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Data collected during 1980/81 at Brighton, Colorado, show clearly that the F-region variations are undersampled in space and time by standard recording procedures. Fast temporal changes, with periods as short as 10 minutes, are directly observable if ionograms are taken in rapid sequences of at least 12 ionograms per hour. In order to obtain a correct spatial sampling, the distances between observing stations should not be much larger than 100 kilometers. This conclusion is derived from the temporal variations of F-layer parameters assuming a propagation velocity typical for acoustic gravity waves. Some direct estimates of a spatial structure scale can be obtained from angle of arrival measurements. Comparisons of foF2 and MUF(3000) indicate that the main effect of gravity waves on the F-region structure is the variation of the height of the layer and to a lesser degree a variation of the maximum electron density.

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Medium Scale Structure of the F-region

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Abstract

Data collected during 1980/81 at Brighton, Colorado show clearly that the F-region variations are undersampled in space and time by standard recording procedures. Fast temporal changes, with periods as short as 10 minutes, are directly observable if ionograms are taken in rapid sequences of at least 12 ionograms per hour. In order to obtain a correct spatial sampling, the distances between observing stations should not be much larger than 100 kilometers. This conclusion is derived from the temporal variations of F-layer parameters assuming a propagation velocity typical for acoustic gravity waves. Some direct estimates of a spatial structure scale can be obtained from angle of arrival measurements. Comparisons of foF2 and MUF(3000) indicate that the main effect of gravity waves on the F-region structure is the variation of the height of the layer and to a lesser degree a variation of the maximum electron density.

Introduction

The standard picture of the F-region is based on hourly observations by ionosondes. More frequent recordings with advanced digital instruments show that very often F-region variations take place with periods of less than half an hour. Therefore, even if [illegible] minute intervals the actual variations of the ion[illegible] undersampled. Assuming that we observe the effects of propagating acoustic gravity waves, the undersampling of the oscillations results in an overestimation of the periods and the wavelengths. This in turn means that distances between existing and planned ionospheric stations are too large for correct spatial sampling of the waves. Therefore, at this time the observed temporal variations in combination with an assumed propagation velocity provide the only means to obtain first order information about the medium scale spatial structure of the F-region on a routine basis.

Digital ionograms recorded during 1980/81 at Brighton, Colorado show characteristics (e.g. virtual height variations and doppler profiles) supporting the hypothesis that short term F-region variations are caused by acoustic gravity waves which seem to be present all the time with varying amplitudes. In addition, some direct evidence for the spatial structure can be obtained from the angle of arrival observations and their frequency or height dependence.

Temporal and spatial structure information obtainable from vertical sounding

Modern technology now permits us to measure the radio phase of a single echo reflected from the ionosphere to one degree or better. It is this quantity with its high precision which provides much more detailed information about the ionosphere [Paul et al., 1976].

The comparison of the phases observed at three or more spaced antennas yields the angle of arrival of an echo which gives an estimate of the tilt of the surface of constant electron density at the reflection level. In many [illegible] the angle of arrival measurement will underestimate the tilt angle at [illegible] point if the angle between the electron density gradient and the vertical is a monotonic or almost monotonic function of the height. Such a situation exists, for example, during the undisturbed sunrise or sunset period, when the ray direction becomes almost horizontal in the vicinity of the reflection point for frequencies reflected close to the height of maximum electron density [Paul, 1985].

A Doppler frequency can be derived from the change of the phase with time. The Doppler velocity is then defined as the product of the radio wavelength and the Doppler frequency. It has to be mentioned that the observation of a Doppler frequency (or Doppler velocity) does not necessarily imply a motion of the reflecting area. The radio phase of an echo is proportional to the phase path which is the integral of the refractive index along the ray path. A decrease in the phase path, or a positive Doppler frequency, can be caused by a decrease in the distance to the reflection level or by a local increase in the electron density somewhere along the ray path. On the other hand, the combined effect of a local increase in the electron density and an increase in path length could result in no apparent change of the phase path, and hence zero Doppler frequency, but the group path would increase significantly in such a situation. Generally, the Doppler frequency (or the Doppler velocity) is an indicator for the presence of temporal changes in the ionosphere, but its interpretation, especially without comparison to the temporal changes of the virtual heights, is very difficult and often not unique [Bennet et al., 1986].

The change of the phase with frequency provides an improved estimate of the virtual path length, which is equal to the virtual height, if the propagation is strictly vertical. An accurate value for this quantity is highly desirable for a variety of analysis procedures like extrapolation of the echo trace for the determination of the critical frequency [Paul et al., [illegible]], electron density profile computation, studies of the temporal variations of the virtual heights at sets of fixed frequencies, etc.

Estimates of spatial and temporal structure parameters

One of the most significant results obtained during the short period of operating a NOAA digital ionosonde at Brighton, Colorado was the detection of the high variability of the ionosphere, especially the F-region. The data reveal that the variations taking place are of a rather complex nature and that the magnitude of those oscillations can vary strongly with time. The MUF(3000), the maximum usable frequency over a 3000 km path, as derived from monostatic (quasi-vertical) ionograms, was selected as an indicator for the variability of the F-region. This quantity, or equivalently the propagation factor M(3000), is a standard propagation parameter routinely scaled at all ionospheric stations. By its definition, the MUF(3000) can be obtained with high precision, if accurate virtual heights and frequency pairs are available, and it is very sensitive to changes in the lower half of the F-region.

A typical example of MUF variations is shown in figure 1. Oscillations with periods mostly in the range from 20 to 30 minutes are clearly visible. There is, however, some indication that the variations may only be coherent over a few periods. Assuming that the observations shown in figure 1 are caused by propagating waves with a velocity of approximately 200 m/sec, the wavelengths for the above mentioned range of periods would be between 240 and 360 km.

Since the MUF(3000) is derived from the virtual heights at frequencies about 10% less than the penetration or critical frequency foF2, we expect to see a similar variations of the virtual heights at fixed frequencies in this frequency range. An example of this behavior is shown in figure 2. The periods visible are again in the 20 to 30 minute range, but we also see that maxima and minima of the virtual heights appear later at lower frequencies (heights). The delay time is approximately 4 minutes over the frequency range shown, which corresponds to a true height range of approximately 50 km. If this height interval divided by the delay time is interpreted as some kind of velocity, we obtain a value of approximately 200 m/sec. While the first period shown in this figure may give the impression that the F-region as a whole may oscillate in height, the second period shows that the higher frequencies penetrate the layer for several minutes and are reflected again later, which can be interpreted as a local reduction of the electron density due to a temporary local expansion of the layer. Comparing the frequencies at the 600 km height level between the times 13:36 and 13:45 we find a temporary decrease of the critical frequency of 2%, equivalent to a reduction of the maximum electron density of 4%. Over the same period of time the MUF(3000) drops from 39.2 MHz to 37.1 MHz, a change of 5.5%.

A timelag between the variations of foF2 and the MUF(3000) is also clearly visible in figure 3. As mentioned earlier the critical frequency foF2 is determined by an extrapolation process based on the variation of the virtual heights with frequency over a small range close to the penetration frequency. This means that the effective height of variations visible in foF2 is lower than the height of the electron density maximum by approximately 10% to 15% of the half-thickness of the layer. On the other hand the height range which determines the MUF(3000) is on average 45% of a half-thickness below the peak. A height difference of 30 km between the two levels therefore seems to be a reasonably accurate estimate. The timelag corresponding to this height difference can be obtained by cross-correlation of the two data sets. With the data shown in figure 3 a maximum of [illegible] correlation was found for a timelag of approximately 3.2 minutes. Combining the height difference and the timelag we obtain an apparent vertical downwards velocity component of 160 m/sec. Velocity estimates of this kind were computed for all high quality data sets which had the necessary temporal resolution of 20 or more ionograms per hour. The results were in the range 100 m/sec to 200 m/sec.

The changes taking place in the F-region can be rather complex, as is evident in figure 4. Here the apparent position of the reflection point is shown for a range of frequencies close to the penetration frequency, for three consecutive ionograms taken in three minute intervals. The numbers used as plotting symbols indicate the order in which the data were recorded. The lowest frequency used in all three traces was 11.3303 MHz, while the highest frequencies were 13.6662 MHz for the first and 13.7610 MHz for the second and the third ionogram. The low frequency end of each trace is always the point closest to the overhead point. We see that in the first ionogram the apparent echo position moves farther away from the overhead point in a north westerly direction with increasing frequency, but then suddenly changes direction by approximately 90 degrees toward the end of the trace. This change of direction occurs for the second ionogram at a lower frequency, and already starts at the lowest frequency used in this display in the third ionogram. With the electron density profile parameters computed from the ionograms we find that the point where the change of direction occurred dropped from a height of 344 km to a height of 305 km over the six minute time interval between the first and last ionogram, corresponding to an apparent velocity of 110 m/sec. The observations shown here have to be interpreted as a rapid change in height and time from one orientation of a prevailing strong F-region tilt to another one with the boundary between the two moving downwards. This example demonstrates that a time interval of three minutes can already be long in terms of F-region variations.

A different example of the complexity of the F-layer dynamics is shown in figure 5. It shows the variation of the point in the ionogram where the MUF(3000) is determined (where the transmission curve is tangent to the ordinary trace of the ionogram) over a period of two hours in the afternoon in three minute intervals. The transmission curves for 35 MHz and 40 MHz are also shown for comparison. The looping curve starts at the right side of the diagram. The tangent point first moves approximately parallel to the 40 MHz transmission curve to lower heights and lower frequencies with little or no change of the MUF(3000). This is followed by changes almost perpendicular to the transmission curves, an increase of the virtual heights and a continuing decrease of the frequencies. Then the frequencies and the heights increase, coupled first with a slower and then a faster increase of the MUF(3000), and a new cycle starts. If the layer was moving up and down without changing its shape, the tangent point would move up and down on the same curve very close to a straight vertical line. Similarly, if the electron density was to decrease or increase at the same rate at all heights, the tangent point would move back and forth along a straight horizontal line. A time lag between the two types of changes is necessary to produce the variations as seen in figure 5. The increase in frequency appears to be lagging consistently by approximately 2-3 sampling intervals behind the increase in height in all the loops shown in this figure. The durations of these cycles can again be used as a measure for the temporal scale and they are in agreement with the periods shown in earlier figures.

Some information about the spatial structure of the F-region can be deduced from the data shown in figures 6a and 6b. Figure 6a shows how the apparent reflection point moves away from the overhead point with increasing frequency during the [illegible] period. A [illegible] similar trend is seen in figure 6b, but here the data [illegible] in the late morning. In both plots the points farthest away from the overhead point were observed at frequencies very close to the penetration frequency. For sunrise conditions a model for the electron density distribution as a function of height and distance from the daylight boundary can be derived from the increase of foF2 as a function of time with reasonable accuracy. Ray tracing studies with such models show that the distance of the apparent reflection point from the overhead point d'(f) is to first order equal to the true distance of the reflection point from the overhead point [Paul, 1985]. This can be explained by the facts that the virtual range overestimates the true distance to the reflection point and the observed angle of arrival underestimates its zenith angle with the two effects compensating each other to a large degree. The apparent distance d'(f) therefore can be used as a first order direct measure for a horizontal scale size - a distance over which significant changes of the electron density can be expected. More detailed information about local gradients or tilts can be obtained by comparison of d'(f) with the corresponding data of a sunrise electron density model.

Figure 7 gives an example of the variation of the apparent echo location over a longer period of time. Each data point shown was obtained from that portion of each ionogram where the MUF(3000) is determined, which means, as explained earlier, that the echoes came approximately from the middle of the lower half of the F-region. The data indicate that there is no preferred azimuthal direction for the angle of arrival or its equivalent, the horizontal component of the electron density gradient. The magnitude of the distance from the overhead point, however, seems to have a maximum in the north-west and south-east direction. It should be mentioned that this direction does not coincide with the magnetic declination, which is 14 degree east for this area.

A clear demonstration of wavelike variations in the F-region is given in figure 8. Here the Doppler frequency, as defined earlier, is shown for both magnetoionic components as a function of the radio frequency. The two traces display very similar sinusoidal variations of the Doppler frequency for approximately half a wavelength. The height difference over the corresponding plasma frequency interval, obtained from profile computation, is approximately 60 km, which implies a vertical wavelength of 120 km. Assuming a period of 20 minutes we obtain a vertical propagation velocity of 100 m/sec, which is in agreement with earlier findings.

Conclusions

The examples reported here show that a variety of parameters indicating the presence of a medium scale structure of the F-region in space and time can be derived from single site observations with an advanced digital ionosonde. We have shown that the MUF(3000) can be observed with high accuracy and that it appears to be a reliable parameter describing the temporal variations of the lower half of the F-layer. Very frequently this parameter shows periodic behavior with periods mainly in the range from 20 to 30 minutes [Paul, 1988]. Discrete events, as illustrated in figure 4, can occur within a much shorter time span and very significant changes can be observed in time intervals as short as 3 minutes. Timelags of similar magnitude are clearly detectable in the variations of the virtual heights at fixed frequencies or by comparison of foF2 with MUF(3000).

The observation of spatial parameters is more limited than the measurement of temporal parameters. Angle of arrival measurements show the presence [illegible] in time consistent with propagating wave phenomena. [illegible] however, are only possible by making assumptions about the propagation velocity. Direct measurements of horizontal wavelengths would require observations from at least three sites separated by approximately half a wavelength. Estimates of the vertical wavelength are more reliable since in many cases they can be directly derived from Doppler profile data as shown in figure 7.

Unfortunately very little can be learned about the magnitude and direction of the propagation velocity of the observed waves. The only directional information available are the estimates of the direction of the gradient of the electron density from the angle of arrival measurements. The direction of this gradient may be equal to the direction of propagation in some situations, e.g. during sunrise, but this may not be true in general. Similar remarks apply to the interpretation of the Doppler measurements which can only give a radial velocity component.

The results presented here give evidence that a medium scale structure is present in the F-region with a spatial scale of the order of tens of kilometers and a temporal scale in the order of minutes. Based on a very large sample of MUF(3000) data [Paul, 1988] from more than 20000 ionograms we have reasons to believe that this type of (moving) structure is present for almost all times, and only the magnitude of the variations is changing with time. Questions about the cause, origin and direction of propagation of such patterns remain still open, but could easily be answered by coordinated multi-static observations.

References:

Bennet, J.A and P.L. Dyson, The effect of small amplitude wave irregularities on radio wave observations of the ionosphere, Radio Sci., 21, 375-387, 1986.

Paul, A.K., J.W. Wright, and L.S. Fedor, The interpretation of ionospheric drift measurements - VI. Angle-of-arrival and group path (echolocation) measurements from digitized ionospheric soundings: the group path vector, J-.A.T.P., 36, 193-214, 1974.

Paul, Adolf K. and D.L Mackison, Scaling F-layer critical frequency from digital ionograms applied to observations during the solar eclipse on 26 February, 1979, J.A.T.P., 43, 221-223, 1981.

Paul, Adolf K., F-region tilts and ionogram analysis, Radio Sci. 20, 959-971, 1985.

Paul, Adolf K., The MUF(3000) as an Indicator for F-region Variations, NOSC Technical Report 1204, January, 1988.

Figure captions

Figure 1. Temporal Variation of the MUF(3000).

Figure 2. Virtual height variation at fixed frequencies.

Figure 3. Comparison of foF2 with MUF(3000).

Figure 4. Apparent position of the reflection points for three consecutive ionograms.

Figure 5. Time lags between changes of electron density and changes of virtual heights as seen by the motion of the tangent point between the echo trace and the transmission curve.

Figure 6a. Change of apparent position of the reflection point with frequency during sunrise.

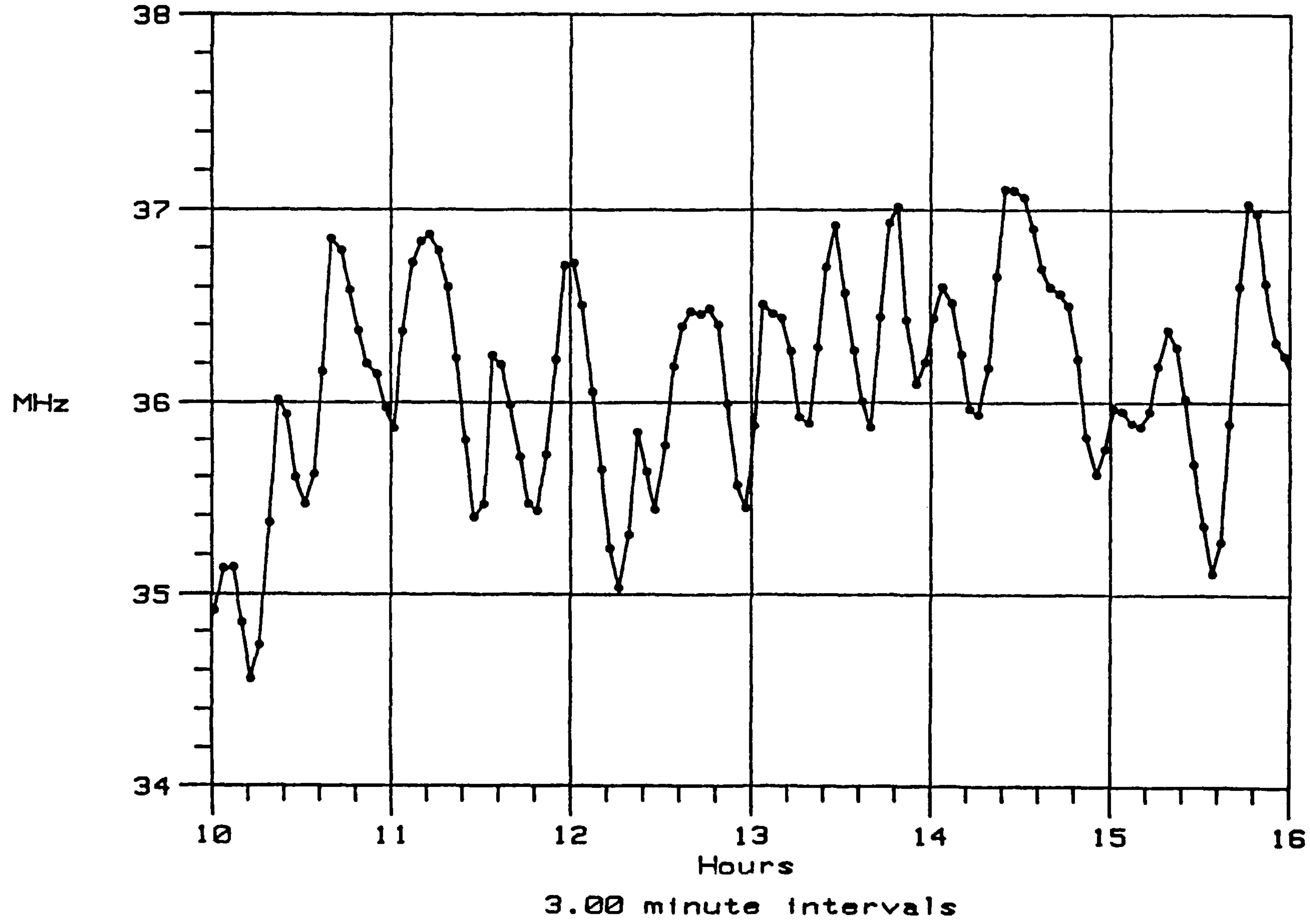
Figure 6b. Change of apparent position of the reflection point with frequency in the late morning.

Figure 7. Horizontal distribution of apparent reflection points for echoes from the the middle of the lower half of the F-region.

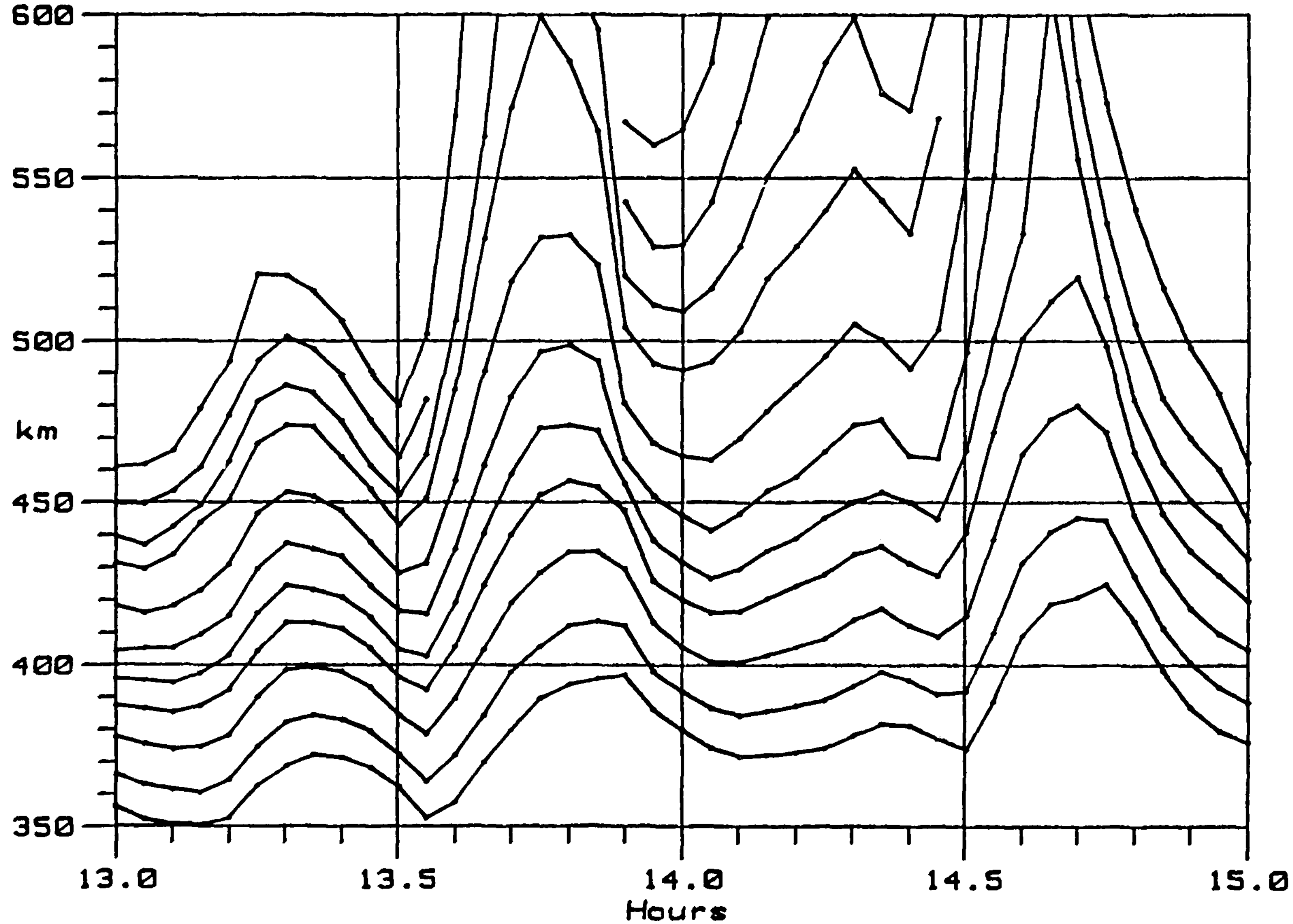
Figure 8. Variation of the Doppler frequency with radio frequency for both magnetoionic components.

MUF(3000)

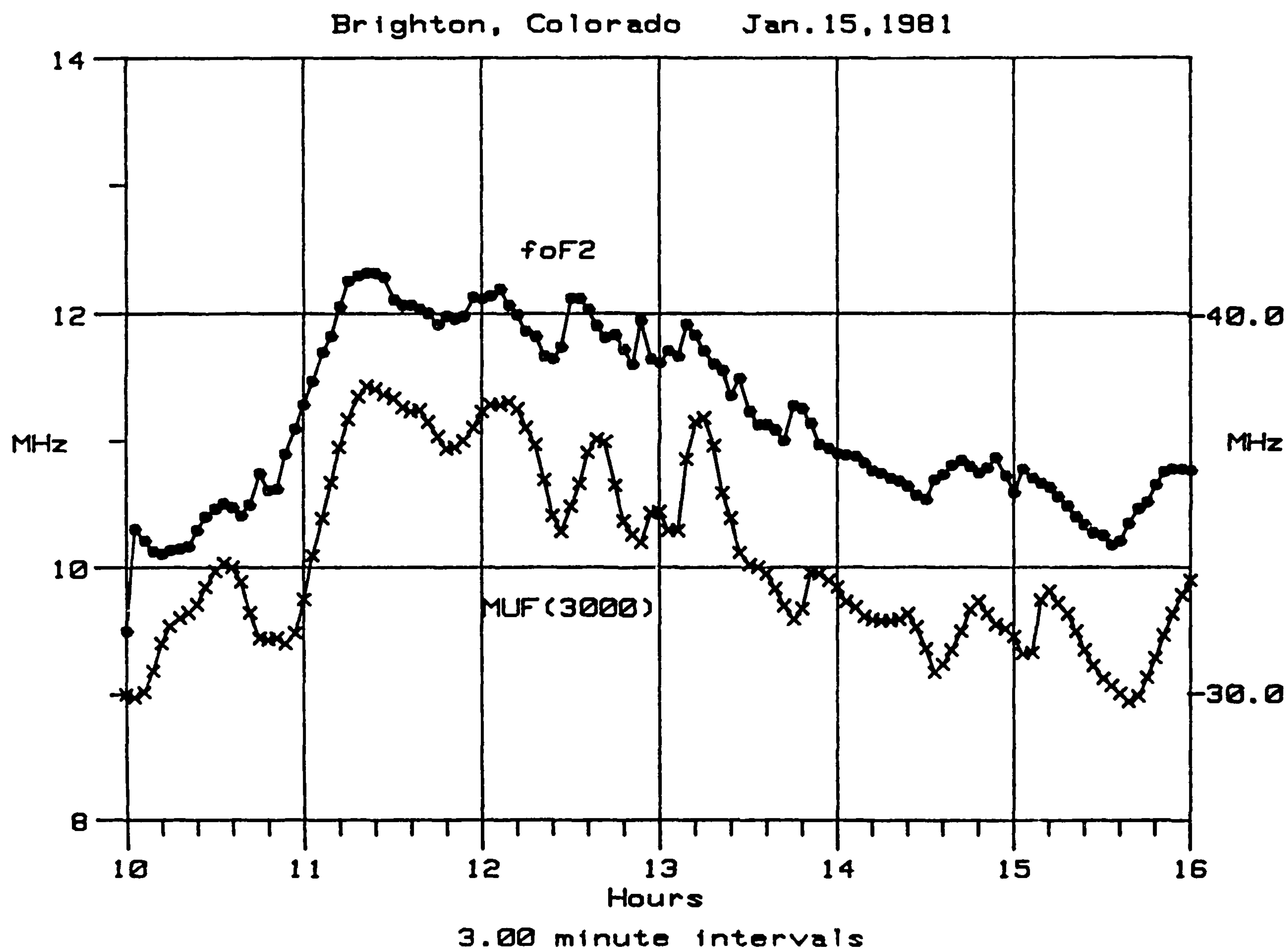
Brighton, Colorado Feb.16,1981



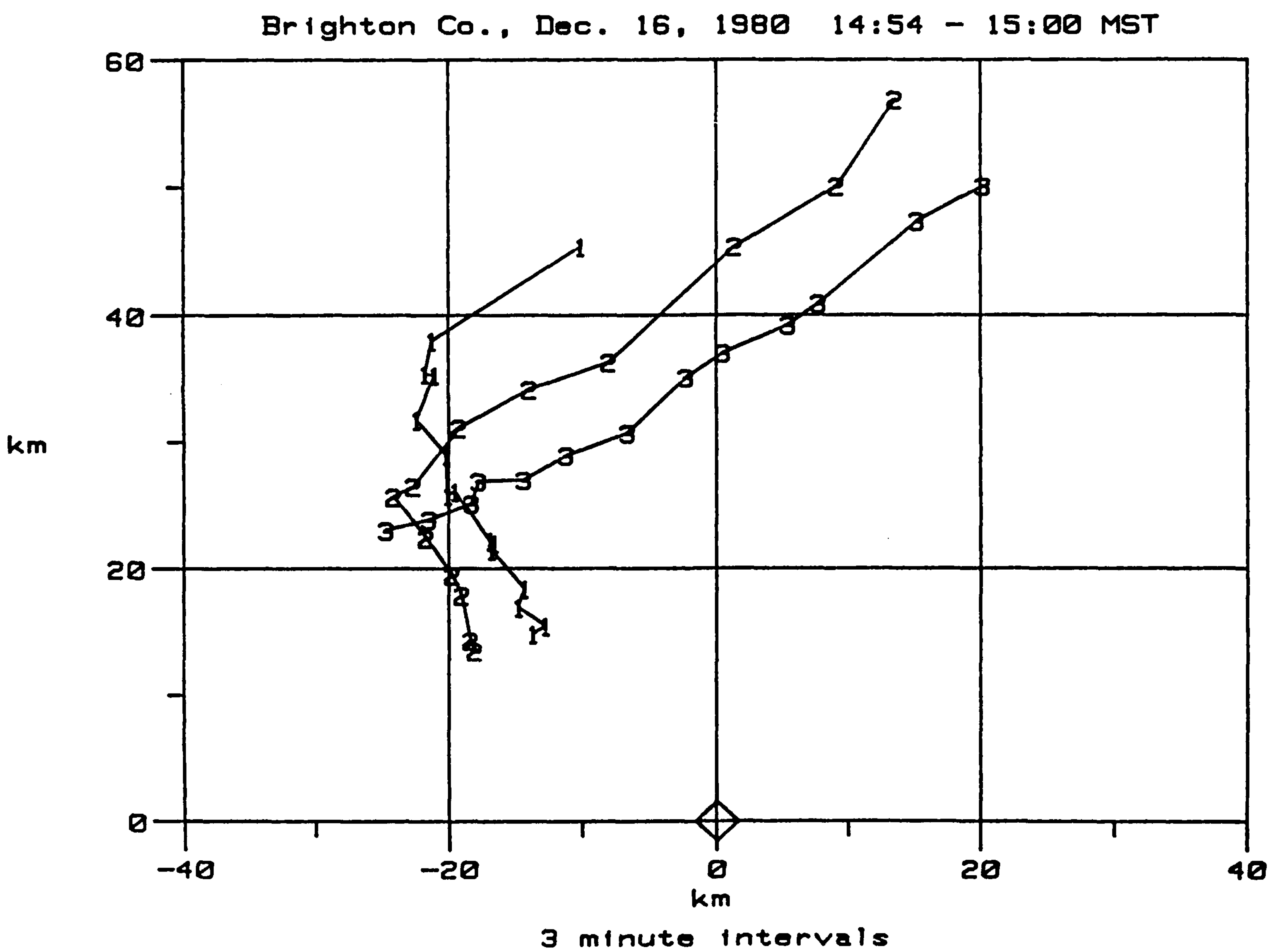
Brighton Co., Dec. 16, 1980



Virtual height variation at fixed frequencies

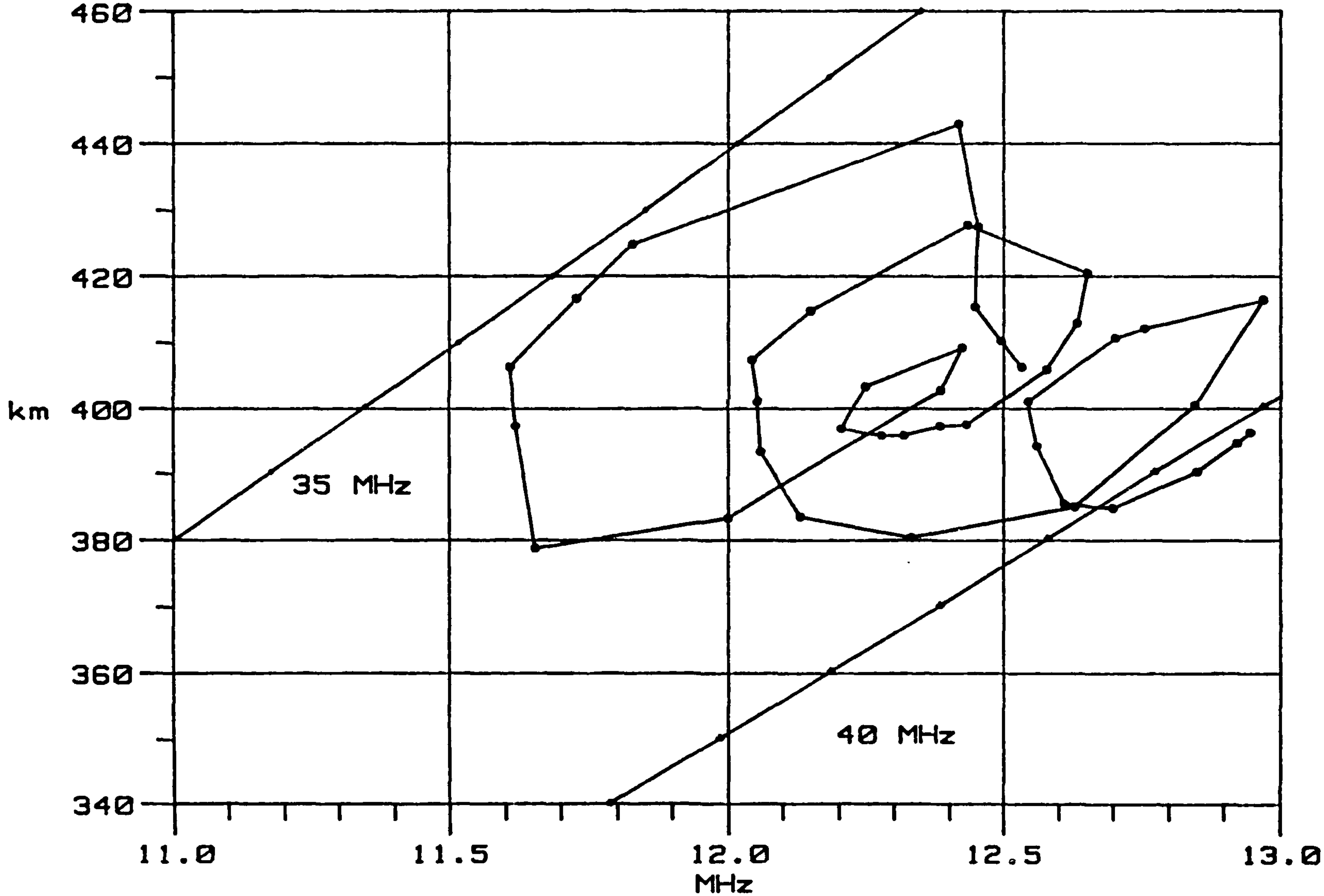


Brighton, Colorado Jan.15,1981
14
12
MHz
10
8
foF2
MUF(3000)
40.0
MHz
30.0
10
11
12
13
14
15
16
Hours
3.00 minute intervals


Brighton Co., Dec. 16, 1980 14:54 - 15:00 MST
km
60
40
20
0
-40
-20
0
20
40
km
3 minute intervals

H'(MUF) / f(MUF)

Brighton, Colorado, Dec.16,1980, 1300 - 1500 MST



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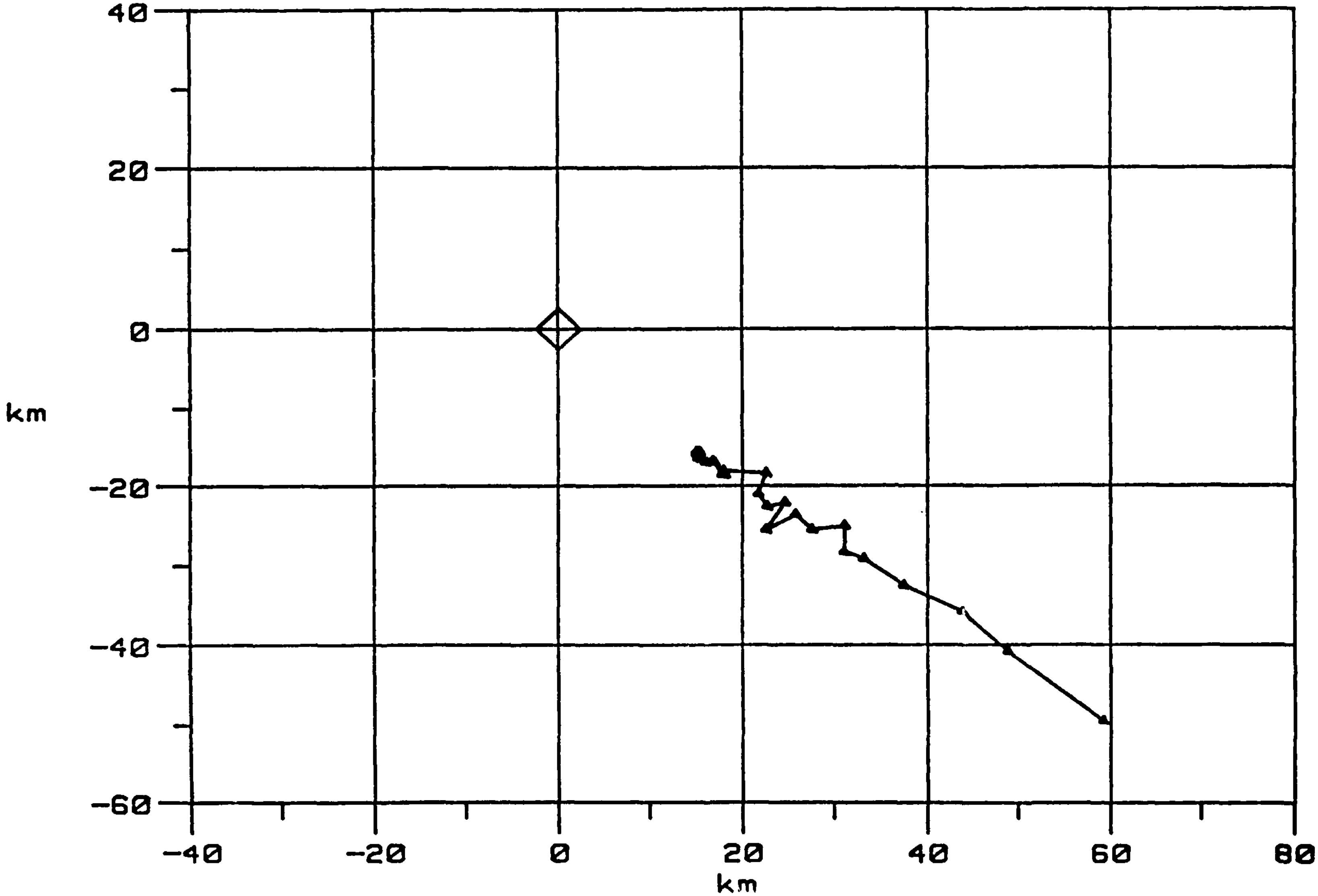

26.0 echos

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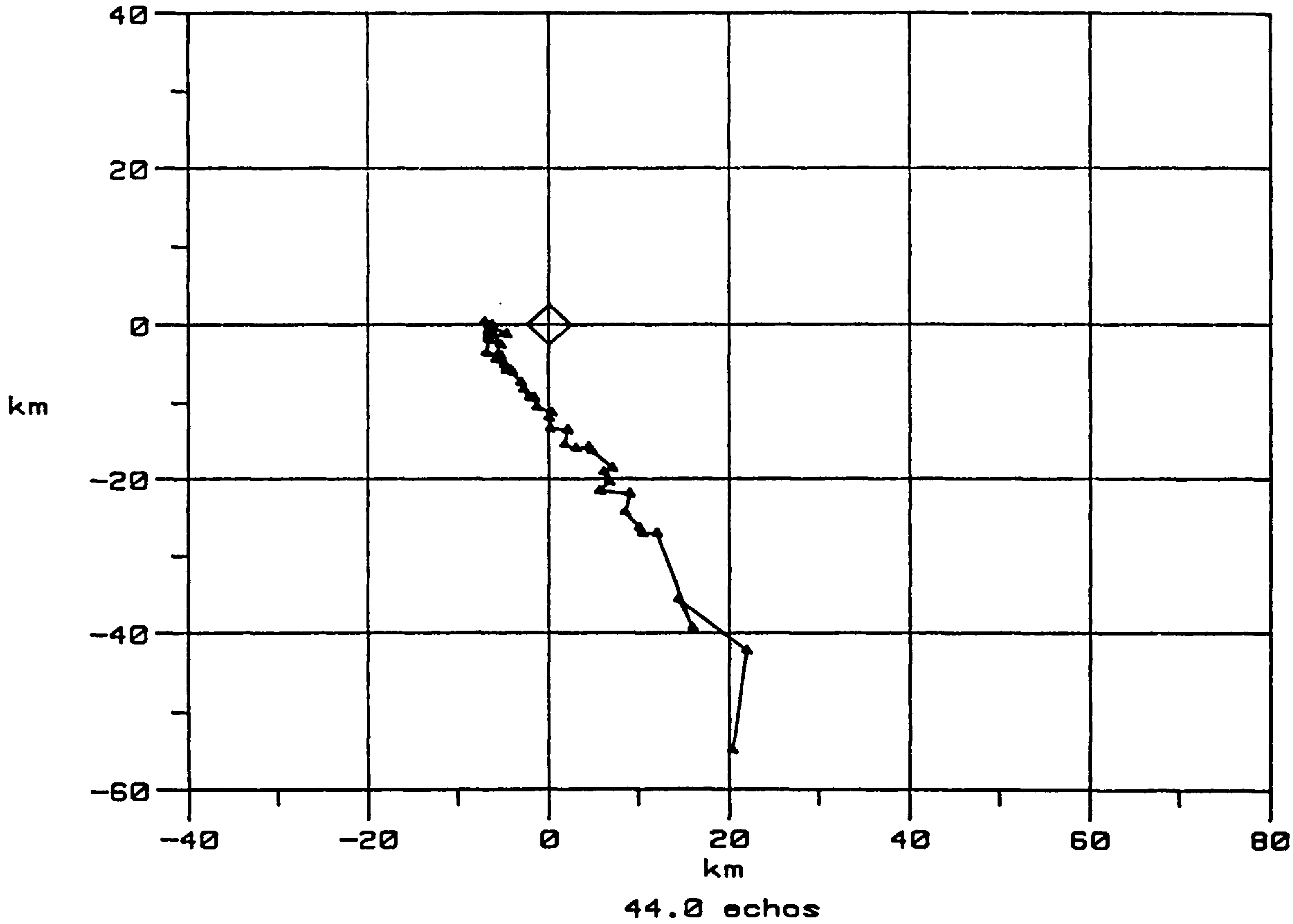
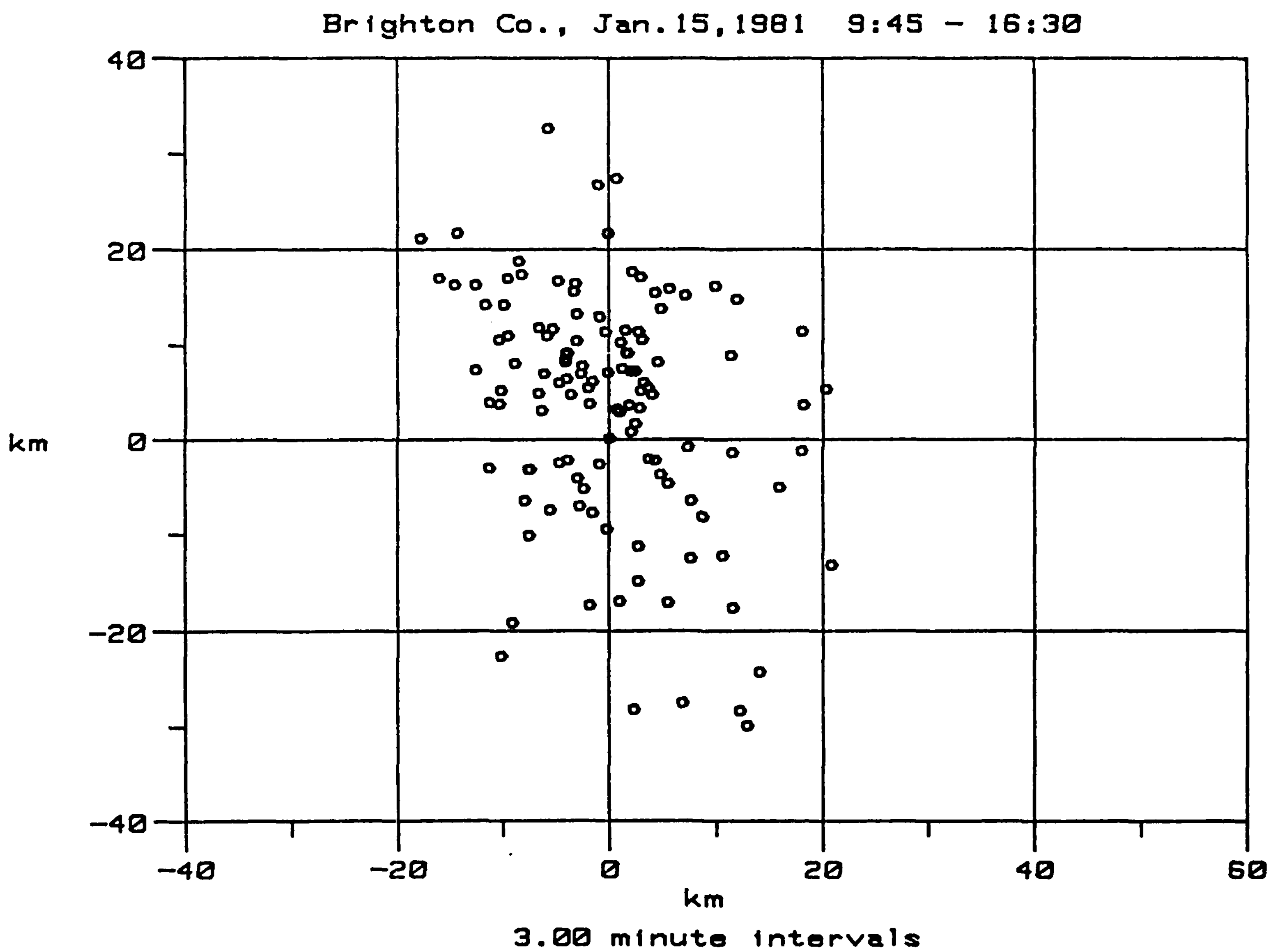
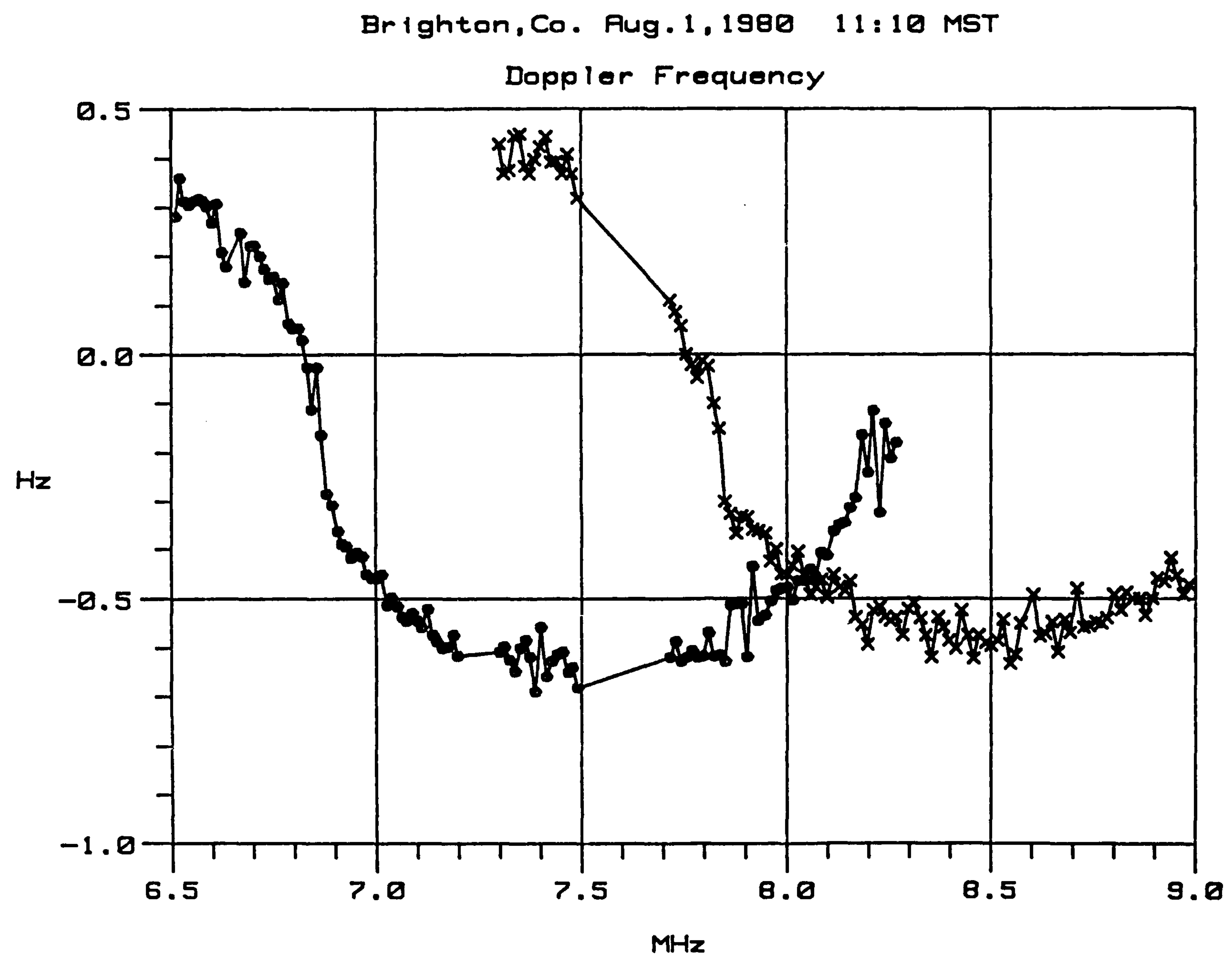




Brighton Co., Jan.15,1981 9:45 - 16:30
40
20
0
-20
-40
km
-40
-20
0
20
40
60
km
3.00 minute intervals


Brighton,Co. Aug.1,1980 11:10 MST
Doppler Frequency
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0.0
-0.5
-1.0
Hz
6.5
7.0
7.5
8.0
8.5
9.0
MHz