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Correlation Distance of Mean Daytime Electron Content

JOHN A. KLOBUCHAR
J.M. JOHANSON

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AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

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In the total electron content (TEC) monitoring station network, ~~operated by the Air Weather Service,~~ an important parameter is the required number of stations for a given percentage improvement over the use of monthly median predicted values. Using data from nine TEC stations, taken a pair at a time, ~~we computed~~ values* of correlation coefficient for the 10 to 16 hour local time period when the diurnal values of TEC are generally highest. Little consistent seasonal differences were found in the correlation coefficient values. Thus

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simple linear relations between station separation and correlation coefficient were chosen for stations having approximate north-south and east-west spacings. For a 50 percent improvement in TEC prediction over a monthly median value, TEC monitoring stations must be spaced approximately 2400 km in longitude and 1600 km in latitude. These values agree reasonably well with previous studies of the correlation distance of the ionospheric parameter f0F2.

Preface

In the compilation of data requisite to this study, several different experimenters have been responsible for collections from various stations. The authors gratefully acknowledge the following: TEC data from Stanford and Edmonton, provided by A. V. daRosa; from Urbana, by K. C. Yeh; from Aberystwyth, by L. Kersley; from Narssarssuaq, by I. Mikkelsen: and from Jamaica, by P. Chin. Discussions with C. Rush have also been of great assistance. To all of these colleagues, the authors express a deep appreciation. Finally, the continued interest and encouragement of J. Aarons in this work is acknowledged with many thanks.

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1. INTRODUCTION

With the increasing positional accuracy requirements of military navigation and satellite ranging systems, the ionospheric parameter total electron content (TEC) is becoming of greater importance because it is directly related to the group delay that the ionosphere imposes upon the RF signal propagation time. The Air Weather Service, Space Environmental Support System,[1] updates predictions of the TEC parameter for operational military systems using near-real-time TEC data from a network of stations located, for the most part, in the northern mid-latitudes. In this report, we will describe the results of efforts to determine the correlation distance of TEC measurements. The results of this study are important for determining the required geographic spacing of TEC monitoring stations for a given percentage improvement at a location where TEC predictions are

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(Received for publication 12 August 1977)

[1] Flattery, T.W., and Ramsay, A.C. (1975) Derivation of total electron content for real time global applications, in Effects of the Ionosphere on Space Systems and Communications, J.M. Goodman, Ed., U.S. Government Printing Office, Washington, D.C.

required. Preliminary work on TEC correlation distance was done by Rao et al[2] and daRosa.[3]

The terms "station spacing" and "correlation distance" used throughout this report refer to distances between subionospheric locations. A subionospheric location is the point below which the slant ray from the station to the satellite intersects a fixed mean ionospheric height, generally 420 kilometers.

In this study, we have assumed that the monthly mean prediction of TEC was correct. In the northern mid-latitudes this has been generally borne out by the results of Hawkins et al[4] and by Mulkern.[5] Of interest here, is the correlation of the day-to-day variability of the TEC, particularly during those times of day when the highest TEC values occur; hence the period when the greatest ionospheric effects influence operational military systems. Accordingly, we have chosen the period from 10 to 16 hours local time to perform correlations of the day-to-day variability at pairs of stations. We refrained from using TEC values over longer intervals of a day, in order to avoid inadvertently correlating diurnal shape changes at pairs of stations. The 24-hour term predominates in a TEC cross correlation power spectra. Therefore, the diurnal correlation will be high, even for very large station spacing, due simply to similar 24-hour behavior of TEC at pairs of stations.[6] The correlation of only the midday component of TEC at pairs of stations was studied, as the absolute values of the day-to-day difference from median values are also generally greatest during this period. A few values of correlation coefficient were computed for nighttime periods as a matter of interest, though the TEC is generally low during the nighttime hours. Daytime values only are used, however, to determine the required station spacing for a given percentage improvement of predictions of TEC.

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[2] Rao, N. Narayana, Youakim, M.Y., and Yeh, K.C. (1971) Feasibility Study of Correcting for the Excess Time Delay of Transionospheric Navigational Ranging Systems, SAMSO TR71-163, Technical Report No. 43, SAMSO, Los Angeles, California.

[3] daRosa, A.V. (1974) Recent results from satellite beacon measurements, Space Research XIV, Akademie-Verlag, Berlin, pp. 209-226.

[4] Hawkins, G.S., and Klobuchar, J.A. (1974) Seasonal and Diurnal Variations in the Total Electron Content of the Ionosphere at Invariant Latitude 54 Degrees, AFCRL-TR-74-0294.

[5] Mulkern, F.A. (1976) Comparison of Predicted Monthly Medians of Total Electron Content with Field Observations, AFCRL-TR-76-0158.

[6] Soicher, H. (1977) Spatial Correlation of Transionospheric Signal-Time Delays, ECOM-4483, U.S. Army Electronics Command, Fort Monmouth, New Jersey.

2. DATA BASE

Continuous measurements of the TEC parameter have been available only since the mid-1960's, as the experimental technique for determination of TEC relies upon the availability of appropriate VHF signals transmitted from geostationary satellites. Such signals from satellites of opportunity are monitored for the changes in Faraday rotation, which can be simply related to equivalent vertical TEC values. The TEC derived from Faraday rotation of VHF radio waves from geostationary satellites is not equal to the group delay of the ionosphere, the parameter normally required by military navigation and satellite ranging systems. A recent study by Fritz,[7] however, has shown that this difference is small during the diurnal peak TEC hours. Also, little actual group delay data are available from geostationary satellites. Faraday rotation data are available from several American longitude sector stations beginning in the late 1960's.

A chain of TEC monitoring stations along an approximate 70 degree west longitude meridian was instrumented in the early 1970's in order to study the latitudinal dependence of magnetic storms; for example Mendillo et al.[8] During the solar maximum years of 1968 and 1969, another chain of TEC monitoring stations was operating in the northern mid-latitudes which extended from Wales, United Kingdom in the east, to Stanford, California in the west. Stations along this chain were separated by no more than 20 degrees of geomagnetic latitude. Figure 1 illustrates the locations of the TEC monitoring stations and the mean subionospheric intersection locations.

Data used in obtaining the cross correlations of TEC from pairs of stations along the longitude chain of stations came from the solar maximum period of 1968 and 1969. Cross correlations of TEC from pairs of stations located along the approximate 70° meridian were calculated for data taken in 1972 and 1974, as many of these stations dis not become operational until after the 1968, 1969 solar maximum. All cross correlations were computed using TEC values for the same local time for the same day at pairs of stations.

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[7] Fritz, R.B. (1976) ATS-6 Radio Beacon Electron Content Measurements at Boulder, July 1974-May 1975, Report UAG-58 World Data Center A, Boulder, Colorado.

[8] Mendillo, M., and Klobuchar, J.A. (1975) Investigations of the ionospheric F region using multistation total electron content observations, J. Geophys. Res. 80(No. 4):643-650.

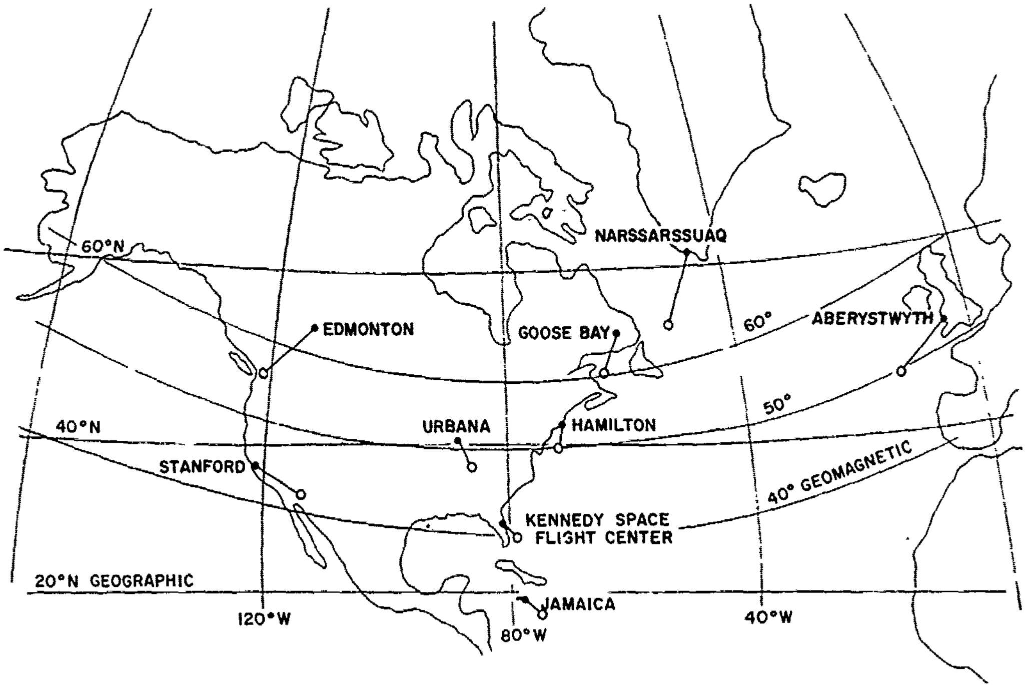

Figure 1. Location of Stations and Their Mean Ionospheric Points Used in TEC Correlation Study

3. SIGNIFICANCE OF CORRELATION COEFFICIENT

It has been pointed out by Gautier et al[9] that the percentage improvement, PI, in the prediction of the parameter f0F2 is related to the correlation coefficient r by:

$$PI = 100[1 - (1 - r^2)^{1/2}] \quad ,$$

assuming a Gaussian distribution. This same relation applies to the TEC uncertainty reduction. A graph of this relationship, illustrated in Figure 2, shows that a 50 percent reduction of TEC uncertainty requires a correlation coefficient of 0.87. That is, if measurements of TEC at a monitoring station are to be used to reduce the TEC uncertainty at a second location by 50 percent, the two locations must exhibit a TEC correlation of 0.87. A correlation coefficient of 0.7 between TEC values taken at the same local time at pairs of stations will result in an improvement, as seen in Figure 2, of only 29 percent in prediction of TEC at one

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[9] Gautier, T.N., and Zacharisen, D.H. (1965) Use of Space and Time Correlation in Short-Term Ionospheric Predictions, Conference Record, First Annual IEEE Communications Convention.

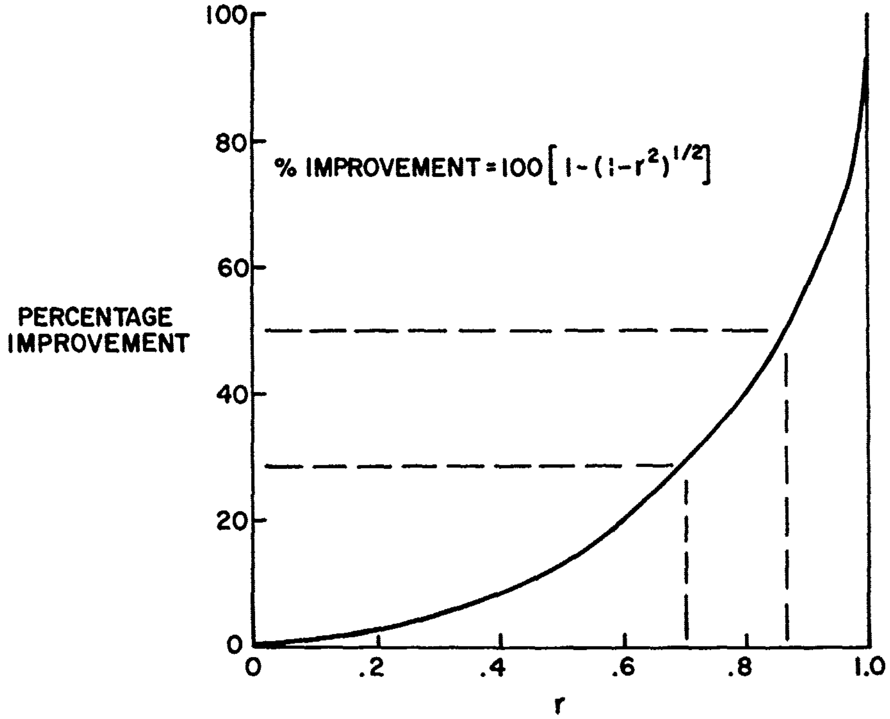

Figure 2. Percentage Improvement vs Correlation Coefficient r

station using data from the second station. This value of r = 0.7, corresponding to a 29 percent uncertainty reduction, is defined here as the "correlation distance." If a 29 percent improvement over the monthly median TEC prediction is required at a given location, then one of the following conditions must be satisfied:

1. If both the station and the location of interest are at the same latitude, then the station must be no greater than one longitudinal correction distance to the east or west of the location.

2. If both the station and the location of interest are to be located along the same meridian, then the station must be available within one latitudinal correlation distance to the north or south of the location of interest.

3. In the more general case, the station must be located within an area defined by an ellipse which is centered on the location of interest, with its major axis defined by twice the longitudinal correlation distance and its minor axis equal to twice the latitudinal correlation distance.

Thus, the required station spacing can be as great as twice the resultant correlation distance. Total electron content data from pairs of stations at various separations were used to determine the limits of this correlation ellipse which satisfy conditions 1 and 2 above.

4. CORRELATION RESULTS: LONGITUDE SEPARATION

The correlation coefficient for the 10 to 16 hour local time period for pairs of stations was calculated for each month and these monthly values were averaged, in order to obtain a seasonal mean value. Figure 3 is a plot of r for each season versus station-pair longitude separation distance in kilometers. The seasons are indicated as W for the winter months of November, December, January and February; S for the summer months of May through August; and E for the equinox months of March, April, September and October. Note in Figure 3 that there is

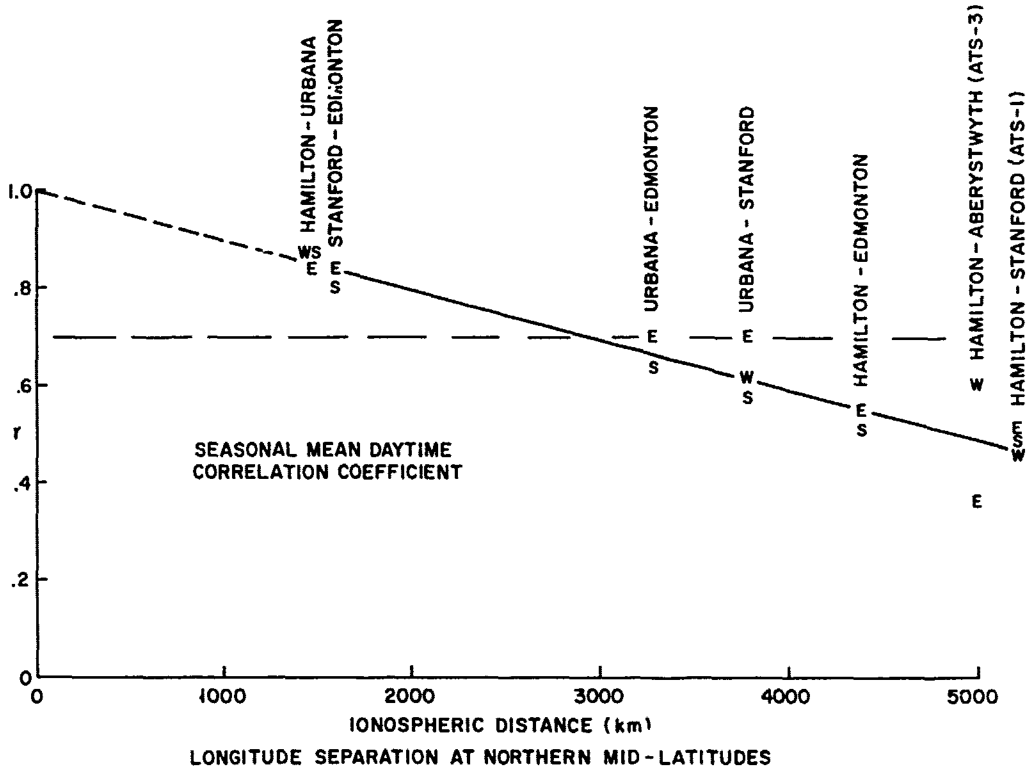

Figure 3. Correlation Coefficient vs Station Longitude Separation in Kilometers

no strong seasonal dependence on r for different station separations. Rush[10, 11] showed that f0F2 exhibited an East-West correlation distance, corresponding to r = 0.7, significantly greater in the equinox months as compared to summer. Winter gave the poorest E-W correlation distance of all seasons, approximately one third the equinox value in Rush's study. In Figure 3, with the exception of two station pairs, the TEC correlations were greatest also during the equinox months. Winter values are certainly not the lowest, except for one station pair.

With the lack of a clear seasonal dependence on r at various pairs of TEC monitoring stations, only one linear dependence of r upon ionospheric longitude separation distance was drawn in Figure 3, and this linear dependence can be seen to have little seasonal change with available data. From Figure 3, the r = 0.7 correlation distance in longitude is approximately 2900 km which corresponds to 26*cos(lat) degrees of longitude. This distance agrees well with the results of Rush[10] for f0F2 for the equinox season; but, it is considerably greater than the correlation distance of approximately 1150 km which Rush found for the winter months. Our lack of TEC data at station spacings less than 1500 km longitude separation, and between 1600 and 3200 km, handicaps the present results as compared with Rush's work in which data from 32 ionosondes were available.

In an attempt to see if a clear, seasonal variation of r could be found for stations of relatively close spacing, a plot of the monthly values of r for the year 1969 was made for the Hamilton, Massachusetts and Urbana, Illinois pair of stations, with an ionospheric intersection spacing of 1500 km as shown in Figure 4. Also in Figure 4 is the seasonal behavior of r for the nighttime hours 23-03 local time. The only seasonal dependence in the daytime TEC correlation is shown by the lower values during the months of April, May and June with highest values in late winter, the month of July and the autumnal equinox months. In Figure 5, the seasonal dependence of r between the Stanford, California and Edmonton, Alberta pair of stations also is maximum in the autumnal equinox months. Figures 6 and 7 show that the highest values of r for the Urbana-Stanford pair and for the Hamilton-Stanford pair also occur during the months of September and October. No clear difference between the value of r for daytime TEC, during summer and winter months, is apparent in Figures 4, 6, and 7. In Figure 5, the values of r for the daytime data of the three available winter months are considerably lower than during the other seasons.

The correlation coefficient for nighttime TEC values from 23 to 03 hours local time was computed as a matter of interest, though these values are not of great

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[10] Rush, C.M. (1972) Improvements in Ionospheric Forecasting Capability, AFCRL-72-0138.

[11] Rush, C.M. (1976) An ionospheric observation network for use in short-term propagation predictions, Telecommunication Journal 43(No. 8):544-549.

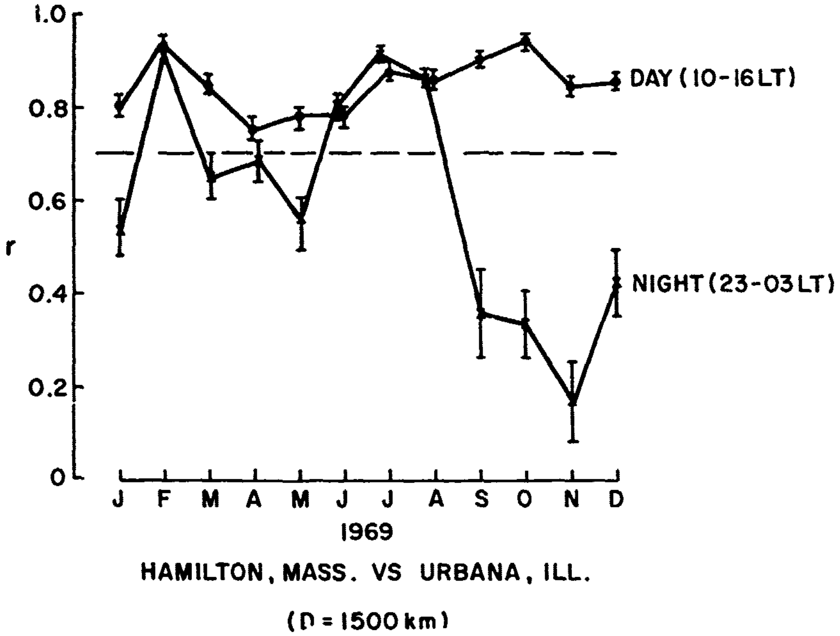


Figure 4. Correlation Coefficient vs Month of the Year 1969 for Day and Nighttime TEC Periods for the Hamilton, Mass. - Urbana, Ill. Station Pair

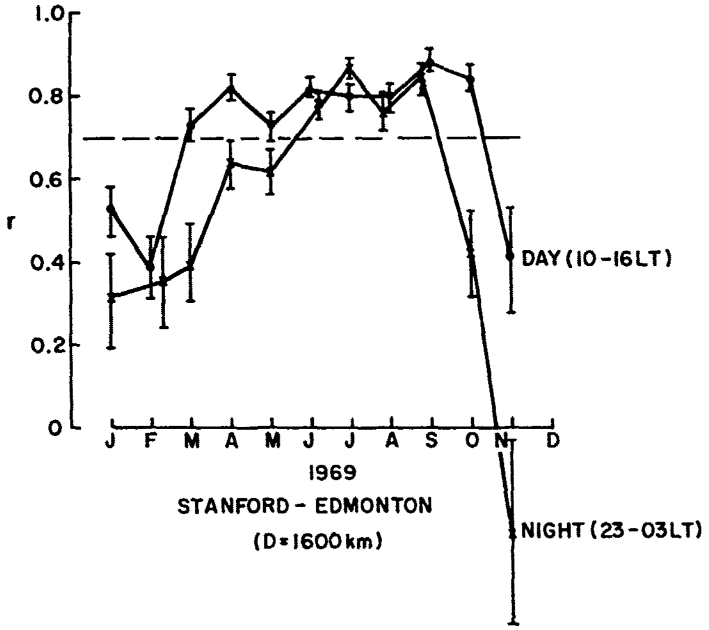


Figure 5. Correlation Coefficient vs Month of the Year 1969 for Day and Nighttime TEC Values Measured at Stanford, California, and Edmonton, Alberta, Canada

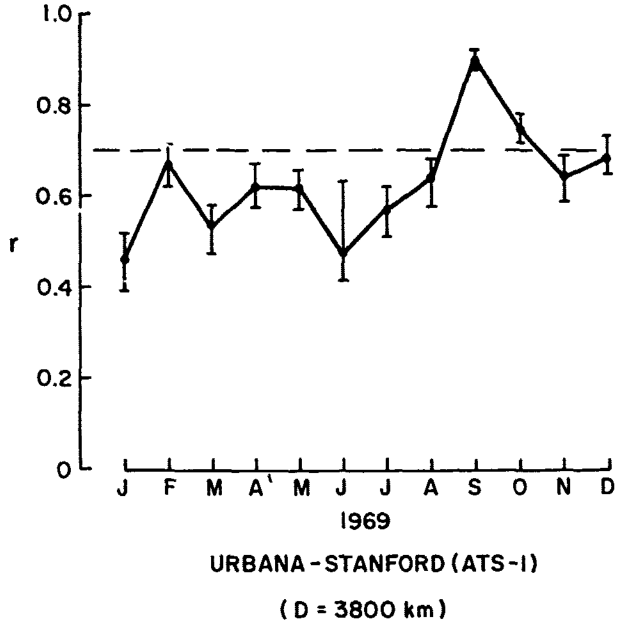


Figure 6. Correlation Coefficient vs Month of the Year 1969 for TEC Values Measured during the 10-16 Local Hour Period at Urbana, Ill., and Stanford, California

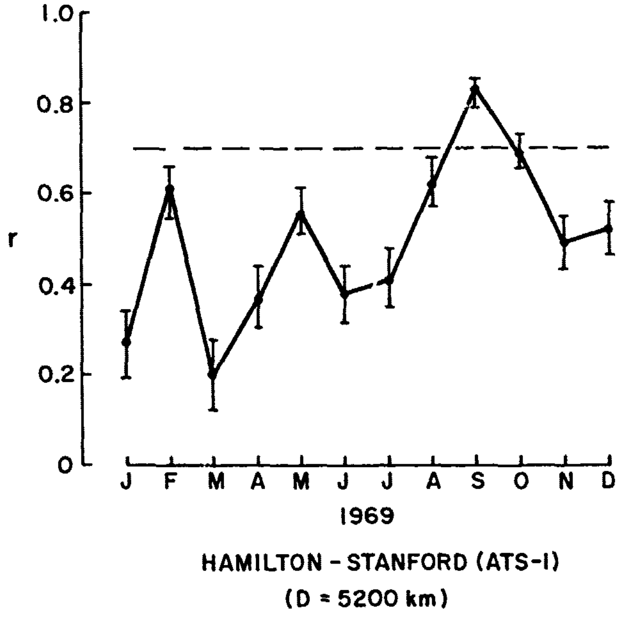


Figure 7. Correlation Coefficient vs Month of the Year 1969 for Daytime TEC Values Measured during the 10-16 Local Hour Period at Hamilton, Mass., and Stanford, California

importance in predictions of TEC due to the much lower nighttime absolute values of TEC. These values of r, plotted for the station pairs at 1500- and 1600-km spacing as shown in Figures 4 and 5, respectively, are highest during the summer months. For the east-west spacing of the Hamilton-Urbana pair, shown in Figure 4, the nighttime values of r are decidedly lowest from September through December. The Stanford-Edmonton station pair has a fairly large north-south geographic component, exhibiting low values of r during the nighttime of all months from November through March. Again, no clear-cut nighttime seasonal behavior in r can be deduced from the available data base.

5. CORRELATION RESULTS: LATITUDE SEPARATION

While data for determining longitude correlation distance were available during the 1969 year of solar maximum, the stations along the 70 degree longitude meridian, used for determining a value of latitude correlation distance, did not become operational until late 1971 in the case of Goose Bay, Labrador, and until 1974 in the case of the Kennedy Space Flight Center, Florida. Thus, it was not possible to make an estimate of correlation distance based upon solar maximum data. Figure 8 illustrates the seasonal mean values of correlation coefficient as a function of station spacing in latitude. Again, as with the longitude separation case, there is no clear seasonal dependence in values of r for various station separations. A single linear curve has been drawn in Figure 8 to represent the average dependence of r upon station latitude separation. The $r = 0.7$ value of correlation distance is approximately 1800 kilometers. This again agrees well with the over-all annual value of 1600 km obtained from averaging the three seasonal values in Rush[11] for the same value of r. Figures 9 through 12 illustrate the monthly daytime values of r for different station separations from 1300 to 4000 kilometers. For the closest two spacings, shown in Figures 9 and 10, values of r for each month for the nighttime hours of 23 to 03 local time are also plotted. The seasonal behavior of the daytime values of r indicate no consistent pattern. The r value is lowest in September for the Hamilton-Goose Bay pair, as shown in

Figure 9, yet highest for the months of August, October and November for the Hamilton-Kennedy pair of stations. Values of r for the nighttime hours are generally lowest during the winter months, as was the case for stations separated in longitude.

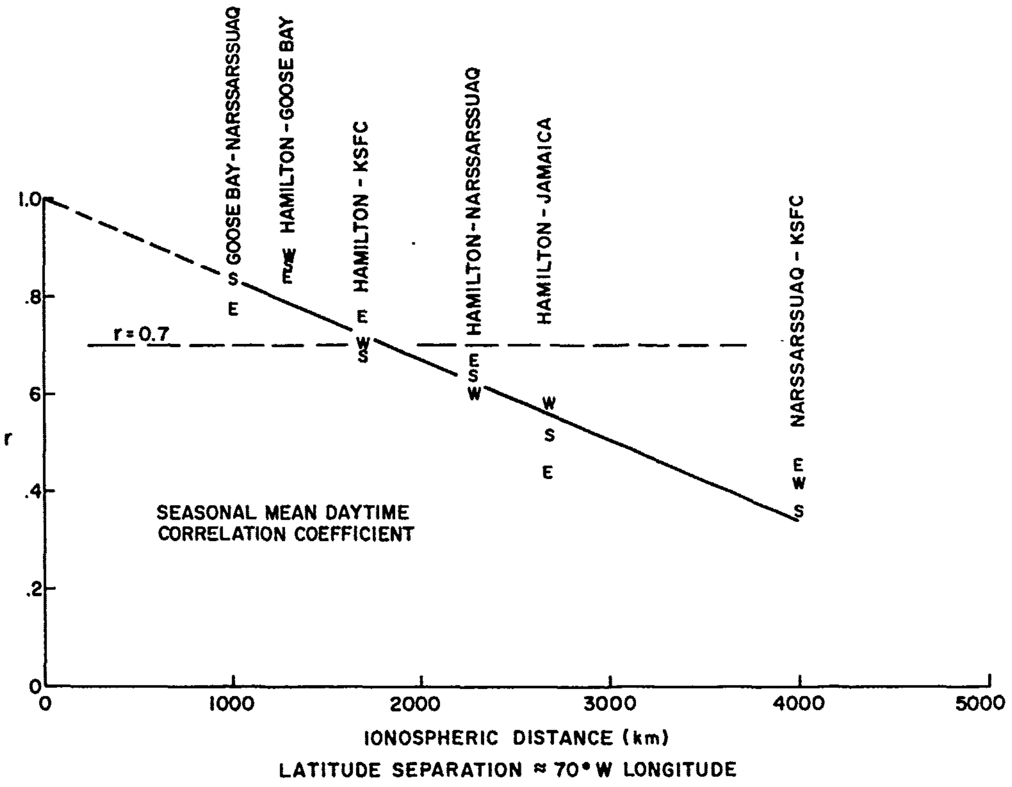


Figure 8. Correlation Coefficient vs Station Latitude Separation in Kilometers

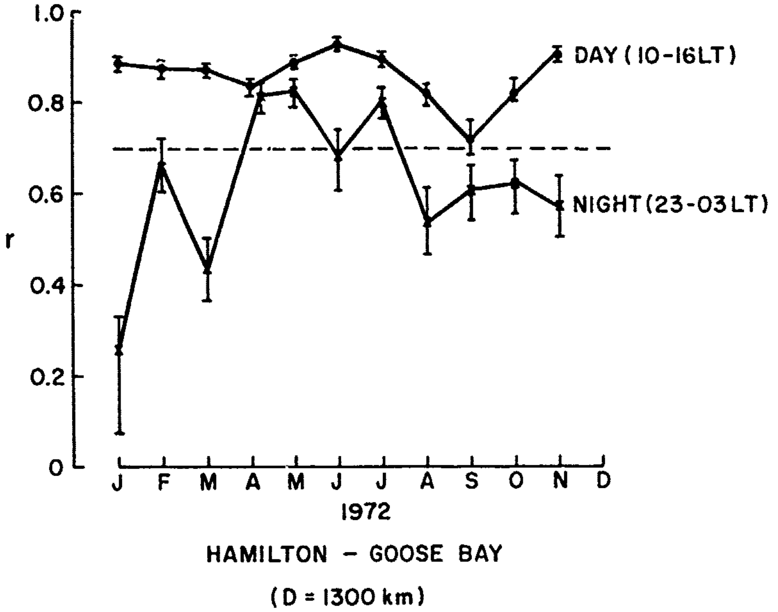


Figure 9. Correlation Coefficient vs Month of the Year 1972 for Day and Nighttime TEC Values Measured at Hamilton, Mass., and Goose Bay, Labrador

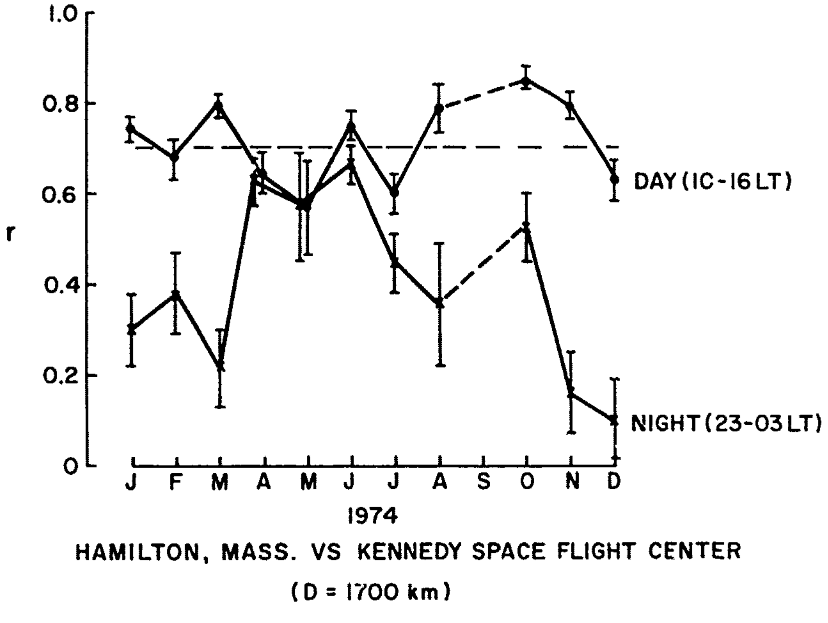
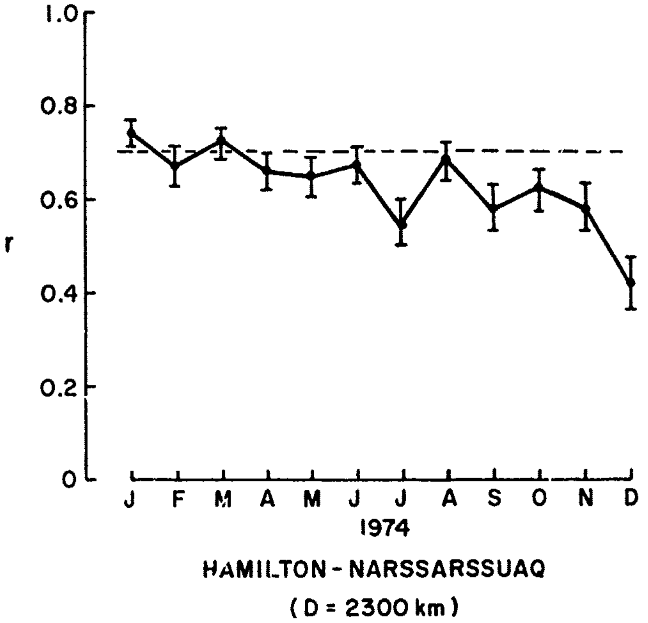


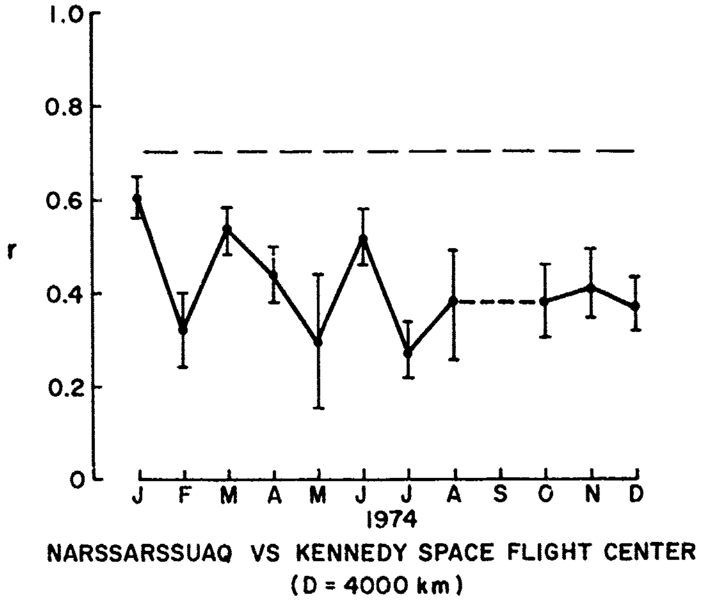
Figure 10. Correlation Coefficient vs Month of the Year 1974 for Day and Nighttime TEC Values Measured at Hamilton, Mass., and Kennedy Space Flight Center, Florida



HAMILTON - NARSSARSSUAQ

(D = 2300 km)

Figure 11. Correlation Coefficient vs Month of the Year 1974 for Daytime TEC Values Measured during the 10-16 Local Hour Period at Hamilton, Mass., and Narssarssuaq, Greenland



NARSSARSSUAQ VS KENNEDY SPACE FLIGHT CENTER

(D = 4000 km)

Figure 12. Correlation Coefficient vs Month of the Year 1974 for Daytime TEC Values Measured during the 10-16 Local Hour Period at Narssarssuaq, Greenland and Kennedy Space Flight Center, Florida

6. DISCUSSION

The spatial and temporal variability of the F region remains of great research interest.[12] It is unlikely that short term solar EUV changes can produce the observed spatial TEC variability; thus, we are left with neutral wind, composition and electrodynamic effects. In our study, we did not attempt to separate magnetically quiet and disturbed periods because in operational use the required station spacing for prediction improvements would have to be chosen for all geomagnetic conditions. The lower correlation distance for stations at nearly the same longitude, but separated in latitude, could likely be due to the different day-to-day strength of the neutral wind in the F region as a function of latitude. The neutral wind, normally blowing away from the subsolar point, can drive ionization up or down in altitude along magnetic field lines to regions of lower or increased loss, which would significantly change TEC. Different strengths of the equatorial electrojet which transport ionization from the magnetic equator to the low midlatitudes can also change the TEC as a function of latitude. Kane[13] suggested that erratic neutral winds originating in the polar regions may produce large scale ionospheric turbulence which may act in a random way in different geographical locations. This turbulence may be a major contributing factor in limiting the TEC correlation distance in both longitude and in latitude.

7. SUMMARY OF RESULTS

The correlation distance, defined as the distance where the correlation falls to 0.7, has been determined for pairs of TEC monitoring stations aligned along approximate east-west and north-south directions. A correlation coefficient of 0.7 implies that data taken at one station can be used to reduce the uncertainty in a TEC prediction at the second station by 29 percent. Station spacings of approximately 2900 km, and 1800 km gave correlation coefficients of 0.7 in the east-west and north-south directions, respectively, for TEC data taken during the 10 to 16 hour local time period. With the limited number of stations from which TEC data were available, no clear seasonal dependence of the correlation distance was found. The correlation coefficient for nighttime data taken between 23-03 hours local time was generally lower, especially during the winter season.

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[12] Rishbeth, H., and Kohl, H. (1976) Topical questions of ionospheric physics: a working group report, J. Atmos. Terr. Phys. 38:775-780.

[13] Kane, R.P. (1975) Day-to-day variability of ionospheric electron content at mid-latitudes, J. Geophys. Res. 80(No. 22):3091-3099.

The implications of these results, for station spacing in an Air Weather Service TEC monitoring station network, in the mid-latitudes, are as follows:

1. For a 29 percent TEC prediction improvement at a given geographic location, a TEC monitoring station must be located within approximately 2900 km or [26*cos(lat)] degrees of longitude of the required prediction location, and within approximately 1800 km or 16 degrees of latitude of the required prediction location. For the same percentage of TEC prediction improvement, the monitoring stations need be spaced at twice the correlation distance spacing.

2. For a 50 percent TEC prediction improvement, the correlation coefficient between pairs of stations must be 0.87. This value corresponds to a spacing between a TEC monitoring station and a given prediction location of 1200 km in longitude and 800 km in latitude.

3. For this 50 percent improvement, TEC monitoring stations are required every 2400 km or [22*cos(lat)] degrees of longitude and every 1600 km or 14 degrees of latitude. During periods when the correlation is lower, such as during winter nighttime hours, the required station spacing is much smaller. However, during those times the absolute values of TEC are generally near their diurnal and annual minimum values and the importance of a large improvement in prediction is minimum also. These results are summarized in Table 1.

Table 1. Required Monitor Station Spacing vs Midday TEC Prediction Improvement

Percent midday TEC prediction improvement (%)	Required monitor station spacing	
	Longitude [*cos (lat) degrees]	Latitude (degrees)
29	52	32
50	22	14

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