The Statistics of Scintillation Occurrence at GPS Frequencies

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Abstract

As part of the research being carried out at the University of New Brunswick on propagation media effects on the Wide Area Augmentation System (WAAS), we are examining the requirements for extending the WAAS ionospheric modelling approach to cover Canadian airspace. This involves identifying and evaluating particular algorithms for the creation of ionospheric delay values and associated error bounds in geographical areas in, and close to, the active auroral zone.

At such latitudes, rapid changes in amplitude and phase of incoming satellite signals tend to be significant, and it is the frequency of occurrence of such scintillations in which we are interested. This paper presents the results of an analysis of dual frequency GPS data from the network of reference stations that make up the Canadian Active Control System (CACS) as well as stations from a WAAS test network. Spatial correlation of scintillation occurrence with models of the auroral oval are also shown.

Particular reference is given to periods of enhanced ionospheric activity, during which scintillations are likely to be more intense and occur more often. Since such storms are likely to occur with greater frequency as the peak of the current solar cycle approaches, a detailed understanding of their effect on WAAS is required.

Introduction

Various researchers have proposed and investigated methods of monitoring the rapid variations of amplitude and phase of GPS signals due to the ionosphere. One of the main reasons for doing this is to investigate the impact of scintillations on the GPS signal. Since its signal power is significantly less than that of L1 and civil dual frequency receivers use non-optimal codeless or semicodeless techniques for tracking L2, resulting in lower signal to noise values, the impact of a rapidly changing ionosphere is much more likely to be felt on the L2 signal. *Nichols et al.* [1999] took advantage of a collocated Ionospheric Scintillation Monitor (ISM)[1] and geodetic-grade receiver at Fairbanks, Alaska to show a distinct correlation between ionospherically-active periods and losses of lock on L2. It would therefore seem reasonable to extend this premise to monitor scintillation activity through monitoring losses of lock on L2. Note that ultimately it is the ability of the GPS receiver to measure ionospheric delay in which we are interested and so, even if L2 dropouts are **not** directly associated with ionospheric activity but the result of some other phenomenon, monitoring losses of lock can still be considered a valid exercise.

This paper reviews some recent work done at UNB to investigate various simple methods for the analysis of the spatial and temporal occurrence of scintillation activity of sufficient strength to affect the L- band GPS signals. Two analysis methods are proposed, and initial results presented.

[1] A single frequency GPS L1 receiver specifically designed to monitor scintillation levels in real time [*Van Dierendonck et al., 1996*].

Data Sources

FAA National Satellite Test Bed

Initial investigations centred around GPS data from the National Satellite Test Bed (NSTB), a testing facility set up by the U.S. Federal Aviation Administration (FAA) to investigate WAAS feasibility. The NSTB consists of a network of dual frequency GPS receivers, 5 of which are in Alaska, an "ionospherically interesting" region. Figure 1 shows the locations of these Alaskan NSTB Testbed Reference Stations (TRSs).

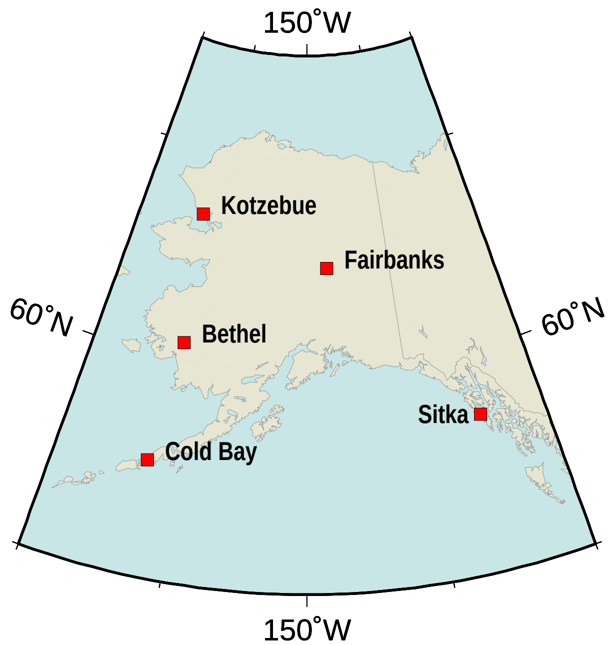

Figure 1. Locations of NSTB Reference Stations in Alaska.

Raw dual frequency data collected at a 1Hz sampling rate was used, and converted to RINEX format before processing. Two separate days were chosen to represent quiet and active ionospheric conditions.

Identification of periods during which the GPS signals are likely to be affected by ionospheric storms at high latitudes in a timely manner is not a straightforward task. Since the geomagnetic field affects the motions of ionized particles, and thus modifies the bulk movement of plasma [*Hargreaves, 1992*], a more active geomagnetic field is likely to indicate a more active ionosphere.

Geomagnetic activity is classified on a global scale via indices such as Kp and Ap, which are the result of processing data from 13 magnetic observatories [*Hargreaves, 1992*]. One drawback of these indices is that they are based mainly on measurements made at mid-latitude sites and are therefore not necessarily representative of the high latitude ionosphere. Nonetheless, the global activity indices are a useful indicator of *possible* local high latitude activity. The Auroral Electrojet (AE) index provides information on the state of the high latitude ionosphere, but is considerably more complicated than either Kp or Ap and consequently is only available some months after the fact [*Kurth and Gurnett, 1998*], compared to a few days lag for Kp and Ap.

27 August 1998 has been thus identified as a storm day, and was used to represent an ionospherically active period, while 13 December 1998 was chosen as a quiet day. Figures 2 and 3 show the 1 minute mean variation in the geomagnetic field measured at College, AK (a suburb of Fairbanks) for the periods 25–29 August and 11–15 December 1998 respectively. These figures show clearly the increased level of geomagnetic activity during 27 August (the central portion of Figure 2) and the relatively inactive field on 13 December (again the central portion).

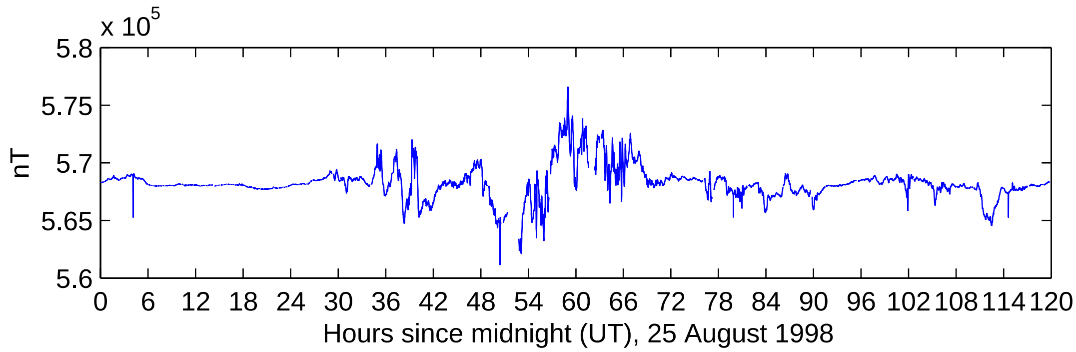

Figure 2. 1 minute mean of total geomagnetic field variation measured at College, Alaska, 25–29 August 1998. Source: [*Intermagnet*, *1999*].

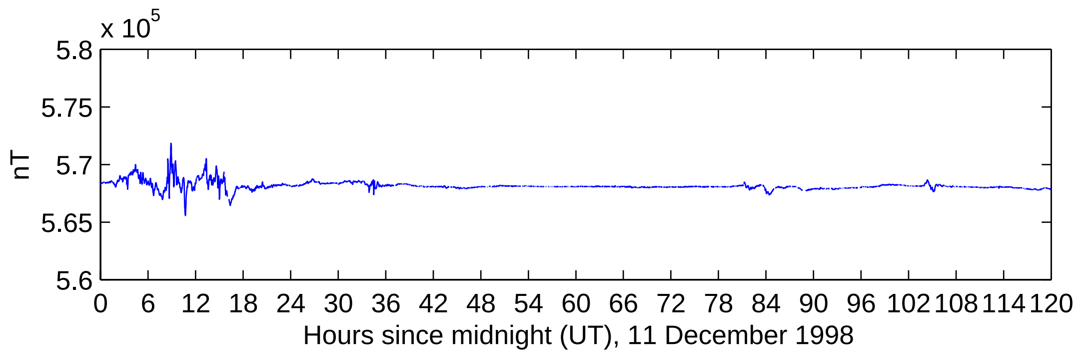

Figure 3. 1 minute mean of total geomagnetic field variation measured at College, Alaska, 11-15 December 1998. Source: [*Intermagnet*, *1999*].

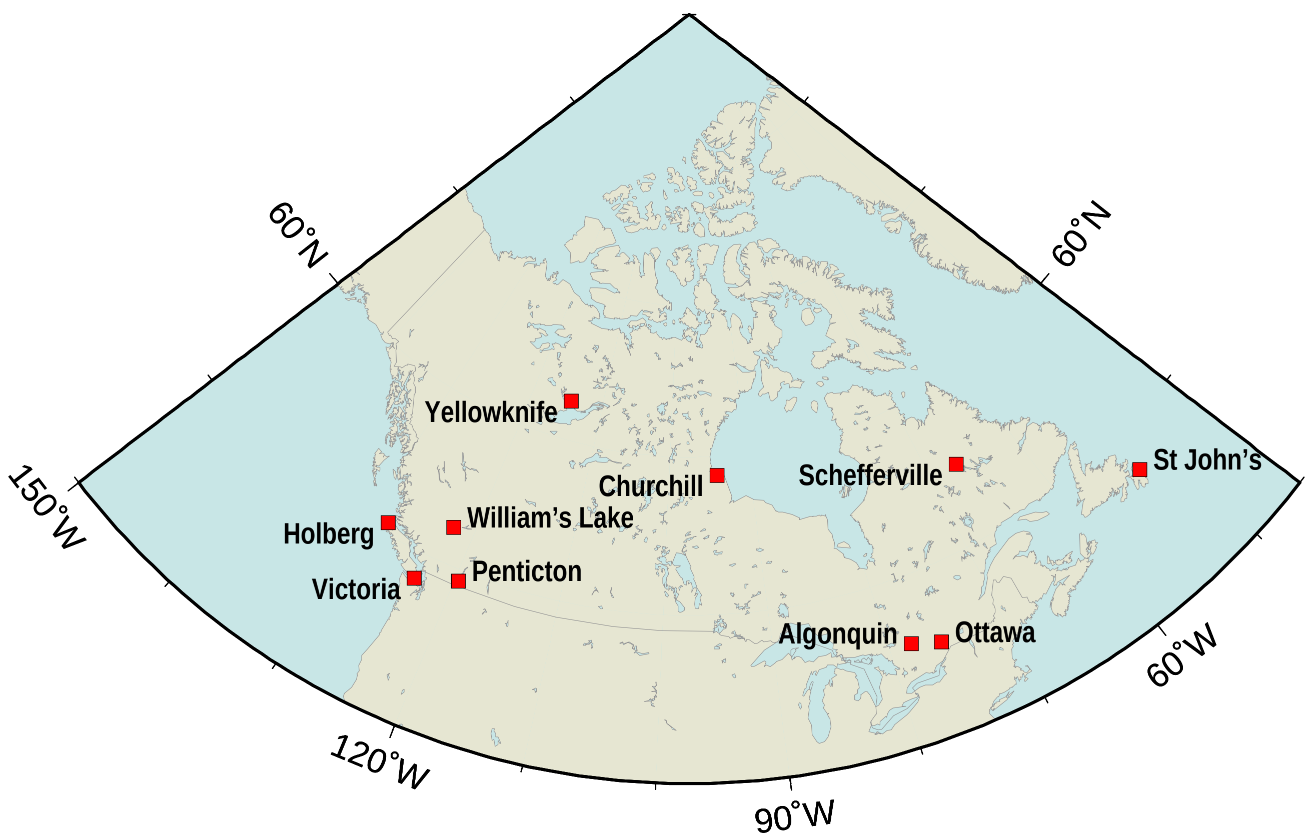

Figure 4. Locations of NRCan Canadian Active Control System receivers.

Canadian Active Control System

Dual frequency GPS data from a number of reference stations which make up the Canadian Active Control System (CACS) [*NRCan, 1999*] was also made available. The CACS is made up of a network of dual frequency GPS receivers using external atomic frequency standards, the locations of which are shown in Figure 4.

Initial investigations were based on three days of 0.5Hz data from the stations at Yellowknife, NWT; Churchill, Manitoba; and Algonquin, Ontario; collected between 17 and 19 February 1999. This distribution of test sites was chosen to provide data from the nominal auroral and sub auroral zones.

Figure 5 shows the geomagnetic field variation measured at Yellowknife during the five day period from 16-20 February 1999. Again, heightened activity on the chosen active day of 18 February is obvious.

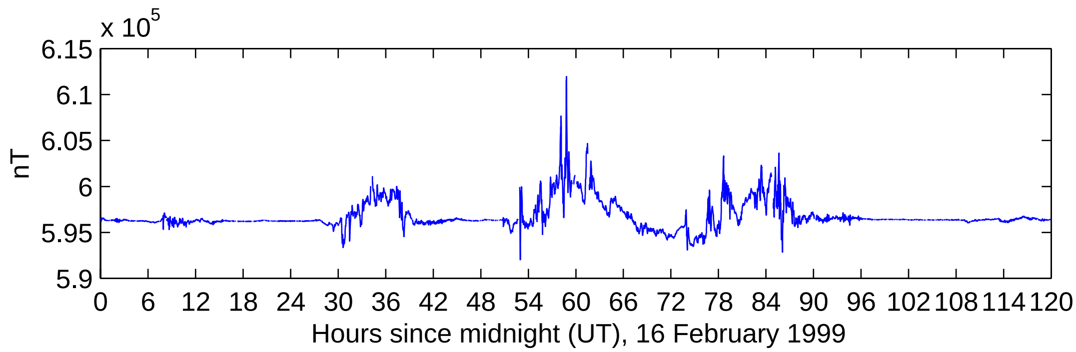

Figure 5. 1 minute mean of total geomagnetic field variation measured at Yellowknife, NWT, 16-20 February 1999. Source: [*Intermagnet, 1999*].

Losses of Lock on L2

As previously mentioned, losses of lock on the L2 signal are proposed as a proxy for monitoring scintillation activity on an operational level, with no other hardware required at sites already equipped with high quality GPS receivers. This is true of both the CACS and NSTB networks.

Alaskan NSTB Receivers

Figure 6 shows the number of satellites expected to be tracked above a 15 degree mask angle, based on the navigation message ephemerides, along with the number for which L2 was not tracked, for 27 August and 13 December 1998 at Fairbanks, Alaska. For the sake of simplicity, the losses of lock have been binned into 1 minute intervals.

Plotted in Figure 7 and Figure 8 is the ratio of the number of satellites lost to the number expected. The second line on these charts shows the variation in the geomagnetic field recorded at the magnetic observatory in nearby College, Alaska.

As is immediately obvious, there is significant correlation between the level of geomagnetic activity reported by the magnetometer, and the number of satellites for which L2 is not tracked. Dropouts of the L1 signal due to rapid changes in ionospheric delay are much less common, although not entirely unheard of [*Nichols et al., 1999*]. Gaps in the magnetometer plots are due to missing data.

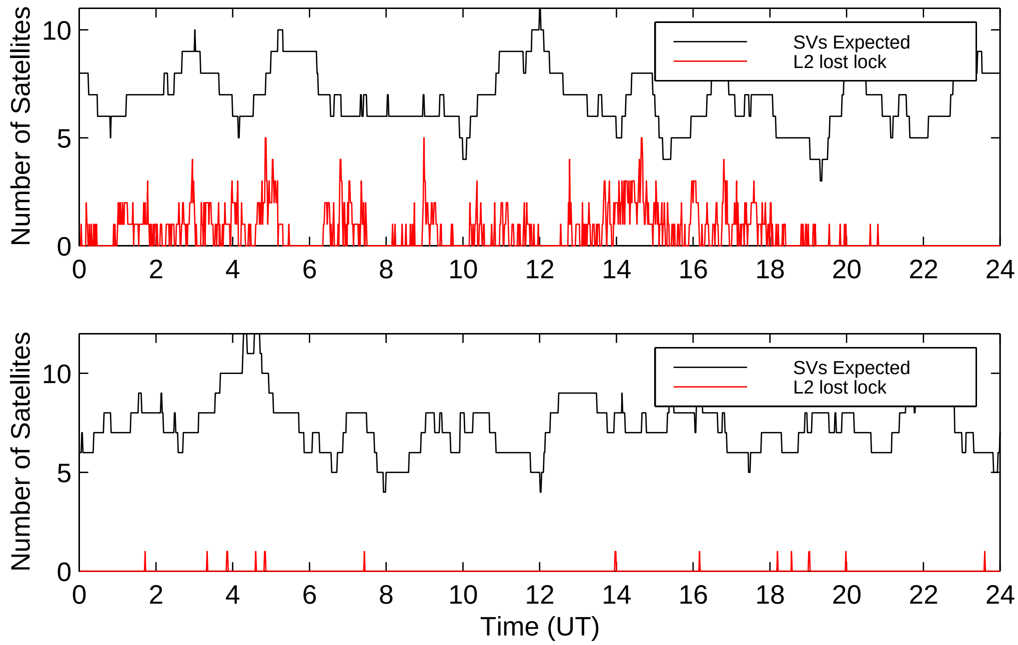

Figure 6. Number of satellites (SVs) expected plotted with the number for which the receiver lost lock on L2 for 27 August (top) and 13 December (bottom) 1998 at Fairbanks, AK.

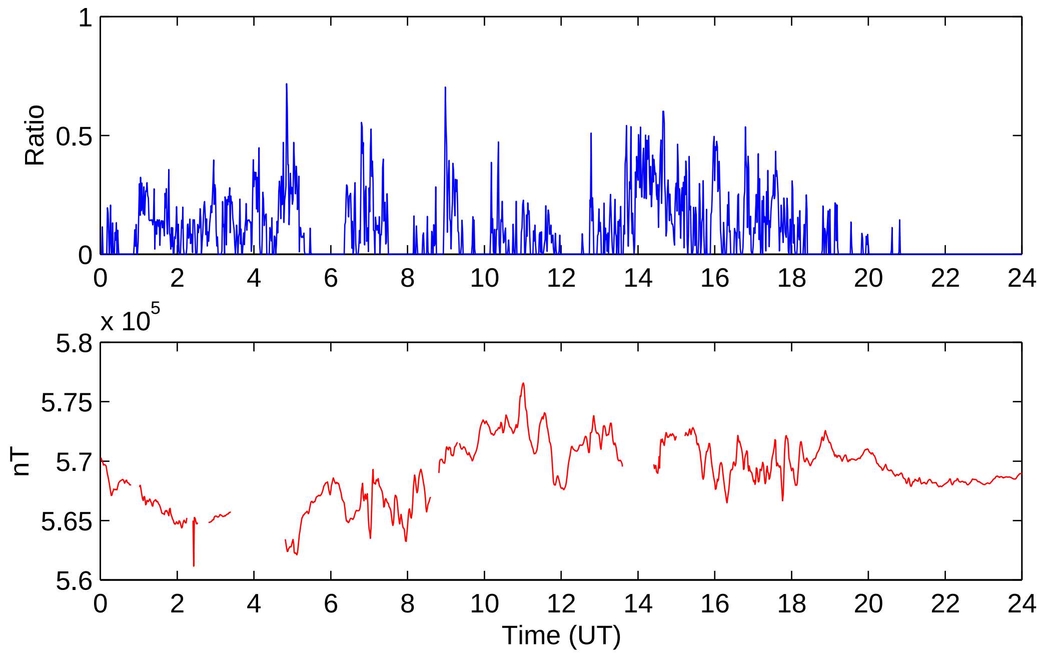

Figure 7. Ratio describing losses of lock on L2 plotted with 1 minute mean of variation of geomagnetic field on 27 August 1998. GPS data was collected at Fairbanks, AK; magnetometer data at College, AK.

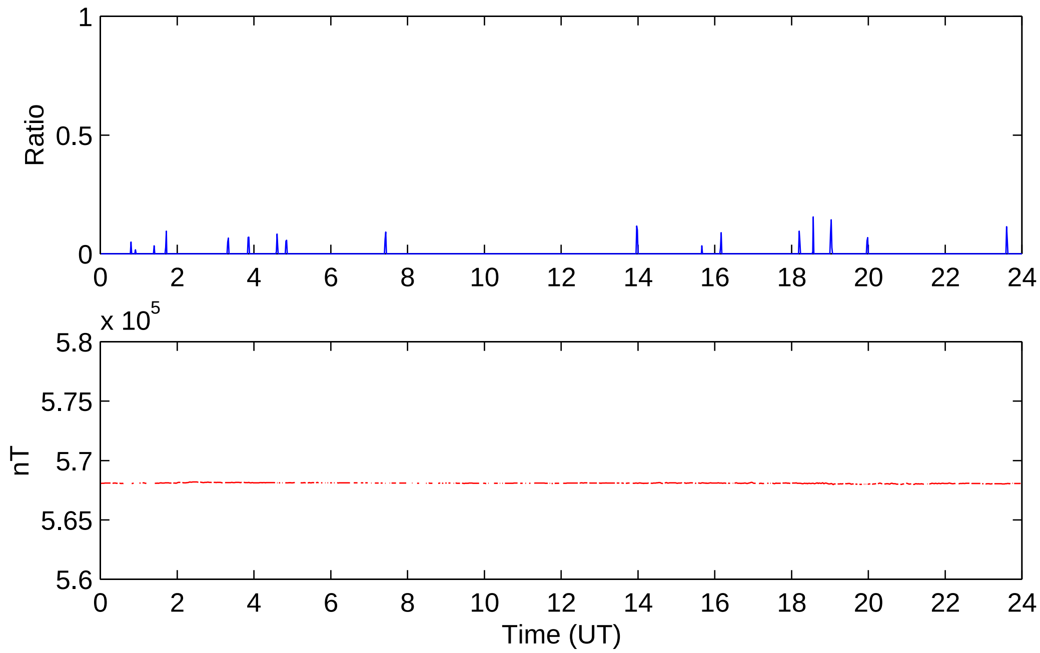

Figure 8. Ratio describing losses of lock on L2 plotted with 1 minute mean of variation of geomagnetic field on 13 December 1998. GPS data was collected at Fairbanks, AK; magnetometer data at College, AK.

Canadian Active Control System

Although the data made available for the CACS stations at Yellowknife, Churchill and Algonquin was collected on a separate day from the NSTB data, ionospheric conditions were similarly active (see Figure 5), and therefore similar results in terms of losses of lock might have been expected. This proved not to be the case however, as is illustrated in Figure 9, which shows the same ratio described above for three days of data collected at Yellowknife.

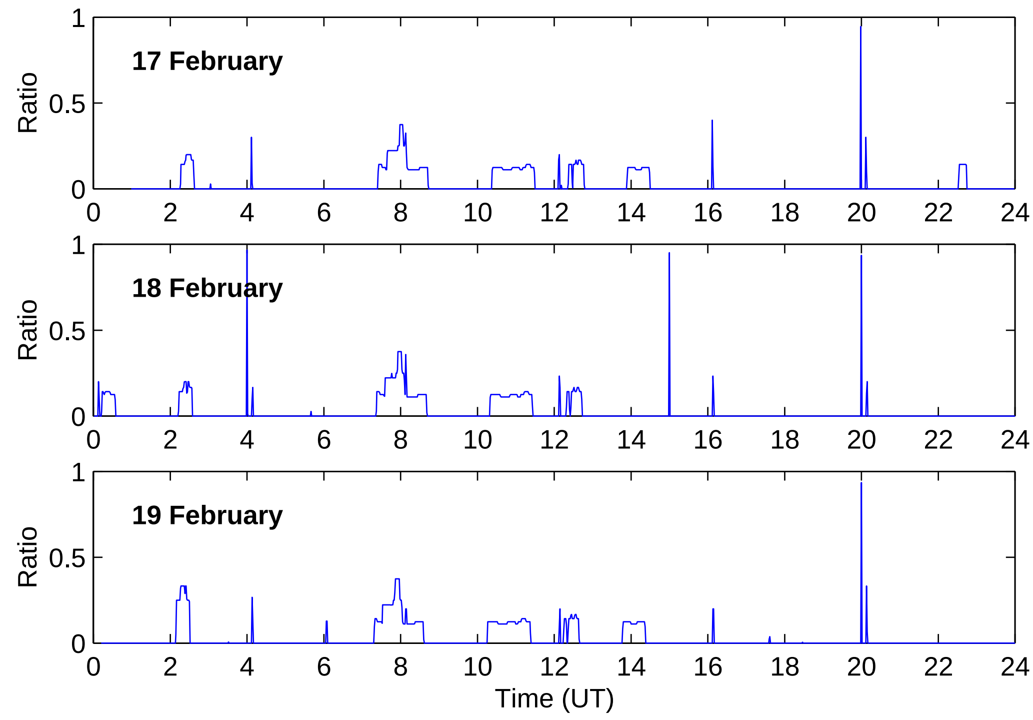

Figure 9. Ratio describing the losses of lock on L2 for 17-19 February 1999 at Yellowknife, NWT.

Close inspection of the plots shows an approximately daily repetition of the pattern of losses of lock across the three days for each of the stations. This would suggest that these losses of lock are multipath- and/or signal blockage-related rather than a result of ionospheric activity.

Unfortunately, this result, although encouraging for continuity of tracking in a network of wide area DGPS reference stations, does not lend itself in the same way to scintillation monitoring as does the "less reliable" NSTB data. This suggests that use of the CACS network of GPS receivers requires some other analysis method.

Rate of Change of Carrier Phase

One other statistic commonly used to quantify scintillation activity is the rate of change of either the carrier phase or the L1-L2 phase difference [*Van Dierendonck et al.*, *1993; 1997*], with the assumption that any cycle slips have been fixed to avoid spikes in this rate of change.

Differencing the L1 and L2 carrier phase observables removes all systematic effects common to both frequencies such as satellite motion, satellite clocks, selective availability and the troposphere. After high pass filtering the resultant time series to remove any remaining long period effects, the standard deviation over 60 second bins (termed σ_{60}) was taken. Figure 10 shows this statistic for PRN27 on three consecutive days at Yellowknife, with the elevation cut-off angle set to 15 degrees in order to minimize the effects of multipath at low elevation angles.

As was inferred in Figure 5, the ionospheric activity during this period was at a maximum on 18 February, and it would be expected that variations in the incoming phase of the GPS signal would therefore be greatest on this day. Figure 10 would appear to support this supposition.

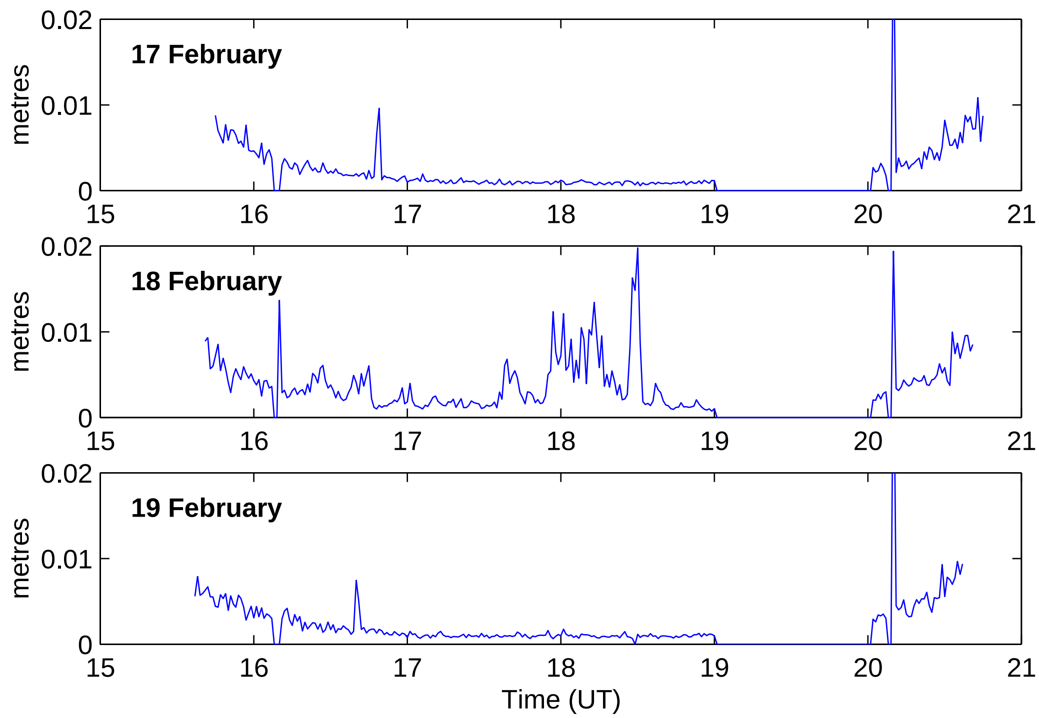

Figure 10. Sixty second standard deviation (σ_{60}) of phase advance for three consecutive days. Data was collected at Yellowknife on 17-19 February 1999. Satellite is PRN27, elevation angle cut-off set to 15 degrees.

Note the structure repeated each day at approximately 2010 UT which is most likely the result of multipath. The gap in the plots between 1900 and 2000 UT is the result of a gap in the data available.

Spatial Distribution of Scintillation Activity

Figure 7 showed the number of losses of lock reported at the Fairbanks TRS and the correlation with local geomagnetic activity. Figure 11 below shows the same actual / expected ratio described above for three TRS receivers in Alaska on 27 August 1998. Figure 1 shows their locations. A striking difference is noticeable between the number of losses of lock reported at Fairbanks and Kotzebue versus that at Cold Bay.

Maps were produced of the ionospheric pierce point locations of each of these L2 losses of lock on a shell located at 300 km altitude. This height was chosen to reflect the assumed altitude of most ionospheric variability of the correct scale size to cause fluctuations in the GPS signal [*Aarons and Basu*, *1994*]. Figure 12 shows a sample of these maps for 0900 to 0930 UT on 27 August. For reference, this time frame is highlighted in Figure 11.

Each satellite track shows periods where L2 is tracked in green, and not tracked in red. It is apparent from this figure that the location of the pierce points for which lock has been lost has some degree of geographic correlation, since points where L2 is not tracked tend to occur in adjacent areas. This suggests that these losses of lock are a result of some phenomena occurring near the chosen 300 km altitude. Further analysis of the spatial correlation of losses of lock at various altitudes is required. Also plotted in Figure 12 is the location of the poleward and equatorward boundaries of the *Holzworth and Meng* [1975] mathematical model of the auroral oval.

This particular model allows the calculation of the location of the auroral oval for values of the auroral activity index Q from 0 (quiet) to 6 (active). Plotted here is the location of the oval at approximately 0900 UT with Q=6. It is perhaps apparent that the predicted location of the oval and the areas in which most losses of lock of the L2 signal occurred are not collocated. Two explanations are proffered for this.

Firstly, if the Holzworth and Meng model were accurate, the inference is that scintillating structures are present in the auroral trough, located to the south of the poleward boundary. What is more likely is that the model is not adequately representing the actual location of the fast changing structures associated with the auroral oval.

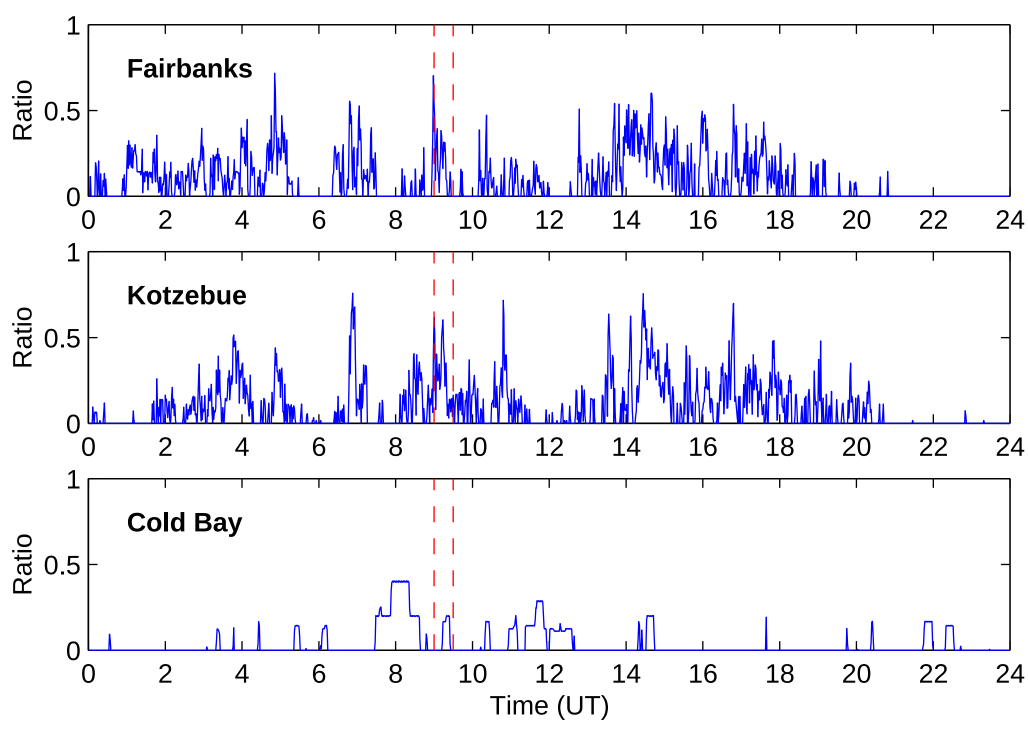

Figure 11. Ratio describing losses of lock on L2 for NSTB reference stations at Fairbanks, Kotzebue and Cold Bay on 27 August 1998.

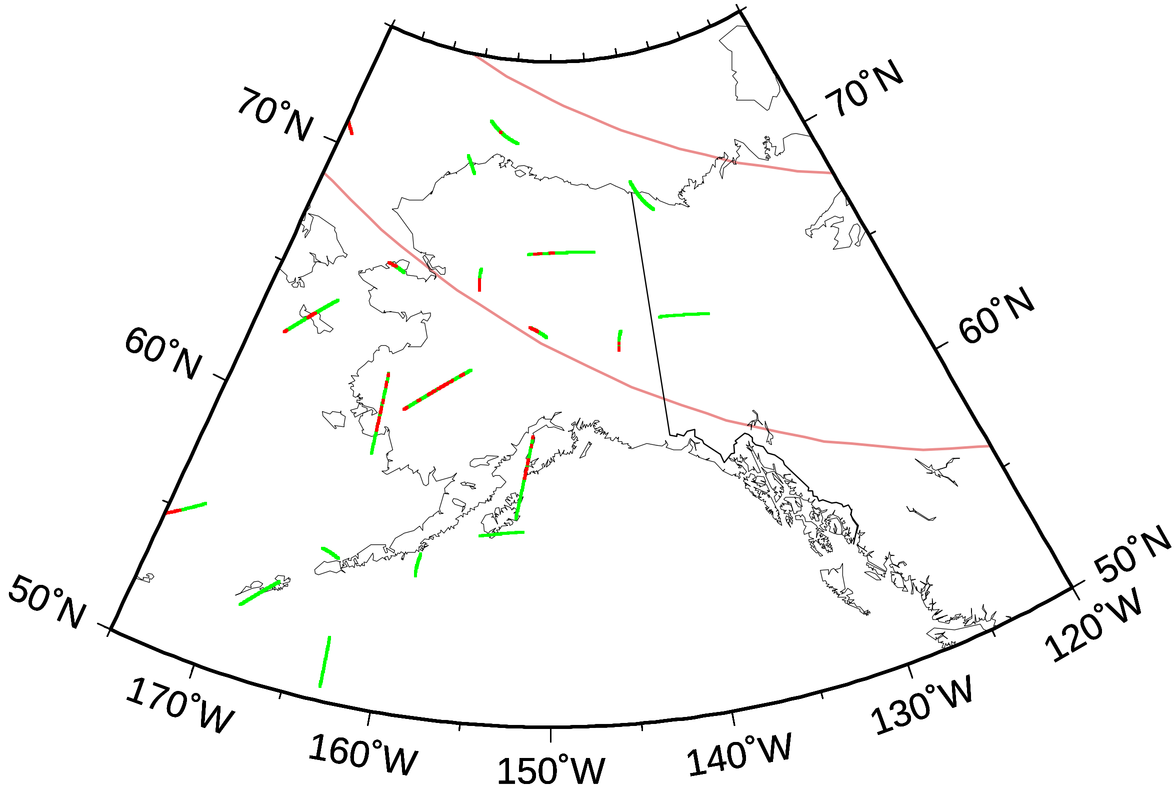

Figure 12 Locations of loss of lock of L2 carrier phase plotted on a shell at 300 km altitude. Data collected at Fairbanks, Kotzebue and Cold Bay from 0900 to 0930 UT on 27 August 1998. The two solid red lines define the poleward and equatorward boundaries of the *Holzworth and Meng* mathematical model of the auroral oval.

Conclusions

The basic premise of the work reported in this paper is that monitoring the number of losses of lock of the L2 signal on an operational basis provides an indication of the level of influence of scintillation activity on GPS. Since WAAS and other wide area DGPS systems make use of the dispersive nature of the ionosphere to measure ionospheric delay via dual frequency receivers, dropouts of the second frequency are a serious problem. Any loss of the L2 signal is likely to happen at the very time when ionospheric delay will have the maximum effect on positional accuracy, and it is therefore important for both the user and service provider to have some idea of the potential for system failure.

While not affecting single frequency users directly in quite the same manner, users who rely on corrections from these services, especially in safety-critical environments such as precision approach and landing of aircraft may also suffer serious consequences. Add to this the (admittedly less likely) scenario of loss of the L1 signal, and it becomes obvious that the monitoring of scintillation activity in real time is vital on systems such as WAAS which rely on dual frequency data to estimate ionospheric delay.

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