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Adaptive Mapping of Mid-Latitude Ionosphere

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FOR THE COMMANDER

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Maps of the monthly median of refractive effects are used by precision navigation and radar systems to correct for measurement errors caused by the ionosphere. Calculated off line using available climatologies of the pertinent ionospheric parameters, they are used in real time systems to remove 70 to 75 percent of the monthly rms error. When greater precision is required, these maps may be adapted by any of several local measurements of current ionospheric conditions. The residual refractive error is dependent on the density of these local measurements in space and time and on their ability to

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characterize the current ionosphere. To simulate a particular adaptive technique, data from a sequence of passes of the Navy Navigation Satellite System satellites are used to represent both the local ionospheric measurement and the subsequent system measurement. Systematic variations of the ionosphere are usefully predicted over a few hours. Local features that have large geophysical scale size, such as the nighttime trough and the plasmapause enhancement of the mid-latitude ionosphere, are tracked by sequential measurements and may be mapped in space and local time across the entire system field of view during quiet geophysical periods. During disturbed periods, however, their dynamic behavior may require more frequent specification and, in addition, very large features can develop which are sharply confined to small areas of the coverage region.

Preface

The authors would like to thank Dr. K. Davies, NOAA-ERL, for ATS-6 data from Boulder, Colorado and Dr. A. Hedberg, Ionospheric Observatory, Uppsala, Sweden, for NNSS observations at Uppsala. We thank Mr. J. Klobuchar, Air Force Geophysical Laboratory, Bedford, Massachusetts for the TEC data from Goose Bay, Labrador; Hamilton, Massachusetts, and the Kennedy Space Flight Center, Florida, and Mr. I. Mikkelsen, Danish Meteorological Institute, Copenhagen, Denmark for the TEC data from Narssarssuaq, Greenland. We also express our thanks to the many others involved in the collection and analysis of this diverse data.

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1. INTRODUCTION

As navigation and radar systems evolve, the requirements for precision range measurements become more stringent. Eventually real time algorithms must be developed to provide increased accuracy in corrections for refractive effects arising from the ionosphere. Relatively simple look-up tables of the expected median correction can be derived from climatologies of the principal ionospheric parameters. Dependent on only smoothed solar conditions, these tables can be prepared several months in advance, and when used, will typically remove 50 to 75 percent of the monthly rms refractive error. For more precise estimates of refractive effects, maps can be developed from climatology for the entire system field of view. Stored in the system processor, these maps may be adapted by pertinent local measurements to provide a real time correction that will represent the response of the ionosphere to current solar-terrestrial conditions and even reflect local features, in some cases (DuLong et al).[1] With the adaptive techniques, the residual refractive error is dependent on the information within the local measurement and the density of measurements in space and time. When the highest precision is required, techniques have been developed for sophisticated systems to directly measure the

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[1] DuLong, D.D., and Allen, R.S. (1976) Specification of Navigation and Radar Errors Caused by the Ionosphere, COSPAR Symposium Proceedings, The Geophysical Use of Satellite Beacon Observations, Boston University.

needed refractive correction for the ionosphere along the path to the target (Allen et al).[2] This paper will examine adaptive techniques, using measurements from the Navy Navigation Satellite System (NNSS) to illustrate some of the promise and some of the problems.

2. THE REFRACTIVE CORRECTION

At UHF and higher radio frequencies (f) the physics for wave refractive effects can be greatly simplified; the local electron density (n) is the only variable that must be considered. Then the ray path is approximated by a straight line with a first order correction for change in apparent range (ΔR) which is directly proportional to the electron content integrated along the slant path (s).

$$\Delta R = k/f^2 \int_0^s n ds . \tag{1}$$

Millman[3] has shown that from this a correction can be made for the first order change in elevation angle. For targets in the upper ionosphere and at low elevation angles the change in the elevation angle (ΔE) is

$$\Delta E = (\cot E_o) \Delta R/R . \tag{2}$$

where Eo is the initial elevation angle. The principle correction, ΔR, may be modeled from existing climatologies of ionospheric parameters (Llewellyn and Bent).[4] Such a modeling shows that the median of the range correction induced by the ionosphere has greatest values just after midday, at the equinoxes, for conditions at the maximum of the solar cycle. This correction, in meters, is illustrated in Figure 1 for a representative radar, using 425 MHz along a slant path to a target with elevation angle 5 deg and altitude 1000 km. These curves represent the twelve month running mean sunspot number ($\overline{R_z}$) at the maxima of the last 20 cycles of solar activity when the peak $\overline{R_z}$ of a cycle could range from 50 for a very quiet to 200 for a very disturbed solar maximum. The fractiles of $\overline{R_z}$ are the lower quartile, median, upper quartile, and upper decile (70, 100, 130, and 150 respectively). If the

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[2] Allen, R.S., DuLong, D.D., Grossi, M.D., and Katz, A.H. (1976) Ionospheric Range Error Correction in Precision Radar Systems by Adaptive Probing of The Propagation Medium, AGARD Conference Proceedings, Propagation Limitations of Navigation and Positioning Systems, Ankara, Turkey, AGARD CP209.

[3] Millman, G.H., and Reinsmith, G.M. (1974) An Analysis of the Incoherent Scatter-Faraday Rotation Technique for Ionospheric Propagation Error Correction, General Electric Co. TIS R74EMH2.

[4] Llewellyn, S.K., and Bent, R.B. (1973) Documentation and Description of the Bent Ionospheric Model, AFCRL-TR-73-0657.

mapping of a correction is made for the entire field of view of a system using parameters in the climatology that represent actual median ionospheric conditions, when it is used to correct real time range measurements, the remaining monthly rms error (δR_m) is about 20 to 25 percent of daytime and about 30 to 35 percent of nighttime median values (DuLong).[5] For the radar of Figure 1, an expected ΔR at the next solar maximum near the equinoxes is 300 m, resulting in a δR_m of about 70 meters. Systems needing greater precision may further reduce refractive effects by using some local ionospheric measurement to adapt this median prediction, in a manner similar to that described by DuLong et al.[1]

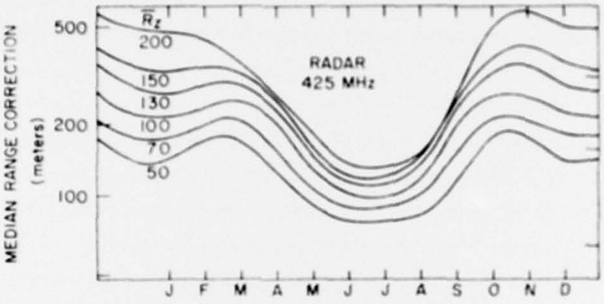

Figure 1. *Monthly Mean Range Correction at Midday* for a 425 MHz Radar Situated Near 50°N Latitude. Target is at 5° elevation angle, 100 km altitude. Each curve, parametric on 12 month running mean sunspot number, represents the expected range correction for solar maximum conditions. At an average solar maximum, $R = \approx 100$, the expected correction is near 300 m at the equinoxes

3. ILLUSTRATIVE TEST OF AN ADAPTIVE MODEL

The residual error when using an adapted model, δR_a, depends on the space and time coherence of day-to-day changes, including local features which occur within the radar field of view. To examine this error, actual TEC data was obtained from observations of NNSS satellites for four days in December 1975, taken at Lindau, FRG, and Graz, Austria, and for three days in October 1974, from Bozeman and Boulder in Colorado (Leitinger and Hartmann).[6] These represent

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5. DuLong, D.D. (1977) Reduction of the Uncertainty of Radar Range Correction, AFGL-TR-77 (in press).

6. Leitinger, R., and Hartmann, G.K. (1976) Time and Latitude Dependence of Ionospheric Electron Content from the Combination of NNSS and ATS-6 Data, COSPAR Symposium Proceedings, the Geophysical Use of Satellite Beacon Observations, Boston University.

quiet and disturbed periods of geomagnetic activity, respectively. The observations were normalized to simultaneous TEC data reduced from single station observations of the beacons of the ATS-6 satellite. By converting the NNSS data to radar range correction, the results can be used to adapt maps of the median range correction and the reduction in refractive error can be examined.

In simulating a procedure for adaptive modeling, data from the first in a sequence of NNSS passes may be used to normalize the prediction of median range correction to conform to the actual conditions at that time. The scaling used along the latitudinal intervals for this pass would then be used to adapt the median along the path at the time of the next NNSS pass. The first pass may be considered a representation of a local ionospheric measurement and the subsequent passes may represent system measurements, such as a radar system measuring the range to a target. The error δR_a, can be compared to the error δR_m, to determine the effectiveness of the adaptive modeling procedure. This may be repeated, using each pass to adapt the model and comparing the predictions of the adapted model at the time of subsequent NNSS passes with the actual observations.

Some of the effects of using this procedure to specify refractive errors in daytime can be seen in Figure 2 for the quiet period in December 1975. The upper set of curves illustrate, on a logarithmic scale, the range correction that the system would have made along the track of an NNSS pass at 1240 LT on 12 December as determined from:

(1) the NNSS observations themselves, dotted line,

(2) the original median predicted by climatology, dashed line,

(3) the median scaled by the prior NNSS pass at 1120 LT, solid line.

The lower set of curves are on a linear scale and represent the absolute value of the residual range error occurring:

(1) using the median from climatology, δR_m, dashed line,

(2) using the adapted median, δR_a, solid line.

The gradients within the predicted median do not match those of the NNSS observations, creating large errors in some regions, but these are reduced significantly by the adapted prediction. Note, however, that using all of the information along the 1120 pass predicts local features which are either absent or displaced at the time of the next pass. Similar effects, observed during the October 1974 period are shown in Figure 3 for the daytime hours of 12 October. The observed values of radar range correction along the latitudinal track of consecutive NNSS passes at 0920, 1040, and 1550 LT, solid lines, rapidly become enhanced with respect to the predicted monthly median, dashed lines, for these local times. If all of the information along the 0920 LT pass were used to scale the median in order to better predict the 1040 LT ionosphere, and similarly the 1040 pass were used to specify the 1550 ionosphere, two effects would occur. First, since the general enhancement persists over several hours, the systematic bias of prediction would be reduced. Second, since major local features with amplitude of about 10 percent have either moved in space or have changed character with time, there is an additional error that indicates smoothing may be necessary in the adaptive modeling.

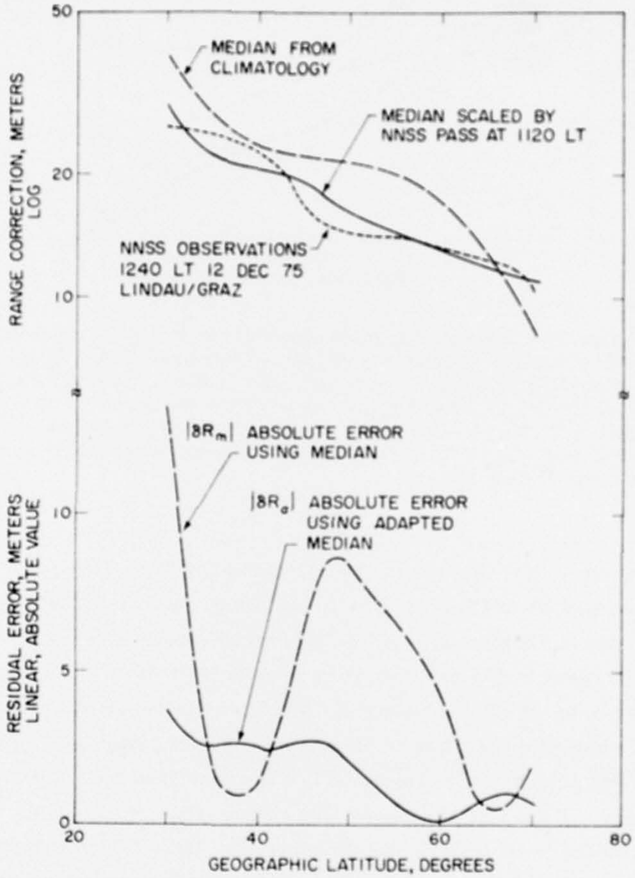

Figure 2. Adaptive Modeling Using Data From NNSS Measurements. The first pass at 1120 LT is used to scale the predicted latitude variation of the range correction at 1120 LT and then the scaled values are predicted forward to 1240 LT. The envelope of the absolute error using the adapted median is significantly less than using just the monthly median. Note that local features along one pass do not match local features of the other but that both have a consistent latitude variation quite different from that of the median

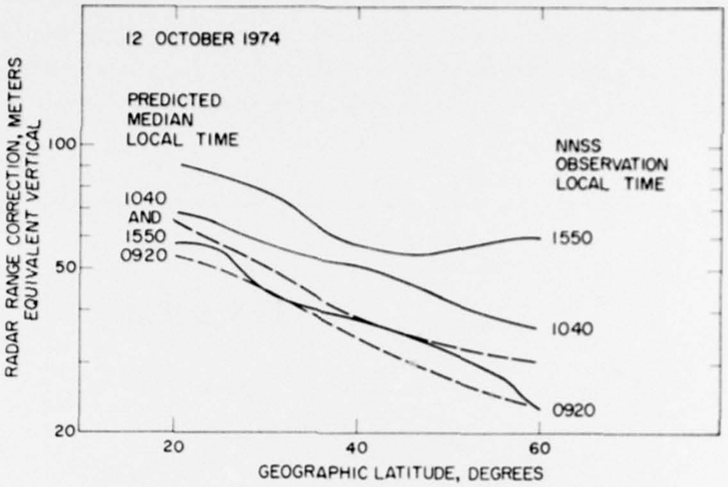

Figure 3. General Enhancement of the Range Corrections Over a Wide Latitude Range on 12 October 1974. The systematic bias between prediction and observation could be removed by adapting the median prediction with simple scaling factors. Local features of about 10 percent amplitude should be filtered out if the adaptions are spaced an hour or two apart

During the early morning hours of this enhanced day, (12 October) the ionosphere was depressed below the expected median in some regions, Figure 4. By 0400 LT there was a deep trough in TEC centered near 49°N Geographic (L≈4) and a diffuse enhancement in the plasmapause region near 40°N (L≈2.7). At 0640 LT these had both moved southward about 2° and the relative depth of the trough had decreased while the plasmapause enhancement had increased. The smoothed presence of these features may be discerned in the expected monthly medians derived from climatology. Note that the persistent depression of observed values during this night was not carried into the sunlit hours; by 0920 LT the observations were almost at the expected values. This is consistent with a previous study of the temporal variability of radar range error at a fixed station, in which it was shown that useful predictions could not be made across the sunlit terminators (DuLong).[5]

The early morning of 12 October 1974, was a relatively quiet period preceding the magnetic disturbances that affected the major portion of the October sample. The features observed during this period were also observed for each of the late afternoon through early morning periods of the quiet sample from December 1975. In the late afternoons of each of the December days there is an enhanced region near 50°N (L≈3.5) that is a well developed, persistent feature, shown in the upper set of curves in Figure 5. By backtracking from 2000 LT in the central set of curves, where the trough in TEC near 55°N ($L \approx 5$) can be identified each day, this feature in the December afternoon can be identified as a plasmapause enhancement of TEC. The lower set of curves in Figure 5 show that both the plasmapause enhancement and the trough persist into the early morning hours, as was also observed in Figure 5 for the October day.

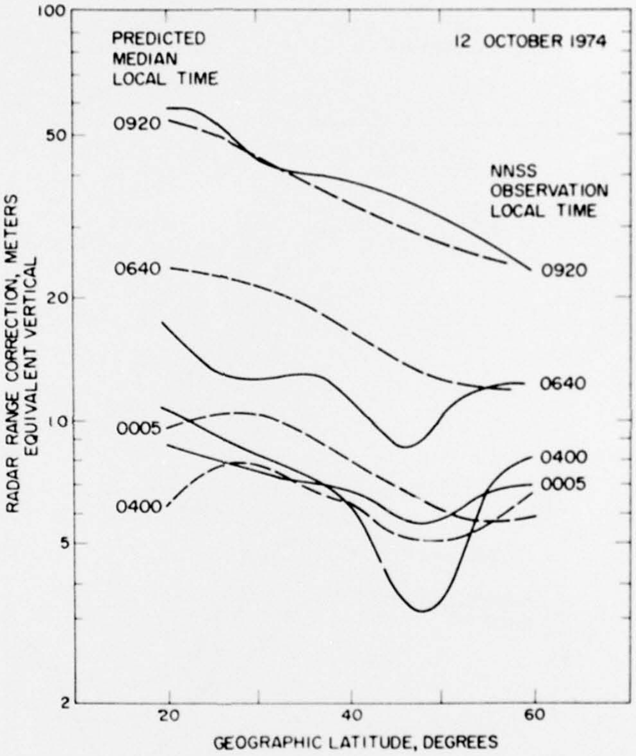

Figure 4. Sample of the Effect of the Trough on Electron Density, Seen Near 49°N Latitude on 12 October 1974, on the Expected Range Correction for a 425 MHz Radar. Predictions adapted for this feature were valid over several hours on this night. Contrast the general depression with respect to the predicted median to the general enhancement seen the following morning (Figure 3)

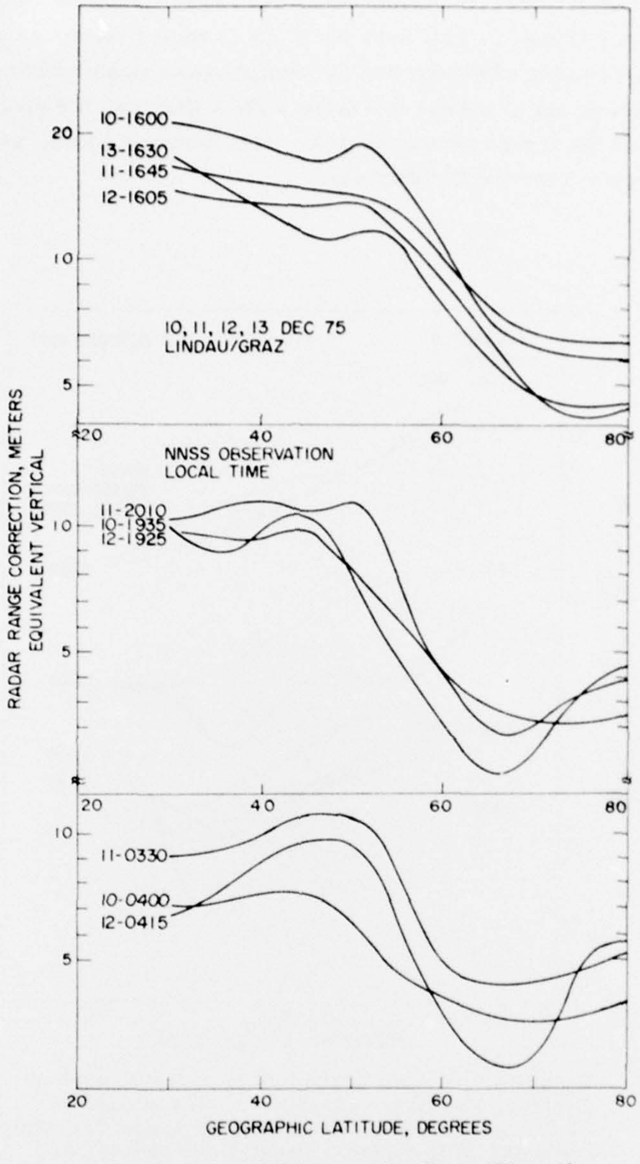

Figure 5. Sample of Consecutive Days When the Observations of NNSS Showed that the Position and Characteristics of the Trough Near 65°N Latitude and the Plasmapause Enhancement Near 50°N Latitude Could be Specified From Hour-to-Hour and Day-to-Day. Adapted predictions scaled from these observations could reduce the error of range correction by several meters

As further illustration of what may be encountered, consider the field of view of a hypothetical radar situated at 80°W. Long., 40°N. Lat., (Figure 6). The range correction along a latitudinal swath near the western horizon can be determined from NNSS passes observed at Boulder, Colorado, as shown in the sample from October 1974. In actual system use, these would reflect the increase in slant

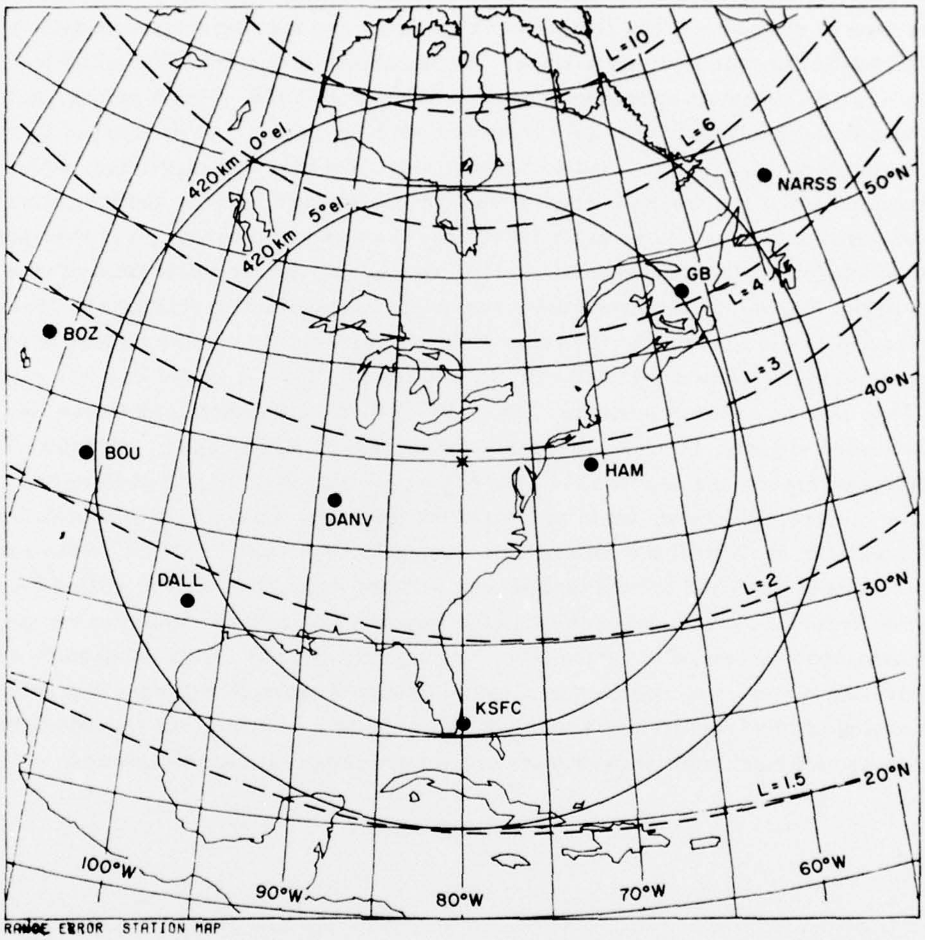

Figure 6. Coverage Diagram of a Hypothetical Radar That Illustrates the Need to Determine How Data From One Part of the Field of View May Best be Used to Adapt Predictions for the Remaining Portion. Continuous measurements of total electron content derived from ATS-3 observations along the eastern seaboard can be compared to NNSS observations made at mid-continent

thickness of the ionosphere as elevation angle decreased, but here it is convenient to stay with equivalent vertical values to be consistent with the reduced NNSS data. Now the question that arises is whether adapted features can be mapped across the entire field of view. Using single station TEC measurements obtained using the VHF beacon on the ATS-3 geostationery satellite at Narssarssuaq, Greenland; Goose Bay, Labrador; Hamilton, Massachusetts; and Kennedy Space Flight Center, Florida, it is possible to construct a similar latitudinal swath near the eastern horizon of the radar. The features of this swath can then be compared with the NNSS data near the western horizon. A comparison of the data in L value and local time for 3 sequential nighttime passes on 12 October 1974, a quiet period, and 3 sequential daytime passes on 13 October 1974, a magnetically disturbed period, are displayed in Figures 7 and 8, respectively. On the quiet night, the sequence of development of the trough in local time near the eastern horizon and its character and position in L value are reproduced near the western horizon. It is then possible to conclude that it would have been useful to map it over the whole field of view. In contrast, during the disturbed day a large enhancement of the ionosphere developed over the eastern portion of the radar field of view, but no similar feature occurred in the western portion. At 1100 LT on 13 October, TEC at Goose Bay was already higher than at adjacent latitudes. By 1200 LT TEC at Hamilton and Goose Bay increased slightly, but at Narssarssuaq it increased significantly. At 1500 LT TEC at Narssarssuaq had decreased to the value observed at 1100 LT; at Hamilton there was a further decrease, while at Goose Bay there was an extreme enhancement. On the western horizon of the radar there was an increase near 1200 LT in the northern coverage of the NNSS passes that agrees with the enhancement seen at that local time at Narssarssuaq, but nothing in the western data is comparable to the major enhancement observed at Goose Bay. During such greatly disturbed periods adaptive modeling would be of most use to a system but this example suggests that extensive mapping of local features in either latitude or longitude should not be undertaken without sufficient knowledge of their spatial and temporal characteristics.

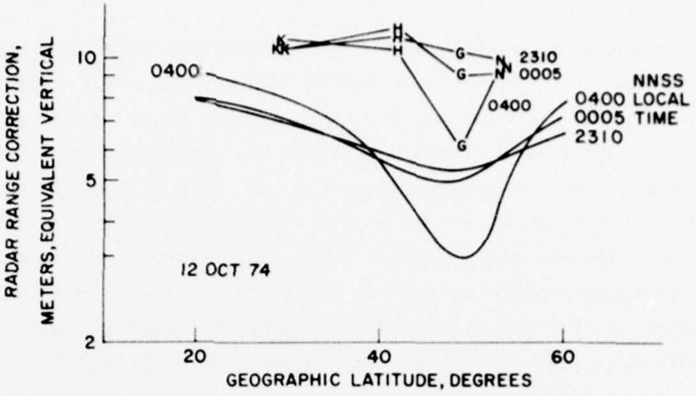

Figure 7. Development of the Trough Along the Eastern Seaboard, Determined From ATS-3 Observation at Narssarssuaq, Goose Bay, Hamilton, and Kennedy (N, G, H, and K) Compared With the Development Over the Mid-Continent as Determined From NNSS Observations. For this quiet night, large features may be mapped in local time and magnetic coordinates over the entire radar field of view

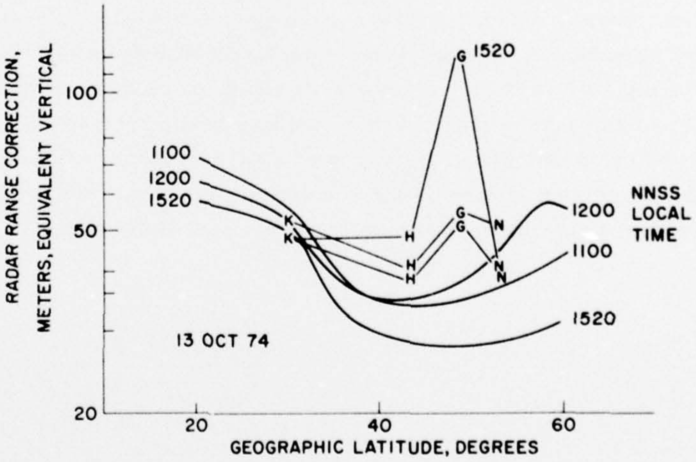

Figure 8. Same Coverages as Figure 7. For this daytime sample there was a very large enhancement of the ionosphere at high latitudes that was confined to the eastern segment of the field of view. During such periods, features could not be adapted across the entire field of view

4. CONCLUSION

Actual observations made with the Navy Navigation Satellite Systems (NNSS) satellites have been used to test a technique which would adapt maps predicting ionospheric refractive effects over the field of radar or navigation systems. In this adaptive technique each NNSS pass is used to scale local features into the monthly median maps. Each adapted map is then used to predict the local behavior of the refraction correction and the results compared with ensuing NNSS passes.

Systematic changes which represent the daily response of the local ionosphere to solar-terrestrial conditions, such as the general enhancement seen over the Boulder region on 12 October 1974, are usefully predicted by this technique but with the restriction that a prediction should not be carried across either sunlit terminator as this could increase error.

During quiet geomagnetic periods, those local features with large geophysical scale size and a consistent identification in climatology, such as the nighttime trough and the plasmapause enhancement, seen so persistently in the 10-13 December TEC observations from Europe, may be profitably tracked by local measurements and indeed may be usefully extended over the field of view. During the daytime some local features may be as large in amplitude but so transitory in either space or time that they are not observed on subsequent passes. In this case it is better to smooth these unknown features prior to adapting the median maps.

As is well known, during disturbed geomagnetic conditions some local features may be very dynamic. Therefore, they must be closely specified in the adaptive technique during such periods. Moreover, very large changes in the ionosphere can occur in constrained portions of the coverage area, such as the intense enhancement observed on 13 October 1974 over the eastern seaboard of North America but not at the mid-continent stations. Such features must be carefully defined in space and time and can not be extended beyond the region of observation.

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