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TECHNICAL REPORT

ATMOSPHERIC REFRACTION MEASUREMENTS AND RELATED EFFORTS

FEBRUARY 1979

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TECHNICAL REPORT

ATMOSPHERIC REFRACTION MEASUREMENTS
AND
RELATED EFFORTS

Prepared by

ELECTRONIC TRAJECTORY MEASUREMENTS GROUP
RANGE COMMANDERS COUNCIL

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ATMOSPHERIC REFRACTION MEASUREMENTS
AND
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EXECUTIVE SUMMARY - Task ET-3 - Atmospheric Refraction Measurements and Related Efforts

1. Atmospheric refraction correction involves two efforts: (1) determination of the refractivity profile and (2) use of that profile in correcting tracking data to compensate for the error. These efforts should be considered as mutually dependent because each will affect the accuracy of the results. In general a great amount of effort has been expended at the various ranges to provide good mathematical techniques for determination and application of the appropriate correction using whatever refractivity is available.

2. This task has examined the effect of radiosonde refractivity measurement errors on the attainable accuracy in correcting the refraction errors. Meteorological Group estimates of rawinsonde sensor errors were used in an extensive statistical study to determine how these errors propogate through the refraction correction procedure. For a moist climate, the results provide a conservative approximation to the magnitude of refraction errors which may remain after the best available refraction corrections are applied.

3. PRINCIPAL CONCLUSIONS

a. Accurate refractivity information is critical for making refraction corrections.

b. For precision missions, rawinsonde data errors may result in position errors which far exceed an acceptable level.

c. For low elevation angle radar data, radar equipment errors are frequently less than the residual refraction error. Thus, the cost effectiveness of radar equipment accuracy improvements may be questionable.

d. Use of surface index of refraction alone in many instances will yield results as good as those provided by rawinsonde profiles.

e. Rawinsonde data can sometimes detect abnormal conditions not available from surface data alone.

f. Reduction of rawinsonde humidity sensor errors is critical to improvement of rawinsonde usefulness.

4. In efforts separate from the ETMG task, the existence of short-term, small-scale atmospheric fluctuations has only recently been adequately described. Results of low elevation angle refractive bending measurements made at USAF/Rome Air Development Center and MIT/Lincoln Laboratories have shown much larger short-term variations than predicted by simulation methods.

a. These short-term (five minutes to one hour) variations are due to small-scale atmospheric irregularities which are constantly changing and which are not measurable by current meteorological sensors.

b. The general conclusion of the analysis of this limitation is, again, that in many cases the use of surface refractivity provides refraction corrections of comparable quality to rawinsonde-derived refraction corrections.

c. To achieve more precise corrections, more sophisticated atmospheric sensors providing real-time, continuous measurements of the refraction environment along a given ray path will be required. In this case "real-time, continuous" means accurate atmospheric parameters every 10 to 20 meters along the ray path, updated at approximately 30-second intervals. It should be noted that achievement of this goal could impose a requirement for improved computational techniques.

5. In summary: Present day use of surface refractive index and/or rawinsonde derived profiles are providing good refraction corrections for elevation angles above 10 degrees, such that the errors in the refraction correction are less than the tracking system instrument error. Below 10 degrees the refraction corrections can be the dominant error source using current techniques. However, even when all radiosonde instrument errors are eliminated, there still exists an atmospheric limitation caused by time and space variability which is of the same order of magnitude as the radiosonde induced sampling errors. Such errors will provide a refraction correction error comparable to and sometimes greater than the tracking system instrument error. This limitation cannot be overcome by any current or projected atmospheric sampling techniques.

6. RECOMMENDATIONS

a. Task the Meteorological Group to more precisely determine the errors in rawinsonde parameters. If they differ from previous estimates, the ETMG study should be reevaluated.

b. Efforts to devise better refraction correction techniques should be deferred until better cost effective refractivity sensors are available.

c. Efforts should be initiated/encouraged to improve means of determining refractivity profiles.

PART II

RADAR TARGET HEIGHT DETERMINATION ERRORS CAUSED BY RAWINSONDE INSTRUMENT ERRORS

PREFACE

The Electronic Trajectory Measurements Group (ETMG) task on refraction correction was originated in September 1972, with the optimistic goal of definitively dissecting the refraction problem, establishing those accomplishments which are possible and recommending equipments and techniques to be used for various situations. As did earlier investigators, we found the problem neither readily bounded nor readily studied.

Since the atmosphere is a continually varying medium, even perfect measurements of refractivity in a given location may not be valid for a nearby region, and shortly after measurement will no longer be valid for the region measured. Rawinsonde or refractometer measurements typically involve the instrument being borne over a long distance during a considerable time period. The normal assumptions that the derived refractivity profile is both spherically symmetric and invariant in time undoubtedly introduce gross errors into any correction technique.

It was decided to begin the refraction study by adopting the questionable symmetric and invariant assumptions, and assuming that the only error in making a correction for the refraction effect is introduced by errors in measurement of the refractivity profile. That profile measurement is assumed to be made by the most typically used instrument, the rawinsonde. If good results are possible under these assumptions, then the sensitivity to relaxation of the questionable assumptions could be made.

RADAR TARGET HEIGHT DETERMINATION ERRORS CAUSED BY RAWINSONDE INSTRUMENT ERRORS

1. INTRODUCTION

Data from precision tracking systems operating in the microwave spectrum must be corrected using tropospheric refractive index information if required levels of accuracy are to be attained. Since radio waves passing through the troposphere are delayed in time and bent downwards, an accurate target position can be determined only if compensation for these effects is sufficient. Correction techniques commonly used range from making no correction at all to computing corrections based on radiosonde data collected before, during and after a tracking event of interest. (NOTE: "Rawinsonde" and "radiosonde" are herein considered to be synonymous.)

The use of radiosonde data in a refraction correction scheme is generally considered to be one of the most accurate methods available to correct for tropospheric refractive bending and range error. However, it is recognized that the rawinsonde system has severe data accuracy problems when used to compute refractive index profiles. In particular, the humidity sensor responds relatively slowly to abrupt changes in humidity, causing the humidity measurement error to be the largest source of error in the calculation of the index of refraction.

An additional problem is the coarse height resolution resulting from use of the pressure sensor as the temperature and relative humidity commutator. Since the lower atmospheric layers are the major contributors to tropospheric refractive bending and range error, proper mapping of this region would require sampling of the lower two kilometers at many levels. Unfortunately, the current radiosonde usually provides less than five levels in the first two kilometers. This is insufficient for reliable detection of ducting and accurate characterization of refractive effects at low elevation angles.

A solution to the height resolution problem utilized by at least one tracking organization is electronic commutation. However, the basic inaccuracy and time response of the sensors is not changed by the addition of electronic commutation. Therefore, this report will address the effects which the rawinsonde system errors may contribute to the error in the target height determination when used in correcting precision tracking radar data. Rawinsonde system errors considered are limited to the sonde sensor inaccuracies. The time lag problem is not included in this analysis.

2. APPROACH

a. Consider the position determined by the use of one tracking radar which produces measured slant range, azimuth and elevation angles to the target. The height calculated from the measured range and elevation angle is the position component most sensitive to inaccuracies in the tropospheric refraction corrections. The target height errors are primarily due to errors in the calculation of the "true" elevation angle from the measured elevation angle. As will be shown later, rawinsonde system errors can result in errors in calculated target height of over 400 meters for objects in space and an error in calculating range of less than 100 meters. Obviously this range error is much less significant and will not be addressed further here. The single tracking sensor consideration does not take into account that the normal tracking situation could involve combinations of data from several tracking devices or from a sequence of tracking periods; some processing techniques for multiple sensor data could decrease the reliance of the target position determination on the measured elevation angle. However, if a tracking handoff involving two or more high precision tracking systems was part of the tracking mission, target height errors due to one sensor could be a significant source of difficulty in effecting a proper transition between successive sensors.

b. Major J. S. Schleher, Staff Meterologist assigned to the 20th Surveillance Squadron, Eglin AFB, Florida, has conducted a study of the effects of rawinsonde errors in determining target height for satellites tracked by the Eglin FPS-85 radar.[1] Various aspects of this study parallel Schleher's effort; in particular, use of the Eglin rawinsonde data and adoption of errors in target height as an error parameter. In addition, we have included several target heights and slant ranges and, more importantly, we have interpreted the actual rawinsonde system errors somewhat differently. In addition, Schleher used monthly average profiles for his base profiles while we have used actual rawinsonde profiles taken during 1976. Differences in the final results of Schleher's work and this paper will be discussed later.

c. The basic approach adopted to provide a reasonable measure of the errors due to the rawinsonde system is Monte Carlo in nature. Using the first refractive index profile in a given month which does not exhibit ducting, the actual slant range to a target at a fixed height was calculated for a series of elevation angles. In this paper the target heights considered are 3 km, 15 km, 40 km, 90 km and 250 km and the radar elevation angles were varied from 0.3 degree to 60.0 degrees. Given the set of actual slant ranges and radar elevation angles for a fixed target height, apparent target heights were calculated using 100 randomly varied (in a manner to be described later) refractive index profiles which had the original profile as a base profile. The final result for each target height and elevation angle combination was an rms variation of the apparent target height. Two soundings, one at 0600Z and the other at 1800Z for each of 12 months and 24 elevation angles each at six heights, were used in this analysis, yielding a total of 3456 rms variation numbers (i.e., 2x12x24x6).

d. The process of calculating the necessary tropospheric refractive bending, range errors and apparent target heights involved the conversion of each profile from meterological parameters to index of refraction and the use of a ray tracing program.

(1) The following expressions were used to calculate the index of refraction at each level:

$$N = (n-1) \times 10^{-6} = 77.6 \frac{P}{T} + 4810 \frac{e}{T^2} \qquad (1)$$

where: N = refractivity
n = index of refraction
P = pressure (mb)
T = temperature (deg. K)
e = water vapor partial pressure (mb)

The water vapor partial pressure, e, is not directly available from the radiosonde data, but can be calculated as shown in equation 1.

$$e = (6.11) \times 10^k \qquad (2)$$

where $k = (TDP \times 7.5)/(237.3 + TDP)$
and TDP = dewpoint temperature (deg. C)

(2) The program used to calculate the range error and bending is a variation of the program used at the National Bureau of Standards (NBS) during the 1950s and 1960s. The ray tracing is basically Schulkins' method and is documented in Bean and Thayer's CRPL Exponential Reference Atmosphere[2] and Bean and Dutton's classic Radio Meteorology.[3]

(a) By using the equations and computation criteria described in reference 2, the computation errors of the ray tracing program are much smaller than errors due to the rawinsonde system inaccuracies. The average base profile using the 1976 rawinsonde data from the United States Air Force Environmental Technical Applications Center (USAFETAC) contained 30 levels with the maximum level typically being 30 kilometers. The original 30-level profile was interpolated, primarily at the lower levels, so that the computation criteria of reference 2 were met. The interpolation routine usually added 15 to 24 levels depending upon the target height chosen and may also extrapolate the top of the profile if the target height was greater than the radiosonde upper level height.

(b) An additional modification was made to the original NBS program to allow the determination of apparent target height given a measured slant range and radar elevation angle. The modification followed the concept developed by Gardner[4] and has proved to be both fast and accurate.

e. Although the rawinsonde systems used have not changed significantly in the last 15 years and are essentially the same within the United States, there are no reliable, consistent measurements of the types and magnitudes of the rawinsonde system errors that can be applied universally. A best *estimate* of expected errors was recently published by the Range Commanders Council Meteorological Group.[5] Table I lists the estimated errors and the limits associated with each of the rawinsonde parameters.

(1) According to reference 5, the error estimates in Table I are "...root mean square (rms) deviations about a mean value which is the best estimate of the measure of the quantity. By assuming a circular normal distribution, which is logical, the rms values can be equated to one standard deviation."

(2) Based upon this definition, we have used the error estimates in Table I as standard deviations in a random number routine from the IBM Scientific Subroutine Package which generated Gaussian distributed random numbers with a specified mean and standard deviation. This routine has been used in several previous statistical analysis programs and the statistics of the generated random numbers are acceptable. At each level, the pressure, temperature and relative humidity from the base profile were varied using the Gaussian random number routine with each parameter value as the mean and the errors defined in Table I as the standard deviation. In the case of the relative humidity parameter, the varied values were constrained to be within the 0 percent to 100 percent range.

(3) One question that arose in the use of a random number routine to create the perturbed atmospheric profiles related to the possible correlation of the errors at each level and between levels. For instance, do either the temperature or relative humidity error values include the case of a constant bias during an individual radiosonde ascent? A search into previously published results which attempted to characterize rawinsonde system errors yielded little information about the correlation or bias question. At least one experiment involving one radiosonde and two co-located ground receiving sites resulted in errors between the final outputs of the two ground sites with magnitudes comparable to the Table I data. This indicated that the overall system errors are due to both the sonde sensors and the radio transmission-receiving-data reduction system. Since none of the references indicated any degree of significant quantitative correlation between errors, we assumed no correlation between parameters at any one level and no correlation between levels. This assumption should result in conservative estimates of errors due to the rawinsonde system since any correlation would tend to reduce the variability of the profiles.

(4) The assumption using the Table I data as standard deviations in a Gaussian random number routine is the major difference

TABLE I

PARAMETER	ERROR ESTIMATE
Temperature	Varies linearly with altitude from 1 degree Centigrade at the surface to 2.5 degrees Centigrade at 30 km.
Pressure	Varies linearly with altitude from 0.1% at the surface to 1.0% at 30 km.
Relative Humidity	Varies linearly with temperature from 5% at +40 degrees Centigrade to 20% at -40 degrees Centigrade

between the techniques used in Schleher's work and this paper. Schleher used the same data as in Table I but assumed the errors to be uniformly distributed within the designated limits. By assuming the errors to be uniformly distributed, the standard deviation of the radiosonde errors was only 58 percent of the standard deviations used in this paper and, perhaps more importantly, no errors larger than the Table I limits can occur. Obviously, the Gaussian assumption used in this paper resulted in larger (but we believe more realistic) variations in the refractive parameters calculated using the randomly varied atmospheres.

f. We have discussed the method of converting the rawinsonde data to index of refraction values, the Gaussian random number routine which produced the perturbed profiles, and the ray tracing program which produced the various refractive parameters needed. The next step is to utilize these tools to produce the desired error analysis.

(1) The basic profile data was supplied by USAFETAC in magnetic tape form. The data consisted of twice daily rawinsonde data runs at 0600Z (local midnight) and 1800Z (local noon) for the year 1976 for the Eglin AFB rawinsonde launching site. The analysis program picked the first profile for each month that did not produce ducting (thus assuring an optimistic nature to results of this study) for elevation angles of 0.3 degree and above. This profile, called the base profile, was used to calculate the actual slant ranges for given target heights and radar elevation angles. These slant ranges and radar elevation angles represented a data set similar to that produced by a radar tracking a target at the given height which has to be corrected by using some form of troposheric refraction parameter estimation algorithm.

(2) In this paper the corrections were derived by using the Gaussian randomly varied profiles as input to the ray tracing program which then calculated an apparent target height. Repeating this ray tracing calculation for 100 varied profiles resulted in a set of apparent target heights for which the standard deviation was calculated. This standard deviation represents the expected error due to the rawinsonde system errors for the target height, elevation angle, time of day and month of the base profile. This procedure was repeated for all of the cases considered.

g. Several steps were taken to test the validity of the specific computer operations used in the final computations.

(1) First, as mentioned earlier, the Gaussian random number routine was tested for correctness in generated values.

(2) Second, the sufficiency for error characterization of 100 randomly varied profiles for each target height, elevation angle and base profile combination was tested by increasing the number to 1000 and

repeating the analysis program. The difference in apparent error was less than eight percent for several base profiles tested. This difference was considered acceptable since high statistical precision is not imperative for a study such as this, and because the savings in computer time resulting from limiting runs to 100 profiles was considerable.

(3) To determine if the use of actual profiles as the base profiles was a problem, the base profile selection program was modified to pick a valid profile later in each month and the entire analysis was repeated. Again, the differences in results were small; less than ten percent. This difference was considered acceptable since we felt the use of actual profiles for the base provides more realistic variation within the profile than using monthly averaged profiles. As a final check, base profiles from 1969 were used in the same analysis program. Again, the differences in results were less than ten percent. During the process of carrying out the actual analysis runs, the test runs and the debugging runs, over 500,000 individual ray tracing calculations were made.

3. ANALYSIS RESULTS

a. The error in height determination due to the rawinsonde system errors ranged from less than one meter for high elevation angles and/or short ranges to over 4000 meters for the August 1800Z case where the elevation angle was 0.3 degree and the target height was 250 km. This posed a major problem for presenting the results from the calculations described above in a concise and meaningful manner. For the purposes of this paper, the results are primarily presented in graphical form and in representative forms rather than as a comprehensive presentation of the entire data set.

b. Figures 1a, 1b, 2a and 2b are a summary of near-worst month time (August, 1800Z - noon local) and near-best month time (January, 0600Z - midnight local) in terms of the rms of the magnitudes of the height errors caused by rawinsonde errors. Each figure provides annotated contours of equal height error plotted on a slant range vs height plot. Note that the range is actually a slant range from the sensor to the target and not a ground range. In addition to the height error contours, the height vs range relationship of typical ray paths is indicated by the dashed lines for selected annotated elevation angles. Figures 1a and 2a cover a height-slant range volume of 250 km by 1500 km and Figures 1b and 2b are a subset covering heights to 40 km and ranges to 720 km.

(1) As expected, the rms height errors become larger as the slant range increases and as the target height or elevation angle decreases; the increase in height error is rapid for decreasing elevation angles below 5 degrees.

EGLIN
JANUARY, 1976, 0600Z (BEST)

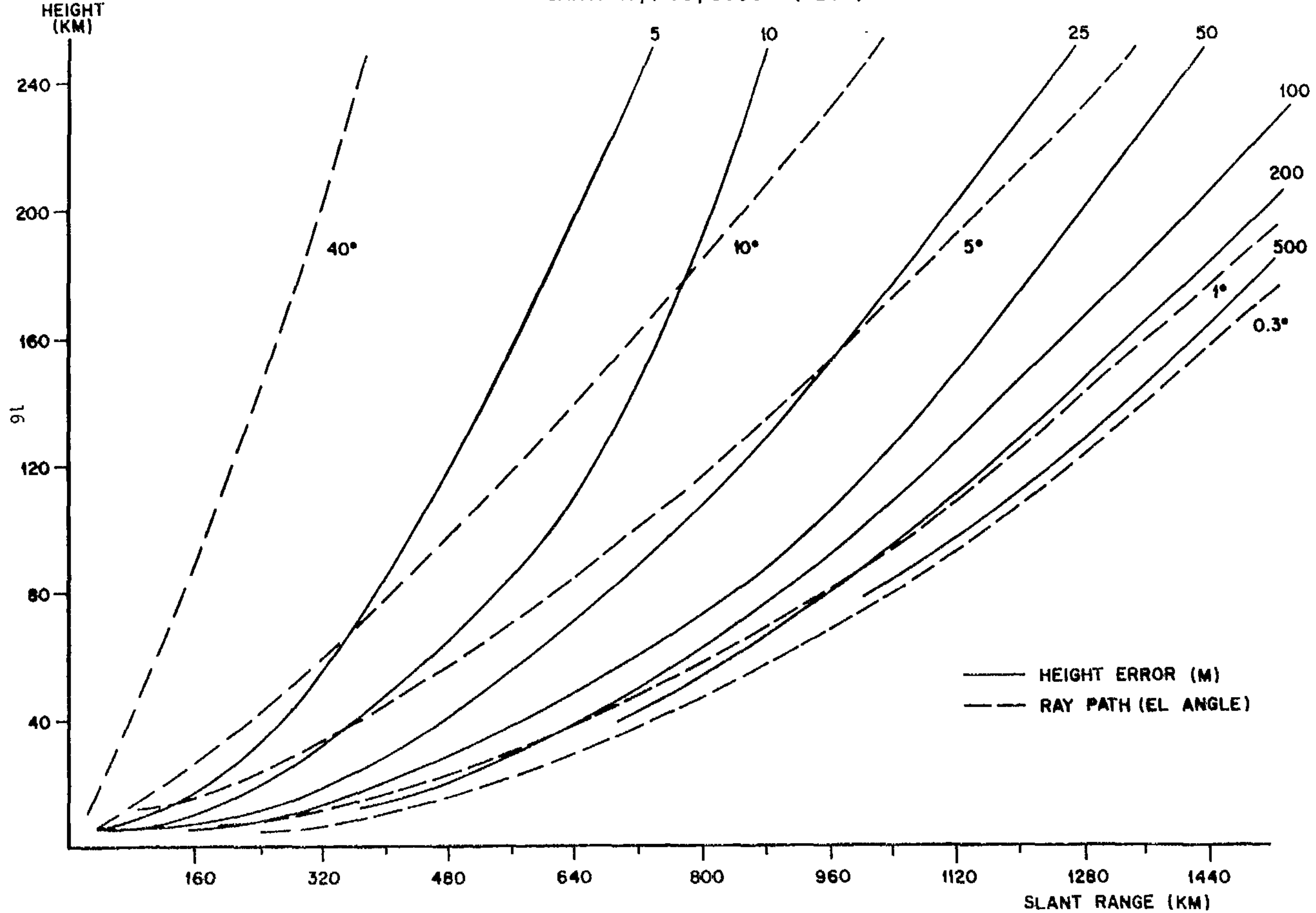

FIG 1A RAWINSONDE INDUCED HEIGHT DETERMINATION ERROR

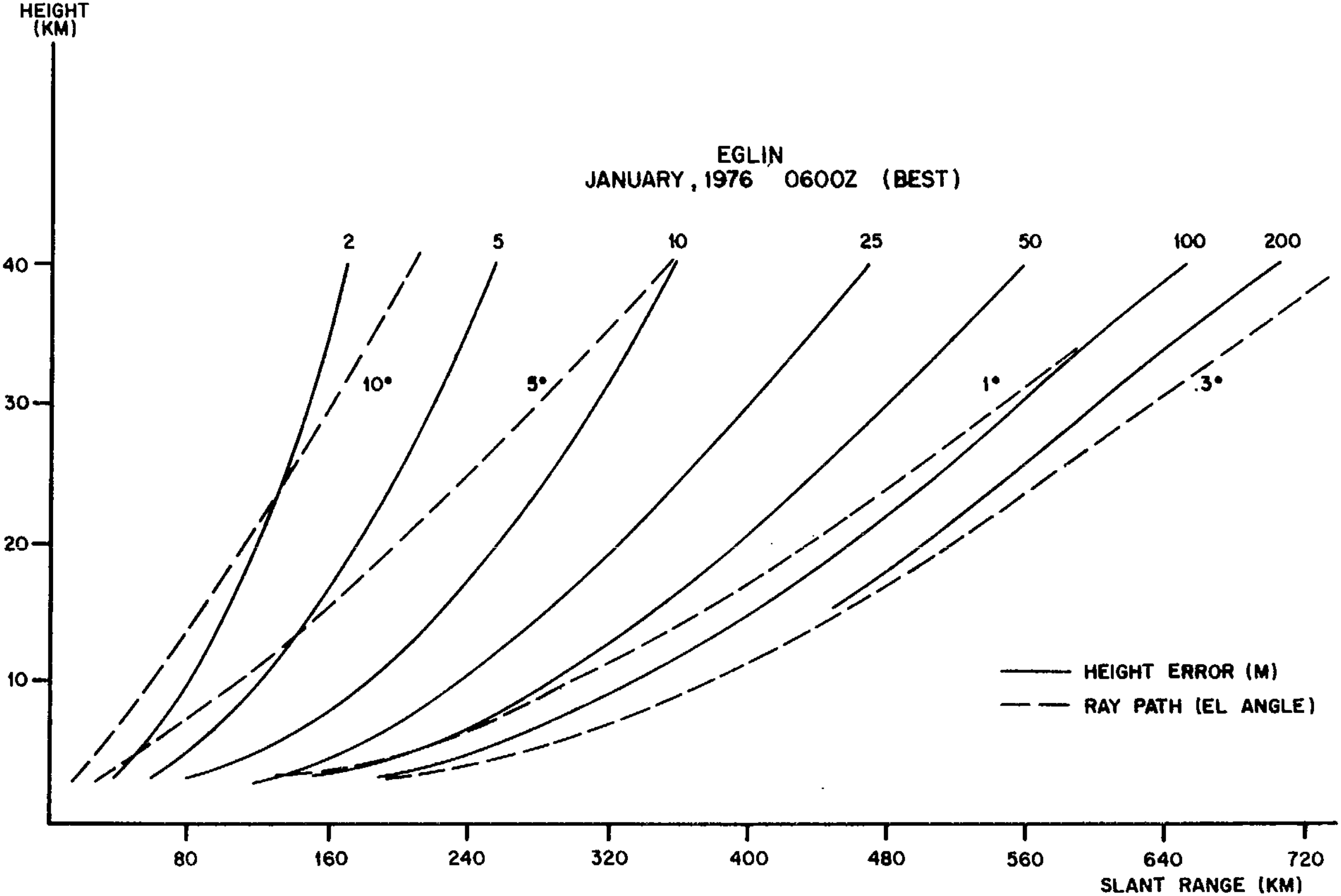

FIG 1B RAWINSONDE INDUCED HEIGHT DETERMINATION ERROR

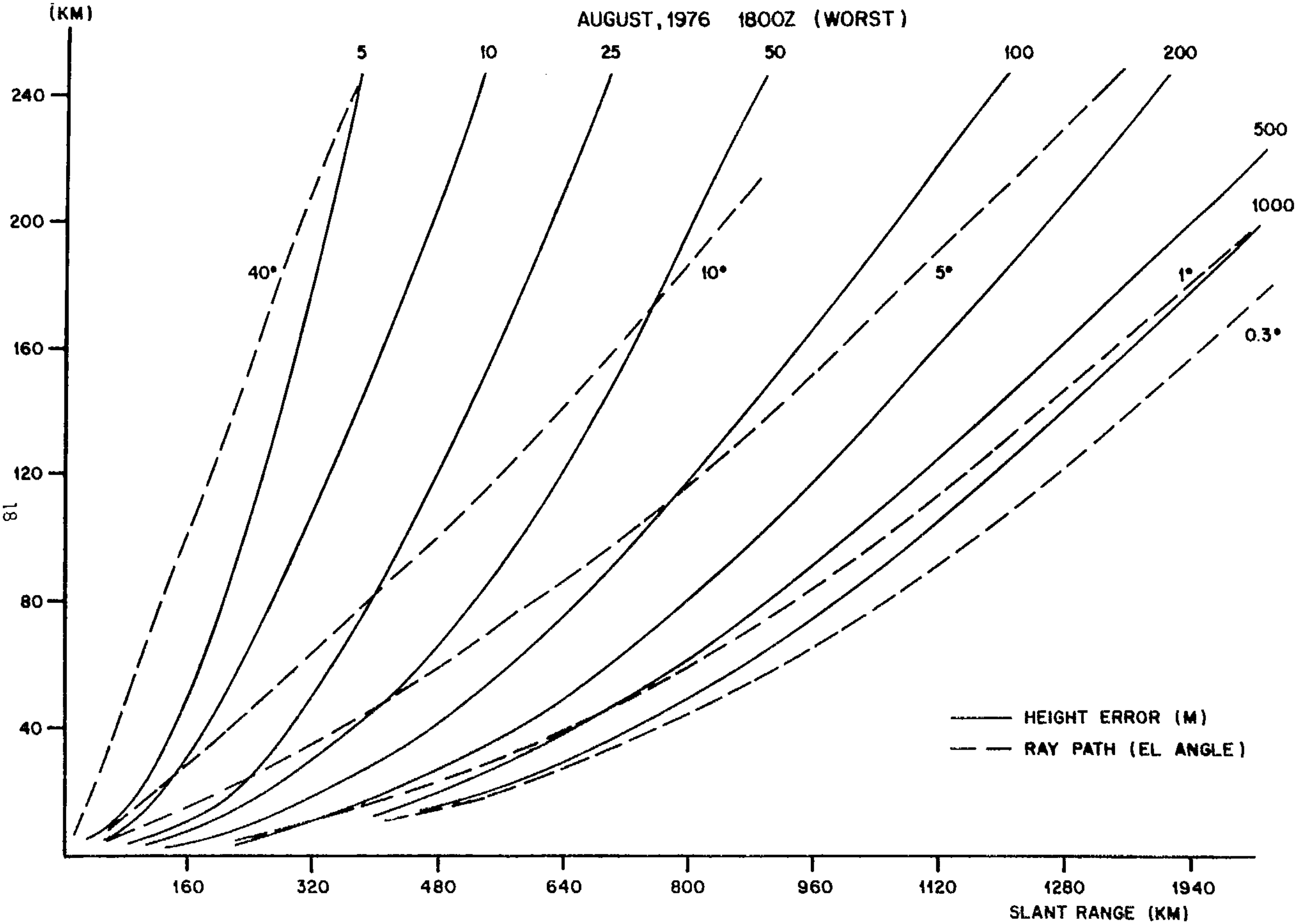

FIG 2A RAWINSONDE INDUCED HEIGHT DETERMINATION ERROR

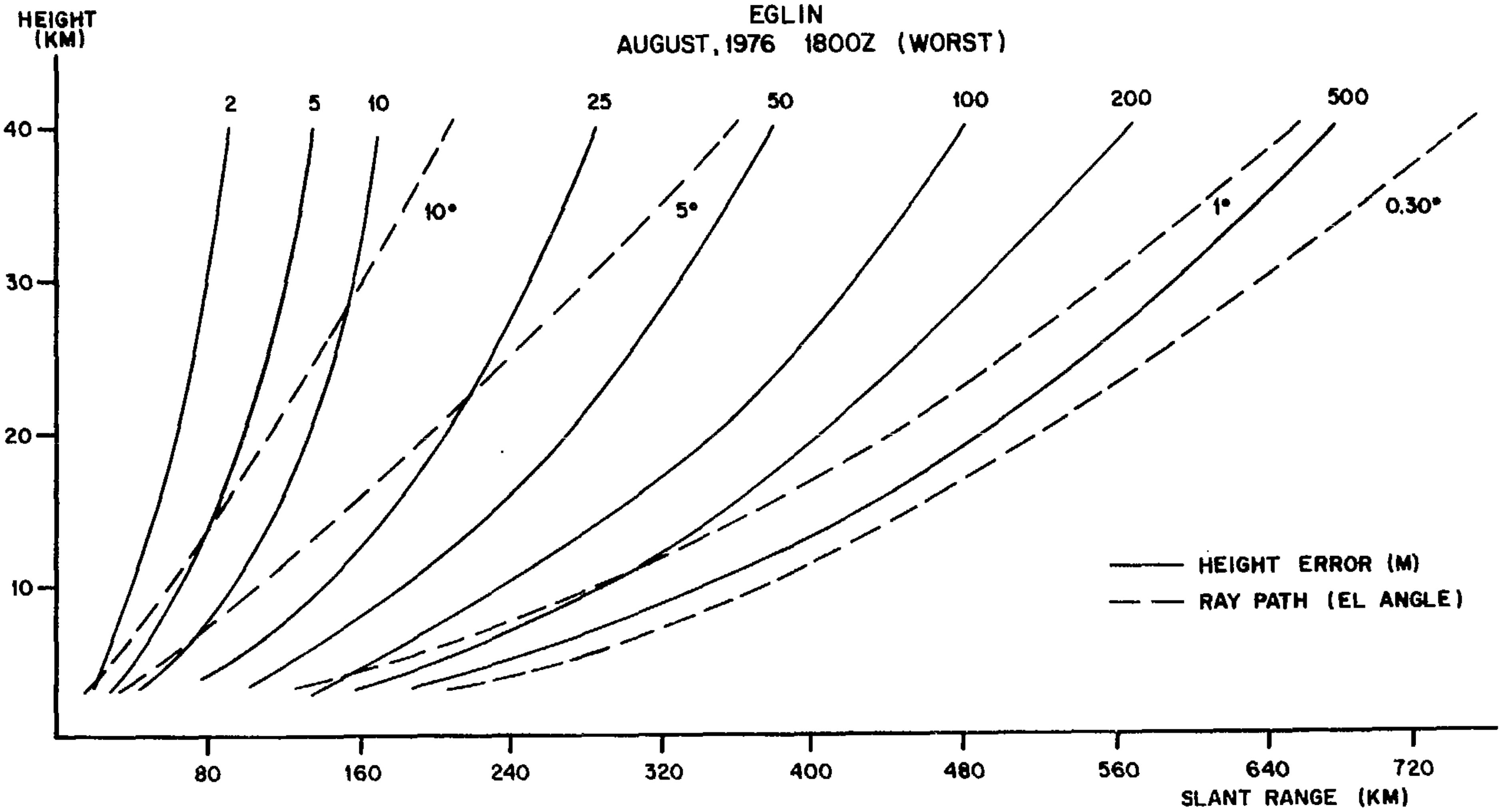

FIG 2B RAWINSONDE INDUCED HEIGHT DETERMINATION ERROR

(a) For an elevation angle of 1.0 degree and for ranges greater than 500 km, the minimum error ranges from about 100 meters to 400 meters during the winter case shown in Figure 1a. The same case in the worst months of July and August resulted in errors from 500 meters to over 1000 meters at the longer ranges. This case could represent very low elevation angle tracking of space objects in low orbits.

(b) We will now examine a second example with an elevation angle of 1.0 degree as before, but restricting the range to less than 600 km (Figures 1b and 2b). For the winter case, the height error varies from 25 meters at a range of 130 km to 100 meters at a range of 600 km. The summer values are greater, about 200 meters for the 130 km range to about 400 meters for the 600 km range. These figures are for targets with heights less than 40 km and could be representative of aircraft tracking examples.

(2) The four figures include curves for higher elevation angles, up to 40 degrees for 1a and 2a and up to 10 degrees for 1b and 2b. The errors are much less for these high angles.

(a) For systems which operate at elevation angles above 5 degrees, the height error due to the rawinsonde system for typical aircraft targets would be less than 25 meters in the summer and less than 5 meters in the winter. For satellite tracking systems operating above 5 degrees, the height errors in the summer would be less than 200 meters for targets with heights of 350 km or less and less than 50 meters in the winter.

(b) An extreme low altitude example would be a target at a height of 3 km and a range of 200 km which corresponds to an elevation angle of 0.3 degree. In the summer a height error of over 400 meters could be expected due to the rawinsonde errors, while in the winter the height error would be approximately 100 meters.

c. Figures 3, 4, and 5 represent the monthly variation in the height error. Their comparisons of height errors due to the rawinsonde system to the natural variability of the atmosphere (defined later) and to apparent height errors resulting from use of only surface refractivity data, represent the most significant result of this study. Again, these figures represent a small portion of the data generated but the time variability is nicely illustrated by the data shown. All three figures use an elevation angle of 1.0 degree but the nominal target heights are different. Data for the 0600Z and 1800Z soundings are shown on each figure; generally, the 1800Z soundings have a larger height error associated with them. The summer errors are approximately twice as large as the winter errors, which is to be expected because summer provides high humidity conditions. The combination of the refractive index sensitivity to humidity and the relatively poor performance of the humidity sensor combine to cause large errors.

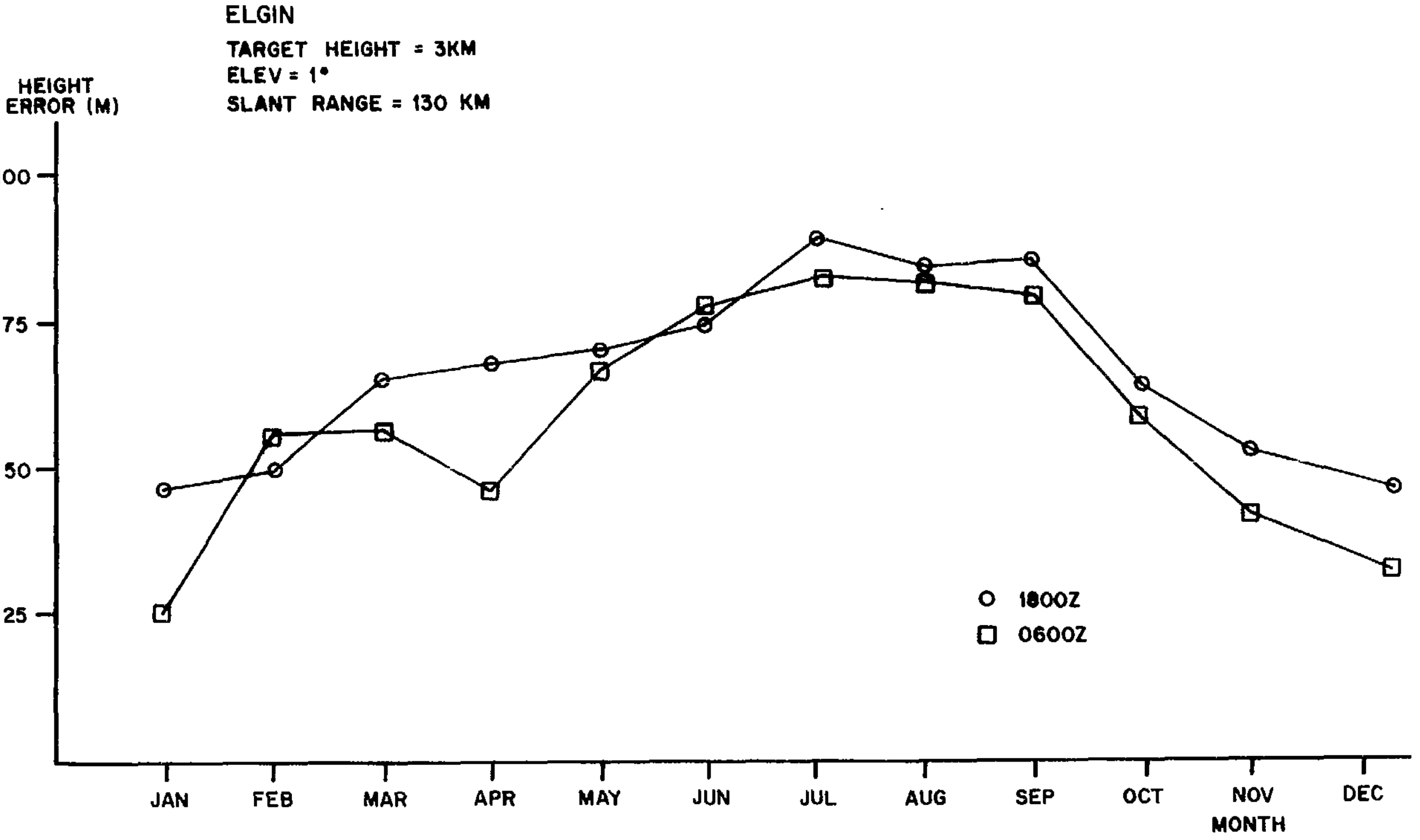

FIG 3 HEIGHT ERROR VS MONTH

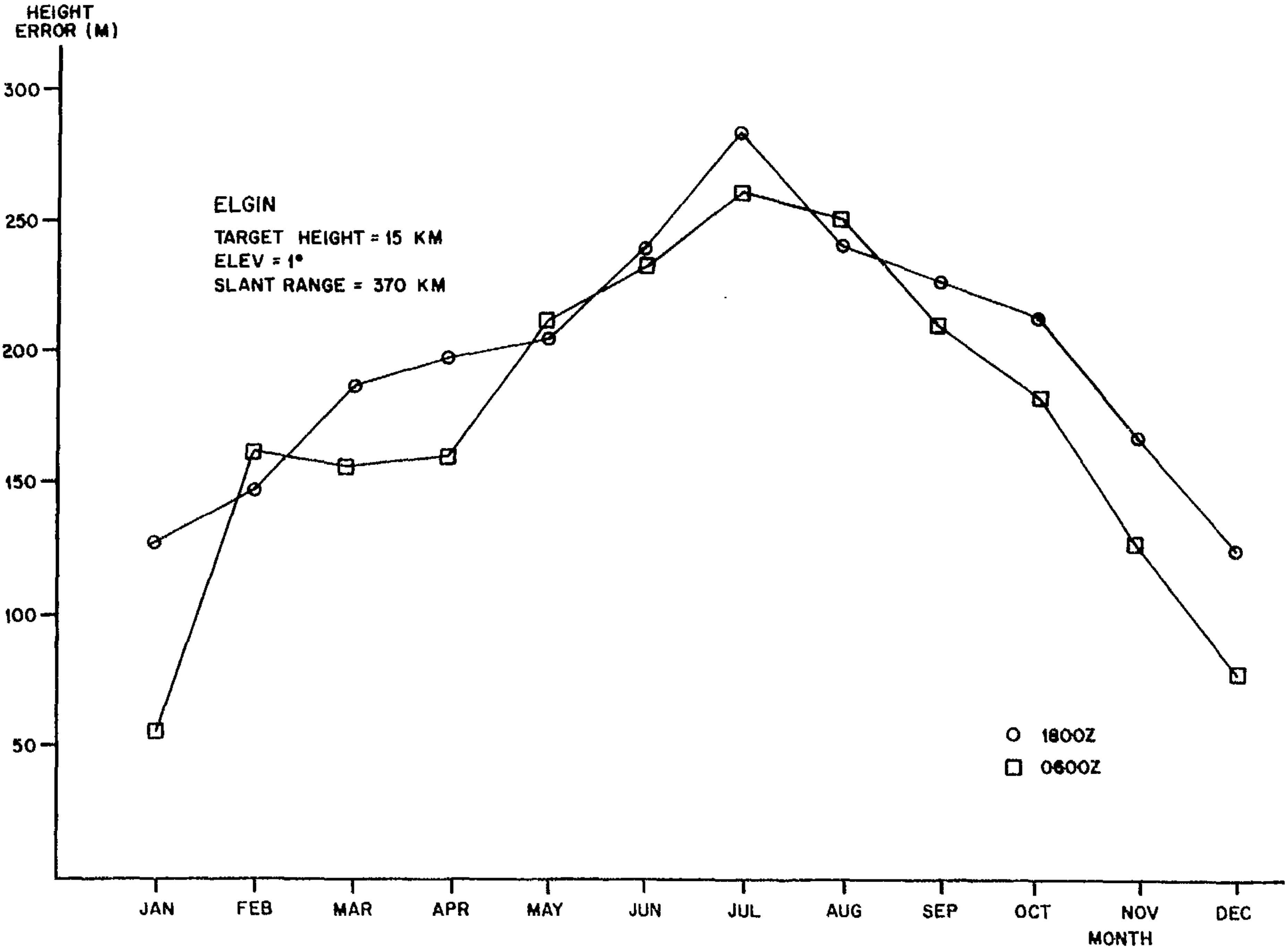

FIG 4 HEIGHT ERROR VS MONTH

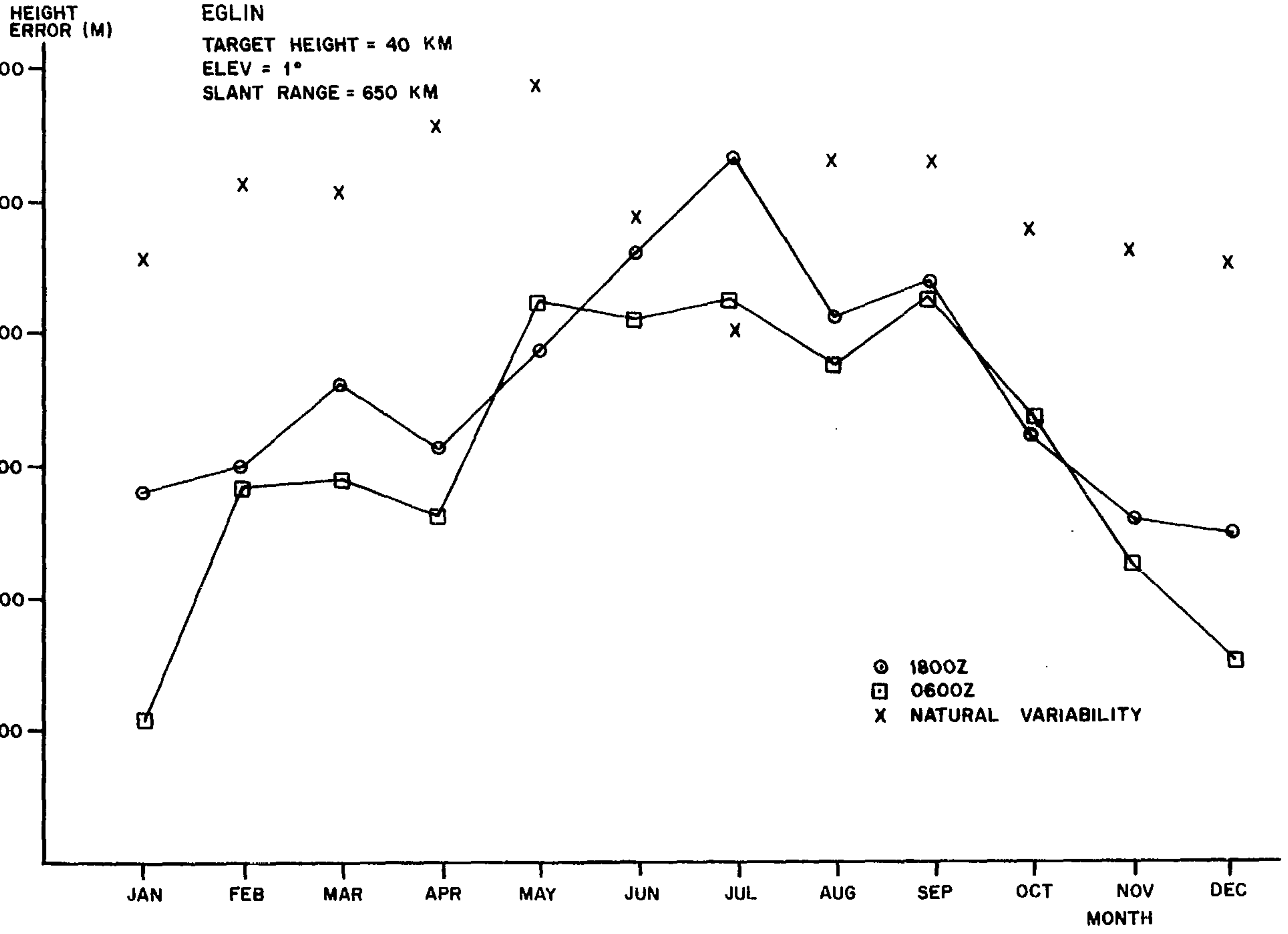

FIG 5 HEIGHT ERROR VS MONTH

(1) In order to determine the relative magnitude of the height errors compared to the natural variability of the atmosphere, the analysis program was modified as follows. For each month all of the rawinsonde profiles on the data tape were ray traced for a range representing a nominal 40 km target height and a 1.0-degree elevation angle. The collection of apparent target heights, one for each profile, was employed in the statistics subroutine used in the main analysis program.

(a) The standard deviation of the target heights is shown on Figure 5 as X's, one for each month.

(b) Since radiosondes are normally released twice per day, there should be at least 60 profiles per month; however, ducting profiles were eliminated and the usual number of accepted profiles was from 54 to 57. (Since ducting causes greater errrors in height determination, the retained data portrays a somewhat optimistic picture.)

(c) We have called this set of standard deviations represented by the X's on Figure 5, the "natural variability" of the atmosphere since the variation of the apparent target heights was due to the variability of the measured atmospheric profiles used. These standard deviations also represent the height error that would occur if the tropospheric refraction corrections were simply a mean correction for each month.

(d) This natural variability analysis was repeated for a few months of data from another year with little change in the results.

(e) It is interesting to note that the natural variability of the troposphere is not much greater than the variability due to the errors generated by the statistically varied rawinsonde data, particularly in the summer months.

(2) Eglin AFB was one of a series of radar sites analyzed in a previous study concerning the refractive environment surrounding each site.[6] Although target height error was not one of the parameters analyzed, the variation of the refractive bending error was calculated.

(a) The mean and standard deviations of the bending error for several elevation angles were calculated using two years of rawinsonde profiles.

(b) Using the nominal slant range to a 40 km target with a 1.0-degree elevation angle, the height variation due to the variation in the bending found in the refractive environment study was 700 meters. This is consistent with the data in Figure 5 because the variation in mean bending from month to month is large and the standard deviations plotted in Figure 5 are standard deviations about the mean for the month.

(3) Although not shown on the figures, the natural variability-target height error ratios were examined for the higher elevation angles. The ratios tended to exhibit the same behavior as was found for the lower angles, i.e., the natural variability was greater than the height error in the winter months and roughly equal in the summer months. The ratio was somewhat higher for the higher elevation angles. For example, in February the 1.0-degree ratio of natural variability to height error was 1.7, while the 10-degree ratio was 2.7. In July the 1.0-degree ratio was 0.75 and the 10-degree ratio was 0.86.

(4) The refractive environment study referenced earlier also developed a set of correction algorithms which computed tropospheric range error and bending as a function of elevation angle and surface index of refraction. The algorithms were tested by comparing the algorithm predictions of bending and range error with the bending and range error calculated using rawinsonde data and a ray tracing program. Taking the rms error of the Eglin bending algorithm using a two-year period of data, the target height error for the case shown in Figure 5 due to the bending algorithm error was only 310 meters. This is a measure of the ability to determine target height of a target above the appreciable atmosphere using only surface index of refraction at the radar site.

d. Figures 6 and 7 indicate the maximum and minimum height error as a function of range for fixed elevation angles of 1.0 degree and 10.0 degrees. One reason for presenting the data in this manner was to compare the results of this study with Schleher's work. Schleher's data was presented in tabular form and his analysis configuration used a fixed slant range of 500 km and several elevation angles. The X's on Figures 6 and 7 show Schleher's results for the Eglin January and August mean models, which can be used as a maximum and minimum error limit for his data. In both figures the results of this paper give height errors which are approximately three times as large in the winter case and twice as large in the summer case. Since the random perturbations applied to the base profiles in this study are larger than Schleher used, it is not surprising to see larger height errors. The predominance of the humidity term in the summer accounts for the smaller percentage increase compared to the winter.

(1) The humidity term contribution to the index of refraction is so large that it masks the temperature and pressure variations. As a result, the refractive index variations near the surface—due to rawinsonde errors—are mainly the result of the humidity variations. In the winter the humidity term contribution is much less and the pressure and temperature terms have more effect on the final error result.

(2) Figures 6 and 7 also indicate the almost linear increase in height error with slant range for a constant 1.0-degree elevation angle. This height error is primarily due to the elevation angle error

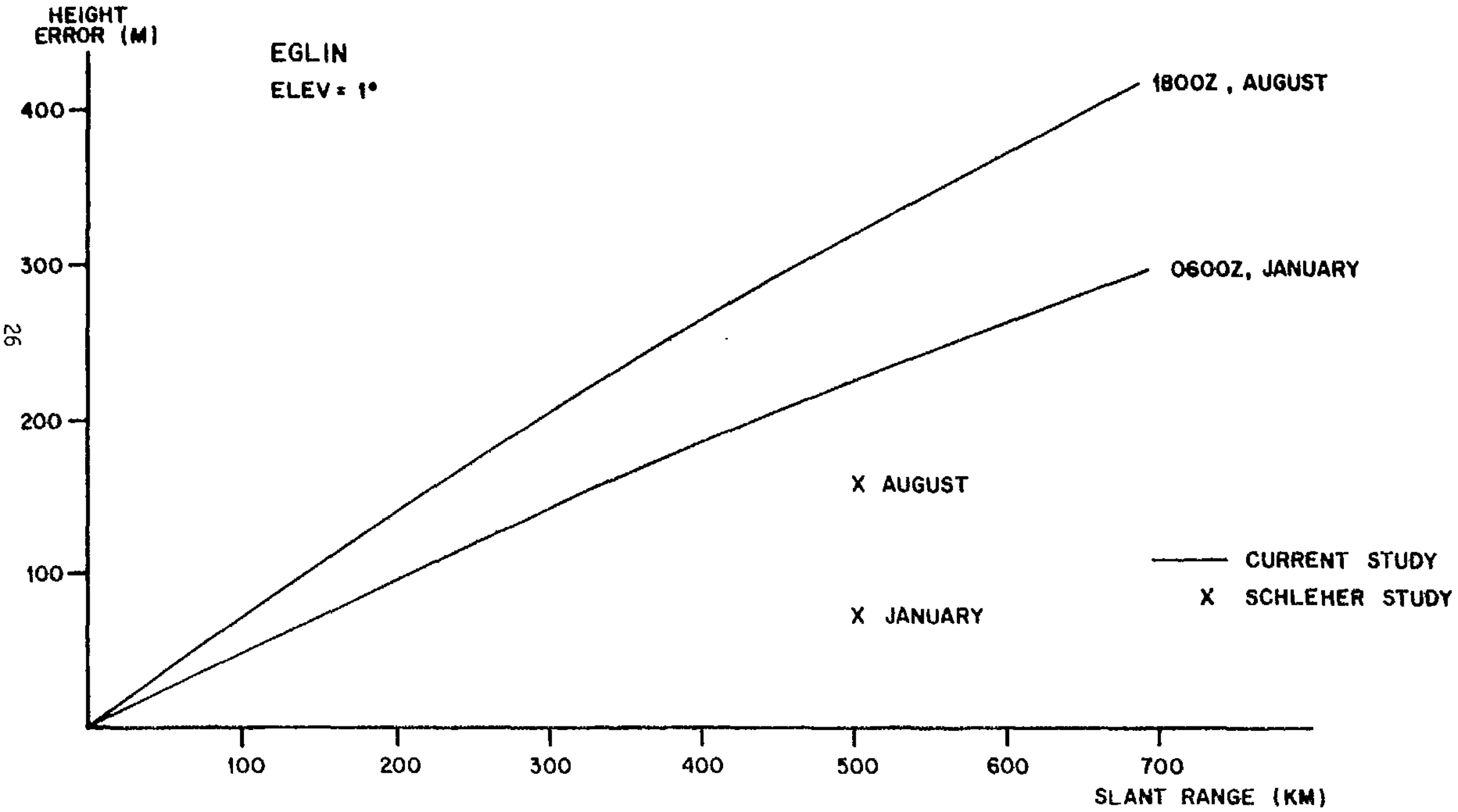

FIG 6 HEIGHT ERROR VS SLANT RANGE

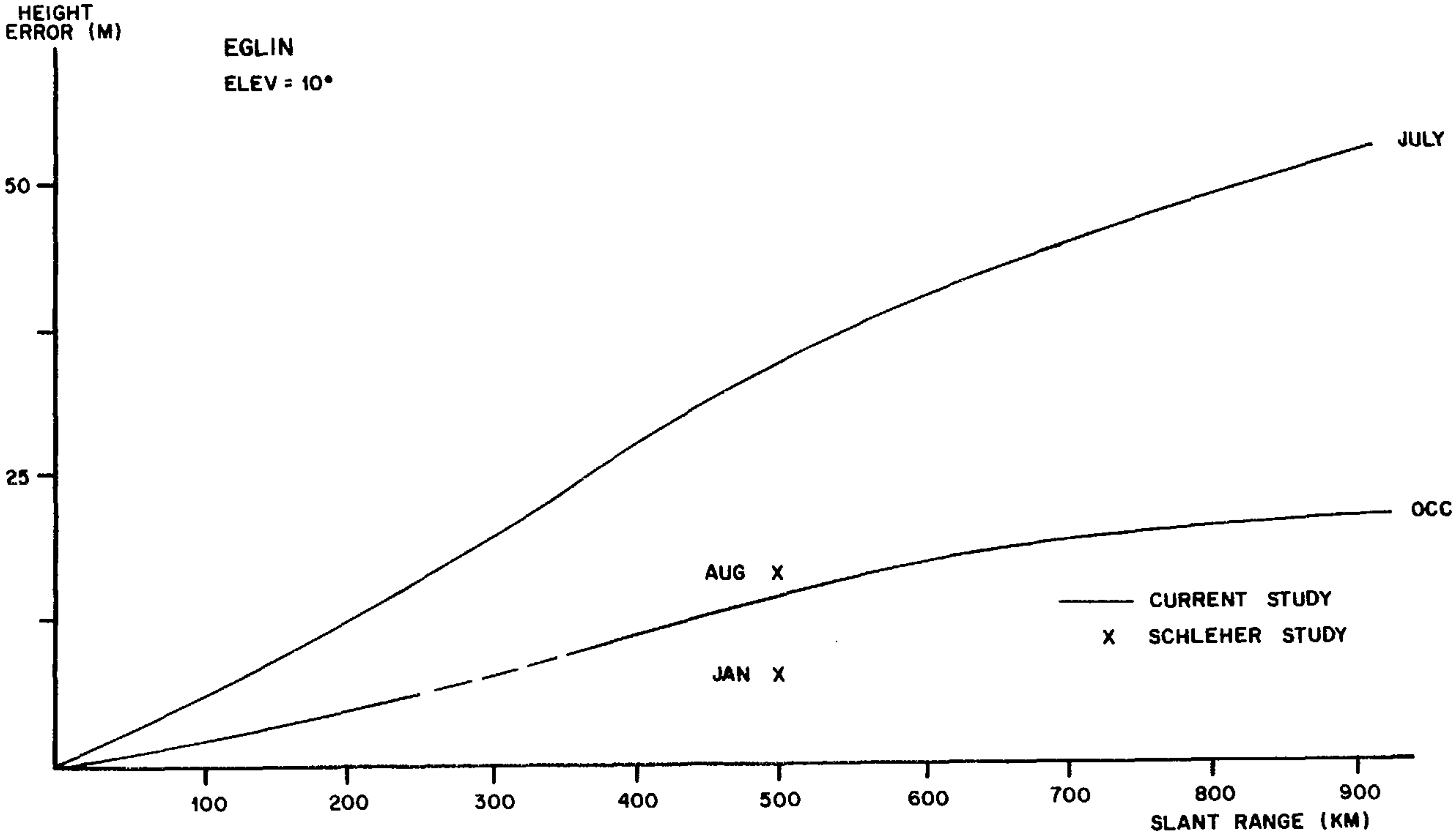

FIG 7 HEIGHT ERROR VS SLANT RANGE

caused by the rawinsonde inaccuracies. The majority of the angle error (ΔE) occurs in the very low layers of the atmosphere and therefore remains essentially constant for slant ranges beyond 150 km. As a result, the uncompensated height error for range R is approximately R sin ΔE for very small elevation angles.

e. The final set of figures presents the error results in a different manner. Figures 8, 9 and 10 present the range of height errors expected for targets of constant height and varying slant range and elevation angle.

(1) Figure 8 could represent an aircraft flying at an altitude of 3 km and moving away from the tracking site. The curves show the maximum and minimum errors in the computed height that could be attributed to errors in the rawinsonde system data used in making a refraction correction. At a slant range of 100 km the height error would be between 15 and 45 meters.

(2) Figures 9 and 10 demonstrate how rapidly the error in determination of height increases for high altitude targets as they approach the horizon.

f. Schleher has written several internal memos relating to tropospheric and ionospheric refraction effects on the AN/FPS-85 radar located at Eglin. One of these studies attempted to determine the effect of the limited rawinsonde launch rate at Eglin.[7]

(1) During 1970 the Eglin AFB rawinsonde station launched four radiosondes daily at 0000Z, 0600Z, 1200Z and 1800Z. Schleher analyzed the height and range differences between consecutive launches for a series of slant ranges and elevation angles.

(2) One subset of the data Schleher presented is applicable to the conditions analyzed in this paper. For a slant range of 500 km and an elevation angle of 2.0 degrees, the nominal target height is 34 km. It was assumed that each rawinsonde profile was completely accurate throughout the radar coverage at the time taken. Using the same range (angle inputs to a ray trace program) apparent height errors were calculated for successive profiles. The differences between two consecutive results is assumed to be the error which results from using the earlier rawinsonde information at the time the current radar observations and rawinsonde soundings are made. The standard deviation of the set of all such target height differences for this case is 281 meters for releases six hours apart and for data collected over one year. The expected rawinsonde system errors for the same conditions would be 40 meters to 160 meters depending upon the month. In the summer the rawinsonde errors could account for one half the differences Schleher found.

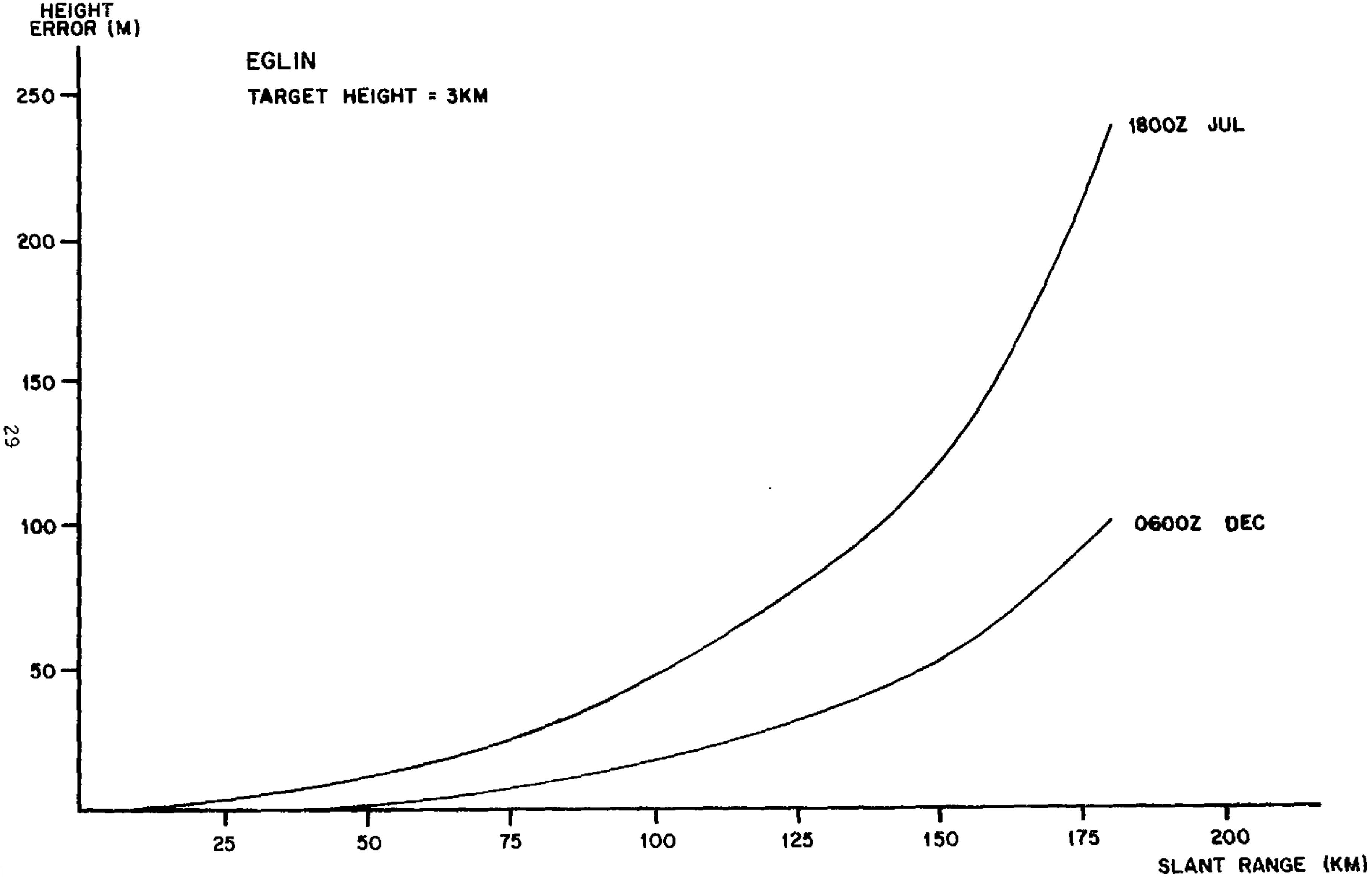

FIG 8 HEIGHT ERROR VS SLANT RANGE

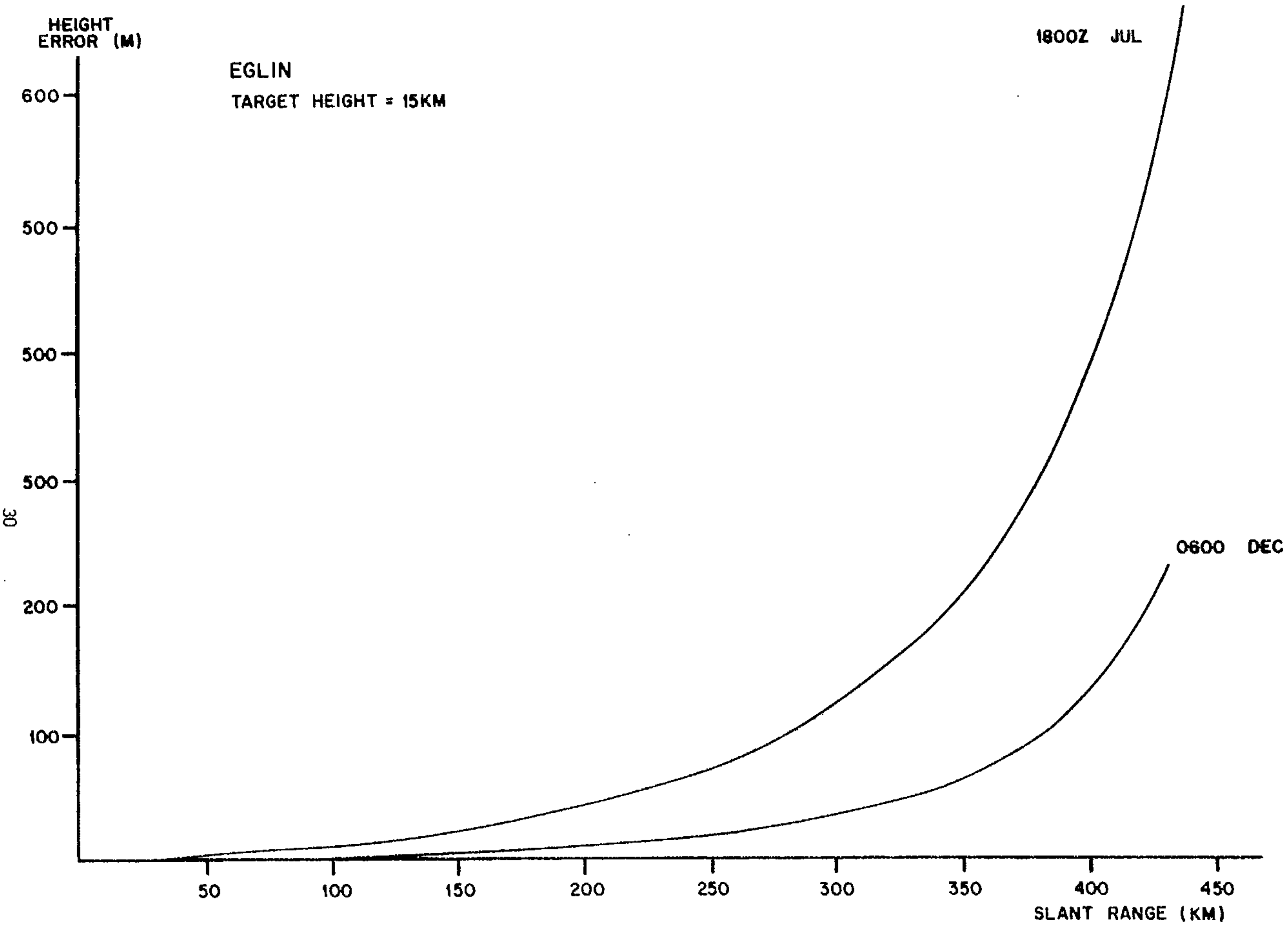

FIG 9 HEIGHT ERROR VS SLANT RANGE

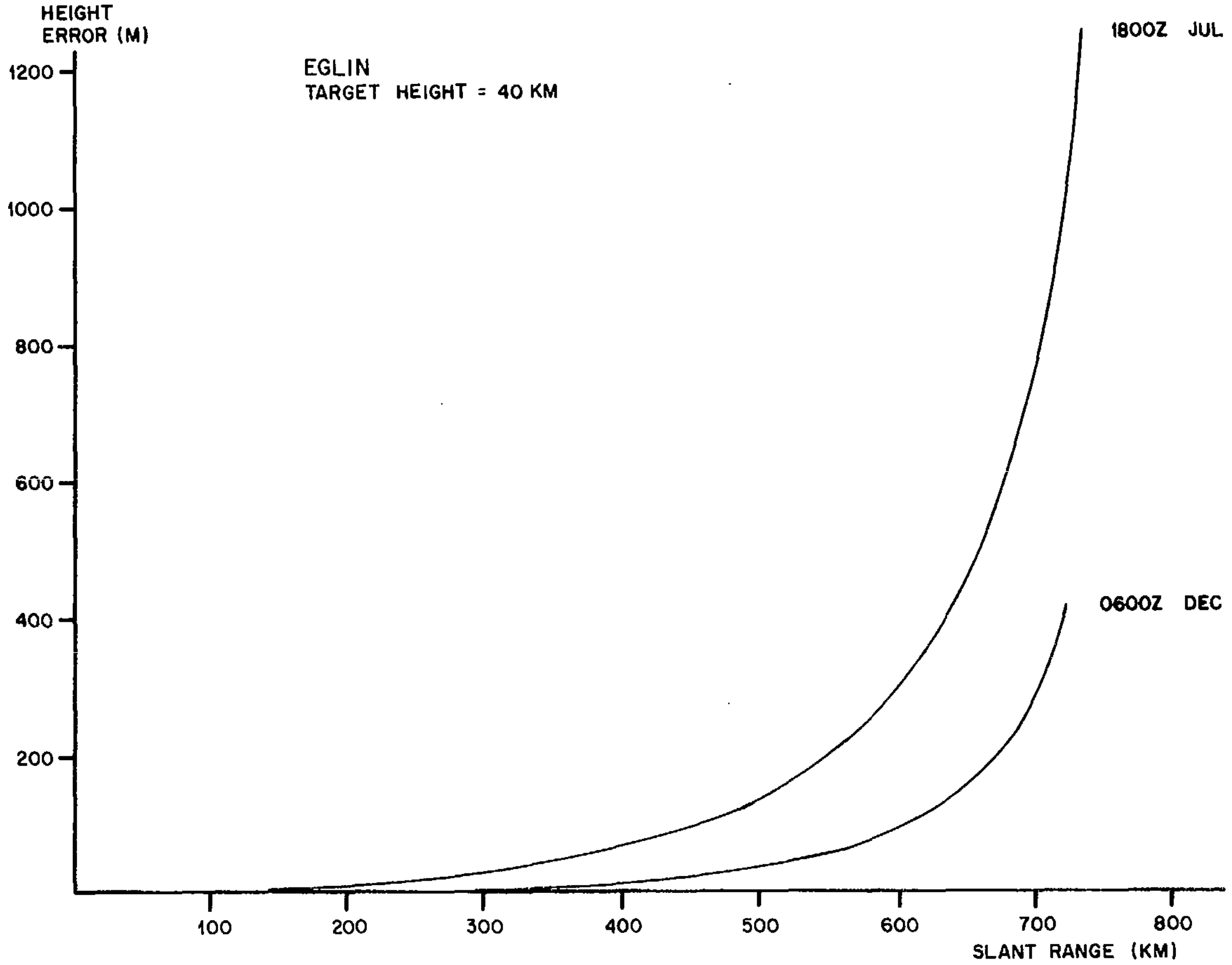

FIG 10 HEIGHT ERROR VS SLANT RANGE

g. The Eglin AFB climatology is near-tropical (coastal with conflicting land and sea air masses and with high humidity near the surface). In order to determine how the results of this study may be dependent on the uniqueness of the Eglin environment, a similar analysis was carried out using data from the Portland, Maine, rawinsonde site. In general the height errors were comparable to those at Eglin in the winter months and smaller by a factor of two thirds in the summer months. Portland falls within the mid-latitude coastal climatology with a smaller mean surface index of refraction and somewhat smaller variations in the surface index than Eglin. In the Eglin-Portland comparison the high humidity at Eglin accounts for the larger height errors in the summer in the same manner as the summer-winter comparison at Eglin. The comparability of the winter results was not surprising since the height error analysis process is not overly sensitive to profile composition when the humidity terms are comparable. It appears that the rawinsonde errors are critical for any climate, but more critical for tropical conditions.

4. CONCLUSIONS

a. The analysis performed provides insight into the criticality of accurate refractivity information for making refraction corrections.

b. The position determination errors resulting from use of typically imprecise rawinsonde data may be far in excess of the error acceptable for precision mission purposes.

c. For low elevation angle radar data, the residual refraction error after corrections using state-of-the-art techniques, exceeds the radar equipment error for precision radars. Thus, the cost effectiveness of improvements to radar accuracy for such radars is questionable.

d. The use of surface index of refraction alone can in many instances yield refraction correction results of comparable quality to that obtained when using a full rawinsonde-derived profile of refractivity. Rawinsonde data can sometimes be valuable in detecting the presence of abnormal conditions (e.g., ducting), which surface observations will not provide.

e. Reduction of the rawinsonde humidity sensor errors is critical to improvement of rawinsonde usefulness.

f. The results of this study are intimately dependent upon the *estimate* of expected rawinsonde errors, not on a precise determination of those errors. Careful handling and special calibration could reduce the errors significantly for any given sonde.

g. Because of the various conservative assumptions adopted in this study the results are conservative, and may be a lower limit to the types of errors typical of Eglin AFB. Errors at other sites may be less than those in the Eglin area.

5. RECOMMENDATIONS

a. A more precise determination of the errors in rawinsonde parameters should be performed, possibly by the Meteorological Group. If the results differ significantly from the values of Table I, the conclusions of this study should be reevaluated.

b. No further attempts should be made to devise better refraction correction techniques until improved means of determining the applicable refractivity profile are found.

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