MITIGATING THE EFFECTS OF SPACE WEATHER ON THE CANADIAN WAAS

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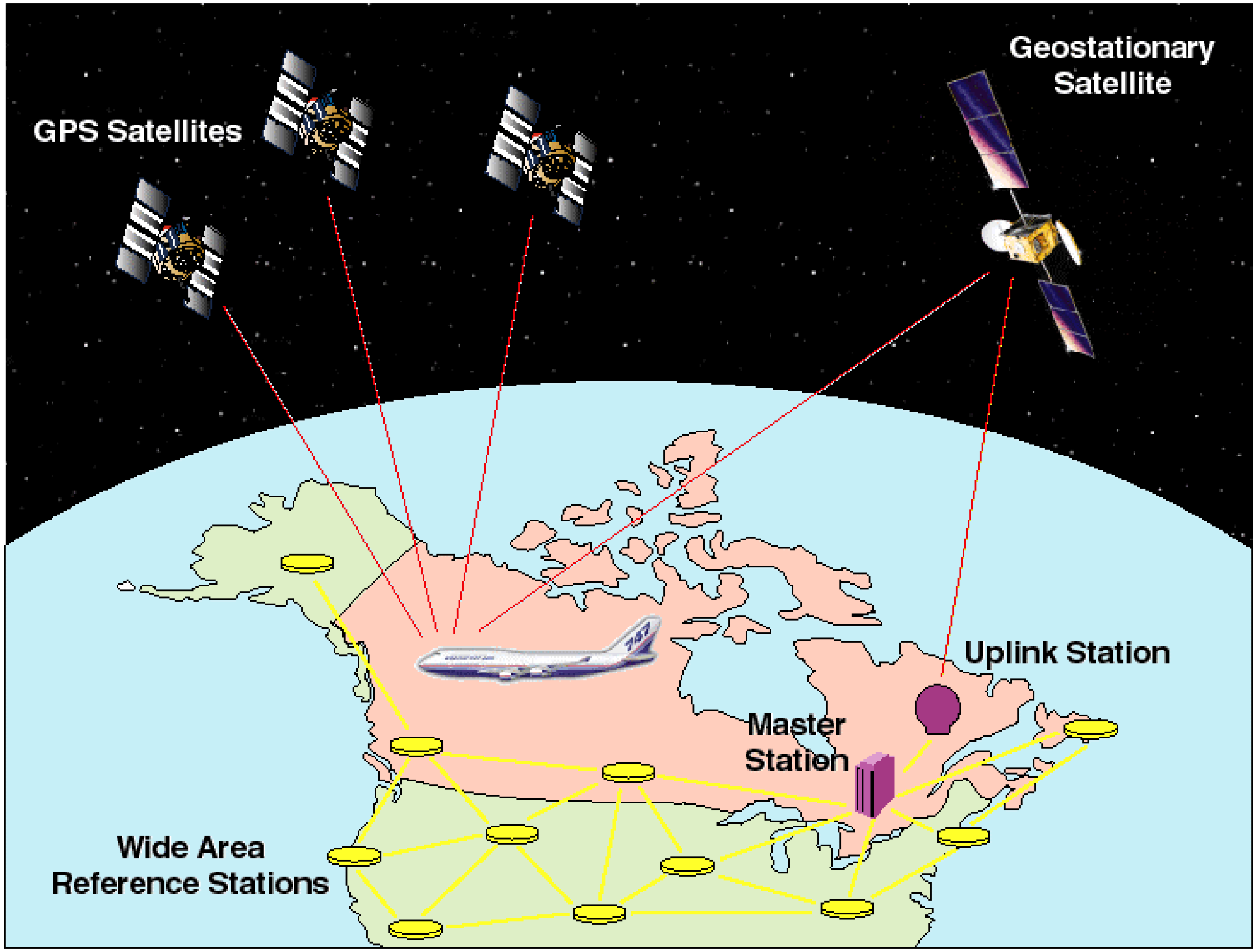
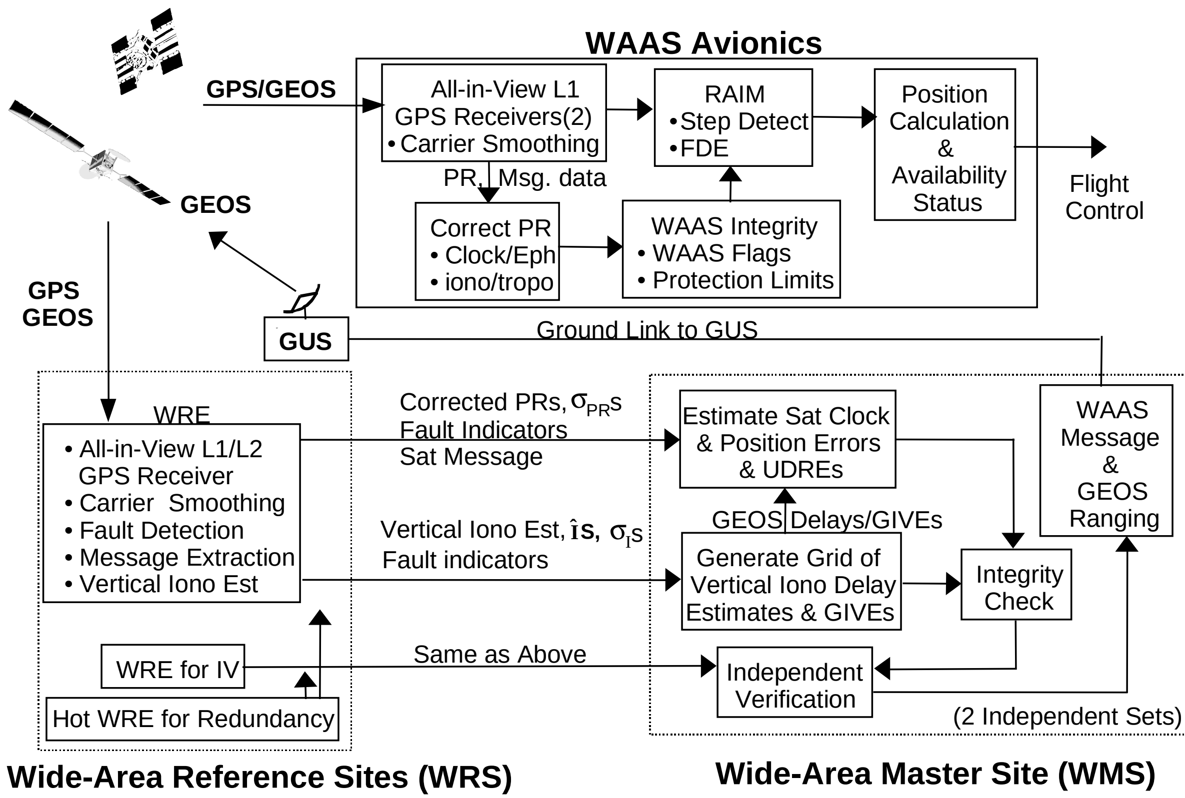
Introduction

- FAA sponsored Wide Area Augmentation System (WAAS) designed to provide en-route through precision approach navigation and integrity information to suitably equipped aircraft
- UNB is currently working with Nav Canada to investigate atmospheric effects on WAAS in Canadian airspace
- The airborne tropospheric model to be used in WAAS avionics was designed and tested at UNB
- As we approach solar maximum, so the potential effect of the ionosphere on GPS and WAAS intensifies; UNB have been charged with investigating ionospheric limitations on WAAS use in Canadian airspace
- CWAAS - Canadian WAAS

CWAAS


GPS Satellites
Geostationary Satellite
Uplink Station
Master Station
Wide Area Reference Stations

WAAS Architecture



From JHU APL *GPS Risk Assessment Study*

WAAS Accuracy Requirements

- Accuracy requirements for WAAS are expressed in terms of the navigation system error (NSE)
- In an operational system, the airborne GPS/WAAS receiver calculates horizontal and vertical protection levels (HPL_{WAAS} and VPL_{WAAS}), which must be less than the allowed NSE with a probability of 99.999% to ensure integrity
  - The HPL and VPL values describe a region, centred on the true position, which is assured to include the indicated horizontal and vertical positions respectively
  - The HPL and VPL values are computed as the sum of the variances of the ionospheric, tropospheric, airborne receiver, clock and orbit errors

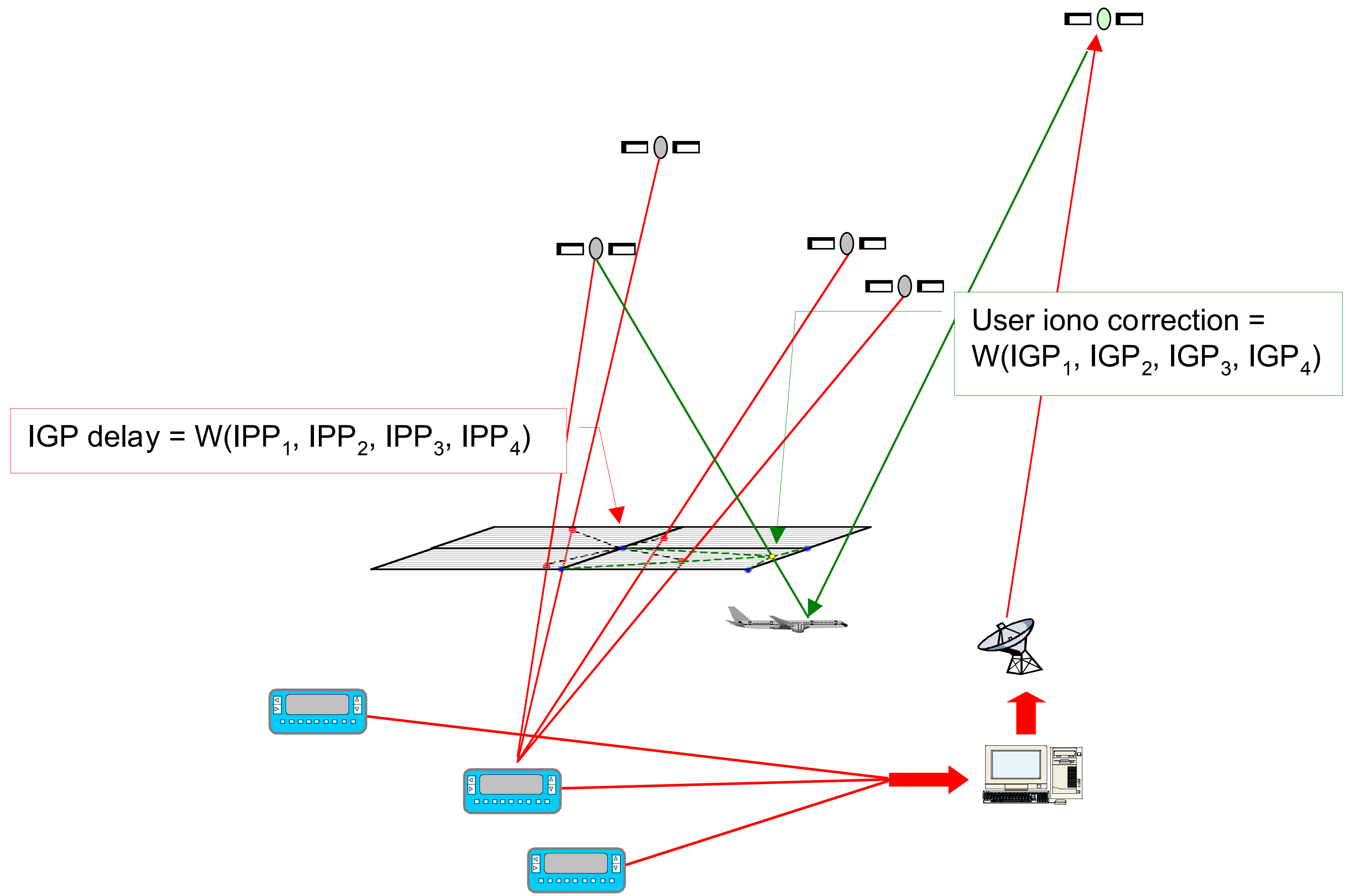
Ionospheric Delay Mitigation Techniques in WAAS

- A network of continuously operating reference receivers provides dual frequency carrier phase and pseudorange measurements
- Line-of-sight ionospheric delay values estimated from each receiver to each satellite
  - This involves estimating and removing the satellite and receiver hardware biases
- Vertical ionospheric delay values at each of a series of ionospheric grid points (IGPs) are estimated along with an error bounding value (GIVE)
  - The surface described by these discrete grid points is at a height of 350km
  - The spacing of these IGPs is latitude dependant, with a 5x5 degree grid at latitudes less than 55N and S, a ten by ten degree grid spacing between 55 and 75N and S, and 10 degrees of latitude by 90 degrees of longitude spacing above 75N and S
- Corrections for user line-of-sight delays, and a user error bounding value (UIVE) can then be created

Representing a Continuous Ionosphere with a Discrete Grid

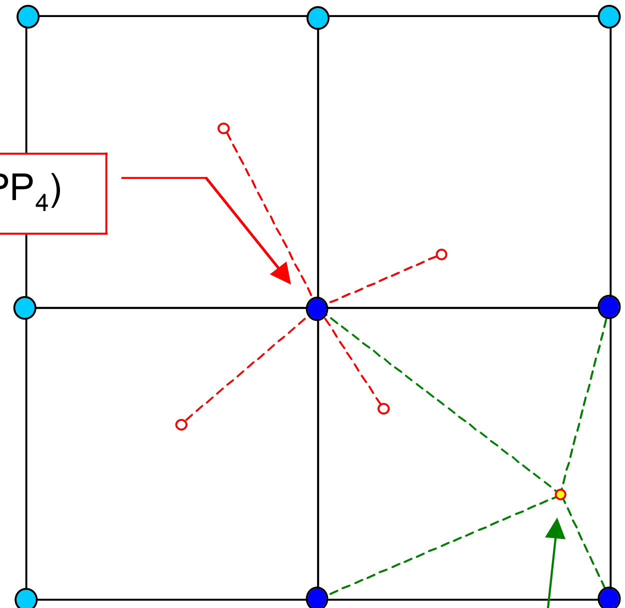
- In order to minimise the WAAS link bandwidth and avionics computation requirements, a discrete set of IGP delays and error bounds are broadcast to the user
- In prevailing conditions at mid latitudes, this grid system has been shown to adequately represent the ionosphere
- During ionospheric storms, the occurrence of which will increase with solar activity, temporal and spatial gradients, especially in the equatorial, auroral and polar zones will require significant degradation of the broadcast IGP accuracy, typical forecasts being an increase of 2-3 times for mid latitudes

WAAS Ionospheric Modelling Concept



WAAS Ionospheric Modelling Concept

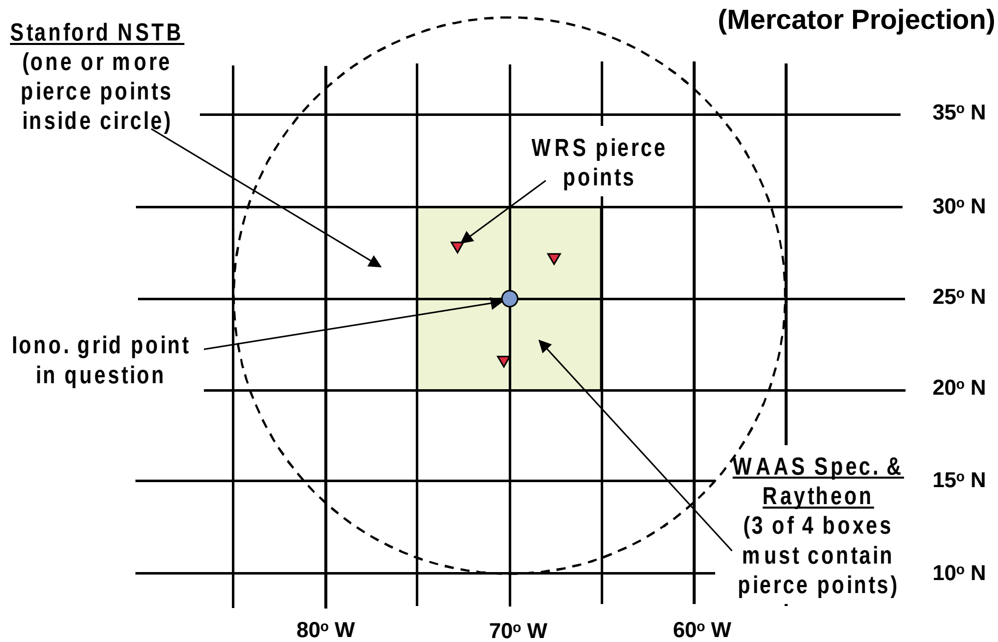
IGP delay = W(IPP_1, IPP_2, IPP_3, IPP_4)



User iono correction = W(IGP_1, IGP_2, IGP_3, IGP_4)

corrected pseudorange = measured pseudorange – (user iono correction * mapping function)

Ionospheric Grid Point Validity



From JHU APL *GPS Risk Assessment Study*

The Concept of GIVE

- The Grid Ionospheric Vertical Error (GIVE) is designed to put a bound on the postcorrection ionospheric vertical error at each of the grid nodes
- The GIVE value should be less than 2m 99.9 % (3.29σ) of the time
- This corresponds to a requirement of ~60cm rms accuracy at each of the grid points

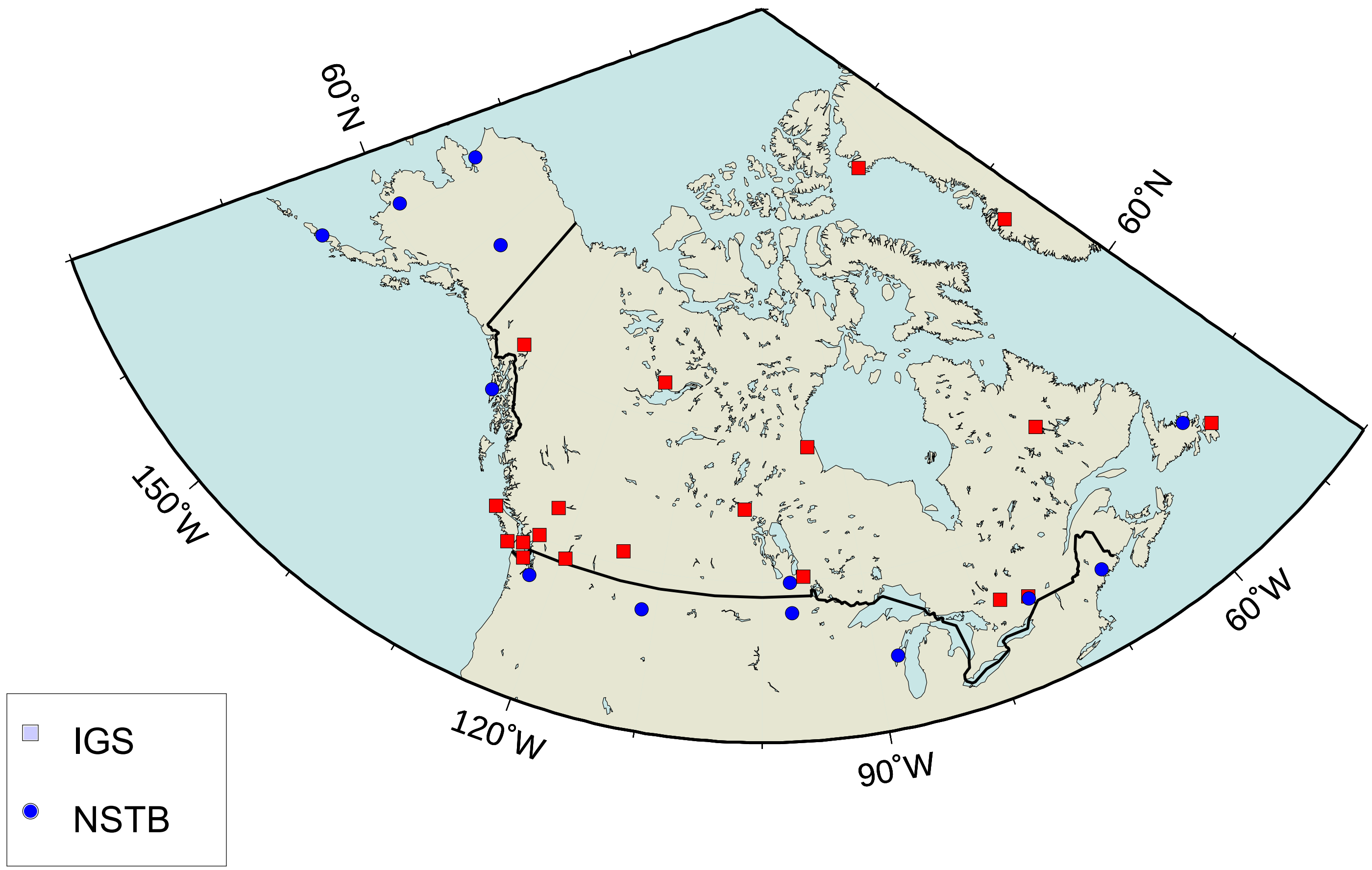
Issues

- Potential ionospheric limitations on WAAS use over the Canadian landmass
  - Grid point density
  - Range error:
    - anecdotal evidence suggests increases in range delays of up to 10 metres within a time interval of 2-3 minutes, and return within about the same time at auroral and polar latitudes during disturbed conditions at solar maximum
  - Scintillation:
    - magnitude and frequency of occurrence of “significant” scintillations in the auroral and sub-auroral zone
    - identification of potentially problematic periods for tracking of GPS and/or WAAS signals both by user and reference receivers
    - prediction of effects of increasing solar activity

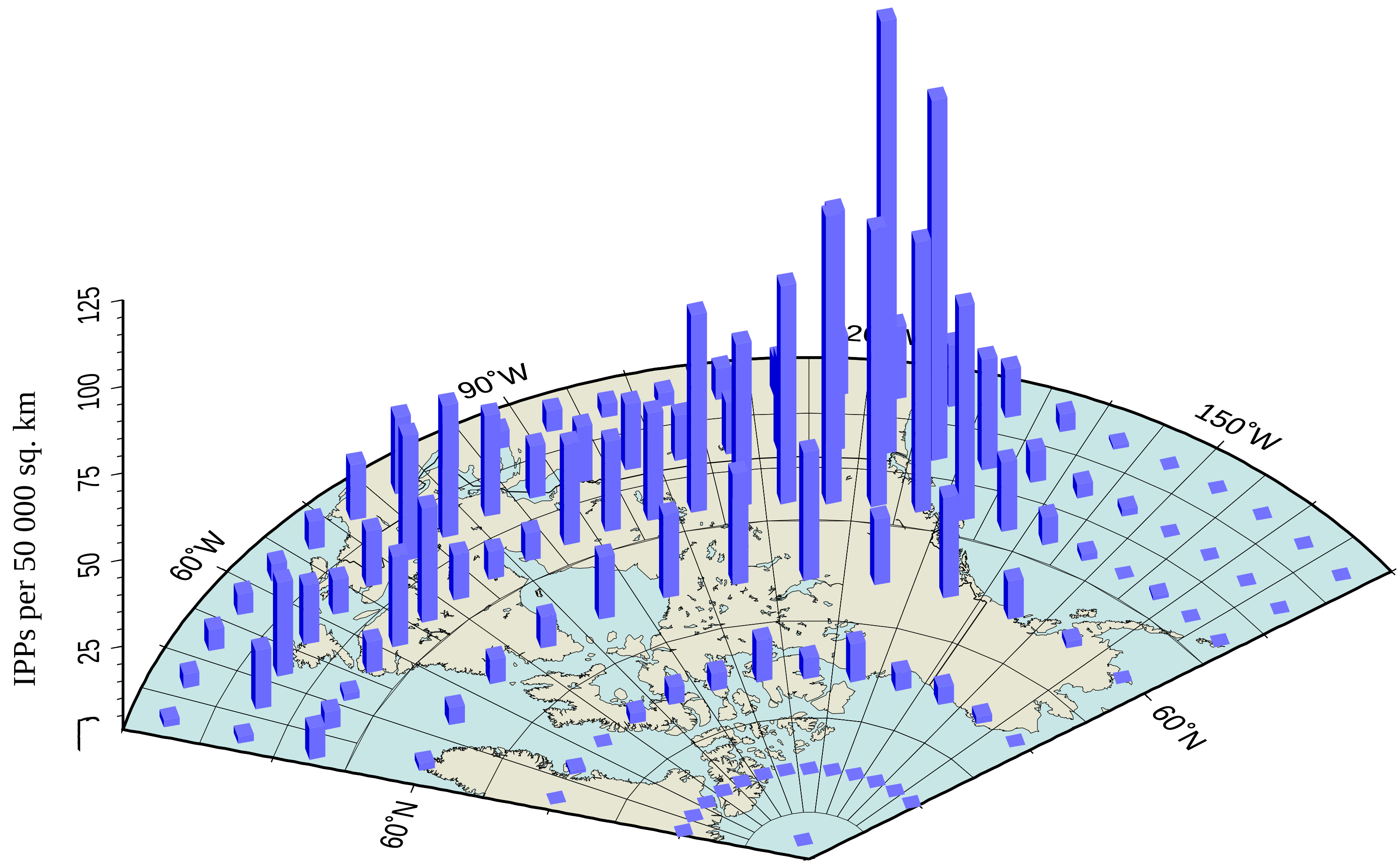
Research - Past, Present and Future

- Work completed to Date
  - Analysis software written to produce graphical representations of pierce point density and grid point status
  - Software written to produce grid ionospheric vertical delays (GIVD) and associated GIVE values.
    - Input data is RINEX format dual frequency GPS from IGS and NSTB sites
- Work in Progress
  - Evaluation of the model accuracy is done via a WAAS user simulation, receiving the "broadcast" delays and GIVEs and applying these to the users pseudorange values
  - How far north will the current network of WAAS reference sites provide reliable ionospheric corrections?

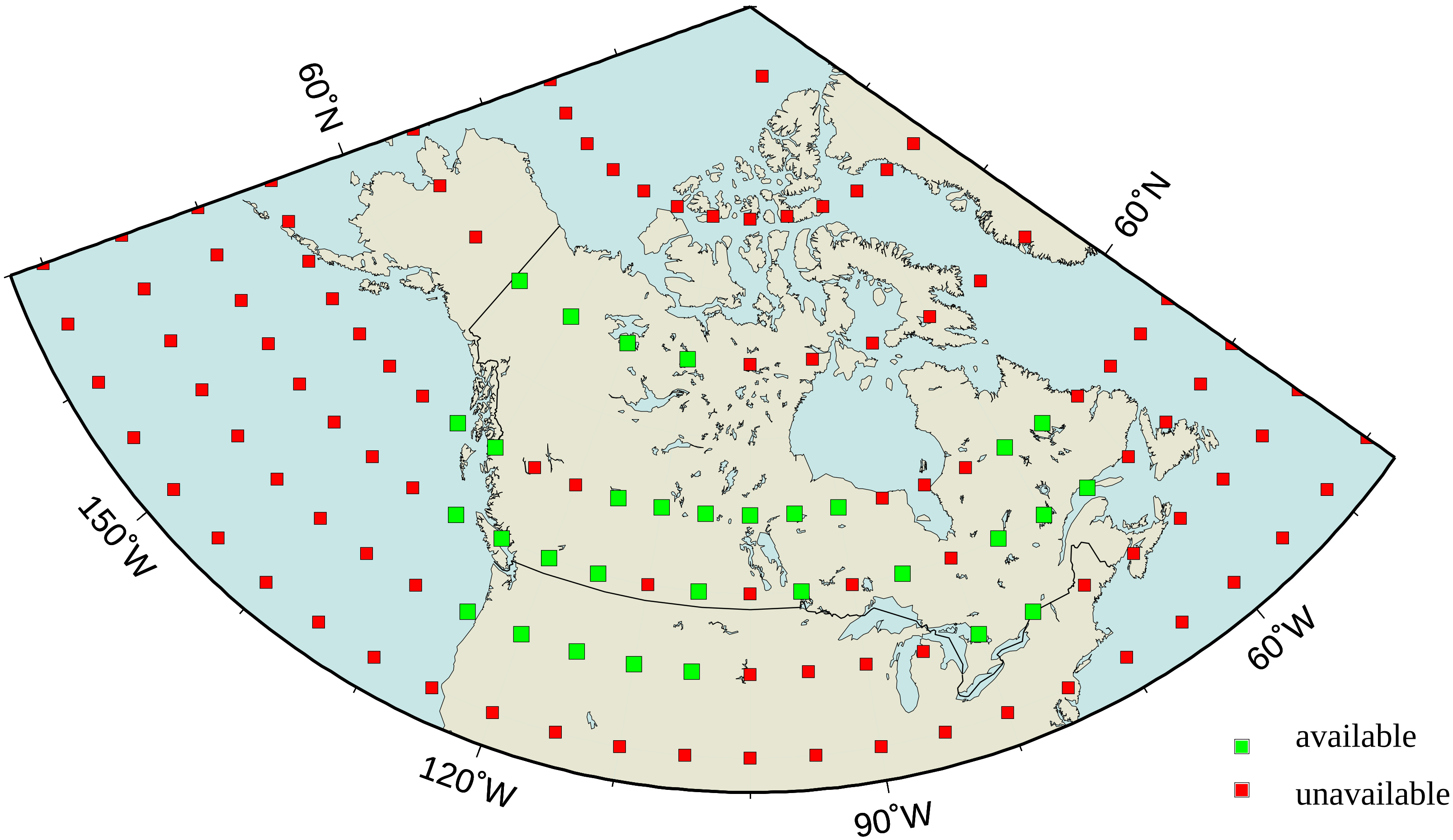
NSTB and IGS Station Locations



Ionospheric Pierce Point Density



Ionospheric Grid Point Status



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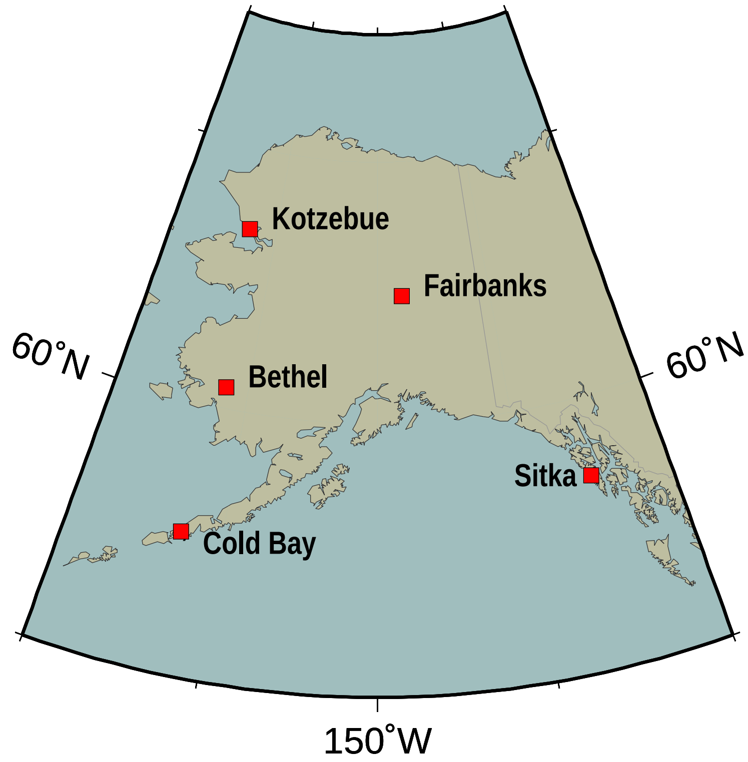
Scintillations

- What are the effects of rapid fluctuations of amplitude and phase of the GPS signal on the user and service provider?
- How can the occurrence of such scintillations be monitored?
- How can the *effect* of such scintillations be monitored?
- Previous work has shown a distinct correlation between enhanced ionospheric activity and losses of lock of the L2 signal.
- Since estimation of the ionospheric delay with GPS relies on utilizing the dispersive nature of the ionosphere, loss of one frequency precludes such measurement.
- This presentation reviews 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.

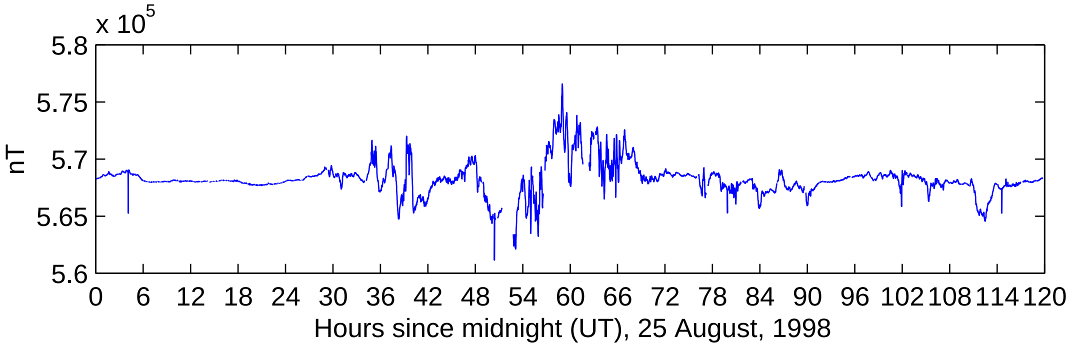
FAA National Satellite Test Bed (NSTB)

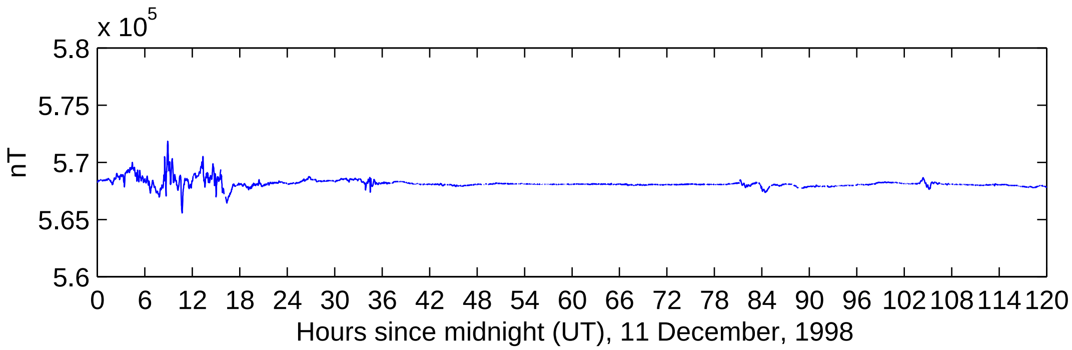
- Network of dual frequency GPS receivers, 5 of which are in Alaska.
- Two days (27 August and 13 December 1998) of 1Hz dual frequency data from Kotzebue, Fairbanks and Cold Bay were used.



Geomagnetic Activity at College, AK

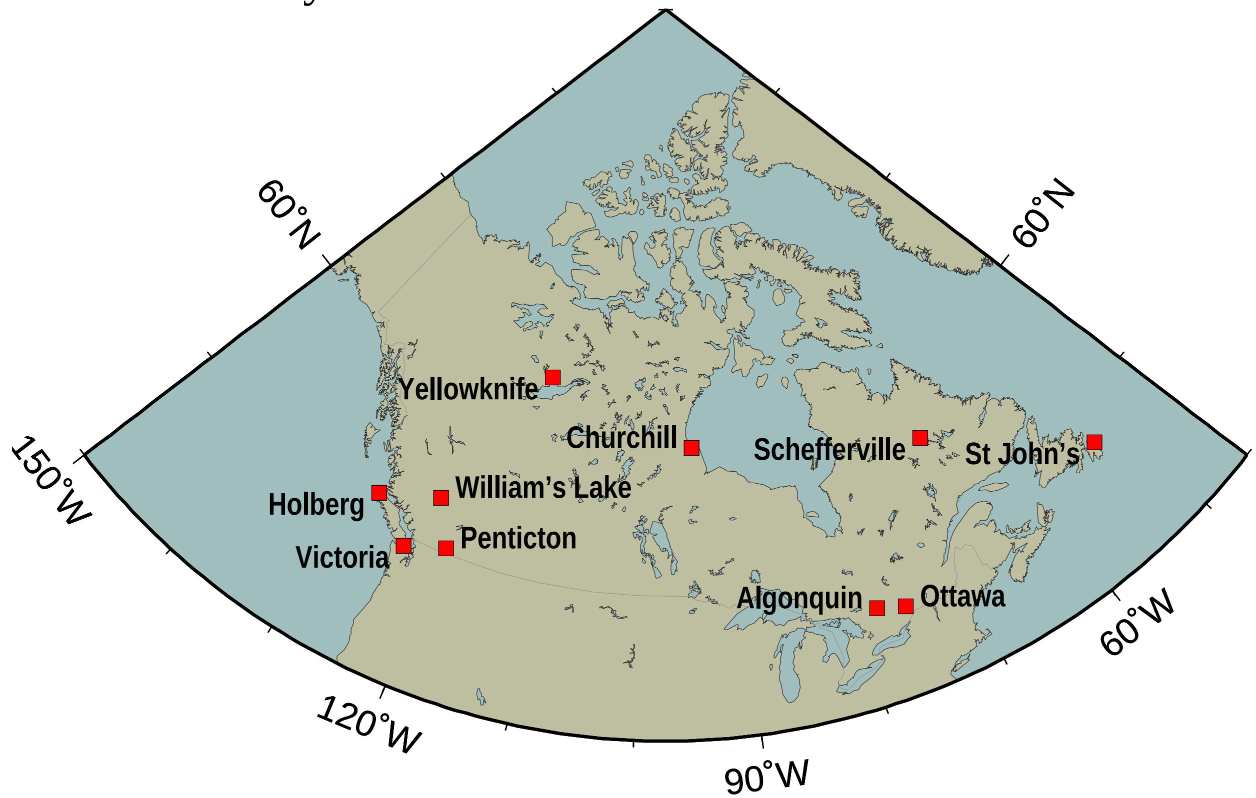
- The 1 minute mean of the total variation of the geomagnetic field measured at College, AK is shown for 25-29 August and 11-15 December, 1998.
- Note the clear increase in geomagnetic activity during 27 August, compared to the surrounding days, and to the period 11-15 December.





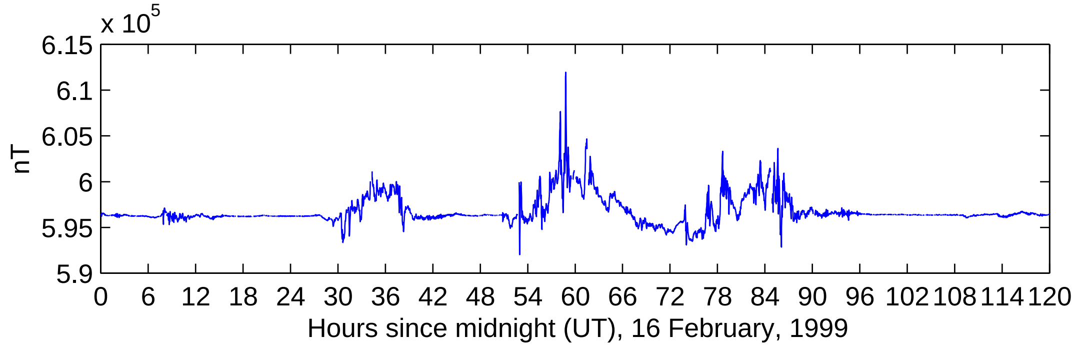
Canadian Active Control System (CACS)

- Network of dual frequency GPS receivers using external atomic frequency standards.
- Three days of 0.5Hz dual frequency data from CACS reference receivers at Yellowknife, Churchill and Algonquin were made available, covering the period 17-19 February 1999.



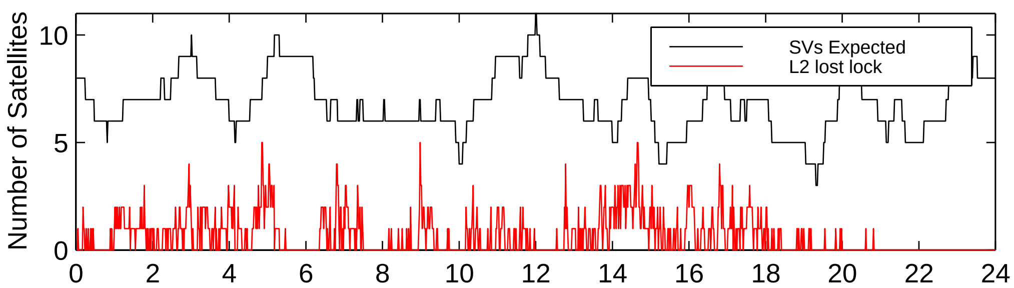
Geomagnetic Activity at Yellowknife, NWT

- The 1 minute mean of the total variation of the geomagnetic field measured at Yellowknife is shown for the period 16-20 February 1999.
- Note the peak of geomagnetic activity during 18 February 1999.

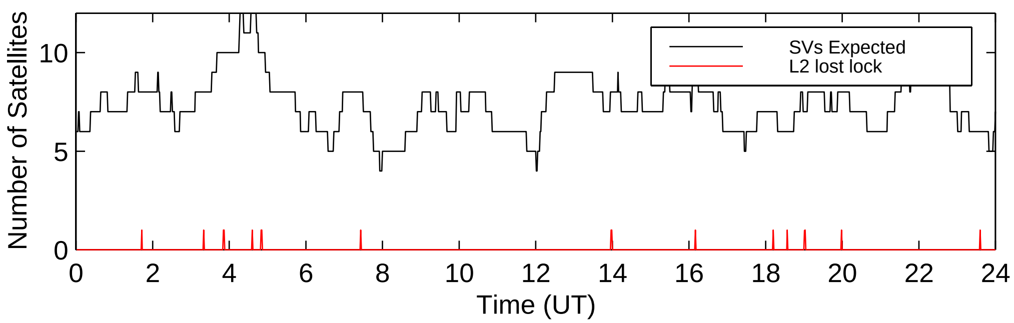


Losses of Lock on L2

- Losses of lock on the L2 carrier phase are proposed as a proxy for monitoring scintillation activity on an operational level.
- No other hardware would be required at sites already equipped with high quality dual frequency receivers.
  - This is true of both the NSTB and CACS networks.



Fairbanks, AK
27 August 1998

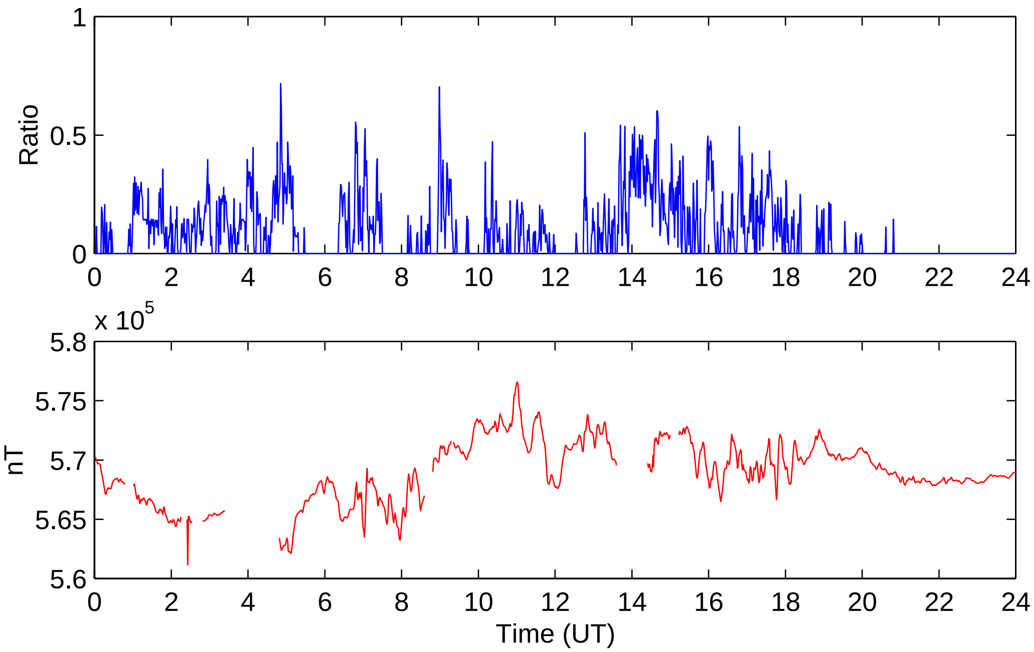


Fairbanks, AK
13 December 1998

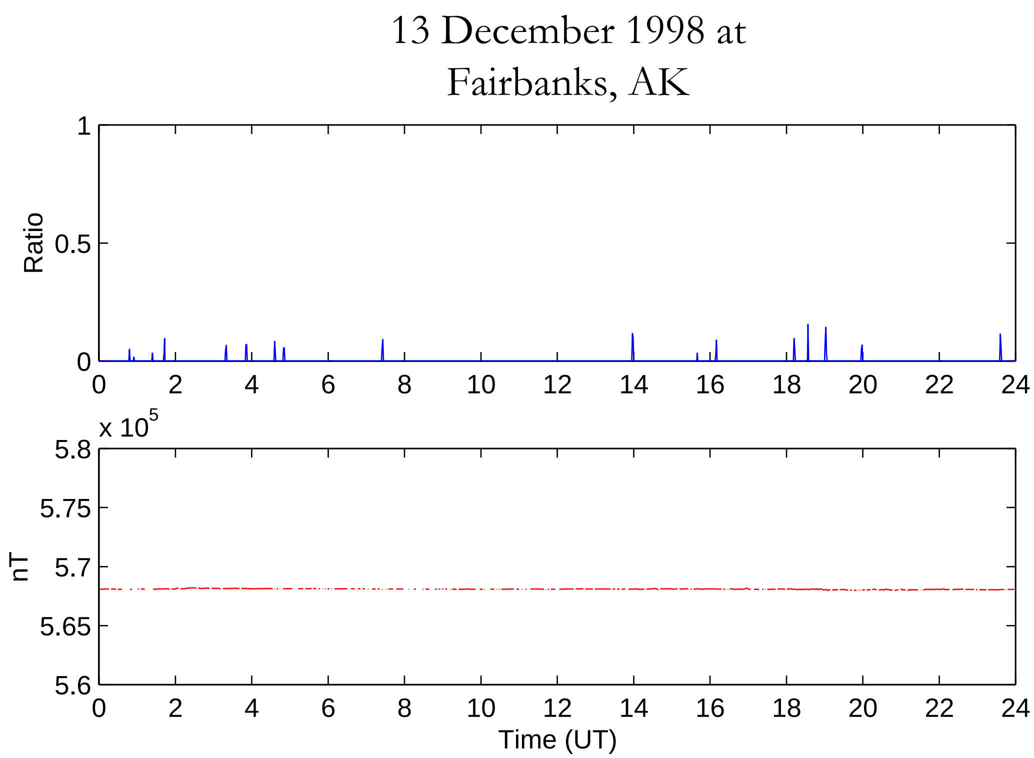
Correlation of Losses of Lock on L2 with Geomagnetic Activity

- Taking the ratio of the number of epochs for which L2 is not tracked to the number of observations expected in each 1 minute bin provides a measure of the impact of ionospheric scintillations on the receiver.

27 August 1998 at
Fairbanks, AK



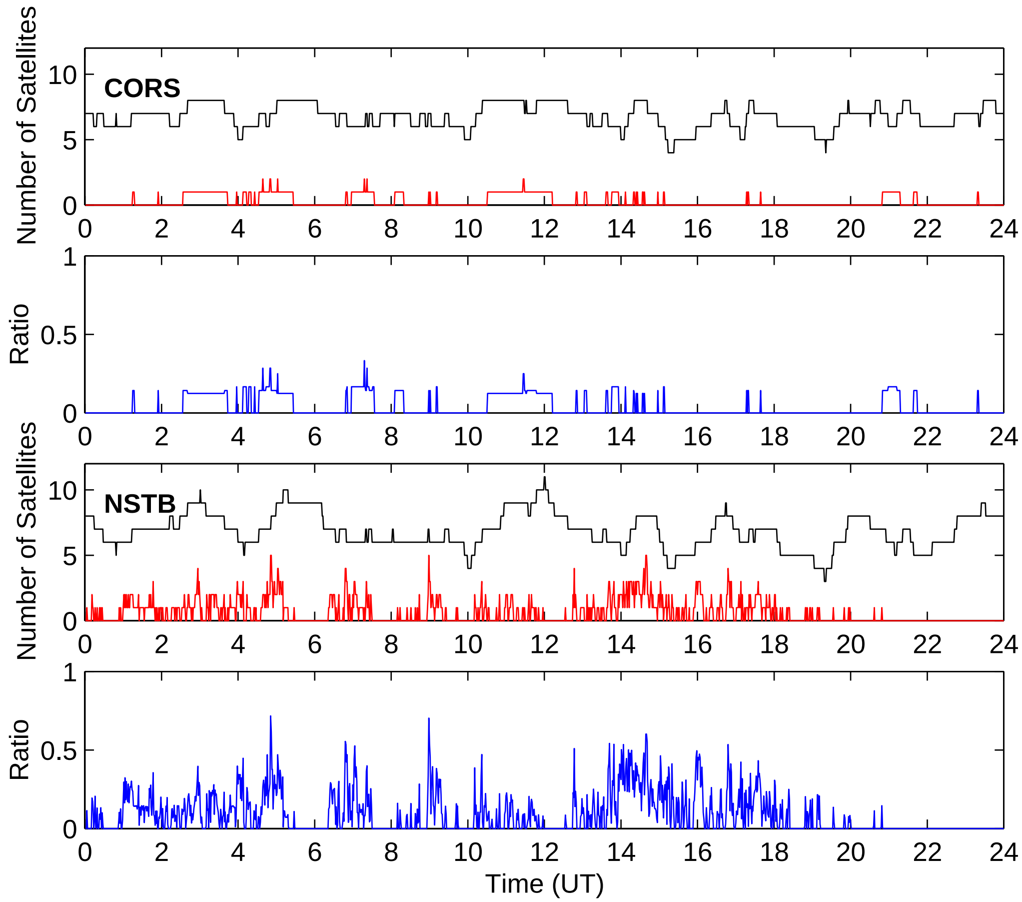
Correlation of Losses of Lock on L2 with Geomagnetic Activity



- It is clear that the ratio of losses of lock to observations expected is correlated with the level of geomagnetic activity

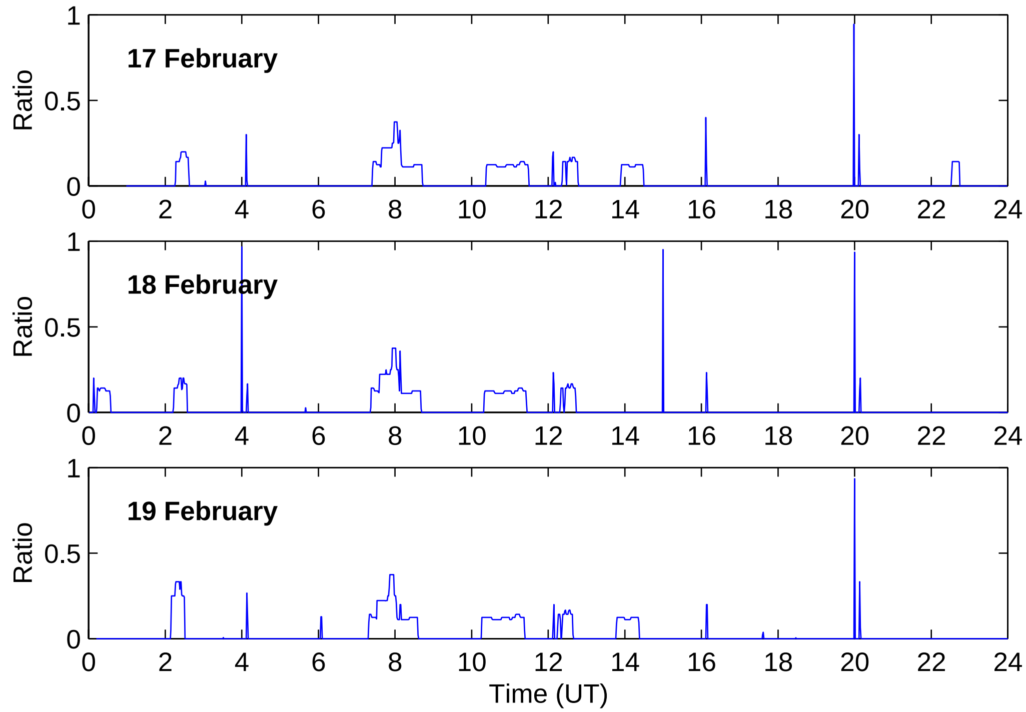
Comparison with CORS Receiver at Fairbanks

- 30 second data from an 8 channel TurboRogue SNR-8000 located in Fairbanks was obtained and used to provide a comparison with the NSTB Trimble data collected on 27 August.
- Significantly better tracking performance appears to be the case for the Rogue



Losses of Lock on L2 at CACS Receivers

- Three consecutive days of dual frequency data from the Yellowknife receiver were analysed for losses of lock on L2.



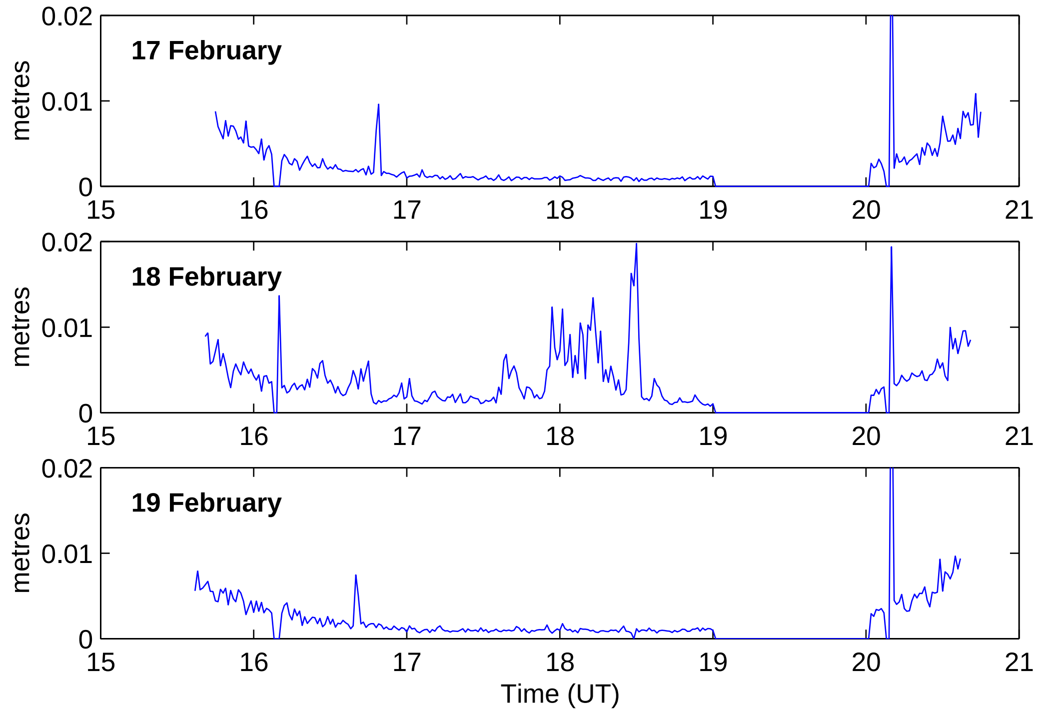
- The approximate repetition of the pattern of losses of lock suggests that these are multipath- and/or signal blockage-related rather than a result of ionospheric activity.

Rate of Change of Carrier Phase

- Given the apparent relative imperviousness of the TurboRogue receivers used at the CACS and CORS sites to rapid fluctuations in the phase of the incoming signal, some other method of quantifying the influence of ionospheric scintillation activity is required.
- Differencing the L1 and L2 carrier phase removes all systematic effects common to both frequencies:
  - satellite motion, satellite clocks, selective availability, troposphere
- High pass filtering removed any remaining constant and long period effects, and the standard deviation of 60 second bins of the data was taken.

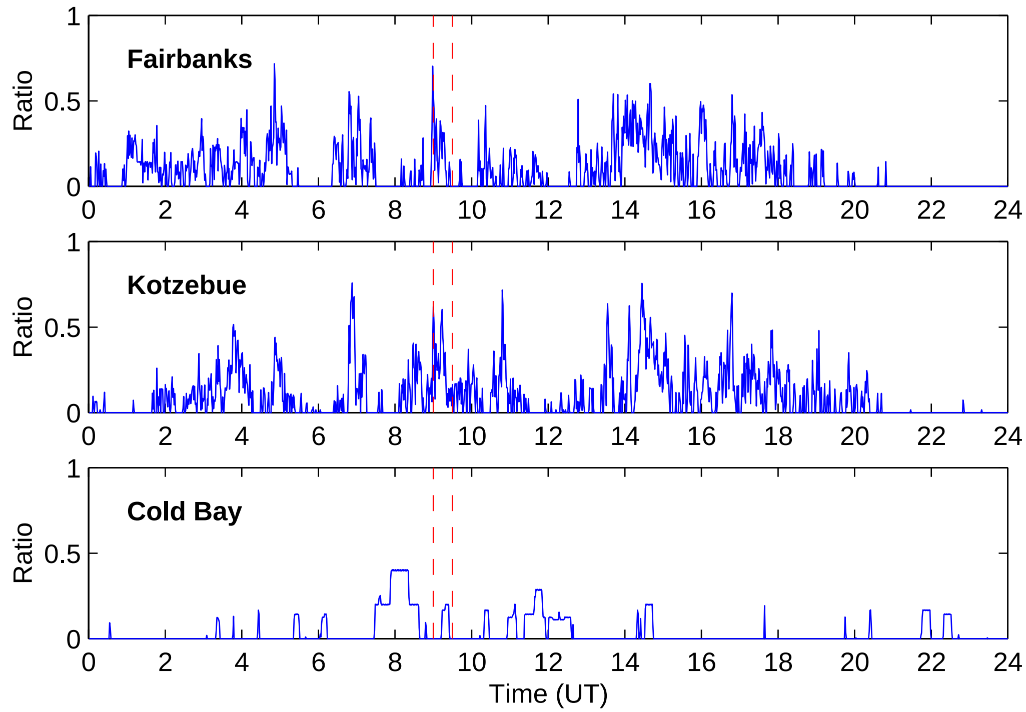
Sixty Second Standard Deviation of L1-L2 Phase Difference

- The elevation angle cut-off was set to 15 degrees in order to partially mitigate multipath effects.
- A comparison with the plots of geomagnetic field variation indicates that the standard deviation of the phase difference mirrors the ionospheric activity.
- Note the residual multipath at approximately 2010 UT



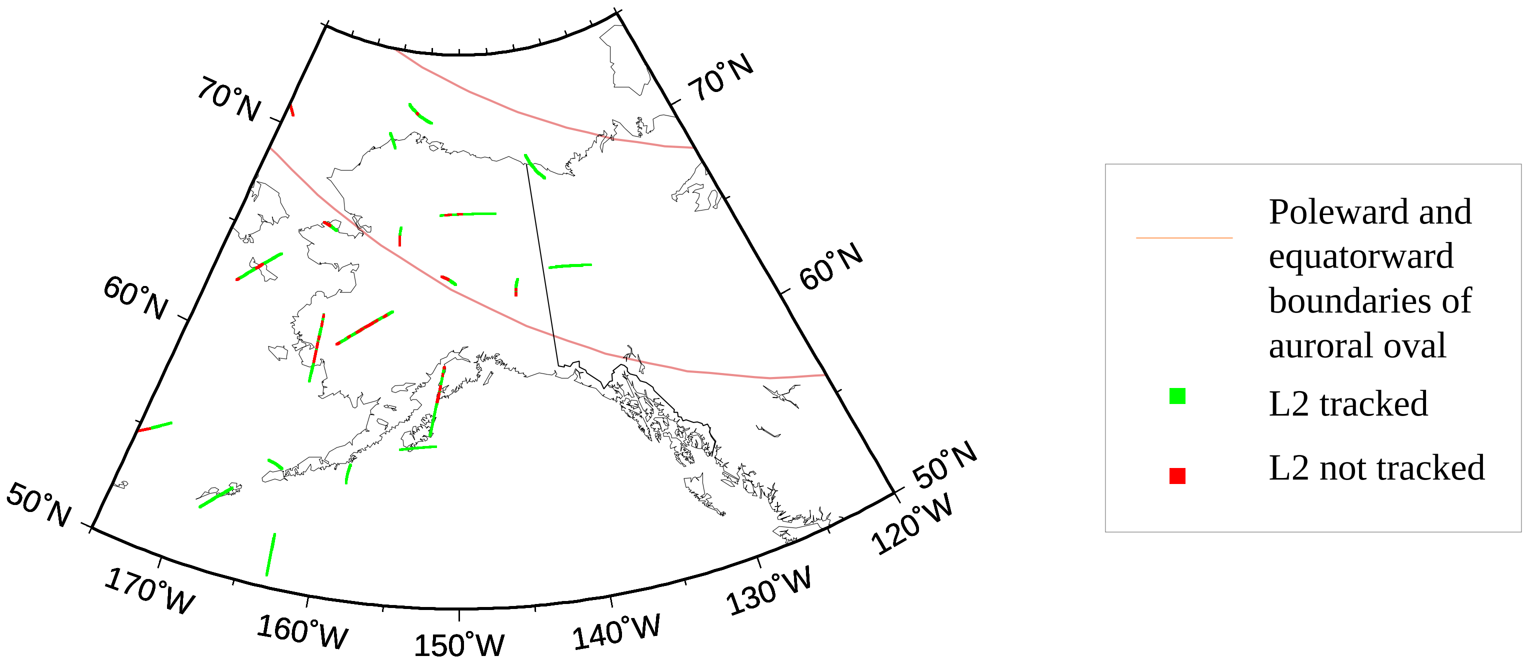
Spatial Distribution of Scintillation Activity

- Plotted below is the L2 loss ratio for 27 August 1998 at Fairbanks, Kotzebue and Cold Bay.
- Note the following:
  - The correlation between the L2 loss patterns at Fairbanks and Kotzebue
  - The striking difference between the number of losses of lock reported at Cold Bay compared to that at Fairbanks and Kotzebue



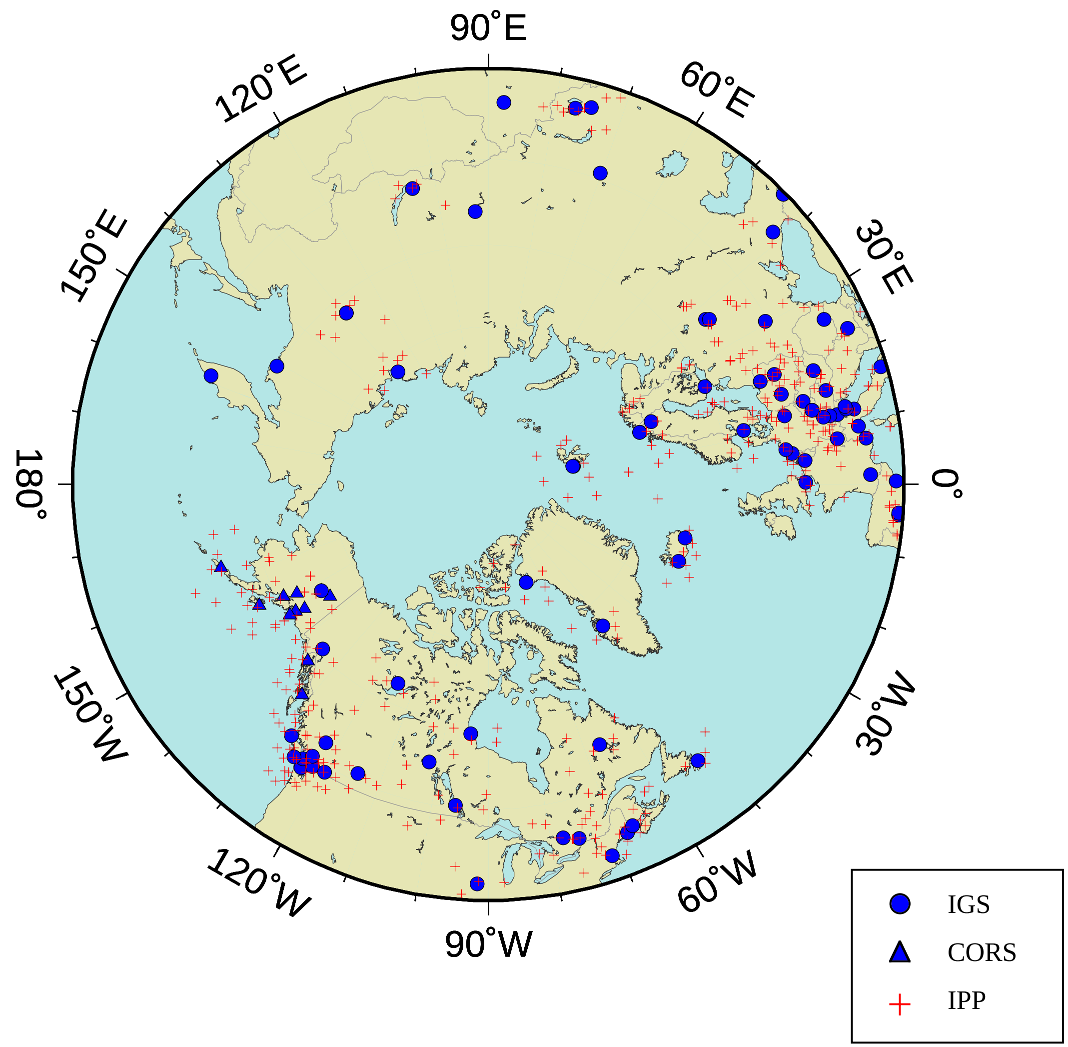
Geographical Distribution of L2 Losses of Lock

- Maps were produced of the pierce point locations of losses of lock of L2 at an altitude of 300km.
  - This height was chosen to reflect the assumed location of F-region disturbances which are thought to be the main source of phase fluctuations at the GPS frequencies.
- Also plotted is the location of the Holzworth and Meng mathematical model of the auroral oval.



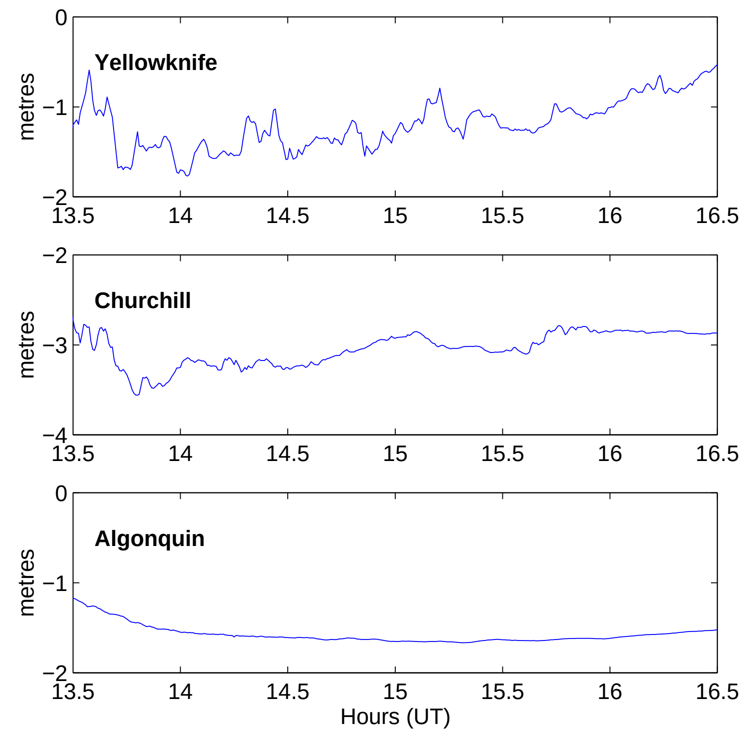
IGS and CORS Stations

- International GPS Service (IGS) and Continuously Operating Reference System (CORS) dual frequency GPS data available freely over the internet
- Data distribution is limited by the locations of these receivers, and there are still large "holes" in coverage



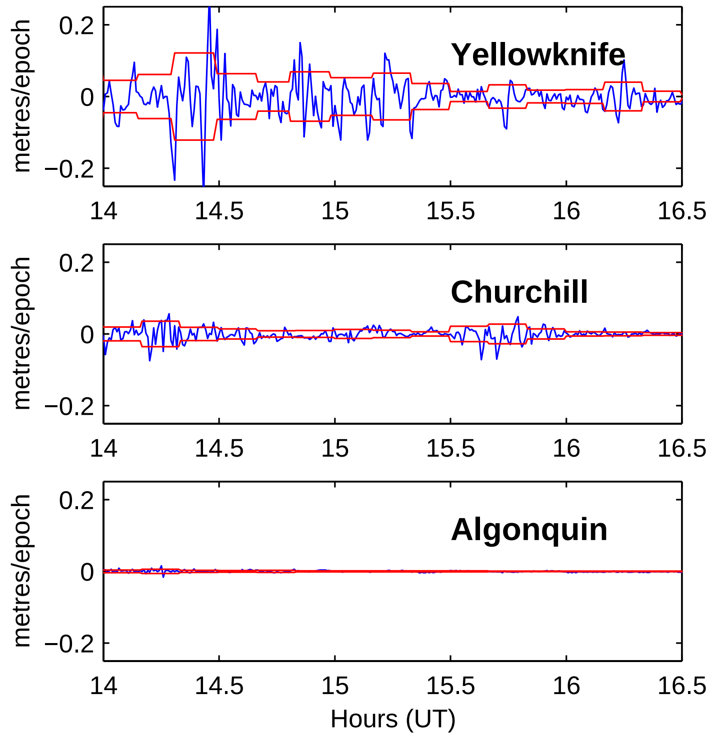
Variation of Ionospheric Delay from Dual Frequency Phase Observations

- Differencing the L1 and L2 phase observations provides a precise but ambiguous measure of ionospheric delay.
- Assuming that no cycles slips occur, the ambiguity is removed, and an accurate measure of the rate of change of ionospheric delay can be obtained.
- Large variations in ionospheric delay indicate large spatial and temporal gradients
- Large spatial and temporal gradients suggest that the satellite to receiver line of sight is passing through the auroral oval



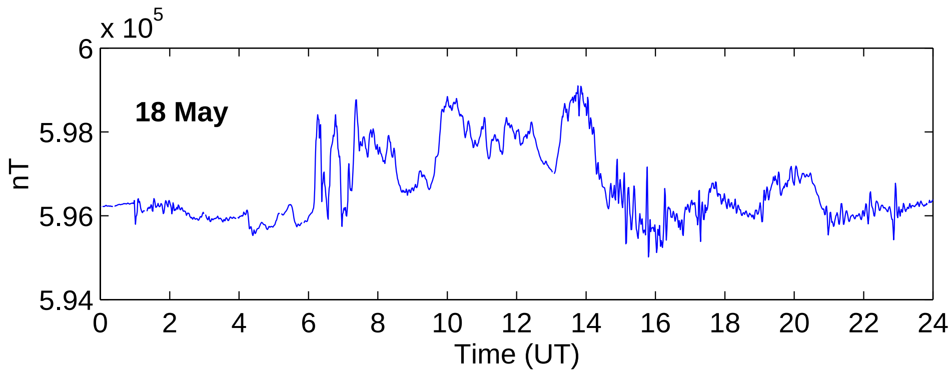
Rate of Change of Ionospheric Delay

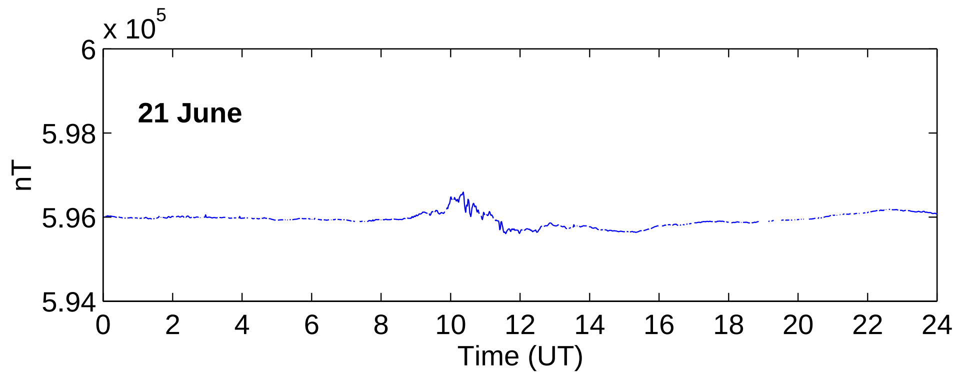
- Differencing successive epochs removes the influence of the unknown ambiguity and the inter-frequency biases
- Data binned into ten minute sections
- Standard deviation taken in each bin
- This parameter is then used as the input to surface fit routine, from which maps of the auroral zone are created



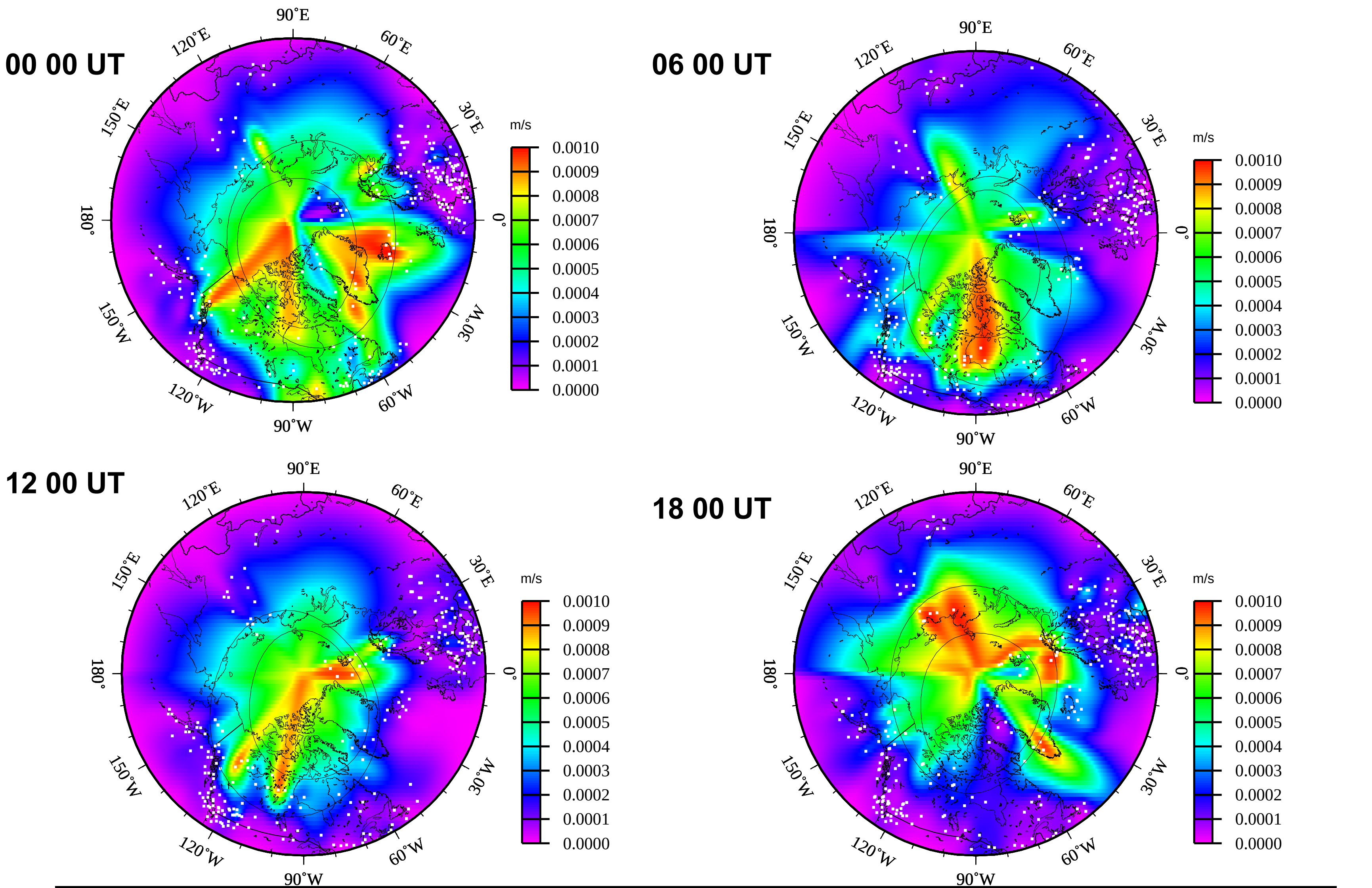
Geomagnetic Field Variation as an Indicator of Auroral Activity

- Fluctuations in the local geomagnetic field occur as a result of enhanced electric currents flowing in the auroral ionization.
- Heightened geomagnetic variability can therefore be seen as a reliable indicator of increased auroral activity.

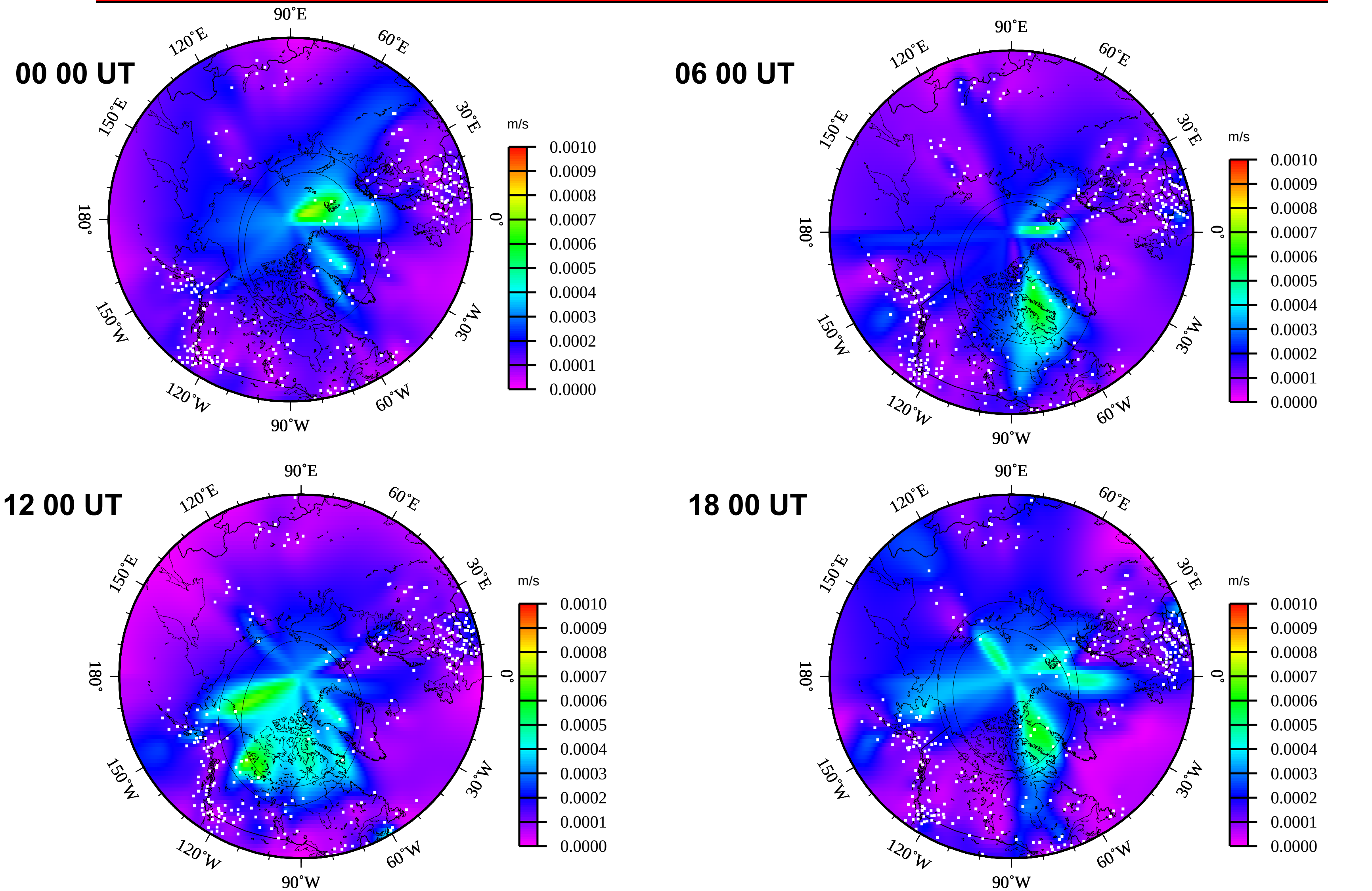




Location of Auroral Oval from GPS Observations: 18 May 1999



Location of Auroral Oval from GPS Observations: 21 June 1999



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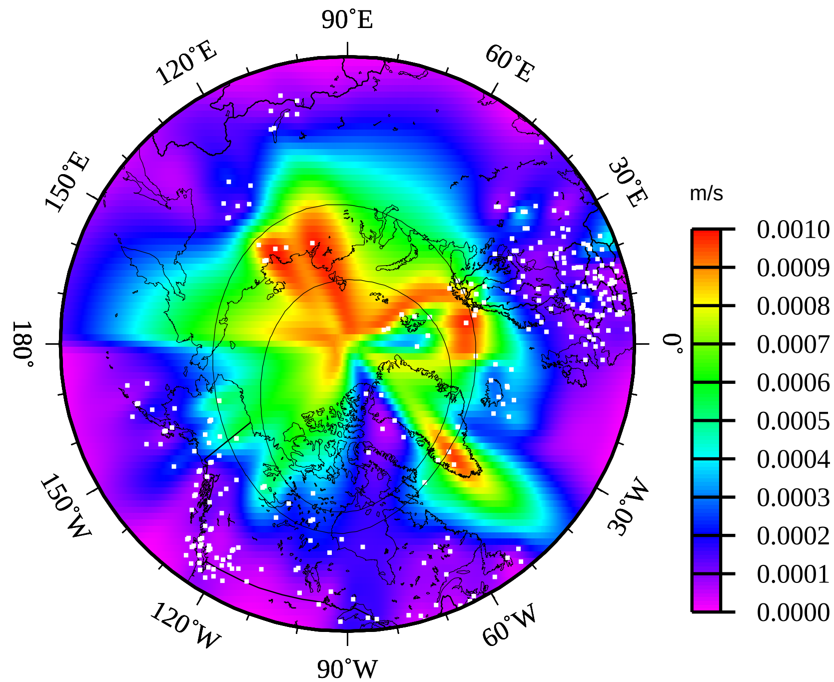
Comparison with NOAA Statistical Auroral Oval



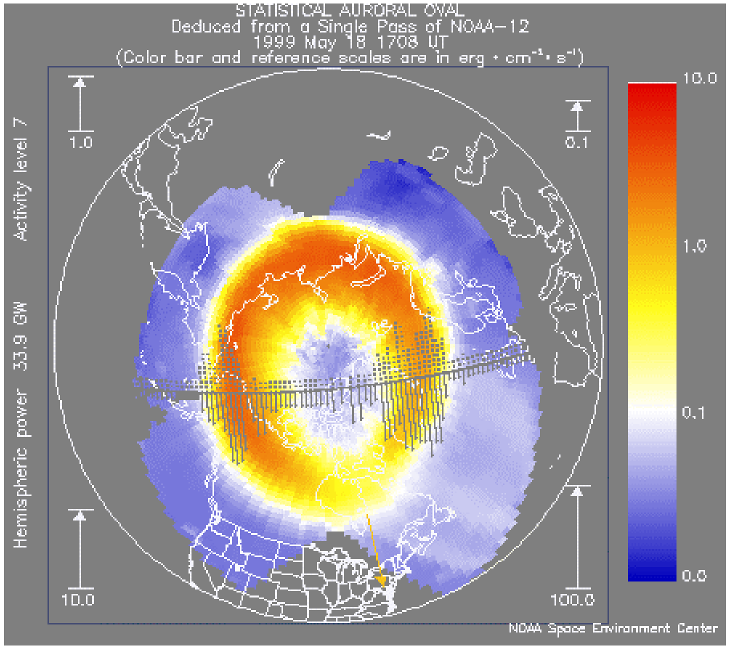


Image provided courtesy of the U.S. Department of Commerce, NOAA, Space Environment Center.

Conclusions

- Monitoring the rate of change of ionospheric delay with GPS shows promise as a method of locating the auroral oval
- Large spatial and temporal gradients in the auroral ionosphere can have an effect on GPS and WAAS in two ways:
  - any grid model is unlikely to have high enough spatial resolution to adequately represent an active auroral zone
  - scintillation activity in the auroral zone is a potential problem, and has been shown to cause losses of lock of the L2 signal
- It is therefore important to understand the spatial extent of areas which are likely to have an effect on GPS
- Due to the higher inclination of satellites, GLONASS data could be used to augment any GPS based monitoring of the auroral zone.

Summary and Future Work

- Implementation of WAAS in Canada requires careful consideration of ionospheric effects
- Validation of WAAS ionospheric grid model a primary task
- Outline system and methodology to monitor operational WAAS/CWAAS ionospheric modelling performance
- Contingency plan if current WAAS model proves to be insufficient