Ionospheric Modeling for WADGPS at Northern Latitudes

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BIOGRAPHIES

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Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching and conducting research since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Prof. Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine.

ABSTRACT

Much work has been undertaken and published on ionospheric modeling for Wide Area DGPS (WADGPS) systems such as the FAA-sponsored Wide Area Augmentation System (WAAS). In mid-latitude regions, typical spatial and temporal variations in ionospheric delay tend to be minimal, and proposed ionospheric models can be broadcast as a set of grid node values along with associated error bounds. Outside of these nominally “quiet” regions however, specifically in the equatorial and auroral zones, the ionosphere is considerably more active, with greater variability both in time and space. Scintillation effects caused by rapid fluctuations in ionization are more prevalent in these zones, and as such, the mitigation of ionospheric delay effects in any WADGPS system which seeks to cover the low or high latitudes may require a more sophisticated modeling process than that for mid-latitude regions.

As part of research being carried out at the University of New Brunswick on propagation media effects on WAAS, we are examining the requirements for extending and augmenting the WAAS ionospheric modelling approach to cover Canadian airspace. This work 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.

In this paper we will identify the specific problems that are associated with ionospheric modelling at high latitudes and over the range of solar activity intensities. Proposed augmentations to be considered include dynamic shell height modelling to enable better performance during auroral storms, and denser grid spacing to take account of larger spatial gradients in the auroral zone.

An analysis of grid point availability is presented, showing the limited coverage afforded in northern Canada by the current reference receiver networks.

INTRODUCTION

As part of a study for the investigation of atmospheric effects on the use of WAAS in Canadian airspace, the University of New Brunswick is currently researching the suitability of the currently proposed ionospheric modeling scheme. Presented here are initial results of these analyses.

IONOSPHERIC MITIGATION TECHNIQUES IN WAAS

The ionospheric modeling scheme proposed for use in the Wide Area Augmentation System has been described extensively elsewhere [see, for example, *Van Dierendonck and Enge*, 1994; *Conker et al*, 1995; and *Chao et al*, 1996] and so only a brief outline is provided here. It will however, be useful to describe the current proposals as outlined by the *FAA* [1997], touching specifically on the limitations encountered at northern latitudes.

In the WAAS scheme, a network of constantly observing GPS receivers at precisely known locations send dual frequency carrier phase and pseudorange observations back to one or more central processing facilities. There, estimates of the delay imparted by the ionosphere along the line of sight from each receiver to each satellite observed are calculated. Interpolation of these measurements to a pre-defined set of grid nodes (ionospheric grid points (IGPs)), at a designated height of 350km, provides a series of ionospheric delay estimates which may be transmitted to users equipped with suitably modified single frequency GPS receivers. The intersection of the line of sight from receiver to satellite and the shell defined by the IGPs is known as an ionospheric pierce point (IPP). The user is then required to interpolate the grid node delays to the location of his IPPs. These estimates can then be used to correct for ionospheric delay.

Estimated along with the grid delays is a bound on the residual error of the vertical ionospheric delay at each IGP. These grid ionospheric vertical error (GIVE) values are used to compute the user ionospheric vertical error (UIVE), the corresponding bound on the user-computed vertical ionospheric delay error.

The grid spacing currently proposed for WAAS calls for a five degree grid at mid latitudes, expanding to a ten degree node separation beyond 55 degrees north. Beyond 75 degrees, there are only four IGPs, located at 85 degrees latitude and spaced 90 degrees in longitude [*FAA*, 1997]. The original rationale behind increasing the grid spacing at northern latitudes was due to the general decrease in longitude spacing as latitude increases. Figure 1 illustrates the proposed grid node locations over Canada and nearby areas.

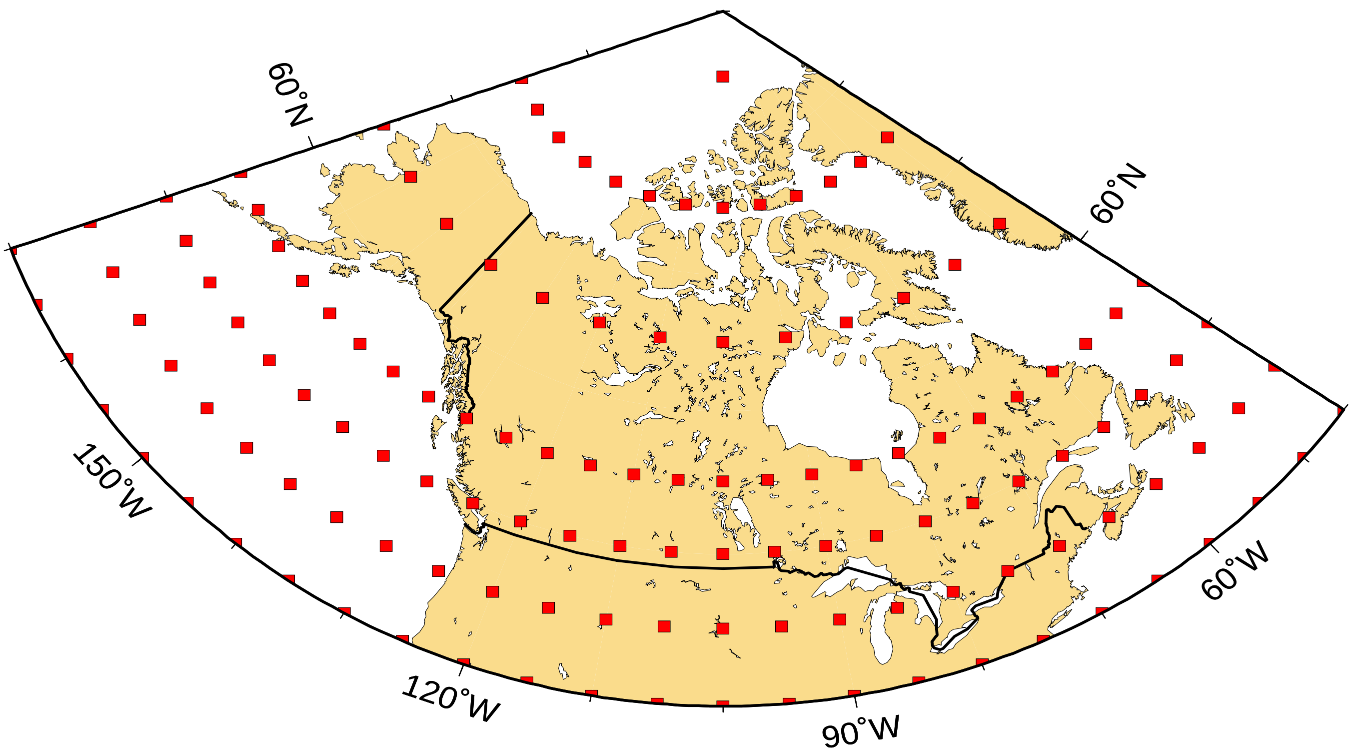

Figure 1. Ionospheric grid point locations based on current FAA specifications.

Notice that, although the spatial gradients in the ionosphere tend to become more complicated in the auroral and polar zones, the grid spacing is increased in these areas, and therefore adequate representation of ionospheric structure may not be possible. Recent work by *Skone and Cannon*, [1997] suggests that a grid spacing of 6 degrees is required for optimal grid performance during geomagnetically disturbed conditions.

The WAAS ionospheric modelling scheme must be robust enough both to withstand the potential of link outages caused by rapid changes in amplitude and phase of the signal as it passes though the ionosphere, and detailed enough to accurately reflect large scale decorrelations. Both of these effects are likely to become more prevalent at high latitudes following an increase in solar activity [*Kunches*, 1997]. Indeed, receivers located in Iceland and Alaska have experienced difficulty tracking during a recent major geomagnetic storm. It is interesting to note however that the TurboRogue receivers used at the Canadian IGS sites were able to continuously track both L1 and L2 through the peak of this same storm.

IONOSPHERIC PIERCE POINT DENSITY

Using the locations of continuously operating dual frequency GPS receivers in Canada and surrounding areas (contiguous United States, Alaska, Greenland) as shown in Figure 2, maps of IPP density based on the current GPS constellation were produced to aid in the analysis of the ability of a similar network to provide the real-time data required for WAAS use in Canada.

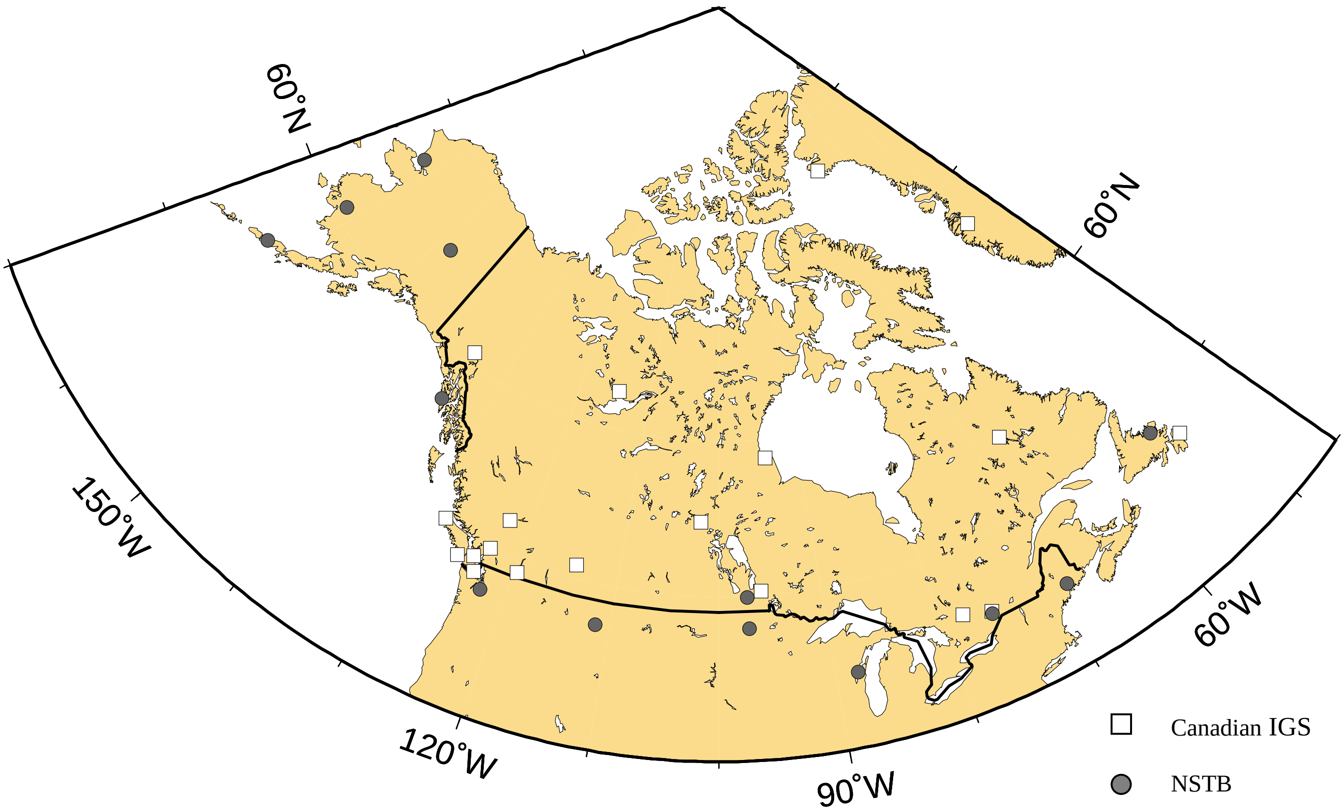

Figure 2. Locations of NSTB and Canadian IGS sites used in analyses.

Figure 3 shows the ionospheric pierce points (IPPs) observed on assuming that data is only available from the sites that make up the National Satellite Test Bed (NSTB). As is immediately obvious, coverage at northern latitudes is severely limited, especially when one considers that, due to the inclination angle of the GPS constellation orbits, the majority of satellite passes observed by a receiver in Canada will be to the south. Notice also the “hole” in coverage to the immediate north of each observing site, likewise a function of the constellation orbits.

Figure 4 shows the IPPs which would be observed on placing a WAAS reference receiver at each of the locations currently occupied by receivers in Canada for which data is available through the International GPS Service (IGS) data retrieval service. Note that coverage is significantly extended to the north, but that data is still limited, especially in the eastern arctic. Placing a receiver in Iqaluit (Baffin Island) immediately improves the data coverage in this area, and this is illustrated in Figure 5, which shows the ionospheric pierce points observed by adding a station at this location.

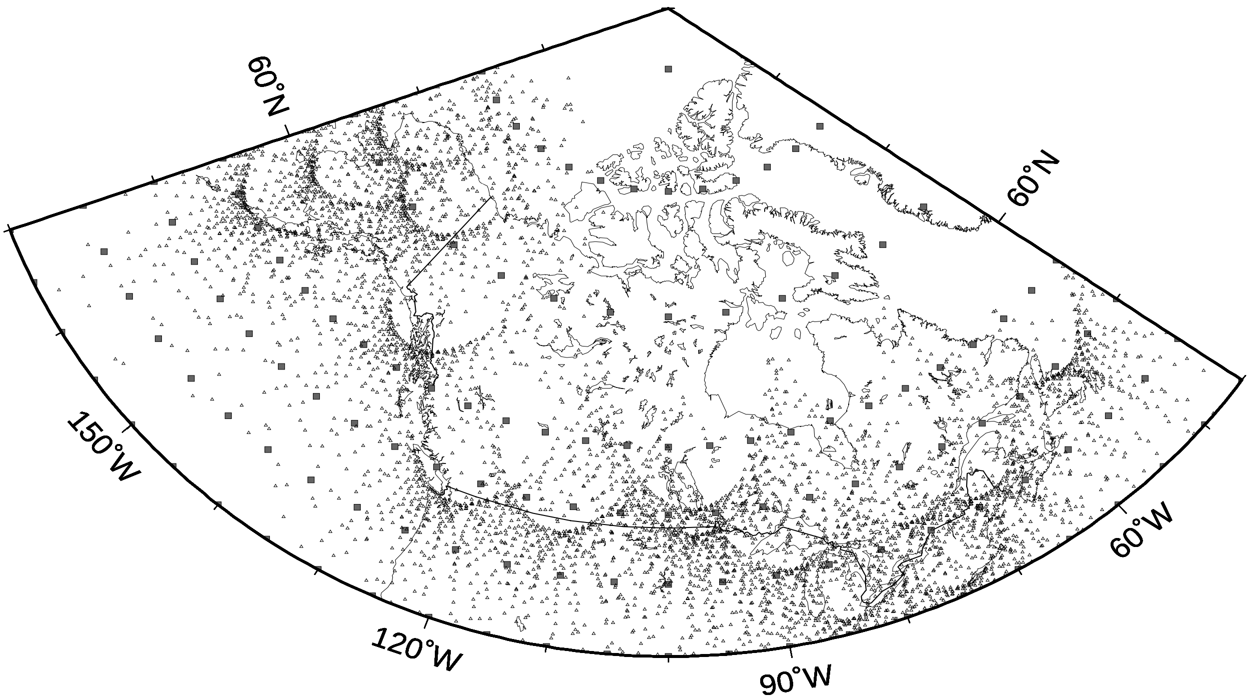

Figure 3. Ionospheric pierce points observed from the current NSTB network of GPS receivers. Shell height is assumed to be 350km, elevation angle cut off is set at 5 degrees, and points are shown for a 12 hour observation period at a 15 minute sample interval.

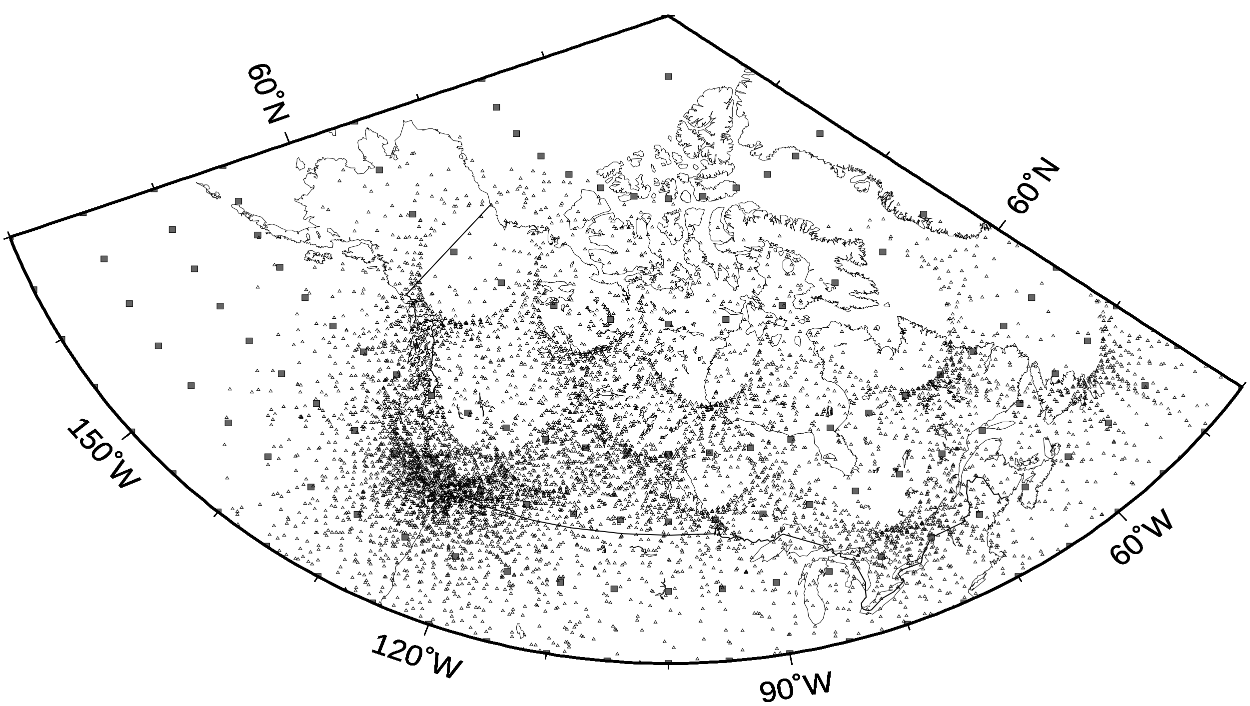

Figure 4. Ionospheric Pierce Points observed from the current network of Canadian IGS sites. Shell height is assumed to be 350km, elevation angle cut off is set at 5 degrees, and points are shown for a 12 hour observation period at a 15 minute sample interval.

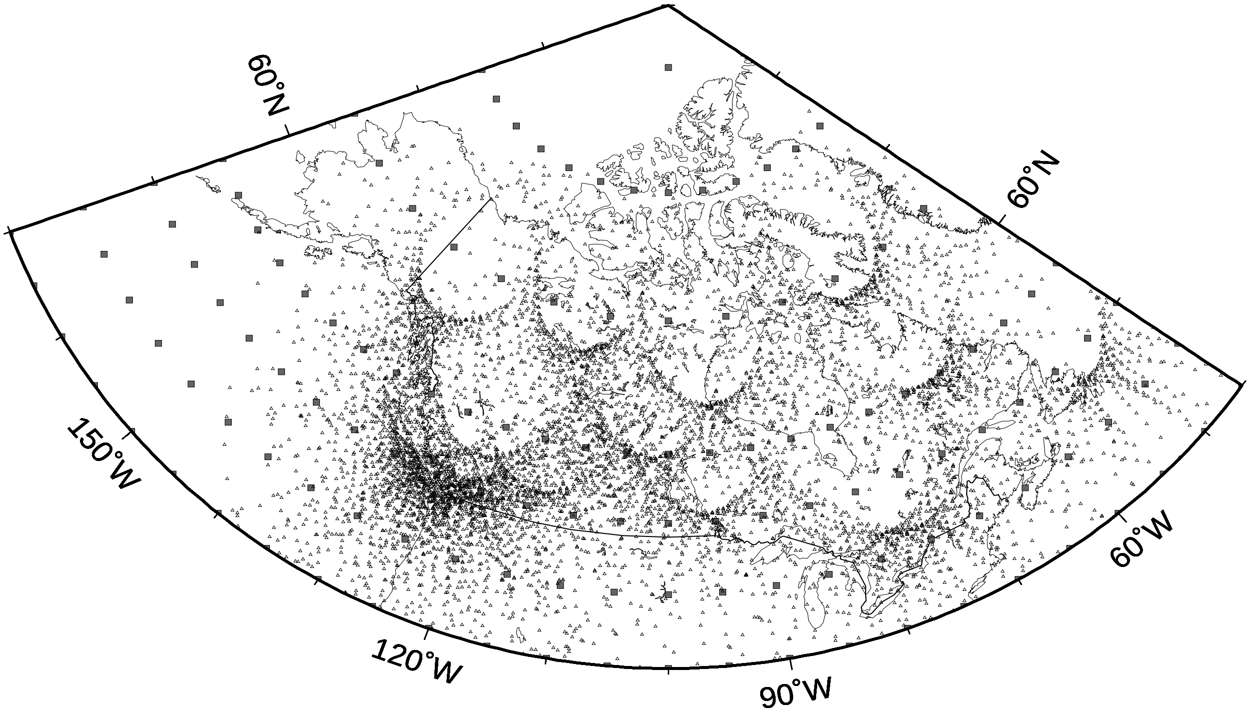

Figure 5. IPPs observed by adding Iqaluit to the network of Canadian IGS sites. Shell height is assumed to be 350km, elevation angle cut off is set at 5 degrees and observations are shown for a 12 hour observation period at a 15 minute data sample interval.

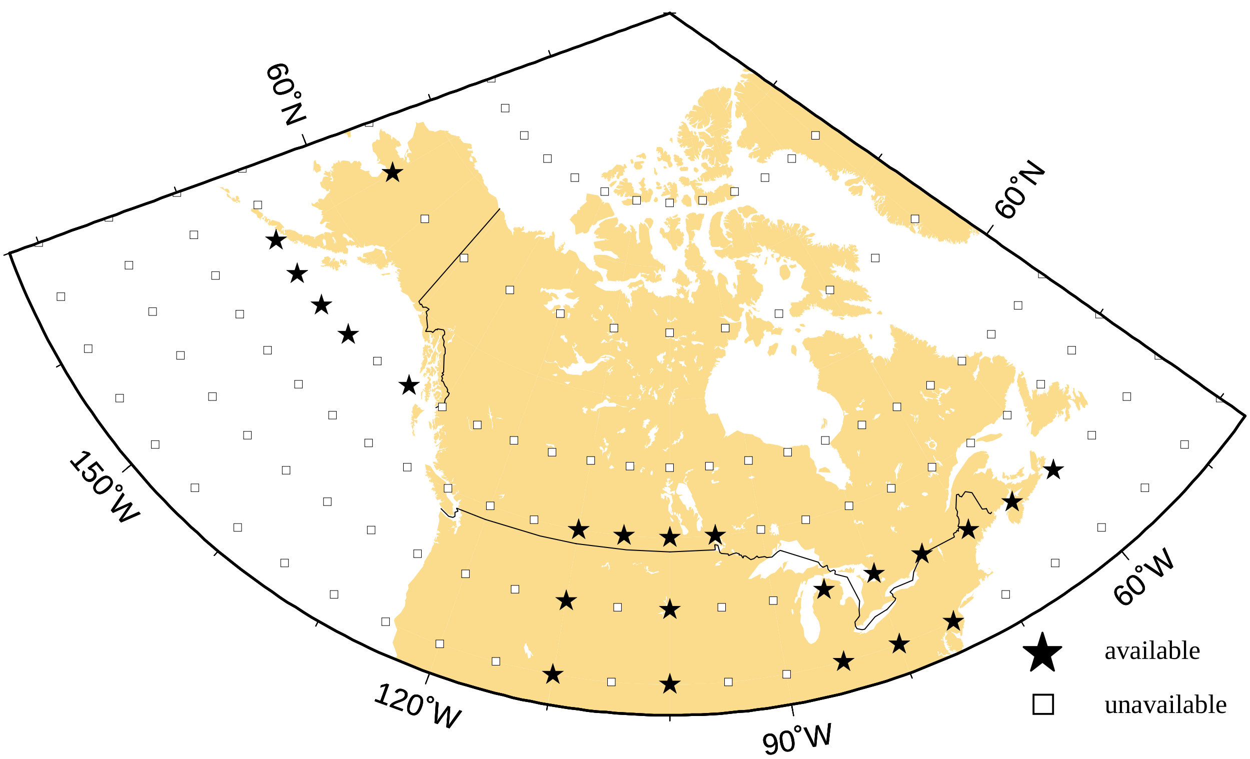

Figure 6. Snapshot of typical IGP status based on the current NSTB network of GPS receivers. Epoch is 0000 UT, 1 January 1998.

The importance of data coverage discussed above in terms of WAAS availability is illustrated in the following series of maps. According to the WAAS specifications [*FAA*, 1997], for a specific Ionospheric Grid Point (IGP) to be marked "available", ionospheric measurements at pierce points in each of the four surrounding grid squares must be observed. Shown in Figure 6 is a snap shot of IGP availability status based on these requirements computed at UNB for an arbitrarily chosen date of 1 January 1998. Notice how few IGPs are marked as available in Canadian airspace. Notice also the restricted availability in Alaskan airspace, a function of the GPS constellation restrictions mentioned earlier.

Figure 7 shows a similar snapshot situation obtained by using the Canadian IGS sites described above. Notice that, even with the increased pierce point density afforded by theses sites, IGP (and hence WAAS) availability is still severely restricted in the eastern arctic and far north.

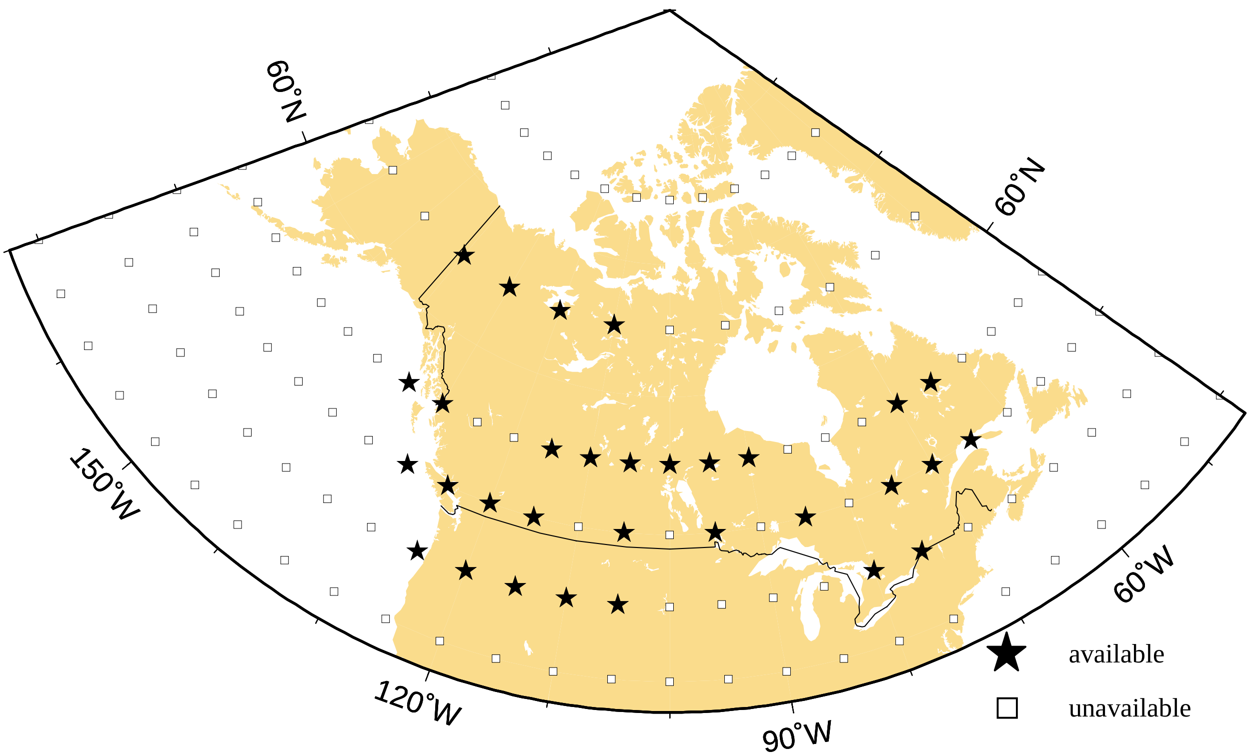

Figure 7. Typical snapshot of IGP status based on the current network of Canadian IGS sites. Epoch is 0000 UT, 1 January 1998.

CORRELATION WITH GEOMAGNETIC FIELD VARIATION

Assessing the performance of WAAS during times of heightened geomagnetic activity is particularly important at northern latitudes. Nominally located between 65 and 72 degrees magnetic latitude, the auroral zone or oval may extend many degrees to the south under magnetically disturbed conditions. Due to the alignment of the geomagnetic field lines, precipitation of energetic solar particles into the auroral and polar cap region produces ionospheric irregularities causing rapid variations in amplitude and phase of electromagnetic signals propagating through the region. These variations are known as scintillations. In the central polar cap in years of solar maximum, GPS receivers may suffer scintillation induced signal fades of magnitude greater than 10dB [*Aarons and Basu*, 1994].

Codeless or semi-codeless dual frequency receivers may exhibit losses of lock on the L2 signal. Such problems have already been observed by receivers in Iceland and Alaska during recent periods of increased geomagnetic activity (ref.). This is likely the result of rapid phase changes in the incoming signal with which exceed the narrow bandwidth of the L2 tracking loops cannot cope.

One particular geomagnetic storm which has attracted the attention of the WAAS community reached a maximum in the early hours (UT) of 4 May 1998. Figure 8 shows a time series of the variations in the geomagnetic field observed at Yellowknife, NWT, each data point being the value averaged over one minute. Note the marked increase in variability at approximately 0300 UT. Plotting these observations with GPS derived measurements of the rate of change of ionospheric delay produced noticeable correlation. Figure 8 shows the first derivative of the slant ionospheric delay measured to PRN26.

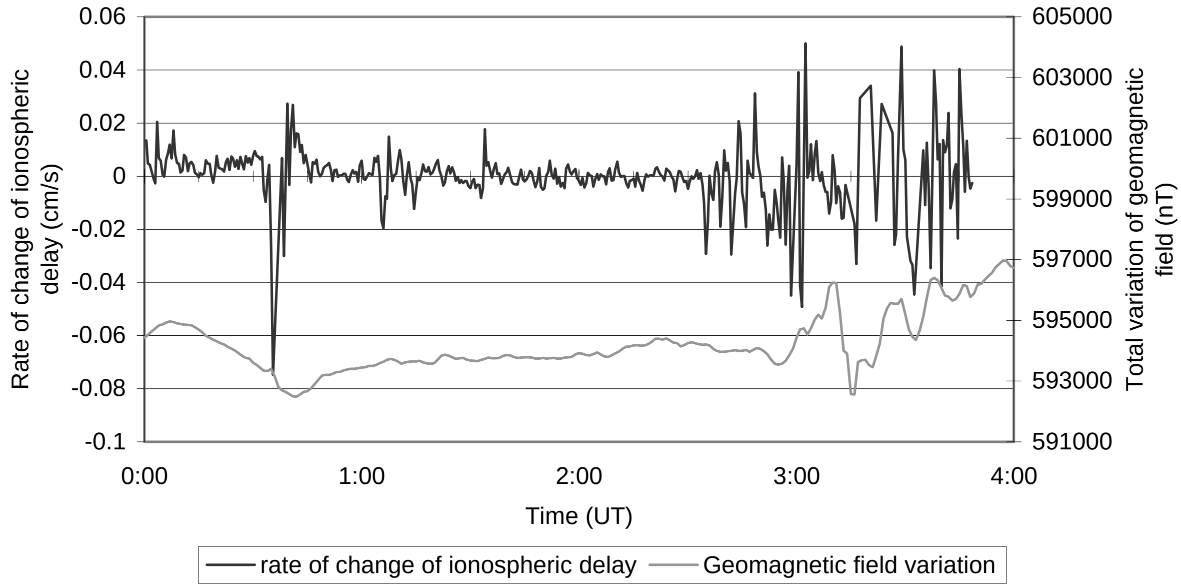

Figure 8. Rate of change of ionospheric delay measured to PRN26, 4 May 1998 from Yellowknife, NWT. Plotted with one minute mean values of total geomagnetic field variation.

WAAS SIMULATIONS

We have initiated testing of the current NSTB ionospheric correction algorithm [*STel*, 1996], based on the requirement outlined in *Van Dierendonck and Enge*, 1994. We have computed vertical TEC estimated for each of the grid nodes identified in Figure 1. Taking dual frequency measurements of carrier phase and pseudorange from each IGS reference receiver in Canada (see Figure 2) plus those in Thule and Kangerlussuaq, on the west coast of Greenland, and Fairbanks, Alaska, the observations are combined according to the equation below using a Hatch smoothing algorithm [*Euler and Goad*, 1991] to estimate the line of sight biased ionospheric delay to each satellite:

$$d_{iono} = \left(\frac{f_{L1}^2}{f_{L2}^2} - 1 \right)^{-1} \left[\frac{\sum B}{\sum W} + L1\_L2 \right]$$

where

$f_{L1} = L1$ frequency

$f_{L2} = L2$ frequency

$L1\_L2 =$ dual frequency differential phase advance

$= L1 - L2$ (in metres)

The term $\frac{\sum B}{\sum W}$ is the weighted bias in the *L1_L2* measurements where:

$$B = \frac{(P2\_P1)_i - (L1\_L2)_i}{v^{P2\_P1} + v^{L1\_L2}}$$

$$W = \frac{1}{v^{P2\_P1} + v^{L1\_L2}}$$

$P2\_P1 =$ dual frequency differential group delay

$= P2 - P1$ (in metres)

$v^{P2\_P1} =$ differential group delay variance

$v^{L1\_L2} =$ differential phase advance variance

The line of sight d_{iono} values are converted to equivalent vertical delay estimates by application of a simple geometric mapping function, and thence transported to surrounding grid nodes by combination with the predicted broadcast (Klobuchar) model. Estimated along with the grid vertical delay values are satellite and receiver hardware biases, and the error bounding GIVE values.

Figure 9 shows an example of the grid ionospheric vertical delays estimated from dual frequency GPS data obtained from each of the Canadian IGS stations identified in Figure 2. Grid node separations are as defined earlier, i.e. a 5 x 5 degree grid below 55 degrees latitude, a 10 x 10 degree separation up to 75 degrees and 10 x 90 degrees from there to the pole.

Limitations of the ionospheric delay estimation strategy seem to be two fold. Firstly, the sparseness of IPPs at northern latitudes means that ionospheric estimates here have been interpolated from a very limited data set. Secondly, the 10 x 10 degree grid over most of Canada limits the spatial resolution of the broadcast IGP delays. Thus the potential for misrepresentation of prevailing conditions is significant, especially during geomagnetically disturbed conditions when spatial and temporal ionospheric gradients can be large.

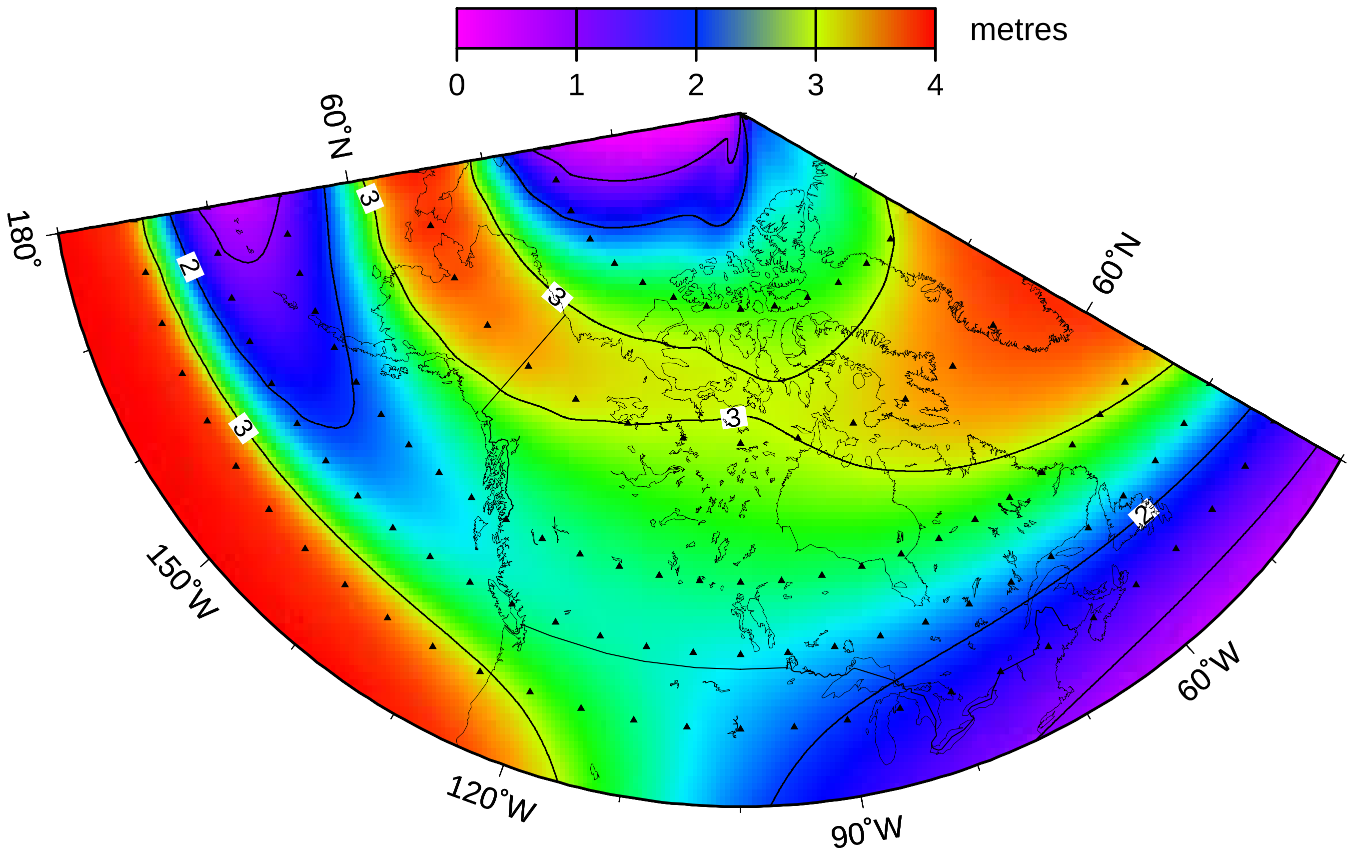

Figure 9. Minimum curvature surface fit to IGP delays estimated using data from Canadian IGS Sites. Time is 1800 UT 14 May 1998.

CONCLUSIONS

As the level of ionospheric activity increases due to a corresponding increase in solar activity, so the stress testing of the WAAS ionospheric modeling scheme will become more important. We have shown here the results of initial investigations into the suitability of the currently proposed ionospheric modeling scheme for WAAS use in a Canadian airspace.

Constraints on the use of WAAS in auroral and polar regions exist on two levels. First, we must examine the ability of the chosen modeling scheme to adequately reflect the short term changes in ionospheric delay which are a feature of the ionosphere at such latitudes. Secondly, rapid fluctuations in the amplitude and phase of the incoming GPS and WAAS signals (scintillations) may actually cause receivers (both user and reference) operating within Canada to lose lock, and therefore navigational capabilities.

If WAAS is to be used extensively in Canada, we must be convinced that the entire system, from data collection to the application of corrections, is capable of withstanding the increase in solar and geomagnetic activity which will doubtless occur as the next sun spot maximum nears.

ACKNOWLEDGEMENTS

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