Statistics of Time Rate of Change of Ionospheric Range Delay

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BIOGRAPHIES

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ABSTRACT

The time rate of change of ionospheric range delay is a potentia! limitation in precise positioning using radio waves from Global Positioning System. (GPS), satellites in the single frequency c/a mode. Dual frequency GPS users with access to the p-code automatically correct for the effects of both the ionospheric range delay and its **rate of change.** Single frequency GPS users can use a simple algorithm for ionospheric range delay to place an absolute scale on their measuremants of c/a code minus carrier, to correct for the time rate of change of ionospheric range delay, but the inherent noisiness of the Ll code data can severely limit the single frequency ionospheric correction capability, es**pecially in** removing the effects of the rate of change of ionospheric range delay.

To investigate the statistics of ionospheric range-rate changes, dual frequency GPS data from stations in parts of the world representative of different ionospheric conditions was obtained from the International GPS Geodynamics Service, (IGS), network, managed by the Jet Propulsion Laboratory, (JPL). Values of dual frequency, **differential carrier phase were computed at one minute intervals and then were high pass filtered to remove** long term changes. Relative ionospheric range delay changes over time intervals of 1, 2, 5, and 10 minutes duration were then computed and the statistics of these rates of change of ionospheric time delay were compiled for **different** times of day, viewing direction, and various conditions of magnetic activity. The largest rates of change of ionospheric range delay **were** observed in the auroral region during periods of high magnetic activity.

INTRODUCTION

One of the potential limitations to ionospheric corrections for the proposed Wide Area Augmentation System, (WAAS), is in how rapidly ionospheric range delay corrections must be made in an operational WAAS. Large scale, slowly changing, ionospheric features can be removed by use of a network of dual frequency ionospheric monitoring stations, (El-Arini, **et. at.,** 1993, 1994). However, rapidly changing ionospheric range delays are generally small scale, and are due to phase fluctuations which occur when the GPS signal passes through a region of irregularities in the ionosphere.

These irregularities produce short term phase fluctuations in the carrier of the radio waves which pass through them. The amplitude of the radio waves also is subject to fades, which can be as deep as 20dB, along with occasional signal enhancements. These effects are commonly called amplitude and phase scintillations. Ionospheric irregularities most often occur in the auroral zone, that part of high latitude region of the earth where charged particles coming from the sun directly impinge on the earth, causing visual aurora, and irregularities in the earth's ionosphere. The near-equatorial region, a belt of up to $\pm 30°$ either side of the magnetic equator, (Goodman and Aarons, 1990), produces the highest recorded scintillations, but generally only during the local evening hours, and in patchy regions of the sky, unlike in the auroral region where the spatial and temporal extent of irregularities can be much greater.

Wanninger, (1993), looked at the occurrence of GPS phase scintillation at the Kokee, Hawaii station, located somewhat north of the equatorial irregularity belt region. He found **a** significant occurrence of phase scintillation equator-wards of the Kokee station during the local nighttime hours, beginning about one hour after local sunset, and occasionally continuing until the following dawn period. His data was taken in 1992, which was on the declining phase of the current 11 year cycle of long term solar activity, but still a year having significant scintillation effects. The current solar minimum is expected to occur sometime in late 1995. Though Wanninger's 1992 data was taken at least two years after the current sunspot cycle maximum, which occurred in 19841990, this maximum was abnormally large, and 1992 was a year having a mean sunspot number more representative of an average solar cycle maximum.

In this paper the emphasis is on GPS observations from the CONUS, and the auroral region north of the CONUS, regions where the WAAS system likely will first be implemented, in order to quantify the magnitude of the short term changes in ionospheric range delay. Unfortunately, GPS data from these stations wag only available online beginning in late 1993, and continuing through July 1994, well down the current solar cycle, not representative of Solar cycle maximum conditions. However, extrapolations to solar maximum conditions can be made, but with an uncertain degree of confidence.

AVAILABLE GPS IONOSPHERIC DATA

In order to determine the statistics of ionospheric range-rate changes, dual frequency GPS data was obtained from the IGS network which provides an excellent opportunity **to** study the behavior of ionospheric range delays and their rates **of change** over a wide range *of* latitudes. The potential use of this data base in ionospheric research is extensive and has been described by Wanniger, (1993). The data base has already been utilized by Wilson, et. al., (1992) to generate global ionospheric maps. In addition, Wilson and Mannucci, (1993) used the IGS data base to estimate instrumental biases in the GPS receivers at the various IGS stations, as well as in individual GPS satellite transmitters. In this study, recent data from the IGS network has been obtained from a wide range of rep resentative mid-latitude and auroral locations in the northern hemisphere, including Ny Alesund Island and Tromso, Norway and several stations in the United States and in Canada.

The ionospheric data available from the IGS consists of 30 second values of carrier phase and group delay at both the GPS L_1 and the L_2 frequencies. From the available data it is possible to determine the statistics of these short term changes in delay. If time rates of change of ionospheric range delay are very large, and unpredictable, the residual range delays, even after correction, can still be unacceptable. On the other hand, if short term ionospheric range delay variations are found to be small, or if they change in an easily predictable manner over time, they will be easier to correct, and these predictable rates **of change** should not pose a problem in the correction process. Statistics of the percent occurrence of changes in ionospheric range delay are presented for **different** times of day, viewing direction and various levels of geomagnetic activity.

DATA PROCESSING PROCEDURE

The **data** used in this study was recorded from December 1993 through July 1994 at the IGS network locations illustrated in Figure 1 and listed below:

Iy Alesund Island	**78.8H.**	**11.8E**
Tromso, Iorvay	**69.71,**	**18.9E**

Fairbanks, AX	64.81, 147.5W
Yellowknife, NW. Terr.	62.31, 114.5W
Albert Head, B. C.	48.2N, 123.5W
St. John's, Newfoundland	47.4N, 52.7W
Westford, HA	42.4N, 71.5W
Goldstone, CA	35.1N, 116.9W
Richmond, FL	25.0N, 80.4W

All stations in the IGS network are equipped with GPS Rogue or Turborogue dual-frequency receivers which record both the differential carrier phase and the differential group delay from up to eight satellites simultaneously. To insure data compatibility, all stations in the network store the data in Receiver INdependent Exchange, (RKNEX) format. In this study, absolute values of ionospheric range delay were not required, since only short term rates of change of ionospheric range delays were needed. In order to isolate short term range delay changes, the differential carrier phase measurements were high pass filtered, with a filter having a cutoff of 15 minutes, to remove diurnal changes and changes induced by the changing satellite elevation angle which are relatively long term. These long term changes can be removed either by modeling, or by the use of dual frequency codeless ionospheric measurements from the WAAS network of stations. Short term changes in ionospheric range delay then were computed over time intervals of 1, 2, 5 and 10 minutes.

The Block II GPS satellites were switched to the a/s or anti-spoofing mode on February 1, 1994. Beginning at that time, the IGS receivers were operated in the codeless mode. Figure 2 shows examples of raw differential group delay and fitted slant ionospheric differential carrier phase data from Yellowknife, Northwest Territories, Canada for satellites operated in both a coded and a codeless mode. Note that the short term fluctuations in ionospheric range delay are seen readily on the differential carrier phase which is not significantly affected by multipath, or by a/s. Both in code and codeless operation it was possible to fit the differential carrier phase data to an absolute scale using the higher elevation portions of the differential group delay data, though, in this study, since only rate of change values are used, absolute values of ionospheric range delay are not necessary.

STATISTICAL RESULTS

Monthly statistics of time rates of change of ionospheric range delay have been produced separately for 4 different time intervals of the day for each station used in this study. Times were converted to local time, (LT), at the receiver station and were grouped as follows: 05-11 hours LT, 11-17 LT, 17-23 LT, and 23-05 LT.

Figures 3 illustrate an example of the raw differential carrier phase, and the high pass filtered data obtained from one GPS satellite pass received at Yellowknive, Northwest Territories, Canada. Note that the short term fluctuations have peak to peak magnitudes of up to f0.3 meters. Figure 4 shows how these fluctuations are resolved over different time intervals. Note that the 1 minute rates of change of ionospheric range delay, shown at the top of Figure 4, are the greatest, followed in order, by those of 2 minute, 5 minute and 10 minute intervals. There are virtually no variations at 10 minute intervals, indicating that short-term fluctuations of differential carrier phase predominate.

Figure 5 shows the statistics of the 1 minute and the 5 minute rates of change of ionospheric range delay. The results shown in Figure 5 are in the form of arithmetic probability plots. In this type of plot, changes in ionospheric range delay are plotted versus their probability of occurrence, in order to illustrate the shape of the distribution. A straight line indicates a "Gaussian" or normal distribution. The slope of the straight line is a measure of the standard deviation of changes about a mean value. Changes from a straight line are measures of the departures from a normal distribution, and normally occur near the very low and the very high probability regions of the plot. For all times of day at Yellowknife, the 1 minute rates of change of ionospheric range delay were higher than the 5 minute rates of change by a large factor, again clearly showing that the changes observed are due to very short period fluctuations in the ionosphere.

In order to be certain that the ionospheric range delay variations seen at Yellowknife were due to short term, irregular changes in the ionosphere, and not to either diurnal or elevation angle changes which occur during a pass, a comparison of high pass filtered and raw, unfiltered ionospheric range delay change statistics was done. The results are shown in Figure 6. Note that the mid-latitute station at Westford, MA has a very small occurrence of 1 minute changes, while the Yellowknife station, located under the auroral region, shows very high 1 minute changes in ionospheric range delay. In both cases the changes over a 15 minute period are simply due to the diurnal and elevation angle effects which are slightly higher at the Westford station. Thus, it is reasonable to look only at the high pass filtered data to determine the statistics of the range delay variations which cannot be modeled.

Figure 7 shows a comparison of rates of change of ionospheric time delay that occurred over a 1 minute period during the local nighttime hours at Yellowknife, Fairbanks, Westford, Albert Head and Richmond during December 1993. It is evident that these changes occur most frequently at Yellowknife and at Fairbanks. Both **of** these stations are located under the auroral region. Figure 8 shows ionospheric range delay rates for a one minute interval for the same stations for the daytime hours of 11-17 local time. Even during the daytime hours the range delay changes are significant at both Yellowknife and Fairbanks. This is because of the irregularities in the auroral region.

The **average** location of the auroral region has been described by Feldstein in Holzworth and Meng, (1975), for various conditions of geomagnetic activity and is depicted in Figure 9, along with the 400 km height intersections of rays from the Yellowknife station to GPS satellites. As Figure 9 also illustrates, the Yellowknife station is under the aurora virtually all the time, and many GPS passes recorded at Fairbanks would also pass through the auroral zone. Measurements made at Albert Head and St. John's are not likely to be affected by the aurora during moderate magnetic conditions. During severe magnetic storms; however, the auroral expands both equatorwards and polewards, and effects can be seen down to the mid-latitudes. This is illustrated in Figure 10, where local daytime time rates of change of ionospheric range delay recorded at St. Johns have been sorted by different levels of magnetic activity, referenced by the magnetic K_p index.

Figure 11 summarizes the results for 1 minute time rates of change in ionospheric range delay for all locations, for 3 seasons, during the local nighttime hours. In this figure, the l%, 5%, 50%, 95% and 99% cumulative probability levels of ionospheric range delay variations are plotted versus the geomagnetic latitude of each station. In all seasons phase scintillation effects become apparent in the auroral zone, at approximately 60" geomagnetic latitude. Figure I1 clearly showed virtually no short term scintillation effects from ap proximately 35" to 58" North geomagnetic latitude, corresponding to 25" to 48" geographic latitude, during this portion of the current solar cycle.

Several months of range delay change statistics were computed from data taken at the Kokee, Hawaii station, located slightly northward of the equatorial anomaly region of peak occurrence of ionospheric irregularities. At the 1994 near-minimum in long term solar cycle activity the occurrence statistics of ionospheric range delay variations in the equatorial region are much lower than those in the auroral region. More study is required to determine why this is the case, but the patchy nature of the equatorial irregularities, and its much more limited **occurrence** frequency, as compared with those in the auroral region, likely significantly affect the overall statistics.

CONCLUSIONS

The data set made available by the IGS network is an important asset to the ionospheric research community. During the time period from late 1993 through July 1994, which is well down in the current 11 year solar activity cycle, only small effects were seen in short term rates of change on ionospheric range delays! not exceeding 0.3 meters per minute, even at the l'% and the 99% statistical points, during the nighttime hours of maximum activity. During years of high solar activity, the anticipated range delay rates of change should be approximately three times larger, but, even then, likely will exceed 1 meter per minute, only below the 1 and above the 99 percentiles of occurrence.

Fortunately, these rates of change are not cumulative over time, that is, they do not represent large: absolute changes over longer periods, but can be characterized as random fluctuations superimposed upon the normal large scale background variations which are adequately corrected by the planned constellation of dual frequency codeless WAAS ionospheric monitoring stations.

These results indicate that the largest short term changes in ionospheric range delays occur in the auroral zone during the nighttime hours. The largest changes occur within 1 minute, indicating that they are related to auroral phase scintillations. The CONUS region is free of significant, short term changes in ionospheric range delay during this period of low solar activity, even at the 1% and the 99% statistical levels.

ACKNOWLEDGEMENTS

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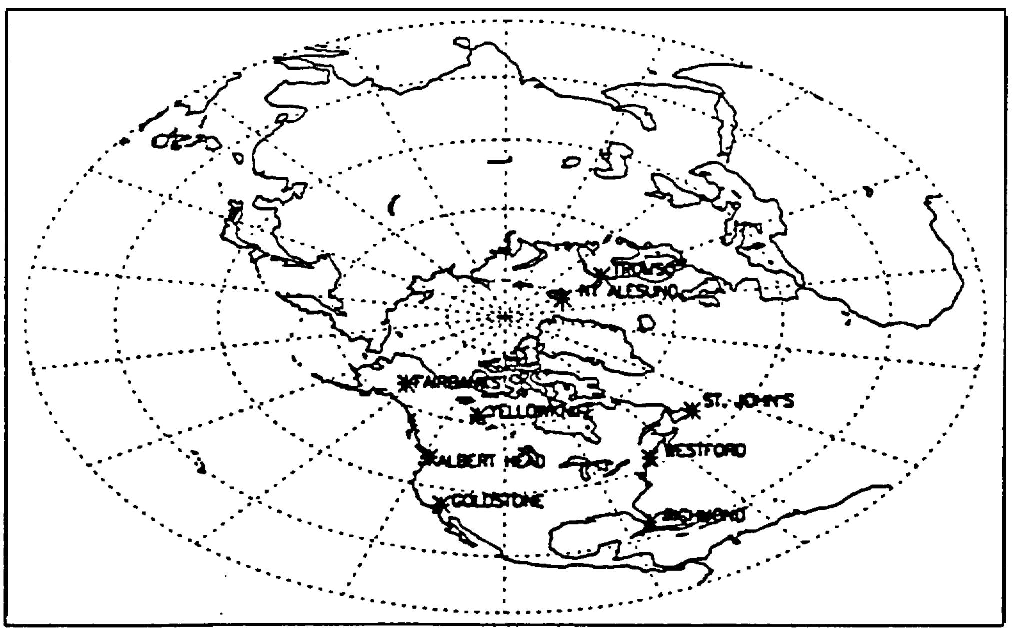

Figure 1. **Map *of* station locations used in rate of change of ionospheric *range* delay study.**

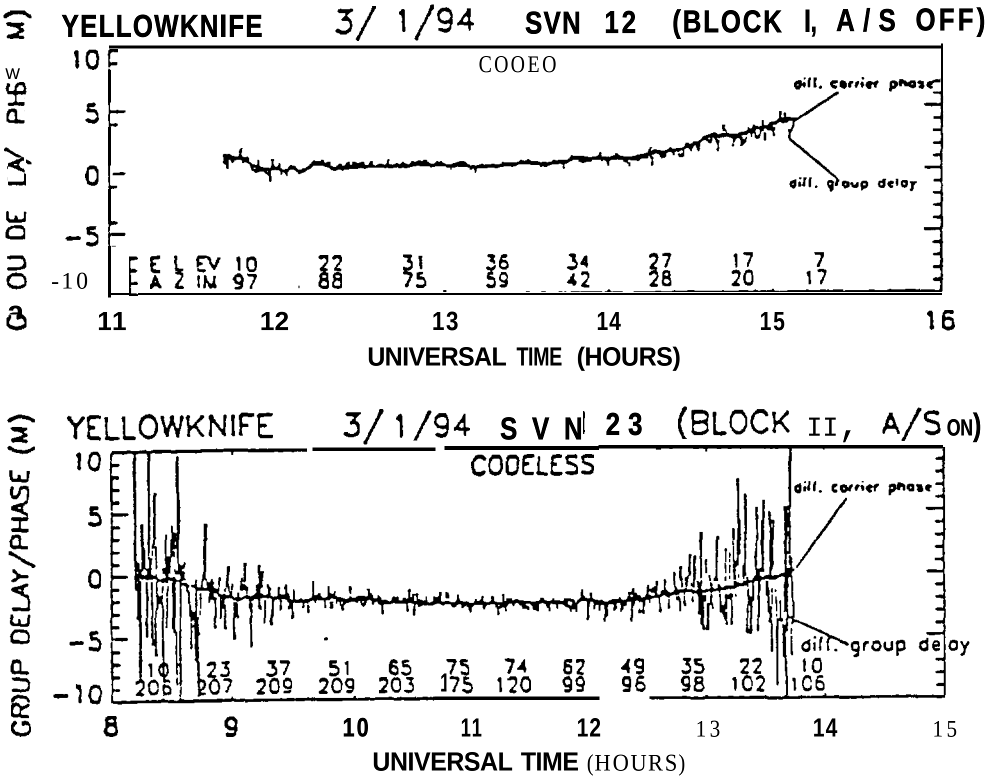

Figure 2. Differential group delay and differential carrier phase under code and codeless conditions.

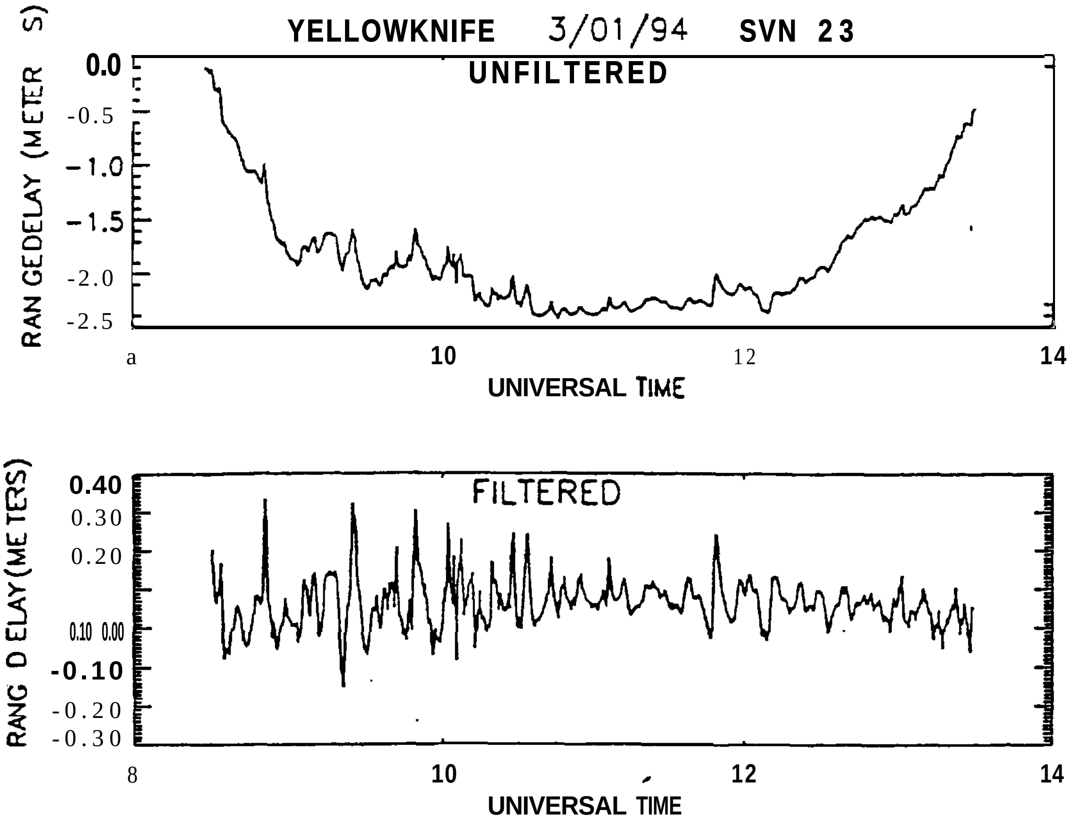

Figure 3. Ionospheric delay variations, before and after removal of low frequency spectral components.

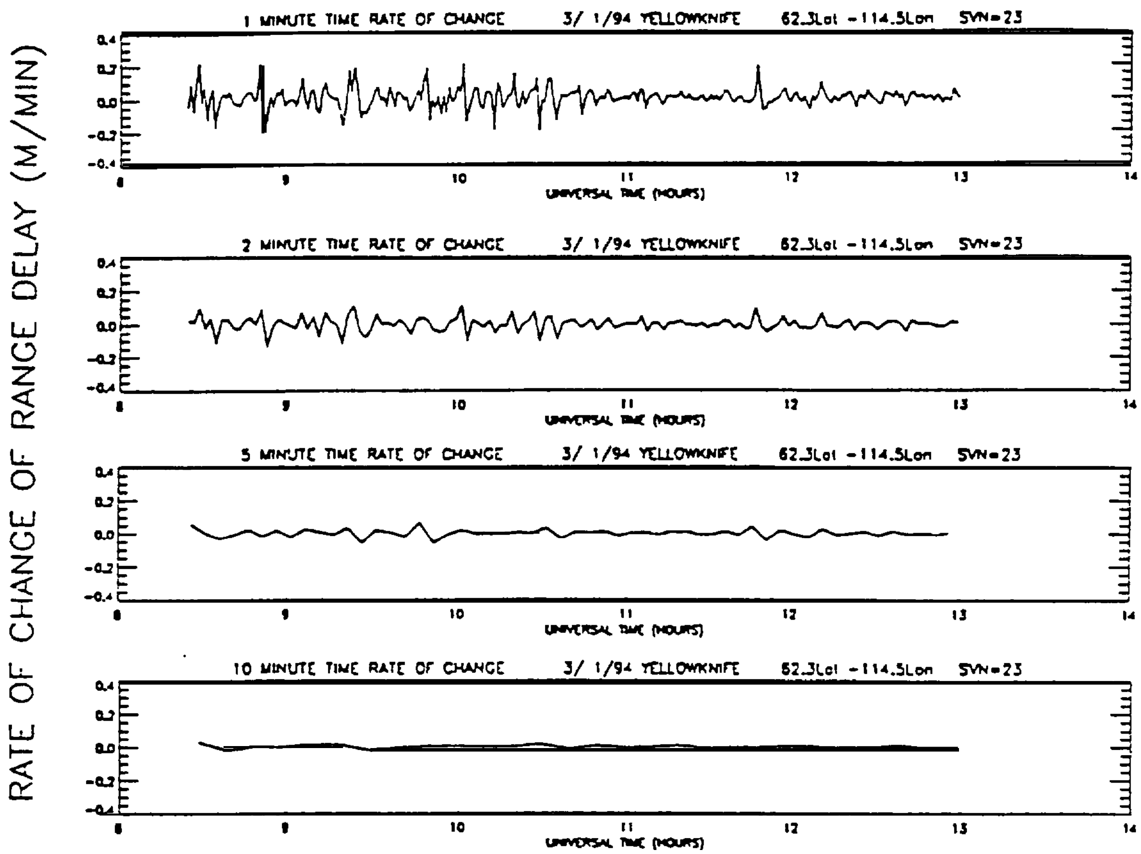

Figure 4. Ionospheric delay variations over the time intervals indicated.

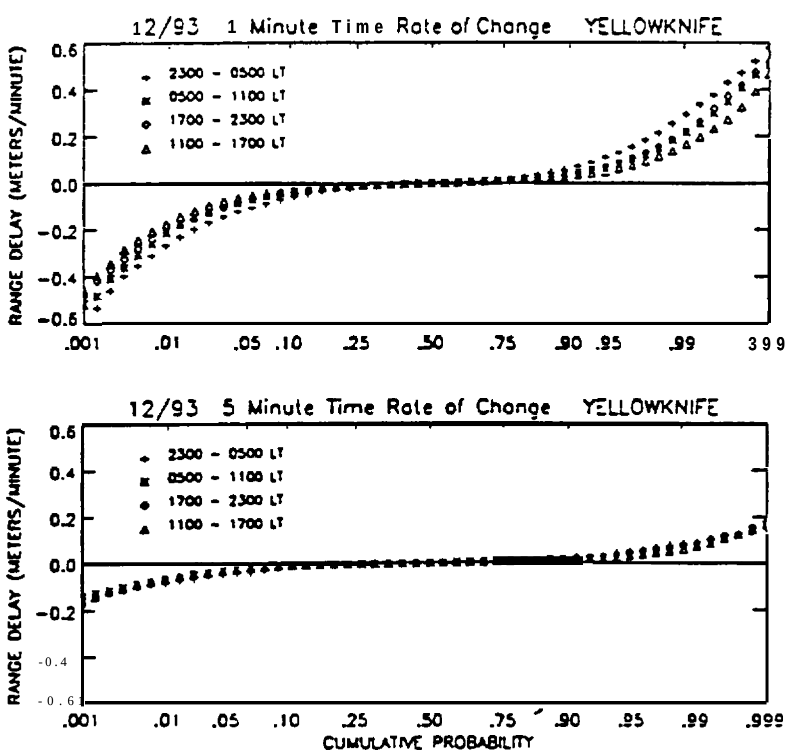

Figure 5. Statistics of ionospheric delay variations over 1 minute and 5 minute periods for different times of day.

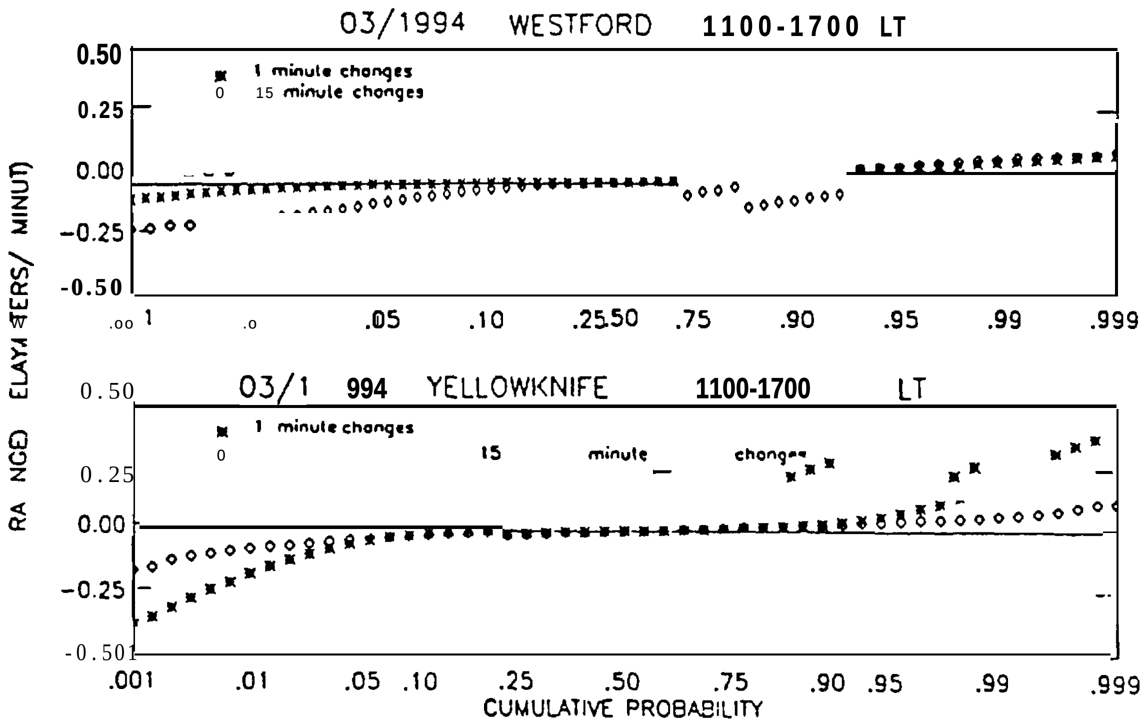

Figure G. Statistics of ionospheric range delay changes for satellite passes from Westford and Yellowknife for which the long period variations were not filtered out.

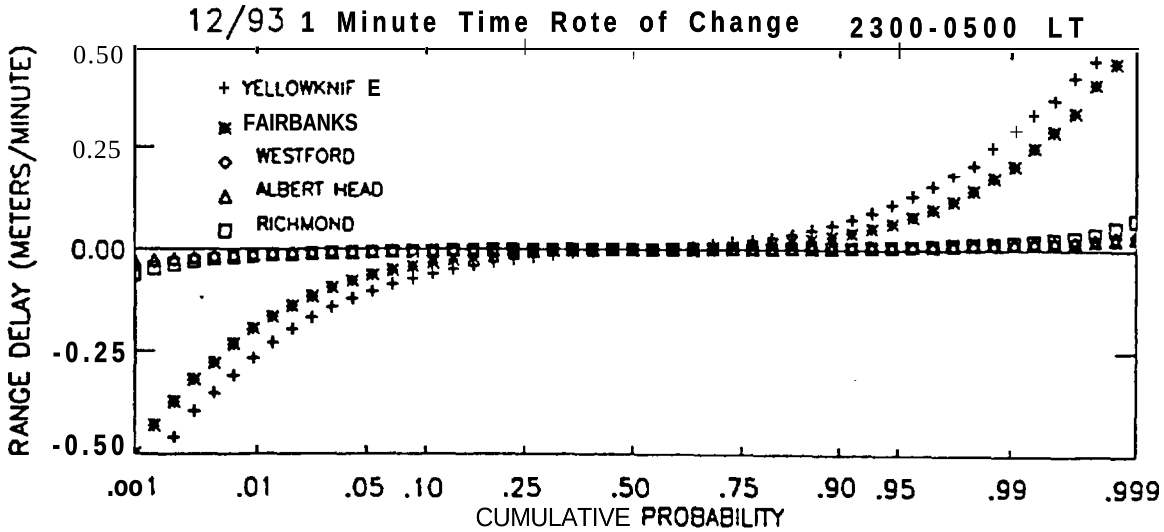

Figure 7. Statistics of ionospheric delay variations for nighttime hours for the stations indicated.

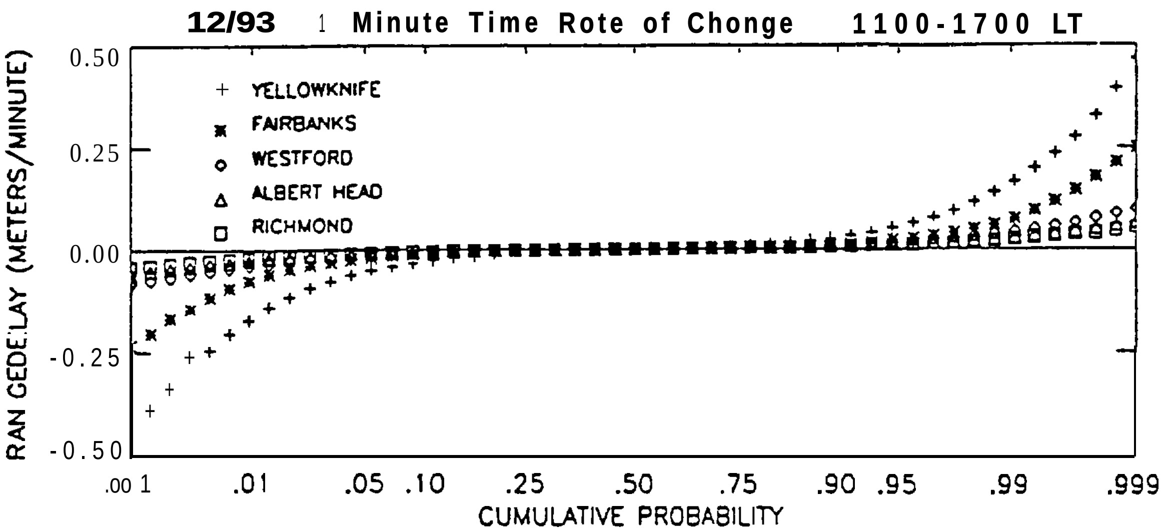

Figure 8. Statistics of ionospheric delay variations for daytime hours for the stations indicated.

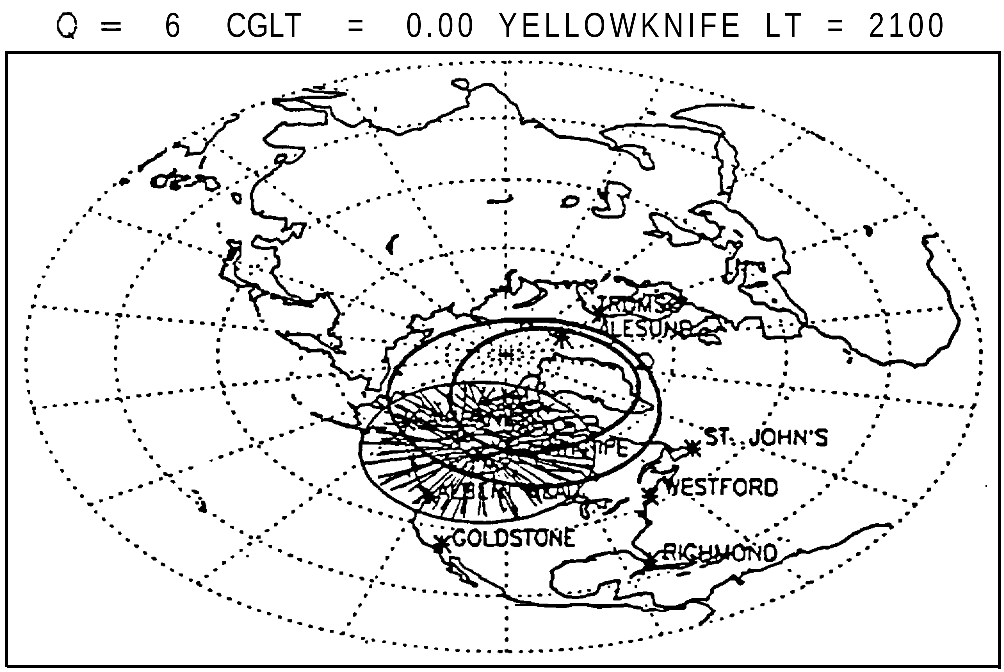

Figure 9. Map of station locations, with the GPS 400 km height intersections of rays from the Ycllowknifc station with the aurora at local nighttime.

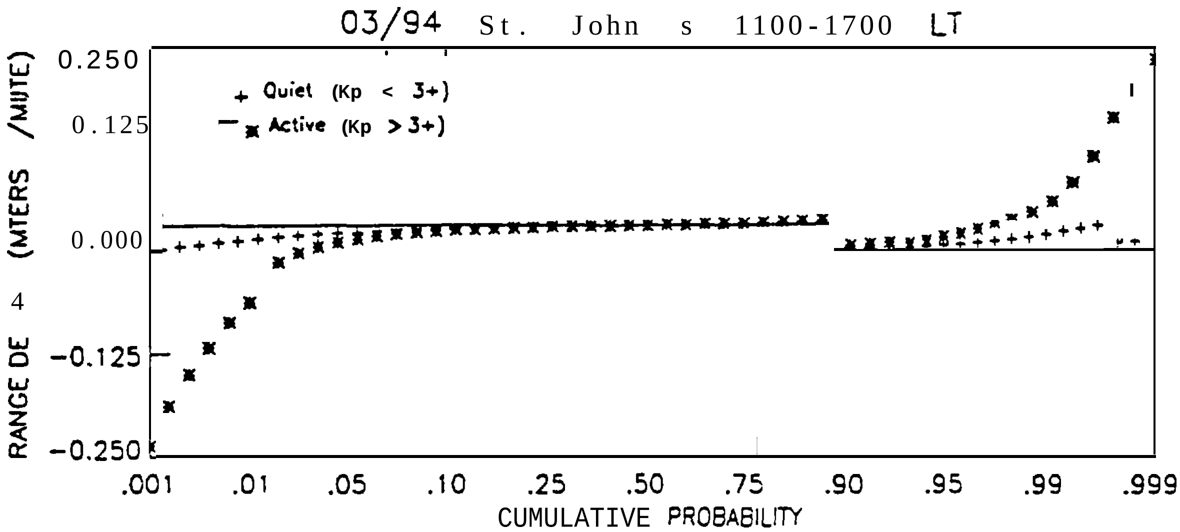

Figure 10. Statistics of daytime ionospheric delay variations for St. Johns, Newfoundland for different conditions of magnetic activity.

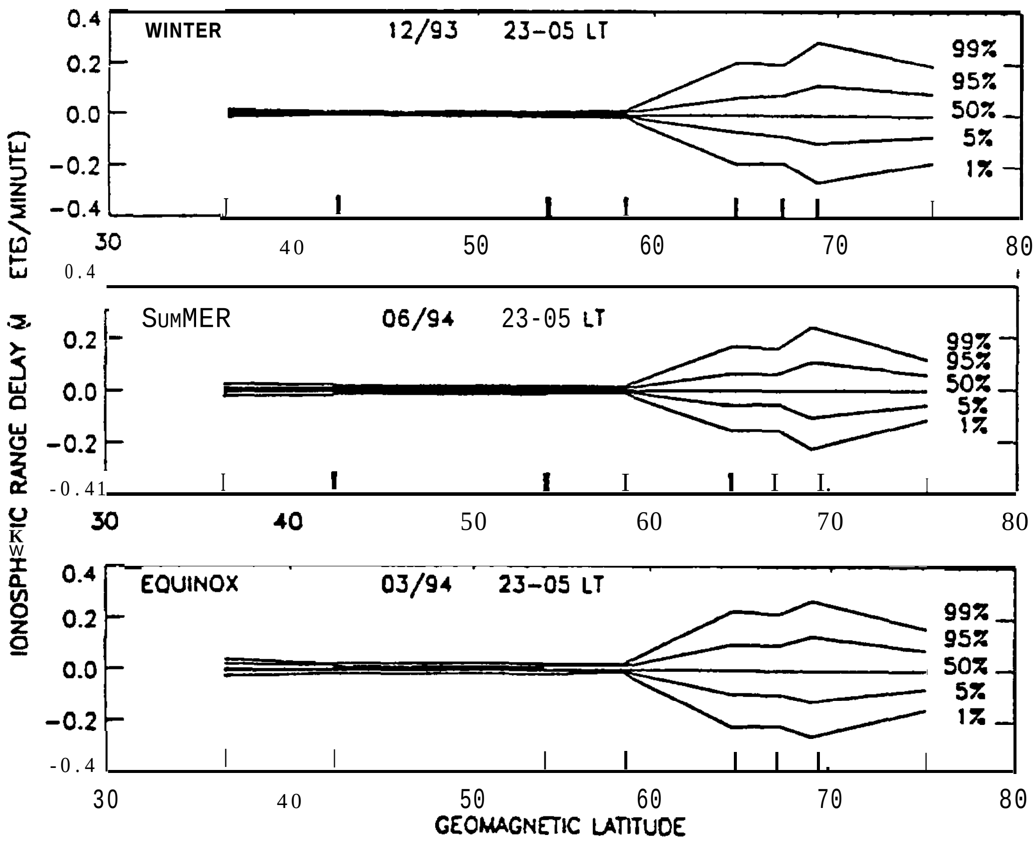

Figure 11. Summary of statistics of nighttime ionospheric delay variations for different seasons versus geomagnetic latitude.