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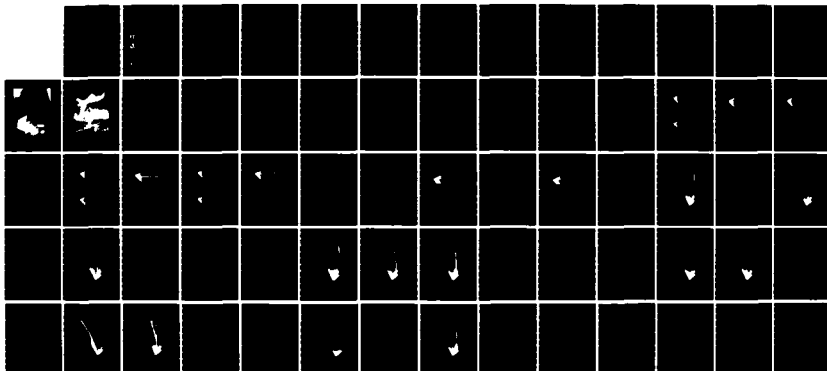
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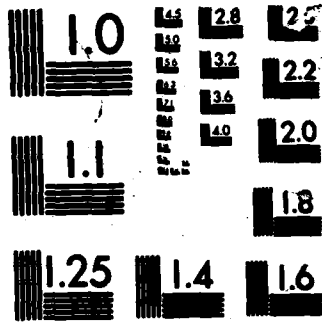
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Meteorological Measurements on Line-of-Sight Microwave Radio Links

J. F. MORRISSEY
Y. IZUMI
O. COTE



22 November 1985



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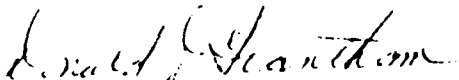
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Preface

We would like to acknowledge the cooperation of Dr. U. Lammers and Mr. R. Marr of the Propagation Branch of the Electromagnetic Sciences Division, Rome Air Development Center, Mrs. Joan-Marie Freni of Systems and Applied Sciences Corp. for programming support, and Mrs. Helen Connell for typing.

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Contents

1. INTRODUCTION	1
2. METEOROLOGICAL MEASUREMENT SITES	2
3. METEOROLOGICAL INSTRUMENTATION	4
4. METEOROLOGICAL MEASUREMENTS	7
5. PACK MONADNOCK-PROSPECT HILL LINK, 1982	13
5.1 Ray Trace for 13 September 1982	14
5.2 Ray Trace for 25 October 1982	17
6. SADDLEBACK-PROSPECT HILL LINK, 1983	23
6.1 25 August 1983	23
6.2 16 September 1983	50
6.3 29 September 1983	50
6.4 30 September 1983	50
7. DISCUSSION	51
8. CONCLUSIONS	56
REFERENCES	59

Illustrations

1. Path Profile for the Monadnock-Prospect Hill Link Showing Locations of Meteorological Observation Sites	2
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Illustrations (contd)

2. Path Profile for the Saddleback-Prospect Hill Link Showing Locations of Meteorological Observation Sites	3
3. Atmospheric Data Acquisition System (ADAS) Manufactured by Atmospheric Instrumentation Research (AIR) Inc., With Expendable Sonde	5
4. Tethered Balloon and Winch With the Nonexpendable Tethersonde	6
5. 25 August 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M	9
6. 29 September 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M	10
7. 30 September 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M	11
8. 1 November 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M	12
9. Modified Refractivity Profiles Measured at Hanscom AFB, 13 September 1982	15
10. Modified Refractivity Profiles Measured at Haystack Site, 13 September 1982	15
11. Ray Trace for Monadnock Link Using Modified Refractivity Profile From Hanscom AFB Sounding at 0756 EDT, 13 September 1982	16
12. Ray Trace for Monadnock Link Using Modified Refractivity Profile From Hanscom AFB Sounding at 0856 EDT, 13 September 1982	16
13. Ray Trace for Monadnock Link Using Modified Refractivity Profile From Haystack Sounding at 0901 EDT, 13 September 1982	17
14. Ray Trace for Monadnock Link Using Sounding Data From Hanscom AFB 0856 and From Haystack Site at 0901, 13 September 1982	18
15. Modified Refractivity Profiles Measured at Hanscom AFB, 25 October 1982	19
16. Modified Refractivity Profiles Measured at Haystack Site, 25 October 1982	19
17. Ray Trace for Monadnock Link Using Sounding Data From Hanscom AFB at 0655 EDT, 25 October 1982	20
18. Ray Trace for Monadnock Link Using Sounding Data From Haystack Site at 0831 EDT, 25 October 1982	20
19. Ray Trace for Monadnock Link Using Sounding Data From Haystack Site at 0921 EDT, 25 October 1982.	21
20. Ray Trace for Monadnock Link Using Sounding Data From Hanscom AFB at 0951 EDT, 25 October 1982	22

Illustrations (contd)

21. Ray Trace for Monadnock Link Using Sounding Data From Haystack Site at 1111 EDT, 25 October 1982	22
22. Ray Trace for Monadnock Link Using Sounding Data From Sites at Haystack at 1011 EDT and Hanscom at 0951 EDT, 25 October 1982	23
23. Modified Refractivity Profiles Measured at Hanscom AFB, 25 August 1983	24
24. Modified Refractivity Profiles Measured at Salem, N.H., 25 August 1983	25
25a. Ray Trace for Saddleback Link Using Sounding Data From Salem at 0552 EDT and Hanscom at 0559 EDT, 25 August 1983	26
25b. Relative Delay Times - Nanoseconds	27
25c. Angle of Arrival - Degrees	27
26a. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0559 EDT, 25 August 1983	28
26b. Relative Delay Times - Nanoseconds	29
26c. Angle of Arrival - Degrees	29
27a. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0559 EDT, 25 August 1983	30
27b. Relative Delay Times - Nanoseconds	31
27c. Angle of Arrival - Degrees	31
28a. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0648 EDT and Hanscom AFB at 0659 EDT, 25 August 1983	32
28b. Relative Delay Times - Nanoseconds	33
28c. Angle of Arrival - Degrees	33
29. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H at 0744 EDT, 25 August 1983	34
30. Modified Refractivity Profiles Measured at Deerfield, N.H., 16 September 1983	35
31. Modified Refractivity Profiles Measured at Salem, N.H. on 16 September 1983	36
32. Modified Refractivity Profiles Measured at Hanscom AFB, 16 September 1983	37
33. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0700 EDT, 16 September 1983	38
34. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0710 EDT, 16 September 1983	39
35a. Ray Trace for Saddleback Link Using Sounding Data From Deerfield, N.H. at 0653 EDT, Salem, N.H. at 0710 EDT and Hanscom AFB at 0700 EDT, 16 September 1983	40
35b. Relative Delay Times - Nanoseconds	41
35c. Angle of Arrival - Degrees	41

Illustrations (contd)

36. Modified Refractivity Profiles Measured at Hanscom AFB, 29 September 1983	42
37. Modified Refractivity Profiles Measured at Salem, N.H., 29 September 1983	43
38. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0718 EDT and Hanscom AFB at 0700 EDT, 29 September 1983	44
39. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0700 EDT, 29 September 1983	45
40. Modified Refractivity Profiles Measured at Hanscom AFB, 30 September 1983	46
41. Modified Refractivity Profiles Measured at Salem, N.H., 30 September 1983	47
42. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0600 EDT, 30 September 1983	48
43. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0557 EDT and Hanscom AFB at 0600 EDT, 30 September 1983	49
44a. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0658 EDT and Hanscom AFB at 0700 EDT, 30 September 1983	52
44b. Relative Delay Times - Nanoseconds	53
44c. Angle of Arrival - Degrees	53
45a. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0955 EDT and Hanscom AFB at 1000 EDT, 30 September 1983	54
45b. Relative Delay Times - Nanoseconds	55
45c. Angle of Arrival - Degrees	55

Meteorological Measurements On Line-Of-Sight Microwave Radio Links

I. INTRODUCTION

From the middle of August to early November in both 1982 and 1983, field-test programs were conducted on the line-of-sight (LOS) microwave communication links in the southern New Hampshire and eastern Massachusetts areas. The links were from Pack Monadnock, N. H. to the Prospect Hill Field Site in Waltham, Mass. in 1982, and from Saddleback Mountain, N. H. to Prospect Hill in 1983. The propagation tests were performed by the Electromagnetic Sciences Division, Rome Air Development Center (RADC). Results of the radio measurements are presented by Lammers and Marr.¹ Meteorological measurements to determine the vertical profiles of microwave index of refraction were made by the Atmospheric Sciences Division, Air Force Geophysics Laboratory (AFGL). This report will be confined to the meteorological measurements and the associated refractivity data. By means of a refractive ray-trace model the effects of the atmospheric structure on radio propagation will be demonstrated for a number of cases.

(Received for publication 12 November 1985)

1. Lammers, U. H. V., and Marr, R. A. Atmospheric Multipath Propagation Over a Long Terrestrial Line-of-Sight Path, RADC-TR-85-79, ADA160392.

2. METEOROLOGICAL MEASUREMENT SITES

Figure 1 shows a cross-section of the topography directly under the Pack Monadnock-Prospect Hill (PM-PH) link of 1982. The overall length of the link

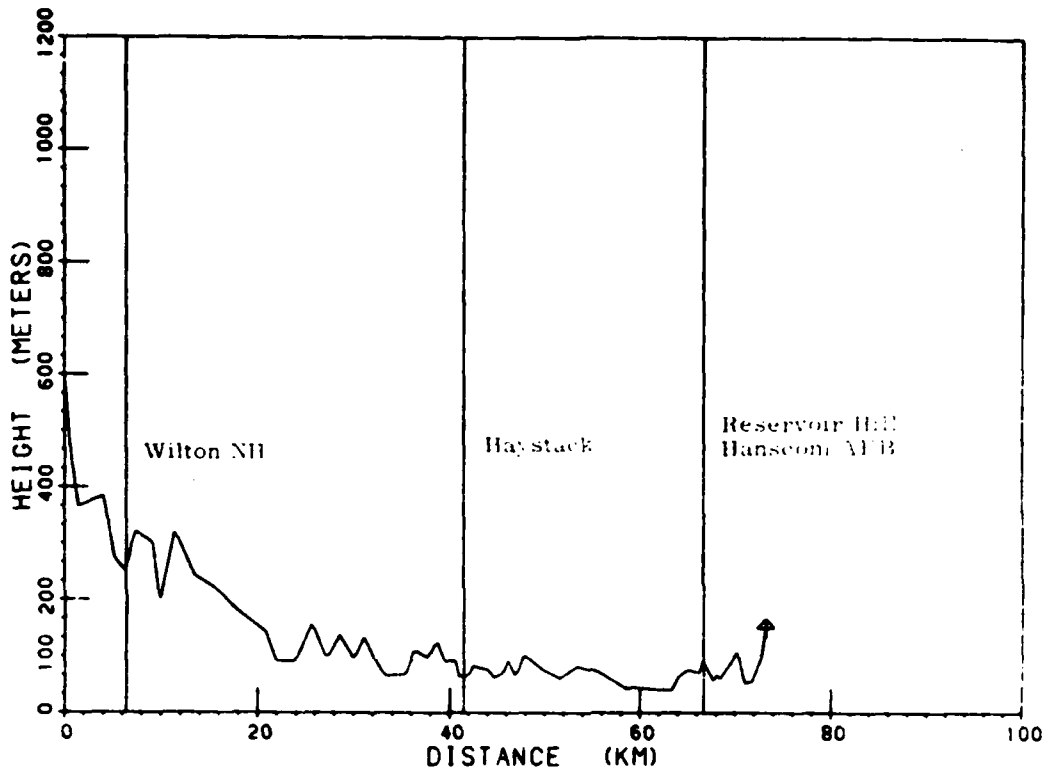


Figure 1. Path Profile for the Monadnock-Prospect Hill Link and the Locations of the Meteorological Observation Sites.

was 73.2 km with the transmitter at Pack Monadnock and the receiver at Prospect Hill. The antenna heights were 589.9 m for the transmitter and 150.2 m for the receiver. The difference in heights amounted to 439.7 m. Two meteorological measurement sites were established at the start of the field program. One was at the Haystack Observatory in Westford, Mass., 41.5 km from Monadnock and near the middle of the 73.2-km path. The other was at Reservoir Hill, Hanscom AFB, 66.7 km from Pack Monadnock and close to the Prospect Hill end of the path. To complement the receiver end of the link, a third site was added later near the transmitter end. This site was at Wilton, N.H., 6.4 km from Pack

Monadnock. It was manned infrequently, using a mobile meteorological sounding unit. The three measurement sites are identified by the vertical lines in Figure 1.

Figure 2 shows the path profile for the Saddleback Mountain-Prospect Hill (SM-PH) link of 1983. The path length was 87.6 km. The antenna height of the

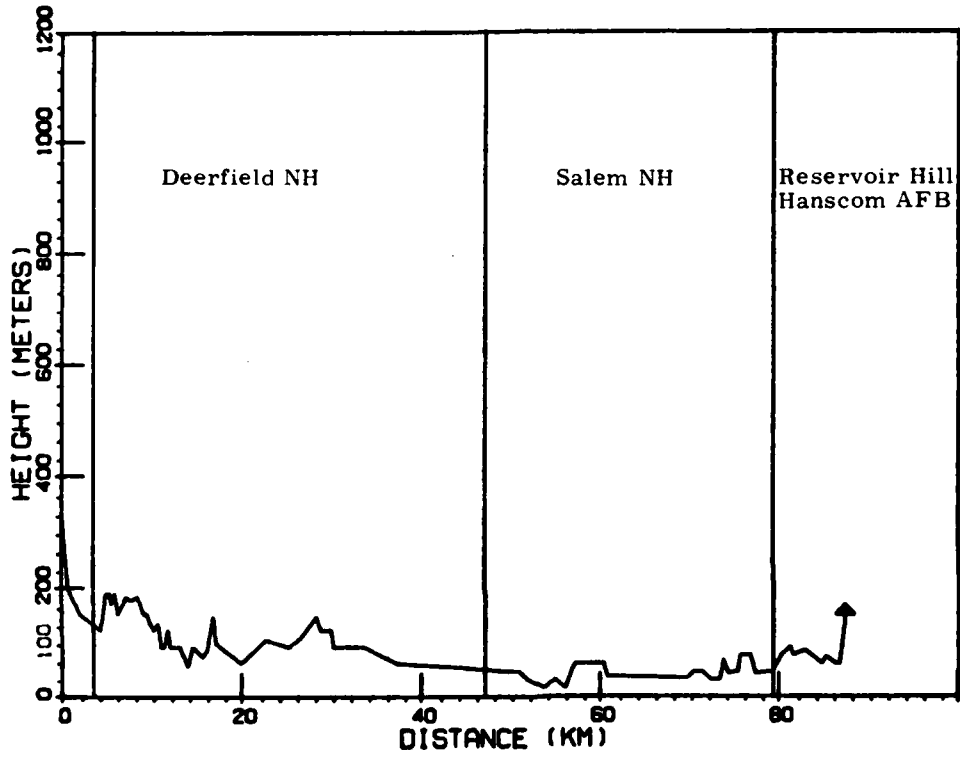


Figure 2. Path Profile for the Saddleback-Prospect Hill Link Showing Locations of Meteorological Observation Sites

transmitter at Saddleback Mountain was 338.0 m, and that of the receiver at Prospect Hill was 150.2 m. Thus, for the 1983 field program, the height difference between the transmitter and receiver was reduced to only 187.8 m. As in 1982, two meteorological sites were set up at the beginning of the field program. One site was at Salem, N.H., 47.4 km from Saddleback Mountain and close to the middle of the link. The other site was again at Reservoir Hill, Hanscom AFB, 79.6 km from Saddleback Mountain and close to the receiver end. There was a third site near the transmitter, but it was used only for one morning during the

field program. This was at Deerfield, N.H., 3.5 km from Saddleback Mountain. The three measuring sites on the SM-PH link are identified in Figure 2.

3. METEOROLOGICAL INSTRUMENTATION

Meteorological measurements were made with an airsonde, a radiosonde-type instrument manufactured by Atmospheric Instrumentation Research (AIR), Inc., Boulder, Colo., Figure 3. Two versions of airsondes were used in the 1982 field program. Both versions directly measured the dry-bulb and wet-bulb temperatures, but the more versatile one measured the air pressure also. A third improved version of the airsonde was used exclusively for all free-balloon soundings during the 1983 field program. The wet-bulb thermistor was replaced with a carbon hygistor humidity sensor that was capable of measuring pressure, temperature, and relative humidity. The airsonde was carried aloft on a 30 g free balloon. The data from all sensors were telemetered to the ground station every five to six seconds and were recorded on a cassette tape. Selected printouts of the transmitted data were made for every second or third time frame in the 1982 field program, while printouts of all measured variables as well as calculated data were made available for every time frame in the 1983 field program. The balloon ascent was monitored for 22 to 28 min after launch, or up to the 700-mb level. On occasions the soundings were cut short when there were indications of prolonged periods of frozen wet bulb (in 1982 only), weak incoming signals, or data rejection by the data-acquisition system due to interference from other sources. To provide good vertical resolution of the atmospheric parameters, efforts were made to control the rise rate of the balloon to between 1.5 and 2.5 m/sec. This combination of balloon-ascent rate and telemetry commutation rate gave a possible vertical resolution of 10 to 15 m. Thus, the airsonde provided much more detail than the standard radiosonde which has a resolution of about 100 m.

In 1983, the tethersonde was introduced into the field program as a sounding instrument. The tethersonde, also manufactured by AIR, Inc., is a nondisposable radiosonde that was carried aloft on a 2.0-m³ tethered balloon (Figure 4). It made direct measurements of wind speed, wind direction, pressure, temperature, and humidity. The tethersonde differs from the airsonde in that the temperature and humidity sensors are aspirated by a fan as opposed to being aspirated by balloon ascent. The wind speed was measured by a three-cup anemometer mounted on top of the sensor package. The blimp-shaped captive balloon was designed to orient itself into the wind, and the tethersonde, which contained a magnetic compass, was suspended in such a manner that it maintained a constant orientation with respect to the balloon. Thus, the wind direction was measured by the magnetic compass, with the balloon acting as a wind vane. Attempts were made to



Figure 3. Atmospheric Data Acquisition System (ADAS) Manufactured by Atmospheric Instrumentation Research (AIR) Inc., With Expendable Sonde



Figure 4. Tethered Balloon and Winch With the Nonexpendable Tethersonde

control the rate of ascent and descent of the tethered balloon to 30 m/min, and to attain the height of 450 m, but at times the strong winds aloft prevented the balloon from ascending at the rate and to the height desired. The data from all sensors of the tethersonde were telemetered to the ground station every 10 sec and were recorded on a tape recorder. Printouts of the data were made every 20 sec. During the 1983 field program, the tethered balloon was operated only at the Salem site.

4. METEOROLOGICAL MEASUREMENTS

Compared with the standard radiosonde, the airsonde together with the tethersonde provided a more desirable fine-scale detail of the temperature and humidity profiles and, in turn, the radio refractivity profile in the lower atmosphere. The simplicity in taking measurements with this equipment provided opportunities for more frequent observations to investigate the temporal changes in the gradients of temperature, humidity, and refractivity. A total of 118 free-balloon soundings were made during the 12-week 1982 field program. A combined total of 108 free-balloon and tethered-balloon soundings were recorded for the 1983 field program. These are the soundings that were judged to be satisfactory from the standpoint of the quality of the observed data and the heights achieved by the balloons. In both 1982 and 1983, a great majority of the measurements were taken during the early morning hours.

For both years, a full-scale meteorological operation that involved two or all three measurement sites relied heavily on the forecast of conditions conducive to anomalous radio propagation during the early morning hours. The conditions were for calm, clear nights leading to intense radiational surface cooling. Subsidence, advection, and frontal passage were also considered. These are the conditions that can produce layers of strong contrasting gradients of temperature and humidity in the lower atmosphere. In 1982, reliance was also placed on the results of the exploratory free-balloon sounding that was made at Hanscom AFB every weekday morning regardless of the weather condition. At times, despite the weather prediction, efforts were made to go into full-scale operation when notified by RADC personnel at the Prospect Hill Field Site that heavy radio activity was in progress on the link. For both years, measurements were continued until the Prospect Hill Field Site reported no signs of anomalous propagation.

The underlying assumption in making these meteorological soundings is that the lower atmosphere is basically layered or stratified. The primary interest is the change in the vertical gradients of temperature and moisture from layer to layer, rather than the changes in the absolute values. As stated by Dougherty

and Dutton,² the stratification can result in refractivity layering -- layers in which contrasting refractivity gradients occur. Examples of atmospheric layering are presented in Figures 5 through 8. The profiles in Figures 5 through 8 are from the earliest soundings made at Hanscom AFB and at Salem on 25 August, 29 September, 30 September and 01 November 1983. RADC rated the variability in the characteristics of the received fields as being light, moderate, or heavy; these four mornings were judged as having heavy activity for a number of hours on the SM-PH link. Except for one morning with scattered cirrus clouds, the skies were reported to be clear. At the surface the winds were observed to be very light or calm. The soundings for all four days at Hanscom AFB and the 01 November sounding at Salem were made with free balloons. On the other three days at Salem, the tethered balloon was used. The balloons were launched shortly before sunrise, or immediately after sunrise. For comparison purposes, the profiles in the figures are plotted only to heights of 500 m. The horizontal dashed lines at 338 m and 150 m in each plot represent the heights of the Saddleback Mountain and Prospect Hill antennas, respectively.

The vertical profiles of temperature, T , and dewpoint temperature, T_d , are shown on the left side of Figures 5 and 8. Obvious differences are noted between most of the low-level profiles obtained at Hanscom AFB (top) and at Salem (bottom). The differences are presumed to be related to local terrain effects; however, the sets of profiles display features that are similar and common to all. The temperature profiles all show an inversion of varying intensity extending from ground level to a few hundred meters. Of interest is the behavior of the dewpoint within the temperature inversion layer. The profiles all show the dewpoint increasing with the air temperature from the ground, to levels slightly above or below the height of the receiving antenna. Although the depth vary, a moist surface layer with steep positive gradient of the dewpoint is thus evident in all the plots. In most cases, the profiles then show an abrupt and marked decrease of the dewpoint, and a dry layer with steep negative gradient of the dewpoint becomes apparent. The thickness of this layer is shown to have large variability in these figures. The interface between the layer of cooler moist air below and warmer dry air above is, in most cases, very sharp.

It should be noted here that the soundings obtained at Salem on 29 September and 30 September show a shallow subrefractive layer at the surface caused by both temperature and dewpoint temperature increasing with height. The transition from the top of this wet and relatively cold point to the dryer warmer conditions at 400 m occurs in two thin layers about 100 m apart.

2. Dougherty, H. T., and Dutton, E. J., The Role of Elevated Ducting for Radio Service and Interference Fields. NTIA Report 81-69, March 1981.

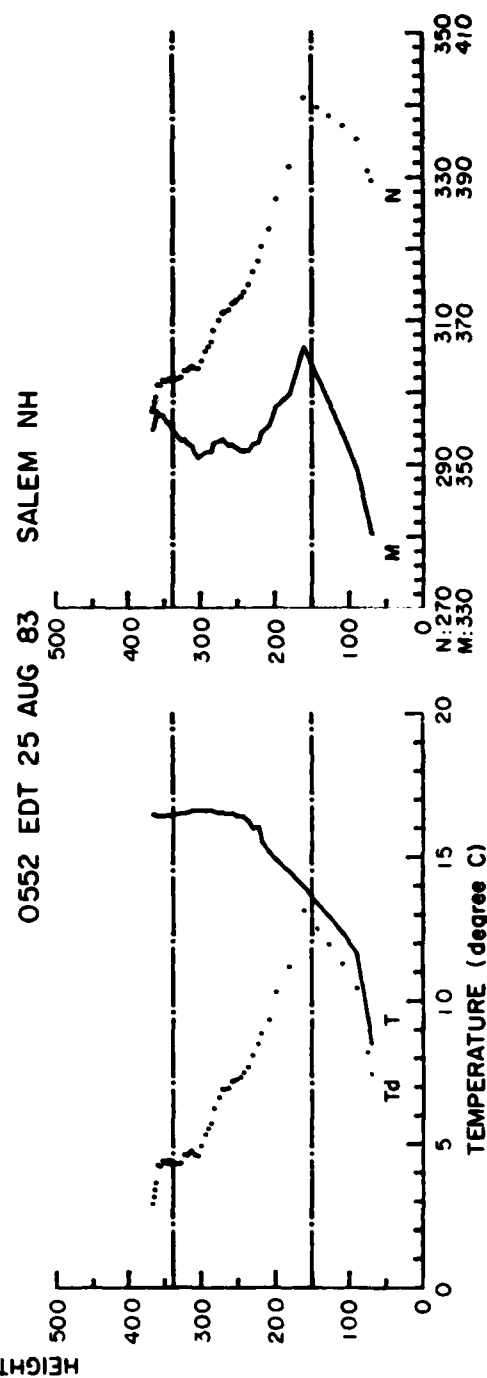
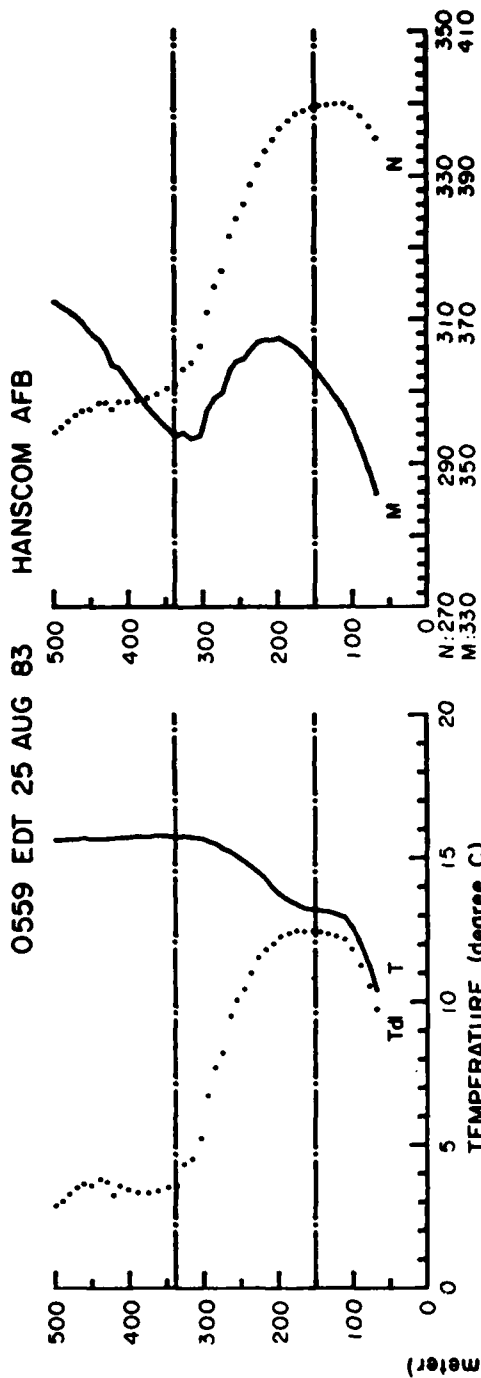


Figure 5. 25 August 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M

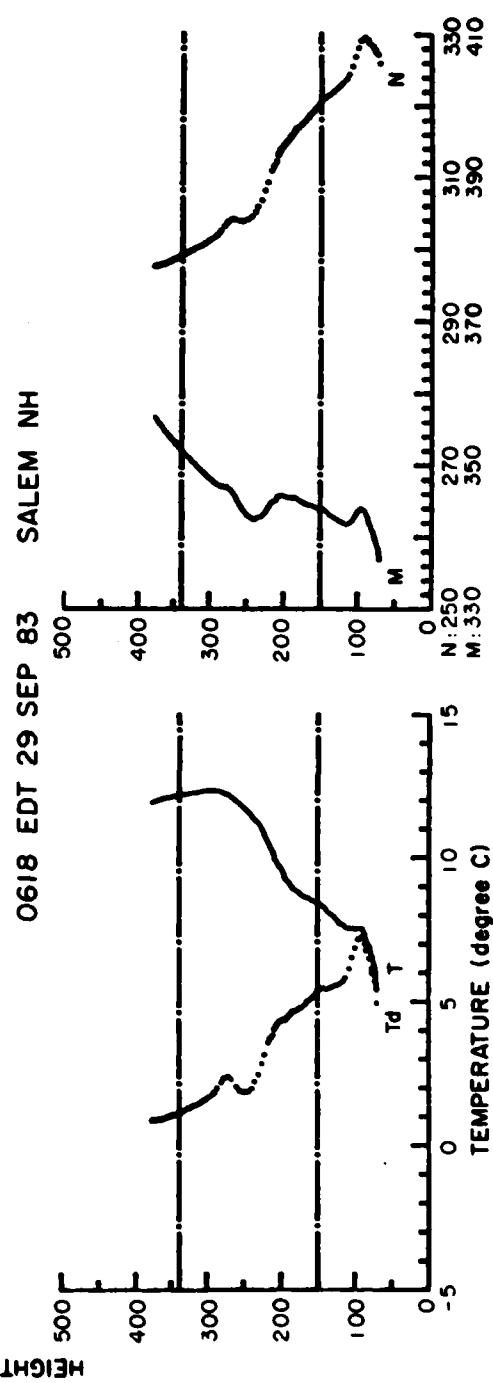
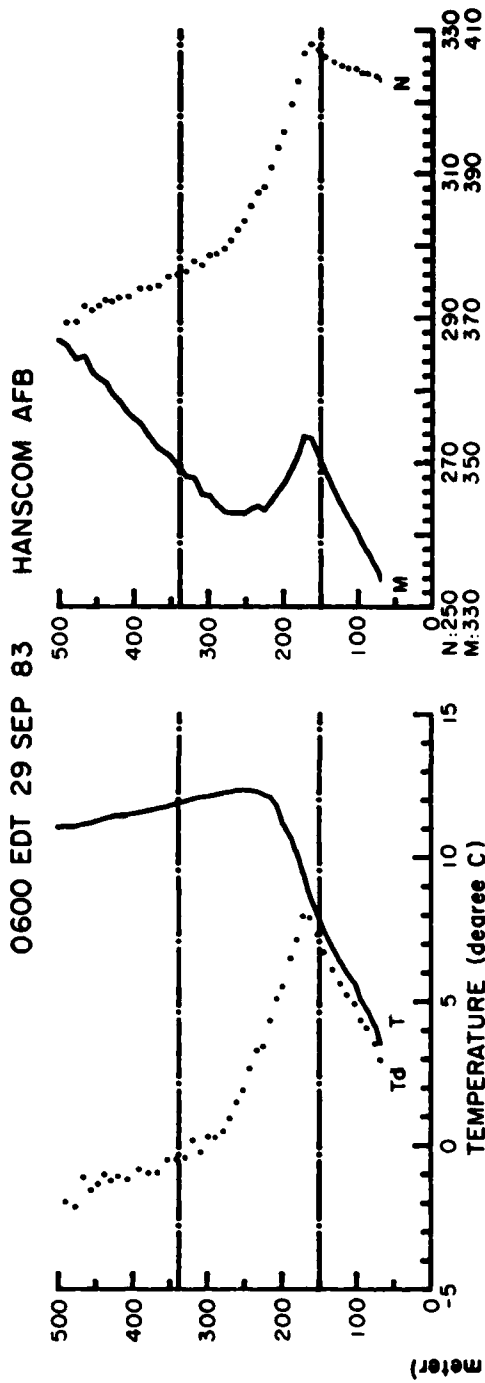


Figure 6. 29 September 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M

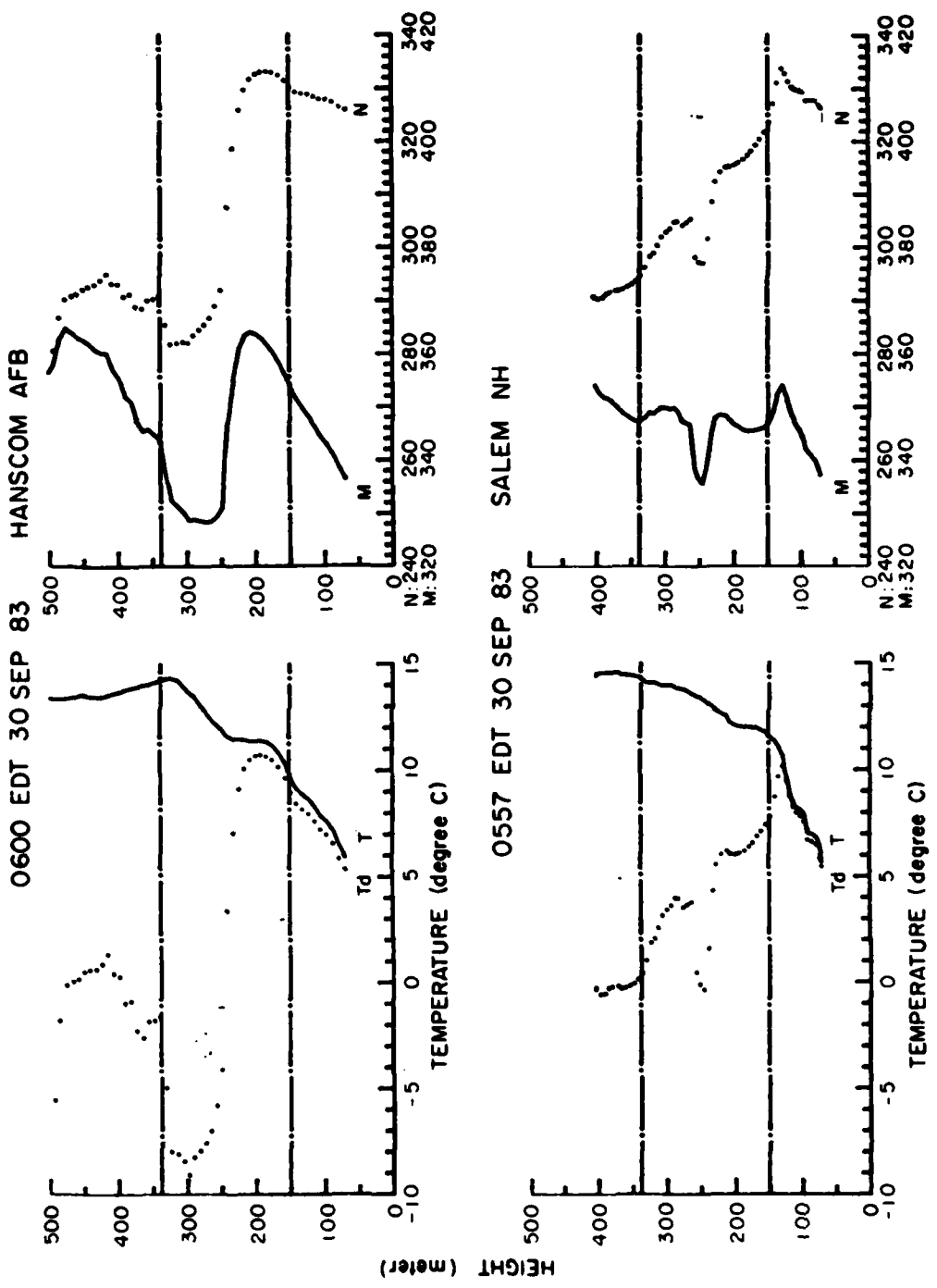


Figure 7. 30 September 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M

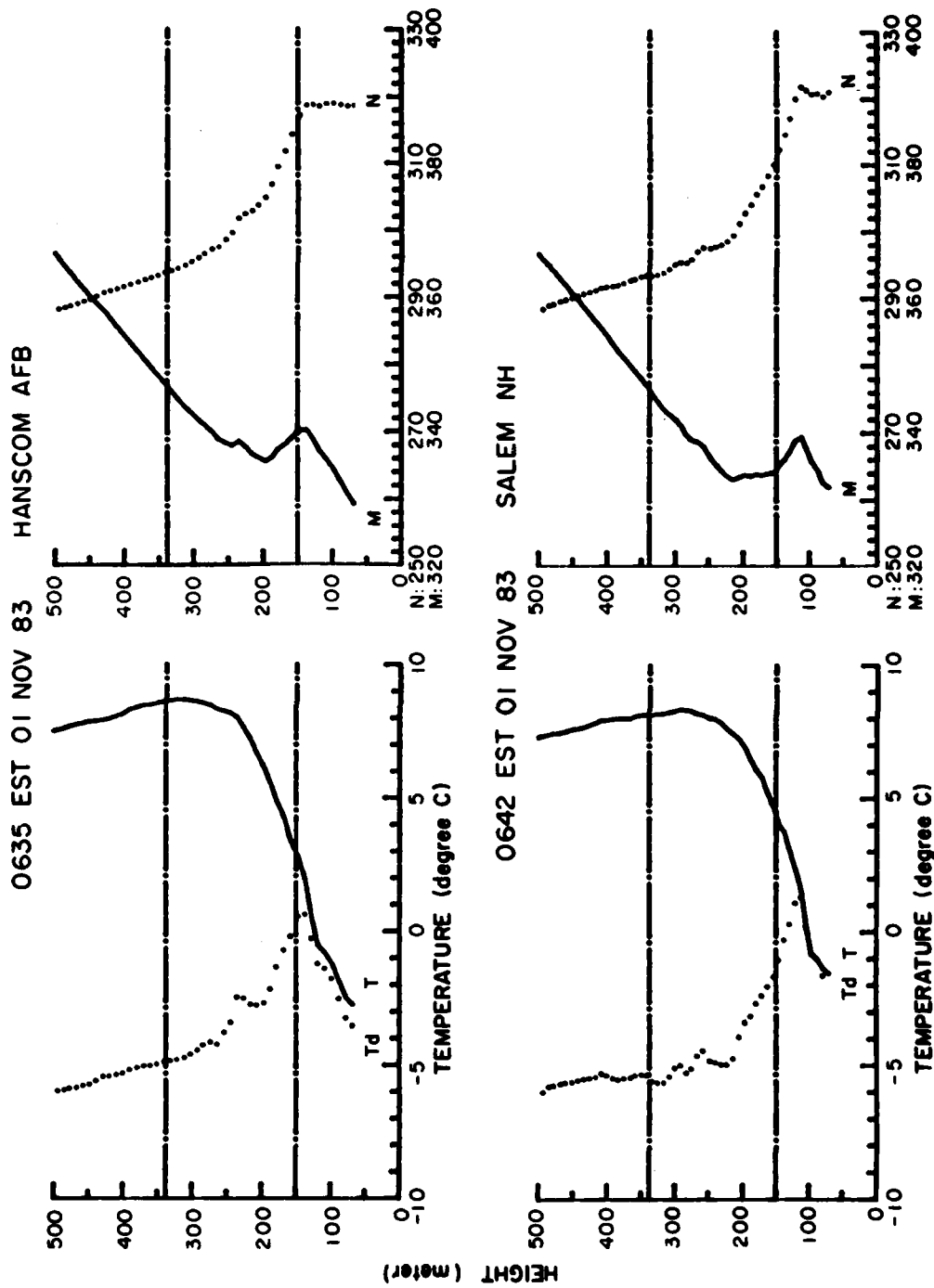


Figure 8. 1 November 1983 - Meteorological Sounding Data for Hanscom AFB and Salem, N.H. Temperature (T), Dewpoint Temperature (Td), Refractive Index (N), Modified Refractive Index M

The refractivity layerings resulting from the distribution of temperature and dewpoint on the left are shown on the right side of the figures. Profiles of the refractive index, N , and the modified refractive index, M , are presented in these figures. The modified refractive index is related to the refractive index by $M = N + 157 Z$, where Z is the height in km. To indicate the direction and intensity of the bending of radio waves, layers or stratified layers are classified as being subrefractive, normal, superrefractive, or ducting. Ordinarily, N decreases with height, and as a layer changes from normal to superrefractive to ducting, the negative gradient of N becomes progressively more negative. Only a strong subrefractive layer with increasing value of N will show a positive gradient, and its presence will be most noticeable in the N -profile. On the other hand, M ordinarily increases with height, and as a layer changes from subrefractive to normal to superrefractive, the magnitude of the positive gradient of M decreases. A ducting layer will show a negative gradient of M , and its existence will be most recognizable in the M -profile. Furthermore, from the M -profile with a ducting layer, the duct type (surface, elevated-surface, or elevated) can readily be determined, and information on the duct width and duct intensity can be extracted. In Figures 5 through 8, the strong temperature and dewpoint contrasts, particularly at the interface between moist and dry layers, show extreme gradients of both refractivity and modified refractivity. The N -profiles all show a subrefractive layer corresponding to the moist layer below. The M -profiles all show a ducting layer corresponding to the dry layer above the interface. The M -profiles of 29 and 30 September at Salem exhibit the pronounced effects of the previously mentioned double-stage decrease of the dewpoint which results in two ducting layers. In both cases, the upper duct is stronger and thicker. In the profile of 30 September, the upper duct actually contains the lower duct embedded in it.

5. PACK MONADNOCK-PROSPECT HILL LINK, 1982

To evaluate the effects of measured refractive profiles on line-of-sight link performances, the refractive ray-trace model described by Morrissey et al.¹ was used extensively. Meteorological soundings made at both Hanscom AFB and Haystack on two separate mornings were selected to demonstrate, by means of ray-trace diagrams, the atmospheric effects on microwave propagation along the 73.2-km PM-PH link. The two mornings were on 13 September and 25 October 1982. RADC personnel reported heavy activity on the morning of 13 September and moderate activity on the morning of 25 October from their propagation experiment on the link. These two mornings were chosen because the soundings

showed layers in which the ducting gradient was exceeded. Neither morning had layers strong enough to satisfy the ducting criteria for the link. This was primarily due to the large vertical displacement of 440 m between the transmitting and receiving antennas. The normal ducting criterion is based on assuming horizontal stratification of the atmosphere. While it was realized that ducting criteria would not be achieved using this assumption, it was hypothesized that a sloped ducting layer might cause ducting.

5.1 Ray Trace for 13 September 1982

Figure 9 presents the vertical profiles of the modified refractivity, M , obtained from soundings taken at Hanscom AFB during the morning hours of 13 September. The dot-dash horizontal lines at 590 m and 150 m represent the heights of the Monadnock and Prospect Hill antennas, respectively. The dotted vertical lines define the depth or thickness of the ducts. Short line segments are used to denote the limits of the ducts that are shallow or have weak gradients of M . The M profiles for the same morning at Haystack are shown in Figure 10. The profiles show strong refractive ducts on all Hanscom AFB soundings, and much weaker ducts on the Haystack soundings. The top of the ducting layer occurs at 400 to 500 m, which is below the transmitter and, hence, would not be expected to produce ducting between the antennas.

The 0756 EDT sounding taken at Hanscom AFB was used as the basis of a ray trace and is shown in Figure 11. The vertical line at 66.7 km indicates the position of the meteorological measurement site. The numbers at the top of this line are the M units scale. The sloping line to the right of this is the M unit data from the sounding. The M unit data is extrapolated below the surface to provide data where rays are below the height of the balloon release. The duct was highest at this time (0756 EDT) and, consequently, the effect of the duct is most noticeable. A "radio hole" is formed just below the top of the duct (<500 m). Due to the geometry of the duct, the received signal should be normal, and the rays appear quite normal in the area of the receiving antenna. The secondary area of diverging rays at about 600 m is the result of a change in the refractive gradient at about 530 m. A ray trace using the 0856 EDT sounding at Hanscom AFB, presented in Figure 12, produces a similar result, but the principal hole is less pronounced. This is due to the ducting layer being about 100 m lower. A ray trace using the 0901 EDT sounding at Haystack, shown in Figure 13, produces a similar plot with areas of diverging rays being slightly less pronounced than in the previous figure. The reason for the lack of large differences between the two plots is that although the duct on the 0901 EDT sounding is much weaker, it is approximately 100 m higher. The ray-bending is more sensitive when the ducting

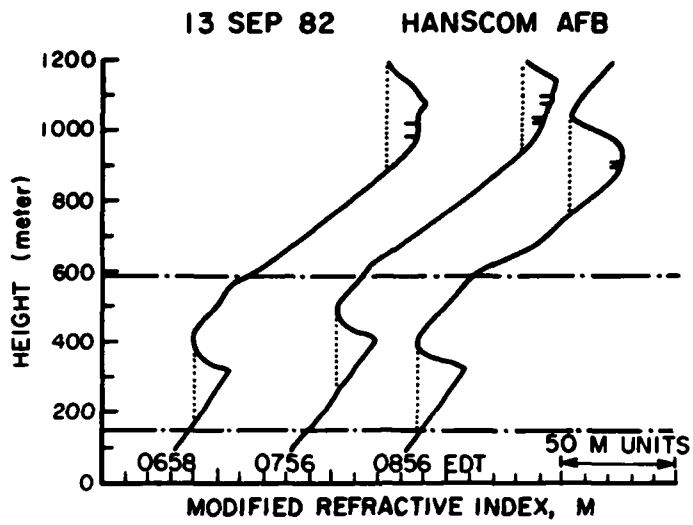


Figure 9. Modified Refractivity Profiles Measured at Hanscom AFB, 13 September 1982

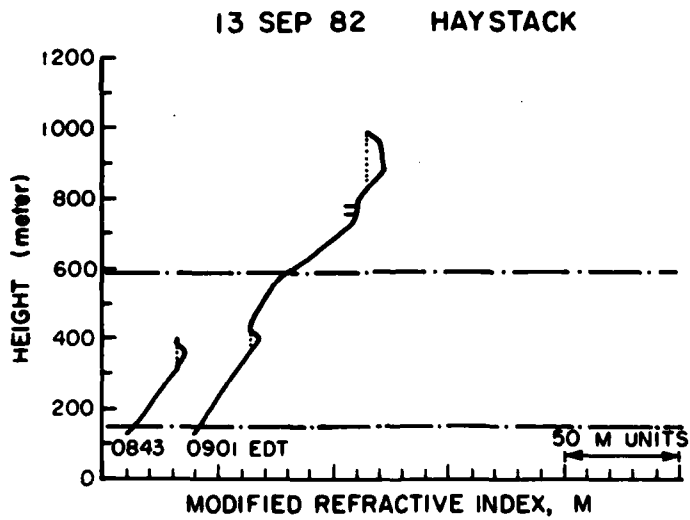


Figure 10. Modified Refractivity Profiles Measured at Haystack Site, 13 September 1982

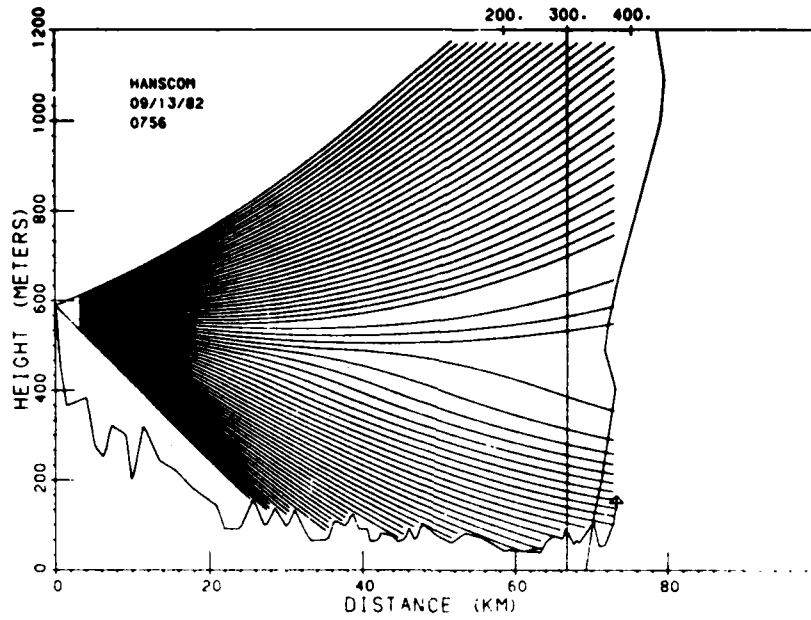


Figure 11. Ray Trace for Monadnock Link Using Modified Refractivity Profile From Hanscom AFB Sounding at 0756 EDT, 13 September 1982

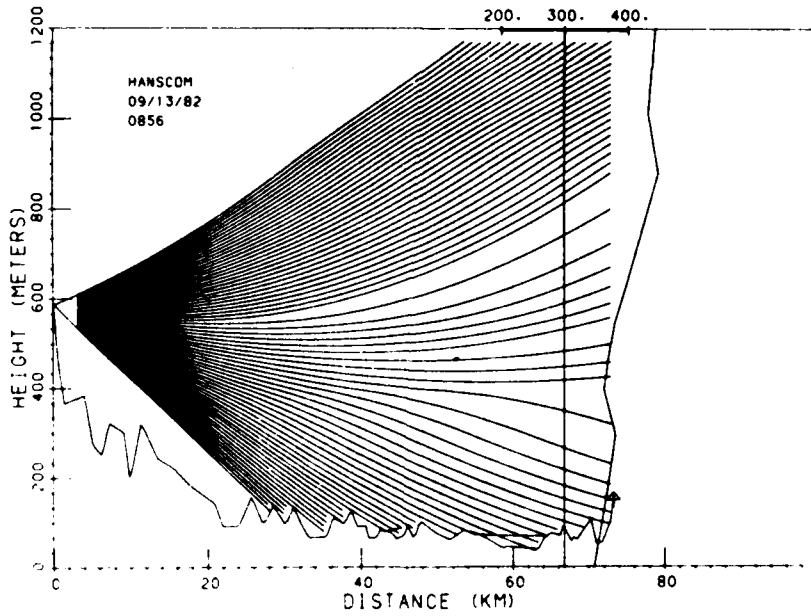


Figure 12. Ray Trace for Monadnock Link Using Modified Refractivity Profile From Hanscom AFB Sounding at 0856 EDT, 13 September 1982

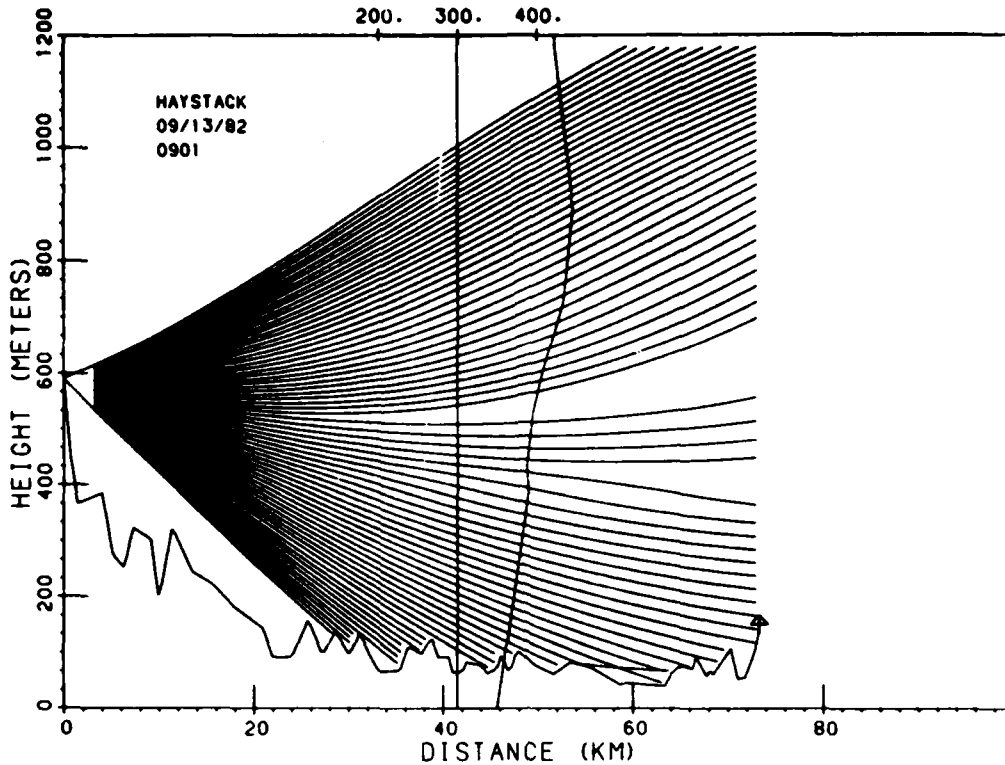


Figure 13. Ray Trace for Monadnock Link Using Modified Refractivity Profile From Haystack Sounding at 0901 EDT, 13 September 1982

layer is closer to the height of the transmitting antenna, as shown by the difference between the 0756 EDT ray trace and the 0856 EDT ray trace. A ray trace using both the 0856 EDT sounding at Hanscom AFB and the 0901 EDT sounding at Haystack, shown in Figure 14, produces a similar result. The ray-trace program that uses two soundings interpolates between soundings, and assumes stratification outside the end soundings.

5.2 Ray Trace for 25 October 1982

The modified refractivity profiles obtained on the morning of 25 October are shown in Figure 15 for Hanscom AFB, and in Figure 16 for Haystack. The soundings show a surface duct with a top at about 200 m. The early sounding shows a disturbance around 600 m which develops into a duct by the 0831 EDT sounding at Haystack. This duct has its top at about 580 m, just below the transmitter,

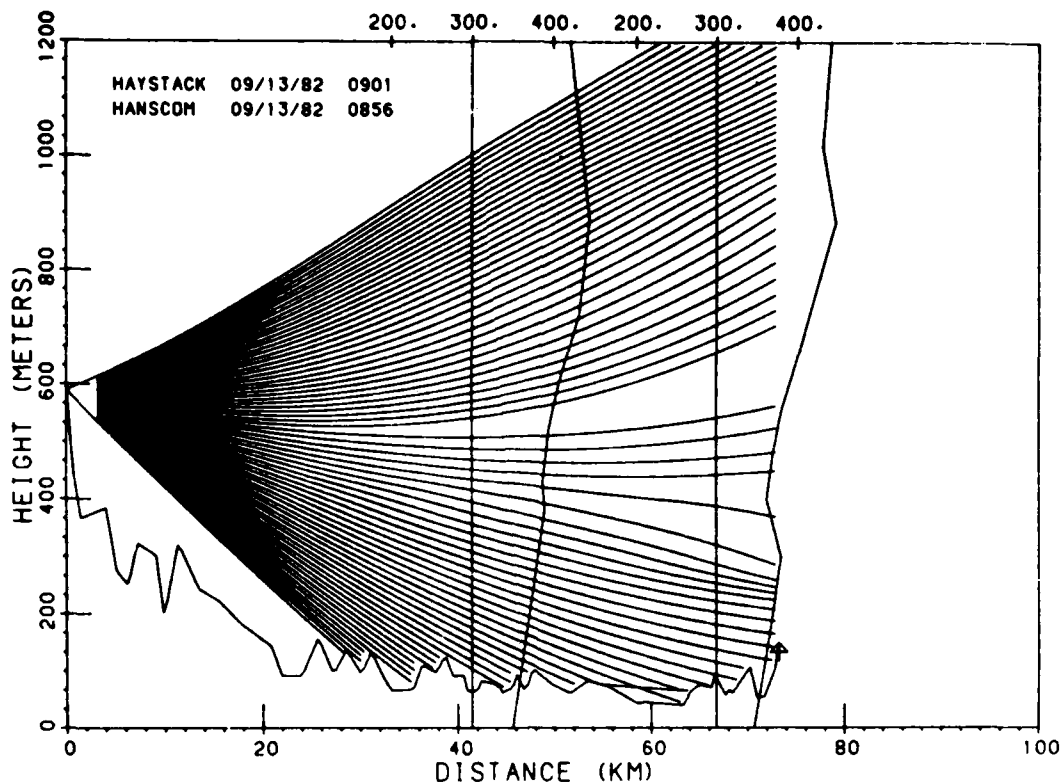


Figure 14. Ray Trace for Monadnock Link Using Sounding Data From Hanscom AFB at 0856 and From Haystack Site at 0901, 13 September 1982

in the 0831 EDT sounding, and rises to about 700 m by the 1011 EDT sounding at Haystack.

The ray trace using the 0655 EDT sounding at Hanscom AFB, shown in Figure 17, is interesting in that a multipath zone develops without the existence of a ducting layer. This is the result of a layer (> 500 m) of lower M gradient overlying a layer (< 500 m) of larger gradient. The rays entering the lower layer are bent more sharply upward, and "catch up" with the rays that just miss the lower layer. Again a slight rarefaction is evident at the receiver, due to the low-level surface duct.

The ray trace using the 0831 EDT sounding at Haystack, in Figure 18, is typical of a transmitter located just above a duct. A large hole is developed. Again the low-level duct produces a slight rarefaction. The ray trace using the 0921 EDT sounding at Haystack in Figure 19 shows the ducting developing as a result

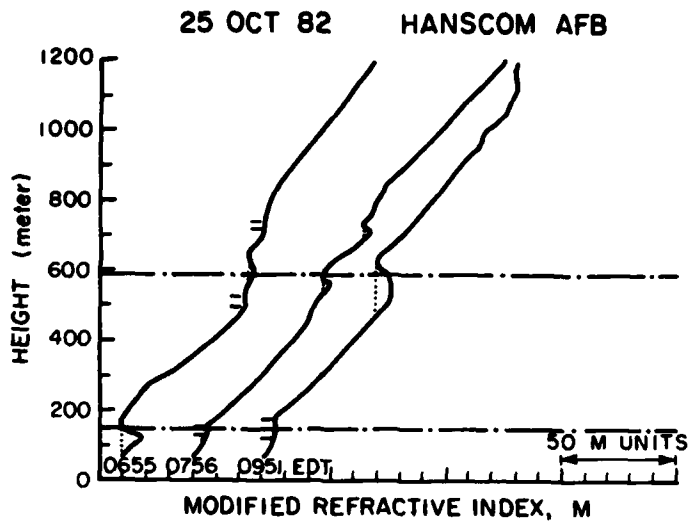


Figure 15. Modified Refractivity Profiles Measured at Hanscom AFB, 25 October 1982

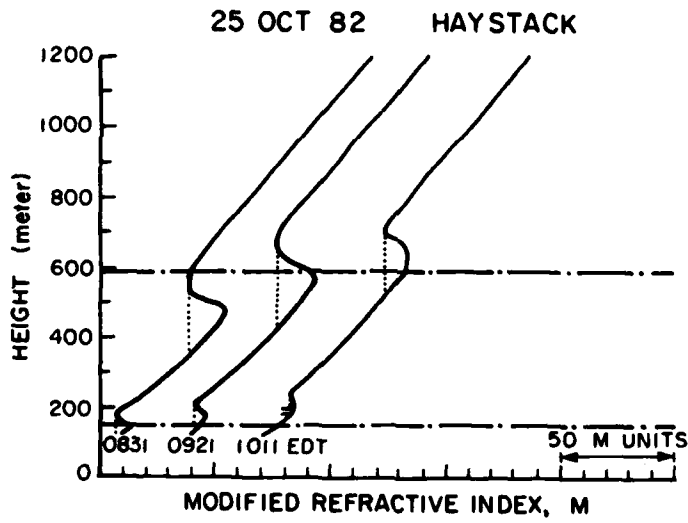


Figure 16. Modified Refractivity Profiles Measured at Haystack Site, 25 October 1982

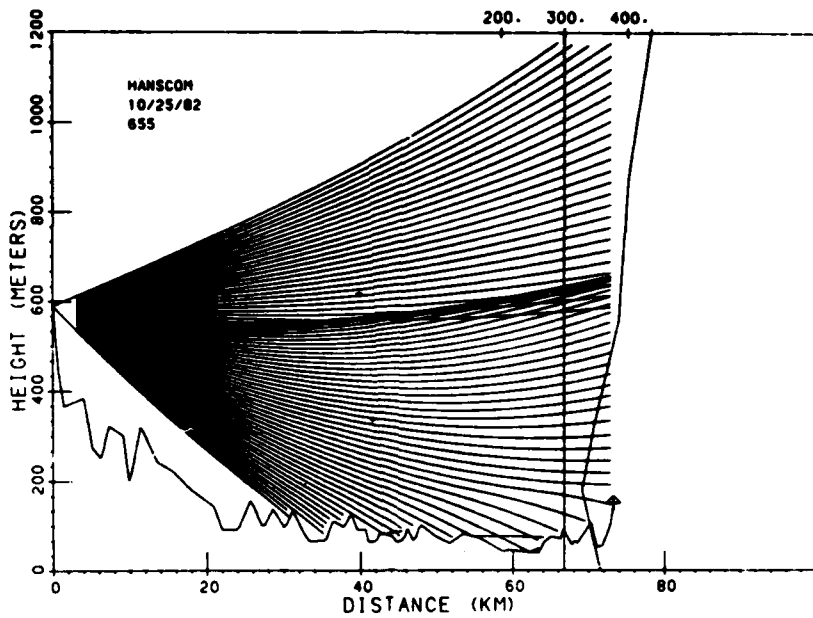


Figure 17. Ray Trace for Monadnock Link Using Sounding Data From Hanscom AFB at 0655 EDT, 25 October 1982

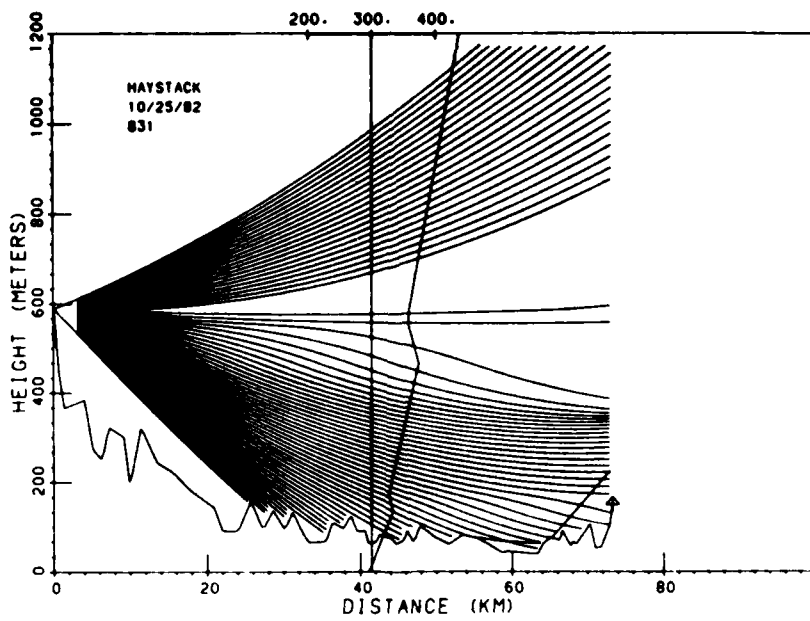


Figure 18. Ray Trace for Monadnock Link Using Sounding Data From Haystack Site at 0831 EDT, 25 October 1982

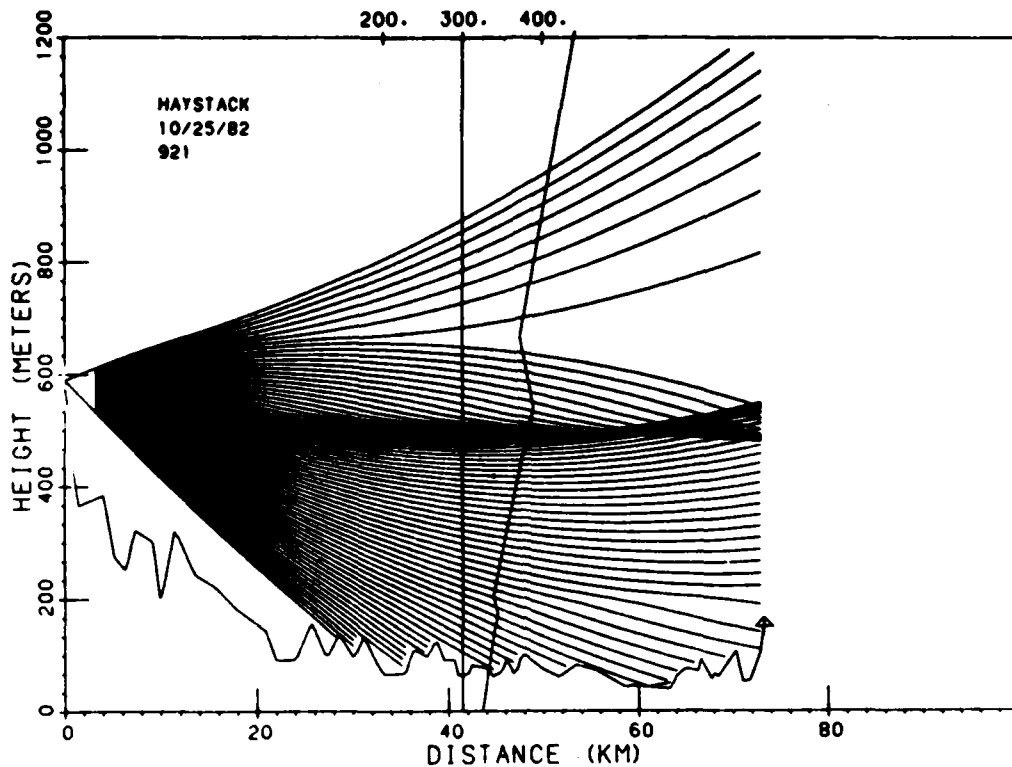


Figure 19. Ray Trace for Monadnock Link Using Sounding Data From Haystack Site at 0921 EDT, 25 October 1982

of the top of the ducting layer moving above the transmitter. Due to the large vertical separation, this ducting is not capable of causing multipath at the receiver. Figure 20, based on the 0951 EDT sounding at Hanscom AFB, also shows ducting, but a slight difference is noted in the ducting area. This is due to the ducting being compounded with the type of multipath noted in Figure 17 for the 0655 EDT sounding at Hanscom AFB. In Figure 21, the ray trace using the 1011 EDT sounding at Haystack is shown, and in Figure 22 the ray trace using the two soundings of 0951 EDT at Hanscom AFB and 1011 EDT at Haystack is presented. Both figures indicated ducting layers but, as in the other ray traces, the multipath regions are well above the receiving antenna.

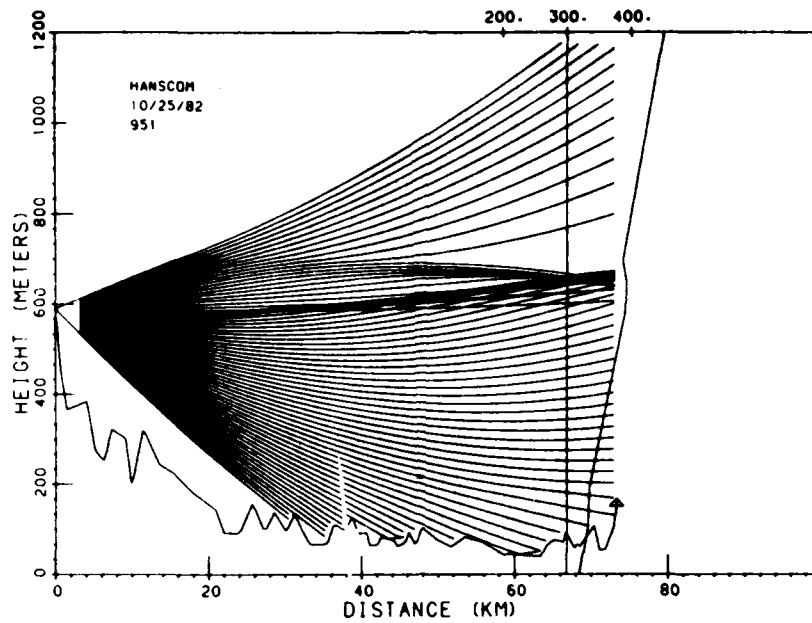


Figure 20. Ray Trace for Monadnock Link Using Sounding Data From Hanscom AFB at 0951 EDT, 25 October 1982

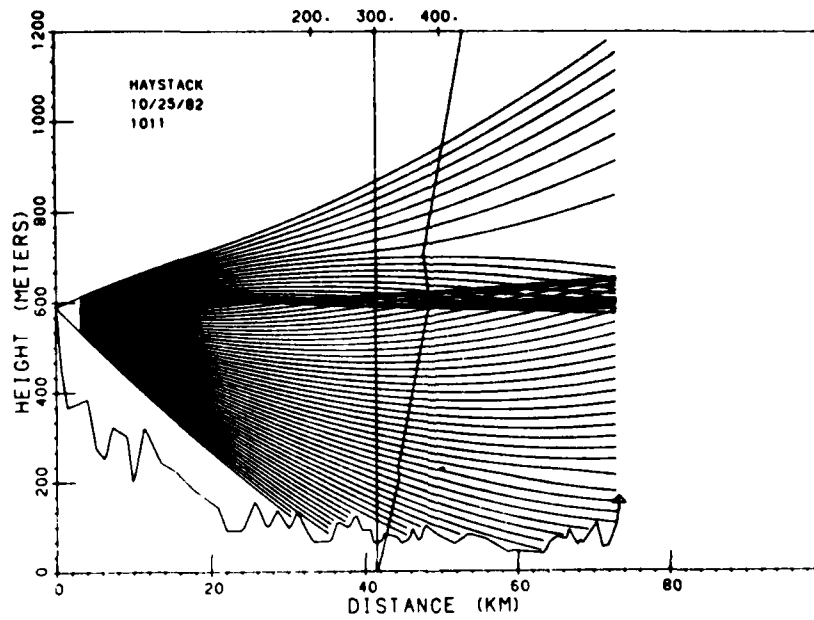


Figure 21. Ray Trace for Monadnock Link Using Sounding Data From Haystack Site at 1111 EDT, 25 October 1982

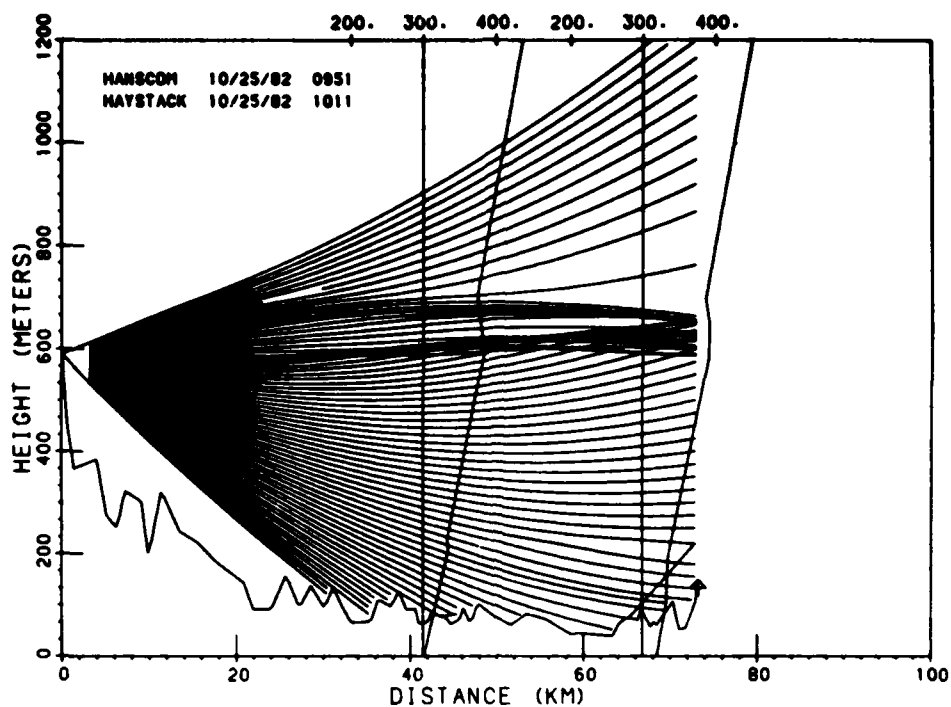


Figure 22. Ray Trace for Monadnock Link Using Sounding Data From Sites at Haystack at 1011 EDT and Hanscom at 0951 EDT, 25 October 1982

6. SADDLEBACK-PROSPECT HILL LINK, 1983

This link was chosen to take advantage of the large receiving antenna at Prospect Hill and to have a shallow enough inclination to allow anomalous propagation effects to be experienced. It was recognized that low-level inversion due to radiation cooling would influence the link and these conditions are predicted with a reasonable measure of success.

6.1 25 August 1983

The modified refractive index profiles for 25 August 1983 are given in Figures 23 and 24 for Hanscom and Salem, respectively. Ray traces and the associated delay times and angle of arrival using the soundings near 0600 are presented in Figures 25, 26, and 27. Figure 25, generated using both Salem

HANSCOM AFB

25 AUG 83

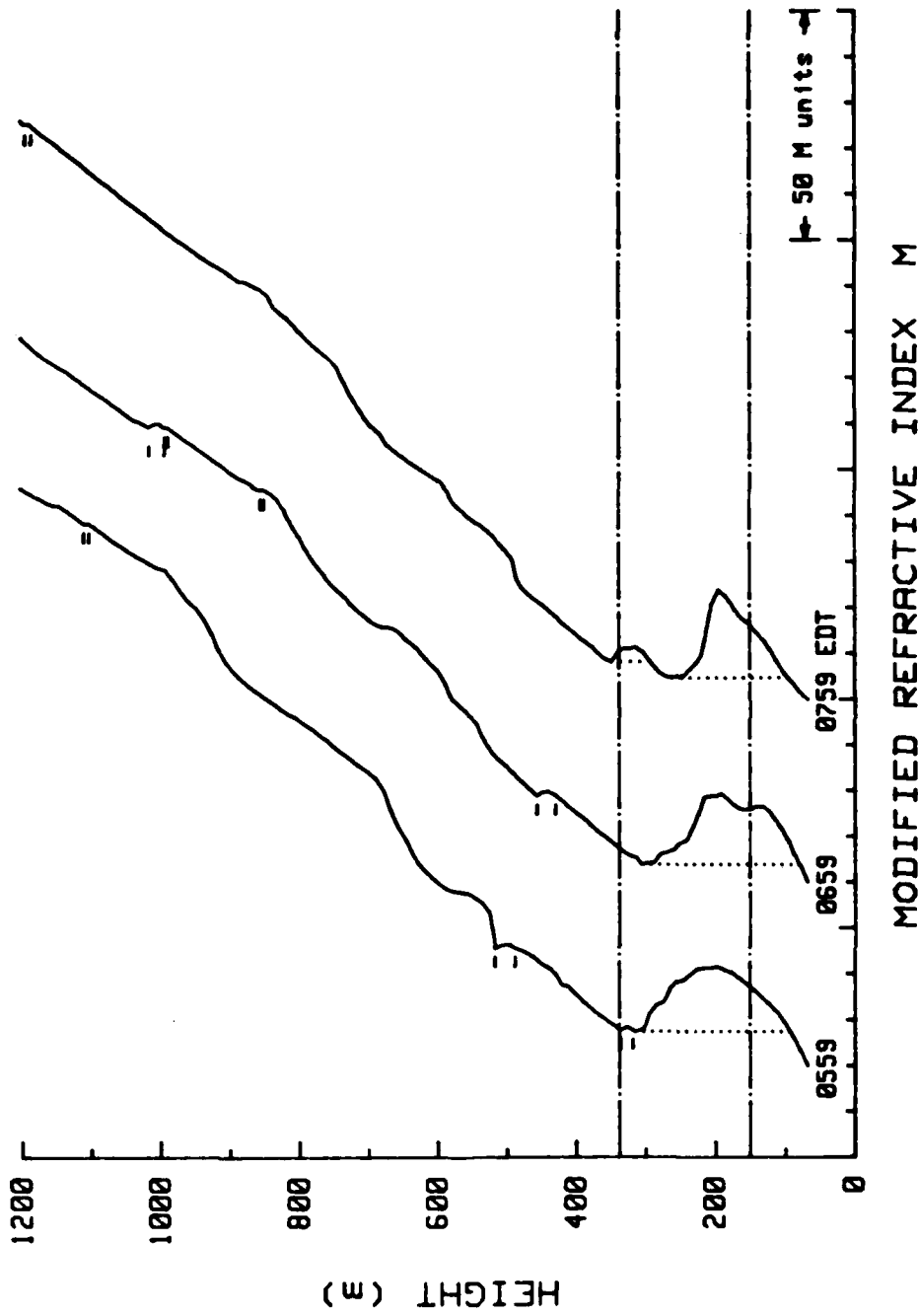


Figure 23. Modified Refractivity Profiles Measured at Hanscom AFB, 25 August 1983

SALEM NH

25 AUG 83

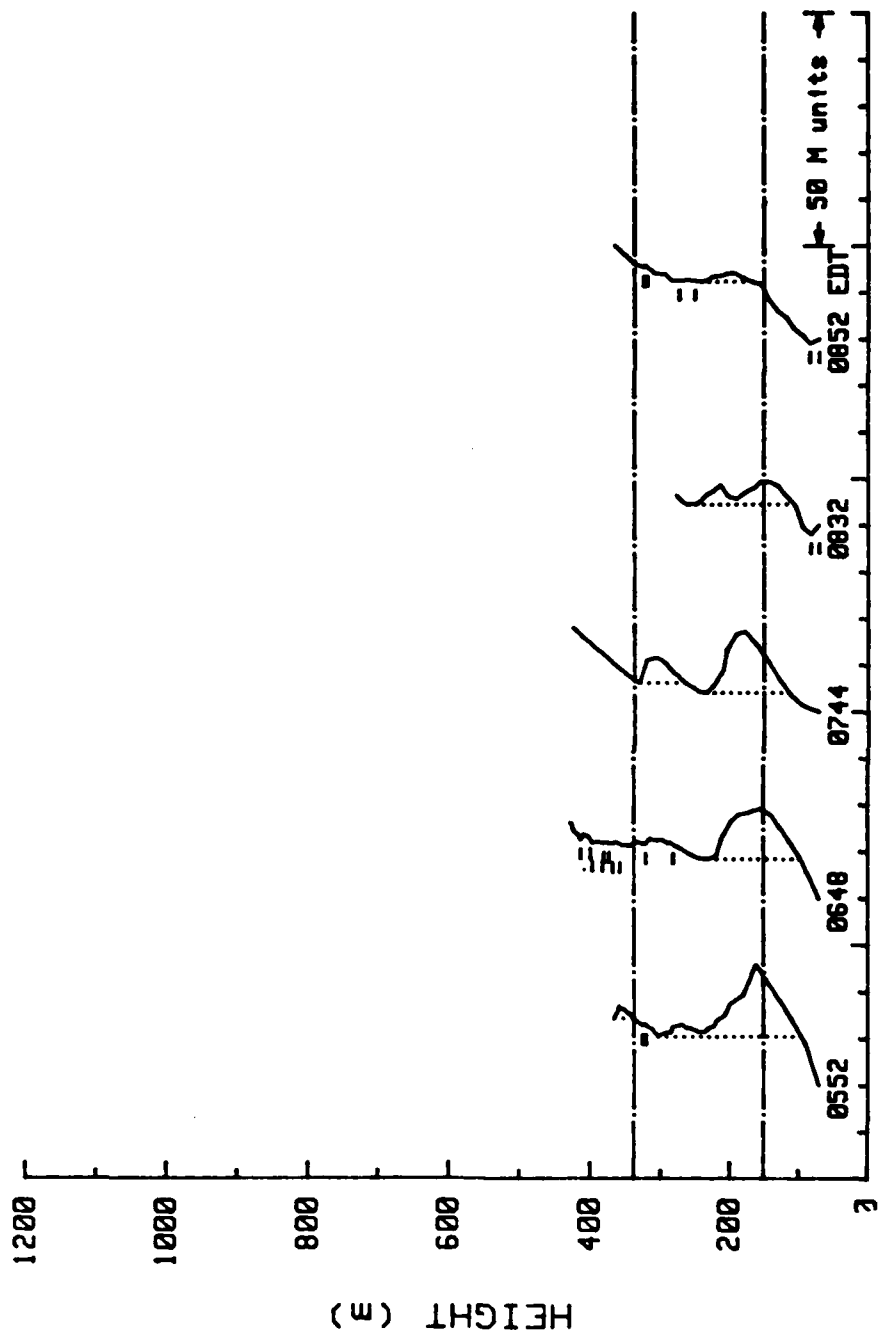


Figure 24. Modified Refractivity Profiles Measured at Salem, N.H., 25 August 1983

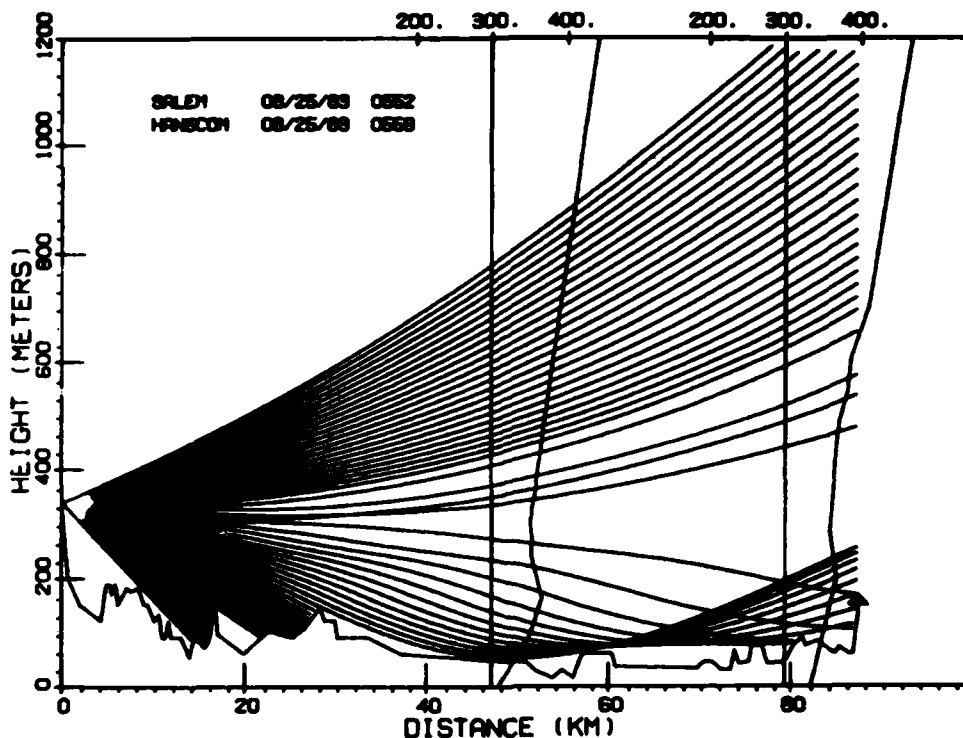


Figure 25a. Ray Trace for Saddleback Link Using Sounding Data From Salem at 0552 EDT and Hanscom at 0559 EDT, 25 August 1983

and Hanscom data, is almost a duplicate of Figure 26, using Salem data alone. This is to be expected due to the geometry and the interpolation scheme used. The Salem sounding has complete control in the first 47 km and partial control (interpolation) between 47 and 79 km, while the Hanscom sounding only has complete control in the last 10 km. The ray trace in Figure 27 differs due to using only the Hanscom sounding which is missing the strong subrefractive layer at the surface. This results in less upward bending of the lower rays and a greater concentration of rays at the antenna. All three ray traces show the antenna to be in a region where the radio signal delay spread is from 0.5 to 1.0 nanoseconds, and the spread in angle of arrival is from 0.4 to 0.7 degrees. These multipath situations are the product of the very strong duct shown on both the Hanscom and Salem soundings (Figures 23 and 24) overlying a strong subrefractive layer.

The M profiles for approximately 0700 still show this strong duct overlying the subrefractive layer. When these soundings, Salem 0648 and Hanscom 0659,

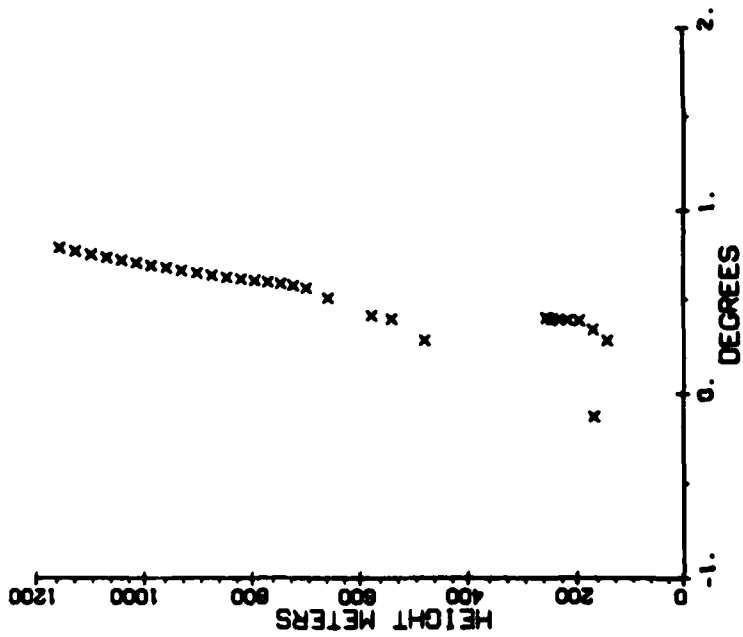


Figure 25c. Angle of Arrival - Degrees

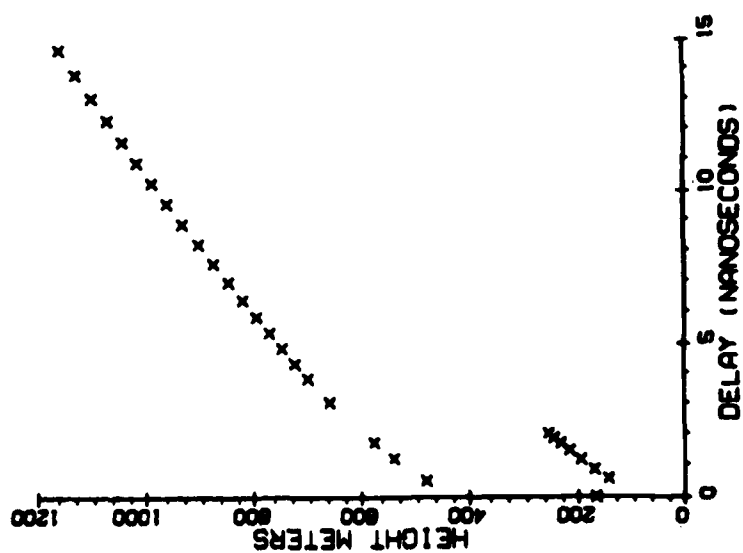


Figure 25b. Relative Delay Times - Nanoseconds

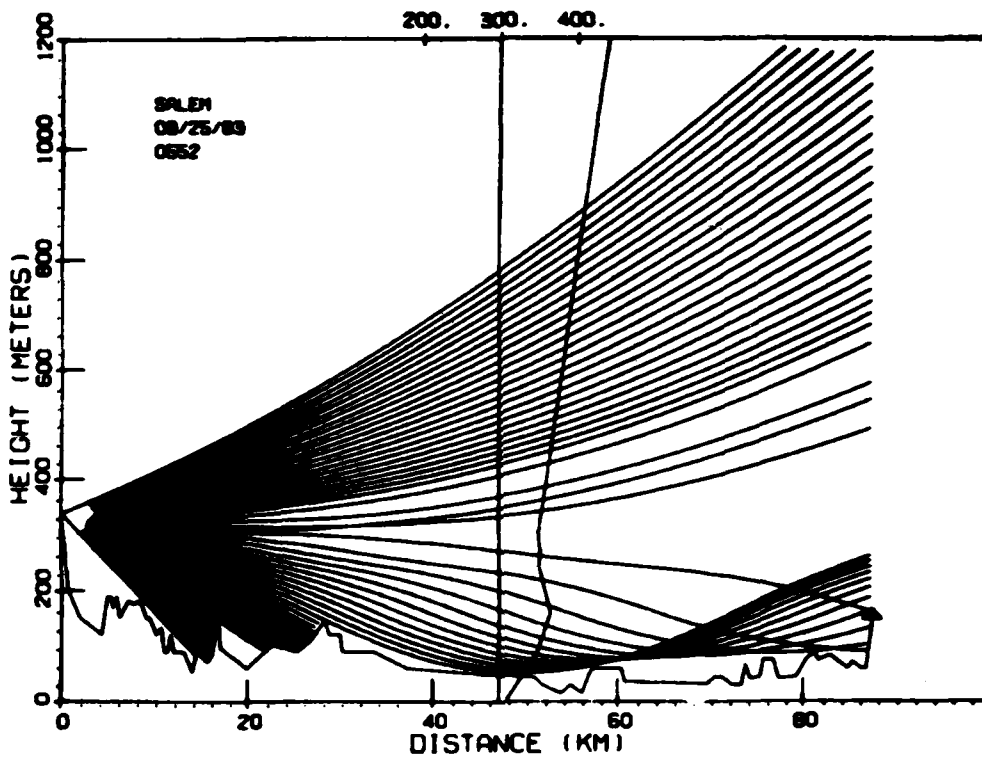


Figure 26a. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0559 EDT, 25 August 1983

are used as a basis for ray tracing (Figure 28) the result is very similar in the immediate vicinity of the receiver, even though the area above the receiver has been changed dramatically. Again we find a delay spread of several tenths of a nanosecond, and an angle of arrival spread of about 0.6 degrees.

The third set of soundings, 0744 Salem and 0759 Hanscom, show a second duct above the main duct at the height of the transmitter, and the subrefractive layer at the surface of both soundings has disappeared. When the Salem sounding is used for ray tracing (Figure 29), we find the antenna in a hole rather than in a multipath zone. This is the result of the new secondary duct capturing the rays that previously came down to the receiver, and the lack of a subrefraction zone close to the earth with enough strength to bend the rays back up to the receiver.

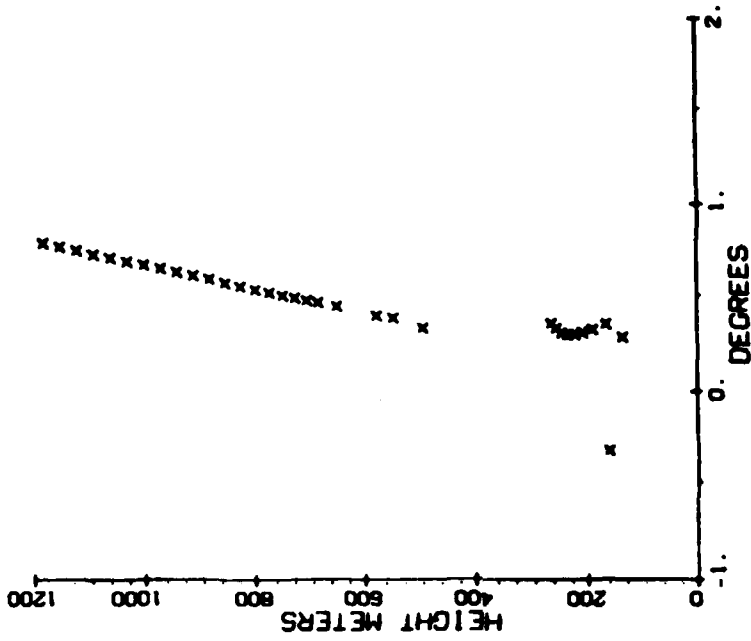


Figure 26c. Angle of Arrival - Degrees

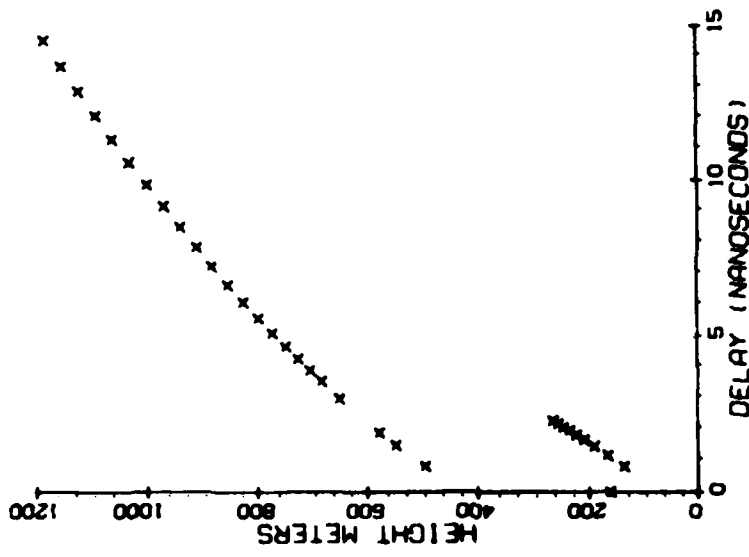


Figure 26b. Relative Delay Times - Nanoseconds

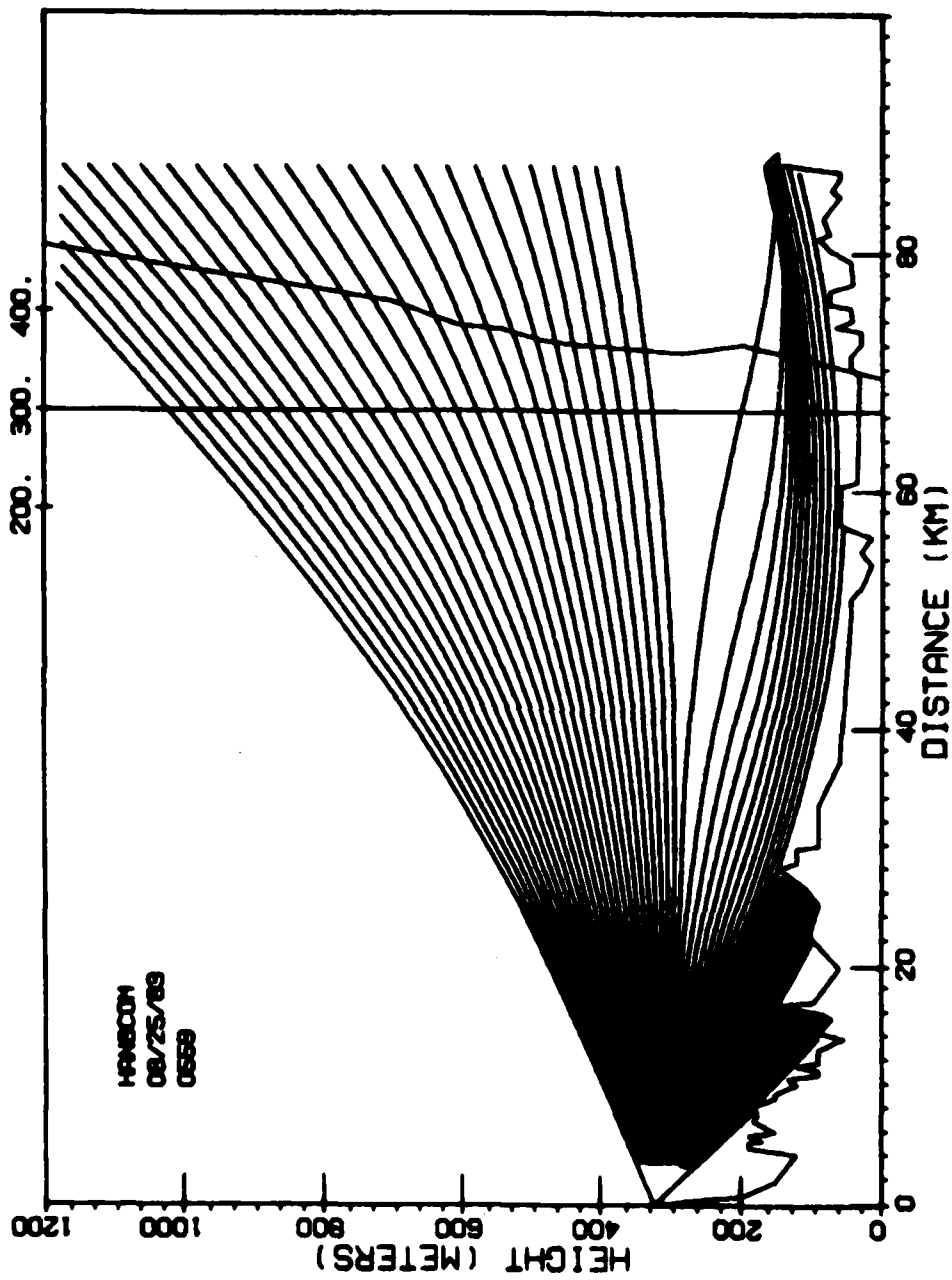


Figure 27a. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0559 EDT, 25 August 1983

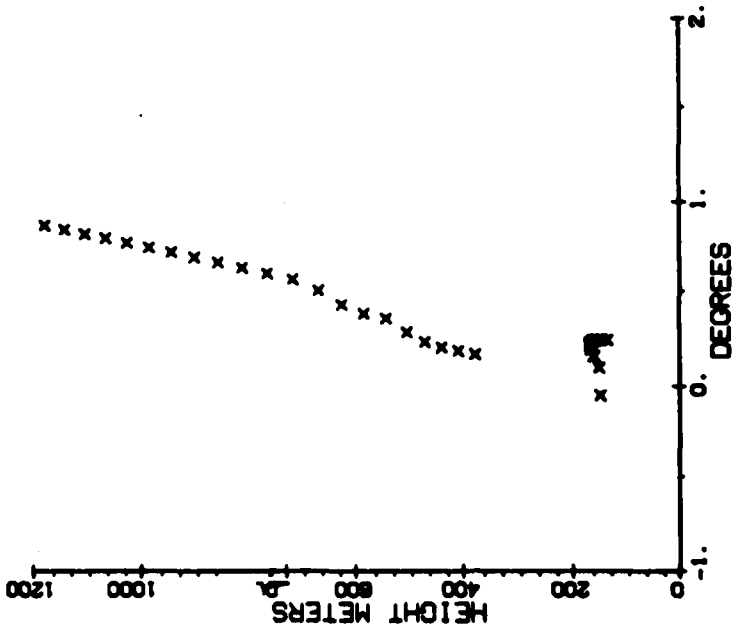


Figure 27c. Angle of Arrival - Degrees

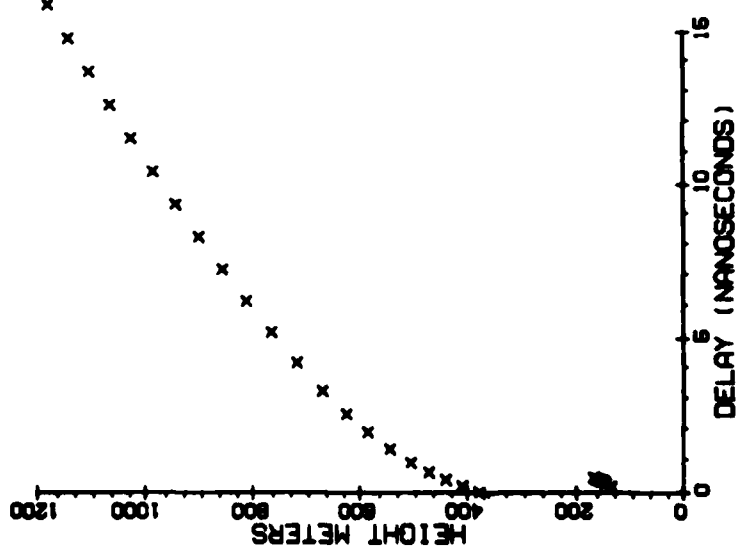


Figure 27b. Relative Delay Times - Nanoseconds

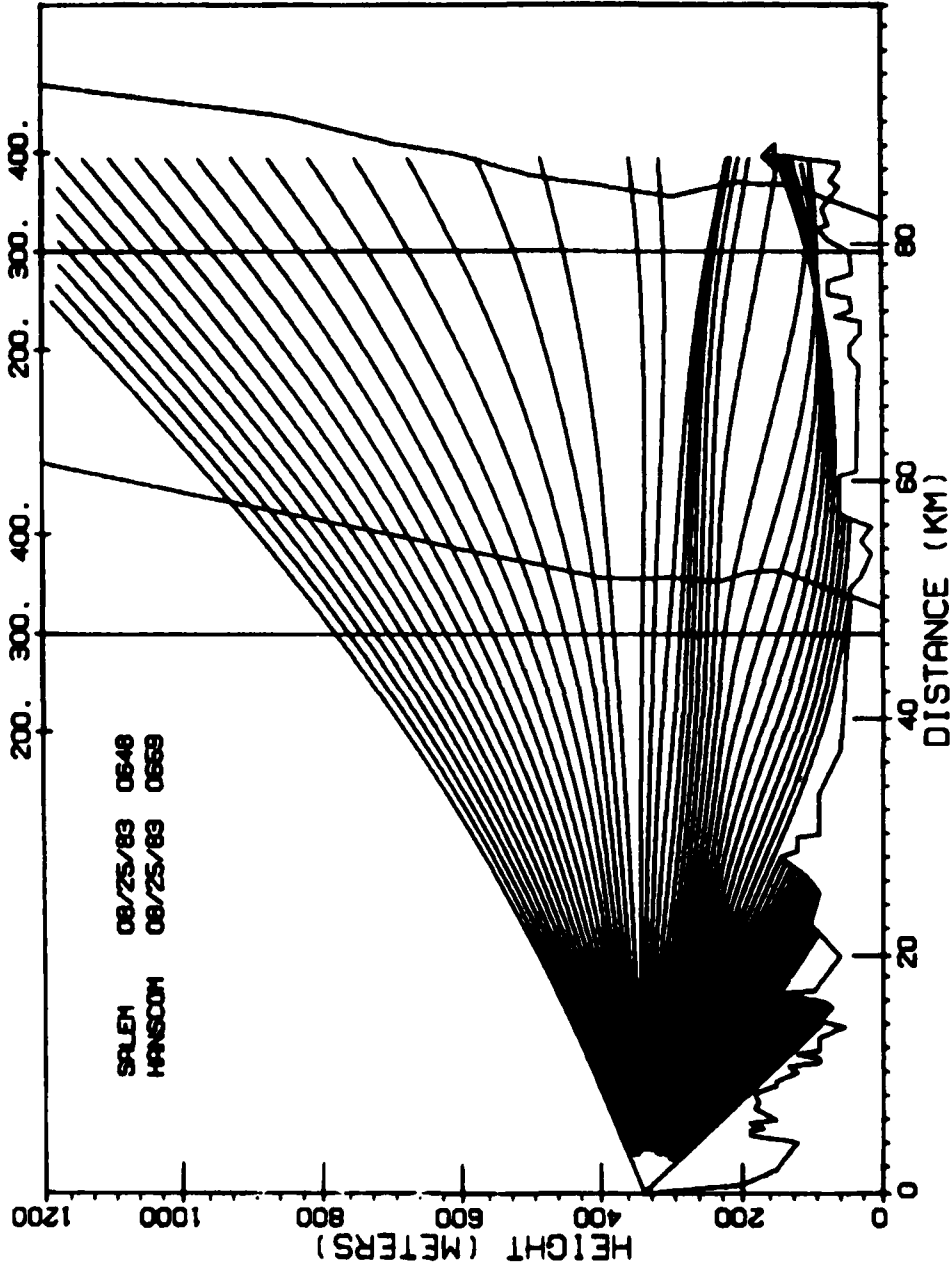


Figure 28a. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0648 EDT and Hanscom AFB at 0659 EDT, 25 August 1983

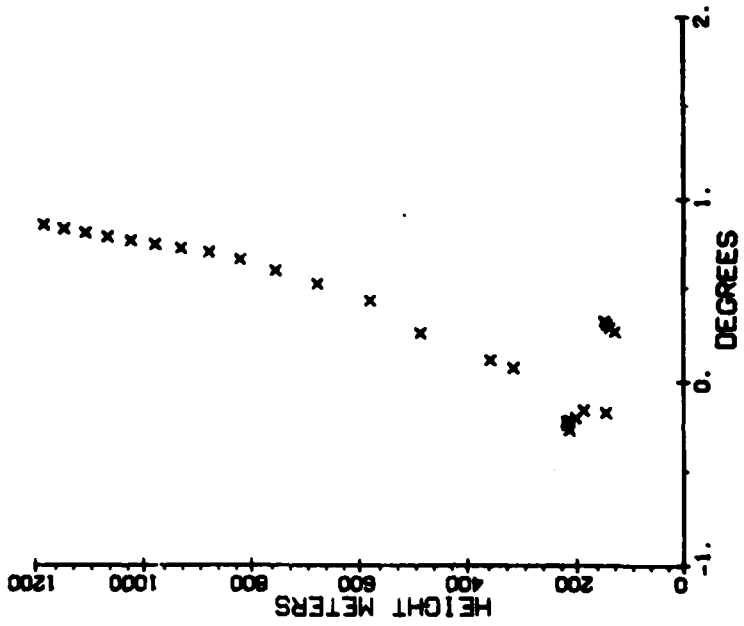


Figure 28c. Angle of Arrival - Degrees

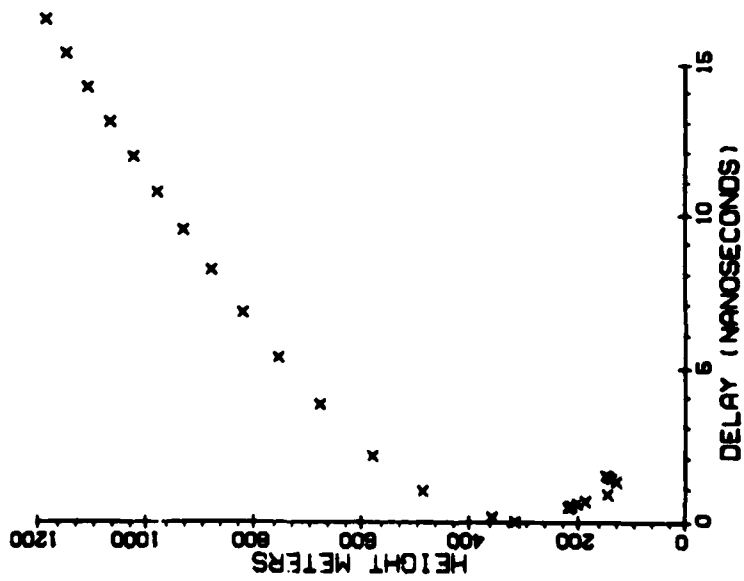


Figure 28b. Relative Delay Times - Nanoseconds

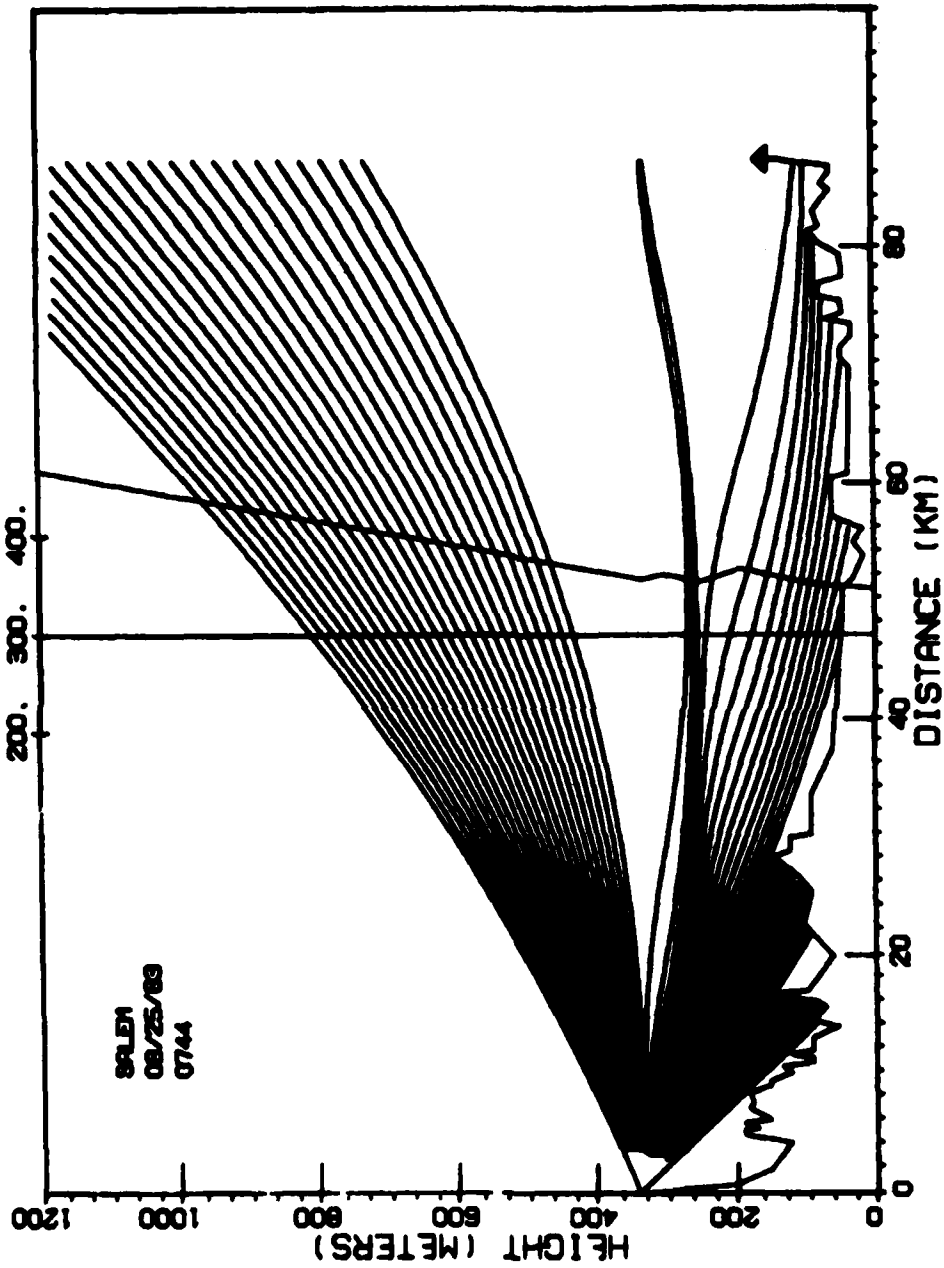


Figure 29. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0744 EDT, 25 August 1983

DEERFIELD NH

16 SEP 83

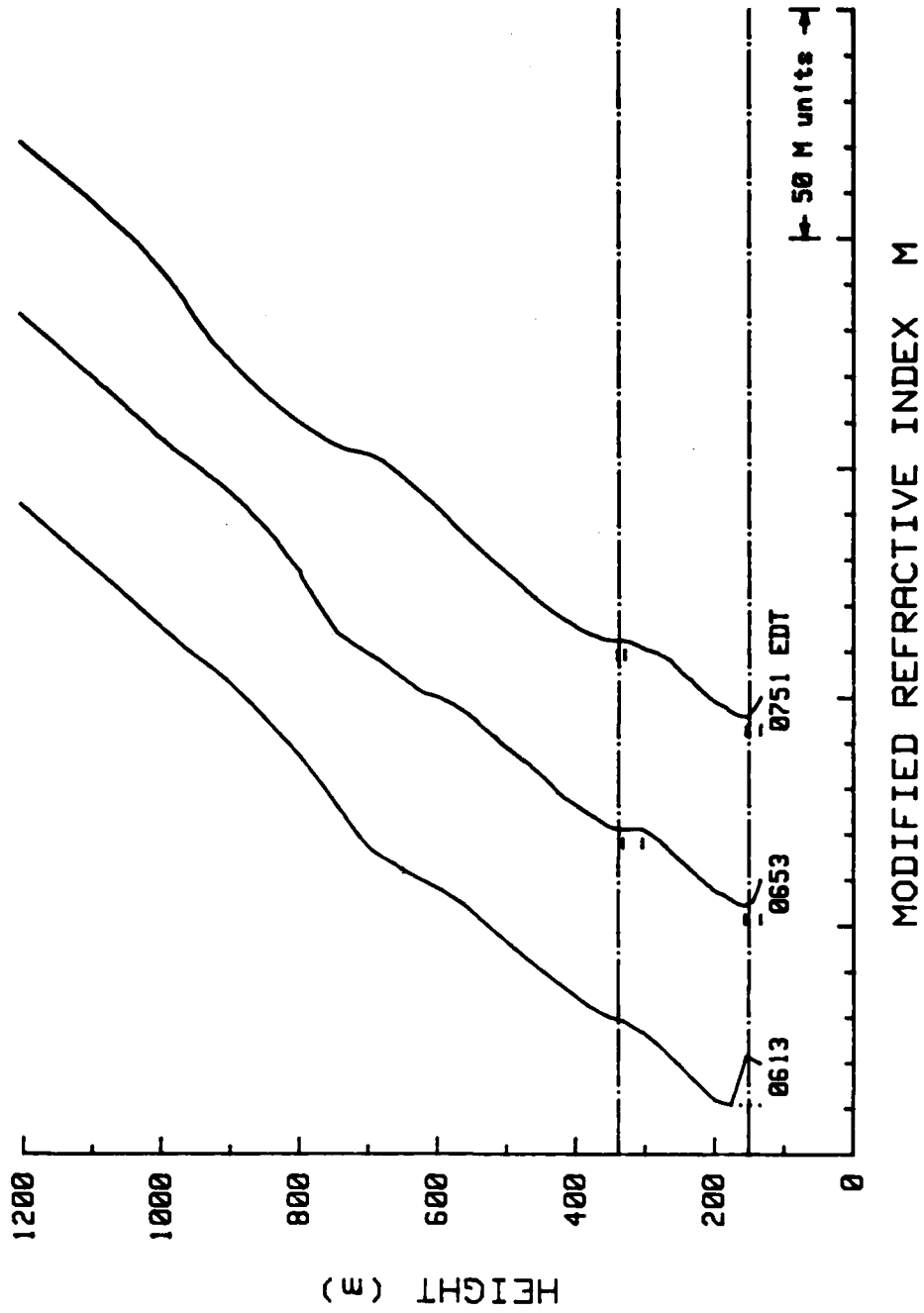


Figure 30. Modified Refractivity Profiles Measured at Deerfield, N.H., 16 September 1983

SALEM NH

16 SEP 83

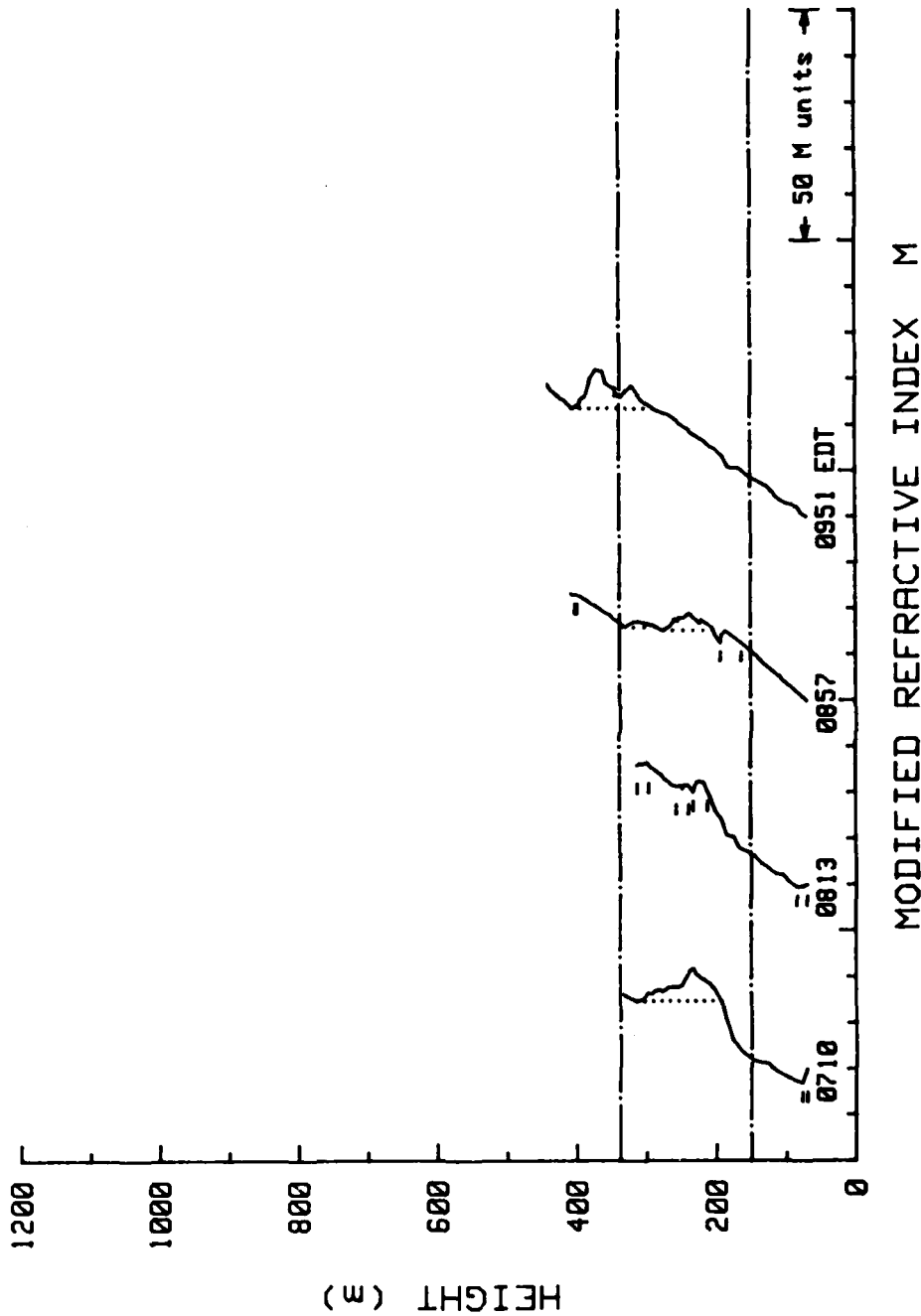


Figure 31. Modified Refractivity Profiles Measured at Salem, N.H., 16 September 1983

HANSCOM AFB

16 SEP 83

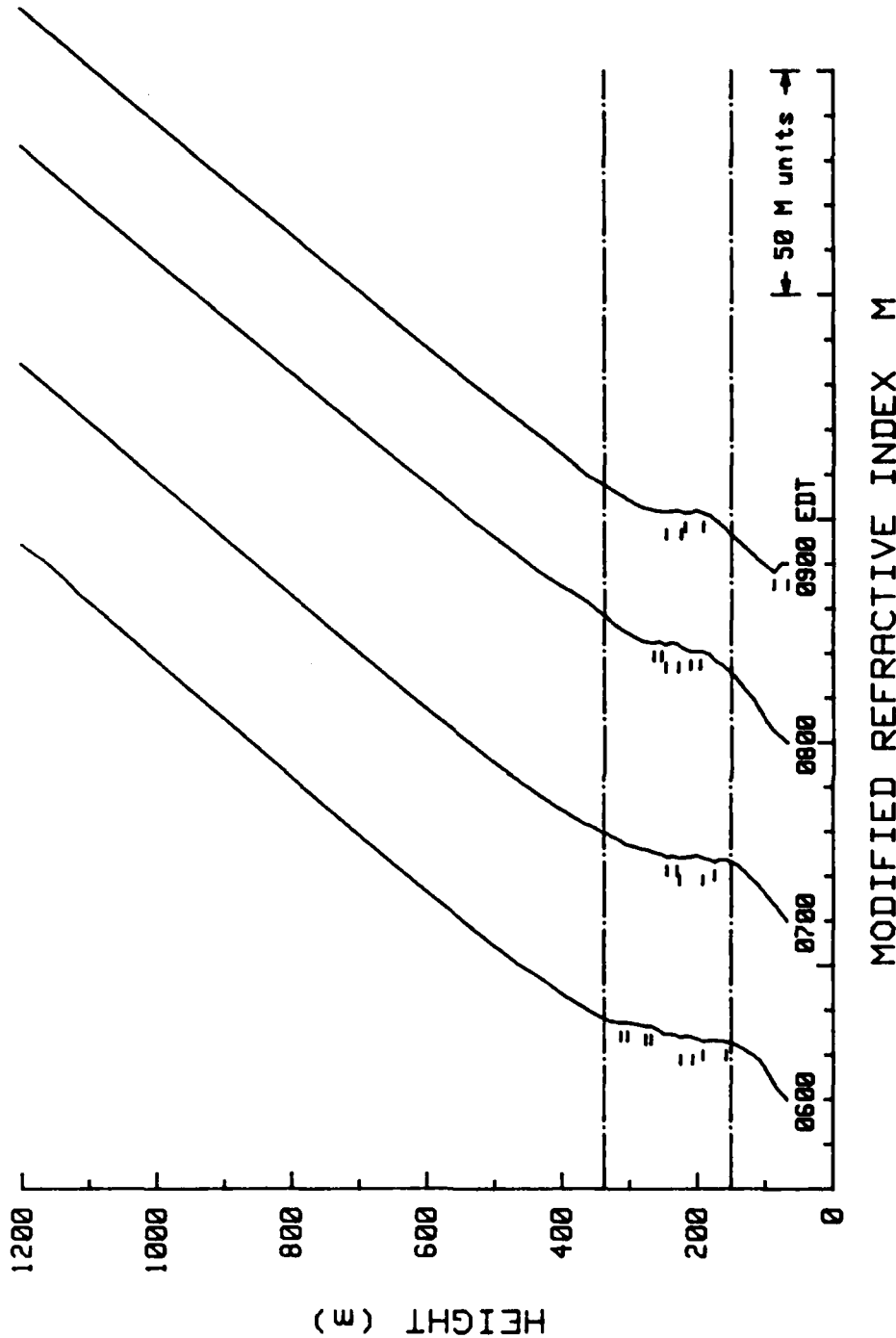


Figure 32. Modified Refractivity Profiles Measured at Hanscom AFB, 16 September 1983

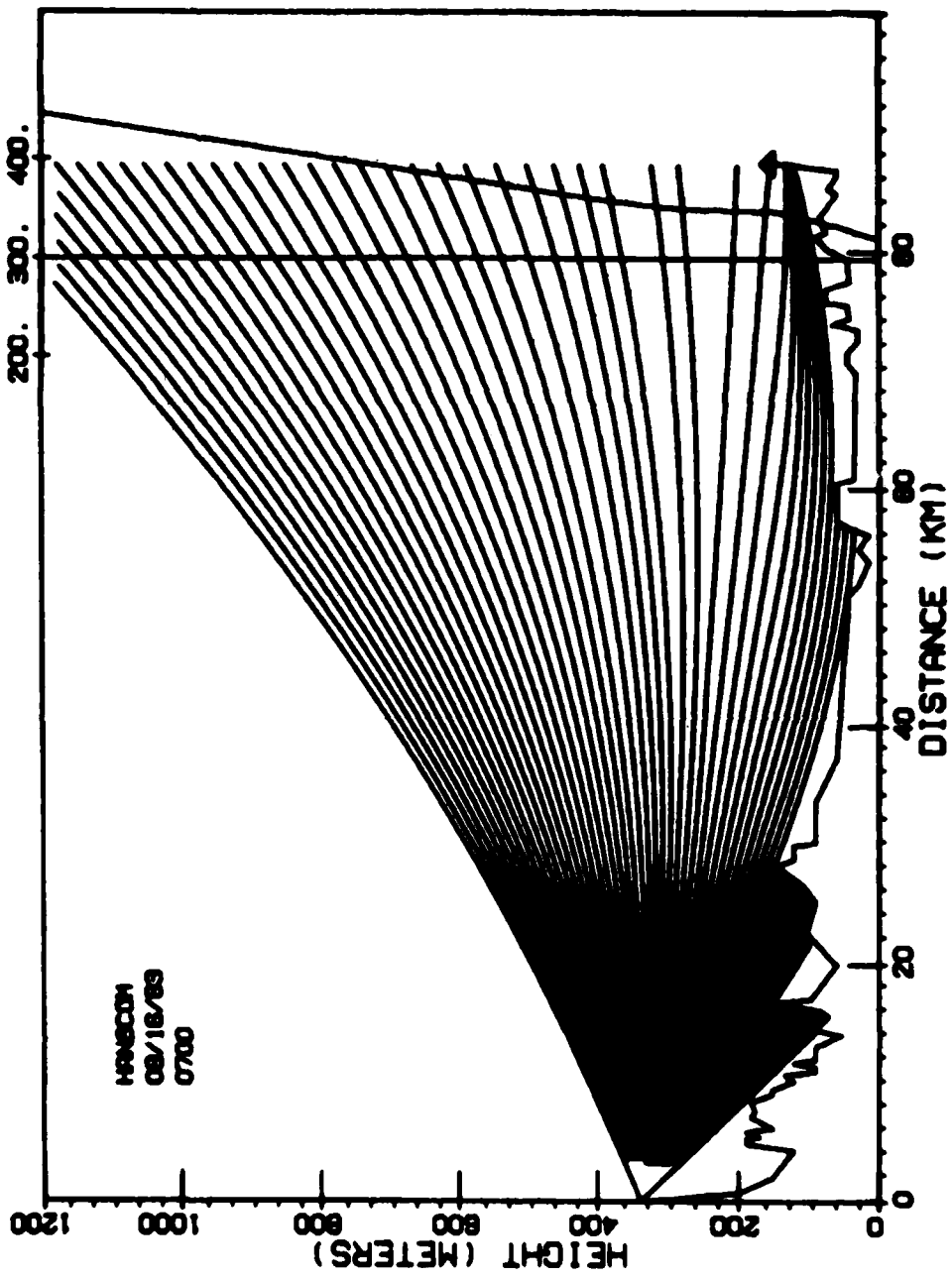


Figure 33. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0700 EDT, 16 September 1983

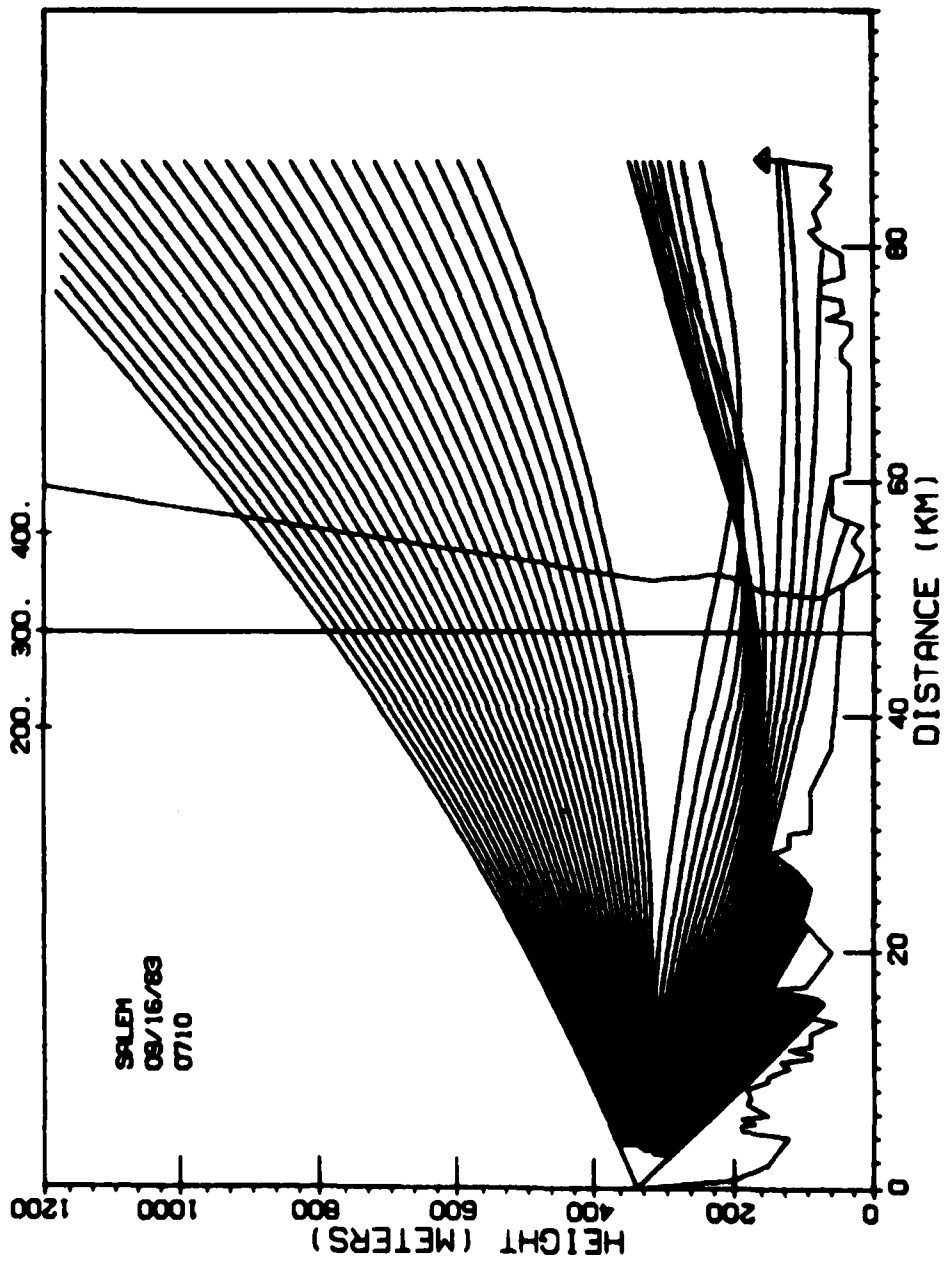


Figure 34. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0710, 16 September 1983

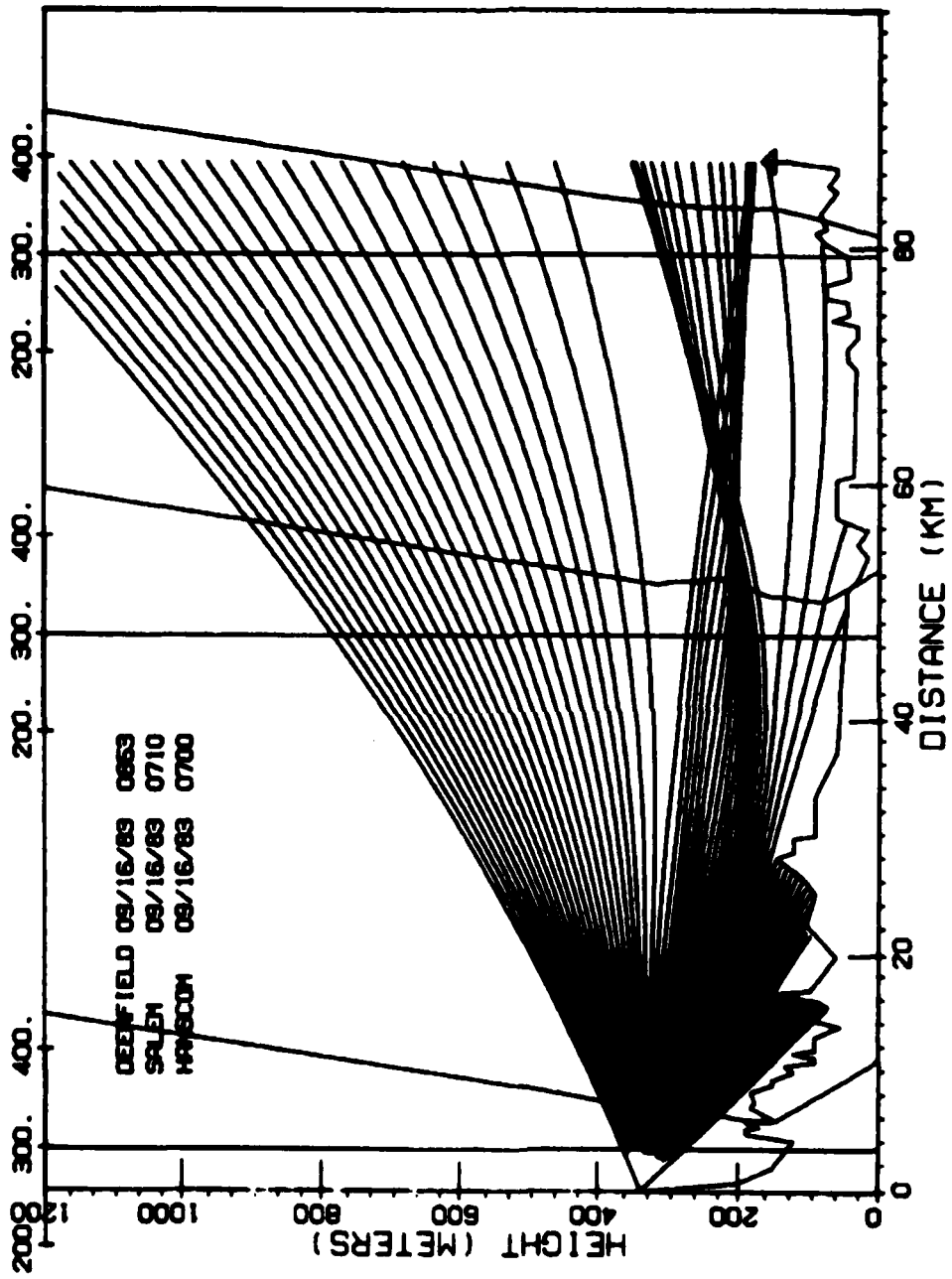


Figure 35a. Ray Trace for Saddleback Link Using Sounding Data From Deerfield, N.H. at 0653 EDT, Salem, N.H. at 0710 EDT and Hanscom AFB at 0700 EDT, 16 September 1983

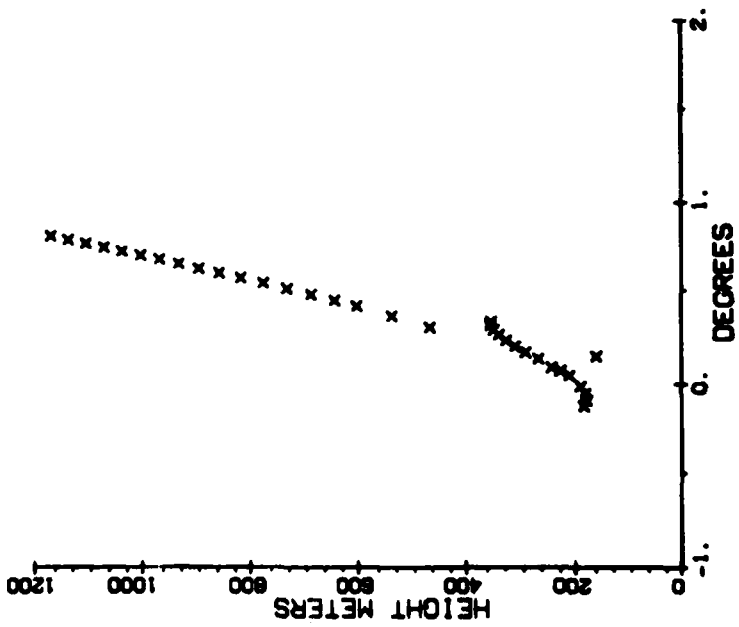


Figure 35c. Angle of Arrival - Degrees

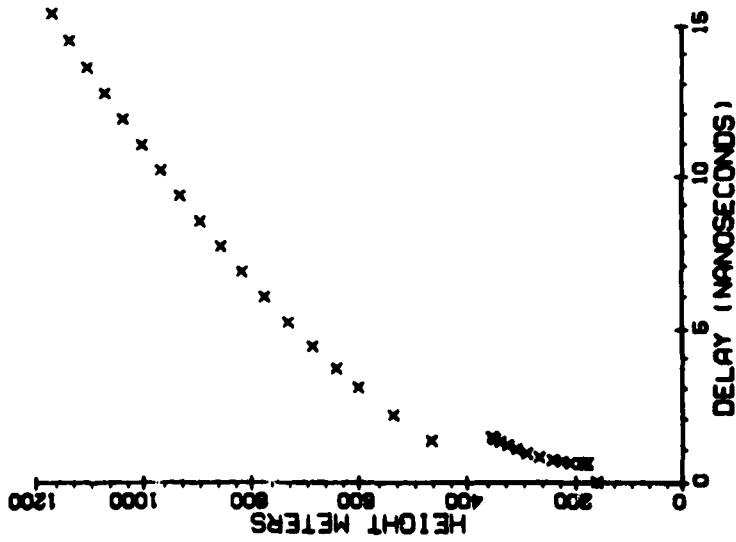


Figure 35b. Relative Delay Times - Nanoseconds

HANSCOM AFB

29 SEP 83

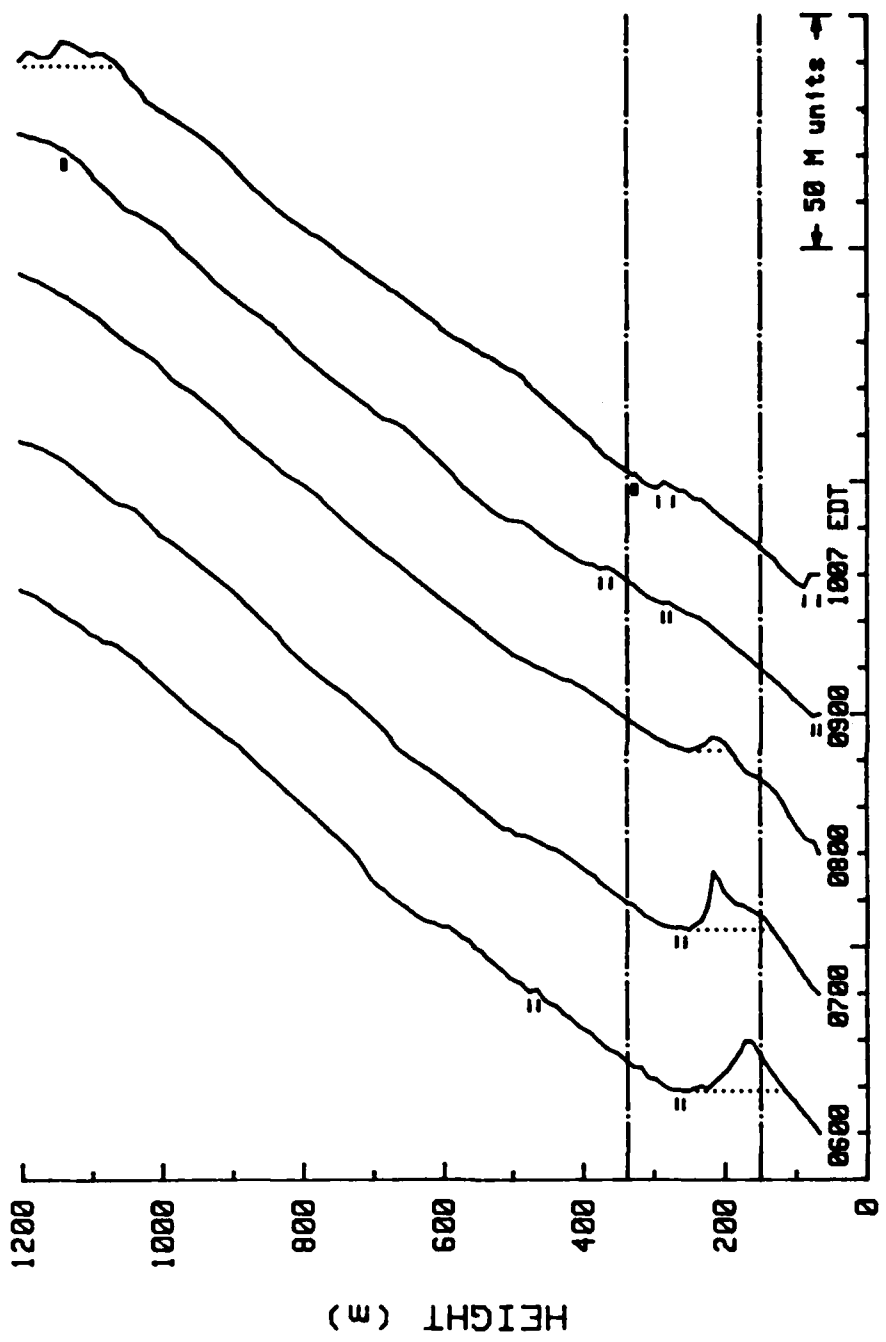


Figure 36. Modified Refractivity Profiles Measured at Hanscom AFB, 29 September 1983

SALEM NH

29 SEP 83

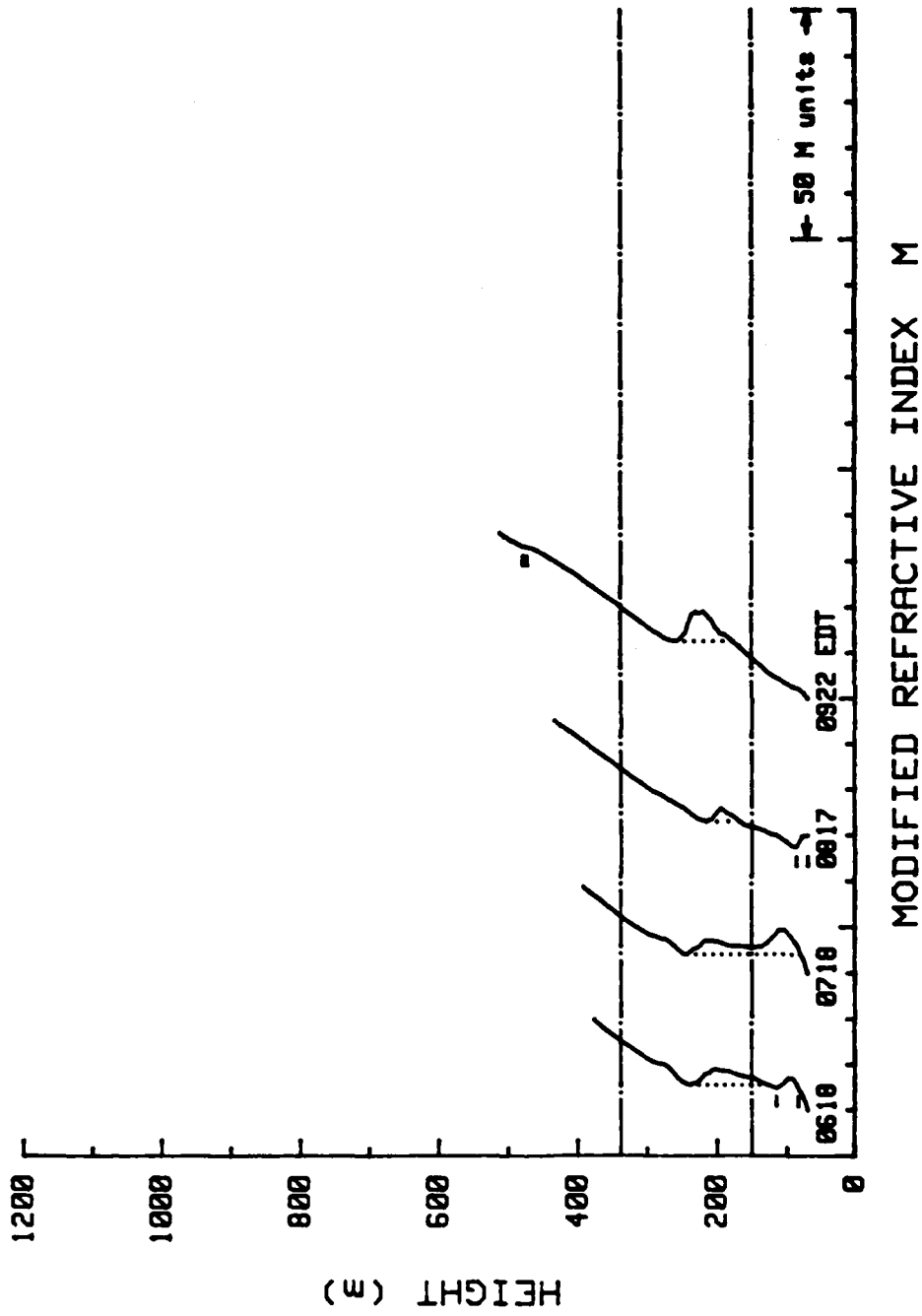


Figure 37. Modified Refractivity Profiles Measured at Salem, N.H., 29 September 1983

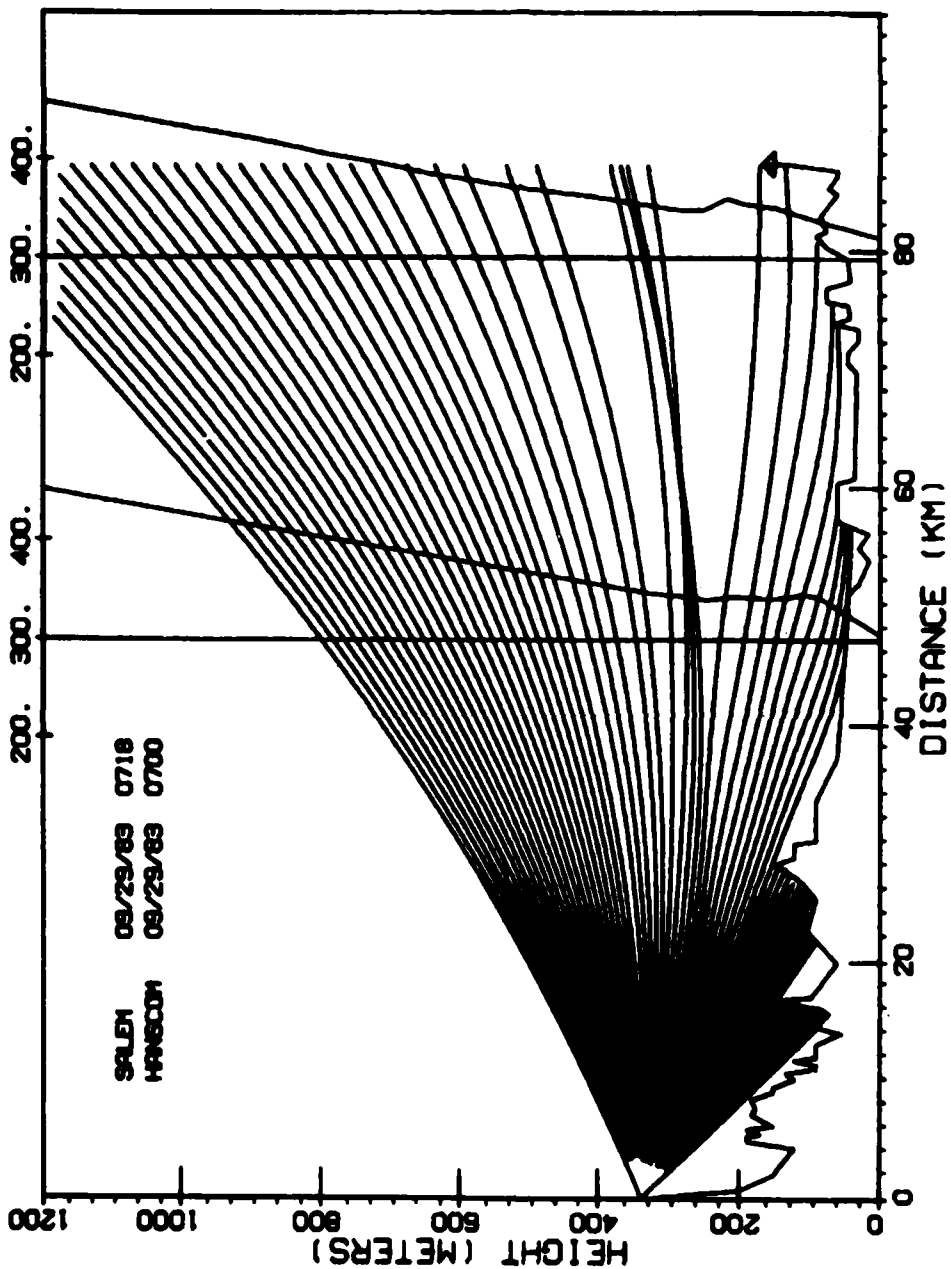


Figure 38. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0718 EDT and Hanscom AFB at 0700 EDT, 29 September 1983

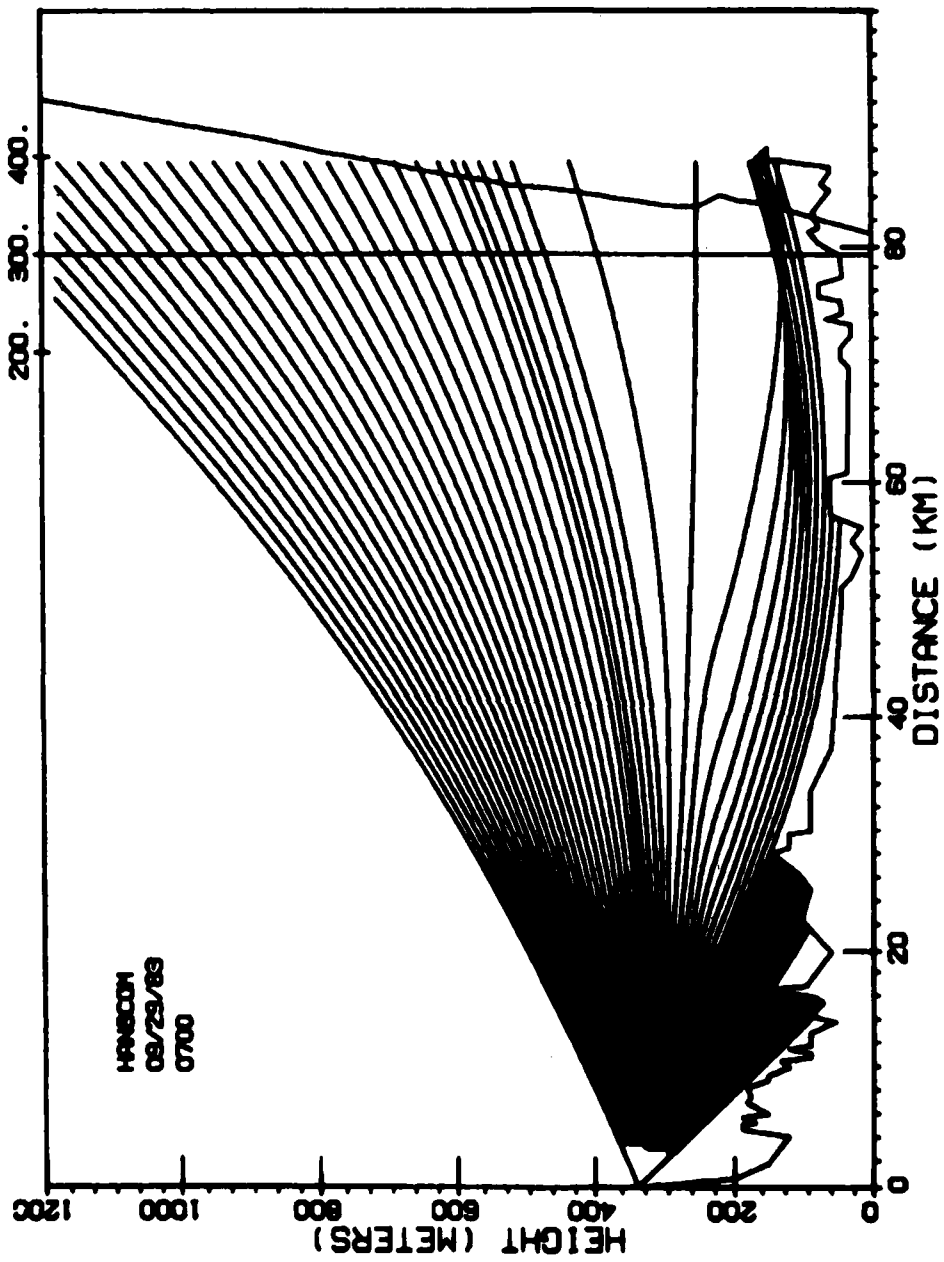


Figure 39. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0700 EDT, 29 September 1983

HANSCOM AFB

30 SEP 83

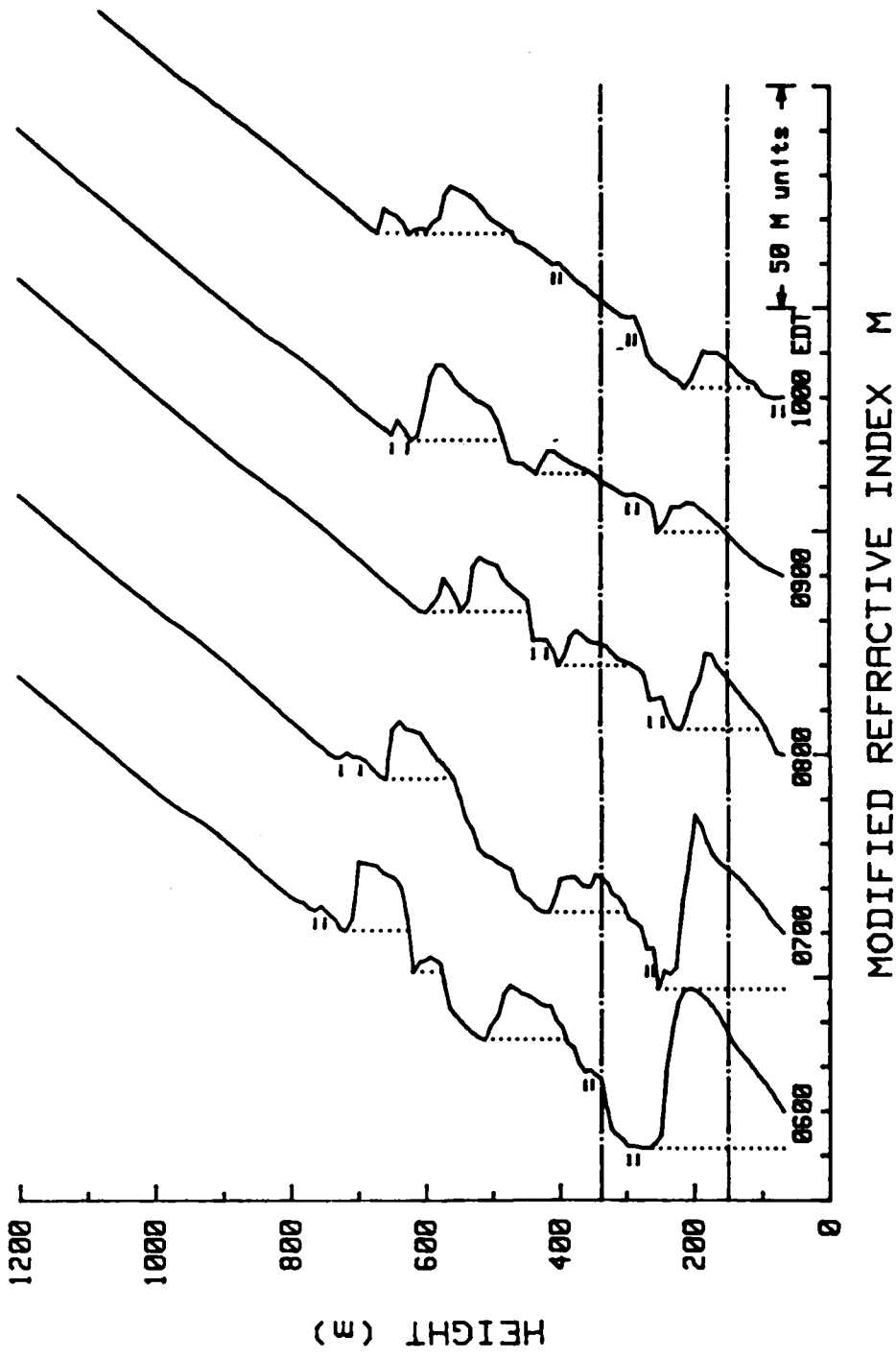


Figure 40. Modified Refractivity Profiles Measured at Hanscom AFB, 30 September 1983

SALEM NH

30 SEP 83

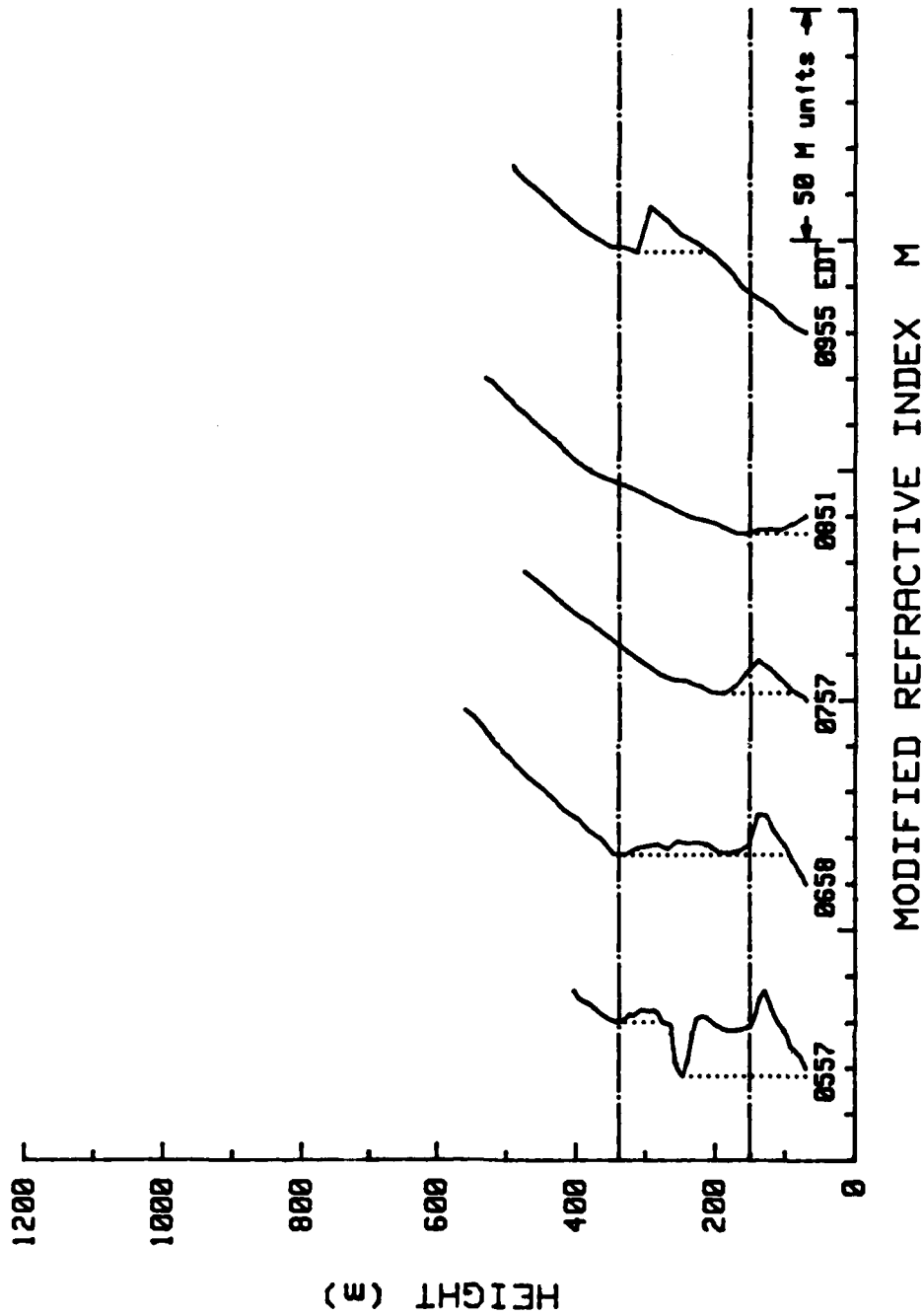


Figure 41. Modified Refractivity Profiles Measured at Salem, N.H., 30 September 1983

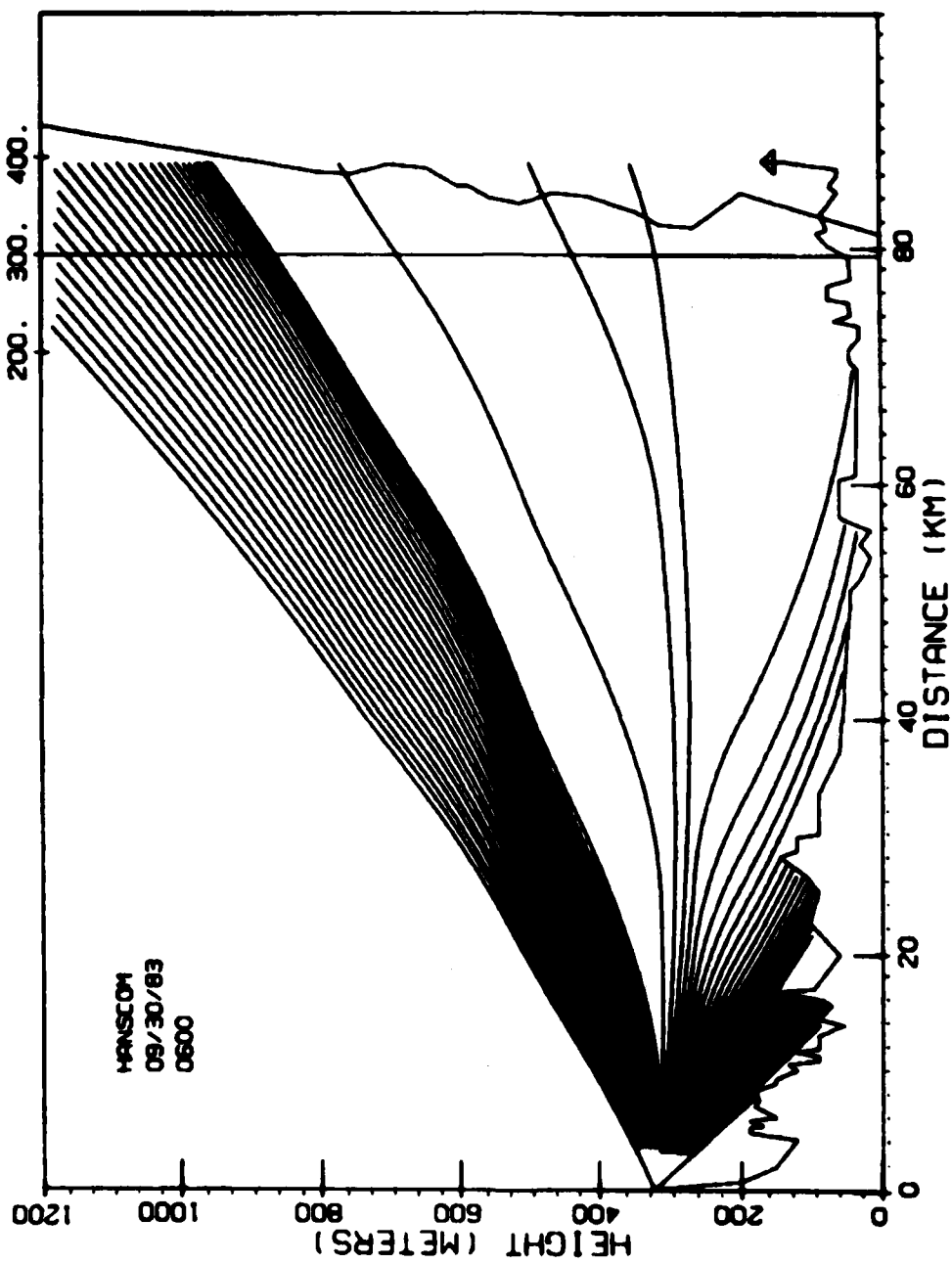


Figure 42. Ray Trace for Saddleback Link Using Sounding Data From Hanscom AFB at 0600 EDT, 30 September 1983

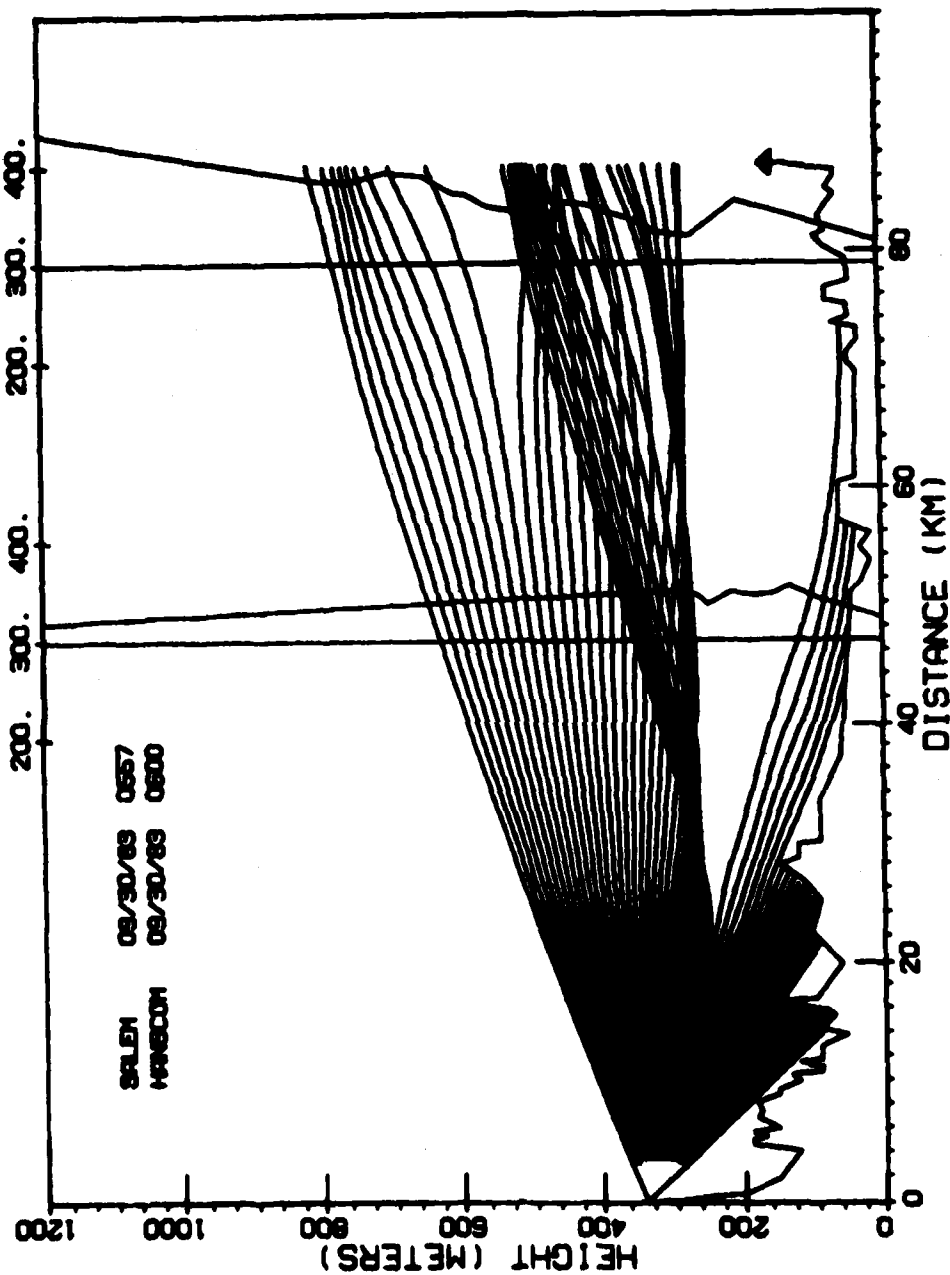


Figure 43. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0557 EDT and Hanscom AFB at 0700 EDT, 30 September 1983

6.2 16 September 1983

Soundings were taken at three locations, Deerfield, N.H. (Figure 30), Salem, N.H. (Figure 31), and Hanscom Field (Figure 32). The Hanscom data show a layer of superrefraction starting at approximately the receiver height overlying a subrefractive layer. The Salem soundings do not show the subrefractive layer at the surface, and the superrefractive layer of Hanscom is replaced by a highly variable layer that changes from ducting to superrefracting. The Deerfield data has a much less pronounced superrefractive layer, and it appears about 100 or more meters higher than at Hanscom.

When the Hanscom 0700 sounding is used for ray tracing (Figure 33), we see a focusing of rays just below the receiver. This is a typical example of the type of multipath that occurs when a layer with a more negative refractive gradient overlies a more positive layer. If the Salem 0710 sounding is used for ray trace (Figure 34), we find the receiver in a hole, and if we use the three soundings at approximately 0700 (Figure 35a) we see the receiver almost in a complex multipath zone.

6.3 29 September 1983

The M profiles for the soundings for Hanscom and Salem are shown in Figures 36 and 37, respectively. While the shape of the M profiles appear different in the surface-to-350 m region, they both show elevated ducts of about the same thickness and height, which has lost most of its strength and thickness by the 0800 soundings. A ray trace (Figure 38) using both soundings around 0700, shows the antenna to be in a region of only slight rarefaction. A ray trace (Figure 39) using just the Hanscom sounding, shows the antenna is a focusing area. This should indicate a potential for large signal shifts, depending on the height of the bottom of the duct at Salem.

6.4 30 September 1983

This day produced the most dramatic ducting structures as evidenced by the M profile data (Figures 40 and 41) for Hanscom Field and Salem, N.H., respectively. The initial sounding at Hanscom, 0600, shows three strong ducting levels. The principal one of interest to the propagation path is the surface-based duct with its top about 280 m. This duct has a gradient of about 1000 N units/km as indicated by both the 0600 and 0700 soundings. A ray trace (Figure 42) using the Hanscom sounding of 0600 is quite predictable. Since the duct is surface-based, all rays entering from above are refracted to the earth, causing the receiver to be in a radio hole. Ray traces using both 0600 soundings (Figure 43) and the Hanscom 0700 sounding (not shown) have the same result. However, when we use both of

the 0700 soundings for ray trace (Figure 44) we see rays are not as strongly refracted toward the ground, and the receiver is just above an area where the rays are focused. This is a consequence of the duct no longer being ground-based in the 0658 Salem sounding, and the Salem sounding having a larger influence due to geometry, as mentioned previously. After the 0800 soundings the strength and position of the ducts is highly variable but is still capable of causing anomalous conditions. This is shown in the ray trace (Figure 45) using both soundings at about 1000.

7. DISCUSSION

The meteorological measurements made in 1982 on the Pack Monadnock-Prospect Hill link, when used in conjunction with a ray-trace program that assumes horizontal stratification of the atmosphere, never predict a major disturbance at the receiver due to refractive bending. This is not totally unexpected given the geometry of the link. The large vertical displacement between the transmitting and receiving antennas almost precludes ducting. In addition to the large height discrepancy of the antennas, the fact that the receiver is lower than the transmitter also makes it unlikely that a major fading due to refraction will occur. The most likely effect is signal enhancement caused by the focusing effect of a duct between the transmitter and the receiver; however, there was no instance when this was predicted from the meteorological sounding data obtained.

It was realized that for ducting to occur, the duct would have to be sloped with an inclination similar to the general slope caused by the antenna height differences and the path length. There is evidence in the meteorological data of a slope to the ducting layers as revealed by several instances not all of which were discussed in Section 5. Over a distance of 25 km, the slope of the layers from Hanscom AFB to Haystack was about 70 m, which is about the difference between the surface heights of these two sites. This can be seen in the 25 October 1982 soundings of 0951 EDT at Hanscom AFB (Figure 13) and of 1011 EDT at Haystack (Figure 14). There is also an instance where strong ducting is evident at one site but much weaker ducting is evident at another site. An example is provided by the 0856 EDT sounding at Hanscom AFB (Figure 7), and the 0901 EDT sounding at Haystack (Figure 8) on 13 September 1982.

The Saddleback link chosen for test in 1983 had a much lower transmitter-to-receiver slope (2.14 m/km) than the Monadnock 1982 test link (6.00 m/km). The selection of the link was determined by the fixed nature of the large 29-ft dish at Prospect Hill and the desire for a path with a lower slope. The path certainly would not be selected for operational communications because of extremely low

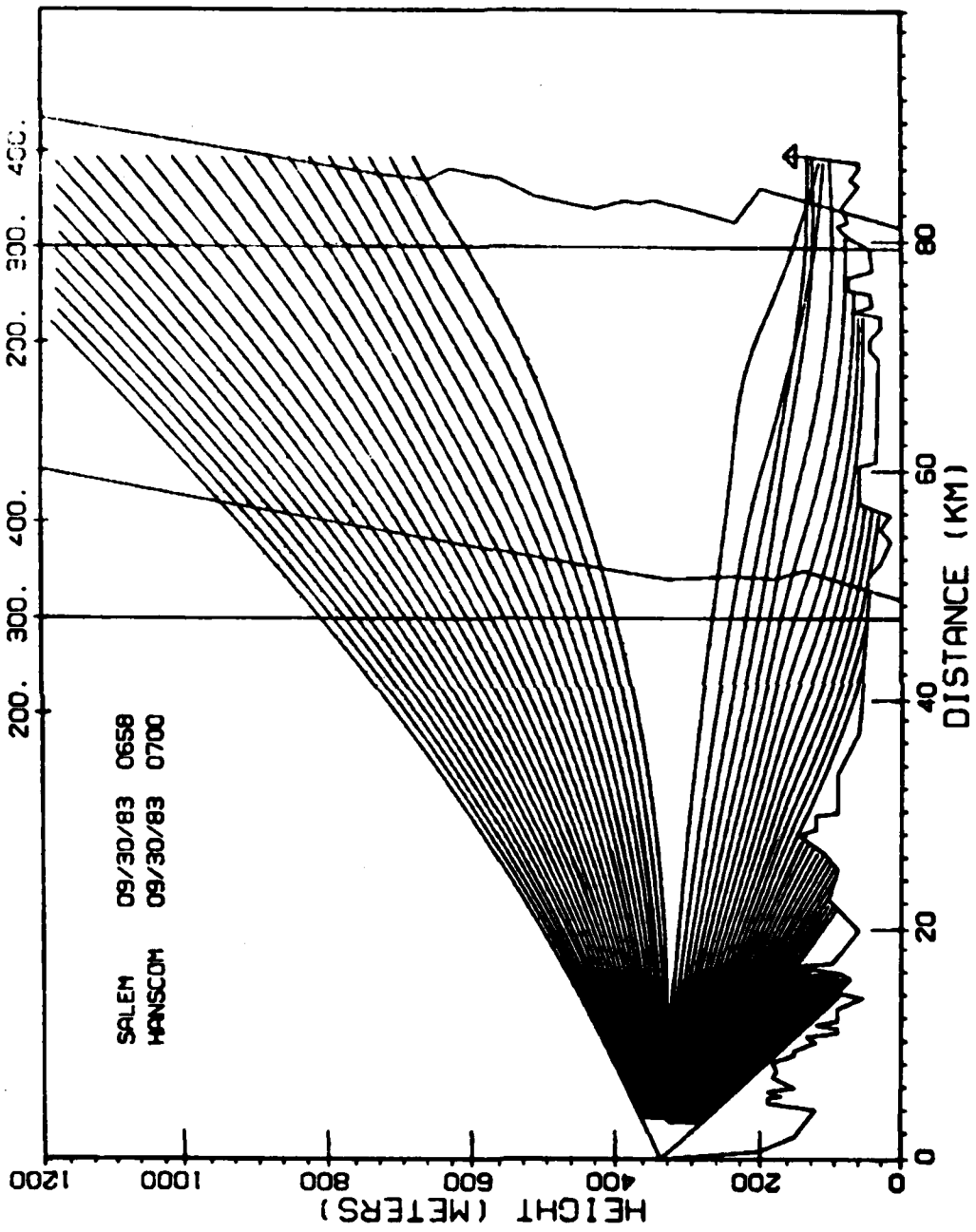


Figure 44a. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0658 EDT and Hanscom AFB at 0700 EDT, 30 September 1983

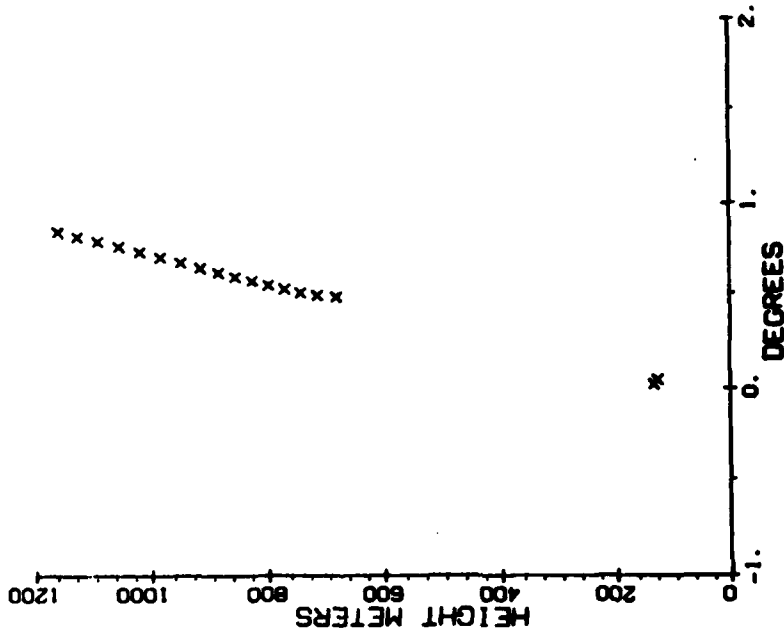


Figure 44c. Angle of Arrival - Degrees

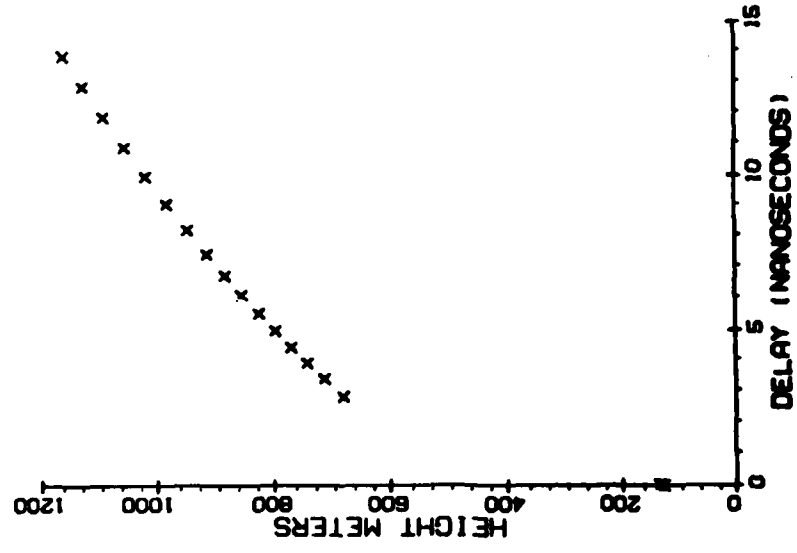


Figure 44b. Relative Delay Times - Nanoseconds

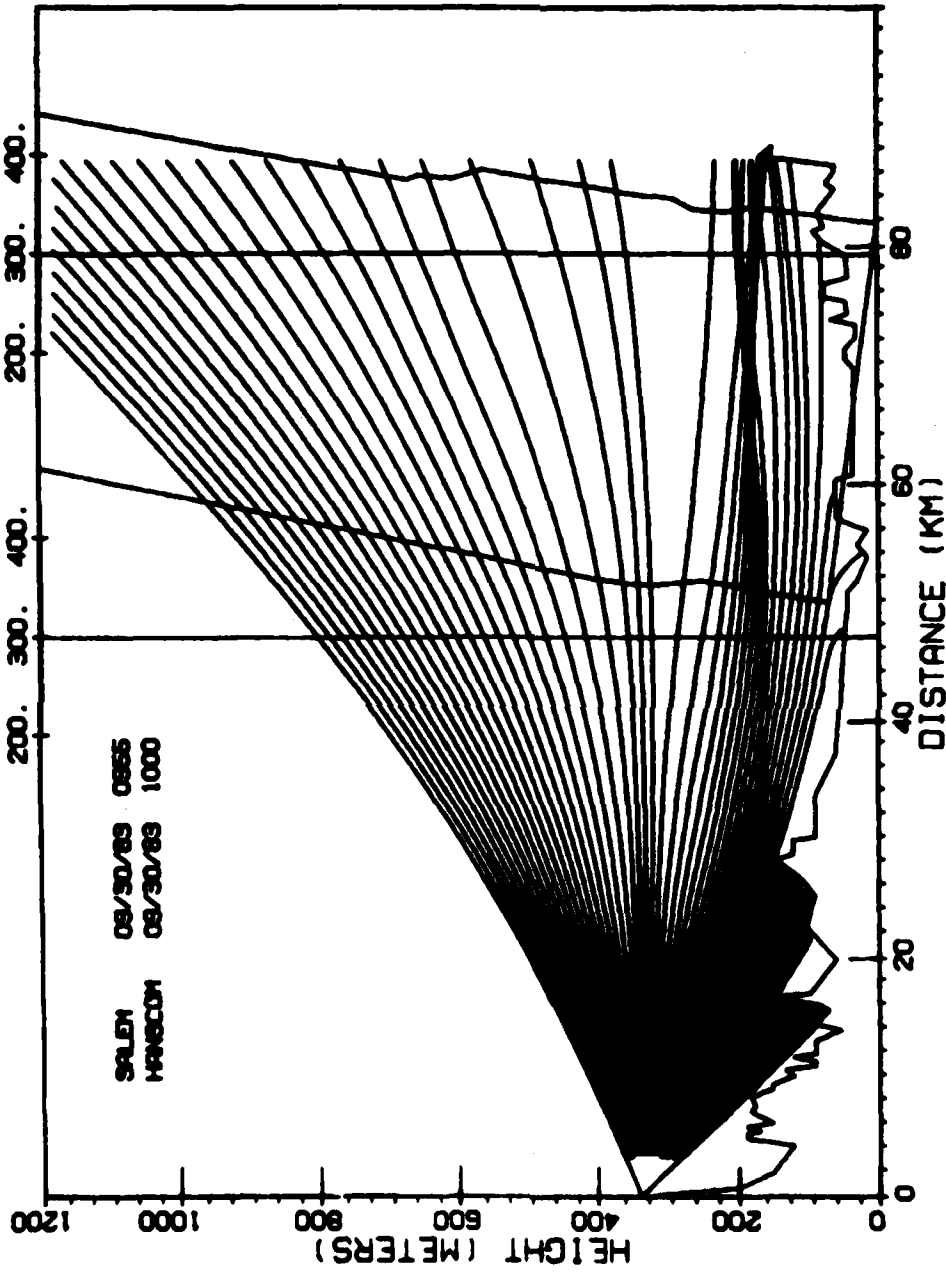


Figure 45a. Ray Trace for Saddleback Link Using Sounding Data From Salem, N.H. at 0955 EDT and Hanscom AFB at 1000 EDT, 30 September 1983

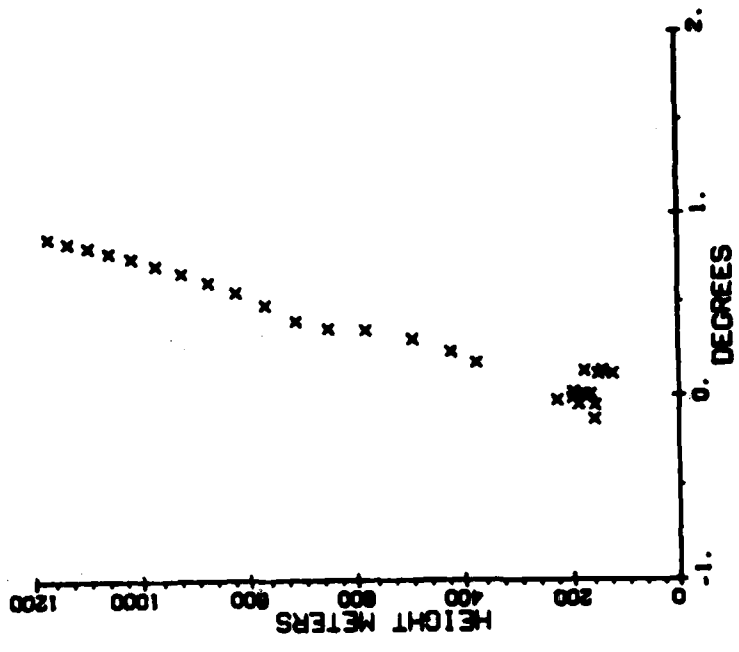


Figure 45c. Angle of Arrival - Degrees

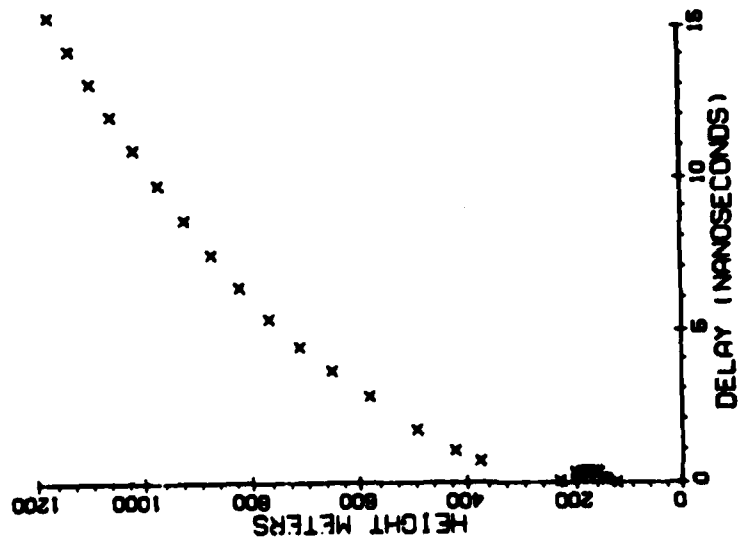


Figure 45b. Relative Delay Times - Nanoseconds

beam clearance. It was anticipated that there would be several disturbances on the link that could be documented. These were principally caused by low-level radiation inversions in the early morning hours. These are able to be predicted reliably, which is very useful in planning the measurements. This strategy resulted in meteorological and path-performance documentation of five events.

The comparisons of the double meteorological-sounding measurements demonstrate great similarity, indicating the general validity of the concept of horizontal homogeneity for propagation considerations. This can be seen in the cases studied; a ducting situation in the Salem sounding almost always has a corresponding duct in the Hanscom sounding. It can be seen in all of the cases studied if we consider only whether a duct exists and how thick it is, or if we look for elevated superrefracting layers. It is not as valid if we look at how strong, ΔM , the duct is, or when we look at details of the ducts. It is even less valid when we look at the layer in close proximity to the ground (<100 m AGL). The propagation is sensitive to some rather minor changes at strategic positions. This can be seen in Figures 43 and 44 for the situation at 0600 and 0700 on 30 September 1983. The difference between these is brought about by the Salem sounding showing the duct to stop about 50 m above ground in the 0700 sounding, because of the development of a subrefractive layer at the surface.

It is noteworthy that not one case was observed where the communication link is in a ducting condition; that is, both antennas in the same duct. Two cases, 25 August 1983 and 30 September 1983, had ducts with sufficient thickness but were not at the correct height, in spite of the fact that the antennas have only 187 meters separation. This is consistent with other line-of-sight tests performed in Germany in 1981. Still, in all of the cases studied, anomalous propagation conditions were predicted by the combination meteorological measurements and a ray-trace model. In addition, in all of these cases, anomalous effects were confirmed using the channel-probe measurements. The results of the channel-probe measurements will be reported on separately by the RADC personnel involved in the test.

8. CONCLUSIONS

High-resolution radiosonde data can be used in conjunction with ray-tracing techniques to evaluate/predict/analyze the performance of microwave LOS communication links. For most cases the use of a single radiosonde site is adequate. When one site is to be used it is recommended that it be as close to mid link as possible. The decision on the use of a second station should be based on economics

mixed with topographic or orographic considerations. The small portable radio-sonde systems available today make it feasible to use these techniques as site-selection tools.

Ducting, defined as having both transmitter and receiver in the duct, is a very rare condition. However, ducting gradients, $\frac{dM}{dZ} < 0$ occur relatively frequently, depending on the local meteorology. This has been observed in these tests and in previous tests in Germany. When these ducting gradients exist and are located somewhere between about 100 m below the lower antenna to the height of the upper antenna they are highly likely to effect strong changes in the received signal. The change can be in the form of signal reduction due to the receiver being in a radio hole, or due to multipath propagation with destructive interference. Similarly, it can result in signal enhancement due to the rays being focused or a multipath with the signals having constructive interference.

In general, the assumption of atmospheric horizontal homogeneity as applied to LOS communication is valid; therefore, one station is used in most cases, provided the site is chosen judiciously. It has been shown, however, that minor differences in two soundings can bring about significant changes in the received signals.

In general, LOS propagation links are strongly influenced by small changes in height where significant changes in the M profiles occur. Because of this, the ray-trace diagrams should be looked at not only at the exact height of the receiver but in the general interval (± 100 m) to anticipate the effect of atmospheric variability.

The 1982 data showed that a link with a large terrain slope (6.0 m/km) is not likely to be subject to anomalous propagation. Even though there was indication of a sloping to ducting layers (2.8 m/km) it was insufficient to cause anomalous propagation effects.

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