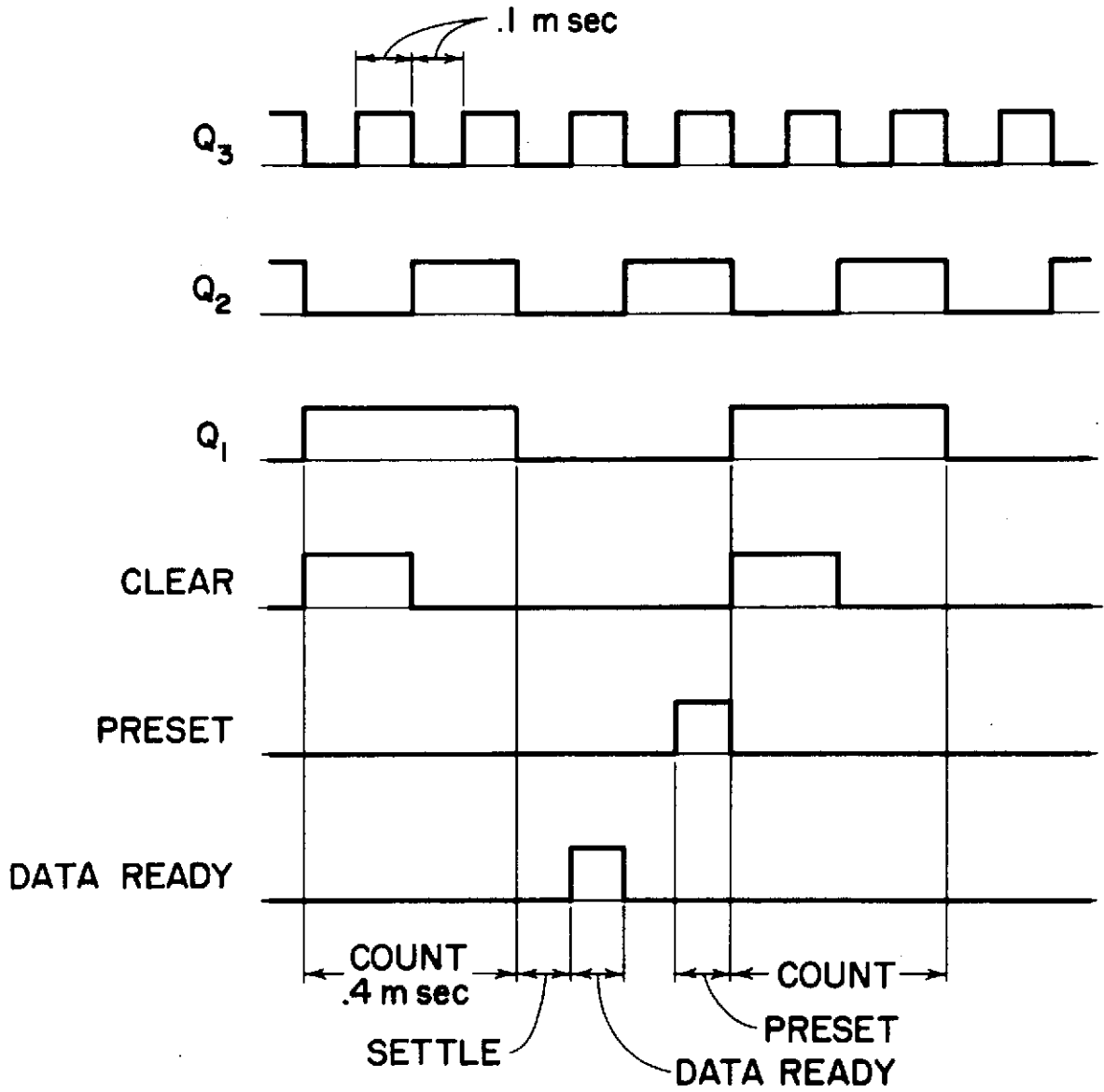
Figure 3.21 Timing diagram for the ionosonde frequency counter.

The data from the latches are converted to 4 decades of BCD using 7 code converter read-only-memories (ROMs). The BCD data drive a frequency display in the computer room, indicating the ionosonde frequency in 10's of kHz.

The 10 most significant bits of the counter are used to determine if the ionosonde frequency is in an allowed frequency band or not. The frequency range from 0 to 20.48 MHz is covered in 1024 segments, each 20 kHz wide. A 1024 bit ROM has one bit for each segment. A "1" is programmed in the ROM for segments that are in prohibited frequency bands and a "0" is in the other bits.

The 1024 bit ROM used in the counter is organized as 256 four-bit words. A 4-bit data selector effectively converts the ROM into a 1024 by 1 organization. If the output of the data selector is 1 during the Data-Ready period, a monostable multivibrator is triggered and puts out a 33 msec pulse used to turn off the ionosonde transmitter. If the ionosonde is in a restricted frequency, the monostable multivibrator is retriggered every 400 μsec and stays set, keeping the ionosonde transmitter off. If the ionosonde frequency is on the edge of an allowed band, because of the uncertainty of $\pm$ 1 in the count, the monostable multivibrator is not retriggered every 400 μsec but once every several 400 μsec periods. As long as the monostable multivibrator is triggered at least once every 33 msec, it stays on and keeps the transmitter off.

The monostable multivibrator Q and $\overline{Q}$ outputs drive 2 high current interface drivers to light LED's, indicating whether the transmitter is on or off and also drive a line which turns the ionosonde transmitter on and off. A switch is provided to override the counter and keep the ionosonde constantly on or off.

4. EXPERIMENTAL RESULTS

This chapter presents an analysis of some of the data collected on the digital ionosonde by methods described in Chapter 2.

The digital ionosonde was operated for about two hours starting between 1300 and 1500 CST several days a week for five months. A frequency of 4.1 MHz was normally used because there is little interference at that frequency and good reflections from the F region are obtained. The extraordinary reflection cannot be seen at this frequency and several runs were made at a higher frequency where both reflections were present.

On each run, the virtual height varies in a quasiperiodic manner with a period of 10 min or more and a height change of more than 10 km and in some cases as much as 50 km. Due to the increasing height of the F region in the afternoon, the fluctuations are superposed on a linear increase of virtual height. The amplitude generally fades with a period of a few seconds because of very small irregularities in the ionosphere. This fading is nearly all removed by the present system which averages over a 10 sec period. Their residual effect is to produce small random height and amplitude variations. Some of the random variation in height is due to errors in the height algorithm described in sections 3.2 and 3.3. Large periodic increases in amplitude occur in some runs with periods of 15 to 30 min due to focusing. Focusing is observed on 75% of the data runs and several of these are described in section 4.3.

The multiple reflection points described in section 2.4 are shown in 33% of the runs. Section 4.4 shows examples of these.

Data taken at frequencies higher than 4.1 MHz, showing both ordinary and extraordinary echoes are described in section 4.5.

Section 4.6 describes some experimental data with features that cannot be explained with the present reflector model described in Chapter 2.

In the next section, a sinusoidal reflector is used to illustrate the effects of the length of the reflector on focusing and multipath.

Section 4.2 describes a data run in which two echoes are close enough to interfere with each other as described in section 3.3.

4.1 *Effects of Reflector Horizontal Wavelength on Focusing and Multipath*

Focusing is caused by the reflector acting as a curved mirror as described in section 2.3. Multipath is when more than one echo is observed from one reflector simultaneously as described in Section 2.4. To illustrate the effects of the reflector wavelength on the occurrence of focusing and multipath, the virtual height and amplitude for sinusoidal reflectors of various wavelengths are calculated The reflectors have the form $H = 250 - 10\cos(2\pi x/P)$ km. The average height and amplitude of the reflectors are typical values for a frequency of 4.1 MHz. P is the wavelength of the reflector. The amplitude and virtual height of an echo from the reflector are calculated for one cycle of the reflector, $0 < x < P$.

The horizontal wavelength of the reflector in Figure 4.1 is 500 km. Only a small amount of focusing occurs in the two-hop amplitude and almost none in the one-hop amplitude. The virtual height of the one-hop comes to a narrower peak than the reflector and the two-hop height is more sharply peaked than the one-hop height. For longer wavelengths, there is less focusing and the virtual height is closer to the reflector height. Near the center of the reflector, the two-hop echo experiences more focusing than the one-hop echo for two reasons. First, the two-hop echo is reflected and focused twice, effectively doubling the depth of the reflector
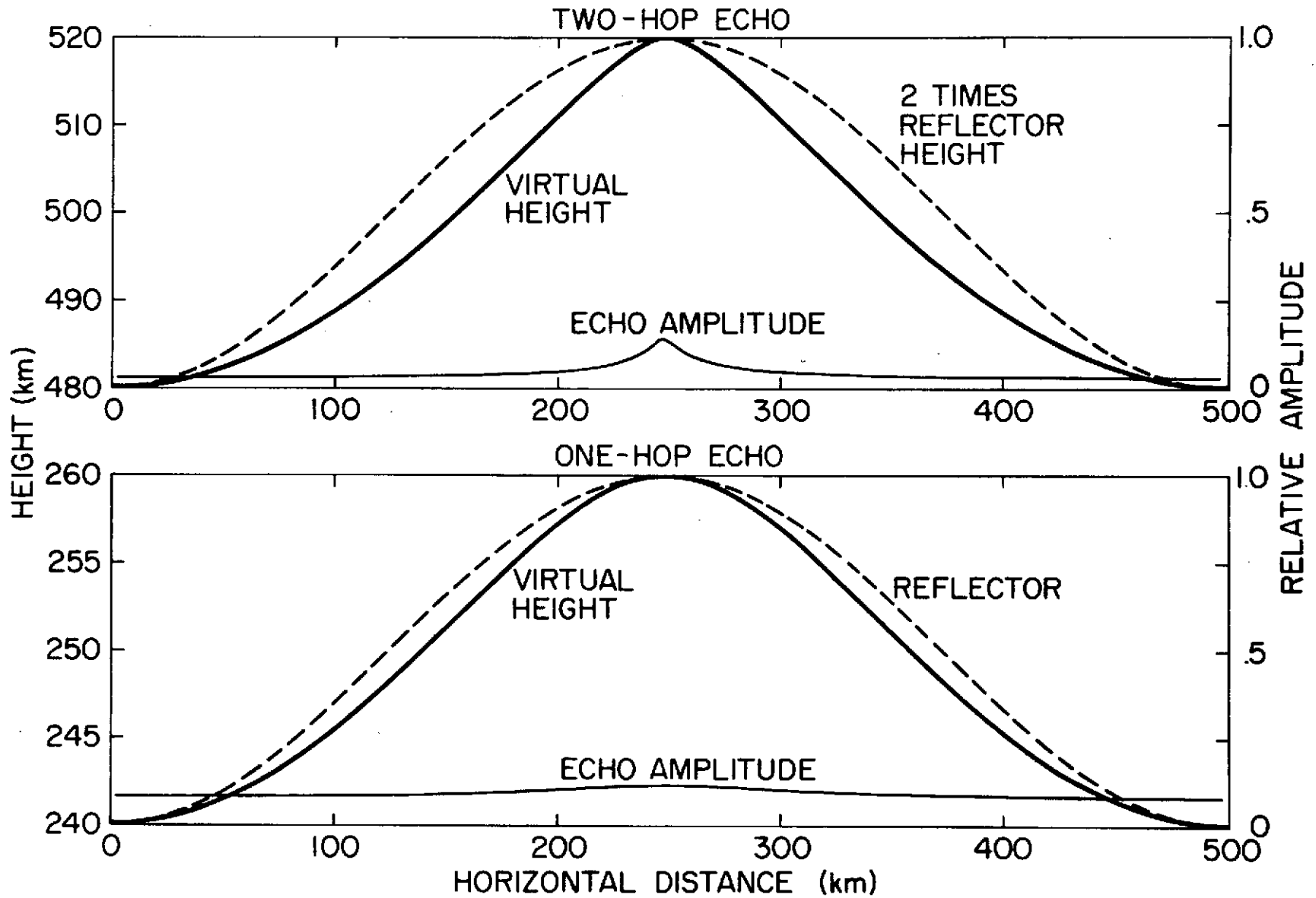
Figure 4.1 One- and two-hop virtual height and echo amplitude for a sinusoidal reflector with P = 500 km.

for the two-hop echo. Secondly, the two-hop echo has to travel twice as far making the apparent reflector for the two-hop echo twice as high. For long wavelengths, the transmitter and receiver are closer to the center of curvature for the apparent two-hop reflector than the one-hop reflector.

As the reflector wavelength decreases to 450 km, the two-hop height comes to a sharp peak and the amplitude shows a large enhancement as shown in Figure 4.2. The one-hop height and amplitude are not much different from the height and amplitude in Figure 4.1.

For a wavelength of 400 km, as shown in Figure 4.3, three reflection points appear in the two-hop virtual height. The one-hop height shows increased distortion and the amplitude shows some focusing.

For a wavelength of 300 km, as shown in Figure 4.4, three reflection points appear on the one-hop virtual height.

Except for the cases of multipath, the maximum and minimum one-hop virtual height correspond to the maximum and minimum height of the reflector.

4.2 *Interference Between Two Echoes with Nearly the Same Virtual Height*

The interference between two echoes is described theoretically in Section 3.3. This section describes an example of this phenomenon.

Figure 4.5 is a graph of 100 min of data taken from 1931 to 2111 CST on May 4, 1973 at 3.1 MHz with almost four cycles of a disturbance with a period of 26 min. The two-hop echo shows four segments of focusing but at other times the two-hop amplitude is too small to be detected. For the first 50 min, the one-hop height has a random fluctuation of about 160 m superimposed on the slower periodic variation. This error is within the accuracy range of the echo detection algorithm as calculated in Section 3.3.
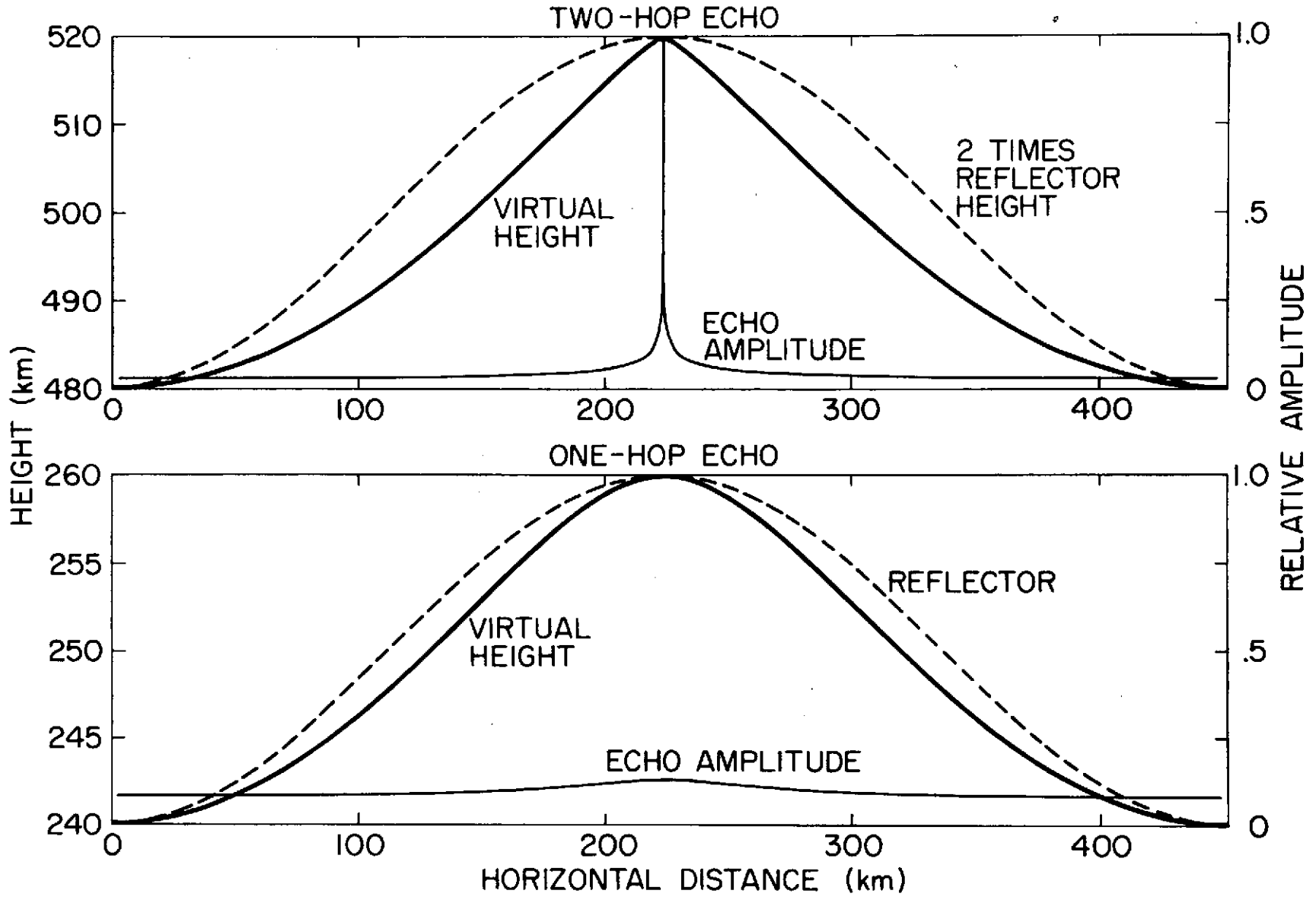
Figure 4.2 One- and two-hop virtual height and amplitude for a sinusoidal reflector with P = 450 km.
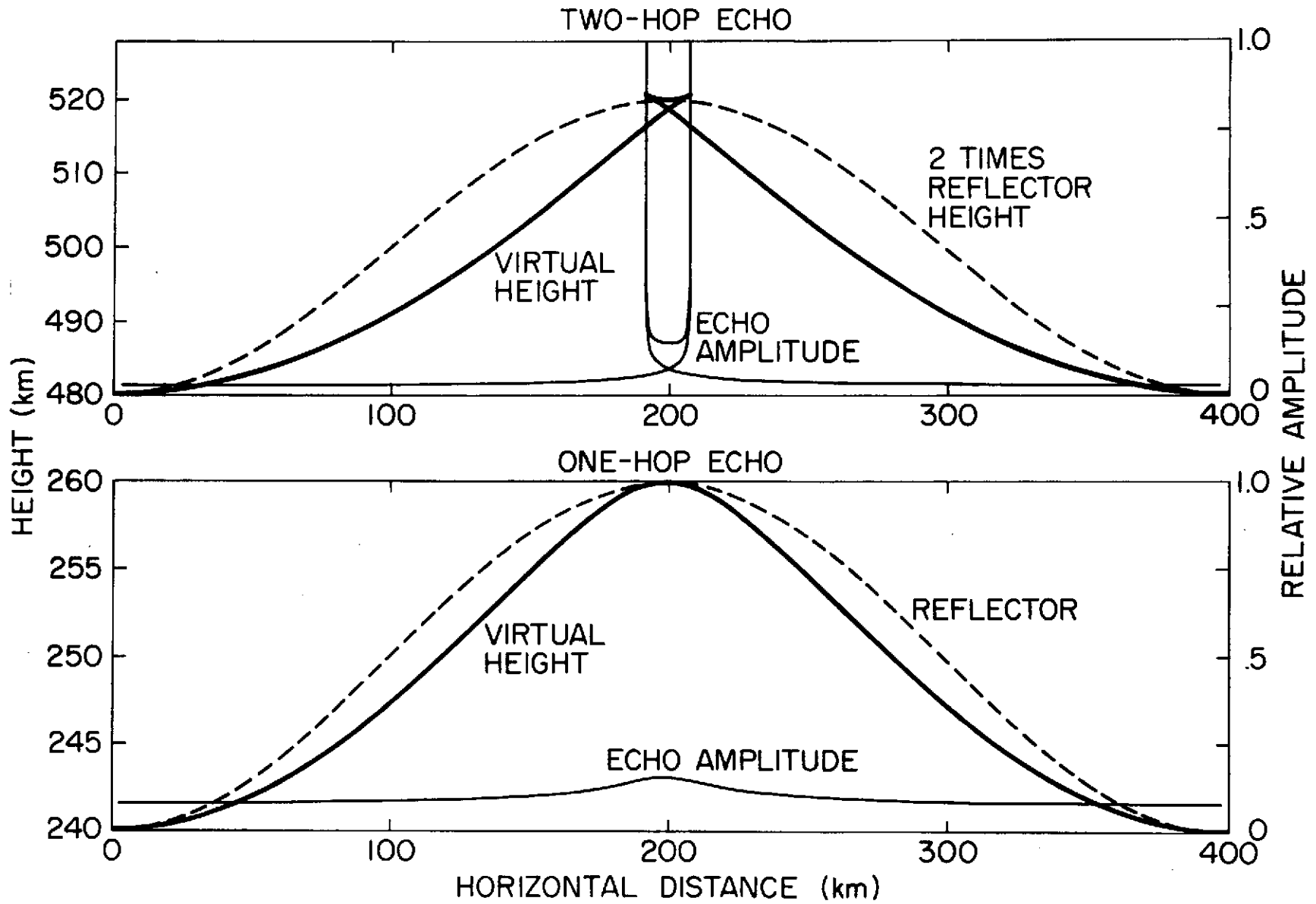
Figure 4.3   One- and two-hop virtual height and amplitude for a sinusoidal reflector with P = 400 km.
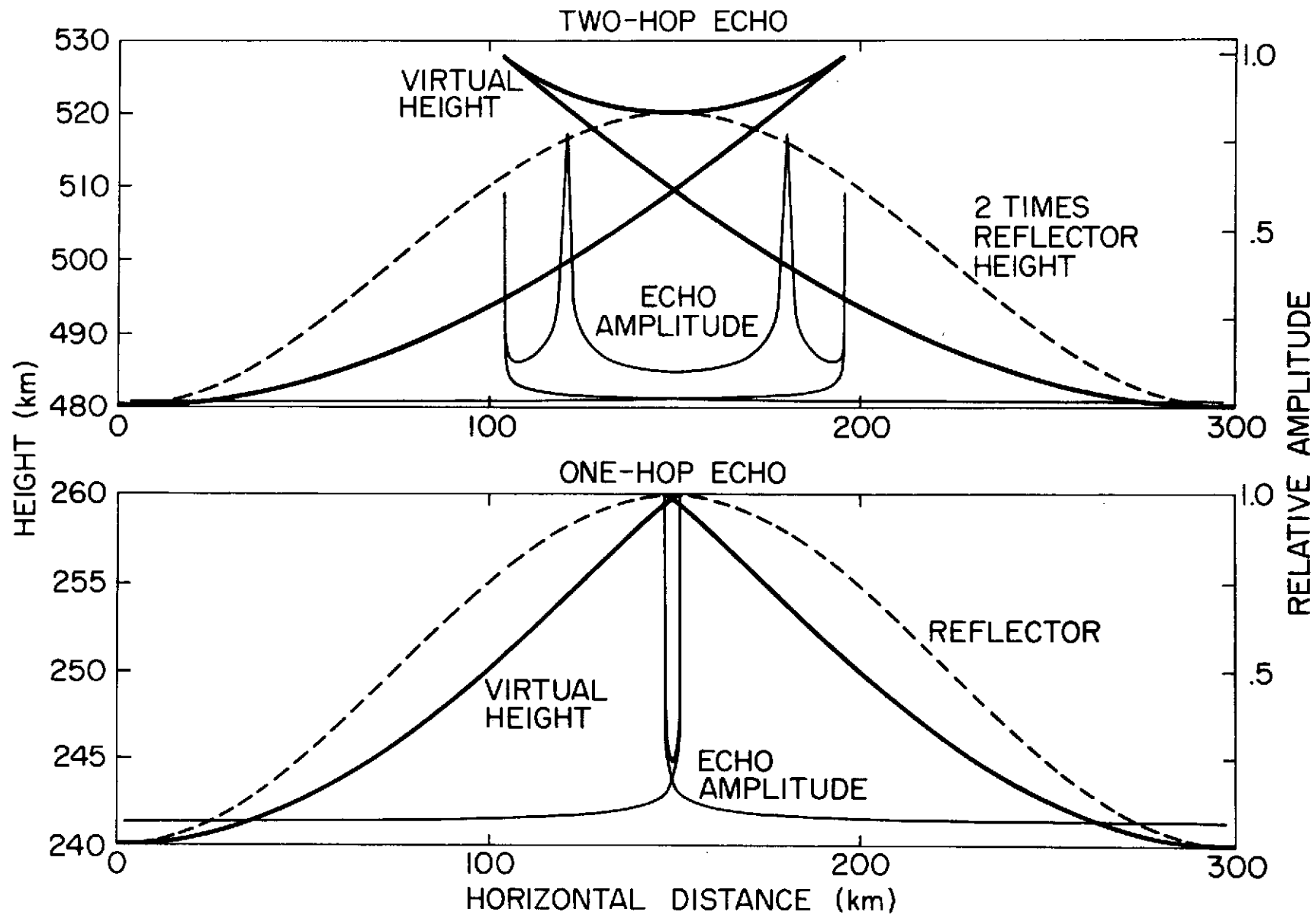
Figure 4.4 One- and two-hop virtual height and amplitude for a sinusoidal reflection with P = 300 km.
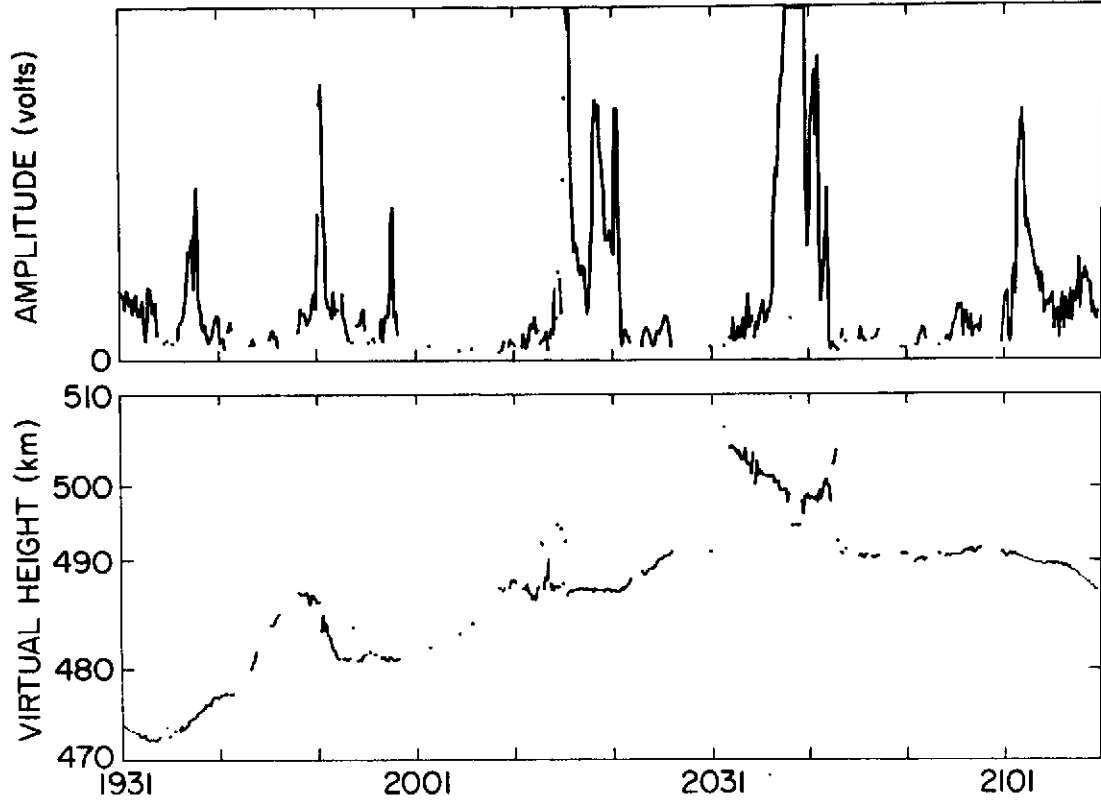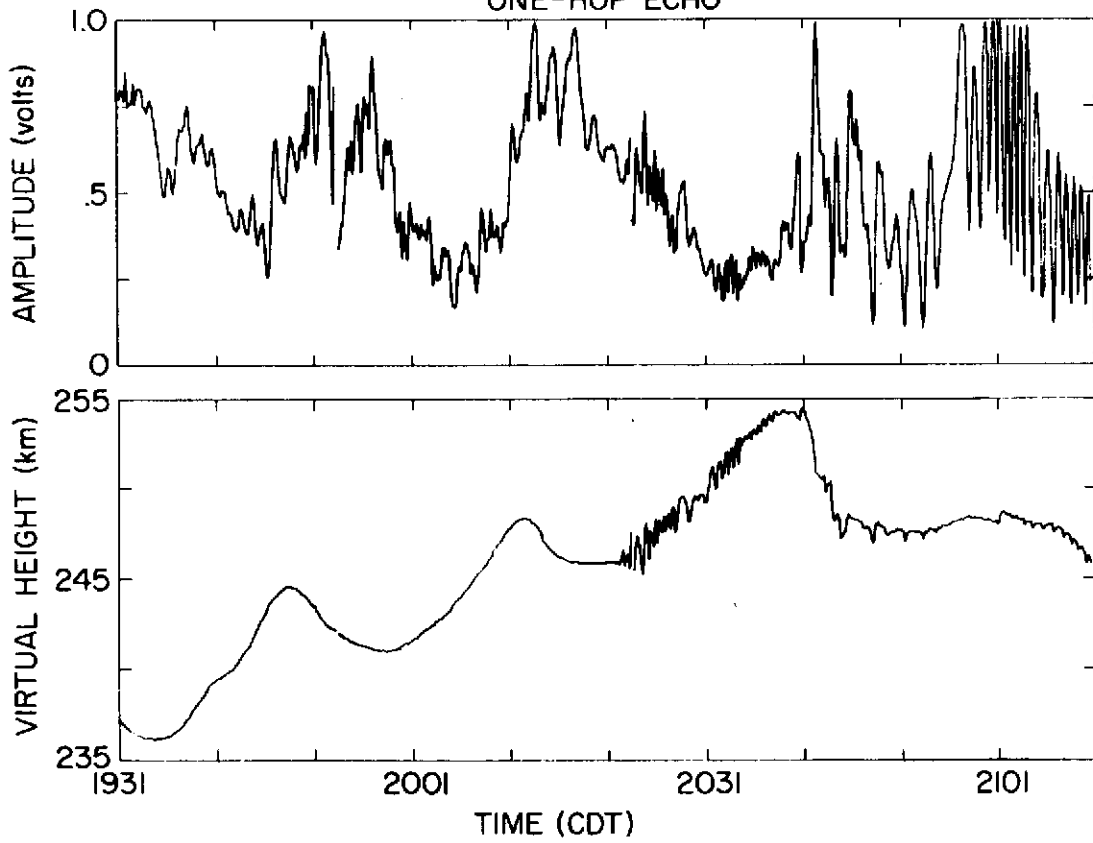
Figure 4.5 Data record taken on May 4, 1973.

An interesting feature of this record is the short-period oscillation in the one-hop height and amplitude from 2022 to 2039. This portion of the graph is expanded in Figure 4.6. The same feature is noted again from 2044 to 2111, but not as clearly. While the data were being taken, two echoes very close together were noted visually, but the echo detection algorithm described in section 3.2 which can detect two echoes close together was not yet in use. The detection algorithm used finds only one echo which is the echo within 10 km of the echo found in the previous 10 sec interval if such an echo exists. If more than one echo is within 10 km of its previous echo, the closest echo to the echo found in the previous 10 sec is picked and printed out. Only the lower echo was detected except at 2023 and 20 sec when the upper echo was detected. The difference in the virtual height of the two echoes decreases from 2022 to 2030 and then increases.

The phase difference between the echoes changes from $0°$ to $180°$ and back to $0°$ every time the difference between their virtual heights changes by one-half wavelength. When the echoes are in phase, the apparent height and amplitude of the lower echo increases and when they are out of phase, the amplitude and apparent height decreases. At 2030, the two echoes are closest together. One minute later, the apparent height and amplitude have gone through one oscillation and the echoes have moved one-half wavelength apart or 48.4 m. The frequency of the oscillations increases indicating that the rate of separation is increasing. At 2035, the oscillations appear to die out. Because the height and amplitude are averaged over 10 sec, what is actually happening is that the height and amplitude are going through one complete oscillation in 10 sec. The rate of separation

ONE-HOP ECHO
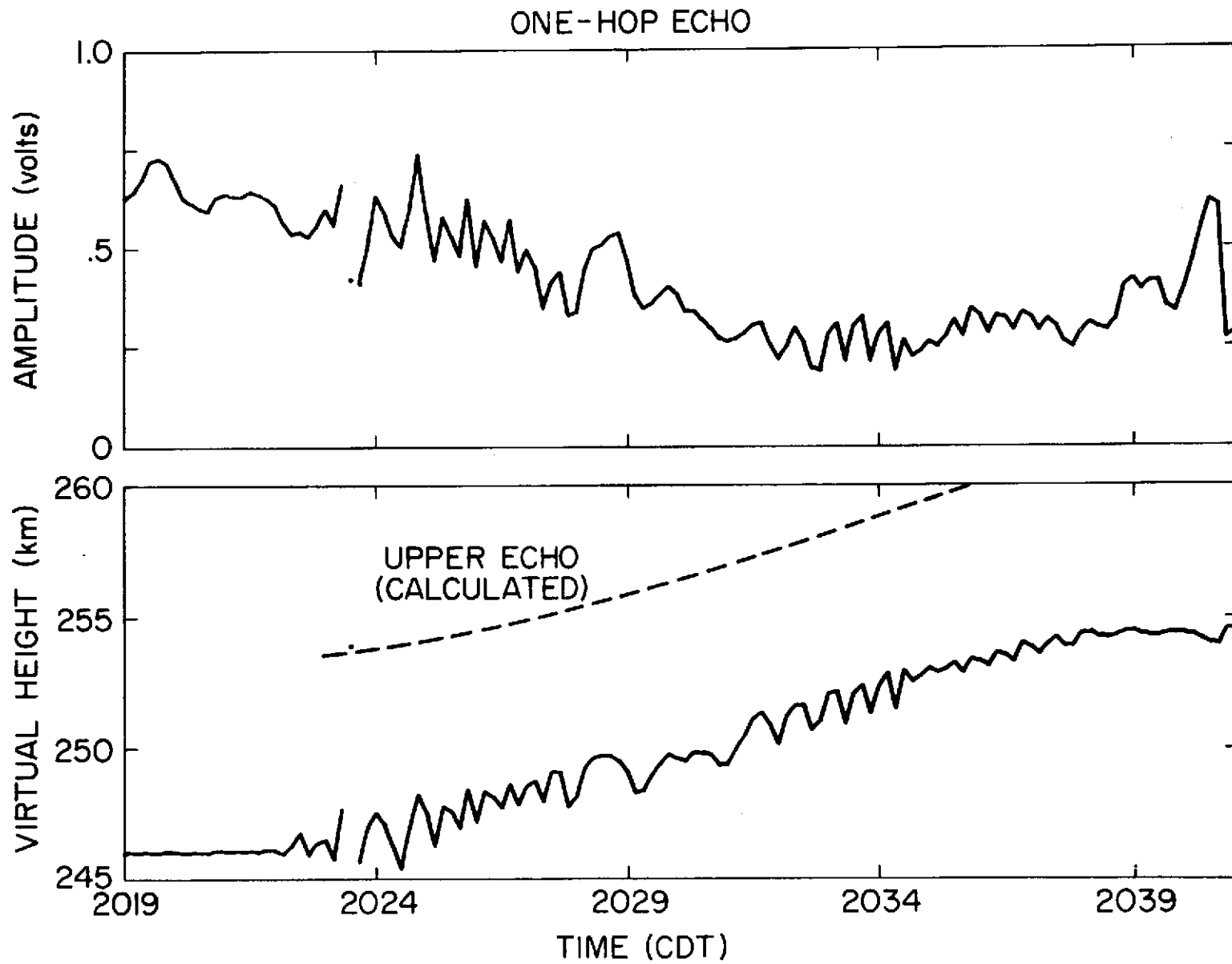
Figure 4.6 Expanded view of part of Figure 4.5 showing interference between two echoes and the calculated position of the higher echo.

continues to increase until the echoes are too far apart to interfere. The same thing appears to happen while the echoes are approaching but it is not as clearly represented in the graph.

From the amount of change in amplitude and height and using Figure 3.8, the approximate virtual height of the second echo near 2030, where the oscillations are slow enough that the 10 sec averaging does not distort the oscillations, is determined and put on Figure 4.6. The number of phase variations determines the height of the upper echo at other times. The calculated position comes close to the one point where the upper echo was detected. The height of this point is also distorted by as much as the lower echo height. The detected point is within this error of the calculated echo position.

The difference between the radial velocities of the two echoes is very small, on the order of a few m sec^{-1}, indicating that their motion is coupled in some way. A possible explanation for the two echoes is that the shape of the reflector is not constant in the Y direction as assumed in section 2.3. Another possibility is that a small additional irregularity exists at the same height as the reflector but displaced several km laterally from the ionosonde antennas in the direction of propagation of the disturbance. The irregularity is displaced vertically by the disturbance and follows the height of the reflector. As the reflector slope increases, the reflection point moves in the direction of propagation of the disturbance and comes closer to the irregularity until, at the inflection point of the reflector, halfway between the minimum and maximum of the reflector, the reflection point is at its closest approach of the irregularity. This is the only occurrence of this phenomenon in five

months of data collection but the same effect occurs when multipath gives two echoes close together.

4.3 Data Showing Focusing

Focusing, as described in Section 2.3, is observed on three-quarters of the data runs taken. Several of these are described in this section.

Figure 4.7 shows 65 min of data taken on May 5, 1973 at 1502 CST. Two cycles of a disturbance are shown with a period of about 22 min. The amplitude shows large enhancements just after each peak in height. The two-hop echo is not included in Figure 4.7 because it is only present twice when focusing increases the two-hop echo amplitude to a point where it is detected. Using the calculator program described in Section 2.4, the reflector shape that produces the focusing effects in Figure 4.7 is determined as shown in Figure 4.8. If the overall dimension of the reflector is reduced to 1700 km, multiple reflection points form. If it is increased to 1900 km, the focusing produced by the first cycle disappears. The dimension of the reflector must be somewhere between 1700 and 1900 km. 1800 km provides a good fit to the data. The wavelength of the distur-bance is then 900 km and the velocity is 680 m sec^{-1}.

Figure 4.9 is a graph of 83 min of data collected on November 2, 1973 at 1336 CST. Three cycles are shown with an average period of 24 min. The extraordinary echo is detected at several points during the run. The amplitude for the one-hop echo shows rapid fading but no clear focusing. The height has a random variation of 630 m superimposed on the periodic variations. Small irregularities in the ionosphere are causing some of the random height variation because the height accuracy of the digital
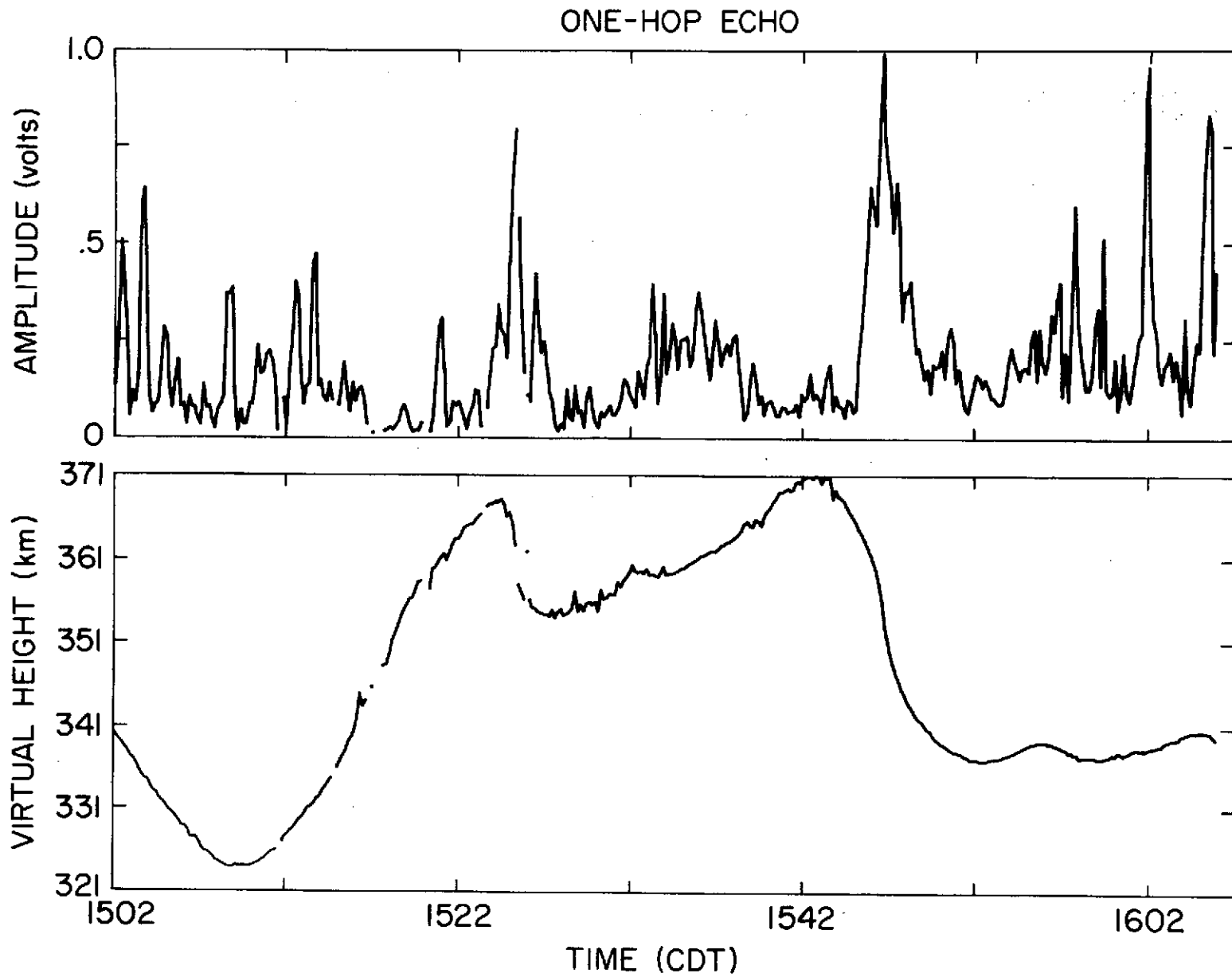
Figure 4.7 Data record taken on May 5, 1973 showing focusing of the one-hop echo.
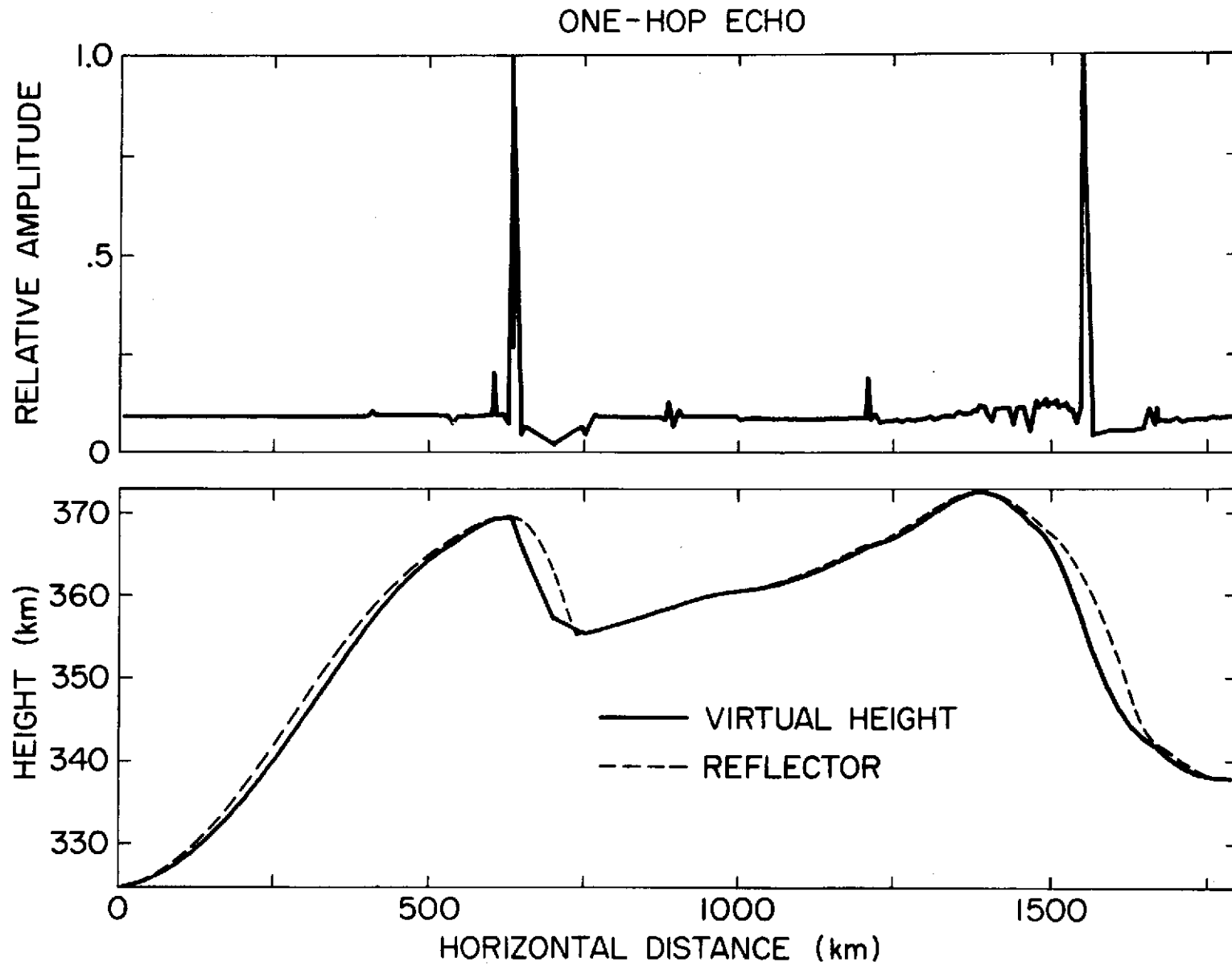
Figure 4.8 Reflector shape that produces virtual height and amplitude curves that match the data in Figure 4.7.
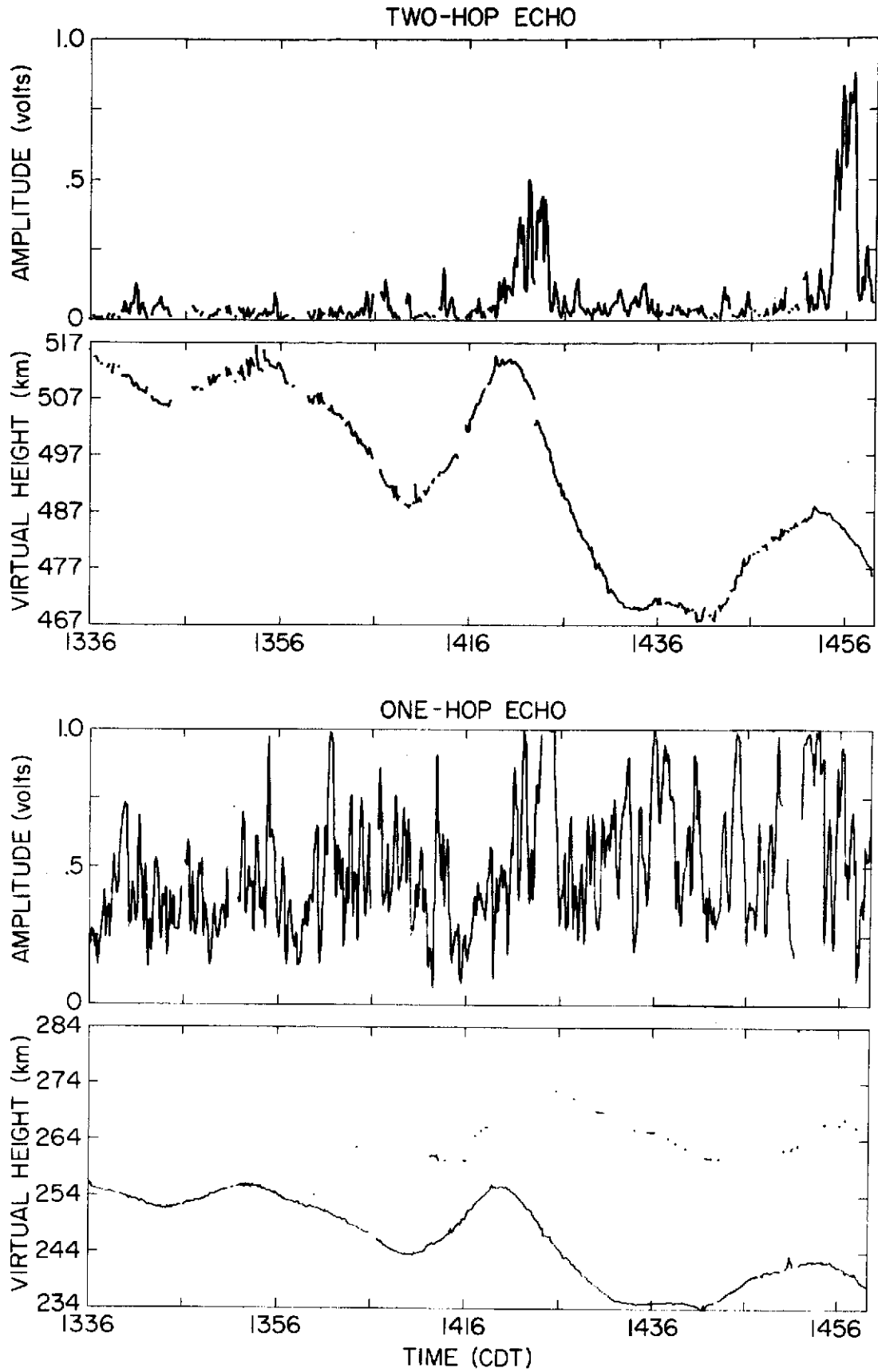
Figure 4.9   Data record taken on Nov. 2, 1972 showing focusing of the
two-hop echo.

ionosonde is greater than this. Signal conditions were very good for this run and the two-hop echo is detected for most of the run. The two-hop amplitude shows two periods of focusing. Figure 4.10 shows the reflector shape and the one- and two-hop height and amplitude calculated from the reflector. A reflector 1000 km long produces the best fit to the data. This gives a wavelength of 475 km and a speed to 396 m sec^{-1}.

4.4 Data Showing Multipath

Multipath occurs when more than one one-hop or two-hop echo is received simultaneously from the reflector as described in Section 2.4. This section presents and discusses several data runs showing this effect.

Figure 4.11 shows 122 min of data collected on September 7, 1973 at 1308 CST and at a frequency of 4.1 MHz. There appear to be 13 cycles of a disturbance in the first 90 min giving an average period of 7 min. The disturbance appears to die out and be replaced by a slower disturbance. Two cycles at 1344 and 1354 show multipath. These are expanded in Figure 4.12. From 1344 to 1345 the two echoes near 240 km have nearly the same virtual height and are close enough to interfere with each other as described in Section 3.3. The echo heights in Figure 4.12 are distorted because the two echoes are close together. The same thing happens with the two echoes near 250 km from 1354 to 1356. The reflector which produces these echoes is shown in Figure 4.13. The wavelength of the disturbance is about 725 km which gives a velocity of 450 m sec^{-1}.

Figure 4.14 show 135 min of data taken on December 8, 1973 starting at 1309 CST and at a frequency of 3.8 MHz. About 6 cycles of a disturbance with a period of 15 min are shown. The ordinary and extraordinary echoes are both recorded and also a number of two-hop echoes. The one-hop echoes
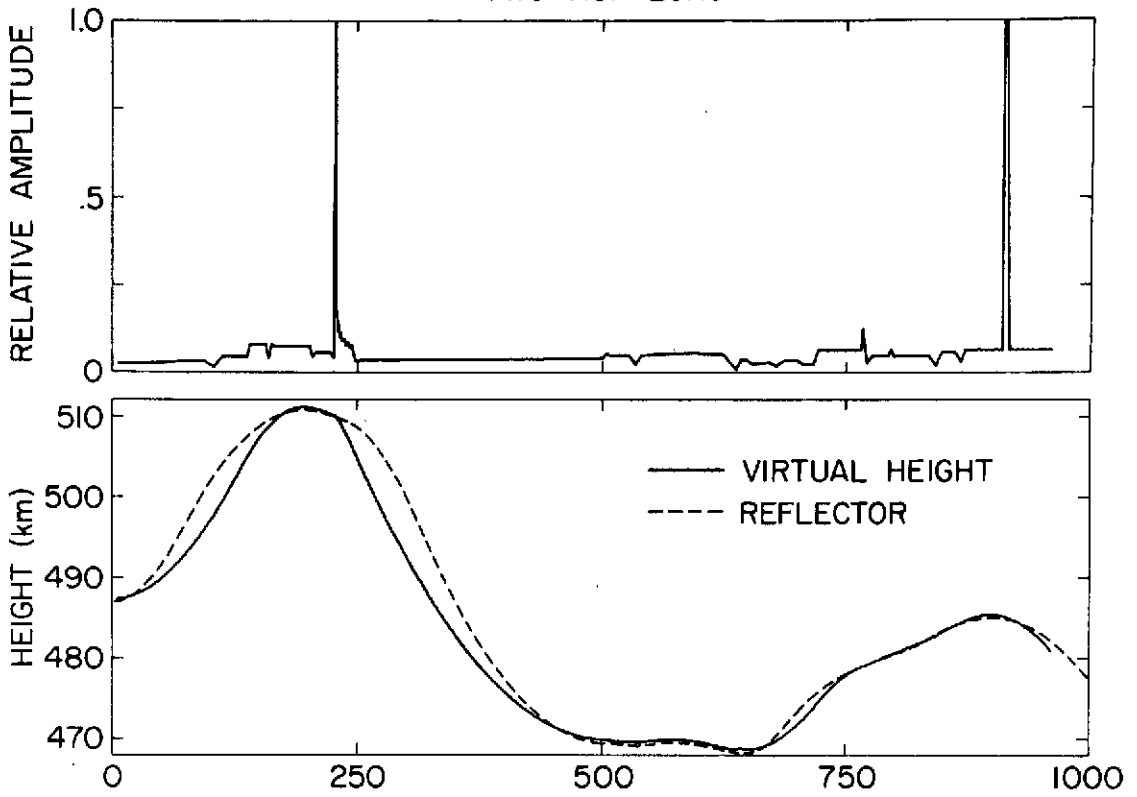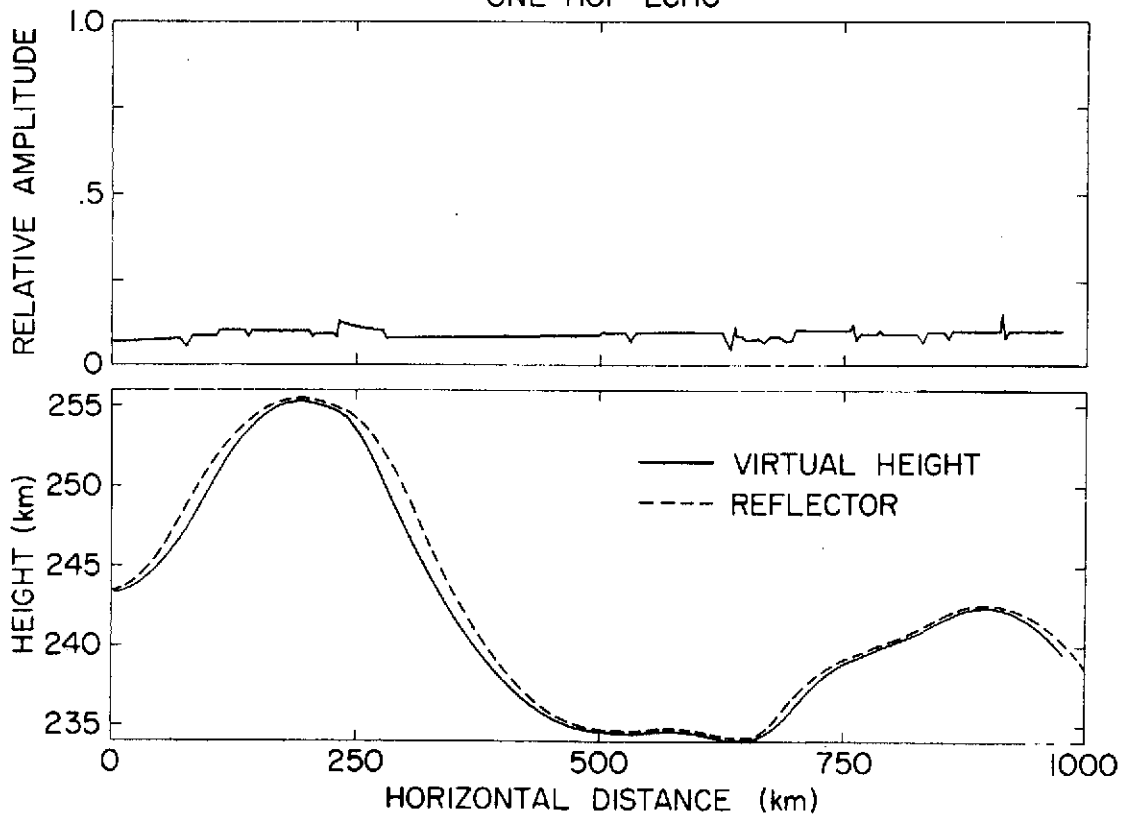
Figure 4.10 Reflector shape that produces virtual height and amplitude curves that match the data in Figure 4.9.
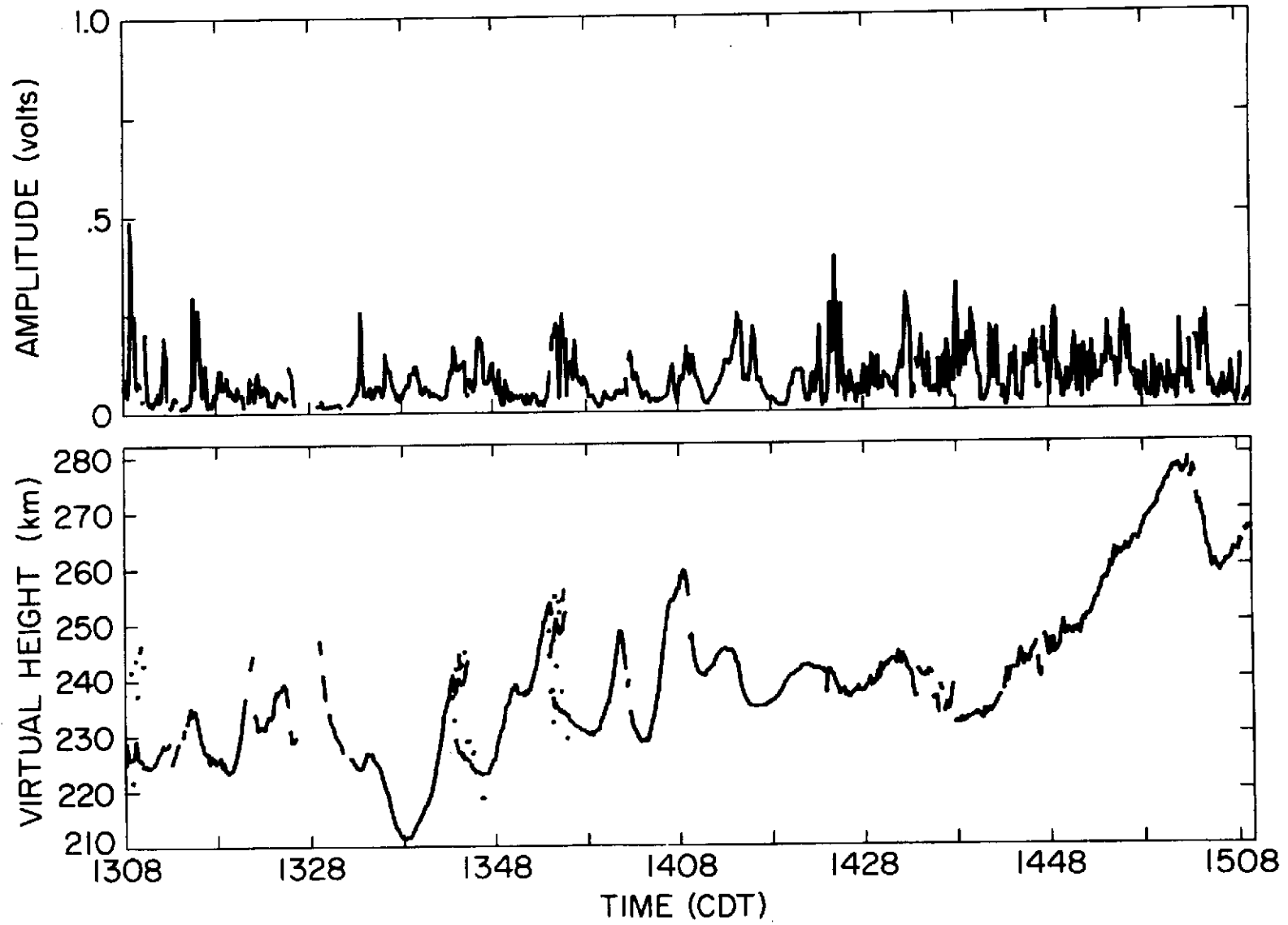
Figure 4.11   Data record taken on Sept. 7, 1973.
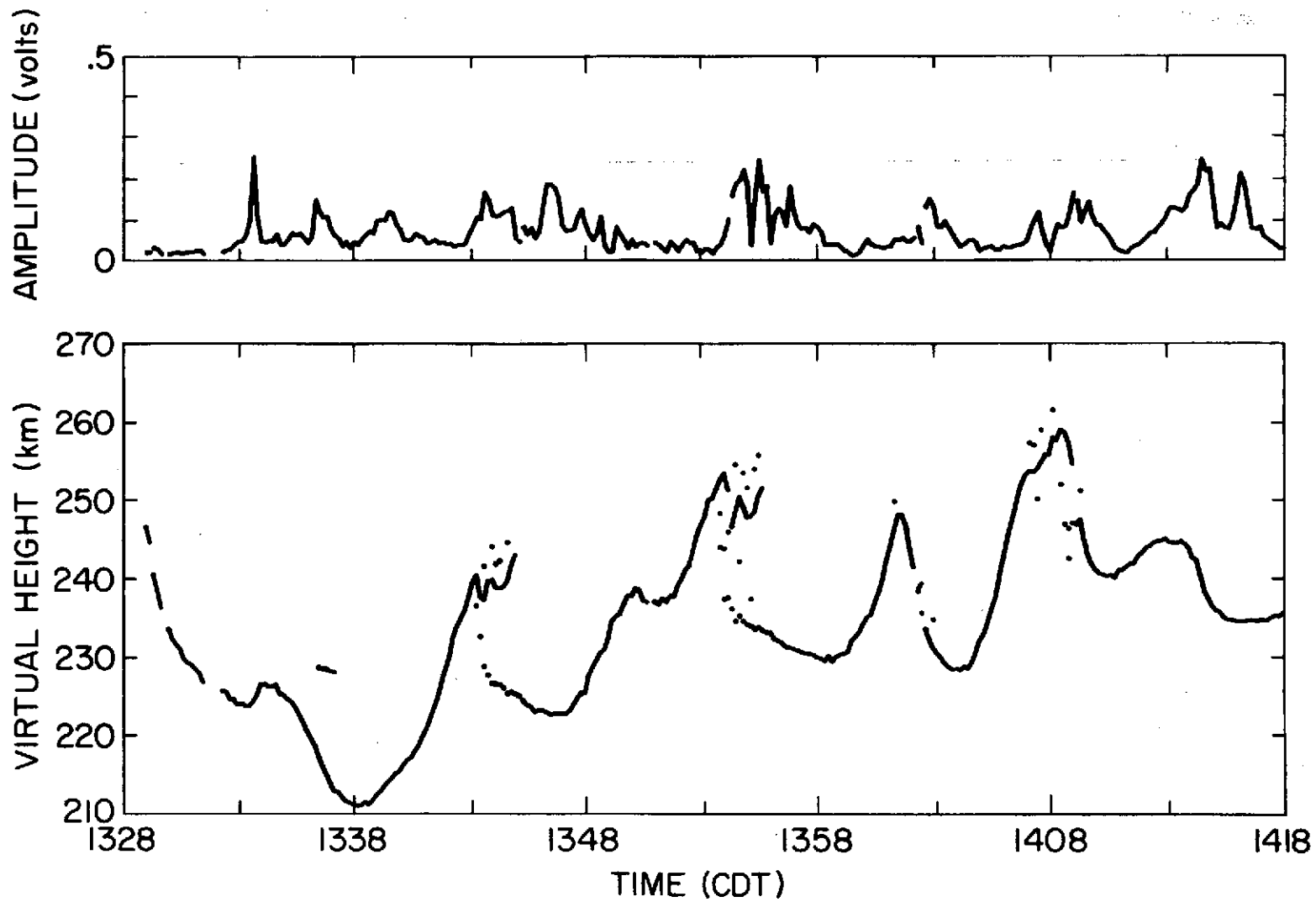
Figure 4.12   Expanded view of part of Figure 4.11 showing multipath.

ONE-HOP ECHO
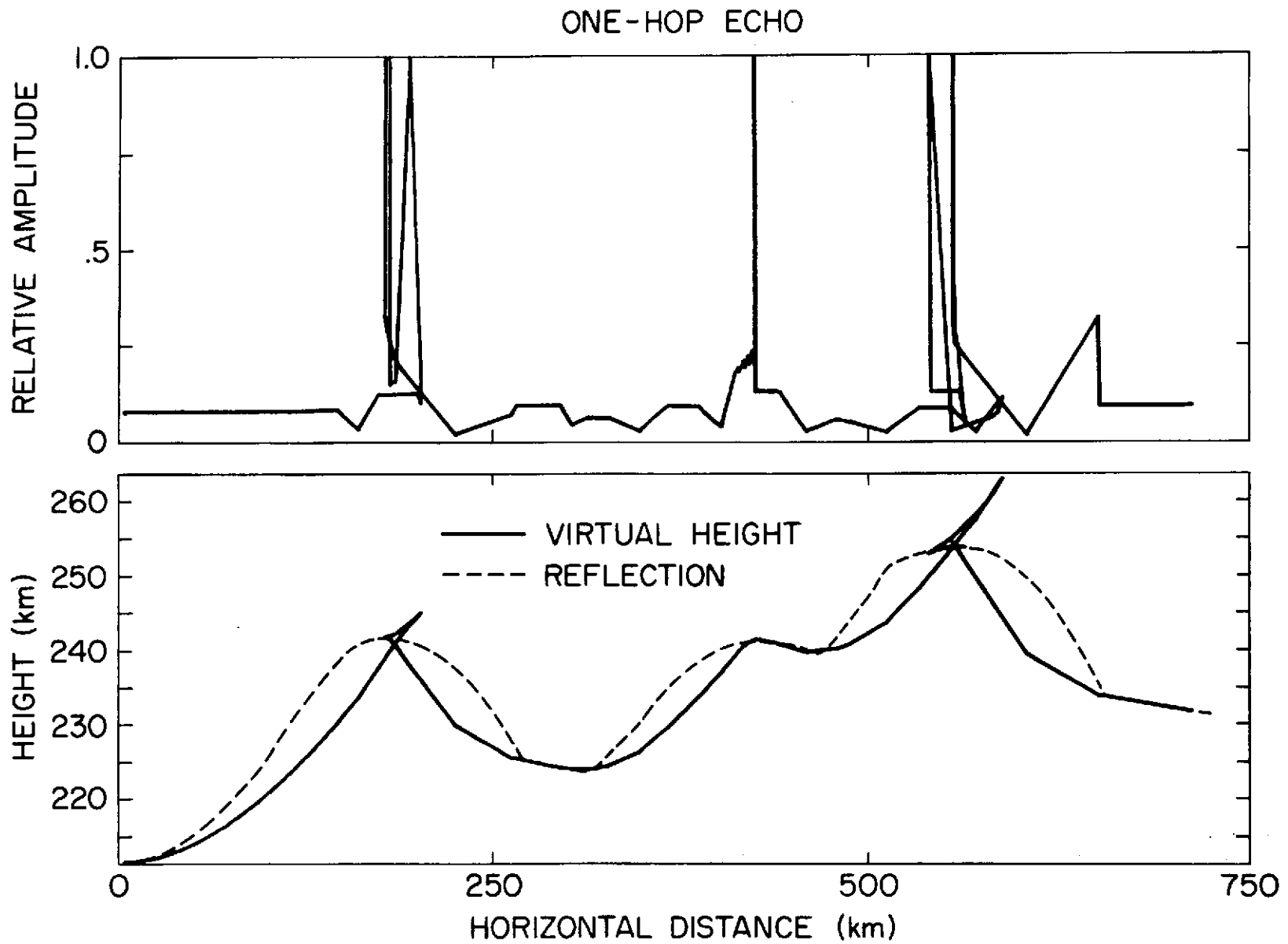
Figure 4.13   Reflector shape that produces virtual height and amplitude curves that match the data in Figure 4.12.
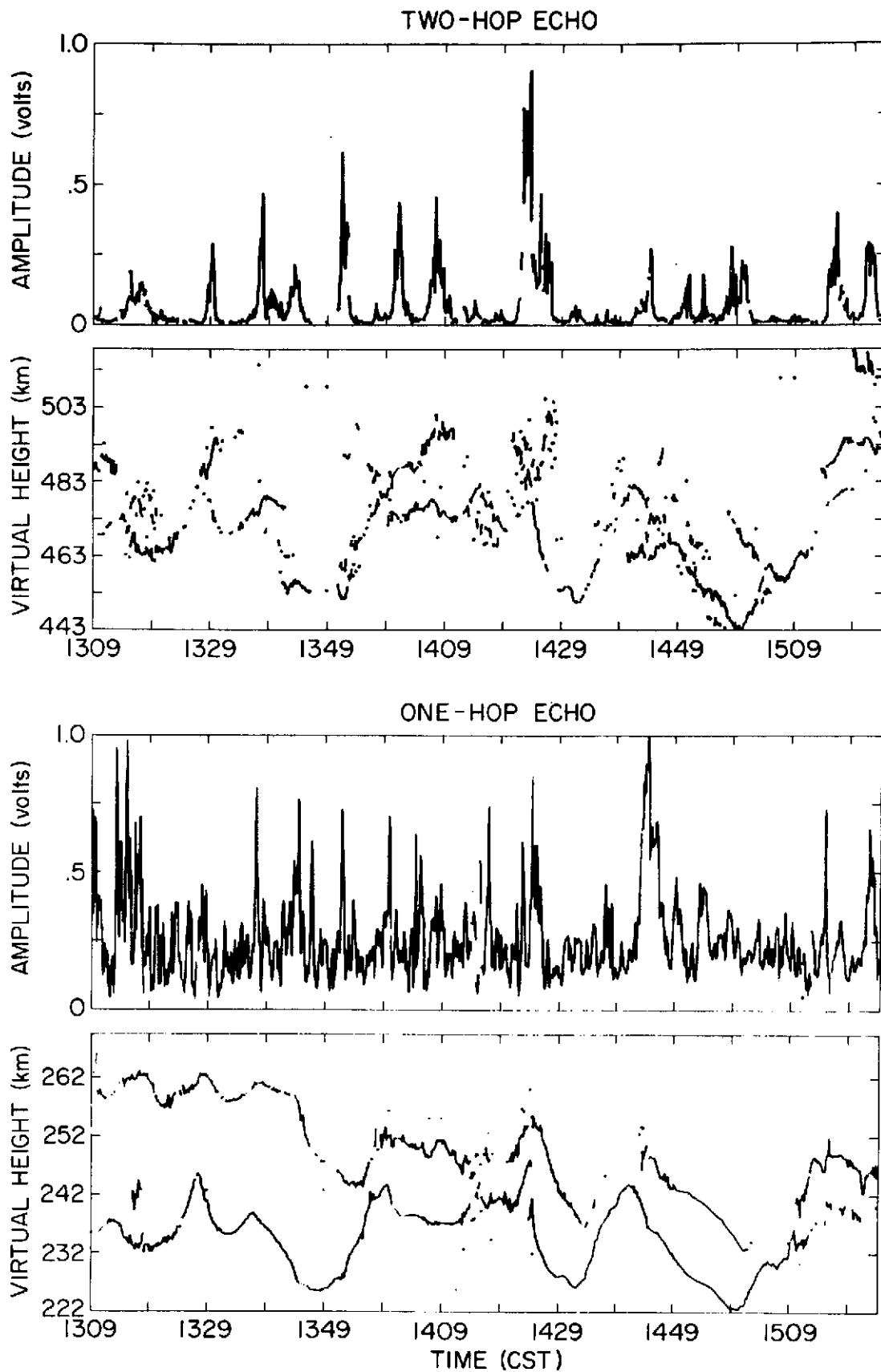
Figure 4.14   Data record taken on Dec. 8, 1973 showing multipath in the two-hop echo.

show little focusing and no splitting. The two-hop echoes are split in at least three places at 1328, 1357 and 1423. The two-hop amplitude is generally too low to give a good picture of what is happening. Figure 4.15 shows a reflector shape which produces two-hop echoes similar to those in Figure 4.14. From this reflector, the approximate wavelength of the disturbance is determined to be 400 km and the velocity of the disturbance is 456 m sec^{-1}.

4.5 *Data Showing Ordinary and Extraordinary Reflections*

This section shows how the ordinary and extraordinary echoes can be used together to determine the direction of the disturbance. Two data records with both ordinary and extraordinary echoes present are analyzed in this section. The basis for the direction measurement is explained in Section 2.6.

Figure 4.14, used as an example of multipath, has both ordinary and extraordinary echoes. The extraordinary reflector is delayed by approximately 55 sec from the ordinary reflector which means the disturbance is traveling roughly in a southerly direction. The frequency used for this run was 4.8 MHz and the F region critical frequency was 7.5 MHz. Using the program to compute lateral deviation described in Appendix IV, the lateral deviation is computed as 9 km and the vertical separation of the reflection points is 16.5 km. The period of the disturbance is approximately 10 min so a value of 45 deg is assumed for the angle of the phase front of the disturbance relative to vertical. Using the formula for the direction of the disturbance derived in Section 2.6 and the velocity of 456 m sec^{-1} calculated in Section 4.4, the angle of propagation of the disturbance relative to north is 19 deg. The angle of propagation is very
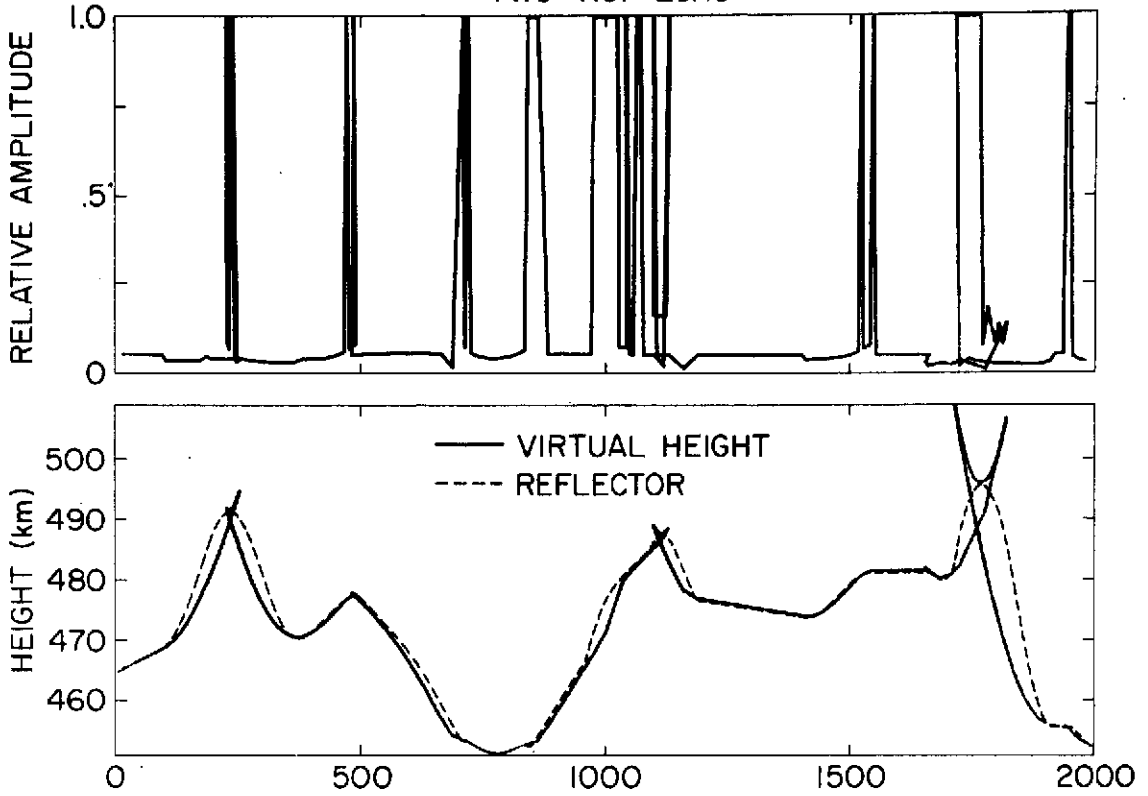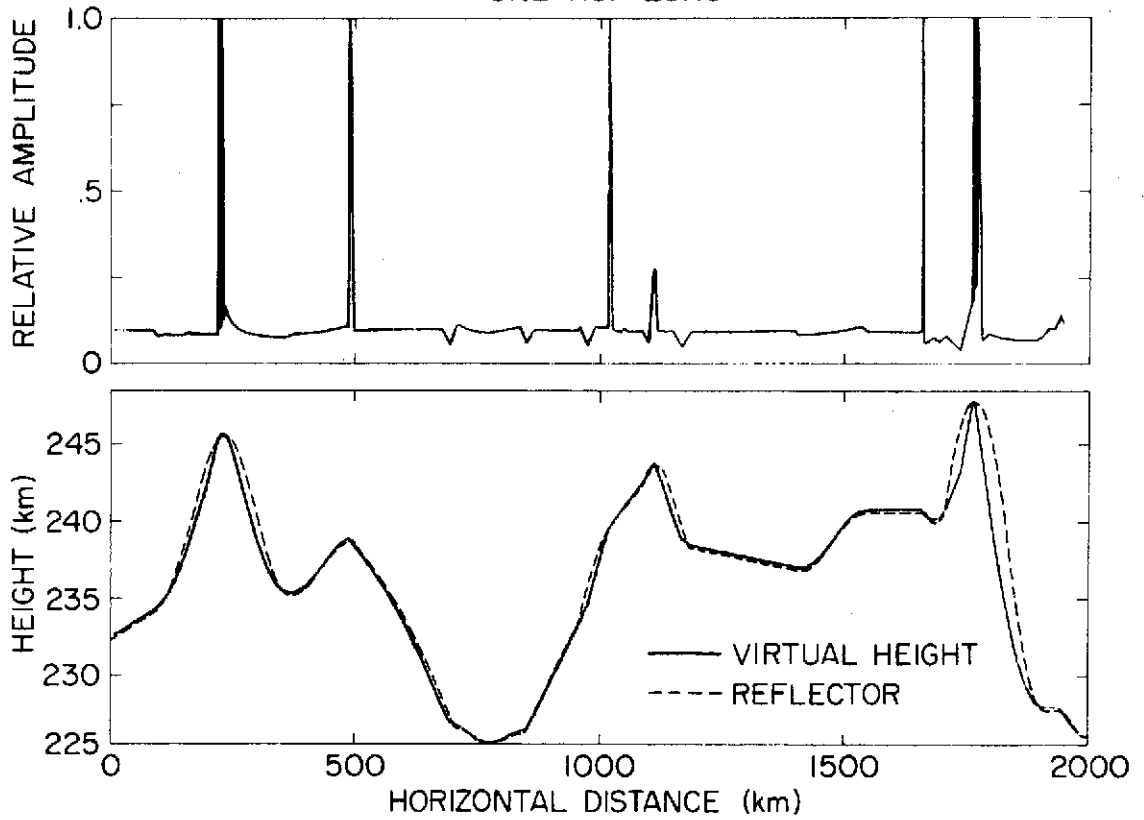
Figure 4.15 Reflector shape that produces virtual height and
amplitude curves that match the data in Figure 4.14.

sensitive to changes in the angle of the phase front. Decreasing the angle to 43.7 deg changes the direction of propagation to directly south.

Figure 4.9, used as an example of focusing in Section 4.3, also shows parts of the extraordinary reflector. The variations in height of the extraordinary reflector are delayed by about 166 sec on the average from the ordinary height variations. This means the disturbance is traveling roughly from north to south. The frequency used for this run is 4.2 MHz and the critical frequency is 9.5 MHz. Using the program to compute lateral deviation, the lateral deviation is 4.12 km and the vertical separation of the reflection points is 8 km. The period of the disturbance is about 25 min. Using a phase front angle of 45 deg, and assuming the disturbance is traveling directly to the south, the projection of the velocity on the north-south axis is 73 m sec^{-1} which is much slower than the velocity of the disturbance calculated as 396 m sec^{-1} in section 4.3. The projection of the velocity on the north-south axis should be larger than the magnitude of the velocity or equal to it if the disturbance is traveling due south. A value of 82 deg for the phase angle is required to make the projection of the velocity equal the magnitude of the velocity. This is very close to the angle of 83 deg measured by *Georges* [1967] for a disturbance with a period of 40 min.

4.6 *Data Showing Unusual Features*

Several data runs contain features which cannot be explained with the present reflector model described in Chapter 2.

Figure 4.16 is a graph of 125 min of data taken on November 17, 1973 at 1340 CST at 4.8 MHz. The amplitude of the one-hop echo is very high and during the first 60 min of the run, the ADC sometimes is saturated.

TWO-HOP ECHO

ONE-HOP ECHO

TIME (CST)
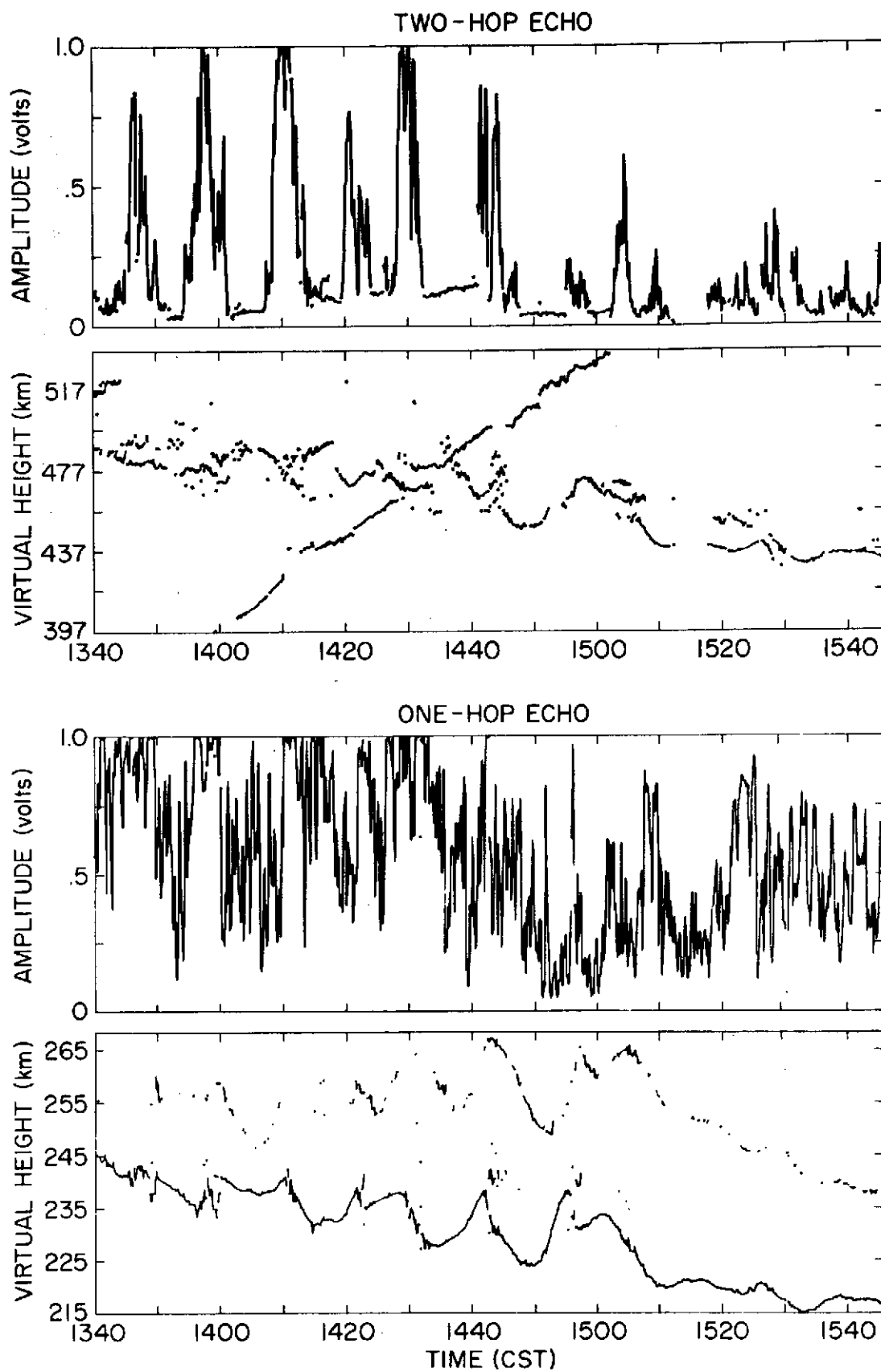
Figure 4.16 Data record taken on Nov. 17, 1973 showing an unusual two-hop echo.

An ordinary and extraordinary reflection are present and the ordinary two-hop echo is also observed. About 11 cycles of a disturbance with a period of 10 min is observed. The amplitude of the disturbance is below normal and because of the saturation of the ADC, the shape of the disturbance is not clear. The two-hop echo shows segments of focusing which correspond to peaks in the ordinary one-hop height but for the most part, the amplitude is too small to get a good picture of the two-hop height variation.

An interesting feature of the two-hop height is the echo which increases linearly in height. The amplitude of this echo increases slowly until about 1440 and then decreases. The amplitude is very steady, showing no signs of fading. The echo is first picked up at 1359 and 20 sec at a height of 397.5 km and increases in height beyond the detection range of ECHO at 1502 and a height of 535 km. The low height of the echo from 1400 to 1430 implies that it is not a two-hop echo since there is no one-hop echo at one-half this height. The amplitude is very constant and higher than the two-hop echo amplitude when it is not focused. This signal could be a type of noise reported by *Gerson* [1962] which he calls β type sweepers. The signal could be caused by another pulse transmitter operating at nearly the same frequency and synchronized to a power line with a slightly different frequency to account for the changing time delay relative to the ionosonde transmitter.

Figure 4.17 shows 93 min of data taken on December 1, 1973 starting at 1310 CST at a frequency of 4.1 MHz. A few cycles of a disturbance with a period of about 20 min are shown. A few extraordinary echoes are also detected. The two-hop echo is present for most of the run. An unusual feature of this record is the second two-hop trace starting at 1417 and
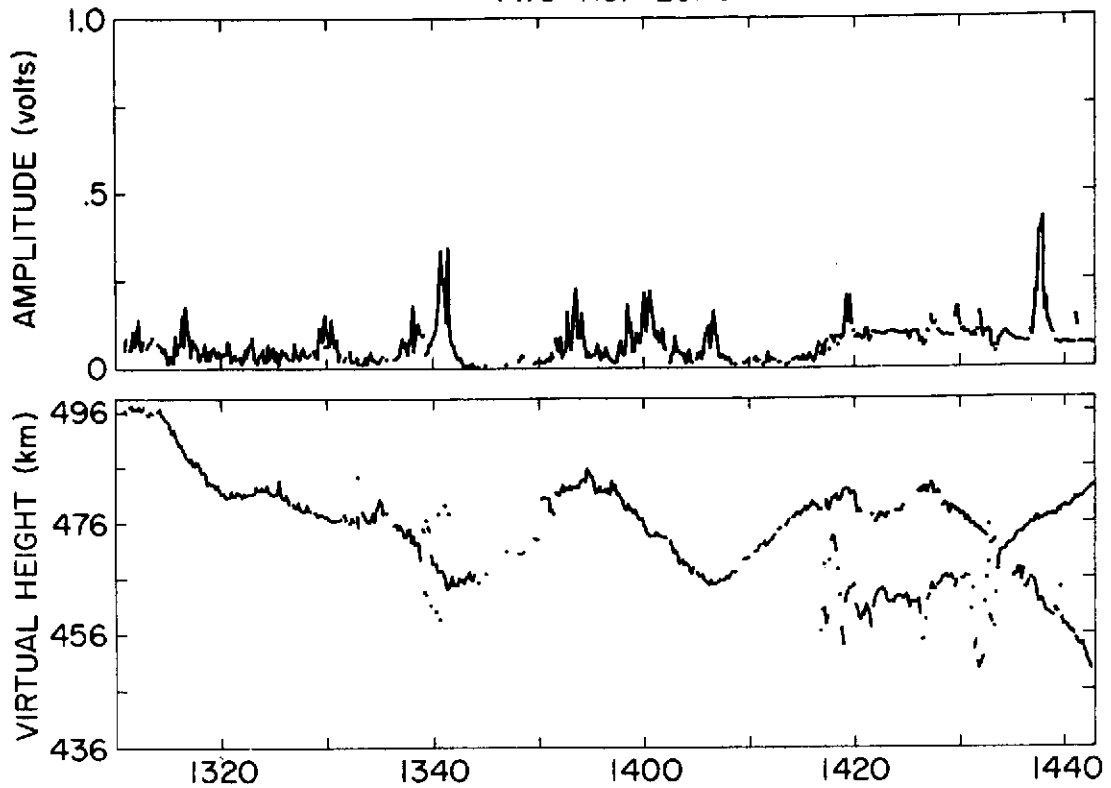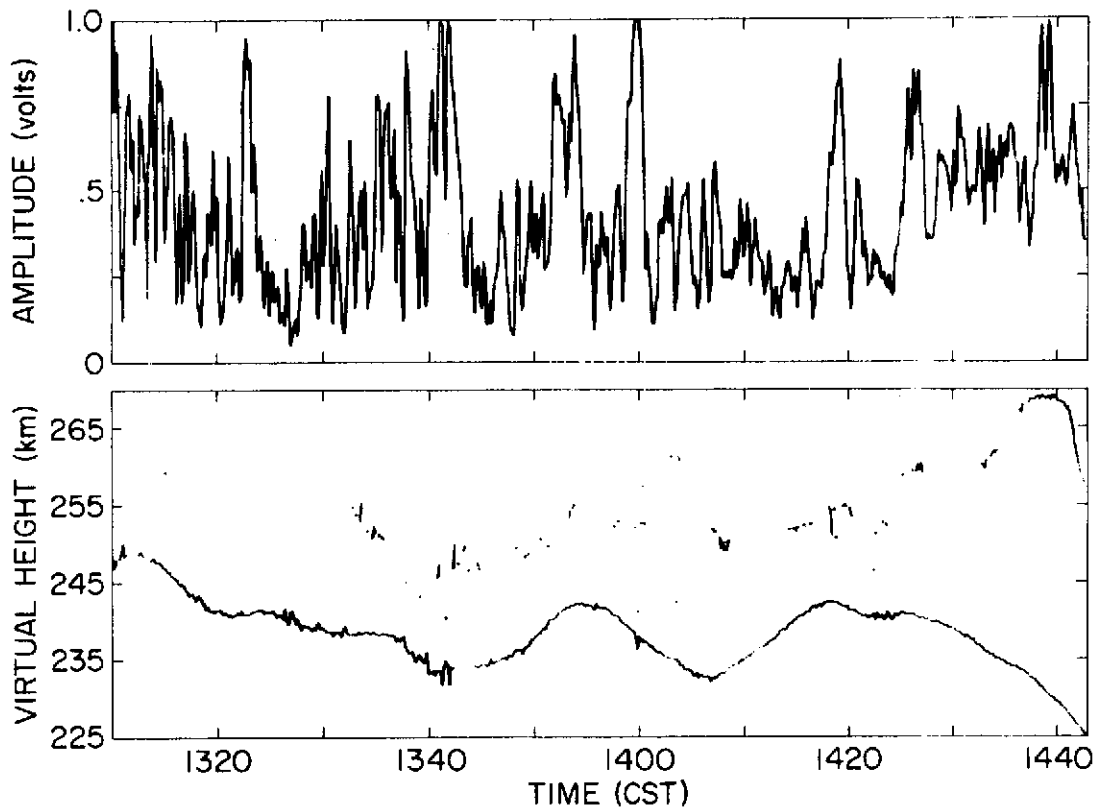
Figure 4.17 Data record taken on Dec. 1, 1973 showing an unusual two-hop echo.

increasing in height until the end of the run. This trace is similar to the one in Figure 4.16 but it is not as straight and does not start as far below the normal two-hop height. The amplitude of the echo is approximately constant for the 25 min that is recorded. It also starts too low to be a two-hop echo. This echo appears to be associated with one cycle of the disturbance and it could be that this is a multipath phenomenon which cannot be explained with the present reflector model.

Figure 4.18 shows 122 min of data taken on October 10, 1973 starting at 1250 CST at a frequency of 4.7 MHz. This graph clearly shows several examples of multipath. There is very little fading in the amplitude and the random height error is less than 200 m. Focusing can clearly be seen on each cycle of the disturbance. The two-hop echo also shows focusing but for the most part the two-hop echo is too weak to be detected. A few extraordinary echoes are detected. At this frequency and on the day the data were taken, the extraordinary echo is below the ordinary echo. The exact shape of the multipath echoes cannot be reconstructed with the present curved reflector model. All multipath echoes using the current reflector model have some form of X or crossover which is not present in Figure 4.18.

ONE-HOP ECHO
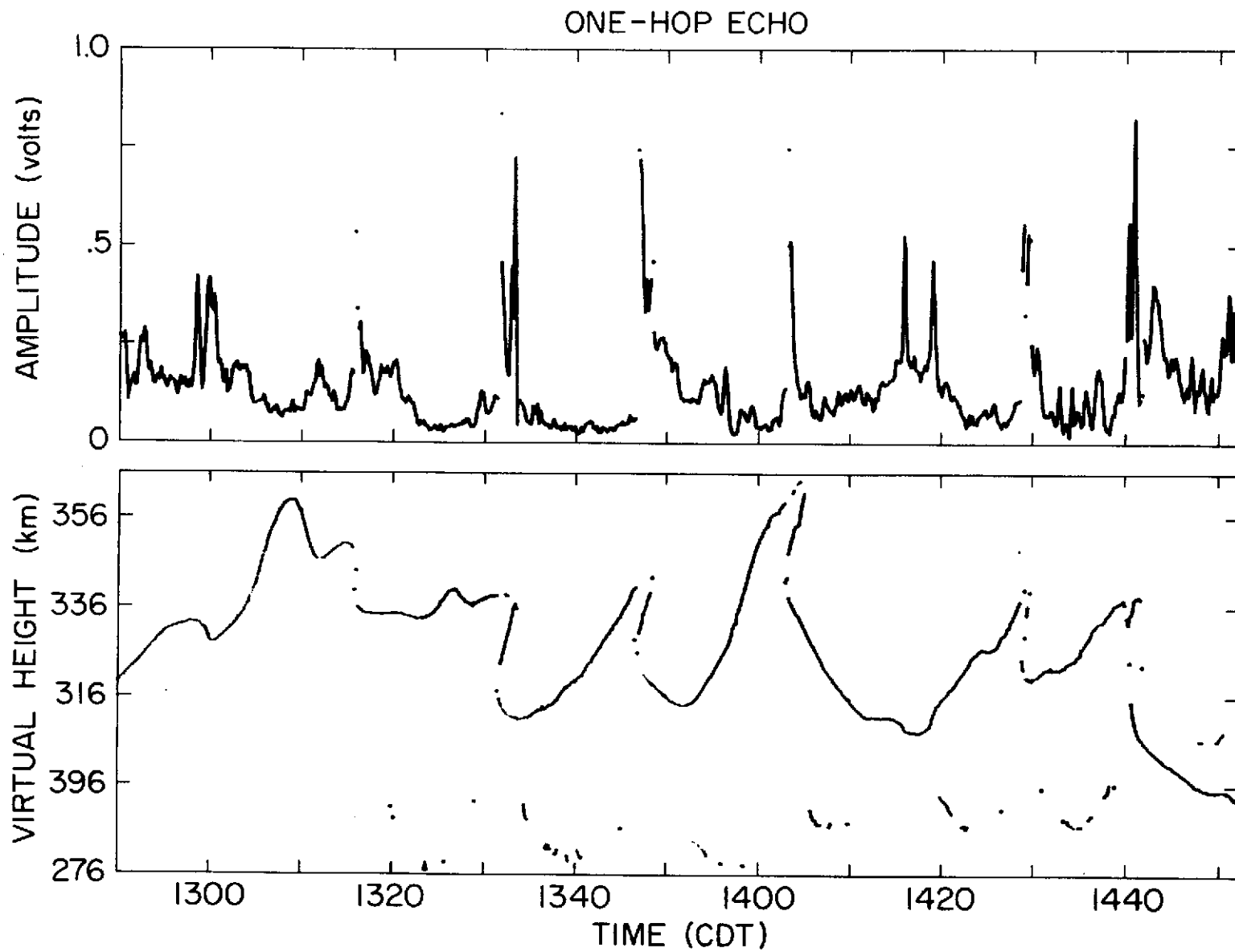
Figure 4.18   Data record taken on Oct. 10, 1973 showing multipath which cannot be explained with the present reflector model.

5. RESULTS AND SUGGESTIONS FOR FUTURE WORK

In the previous chapters, a system for collecting accurate fixed-frequency virtual-height data and methods for analyzing the data to determine speed and direction of traveling ionospheric disturbances are presented. Virtual height is measured with a time resolution of 10 sec and with a height resolution of less than 300 m and in some cases as little as 50 m. Five months of data from the digital ionosonde shows quasi-periodic height variations on all data records with periods of 5 to 30 min and amplitudes of 10 to 50 km. Focusing is apparent on 75% of the records and multipath is observed on 33% of the records.

The horizontal wavelength of the disturbance is determined by matching virtual height and amplitude calculated from an assumed re-flector shape with the data from the digital ionosonde system. Several data records analyzed in this manner indicate wavelengths from 400 to 900 km and speeds of 400 to 680 m sec^{-1}. The direction of the distur-bance is determined by measuring the time delay between the appearance of prominent features of the disturbance at the ordinary and extra-ordinary reflection points. Two records analyzed in this manner indicate that the disturbance is traveling approximately due south.

To graph the data from the digital ionosonde on the plotter, large amounts of paper tape are punched out on the PDP-15 and generally used only once to make a graph of the data. The partial reflection experiment and presumably future experiments will collect data on the PDP-15 and graph it on the plotter. The paper punch on the PDP-15 occasionally makes errors in punching the tape and the paper tape reader connected to the calculator also makes occasional errors in reading the tape. The tape

reader also has no convenient way of handling large pieces of paper tape. For these reasons, another method of transferring data between the PDP-15 and the calculator is desirable. A magnetic cassette tape unit could be attached to the PDP-15 through the digital input-output port. This would eliminate the need to use paper tape for transferring large amounts of data. It would be necessary to find out the format used by the calculator in writing on the cassette tapes and program the PDP-15 to write tapes in the same format.

The frequency counter described in Section 3.6 makes computer control of the ionosonde frequency possible. It should be possible to switch the ionosonde between several frequencies to get a vertical profile of the disturbance. The frequency counter also simplifies writing a program to take digital ionograms.

To investigate the unexplained data and increase the accuracy of the wavelength measurements, ray tracing could be used with a model of the ionosphere as disturbed by gravity waves. *Clark* [1970] develops a computer model of the ionosphere disturbed by gravity waves and a set of differential equations for ray tracing by *Haselgrove* [1963] is implemented on the HP-9830 calculator. A data collection program that takes continuous digital ionograms or one that takes an ionogram every few minutes and fixed frequency virtual height data at other times could be used to determine the electron density distribution.

A first step in improving the data from the digital ionosonde is to add phase measuring capability by adding two synchronous detectors to the ionosonde. The computer, using the digital output port sets the height at which two sample-and-hold circuits sample the output of the synchronous

detectors. After the ADC finishes sampling the magnitude of the amplitude as it does in the present system, the two sample-and-hold voltages are multiplexed into the ADC input and sampled.

A further improvement is to measure the angle of arrival of the echo. Two more antennas, two more receivers, four more synchronous detectors and four sample-and-hold units would be required. Since the computer can rapidly change the height at which the sample and hold circuits sample, if there are more than one echo, a different echo can be looked at with each transmitter pulse. The direction of propagation of the disturbance is obtained directly and unambiguously from the angle-of-arrival measurement.

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APPENDIX I. OPERATING INSTRUCTIONS FOR THE DIGITAL IONOSONDE AND A

LISTING OF THE DATA COLLECTION AND DISPLAY PROGRAMS

The following procedure is used to operate the fixed frequency data collection system. A listing of the programs is included after the operating instructions.

1. Turn on Hazeltine 2000 video terminal and the PDP-15 computer. Press the ONLINE button on the Terminet 1200 TTY. The address switches on the PDP-15 should be set to 00111_8. Press STOP and RESET at the same time. Then press START. The following should appear on the foreground TTY.

   FKM15 V3A

   $}

If not, see the procedure for cold starting the PDP-15 taped next to the computer console.

2. Turn on the encode gate generator and monitor oscilloscope. Disconnect the coaxial cable from the PR receiver to the ADC input and connect the cable from the ionosonde video attenuator to the ADC input. The cable from the PR encode gate generator is similarly disconnected from the ADC encode input and replaced with the cable marked IONOSONDE ENCODE PULSE.

3. Mount the tape marked Ionosonde Programs on tape unit 2. At the foreground TTY type the underlined portion of the following.

   $}N 2 cr   cr means press the CARRIAGE RETURN

   $}A DT2 -4, -5/DK2 2 cr   key

   $}MPOFF cr

   $}SHARE cr

```
$}GLOAD cr

FGLOAD V2A

$}PROC,HDATA esc              esc means press the ESCAPE key
```

At the background console type the following.

```
BKM15 V3A

$}A DT2 -4,-5 cr

$}GLOAD cr

BGLOAD V2A

$}BGRAPH,BDATA esc
```

4. At the ionosonde, turn on the power supply for the line drivers and
the monitor oscilloscope. Turn the RECORDING START/INTERVAL SECECTOR
switch to manual, turn the camera switch off and turn the data
oscilloscope power supply off. Run one sweep to determine Fof2 and
then set the frequency as desired. Reduce the transmitter power to
save tube life as far as is consistant with good echo amplitude.

5. To start the collection programs, set console switch 0 to 1 and
switch 17 to 0 and type the following.

```
OPERATION

0 cr

HEIGHT

APPROX ECHO HEIGHT cr
```

The approximate height is determined from the monitor scope. The
TTY will print the echoes within 75 km of the height selected. The
shape of the first echo printed is displayed on the Hazeltine. When
the exact height has been determined, set console switch 0 to 0 and
wait until OPERATION is typed on the TTY. Set switch 0 to 1 and type

the following.

OPERATION

1 cr

HEIGHT

ACCURATE ECHO HEIGHT cr

FILE NAME

XXXXX XXXX cr

Where the X's can be any printing characters or spaces such as the date
and time. The program will type out a heading. Write in the operating fre-
quency and the critical frequency. To stop the data collection, set switch
0 to 0.

6. To transfer the data stored on the disk to paper tape, type the
   following on the foreground TTY.

   ↑B↑C

   FKM15 V3A

   $}A PPO 4/DK2 5 cr

   $}PIP cr

   PIPBF V14A

   >T PPO←DK2 XXXXXX XXX (A) cr

To transfer the data to magnetic type, type the following.

   ↑B↑C

   FKM15 V3A

   $}A DT2 4/DK2 5 cr

   $}PIP cr

   PIPBF V14A

   >T DT2←DK2 XXXXXX XXX (A) cr

XXXXXX XXX are the same 9 characters typed in for the file name in step 5 but with the space after the 6th character instead of the 5th.

PROGRAM LISTING

```
C           RPROC    FIXED FREQUENCY DATA PROCESSING PROGRAM
            REAL HDATA(600),EH(10),HT(5),FNAME(2),SB(2)
            INTEGER CDATA(530),T(1024),EA(10),IA(5)
            INTEGER TO,T1,T2,F,FI,FR,OP,BG,COL,ALT,DT
C           ---------------------------------------------------------
C           ARRAYS
C           CDATA CONTAINS THE AVERAGE OF 600 FRAMES OF DATA
C           T IS USED TO CONVERT ADC NUMBERS TO BINARY
C           HDATA CONTAINS THE HEIGHT OF THE MAIN ECHO PICKED BY PCK
C           FOR EACH 10 SEC INTERVAL
C           EH AND EA CONTAIN THE HEIGHT AND AMPLITUDE OF UP TO 10
C           ECHOES DETECTED BY ECHO
C           HT AND IA CONTAIN THE HEIGHT AND AMPLITUDE OF UP TO 3
C           ONE-HOP AND 2 TWO-HOP ECHOES THAT ARE PRINTED AND
C           STORED ON THE DISK
C           FNAME IS THE NAME OF THE FILE USED TO STORE HEIGHT AND
C           AMPLITUDE DATA. THE FORMAT FOR INPUTING FNAME IS XXXXX XXXX
C           WHERE X IS ANY PRINTING CHARACTER OR SPACE
C           SB CONTAINS " " AND "*", A * IS PRINTED WHEN MORE ECHOES
C           ARE DETECTED THAN CAN BE PRINTED
C           ---------------------------------------------------------
C           VARIABLES
C           TO IS THE THRESHOLD USED BY ECHO
C           T1 AND T2 ARE THE ONE-HOP AND TWO-HOP THRESHOLDS
C           FI IS THE NUMBER OF FRAMES IGNORED DUE TO NOISE OR DUE
C           TO ADC TIMING ERRORS
C           BG IS THE HEIGHT OFFSET DUE TO THE 30 USEC ENCODE GATE DELAY
C           DT IS THE .DAT ASSIGNMENT OF A DISK
C           COL IS USED TO PRINT ";"
C           ALT IS USED TO END A LINE WITH AN ALTMODE WHICH SUPPRESSES
C           THE NORMAL CARRAGE RETURN
            COMMON/DATAS/CDATA,BG,TO,FRI
            COMMON/DTS/T,HDATA
            DATA SB(1),SB(2)/1H ,1H*/
            FR=600
            DT=2
            BG=30
            IFLAG=1
            ALT=((7*8+6)*8+4)*512
            COL=(3*8+5)*4096
            FRJ=75000./16384.
C           SET UP TABLE TO CONVERT ADC NUMBERS TO
C           INTEGERS IN THE RANGE 213 CO -218
            DO 1 I=1,512
            X=FLOAT(I-1)*32./75.
            J=INT(X)
            IF (X-FLOAT(J) .GT. .5) J=J+1
1           T(I)=J
            DO 2 I=513,1024
            X=FLOAT(1025-I)*32./75.
            J=INT(X)
            IF (X-FLOAT(J) .GT. .5) J=J+1
2           T(I)=-J
C=========================================================================
100         WRITE(6,50)
50          FORMAT(10H1OPERATION)
C           INITIALIZE THRESHOLD USED IN SUBROUTINE ECHO
            T1=10000
            T2=10000
```

```
C          DATA FOR BACKGROUND PROGRAM
           CALL BGDAT(IFLAG,KKK,CDATA,HDATA,NH,IM,IS,F,TI)
           READ(6,51) OP
C          OPERATION = 0 PRINT ALL ECHOES FOUND NEAR XHT
C                    = 1 LOOK FOR ECHOES NEAR XHT AND 2*XHT
C
C                          PRINT ECHO HEIGHT AND AMPLITUDES AND STORE DATA
C                          ON .DAT 2 THIS DEVICE SHOULD BE A DISK
C                          A DECTAPE TAKES TOO LONG
51         FORMAT(I4)
           WRITE(6,52)
52         FORMAT(7H HEIGHT)
           READ(6,53) XHT
53         FORMAT(F5.1)
           IF(OP .EQ. 0) GO TO 3
           WRITE(6,54)
54         FORMAT(10H FILE NAME)
           READ(6,55) FNAME(1),FNAME(2)
55         FORMAT(A5,1X,A4)
           CALL ENTER(DT,FNAME)
C          ONE EXTRA LINE MUST BE ADDED TO THE BEGINNING OF THE FILE
C          AND TWO AT THE END FOR THE HP 9830 GRAPH PROGRAM TO
C          WORK PROPERLY
           WRITE(DT,64) 0,600,0,0,0.,0,0.,0
C          WRITE HEADING
           WRITE(6,56)
56         FORMAT(1X//1X,4HDATE,20X,10HFREQ (MHZ),20X,9HCRIT FREQ///
          115X,5H1 HOP,28X,5H2 HOP/22H  TIME  FR    HGT   AMP,
          224X,9HHGT    AMP)
C          ARGUEMENTS FOR RDATA
3          CALL RDAT(T,CDATA,FI)
           NH=0
C----------------------------------------------------------------------
C          BEGINNING OF DATA COLLECTION
200        CALL GO(LL)
C          LL=1 IF SWITCH 0 IS SET
C            =1 IF SWITCH 0 IS RESET
           IF (LL .EQ. 0) GO TO 20
C          NH COUNTS # OF 10 SECOND PERIODS SINCE START
           NH=NH+1
C          IT IS RESET AFTER 100 MIN
           IF (NH .GT. 600) NH=1
C          IM AND IS ARE THE TIME IN MINUTES AND 10'S OF SECONDS
           IM=(NH-1)/6
           IS=NH-1-IM*6
C          WAIT FOR ADC INTERRUPT ROUTINE TO FILL CDATA
           CALL RDATA
           F=FR-FI
C          CALCULATE FACTOR TO CONVERT NUMBERS IN CDATA TO MILLIVOLTS
           FRI=FRJ/FLOAT(F)
           IF (OP .EQ. 1) GO TO 30
C----------------------------------------------------------------------
C          THE FOLLOWING SECTION PRINTS ECHO HEIGHTS FOUND NEAR
C          XHT. IT IS USED TO GET AN ACCURATE HEIGHT FOR STARTING THE
C          DATA COLLECTION
           IX=INT(XHT*2./3.)-BG+1
           TO=TI
C          IX IS THE CENTER OF THE REGION IN CDATA THAT IS SEARCHED
C          FOR ECHOES
           CALL ECHO(IX,NE,EH,EA)
```

```
        TI=TO
        IF (NE .EQ. 0) GO TO 11
C.      LOOK FOR THE LARGEST ECHO
        L=1
        DO 10 I=1,NE
10      IF (EA(I) .GT. EA(L)) L=I
C       CENTER THE BACKGROUND ECHO SHAPE GRAPH ON THE HIGHEST ECHO
        KKK=INT(EH(L)*2./3.+.5)-BG+1
        HDATA(NH)=EH(L)
        IFLAG=0
        WRITE(6,57) IM,COL,IS,F,(EH(I),I=1,NE)
57      FORMAT(1X,I2,A1,I1,1H0,I4,10F6.1)
        GO TO 200
C       NO ECHOES FOUND
11      KKK=IX
C       START THE BACKGROUND ECHO SHAPE PROGRAM, DO NOT FIT PARABOLA
        IFLAG=-1
4       WRITE(6,57) IM,COL,IS,F
        GO TO 200
C------------------------------------------------------------------
C       IF OPERATION = 1, CLOSE DATA FILE
20      IF (OP .EQ. 0) GO TO 100
        I=-1
        WRITE(DT,64) I,600,0,0,0.,0,0.,0
        WRITE(DT,64) I,600,0,0,0.,0,0.,0
        CALL CLOSE(DT)
        GO TO 100
C------------------------------------------------------------------
C       DATA COLLECTION
30      IX=INT(XHT*2./3.)-BG+1
C       WRITE FIRST PART OF LINE. ALT SUPPRESSES CARRIAGE RETURN
        WRITE(6,58) IM,COL,IS,F,ALT
58      FORMAT(1X,I2,A1,I1,1H0,I4,1X,A1)
C       ZERO OUT HEIGHT AND AMPLITUDE ARRAYS
        DO 31 I=1,5
        HT(I)=0.
31      IA(I)=0
        HDATA(NH)=0.
        LL=0
        TO=T1
C       SEARCH FOR ECHOES NEAR XHT
        CALL ECHO(IX,NE,EH,EA)
        TI=TO
        IF (NE .EQ. 0) GO TO 46
C       FIND ECHO CLOSEST TO XHT
        CALL PCK(J,EH,XHT,NE)
        K=1
        IF (J .EQ. 0) GO TO 32
C       MAIN ECHO FOUND
        X=EH(J)
        HT(1)=X
        IA(1)=EA(J)
        EA(J)=-1000
        KKK=INT(X*2./3.+.5)-BG+1
C       NEW XHT
        XHT=X
C       SAVE HEIGHT FOR HEIGHT VS. TIME GRAPH
        HDATA(NH)=X
```

```
C          START BACKGROUND GRAPH PROGRAM
           IFLAG=0
           K=2
C          ARRANGE OTHER ECHOES IN ORDER OF THERE AMPLITUDES
32         DO 34 LL=K,3
           IF (NE .LT. LL) GO TO 35
           I=1
           DO 33 J=1,NE
33         IF (EA(J) .GT. EA(I)) I=J
           HT(LL)=EH(I)
           IA(LL)=EA(I)
34         EA(I)=-1000
           LL=4
35         LL=LL-1
C          PRINT OUT ONE-HOP ECHOES AND THEIR AMPLITUDES
C          1H+ SUPPRESSES LINE FEED AT THE START OF A LINE
           DO 36 I=1,LL
36         WRITE(6,59) HT(I),IA(I),ALT
59         FORMAT(1H+,1X,F6.2,I4,A1)
37         J=2
C          IF THERE ARE MORE THAN 3 ONE-HOP ECHOES, PRINT A *
           IF (NE .LE. 3) J=1
           WRITE(6,60) SB(J),ALT
60         FORMAT(1H+,2A1)
           IX=INT(XHT*4./3.)-BG+1
           L=4
           TO=T2
C          LOOK FOR TWO-HOP ECHOES
           CALL ECHO(IX,NE2,EH,EA)
           T2=TO
           IF (NE2 .EQ. 0) GO TO 41
C          SPACE OVER TO TWO-HOP COLUMNS
           L=(3-LL)*11
           WRITE(6,61) (SB(I),I=1,L),ALT
61         FORMAT(1H+,50A1)
C          ARRANGE TWO-HOP ECHOES IN ORDER OF THEIR AMPLITUDES
           DO 39 L=4,5
           IF (NE2 .LT. L-3) GO TO 40
           I=1
           DO 48 J=1,NE2
48         IF (EA(J) .GT. EA(I)) I=J
           HT(L)=EH(I)
           IA(L)=EA(I)
C          PRINT OUT TWO-HOP ECHO HEIGHT AND AMPLITUDE
           WRITE(6,59) HT(L),IA(L),ALT
39         EA(I)=-1000
           L=6
40         IF (NE2 .LE. 2) GO TO 41
C          END LINE WITH A * IF THERE ARE MORE THAN 2 TWO-HOP ECHOES
           WRITE(6,62)
62         FORMAT(2H+*)
           GO TO 42
41         WRITE(6,63)
63         FORMAT(2H+ )
C          ELIMINATE SPACES IN ARRAY IH AND HT
42         L=L-4
           DO 43 I=1,L
           J=LL+I
           K=3+I
```

```
        HT(J)=HT(K)
 43     IA(J)=IA(K)
        L=L+LL
        IF (L .GE. 5) GO TO 45
        J=L+1
        DO 44 I=J,5
        HT(J)=0.
 44     IA(J)=0
 C      STORE DATA ON .DAT 2
 45     WRITE(DT,64) HH,F,L,LL,(HT(I),IA(I),I=1,2)
 64     FORMAT(1X,I3,I4,I2,I2,2(F7.2,I4))
 C      IF THERE ARE MORE THAN 2 ECHOES TOTAL, STORE THE REST
 C      ON THE NEXT LINE
        IF (L .LE. 2) GO TO 200
        WRITE(DT,65) (HT(I),IA(I),I=3,5)
 65     FORMAT(1X,3(F7.2,I4))
        GO TO 200
 C      NO ECHOES FOUND, GRAPH AMPLITUDE NEAR XHT BUT DO NOT
 C      FIT PARABOLA
 46     KKK=IX
        IFLAG=-1
        GO TO 37
        END



        .TITLE  RDATA    /MACRO SUBPROGRAMS FOR RRPROC
        .GLOBL  RDATA,RDAT,BGDAT,.DA,GO
        .DEC
NSAM=530
TH=50
FR=600
        .OCT
CP=204
SCR=112
TT=6
/----------------------------------------------------------------
GO      0               /SET SW TO 1 IF DATA SWITCH 0 IS SET
        JMS*    .DA     /         0 IF DATA SWITCH 0 IS RESET
        JMP     .+2
SW      0
        DZM*    SW
        LAS
        SPA
        ISZ*    SW
        JMP*    GO
/----------------------------------------------------------------
RDAT    0               /PARAMETERS FOR DATA COLLECTION
        JMS*    .DA
        JMP     .+4
T       0               /LOC OF LOC OF ARRAY TO CONVERT ADC #'S TO BIN #'S
BUF3    0               /LOC OF LOC OF AVERAGED INTEGER DATA
I       0               /LOC OF # OF FRAMES IGNORED
        .INIT   TT,1,RDAT
        DZM*    (CP     /FOREGROUND IS ^C CONFIRMER
        LAC*    T
        DAC     T       /PUT LOC OF ARRAY T IN T
        LAC*    BUF3    /PUT LOC OF ARRAY CDATA IN BUF3
```

```
            DAC     BUF3
            LAC     (NSAM*3 /SET UP CODE TO TAKE ADC DATA FROM BUF1
            PAL             /CONVERT IT TO INTEGERS IN THE RANGE 218
            CLX             /TO -218 AND ADD IT TU BUF3
            LAC     T2      /STRAIGHT LINE CODE IS NEEDED TO ACHIEVE HIGH
   A        DAC     T2,X    /SPEED
            IAC
            AXS     3
            JMP     A
            CLX
            LAC     T2+1
   B        DAC     T2+1,X
            IAC
            AXS     3
            JMP     B
            CLX
            LAC     T2+2
   C        DAC     T2+2,X
            IAC
            AXS     3
            JMP     C
            LAC     (NSAM   /ZERO OUT BUF2
            PAL
            CLX
   D        DZM     BUF2,X
            AXS     1
            JMP     D
            LAC     (-FR    /SETUP NUMBER OF FRAMES TO BE AVERAGED
            DAC     F
            LAC     (1      /SET FLG TO 1, SET TO 0 WHEN 600 FRAMES HAVE
            DAC     FLG     /BEEN AVERAGED
            DZM     FIG     /ZERO OUT # OF FRAMES DISCARDED AS TOO NOISY
            JMS     ADGET   /START A TO D CONVERTER
            JMP*    RDAT
/------------------------------------------------------------------------
BGDAT       0               /DATA FOR BACKGROUND PROGRAMS
            JMS*    .DA
            JMP     .+12
FLAG        0               /LOC OF WORD SET TO 0 WHEN AN ECHO HAS BEEN FOUND
K           0               /CENTER OF MAIN ECHO
CDATA       0               /ARRAY OF AVERAGED DATA
HDATA       0               /ARRAY OF HEIGHT VS TIME DATA
NH          0               /LOC OF NUMBER OF 10 SECOND PERIODS
IM          0               /LOC OF TIME IN MINUTS
IS          0               /LOC OF TIME IN SECONDS
FRI         0               /LOC OF AMPLITUDE NORMALIZATION FACTOR
THR         0               /LOC OF 1 HOP THRESHOLD
            LAC*    CDATA
            DAC     CDATA
            LAC*    HDATA
            DAC     HDATA
            LAC     (FLAG   /LOC SCR IS UNUSED REGISTOR IN .SCOM TABLE
            DAC*    (SCR    /BGD PROG LOOKS THERE TO FIND LOC OF FLAG
            JMP*    BGDAT   /AND OTHER DATA
/------------------------------------------------------------------------
RDATA       0               /WAIT FOR ALL FRAMES TO BE COLLECTED
            LAC     F
            PAX
            LAC     FLG
```

```
        SZA
        JMP     E
        .WAIT   TT         /ALL 600 FRAMES COLLECTED BEFORE PROGRAM GOT TO
        .WRITE  TT,2,MSG2,6    /THIS POINT, SLOW PROC,  TIME SCALE IS OFF
        JMP     H
E       PXA                /ALL 600 FRAMES NOT COLLECTED YET
        TAD     (10        /IF THERE ARE LESS THAN 10 FRAMES LEFT TO BE
        SMA                /AVERAGED IN, GO TO G AND LOOP UNTILL ALL
        JMP     G          /HAVE BEEN AVERAGED
        DAC     .+4        /OTHERWISE START TIMER FOR (F-10)/60 SECONDS
        .TIMER  0,TINT,0          /AND GIVE TIME TO BACKGROUND
        .IDLE
TINT    0                  /RETURN HERE WHEN TIME ELAPSES
        DZM     TINT
G       LAC     FLG        /SHOULD TAKE 1/6 SEC TO FINISH COLLECTION
        SZA                /IF TIME IS UP CONTINUE
        JMP     J          /OTHERWISE GO TO J
H       ISZ     FLG        /RESET FLAG
        DZM     DIE        /ZERO OUT DIE, ADC WORKED OK
        LAC     TFIG       /TRANSFER FRAMES IGNORED
        DAC*    I
        JMP*    RDATA      /RETURN
J       LAC     (-1
        DAC     DIE
        .TIMER  60,DEAD,0         /START TIMER FOR 1 SECOND
L       LAC     FLG        /LOOP UNTILL ALL FRAMES HAVE BEEN COLLECTED
        SZA
        JMP     L
        JMP     H
DIE     0
DEAD    0                  /IF 1 SEC TIMER HAS ELAPSED AND ALL FRAMES ARE
        ISZ     DIE        /COLLECTED, DIE=0, RETURN
        SKP                /IF ALL FRAMES HAVE NOT BEEN COLLECTED, DIE=-1
        JMP     M          /THE ADC FAILED TO START WHEN COMMANDED TO
        .RLXIT  DEAD
M       DZM     DEAD
        LAC     (NSAM      /PREPARE TO RESTART ADC
        PAL                /ZERO OUT BUF2
        CLX
N       DZM     BUF2,X
        AXS     1
        JMP     N
        LAC     (-FR
        DAC     F
        LAC     (1
        DAC     FLG
        DZM     FIG
        JMS     ADGET      /RESTART ADC
        .WAIT   TT         /PRINT ERROR MESSAGE
        .WRITE  TT,2,MSG1,12
        JMP     SW+1       /RETURN TO RPROC
/------------------------------------------------------------------------
MSG1    2000               /ERROR MESSAGES
        0
        .ASCII  /ADC DIED/<15>
MSG2    2000
        0
        .ASCII  /SP/<15>
/------------------------------------------------------------------------
```

```
/        ADC INTERFACE INSTRUCTIONS
ADWI=703724       /WRITE INITIALIZE
ADSO=703701       /SKIP ON OVERFLOW
ADST=703721       /SKIP ON TIMING ERROR
ADCO=703704       /CLEAR OVERFLOW
ADCT=703744       /CLEAR TIMING ERROR FLAG
.SETUP=155
.SCOM=100
ADWCR=26
ADCAR=ADWCR+1
ADGET    0                    /ADC SERVICE ROUTINE
         JMP     ADFST   /FIRST TIME THRU GO TO ADFST
         DAC*    (ADWCR) /PUT NUMBER OF SAMPLES TO BE COLLECTED IN LOC 27
         LAC     (BUF1-1 /PUT LOC OF BUF1 IN LOC 26
         DAC*    (ADCAR)
         ADWI            /START ADC
         JMP*    ADGET
ADFST    LAC*    (.SETUP)
         DAC     .
         JMS*    .-1
         ADSO
         ADINT
         LAC*    (.SCOM+51
REALTP   DAC     .
         LAC*    (.SCOM+54
CALL4    DAC     .
         LAW     -NSAM
         DAC     ADGET+1
         JMP     ADGET+2
ADINT    0                    /ADC INTERUPT ROUTINE
                             /PROCESSING STARTS HERE AFTER ONE FRAME HAS
                             /BEEN COLLECTED. THE DATA IN A FRAME IS
                             /ADDED TO BUF2 AND EVERY 600 FRAMES, BUF2 IS
                             /TRANSFERED TO BUF3 AND BUF2 IS ZEROED OUT
                             /THEN THE ADC IS RESTARTED. ALL THIS MUST BE
                             /DONE IN LESS THAN 11.4 MSEC TO PREVENT
                             /MISSING A FRAME OR STARTING THE
                             /ADC IN THE MIDDLE OF A FRAME
         DBA
         DAC     ADSA
         ADST
         SKP
         ISZ     ERR     /SET ERR TO 1 IF A TIMING ERROR HAS OCCURED
         ADCO            /IN THE ADC INTERFACE
         ADCT
         LAC     (600000+RTS        /SET UP ENTRY TO THE PROCESSING
         JMS*    REALTP  /SUBROUTINE AT A LOWER PRIORITY LEVEL
         JMS*    CALL4
         ADINT
         0
         LAC     ADSA
         DBR
         JMP*    ADINT
RTS      0
         DAC     AREG    /SAVE THE A, X AND L REGISTERS
         PXA
         DAC     XREG
         PLA
         DAC     LREG
```

```
        LAC     ERR
        DZM     ERR     /ZERO OUT ERR
        SZA             /IF THERE WAS A TIMING ERROR, GO TO S
        JMP     S       /DATA FOR THIS FRAME IS LOST
        LAC     T       /SET UP FOR CONVERTING ADC NUMBERS TO INTEGERS
        PAX
        LAC*    BUF1,X  /IF THE AMPLITUDE OF THE FIRST SAMPLE IS GREATER
        TAD     (-TH    /THAN A THRESHOLD THE WHOLE FRAME IS ASSUMED TO
        SMA             /BE NOISY AND IT IS IGNORED
        JMP     S
T2      LAC*    BUF1,X  /CONVERT NUMBER IN BUF1 TO INTEGER
        TAD     BUF2    /ADD CORRESPONDING ENTRY OF BUF2
        DAC     BUF2    /STORE SUM BACK IN BUF2
        .BLOCK  3*NSAM-3        /REPEAT FOR EACH SAMPLE IN BUF1
P       ISZ     F       /DONE WITH ONE FRAME, ADD ONE TO F
        JMP     R       /IF ALL FRAMES ARE NOT COLLECTED, GO TO R
        LAC     FIG     /ALL FRAMES COLLECTED, SAVE THE NUMBER OF FRAMES
        DAC     TFIG    /IGNORED
        DZM     FIG
        LAC     (-FR    /SETUP TO RESTART ADC
        DAC     F
        DZM     FLG
        LAC     (NSAM   /TRANSFER BUF2 TO BUF3 AND ZERO OUT BUF2
        PAL
        CLX
Q       LAC     BUF2,X
        DAC*    BUF3,X
        DZM     BUF2,X
        AXS     1
        JMP     Q
        LAS             /IF DATA SWITCH 0 IS SET GO TO R, CONTINUE
        SPA             /PROCESSING
        JMP     R
        LAC     LREG    /IF DATA SWITCH 0 IS 0, LOAD REGISTERS WITH
        PAL             /THEIR ORIGINAL CONTENTS AND RETURN
        LAC     XREG
        PAX
        LAC     AREG
        .RLXIT  RTS
R       LAC     XREG    /RESTORE REGISTERS, RESTART ADC AND RETURN
        PAX
        LAC     LREG
        PAL     .
        JMS     ADGET
        LAC     AREG
        .RLXIT  RTS
S       ISZ     FIG
        JMP     P
ADSA    0
TFIG    0
F       0
FLG     0
FIG     0
AREG    0
XREG    0
LREG    0
ERR     0
BUF1    .BLOCK  NSAM
BUF2    .BLOCK  NSAM
        .END
```

```fortran
      SUBROUTINE ECHO(IX,NE,EH,EA)
C     SUBROUTINE ECHO SEARCHES THE AREA FROM 50 DIVISIONS
C     BELOW IX TO 50 DIVISIONS ABOVE IX FOR ECHOES
C     A THRESHOLD IS CALCULATED AS BEING 5 TIMES THE AVERAGE
C     NOISE. AN ECHO IS 4 OR MORE CONTINUOUS SAMPLES ABOVE
C     THE THRESHOLD
      REAL EH(10)
      INTEGER CD(530),CDATA(101),EA(10),T,BG
      COMMON /DATAS/ CD,BG,T,FRI
      NE=0
      MIN=CD(IX)
      U=0.
      J=0
C     DO NOT SEARCH OUTSIDE OF CDATA
      IF (IX .LT. 51) IX=51
      IF (IX .GT. 475) IX=475
      DO 1 I=1,101
      II=IX-51+I
      K=CD(II)
C     AN AMPLITUDE ABOVE THE THRESHOLD IS ASSUMED TO BE
C     PART OF AN ECHO AND NOT INCLUDED IN THE NOISE
      IF (K .GT. T) GO TO 1
      IF (K .LT. MIN) MIN=K
C     SUM UP NOISE SAMPLES
      U=U+FLOAT(K)
      J=J+1
1     CDATA(I)=K
C     IF THRESHOLD IS TOO LOW THERE WILL NOT BE ENOUGH NOISE SAMPLES
      IF (J .LT. 50) GO TO 11
C     CALCULATE AVERAGE NOISE AND NEW THRESHOLD
13    U=U/FLOAT(J)
      T=MIN+5*(INT(U)+1-MIN)
      I=1
C     SKIP OVER SAMPLES ABOVE THRESHOLD AT BOTTOM OF RANGE
C     ALL OF THAT ECHO MAY NOT BE IN THE ARRAY
3     IF (CDATA(I) .LT. T) GO TO 4
      I=I+1
      IF (I .GT. 101) RETURN
      GO TO 3
C     LOOK FOR AN AMPLITUDE ABOVE THE THRESHOLD
4     IF (CDATA(I) .GT. T) GO TO 5
      I=I+1
      IF (I .GT. 101) RETURN
      GO TO 4
C     FIND WIDTH OF REGION ABOVE THRESHOLD AND MAXIMUM AMPLITUDE
5     K=I
      DO 6 J=1,101
      M=J+I
      IF (M .GT. 101) RETURN
      IF (CDATA(M) .GT. CDATA(K)) K=M
      IF (CDATA(M) .LT. T) GO TO 7
6     CONTINUE
7     I=M
C     IF WIDTH IS LESS THAN 4 DIVISIONS, IT IS NOT AN ECHO
      IF (J .LT. 4) GO TO 4
      I=I-J
      NE=NE+1
      IF (NE .GT. 10) RETURN
```

```
C         FIND PARAMETERS OF ECHO AND FIT A PARABOLA TO IT
          Z=CDATA(K-1)
          C=CDATA(K)
C         RECORD ECHO AMPLITUDE
          EA(NE)=C*FRI+.5
          X=CDATA(K+1)
          A=(X-C-C+Z)/2.
          B=(X-Z)/2.
C         CALCULATE INTERPOLATED HEIGHT
          Z=-B/(A+A)
          A=A*.6
C         RECORD ECHO HEIGHT
          EH(NE)=(Z+FLOAT(IX+K+BG-52))*3./2.
C         CALCULATE WIDTH OF ECHO AT A POINT HALF WAY BETWEEN THE
C         MINIMUM AND THE MAXIMUM AMPLITUDE OF THE ECHO
          W=(B*B/A-(2.*(C-FLOAT(MIN)*FRI)))/A
          IF (W .LE. 0.) GO TO 10
          W=SQRT(W)
          I1=K-INT(W)
          I2=K+INT(W)
          IF (I1 .LT. 1) I1=1
          IF (I2 .GT. 101) I2=101
C         SUBTRACT PARABOLA FROM PART OF ECHO ABOVE THE HALF WAY
C         POINT AND SUBTRACT AN INVERTED PARABOLA FROM THE PART
C         OF THE ECHO BELOW THE HALF WAY POINT
          DO 8 J=I1,I2
          X=K-K
          Y=(A*X+B)*X+C
          IF (ABS(X) .LT. W/2.) GO TO 8
          U=W
          IF (X .LT. 0.) U=-W
          Y=-(A*(X-U)+B)*(X-U)+FLOAT(MIN)
8         CDATA(J)=CDATA(J)-INT(Y)+MIN
          IF (NE .EQ. 1) GO TO 4
          X=EH(NE)-EH(NE-1)
          IF (X .LT. 0.) GO TO 4
          IF (X .GT. 14.) GO TO 4
          X=FLOAT(EA(NE))/FLOAT(EA(NE-1))
          IF (X .GT. .225) GO TO 4
10        NE=NE-1
          I=M
          GO TO 4
C         IF THRESHOLD IS TOO LOW, RECOMPUTE IT STARTING WITH
C         A HIGHER VALUE
11        T=250./FRI
          J=0
          U=0.
          DO 12 I=1,101
          IF (CDATA(I) .GT. T) GO TO 12
          U=U+FLOAT(CDATA(I))
          J=J+1
12        CONTINUE
          IF (J .LT. 50) RETURN
          GO TO 13
          END
```

```
      SUBROUTINE PCK(J,H,XHT,NE)
C     SUBROUTINE PCK FINDS THE ECHO CLOSEST TO XHT AND SETS J
C     EQUAL TO THE POSITION OF THAT ECHO IN ARRAY H. IF NO ECHO
C     IS WITHIN 20 KM OF XHT, J IS SET TO 0 ON RETURN
      REAL H(10)
      D=20.
      J=0
      DO 1 I=1,NE
      A=ABS(H(I)-XHT)
      IF (A .GT. D) GO TO 1
      J=I
      D=A
1     CONTINUE
      RETURN
      END




C     BGRAPH
C     PROGRAM BGRAPH PRODUCES A GRAPH OF THE HEIGHT VARIATION OF THE
C     MAIN ECHO OVER AN 11 MINUTE PERIOD OR A GRAPH OF THE ONE-
C     AND TWO-HOP ECHO SHAPES
      REAL A(25,3),F(67)
      INTEGER B(25),D(25),TI(12),BG,FR,T,COL,FF
      COMMON/DAT/A,F
      DATA BLAN,STAR/1H ,1H*/
      COL=(3*3+5)*4096
      CALL INIT(B,D,K,FR,T,FF)
C     READ SETTING OF SWITCH 17, IF SET, GO TO 2 AND GRAPH HEIGHT
C     VS. TIME  IF IT IS RESET, TO TO 10 AND GRAPH THE ECHO SHAPE
1     CALL SWR
      IF(K) 1,10,2
C     READ STARTING TIME FOR HEIGHT VS. TIME GRAPH
2     READ(6,50) IT
50    FORMAT(I2)
C     CLEAR SCREEN
      CALL ZAP(25)
      FMAX=0.
      FMIN=1000.
C     FIND PRESENT TIME
      CALL NFRM
      J=IT*6+1
C     IF STARTING TIME IS GREATER THAN PRESENT TIME GO BACK AND
C     READ SWITCH SETTING AGAIN
      IF (K .LE. J) GO TO 1
C     SET END TIME AT K OR 11 MIN GREATER THAN STARTING TIME,
C     WHICHEVER IS SMALLER
      IF (K .GT. J+66) K=J+66
      DO 3 I=J,K
      CALL HGET(C,I)
      IF (C .EQ. 0.) GO TO 3
C     FIND MINIMUM AND MAXIMUM HEIGHT OVER THE RANGE OF THE GRAPH
      IF (C .GT. FMAX) FMAX=C
      IF (C .LT. FMIN) FMIN=C
3     CONTINUE
C     CALCULATE NORMALIZATION FACTOR
      SP=(FMAX-FMIN)/25.
```

```
C            DIVIDE THE HEIGHT RANGE INTO 25 PARTS
             DO 6 II=1,25
             FMIN=FMAX-SP
             FH=FMAX-SP/2.
             M=1
             DO 4 I=1,67
4            F(I)=BLAN
C            FIND ECHOES IN PRESENT PART OF HEIGHT RANGE
             DO 5 I=J,K
             CALL HGET(C,I)
             IF (C .EQ. 0.) GO TO 5
             IF (C .GT. FMAX) GO TO 5
             IF (C .LE. FMIN) GO TO 5
             M=I+1-J
             F(M)=STAR
5            CONTINUE
C            OUTPUT ONE LINE OF THE GRAPH
             WRITE(6,51) FH,(F(I),I=1,M)
51           FORMAT(1X,F5.1,67A1)
             FMAX=FMIN
6            CONTINUE
C            SETUP AND WRITE OUT THE TIME AXIS
             DO 7 I=1,12
7            TI(I)=IT+I-1
             WRITE(6,52)(TI(I),I=1,12)
52           FORMAT(1X,12I6)
             GO TO 1
C----------------------------------------------------------------
C            ECHO SHAPE GRAPH
10           BG=30
             FF=1
C            FILL ARRAYS B AND D WITH PROPER SECTION OF CDATA
             CALL BDATA
             N=2+FF
C            CALCULATE FACTOR TO CONVERT INTEGERS IN B AND D TO MILLIVOLTS
             FRI=75000./(16384.*FLOAT(FR))
             THR=FLOAT(T)*FRI
C            CONVERT DATA IN B AND D TO MILLIVOLTS AND PUT IN REAL ARRAY
             DO 11 I=1,25
             J=26-I
             A(J,2)=FLOAT(D(I))*FRI
             A(J,1)=FLOAT(B(I))*FRI
11           CONTINUE
             PM=0.
C            SKIP PARABOLA FIT IF NO MAIN ECHO WAS FOUND
             IF (FF .EQ. 0) GO TO 12
             CALL PARA(A,PM)
             KK=K+BG-1
             PM=1.5+(FLOAT(KK)+PM)
C            GET TIME AND CLEAR SCREEN
12           CALL TIME(IM,IS)
             CALL ZAP(28)
             CALL GRAPH(N,KK,IM,COL,IS,PM,THR)
             GO TO 1
             END
```

```
                .TITLE BDATA
/               THESE SUBROUTINES TAKE DATA FROM THE FOREGROUND PROGRAMS AS
/               NEEDED TO DEVELOP THE GRAPHS ON THE BACKGROUND TERMINAL
                .GLOBL SWR,BDATA,HGET,INIT,.DA,NFRM,TIME
SCR=112
INIT    0                       /INITIALIZATION ROUTINE
        JMS*    .DA             /ARGUEMENTS ARE SET UP NOW TO SAVE TIME LATER
        JMP     .+7
B       0
D       0
K       0
FR      0
THR     0
FF      0
        LAC*    (SCR            /LOCATION SCR IS AN UNUSED REGISTER IN THE
        DAC     LOC             /TABLE. IT CONTAINS THE LOC OF THE ARRAY IN
        LAC*    LOC             /WHICH THE LOC OF DATA FOR BGRAPH IS KEPT
        DAC     FLAG            /FLAG IS LOC OF WORD WHICH IS SET TO 0 OR -1
        ISZ     LOC             /DEPENDING ON WHETHER AN ECHO WAS FOUND OR NOT
        LAC*    LOC
        DAC     KA              /KA IS LOC OF WORD CONTAINING INDEX OF CENTER
        ISZ     LOC             /OF MAIN ECHO IN CDATA
        LAC*    LOC
        DAC     CDATA           /CDATA CONTAINS LOC OF ARRAY CDATA
        ISZ     LOC
        LAC*    LOC
        DAC     HDATA           /HDATA CONTAINS LOC OF ARRAY HDATA
        ISZ     LOC
        LAC*    LOC
        DAC     NH              /LOC OF NUMBER OF 10 SEC. PERIODS SINCE START
        ISZ     LOC             /OF DATA COLLECTION
        LAC*    LOC
        DAC     LIM             /LIM AND LIS CONTAIN LOCATION OF TIME IN
        ISZ     LOC             /MINUTES AND SECONDS SINCE THE START
        LAC*    LOC             /OF DATA COLLECTION
        DAC     LIS
        ISZ     LOC
        LAC*    LOC
        DAC     F               /LOC OF WORD CONTAINING # OF FRAMES AVERAGED
        ISZ     LOC
        LAC*    LOC
        DAC     T               /LOC OF WORD CONTAINING ONE-HOP THRESHOLD
        JMP*    INIT
        .DEC
/-------------------------------------------------------------------
BDATA   0               /THIS SUBROUTINE TRANSFERS DATA FROM CDATA TO B AND D
A       LAC*    FLAG    /STAY IN THIS LOOP UNTIL FLAG IS SET TO 0 OR -1
        SZA!SMA
        JMP     A
        IAC
        SNA             /IF FLAG IS -1, PUT 0 IN FF, NO MAIN ECHO
        DZM*    FF
        LAC     (1      /RESET FLAG TO 1
        DAC*    FLAG
        LAC     (-25    /PREPARE TO TRANSFER 25 WORDS FROM CDATA TO B
        DAC     COUNT   /AMPLITUDE NEAR XHT
        LAC*    B
        DAC     BB      /LOC OF ARRAY B
        LAC*    KA      /GET CENTER OF ONE-HOP ECHO
```

```
              DAC*    K
              TAD     CDATA
              TAD     (-13      /FIRST WORD OF B IS AMPLITUDE 12 DIVISIONS BELOW
              DAC     I         /THE CENTER OF THE ONE-HOP ECHO
       C      LAC*    I         /TRANSFER DATA
              DAC*    BB
              ISZ     I
              ISZ     BB
              ISZ     COUNT
              JMP     C
              LAC     (-25      /SET UP COUNT FOR SECOND CURVE ON GRAPH,
              DAC     COUNT     /AMPLITUDE NEAR 2*XHT
              LAC*    D         /LOC OF ARRAY D
              DAC     BB
              LAC*    KA
              TAD*    KA
              TAD     CDATA
              TAD     (16
              DAC     I
       CT     LAC*    I         /TRANSFER DATA
              DAC*    BB
              ISZ     I
              ISZ     BB
              ISZ     COUNT
              JMP     CT
              LAC*    T         /GET THRESHOLD AND NUMBER OF FRAMES COLLECTED
              DAC*    THR
              LAC*    F
              DAC*    FR
              JMP*    BDATA
/----------------------------------------------------------------------
HGET   0                       /THIS ROUTINE RETURNS THE HEIGHT OF THE MAIN
              JMS*    .DA       /ECHO FOUND AT TIME IT*10 SECONDS
              JMP     .+3
CC     0
II     0
              LAC     HDATA
              TAD*    II
              TAD*    II
              TAD     (-2
              DAC     II
              LAC*    II
              DAC*    CC
              ISZ     II
              ISZ     CC
              LAC*    II
              DAC*    CC
              JMP*    HGET
/----------------------------------------------------------------------
NFRM   0                       /THIS SUBROUTINE RETURNS THE NUMBER OF 10 SECOND
              LAC*    NH        /PERIODS THAT HAVE ELAPSED SINCE THE START OF
              DAC*    K         /THE COLLECTION
              JMP*    NFRM
/----------------------------------------------------------------------
SWR    0                       /THIS SUBROUTINE RETURNS 1 IF SWITCH 17 IS
              LAS               /SET AND 0 IF IT IS RESET
              AND     (1
              DAC*    K
              JMP*    SWR
/----------------------------------------------------------------------
```

```
TIME        O                       /THIS SUBROUTINE RETURNS THE TIME IN MINUTES AND
            JMS*    .DA             /SECONDS SINCE THE START OF COLLECTION
            JMP     .+3
IM          0
IS          0
            LAC*    LIM
            DAC*    IM
            LAC*    LIS
            DAC*    IS
            JMP*    TIME
LIM         0
LIS         0
CDATA       0
KA          0
FLAG        0
I           0
COUNT       0
NH          0
HDATA       0
BB          0
LOC         0
T           0
F           0
            .END
```

```
      SUBROUTINE PARA(A,PM)
C     SUBROUTINE PARA FITS A PARABOLA TO THE ONE-HOP ECHO AND
C     DETERMINES THE ASSUMED SHAPE OF THE ECHO
      REAL A(25,3),MIN
      J=1
C     SET A(I,3) TO -1000 SO UNUSED PARTS WILL NOT APPEAR
C     ON THE GRAPH
      DO 1 I=1,25
      A(I,3)=-1000.
1     IF (A(I,1) .LT. A(J,1)) J=I
C     DETERMINE THE PARAMETERS OF THE PARABOLA
      MIN=A(J,1)
C     Z IS THE AMPLITUDE 1.5 KM BELOW THE CENTER OF THE ECHO
C     X IS THE AMPLITUDE 1.5 KM ABOVE THE CENTER OF THE ECHO
      Z=A(14,1)
      C=A(13,1)
      X=A(12,1)
      AC=(Z-C-C+X)/2.
      B=(X-Z)/2.
      PM=-B/(AC+AC)
      AC=AC*.6
      W=SQRT((B*B/AC-(2.*(C-MIN)))/AC)
      I1=13-INT(W)
      I2=13+INT(W)
      IF (I1 .LT. 1) I1=1
      IF (I2 .GT. 25) I2=25
C     CALCULATE SHAPE OF MODIFIED PARABOLA
      DO 8 I=I1,I2
      X=13-I
      Y=(AC*X+B)*X+C
      IF (ABS(X) .LT. W/2.) GO TO 8
```

```
          U=0
          IF (X .LT. 0.) U=-0
          Y=-(AC*(X-0)+B)*(X-0)+MIN
8         A(I,3)=Y
          RETURN
          END




          SUBROUTINE GRAPH(N,K,IM,COL,IS,PM,THR)
C         THIS SUBROUTINE PRODUCES A GRAPH OF THE AVERAGE AMPLITUDE
C         NEAR XHT AND 2*XHT. IF AN ECHO IS FOUND NEAR XHT, N=3 AND A
C         MODIFIED PARABOLA IS FITTED TO THE ECHO AND DISPLAYED ON THE
C         GRAPH, OTHERWISE N=2 AND NO PARABOLA IS GRAPHED.
C         K IS THE LOCATION OF THE MAIN ONE-HOP ECHO IN CDATA
C         IM AND IS ARE THE TIME IN MINUTES AND SECONDS
C         COL IS THE CODE FOR THE SYMBOL :
C         PM IS THE INTERPOLATED HEIGHT OF THE MAIN ECHO
C         THR IS THE THRESHOLD USED BY SUBROUTINE ECHO FOR THE
C         ONE-HOP ECHO
          REAL A(25,3),D(4),F(67)
          INTEGER COL
          COMMON/DAT/A,F
          DATA D(1),D(2),D(3),D(4)/1H0,1H#,1H+,1H*/
          DATA DASH,BLAN,EYE,ZERO,T/1H-,1H ,1HI,1H0,1HT/
          FMAX=-500.
          FMIN=500.
C         FIND MINIMUM AND MAXIMUM IN A(I,J) DO NOT COUNT THE PARABOLA
C         IN FINDING THE MINIMUM
          DO 1 I=1,25
          IF (A(I,1) .LT. FMIN) FMIN=A(I,1)
          IF (A(I,2) .LT. FMIN) FMIN=A(I,2)
          DO 1 J=1,N
1         IF(A(I,J) .GT. FMAX) FMAX=A(I,J)
          IF(FMIN) 2,3,3
C         NEGATIVE MINIMUM
C         CALCULATE 0 POSITION
2         IY=INT(-FMIN*6./(FMAX-FMIN))+1
          IF (IY .GT. 3) GO TO 20
C         CALCULATE AMPLITUDE NORMALIZATION FACTOR
          SP=FMAX/FLOAT(6-IY)*.1
          GO TO 5
C         LIMIT 0 POSITION OF MIN IS TOO NEGATIVE
20        IY=3
          SP=-FMIN/30.
          GO TO 5
C         POSITIVE MINIMUM
3         IY=0
          SP=FMAX/60.
C         SET UP FIRST LINE
5         DO 13 I=2,40
13        F(I)=DASH
C         PUT AN "I" IN EVERY 10TH POSITION
          DO 14 I=1,41,10
14        F(I)=EYE
          JZ=IY*10+1
C         INDICATE 0 POSITION
          F(JZ)=ZERO
```

```
C          WRITE FIRST LINE INCLUDING TIME AND HEIGHT OF ONE-HOP ECHO
           WRITE(6,4) (F(J),J=1,41),IM,COL,IS,PM
4          FORMAT(12H H(K)   AMP ,41A1,I4,A1,I1,1H0,3H  I,F8.3,2H I)
C          DO FOLLOWING FOR EACH OF THE 25 LINES OF THE GRAPH
           DO 16 I=1,25
C          MAX INDICATES THE LENGTH OF THE LINE
           MAX=JZ
C          IA IS AMPLITUDE OF ONE-HOP TRACE
           IA=INT(A(I,1)+.5)
C          FH IS THE CORRESPONDING HEIGHT
           FH=FLOAT(K+13-I)*1.5
C          BLANK OUT THE LINE
           DO 7 J=1,61
7          F(J)=BLAN
C          ADD 0 AMPLITUDE LINE
           F(JZ)=EYE
C          ADD SYMBOLS FOR EACH OF THE OTHER TRACES
           DO 8 J=1,N
           IM=INT(A(I,J)/SP+.5)+JZ
           IF (IM .LT. 0) GO TO 8
           IF (IM .GT. MAX) MAX=IM
           IF(F(IM)-BLAN) 9,10,9
C          IF THERE IS ALREADY A SYMBOL IN THAT PLACE, PUT A * THERE
9          F(IM)=D(4)
           GO TO 8
10         F(IM)=D(J)
8          CONTINUE
6          IF (I .NE. 1) GO TO 16
C          INDICATE THRESHOLD ON THE THIRD LINE
           J=INT(THR/SP+.5)+JZ
           IF (J .LT. 1) J=61
           IF (J .GT.61) J=61
           IF (J .GT. MAX) MAX=J
           F(J)=T
16         WRITE(6,11) FH,IA,(F(J),J=1,MAX)
11         FORMAT(1X,F5.1,I5,1X,61A1)
           RETURN
           END




           .TITLE ZAP
           .GLOBL ZAP,.DA
           .IODEV 6
ZAP        0
           JMS*    .DA
           JMP     .+2
ARG        0
           .WAIT   6
           LAW     (-1000
           DAC     CNT
LOP        ISZ     CNT
           JMP     LOP
           LAC     (176.
           JMS     PRNT
           LAW     (-1000
           DAC     CNT
BACK       ISZ     CNT
```

```
          JMP      BACK
          LAC*     ARG
          JMS      PRNT
          JMP*     ZAP
PRNT      0
          DAC      OUT
          .WRITE   6,3,BUF,3
          .WAIT    6
          JMP*     PRNT
BUF       2000
          0
OUT       0
          0
CNT       0
          .END
```

APPENDIX II. OPERATING INSTRUCTIONS AND A LISTING OF PROGRAM GRAPH

The following procedure is used to graph the data from the digital ionosonde once the data is on paper tape. A listing of the graph program is included after the operating instructions.

1. Turn on the calculator and the plotter. Insert the tape cassette marked Ionosonde Programs, type LOAD1 and press EXECUTE.

2. Adjust the plotter to the size of paper used and put a black pen in the plotter.

3. Turn on the paper tape reader, insert the paper tape and press READ.

4. At the calculator, press RUN and EXECUTE. Enter the number of 10 sec periods of data on the tape. If 0 is entered, the entire tape is read. The data are stored in the magnetic tape casette in blocks of 20 min.

5. When the data are on the magnetic tape, type in a heading for the graph such as the date and time of the data. If several graphs of the same data are needed, after one has been made, type CONT 520 and press EXECUTE to return to this point.

6. Enter the limits of the portion of the data to be graphed in minutes and seconds. If 0, 0 is typed in as the START and END times, all the data are graphed.

7. Type in the minimum height to be graphed. All echoes below this height are ignored. The calculator now makes one pass through the tape to determine the minimum and maximum heights and then plots an axis and the heading.

8. When the display reads PEN? change the pen to a blue one, type 0 and

press EXECUTE. The height data are now plotted for one one-hop and one two-hop echo.

9. When the display again reads PEN? change the pen to a red one, type 0 and press EXECUTE. The one-hop and two-hop amplitudes are now plotted.

10. When the display again reads PEN? put the blue pen back in the plotter, press 0 and EXECUTE. The extra one-hop and two-hop echoes are now added to the graph.

```
10 COM HS[5,120],AI[5,120]
20 DIM OI[4],Y$[30]
30 F=3
40 M=N=N1=1
50 G=I5=I7=0
60 DISP "FRMS";
70 INPUT I6
80 IF I6>0 THEN 100
90 I6=1439
100 IF N1+I7*600 >= I6 THEN 460
110 ENTER (1,120)N1,F1,E,E1,(FORI=1TO2,H[I,M],A[I,M])
120 FORMAT F3.0,F4.0,2F2.0,F7.2,F4.0,F7.2,F4.0
130 IF N1=0 THEN 100
140 IF N1<0 THEN 460
150 IF N1=N THEN 220
160 IF ABS(N+4-N1)<4 THEN 390
170 I7=I7+1
180 N=N-600
190 IF N1=N THEN 220
200 IF ABS(N+4-N1)<4 THEN 390
210 STOP
220 IF E<3 THEN 250
230 ENTER (1,240)(FORI=3TO5,H[I,M],A[I,M])
240 FORMAT F7.2,F4.0,F7.2,F4.0,F7.2,F4.0
250 E2=E-E1
260 FOR I=5 TO 1 STEP -1
270 IF I<4 THEN 350
280 IF E2<I-3 THEN 330
290 J=E1+I-3
300 H[I,M]=H[J,M]
310 A[I,M]=A[J,M]
320 GOTO 360
330 H[I,M]=A[I,M]=0
340 GOTO 360
350 IF I>E1 THEN 330
360 NEXT I
370 GOSUB 1230
380 GOTO 100
390 FOR I=1 TO 5
400 H[I,M+1]=H[I,M]
410 A[I,M+1]=A[I,M]
420 H[I,M]=A[I,M]=0
430 NEXT I
440 GOSUB 1230
450 GOTO 150
460 FOR I=1 TO 5
470 FOR J=M TO 120
480 H[I,J]=A[I,J]=-1006
490 NEXT J
500 NEXT I
510 STORE  DATA F
520 FIND 3
530 DISP "NAME";
```

```
540 INPUT Y$
550 DISP "START";
560 INPUT I1,I2
570 I1=I1*6+I2/10+1
580 DISP "END";
590 INPUT I2,I3
600 I2=I2*6+I3/10+1
610 DISP "MIN";
620 INPUT M9
630 IF I2>1 THEN 650
640 I2=1439
650 I5=1
660 GOSUB 1340
670 O[1]=O[3]=0
680 O[2]=O[4]=1000
690 IF M[1,M]<0 THEN 840
700 FOR J=1 TO 2
710 K=J+J
720 FOR I=3*J-2 TO K+1
730 S=M[I,M]
740 IF S=0 THEN 790
750 IF S<O[K-1] THEN 770
760 O[K-1]=S
770 IF S>O[K] OR S<M9 THEN 790
780 O[K]=S
790 NEXT I
800 NEXT J
810 IF N=I2 THEN 850
820 GOSUB 1230
830 GOTO 690
840 I2=N-1
850 FIND 3
860 SCALE -0.1,1.05,-1.25,1.25
870 FOR J=1 TO 2
880 K=J+J
890 S=O[K-1]-O[K]
900 OFFSET 0,1.2*J-2.3
910 GOSUB 1380
920 NEXT J
930 LABEL (*,3,2,0,0.6)
940 PLOT 0.5,1.05,1
950 CPLOT -LEN(Y$)/2,0
960 LABEL (*)Y$
970 LABEL (*,1.7,2,0,0.6)
980 FOR O=1 TO 2
990 GOSUB 2070
1000 FOR L=1 TO 2
1010 R=3*L-2
1020 OFFSET 0,1.2*L-2.3
1030 PLOT 0.85,1.07,1
1040 K=L+L
1050 IF O=2 THEN 1110
1060 LABEL (*)"HEIGHT";
```

```
1070 S=O[K-1]-O[K]
1080 I3=R
1090 GOSUB 1690
1100 GOTO 1150
1110 CPLOT 0,-0.87
1120 LABEL (*)"AMPLITUDE";
1130 I3=R+1
1140 GOSUB 1690
1150 NEXT L
1160 NEXT Q
1170 GOSUB 2070
1180 OFFSET 0,-1.1
1190 I3=3
1200 GOSUB 1690
1210 PLOT 1.05,2.35,1
1220 STOP
1230 N=N+1
1240 M=M+1
1250 IF M<121 THEN 1300
1260 M=1
1270 IF I5=1 THEN 1310
1280 STORE   DATA F
1290 F=F+1
1300 RETURN
1310 PEN
1320 LOAD   DATA F
1330 GOTO 1290
1340 F=INT((I1-1)/120)+3
1350 N=I1
1360 M=I1-(F-3)*120
1370 GOTO 1310
1380 I3=(I2-I1)/6
1390 LABEL (*,1.7,2,0,0.6)
1400 FOR I=0 TO I3 STEP 10
1410 PLOT I/I3,0,1
1420 CPLOT -3.3,-1.1
1430 IF I<10 THEN 1450
1440 CPLOT 0.4*INT(1+I/100),0
1450 LABEL (1470)I;
1460 NEXT I
1470 FORMAT F4.0
1480 X=20
1490 IF S/X>4 THEN 1510
1500 X=10
1510 FOR I=0 TO S/X
1520 PLOT 0,I*X/S,1
1530 CPLOT -6.5,-0.3
1540 LABEL (1560)(O[K]+I*X);
1550 NEXT I
1560 FORMAT F5.0,"."
1570 XAXIS 0,10/I3,0,1
1580 YAXIS 0,X/S,0,1
1590 PLOT -0.055,0.3,1
```

```
1600 LABEL (*,1.7,2,PI/2,0.6)"HEIGHT  (KM)";
1610 LABEL (*,1.7,2,0,0.6)
1620 PLOT 0.5,0,1
1630 CPLOT -6,-2.1
1640 LABEL (*)"TIME  (MIN)";
1650 PLOT 0.2,1.02,1
1660 LABEL (1670)J
1670 FORMAT F3.0," HOP"
1680 RETURN
1690 GOSUB 1340
1700 Y=0
1710 P=I2-I1
1720 IF I3=3 THEN 1800
1730 J=2
1740 X=H[R,M]
1750 IF X<O[K] THEN 1860
1760 IF ABS(X-Y)>3 THEN 1780
1770 GOTO 1800
1780 PEN
1790 J=-2
1800 GOSUB I3 OF 1900,1920,1940,1900,1920
1810 PLOT (N-I1)/P,G,J
1820 Y=X
1830 IF N=I2 THEN 1880
1840 GOSUB 1230
1850 GOTO 1720
1860 J=1
1870 GOTO 1810
1880 PEN
1890 RETURN
1900 G=(X-O[K])/S
1910 RETURN
1920 G=A[R,M]/1000
1930 RETURN
1940 FOR J=1 TO 2
1950 K=J+J
1960 S=O[K-1]-O[K]
1970 FOR I=K+J-1 TO K+1
1980 X=H[I,M]
1990 IF X <= M9 THEN 2030
2000 G=(X-O[K])/S+1.2*J-1.2
2010 PLOT (N-I1)/P,G
2020 PEN
2030 NEXT I
2040 NEXT J
2050 J=1
2060 RETURN
2070 PLOT 1.05,1.15,1
2080 FIND 3
2090 DISP
2100 DISP "PEN";
2110 INPUT I3
2120 RETURN
```

APPENDIX III.   OPERATING INSTRUCTIONS AND A LISTING OF PROGRAM SHAPE

Program SHAPE calculates the virtual height and amplitude for a reflector and provides easy methods for modifying the reflector shape to make the calculated virtual height and amplitude match the experimental data.

1. Turn on the calculator and plotter, insert the tape cassette marked Ionosonde Programs and type LOADKEY0 and press EXECUTE. Put the function key overlay marked SHAPE over the function keys.

2. Press RUN and INIT (f_0). The calculator asks for the limits of the reflector size. If a portion of a graph produced by GRAPH is to be analyzed, a sheet of graph paper is put on the graph with the X axis lined up with the lowest virtual height and the Y axis lined up with the first sample point. The X coordinate of the last sample point and the Y coordinate of the highest virtual height, both in units of grid intervals are entered into the calculator. If the two-hop height in grid units is to graphed, the height variation of the two-hop echo is entered next. Otherwise go to step 3.

3. Press POINTS (f_1) and enter the coordinates, in grid units, of key points such as relative minima and maxima which have the same height as the reflector height.

4. Points are connected with a half cycle of a sine curve by pressing HALF-SINE (f_2). Enter the X coordinates of the two points to be connected with a half sine and press EXECUTE.

5. To connect two points with a straight line, press CURVE FIT (f_3). Enter 2 as the number of points and then enter the X coordinates of the two points to be connected with a straight line. A curve through

more than two points is made by specifying the number of points to be greater than two and then enter that number of X coordinates of points to be fitted. The first coordinate is the starting point of the curve and the last point entered is the end point of the curve.

6. FILL (f_{13}) is used to modify the reflector curve shape by adding or subtracting a sine-shaped segment from the reflector. The start and end points of the segment to be modified and the amount in grid units to be added are entered.

7. Place the graph paper in the plotter and press MOVE PEN (f_{12}). Press the space bar to move the pen and adjust the pen position controls until the pen moves between the origin of the graph and the coordinate made up of the X ordinate of the last sample and the Y ordinate of the maximum height. The resulting plots will be the same size as the graphed data.

8. Press PARAM (f_4). Enter the estimated horizontal length of the reflector in km, the height of the lowest echo and the difference between the maximum and minimum virtual height.

9. Press AXIS (f_6) to draw and label an axis for the one-hop echo. Shift f_6 or f_{16} draws and labels an axis for the two-hop echo.

10. Press REF SHAPE (f_7) to draw the one-hop reflector shape. Shift f_7 or f_{17} draws the two-hop reflector shape which is twice as high as the one-hop reflector at all points.

11. Press RES HEIGHT (f_8) to draw the one-hop virtual height calculated from the one-hop reflector. Press f_{18} to draw the two-hop virtual height.

12. Press AMP (f_9) to draw the amplitude of the one-hop echo. Press f_{19} to draw the two-hop echo amplitude.

13. In the case of multipath, NORM (f_5) changes the scale factor used in graphing the reflector shape and the virtual height so that the maximum excursions in height fit on the graph. It should not be used when trying to match a reflector to a data graph because the scale size may be changes. Shift f_5 or f_{15} does the same thing for the two-hop graph.

14. HEIGHT (f_{11}) displays the height of the reflector in grid units for any X coordinate.

```
10 REM KEY   0
20 REM INITIALIZATION
30 DIM H$[256],U$[7,7],C$[7],F$[7]
40 SCALE -0.08,1.06,-0.1,3
50 LABEL (*,1,2,0,1)
60 X2=0
70 DISP "UPPER LIMITS X,Y";
80 INPUT X5,Y5
90 Y9=Y5
100 DISP "VERT SIZE OF 2 HOP   Y";
110 INPUT Y9
120 END
```

```
10 REM KEY   1
20 REM INPUT POINTS
30 DISP "INPUT POINTS X,Y";
40 INPUT X1,Y1
50 H[FNA(0)]=Y1/Y5
60 GOTO 30
```

```
10 REM KEY   2
20 REM HALF SINE
30 DISP "HALF SINE FROM X1 TO X2";
40 INPUT X1,X2
50 Y1=H[FNA(0)]
60 Y2=H[X2]
70 T=PI/(X2-X1)
80 T1=(Y2+Y1)*0.5
90 T2=T1-Y2
100 FOR I=X1 TO X2
110 H[I]=T1+T2*COS((I-X1)*T)
120 NEXT I
130 GOTO 30
```

```
10 REM KEY   3
20 REM CURVE FIT
30 DISP "# OF POINTS";
40 INPUT N
50 REDIM U[N,N],C[N],F[N]
60 FOR I=1 TO N
70 DISP "POINT";I;
80 INPUT X1
90 F[I]=H[FNA(0)]
100 U[I,1]=1
110 FOR J=2 TO N
120 U[I,J]=U[I,J-1]*X1
130 NEXT J
140 NEXT I
150 I1=U[1,2]
160 I2=U[N,2]
```

```
170 MAT U=INV(U)
180 MAT C=U*F
190 FOR I=I1 TO I2
200 H[I]=0
210 FOR J=1 TO N
220 H[I]=H[I]*I+C[N-J+1]
230 NEXT J
240 NEXT I
250 GOTO 30


10 REM  KEY  4
20 REM PARAMETERS
30 DISP "LENGHT";
40 INPUT P
50 P1=P4=0
60 P2=P3=P7=P8=P
70 P5=P/255
80 P6=0.5/P5
90 DISP "HEIGHT";
100 INPUT H0
110 DISP "AMPLITUDE P-P";
120 INPUT A
130 V1=H0
140 V2=H0+A
150 V3=A
160 V4=H0+H0
170 V6=A+A
180 V5=V4+V6
190 END


10 DEF FNB(Z)
20 K=H0+H[I]*A
30 M=A*(H[I+1]-H[I-1])*P6
40 M2=(H[I]+H[I]-H[I-1]-H[I+1])*A/(P5*P5)
50 K1=ATN(M)
60 K1=K1+K1
70 RETURN Z


10 REM KEY  11
20 REM DISPLAY HEIGHTS
30 DISP "X1";
40 INPUT X1
50 DISP H[FNA(0)]*Y5;
60 GOTO 30


10 REM KEY  12
20 REM MOVE PEN TO 0,0 AND 1,1
30 PLOT 0,0,1
40 WAIT 32000
```

```
50 PLOT 1,1,1
60 WAIT 32000
70 GOTO 30


10 REM KEY  13
20 REM MODIFY CURVE
30 DISP "START,STOP,INCRIMENT";
40 INPUT X1,X2,D
50 Z=FNA(0)
60 J=X2-X1
70 D=D/Y5
80 FOR I=X1 TO X2
90 H[I]=H[I]+D*SIN((I-X1)*PI/J)
100 NEXT I
110 GOTO 30


10 DEF FNA(Z)
20 X1=INT(X1*255/X5+1)
30 X2=INT(X2*255/X5+1)
40 RETURN X1


10 REM KEY  5
20 REM NORMALIZE
30 V1=H0
40 V2=H0+A
50 P1=0
60 P2=P
70 FOR I=2 TO 255
80 Z=FNB(0)
90 V=K*SQR(1+M*M)
100 X=K*M+(I-1)*P5
110 IF V>V1 THEN 130
120 V1=V
130 IF V<V2 THEN 150
140 V2=V
150 IF X>P1 THEN 170
160 P1=X
170 IF X<P2 THEN 190
180 P2=X
190 NEXT I
200 V3=V2-V1
210 P3=P2-P1
220 END


10 REM KEY  6
20 REM AXIS
30 PLOT 1,0
40 PLOT 0,0,2
50 PLOT 0,1,-1
```

```
60 DISP "LABEL STEP SIZE IN KM  X,Y";
70 INPUT X1,Y1
80 T=INT(V2/Y1)*Y1
90 PLOT 0.01,(T-V1)/V3,-2
100 PLOT 0,(T-V1)/V3,-1
110 CPLOT -4.3,-0.3
120 LABEL (*)T;
130 T=T-Y1
140 IF T >= V1 THEN 90
150 T=INT(P1/X1)*X1
160 IF T=P1 THEN 180
170 T=T+X1
180 PLOT (T-P1)/P3,0.01,-2
190 PLOT (T-P1)/P3,0,-1
200 CPLOT -1.3,-1.3
210 IF T=0 THEN 230
220 CPLOT -INT(LGT(T))/2,0
230 LABEL (*)T;
240 T=T+X1
250 IF T <= P2 THEN 180
260 END


10 REM KEY  7
20 REM ASSUMED REFLECTOR SHAPE
30 J=0
40 FOR I=1 TO 256
50 IF (I-1)*X5/2550>J THEN 100
60 PLOT ((I-1)*P5-P1)/P3,(H[I]*A+H0-V1)/V3,-2
70 NEXT I
80 PEN
90 END
100 J=J+1
110 PEN
120 GOTO 60


10 REM KEY  8
20 REM RESULTING HEIGHT
30 J=0
40 FOR I=2 TO 255
50 Z=FNB(0)
60 V=K*SQR(1+M*M)
70 X=K*M+(I-1)*P5
80 IF (I-1)*X5/2550>J THEN 130
90 PLOT (X-P1)/P3,(V-V1)/V3,-2
100 NEXT I
110 PEN
120 END
130 J=J+1
140 PEN
150 GOTO 90
```

```
10 REM KEY  9
20 REM RESULTING ECHO AMPLITUDE
30 R1=R=-(10↑99)
40 J=0
50 FOR I=2 TO 255
60 Z=FNB(0)
70 V=K*SQR(1+M*M)
80 IF M2=0 THEN 230
90 R=((1+M*M)↑1.5)/M2
100 IF R=V THEN 150
110 IF R1>0 AND R1<V AND R>V THEN 150
120 IF R1>V AND R<V AND R>0 THEN 150
130 A3=H0*SQR(ABS(R/(R-V)))/V
140 IF A3<10 THEN 160
150 A3=10
160 X=K*M+(I-1)*P5
170 IF (I-1)*X5/2550>J THEN 250
180 PLOT (X-P1)/P3,A3/10,-2
190 R1=R
200 NEXT I
210 PEN
220 END
230 A3=H0/V
240 GOTO 160
250 J=J+1
260 PEN
270 GOTO 180


10 REM KEY  15
20 REM NORMALIZE 2 HOP
30 V4=H0+H0
40 V5=V4+A+A
50 P4=0
60 P8=P
70 FOR I=2 TO 255
80 Z=FNB(0)
90 IF M>1 THEN 230
100 V=K*(1+1/COS(K1))
110 X=K*TAN(K1)+(I-1)*P5
120 IF V>V4 THEN 140
130 V4=V
140 IF V<V5 THEN 160
150 V5=V
160 IF X>P4 THEN 180
170 P4=X
180 IF X<P8 THEN 200
190 P8=X
200 NEXT I
210 V6=V5-V4
220 P7=P8-P4
230 END
```

```
10 REM KEY  16
20 REM 2 HOP AXIS
30 PLOT 1,1.25
40 PLOT 0,1.25,2
50 PLOT 0,2.25,-1
60 DISP "LABEL STEP SIZE IN KM  X,Y";
70 INPUT X1,Y1
80 T=INT(Y5/Y1)*Y1
90 PLOT 0.01,(T-V4)/V6*Y9/Y5+1.25,-2
100 PLOT 0,(T-V4)/V6*Y9/Y5+1.25,-1
110 CPLOT -4.3,-0.3
120 LABEL (*)T;
130 T=T-Y1
140 IF T >= V4 THEN 90
150 T=INT(P4/X1)*X1
160 IF T=P4 THEN 180
170 T=T+X1
180 PLOT (T-P4)/P7,1.26,-2
190 PLOT (T-P4)/P7,1.25,-1
200 CPLOT -1.3,-1.3
210 IF T=0 THEN 230
220 CPLOT -INT(LGT(T))/2,0
230 LABEL (*)T;
240 T=T+X1
250 IF T <= P8 THEN 180
260 END


10 REM KEY  17
20 REM ASSUMED REFLECTOR SHAPE  2 HOP
30 J=0
40 FOR I=1 TO 256
50 IF (I-1)*X5/2550>J THEN 100
60 PLOT ((I-1)*P5-P4)/P7,(2*(H[I]*A+H0)-V4)/V6*Y9/Y5+1.25,-2
70 NEXT I
80 PEN
90 END
100 J=J+1
110 PEN
120 GOTO 60


10 REM KEY  18
20 REM RESULTING 2 HOP ECHO PATTERN
30 J=0
40 FOR I=2 TO 255
50 Z=FNB(0)
60 IF M>1 THEN 140
70 V=K*(1+1/COS(K1))
80 X=K*TAN(K1)+(I-1)*P5
90 IF (I-1)*X5/2550>J THEN 160
100 PLOT (X-P4)/P7,(V-V4)/V6*Y9/Y5+1.25,-2
110 NEXT I
```

```
120 PEN
130 END
140 PEN
150 GOTO 110
160 J=J+1
170 PEN
180 GOTO 100


10 REM KEY  19
20 REM RESULTING 2 HOP AMPLITUDE
30 R=-(10†99)
40 K2=H0
50 W1=W=-H0
60 FOR I=2 TO 255
70 Z=FNB(0)
80 S=K/COS(K1)
90 V=K+S
100 IF M2=0 THEN 270
110 R=((1+M*M)†1.5)/M2
120 IF M>1 THEN 290
130 W=R*S/(S+S-R)
140 T=R*(K+K-W)/(K+K+K+K-W-W-R)
150 IF ((W>K AND W1<K2) OR (W<K AND W1>K2)) THEN 190
160 IF ((W>K+K AND W1<K2+K2) OR (W<K+K AND W1>K2+K2)) THEN 190
170 A3=H0*SQR(ABS(W*T/((K+K-W)*(T-S))))/S
180 IF A3<10 THEN 200
190 A3=10
200 X=K*TAN(K1)+(I-1)*P5
210 PLOT (X-P4)/P7,A3/10+1,1,-2
220 K2=K
230 W1=W
240 NEXT I
250 PEN
260 END
270 A3=H0/S*SQR(0.5*S/(V))
280 GOTO 200
290 PEN
300 GOTO 240
310 J=J+1
320 PEN
330 GOTO 210
```

APPENDIX IV. OPERATING INSTRUCTIONS AND A LISTING OF

THE PROGRAM TO COMPUTE LATERAL DEVIATION

This program computes the separation of the ordinary and extraordinary reflection points using the formula for lateral deviation given in *Budden* [1961]. The separation of the reflection points is used to find the direction of propagation of the disturbance as discussed in Section 2.6.

To run the program, turn on the calculator and printer, insert the cassette marked ionosonde programs and type LOAD2 and press execute. When the program is loaded press run and execute. Enter the ionosonde operating frequency and the critical frequency when the calculator asks for them and a table similar to Table 2.1 is printed.

```
10 DIM D[2],H[2]
20 FIXED 4
30 H[1]=H[2]=X=0
40 DISP "OPERATING FREQUENCY IN MHZ";
50 INPUT F
60 PRINT "OPERATING FREQUENCY =";F
70 DISP "CRITICAL FREQUENCY IN MHZ";
80 INPUT F2
90 PRINT "CRITICAL FREQUENCY =";F2
100 F=F*10↑6
110 F2=F2*10↑6
120 N1=F2*F2/80.6
130 Z1=200
140 X1=80.6/(F*F)
150 B=0.56*10↑(-4)
160 L=-0.15/0.56
170 N2=0.54/0.56
180 Y=(2.8*10↑10)*B/F
190 PRINT "         LATERAL DEVIATION      DX/DZ      Y=";Y;"   1-Y=";1-Y
200 PRINT "  Z(KM)     X        0       X       0       N       X"
210 Y1=N2*Y
220 Y2=L*Y
230 K=0.05
240 Z=J=0
250 FOR L=1 TO 20
260 Z=Z+K
270 N=N1*(1-((Z-Z1)/Z1)↑2)
280 X3=X
290 X=N*X1
300 FOR I=1 TO 2
310 IF X >= 1-(2-I)*Y THEN 420
320 O=I+I-3
330 T=Y2*Y2/(2*(1-X))
340 U=1-X/(1-T+O*SQR(T*T+Y1*Y1))
350 D[I]=-O*Y1*Y2*(1-U)/SQR(4*Y1*Y1*(1-X)*(1-X)+Y2↑4)
360 H[I]=H[I]+D[I]*K
370 NEXT I
380 NEXT L
390 WRITE (15,400)Z,H[1],H[2],D[1],D[2],N,X
400 FORMAT F7.2,4F9.4,E10.2,F9.4
410 GOTO 250
420 IF J=1 THEN 490
430 WRITE (15,400)Z,H[1],H[2],D[1],D[2],N,X3
440 J=1
450 S1=H[1]
460 S2=Z
470 H[1]=D[1]=0
480 GOTO 370
490 IF I=1 THEN 370
500 WRITE (15,400)Z,H[1],H[2],D[1],D[2],N,X3
510 X=H[2]-S1
520 Y=Z-S2
530 PRINT
540 WRITE (15,550)X,Y
550 FORMAT "LATERAL SEPARATION IS",F7.3,"KM   VERTICAL SEPARATION IS",F7.3,"KM"
560 STOP
```