e-POP GAP Occultation Receiver (GAP-O) onboard CASSIOPE

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Outline

- **CASSIOPE satellite & e-POP payload, including GAP**
- **GAP-O Occultations**
- **Ionosphere electron density profiles**
- **GAP-O receiver bias**
- **Ground/GAP-O observations of high latitude structures**
- **Visualization tools and data availability**

- **Designed to study solar wind-magnetosphere-ionosphere (SW-M-I) coupling processes in polar regions, including polar ion/neutral outflow, ionospheric structure, and radio propagation**

- **CASSIOPE:** Cascade Smallsat and Ionospheric Polar Explorer

- **e-POP:** Enhanced Polar Outflow Probe

- **GAP:** GPS Attitude, Positioning, and Profiling Experiment

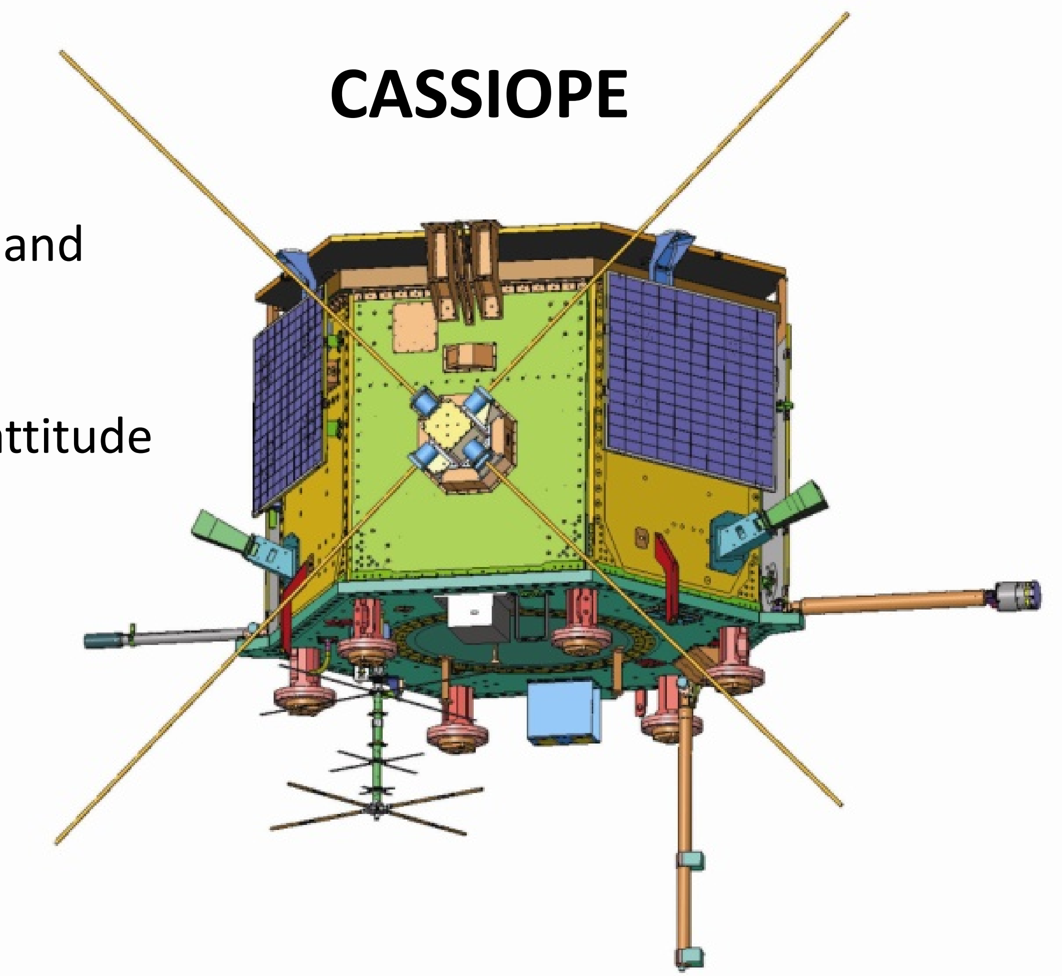
    - **P.I.:** Richard Langley (University of New Brunswick Geodesy and Geomatics Engineering)

    - **GAP-A:** 4 zenith facing antennas for navigation, spacecraft attitude and orbit determination

    - **GAP-O:** 1 anti-ram facing antenna for occultation

    - Dual frequency NovAtel OEM-4 receivers

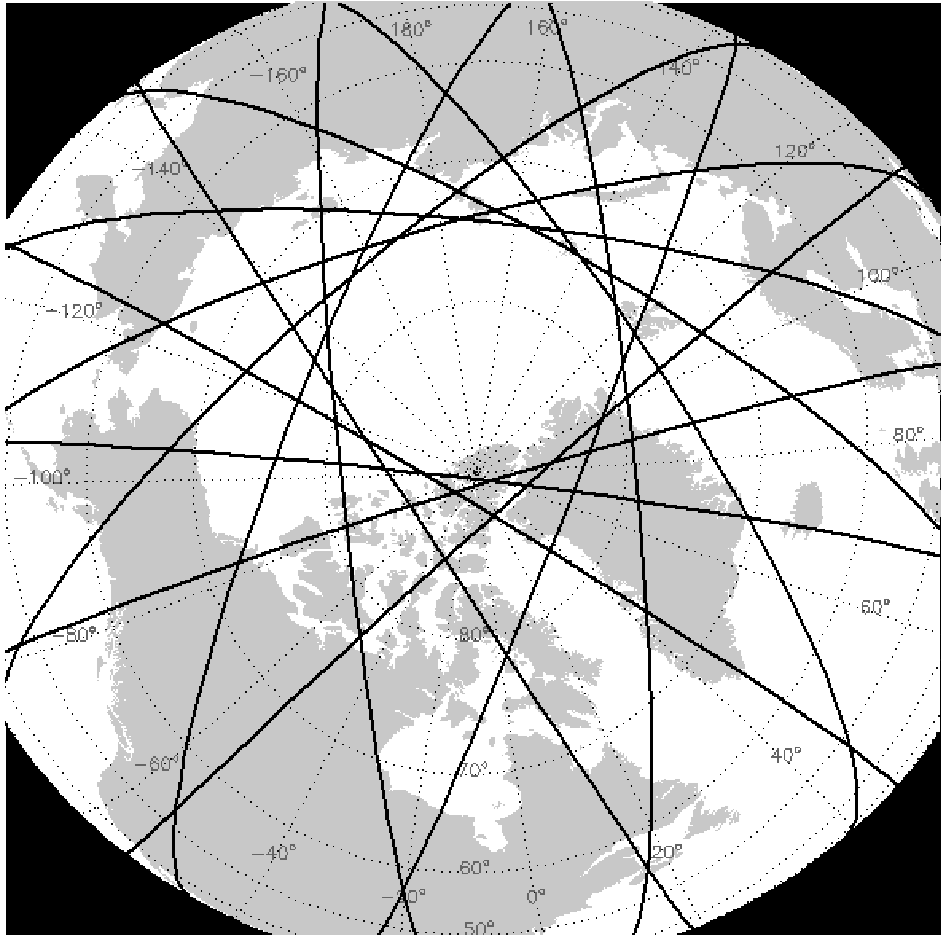
    - L1 & L2 carrier phase, pseudorange, nominal C/N_0 at 20-100 Hz resolution



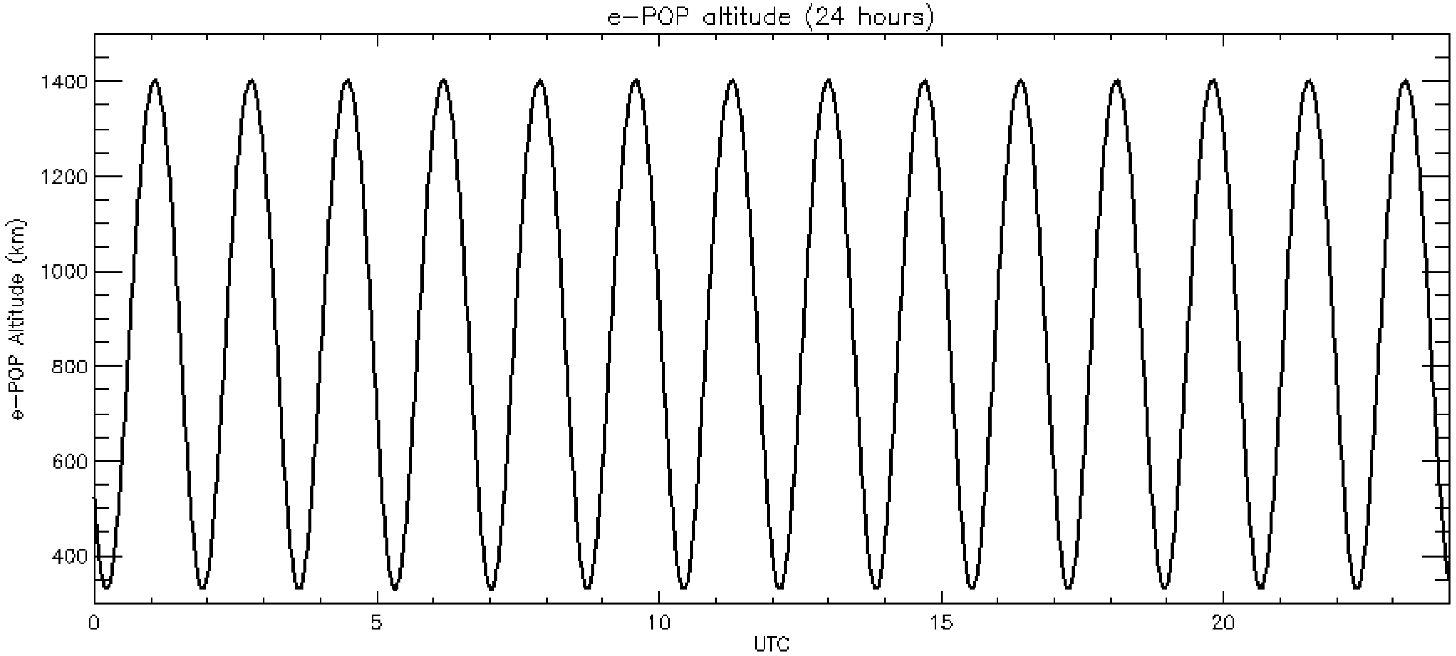
CASSIOPE orbit

- **Launched in late 2013**
- **Initial perigee: 325 km**
- **Initial apogee: 1500 km**
- **81° Inclination**
- **~1h 40min orbital period**

Ground Track (24 hours) – January 1, 2015



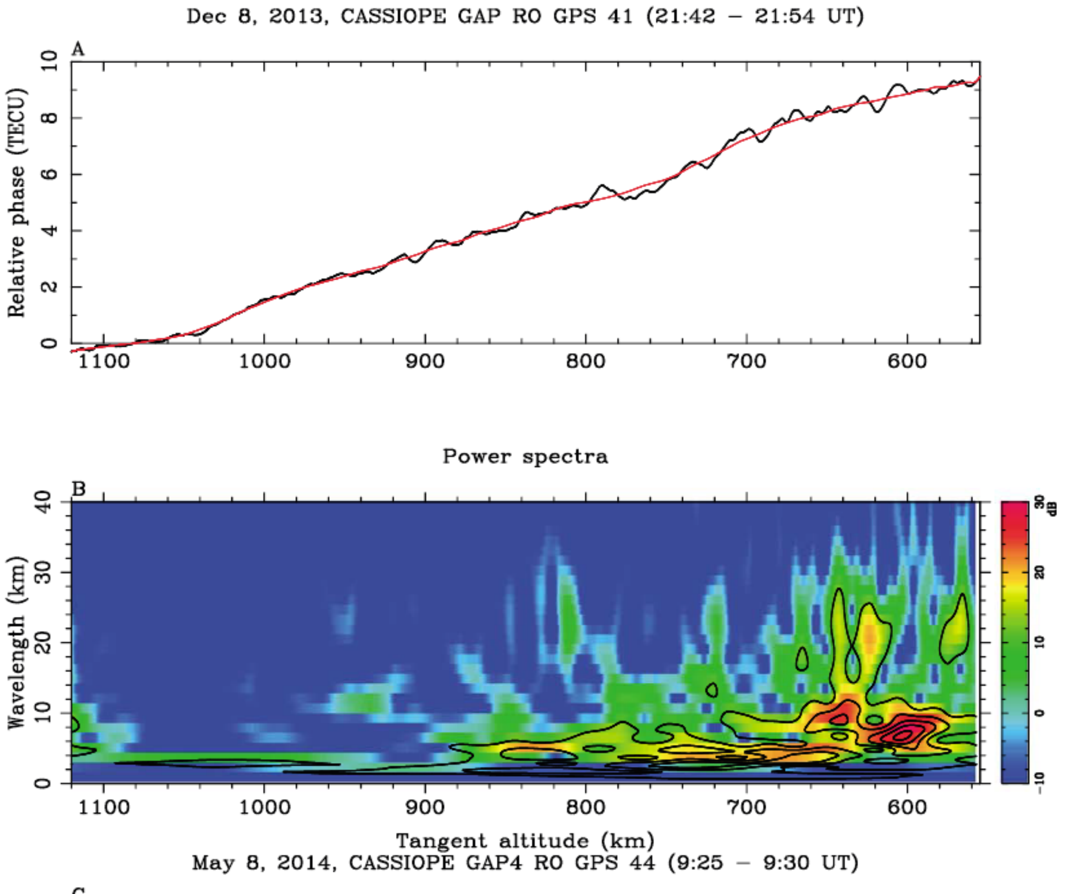
e-POP Altitude(24 hours) – January 1, 2015



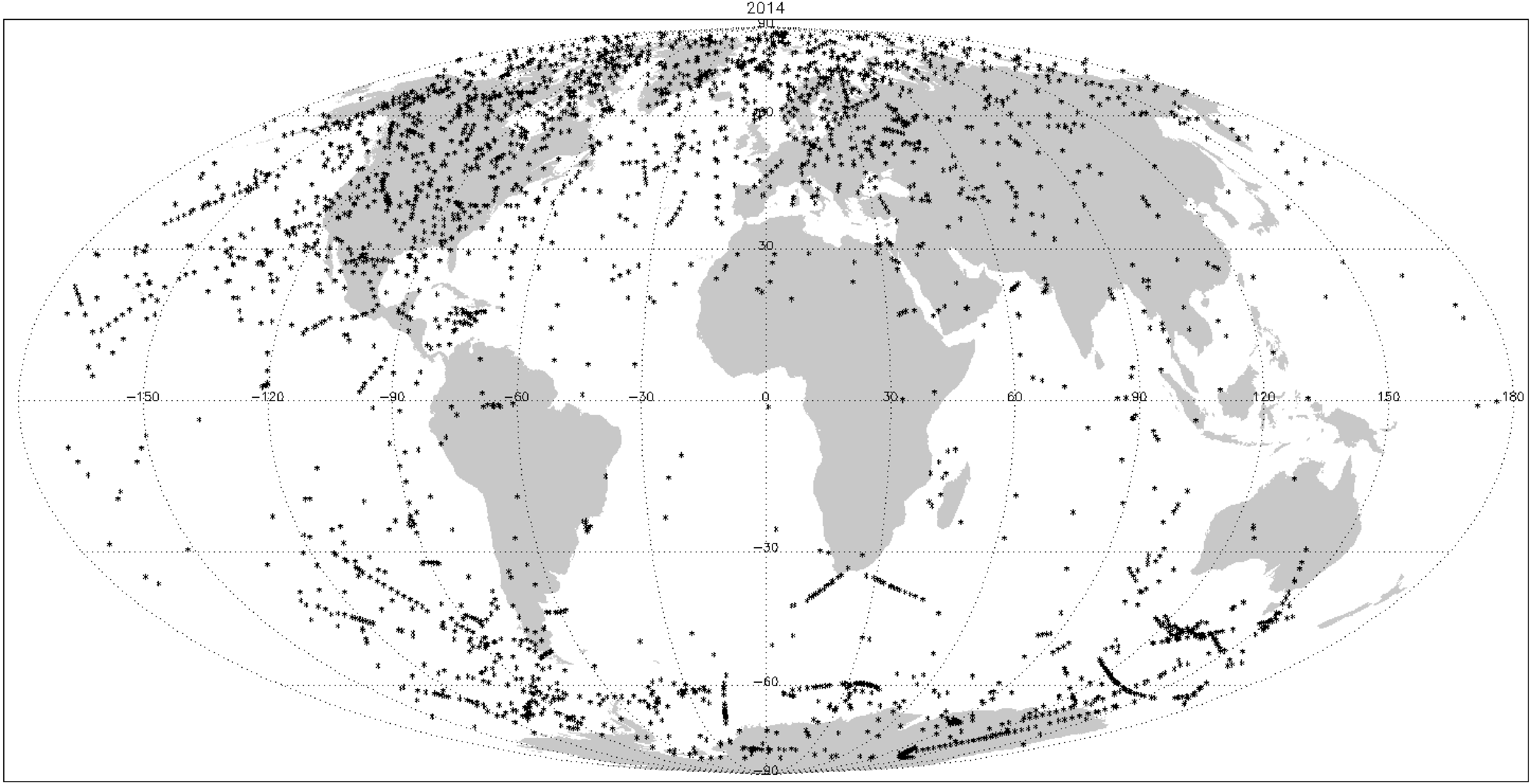
GAP-O Publications

D. Kim and R.B. Langley; The GPS attitude, positioning, and profiling experiment for the enhanced polar outflow probe platform on the Canadian CASSIOPE satellite	Geomatica (2010), 64(2), 233-243
E.B. Shume, A. Komjathy, R.B. Langley, O. Verkhoglyadova, M.D. Butala, and A.J. Manucci; Intermediate scale plasma irregularities in the polar ionosphere inferred from GPS radio occultation	Geophys. Res. Lett. (2015) DOI: 10.1002/2014GL062558

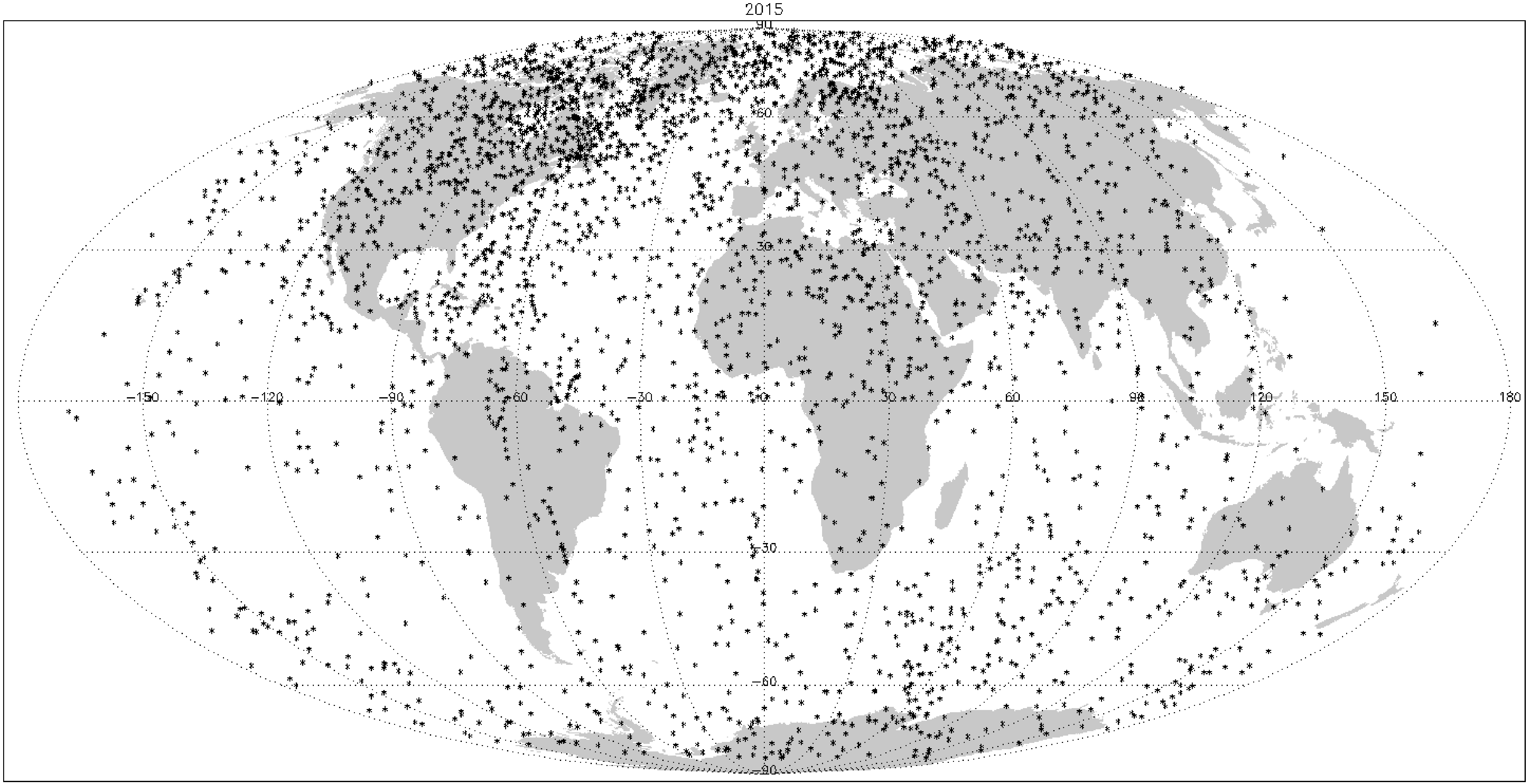
Shume et al. [2015]



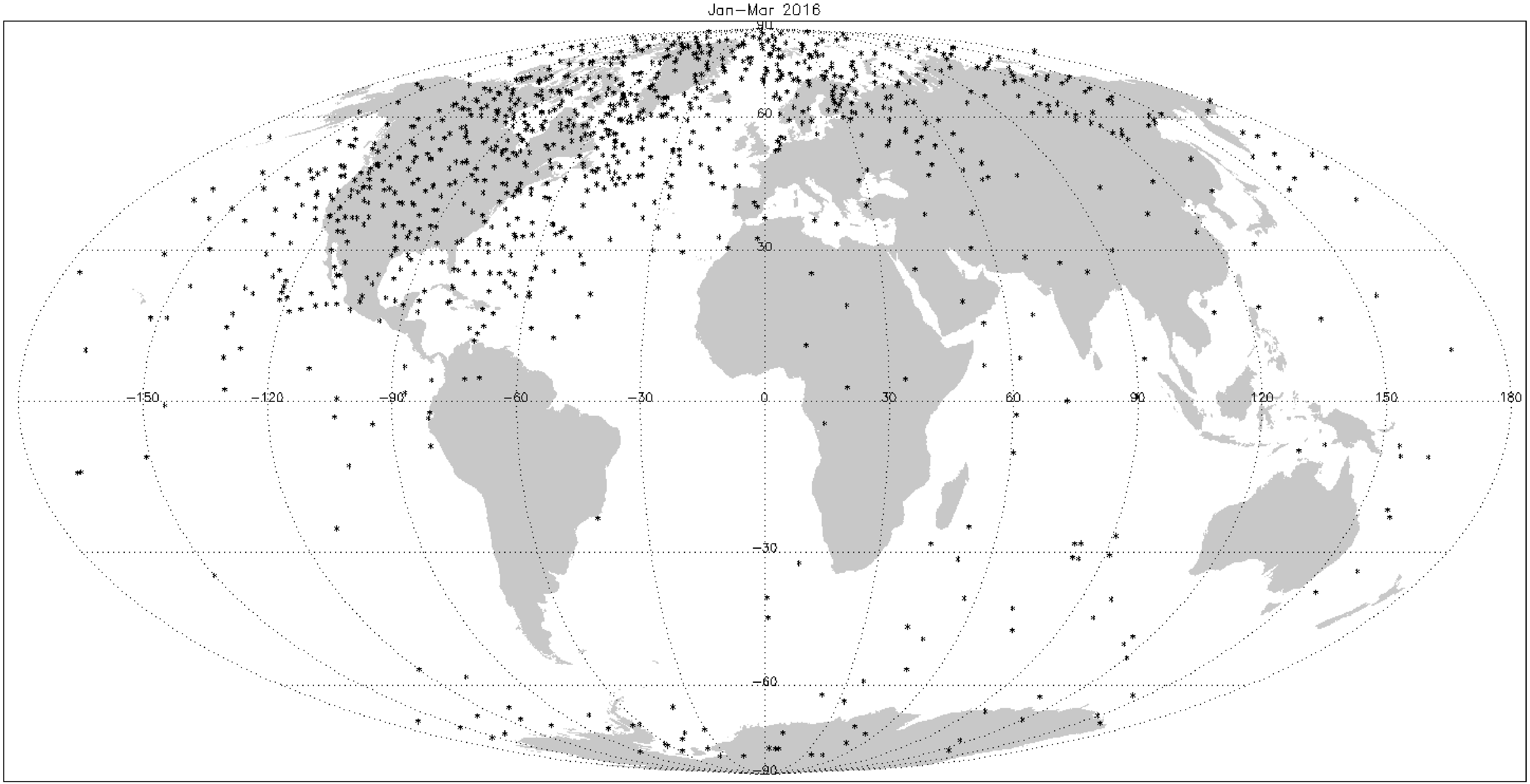
GAP-O Occultations – Year 2014
(Only events with useable data)



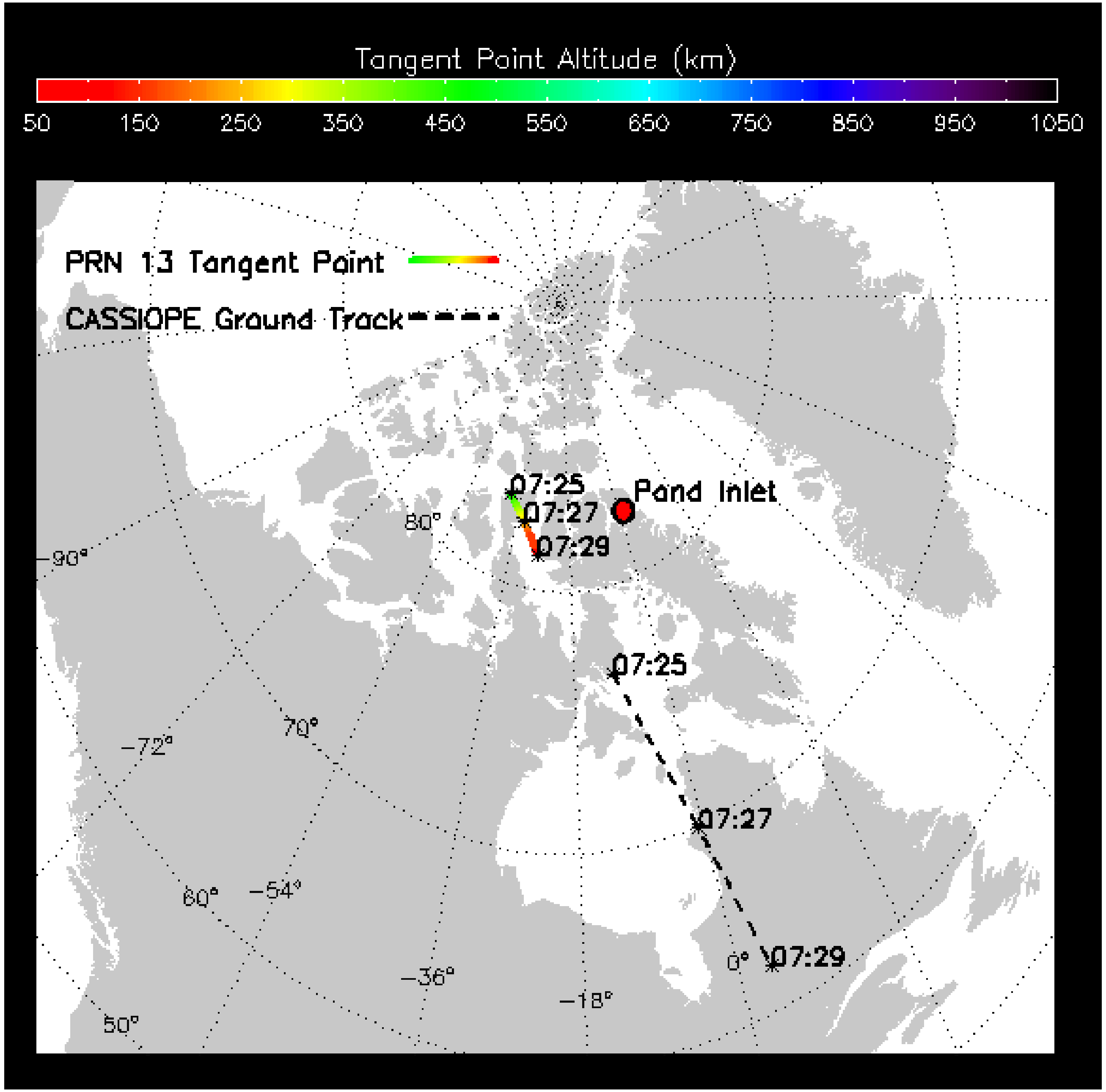
GAP-O Occultations – Year 2015
(Only events with useable data)

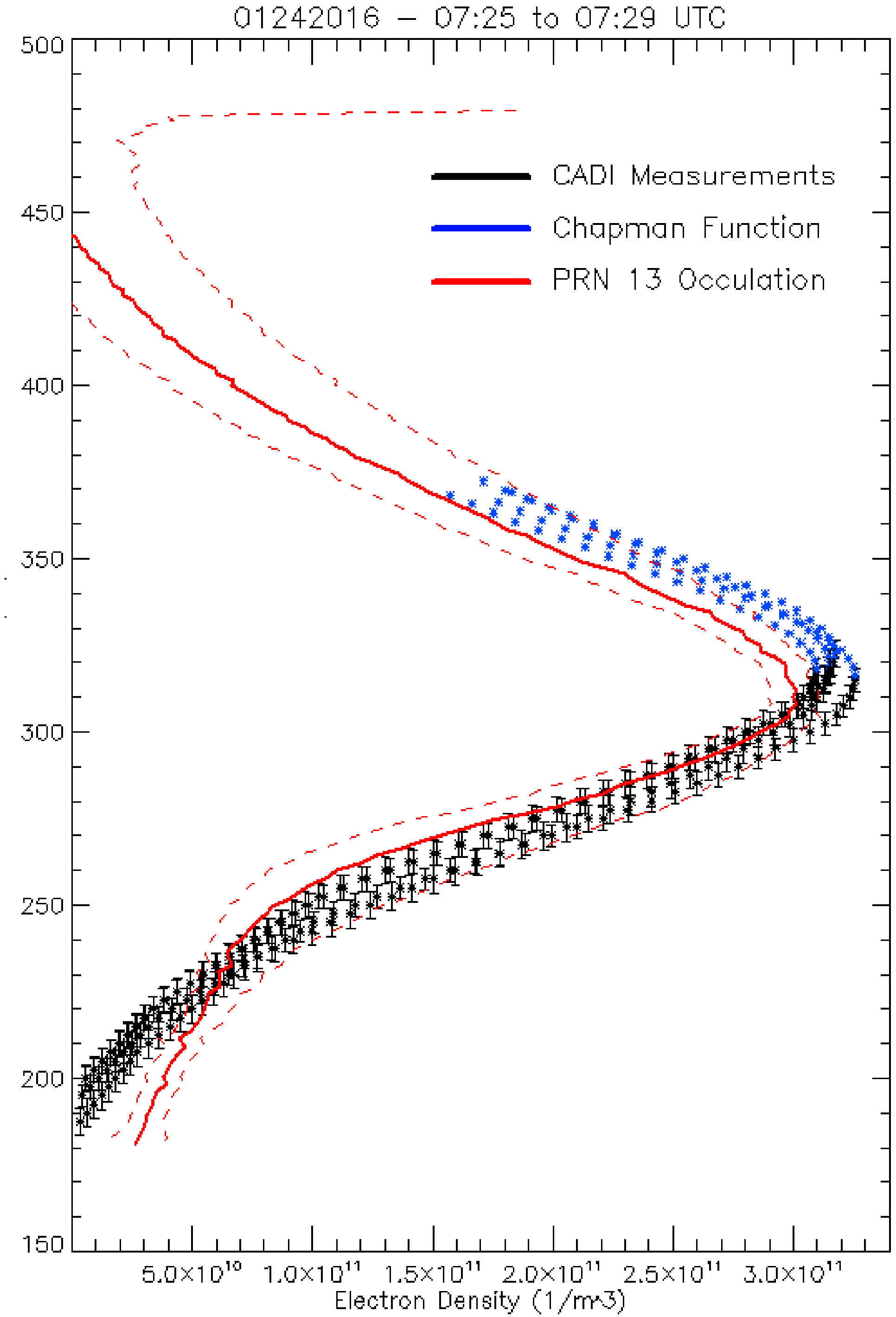


GAP-O Occultations – January to March 2016
(Only events with useable data)



Density profiles – Abel Inversion





Differential code biases (DCBs)

- Frequency dependent differential delays:
  - GPS Satellite biases (DCB_S) – e.g. ftp://ftp.unibe.ch/aiub/CODE/
  - GPS Receiver biases (DCB_r) - unknown

Unknown integer cycle ambiguity

TEC derived from carrier phase (L):

$$TEC_{L,i} = TEC_{abs,i} + \frac{40.3(f_1^2 - f_2^2)}{f_1^2 f_2^2}\left(\frac{N_{1,i}c}{f_1} - \frac{N_{2,i}c}{f_2}\right) + \varepsilon_{L,i}$$

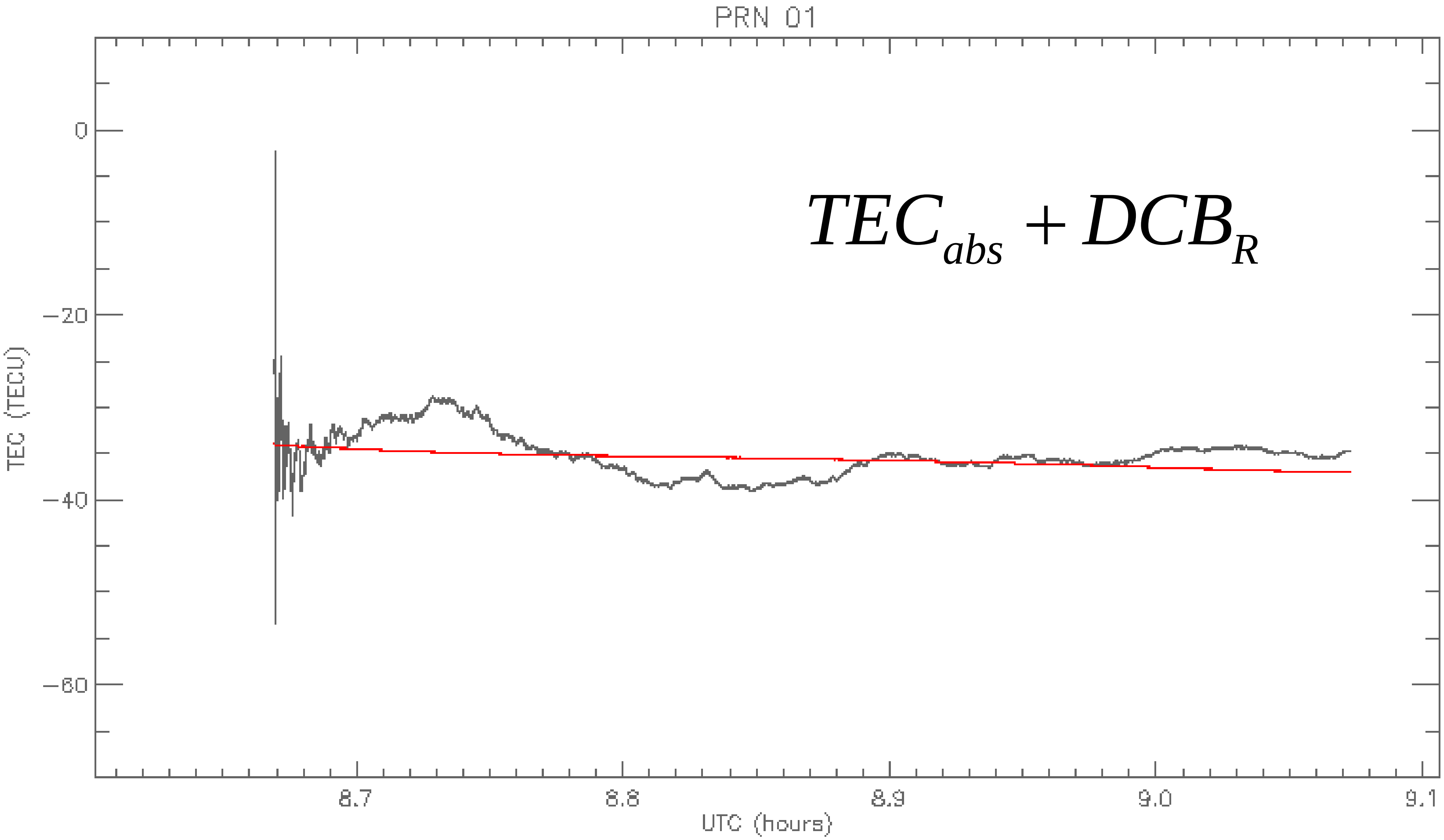
TEC derived from pseudorange (P):

$$TEC_{P,i} = TEC_{abs,i} - DCB_{s,i} - DCB_r + \varepsilon_{p,i}$$

Error terms

- DCB estimation for LEO receivers is tricky:
  - Fast moving satellites, which sample range of locations over a short time
  - Multipath and cycle slips reduce accuracy of DCB estimation methods
  - Typically only an hour or two of GAP-O measurements each day

GAP-O Phase levelled TEC – Jan 6, 2014



Phase levelling algorithm: *Stephens et al. (2011), New leveling and bias estimation algorithms for processing COSMIC/FORMOSAT-3 data for slant total electron content, Radio Science, 46, doi:10.1029/2010RS004588.*

Receiver bias estimation techniques

- Minimization of Standard Deviations
- Zero-TEC Method(s)
- Least Squares (LSQ) Method
- **Validation of receiver bias estimate using ground-based ionosonde & GPS TEC**

Minimization of Standard Deviations

Ma and Maruyama (2003), Determination of GPS receiver differential biases by neural network parameter estimation method, Radio Science, 40, doi:10.1029/2004RS003072.

- Using topside TEC measurements (above e-POP):
  - Assume that the ionosphere is regionally homogenous
  - Ideally, vertical TEC (VTEC) calculated from different GPS satellite ray paths will be equal
  - Calculate the time-averaged mean and standard deviation of VTEC from multiple GPS satellites.
  - Find the receiver DCB that minimizes the standard deviation.

$$VTEC = (TEC_{biased} - DCB_r) \cdot M(E)$$

Minimization of Standard Deviations – Mapping Functions for LEO

Thin layer model (TLM) *[e.g. Zhong et al., 2015]:*

$$M(E_{sat}) = \sqrt{1 - \left(\frac{R_{orbit}}{R_{shell}}\right)^2 \cos^2(E_{sat})} \qquad R_{shell} = R_{orbit} + 300\,km$$

F&K *[Foelsche and Kirchengast, 2002]*:

$$M(E_{sat}) = \frac{\sin(E_{sat}) + \sqrt{\left(\frac{R_{shell}}{R_{orbit}}\right)^2 - \cos(E_{sat})}}{1 + \frac{R_{shell}}{R_{orbit}}}$$

Lear *[Lear, 1987]*:

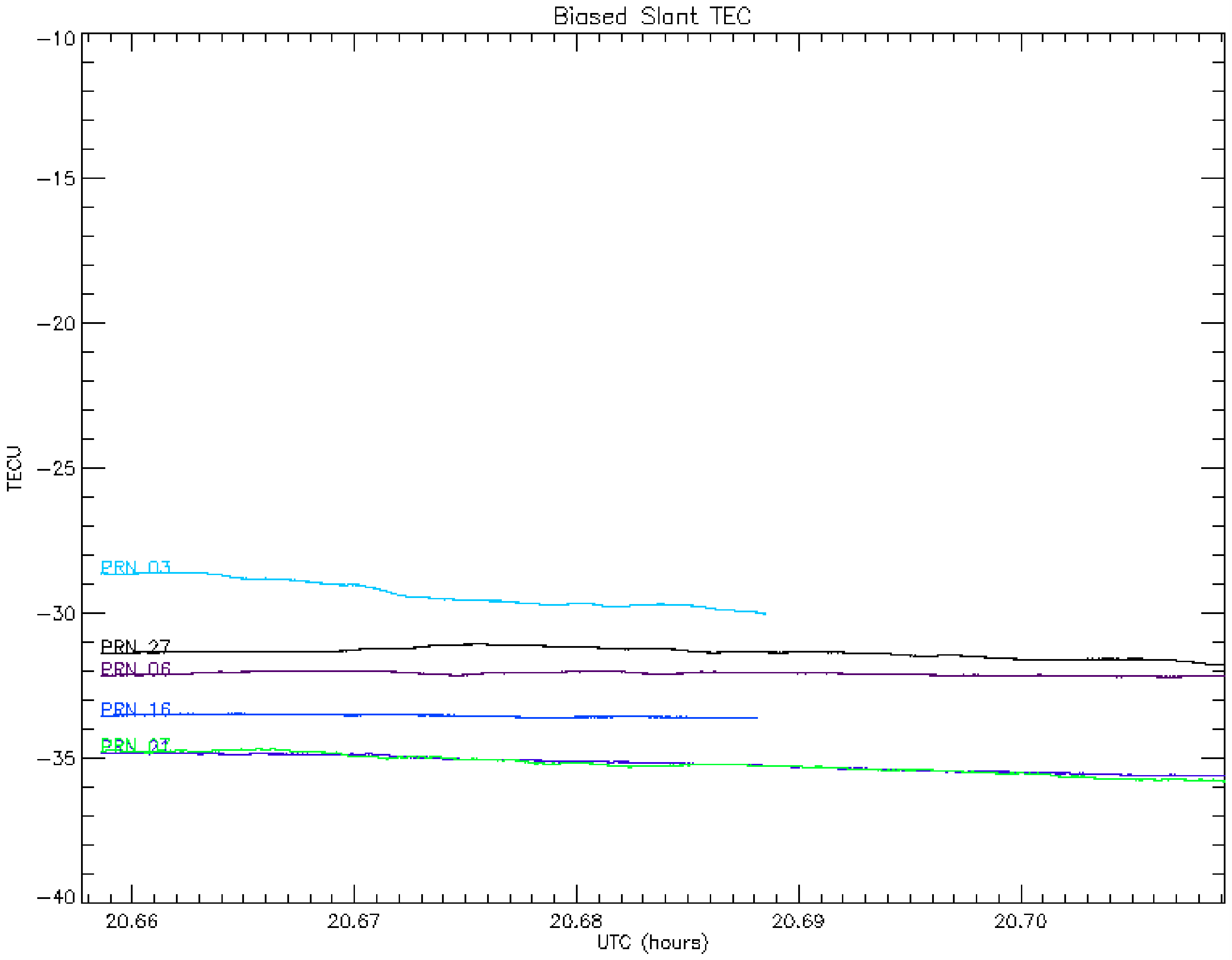
$$M(E_{sat}) = \frac{2.037}{\sin(E_{sat}) + \sqrt{1.076 - \cos^2(E_{sat})}}$$

A simple sine projection:

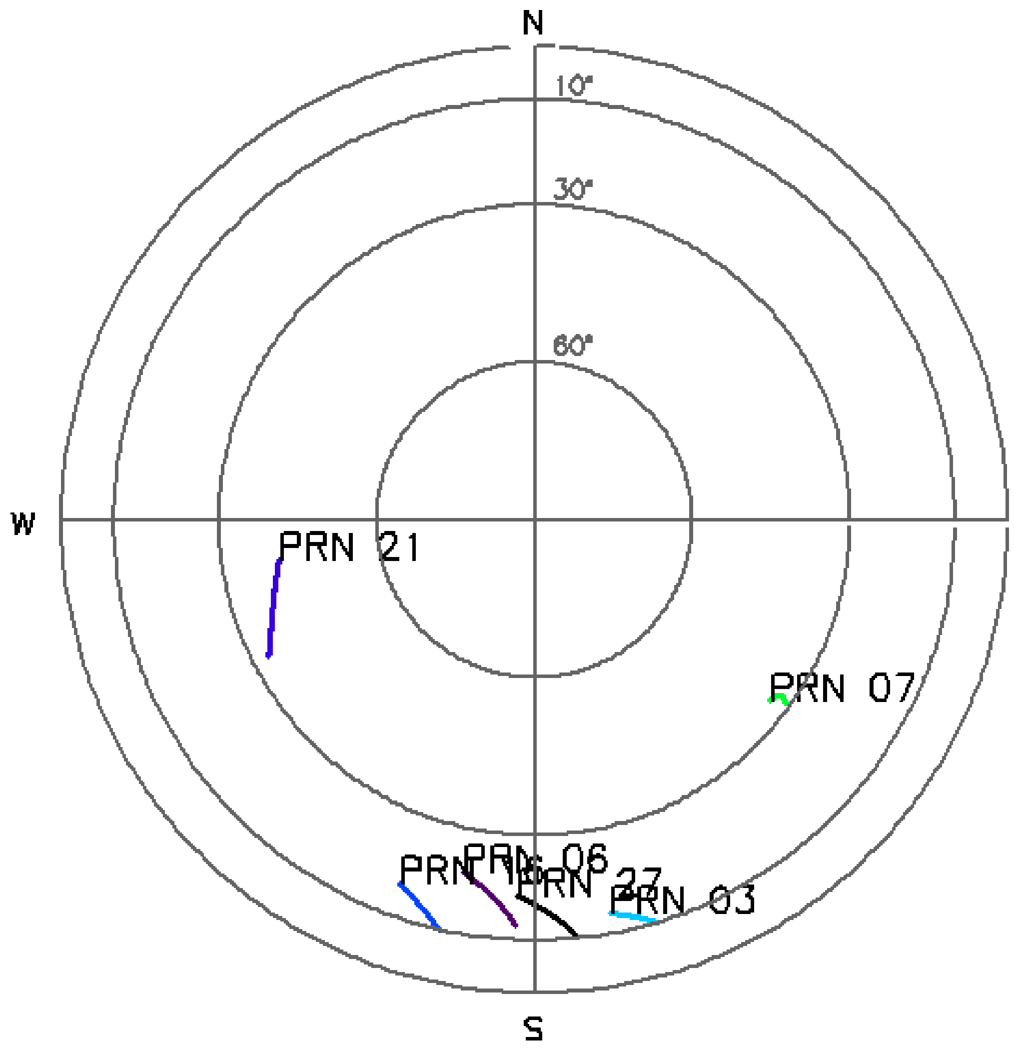
$$M(E_{sat}) = \sin(E_{sat})$$

Minimization of Standard Deviations – Jan 2, 2014

Biased Slant TEC



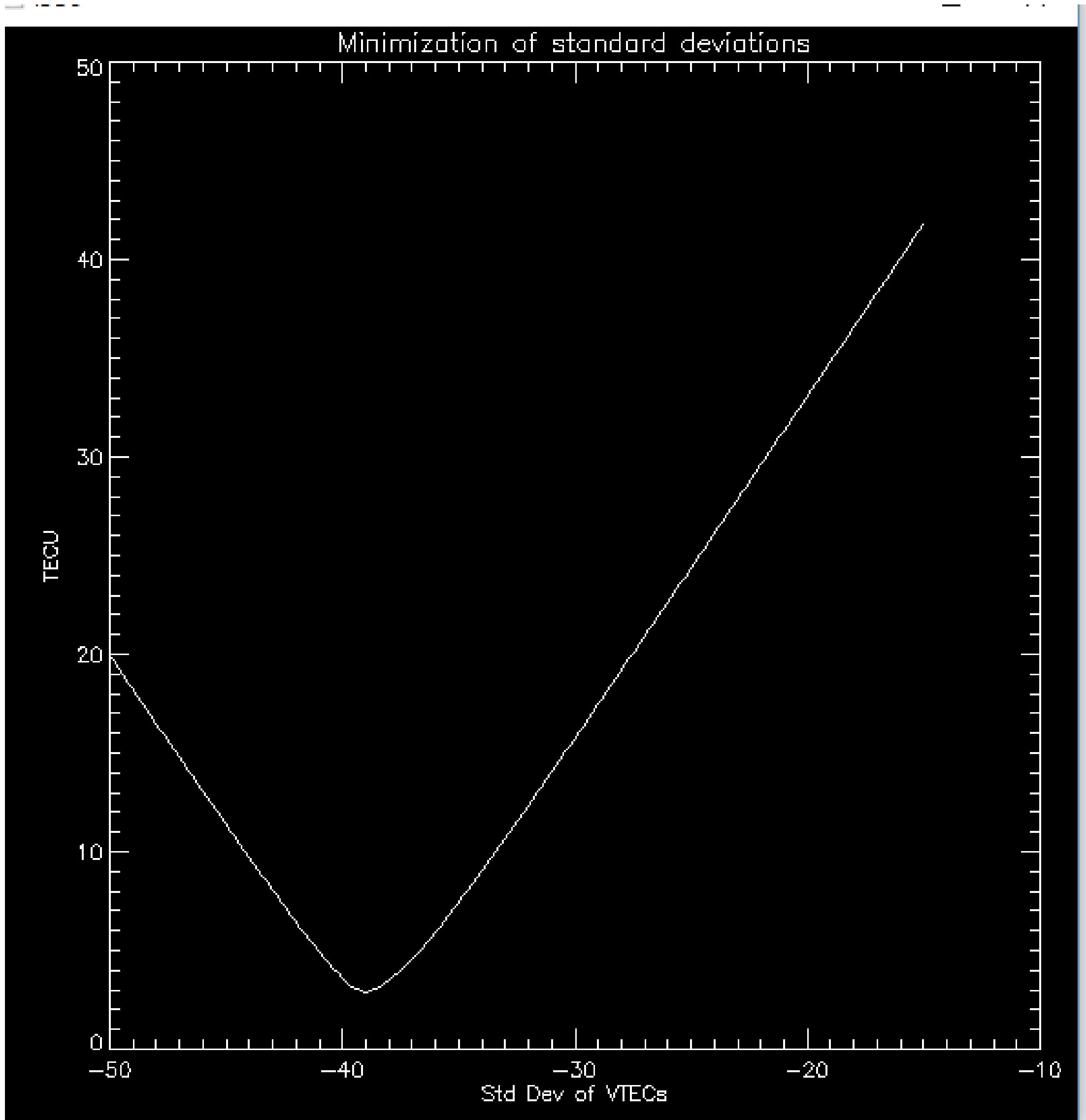
Skyplot (10 degrees elevation cutoff)

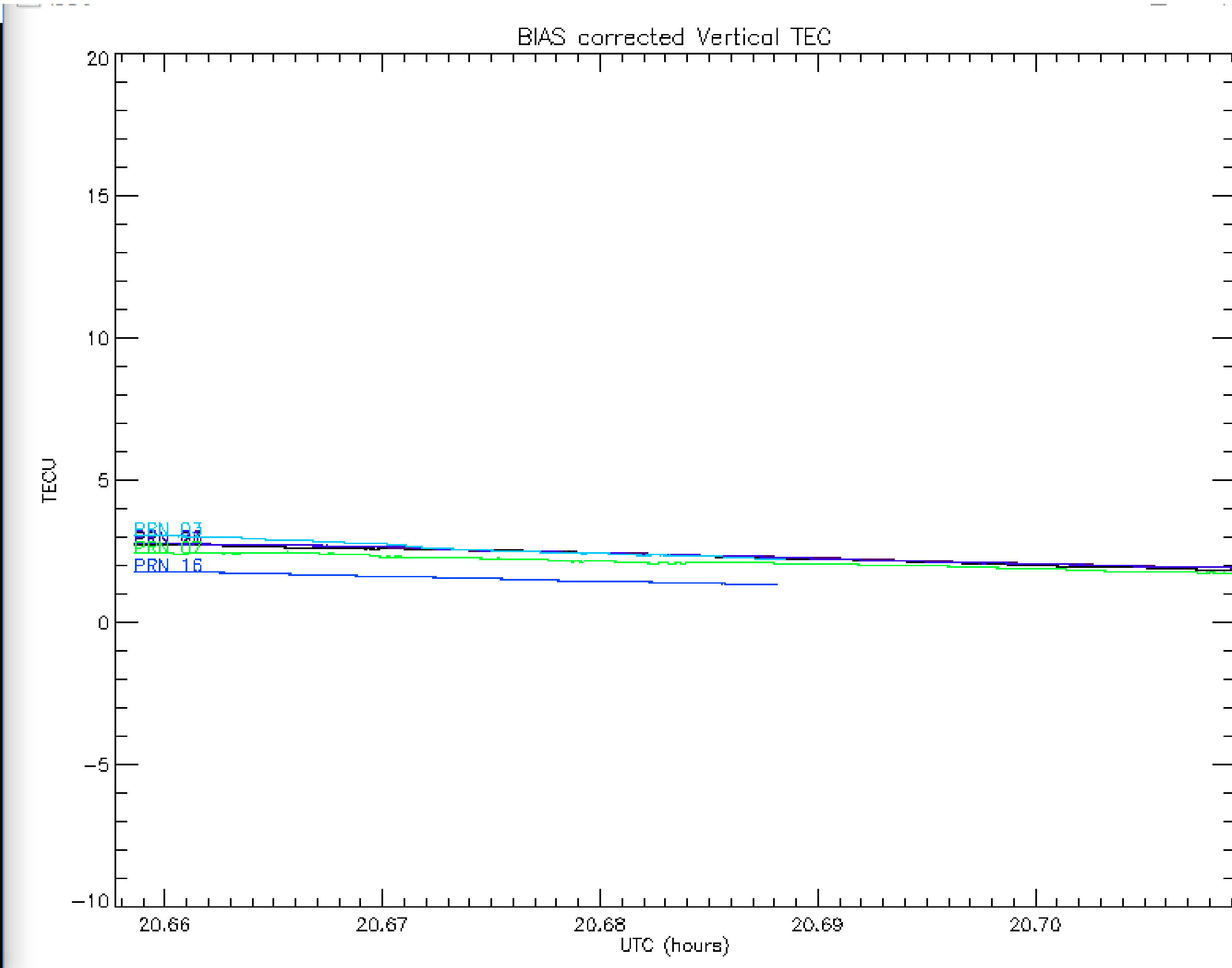


Minimization of Standard Deviations – Jan 2, 2014

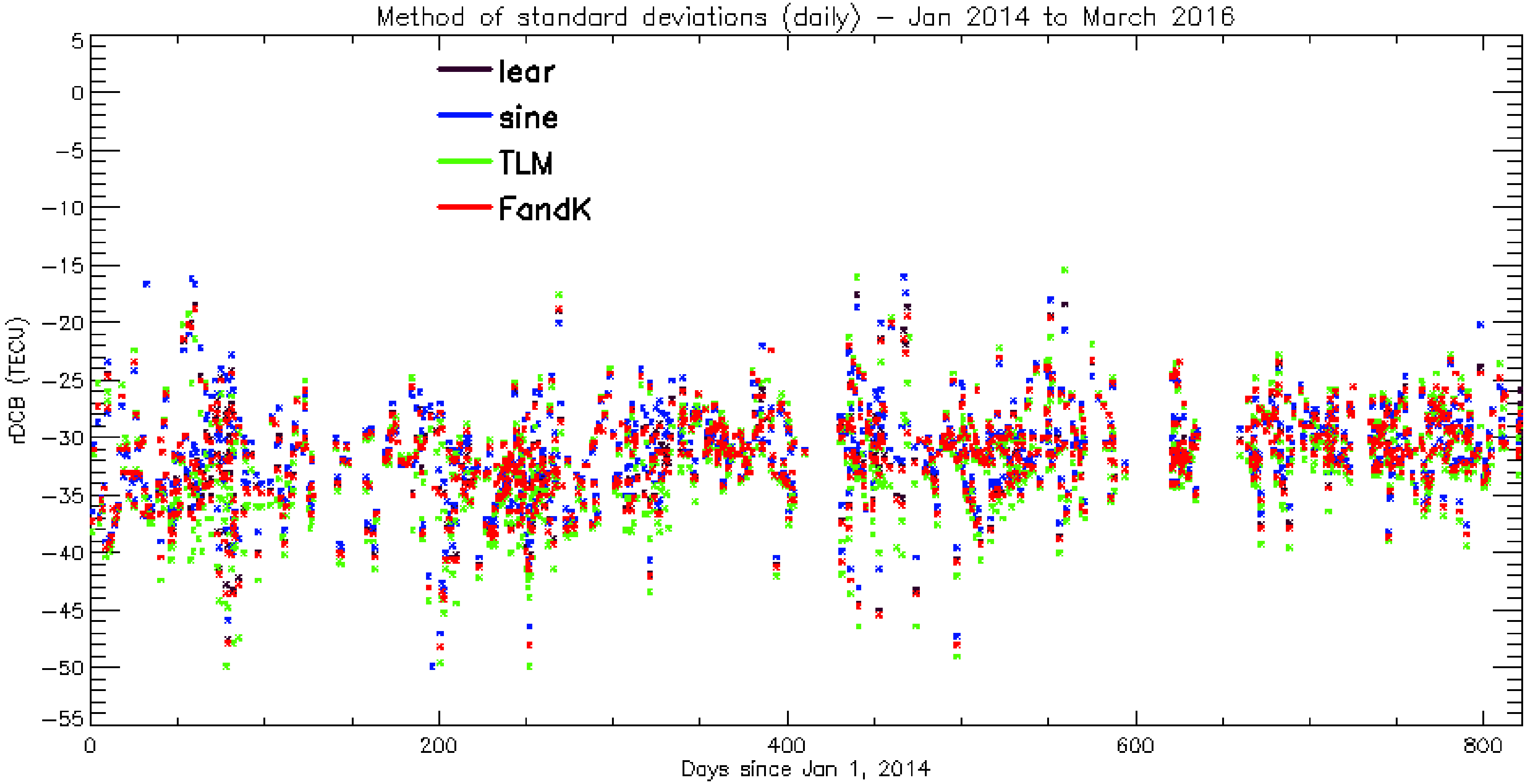
Time averaged standard deviation: $\left\langle \sqrt{\frac{1}{N}\sum_{i=0}^{N}\left(VTEC_i - \frac{1}{N}\sum_{i=1}^{N} VTEC_i\right)} \right\rangle_{UTC}$

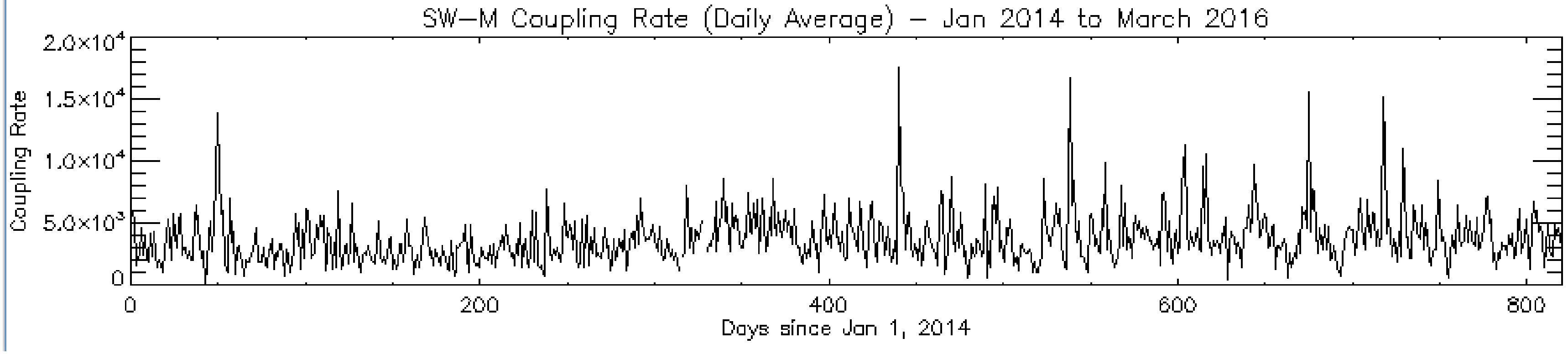
Projected vertical TEC (using TLM projection) for DCB=-39 TECU





MSD rDCB estimates (daily) – Jan 1, 2014 to April 1, 2016





- No clear dependence of day-to-day rDCB variability on solar wind conditions or geomagnetic indices (Kp, DST, etc.).
- Real temporal variations in rDCB (e.g. associated with temperature changes), or due to errors inherent to estimation method?

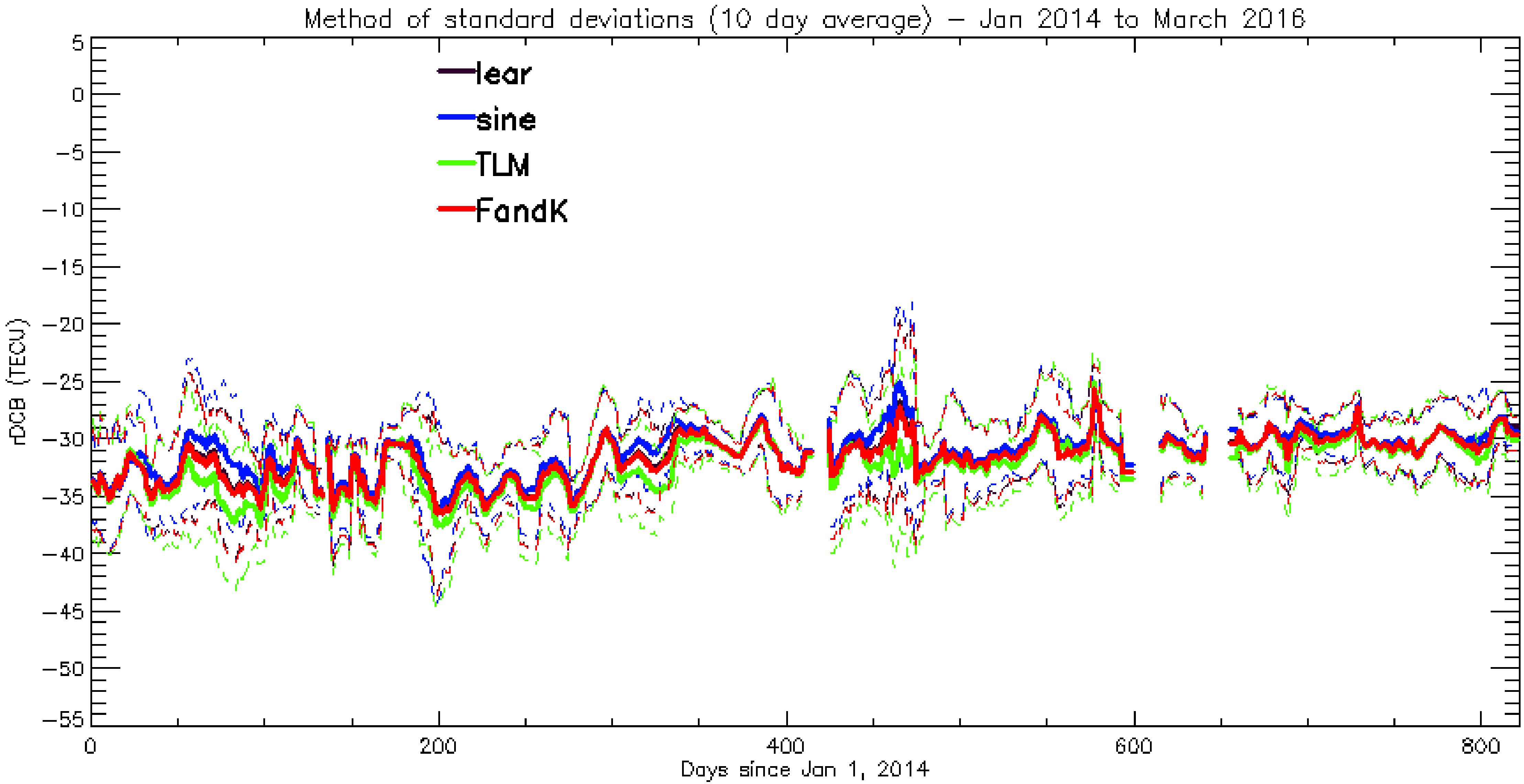
SW-M Coupling Rate [*Newell et al., 2007*]:

$$\frac{d\Phi}{dt} = v_{sw}^{4/3}\left(\sqrt{B_y^2 + B_z^2}\right)^{\frac{2}{3}} \sin^{\frac{8}{3}}\left(\frac{\phi}{2}\right)$$

$$\phi = \tan^{-1}\left(\frac{B_y}{B_z}\right)$$

MSD rDCB estimates (10 day running average) – Jan 1, 2014 to April 1, 2016

- Apparent long period trend in receiver bias: -35 TECU to -30 TECU over 2 years

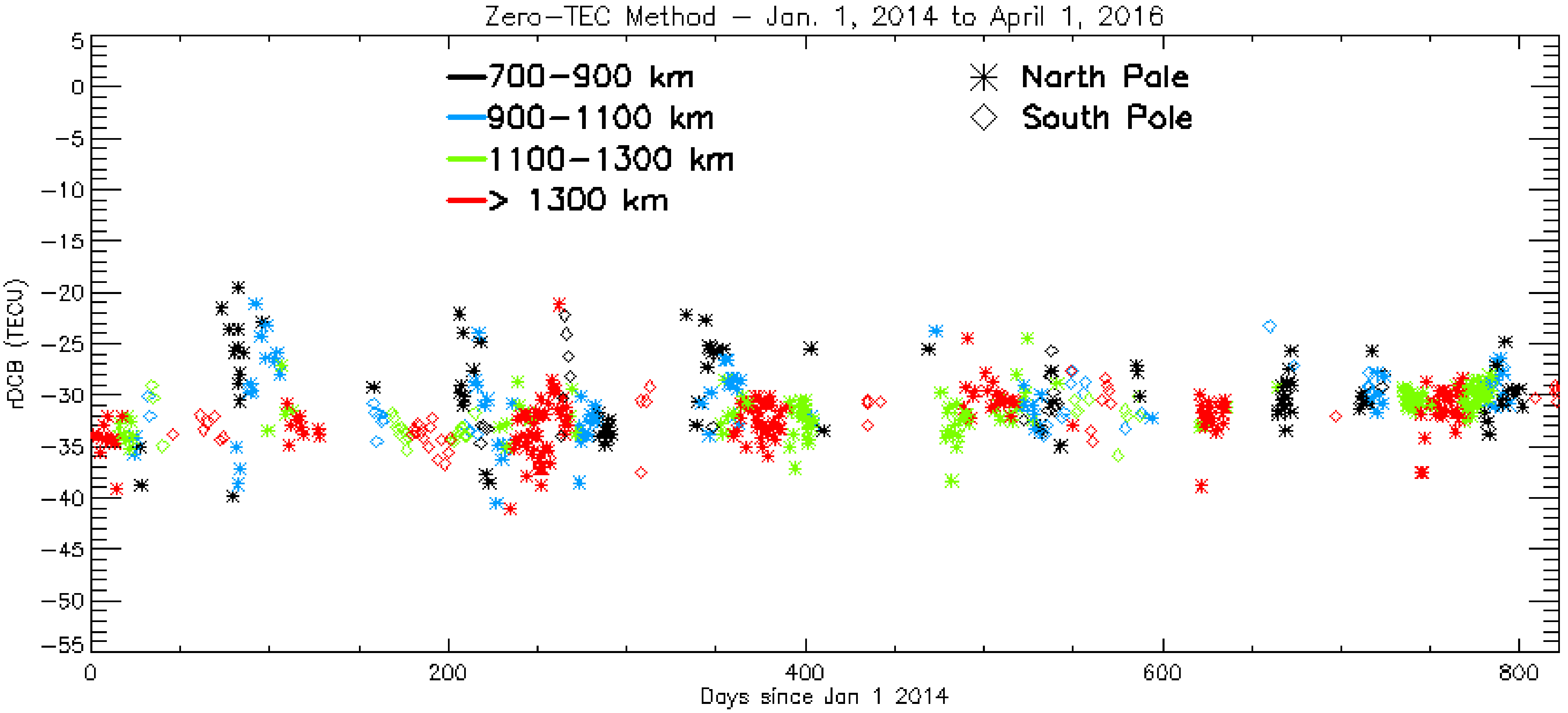


Zero-TEC Method

- Assume that TEC above e-POP is zero
  -Ideally at apogee, winter polar cap, near solar minimum
- Estimate receiver bias from lowest observed topside TEC
- Advantage: Fast and simple
- Disadvantage:
  - TEC above e-POP is non-zero
  - e-POP not always at apogee in the polar cap
  - Outliers

Zero-TEC Method

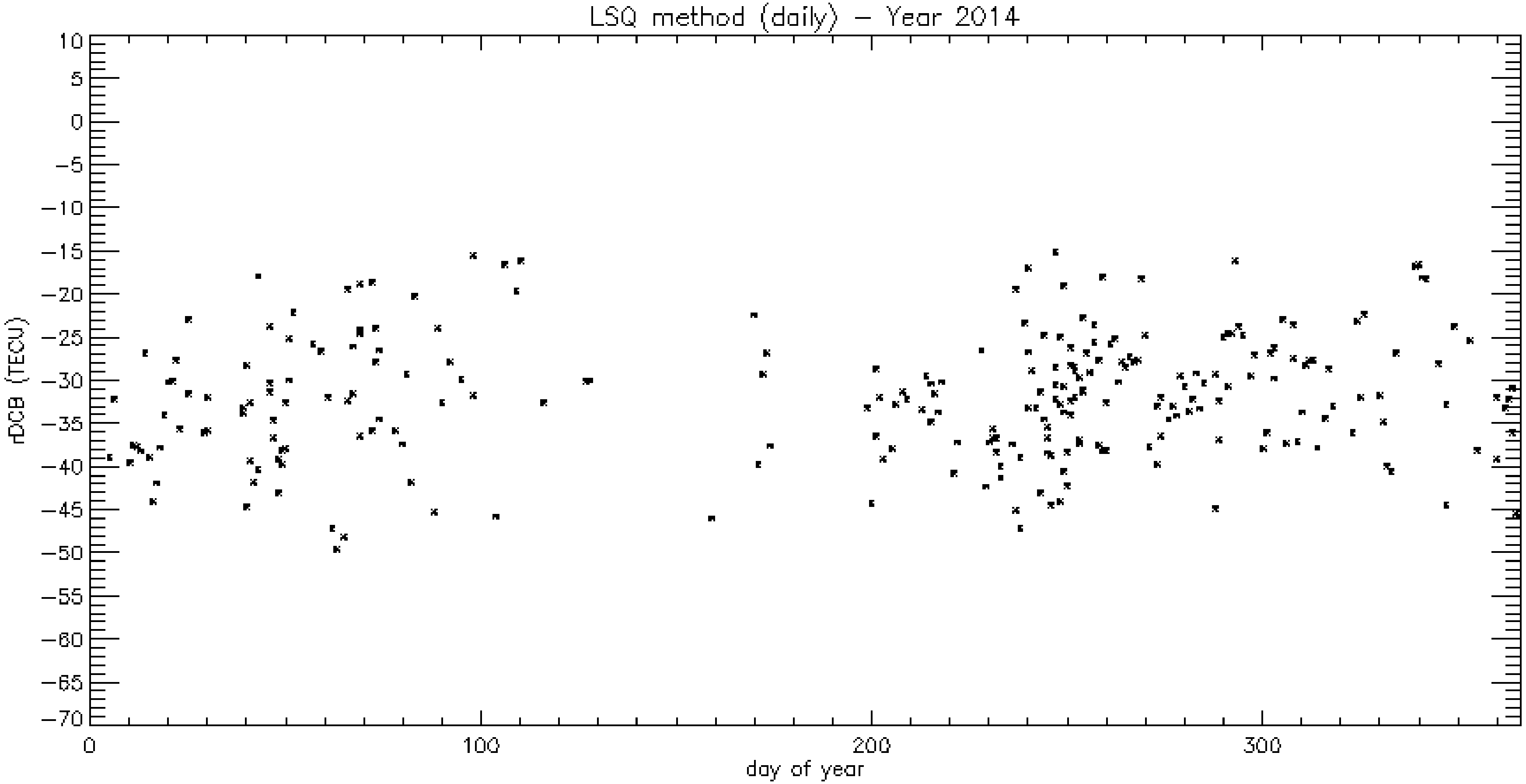
- For polar cap passes at > 70 and < -70 degrees magnetic latitude: calculate average TEC for GPS satellites at >50 degrees elevation



Least Squares (LSQ) Method

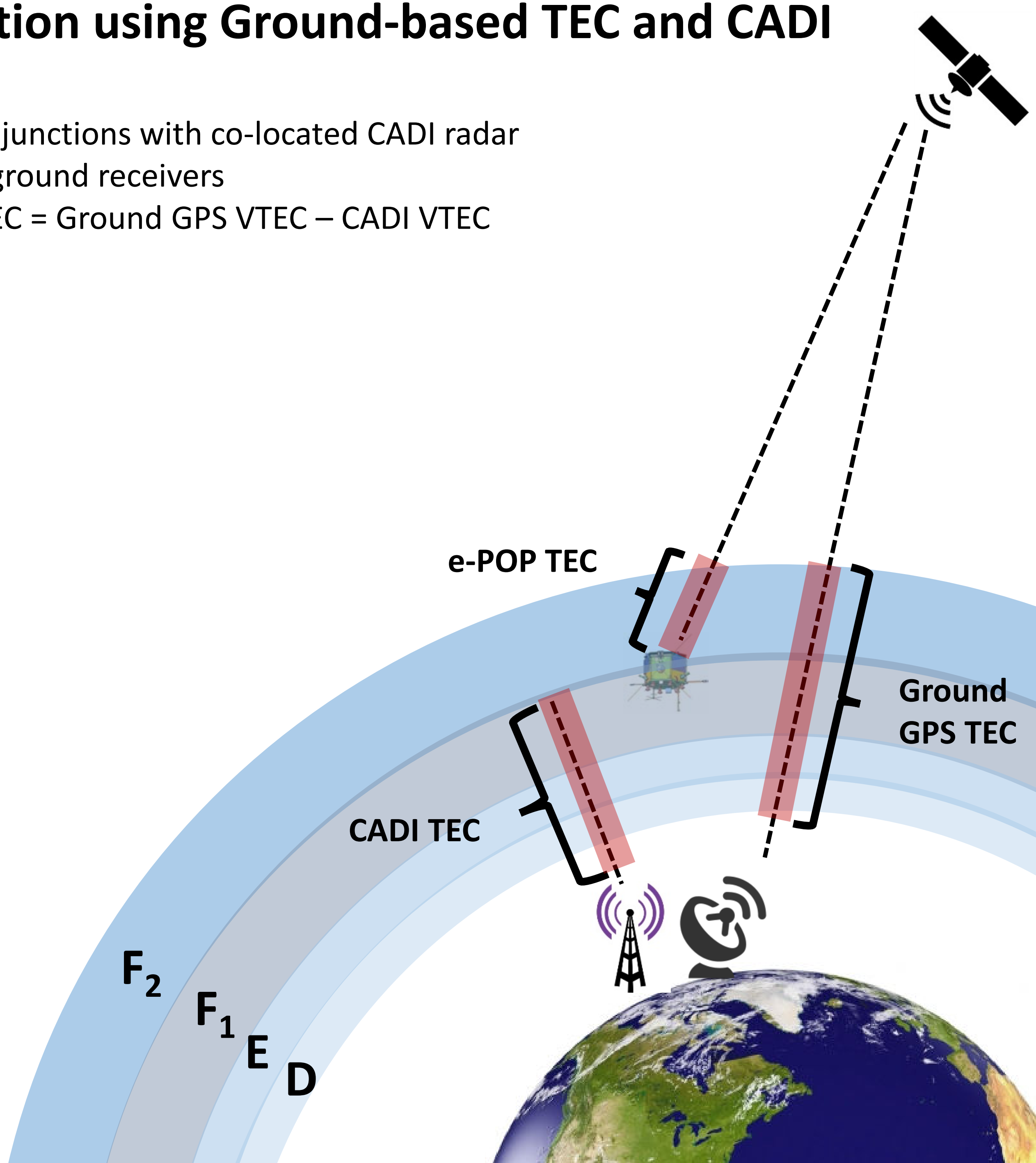
- Assume equivalent VTEC from satellite pairs with near-proximity ray paths
- Combine each satellite pair to obtain a daily set of linear equations
- Solve resulting system of linear equations using LSQ method

$$(TEC_{biased,1} - DCB_r) \cdot M(E)_1 = (TEC_{biased,2} - DCB_r) \cdot M(E)_2$$

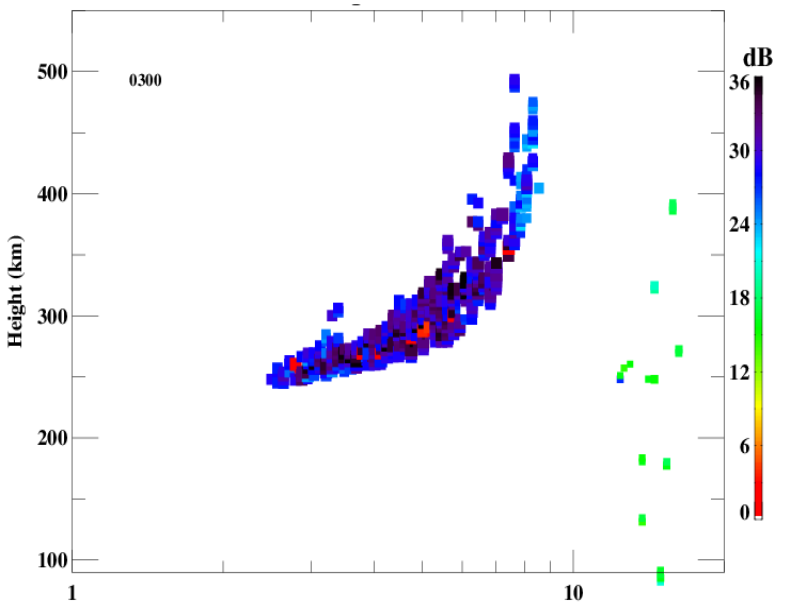


rDCB validation using Ground-based TEC and CADI

- e-POP conjunctions with co-located CADI radar and GPS ground receivers
- e-POP VTEC = Ground GPS VTEC – CADI VTEC



CADI ionogram (bottom-side electron density)

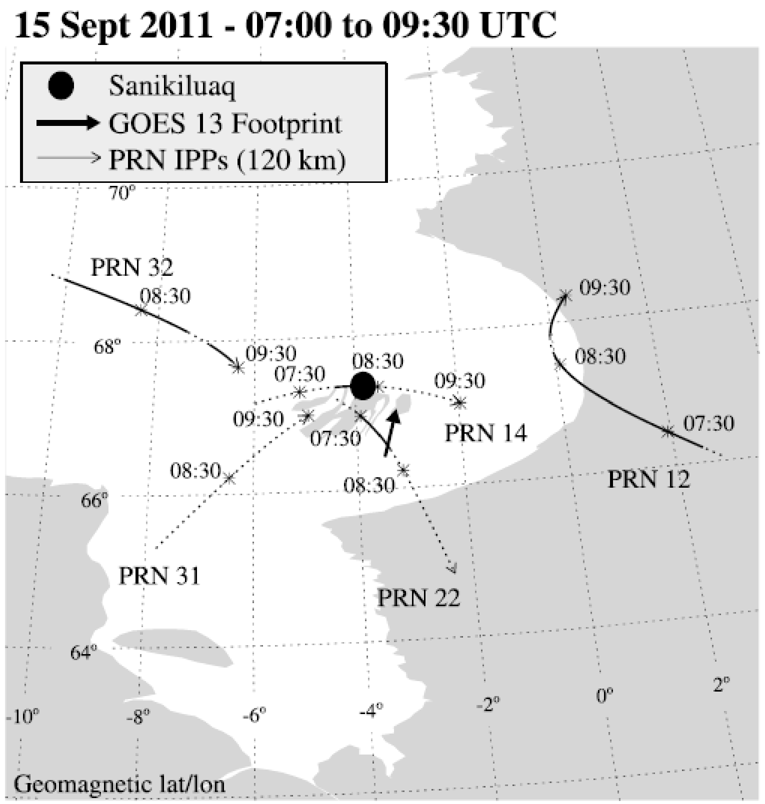


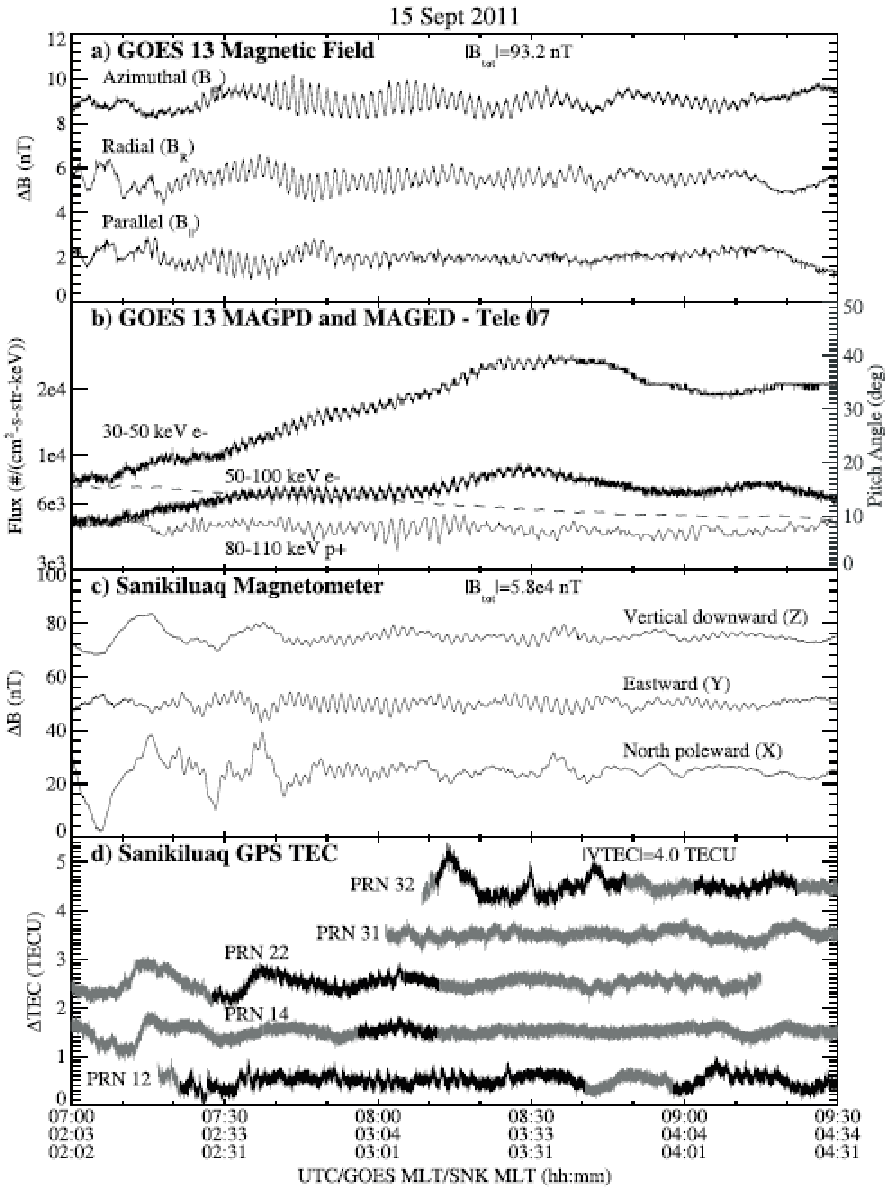
e-POP – Resolute CADI conjunctions (within 3 degrees latitude/longitude)

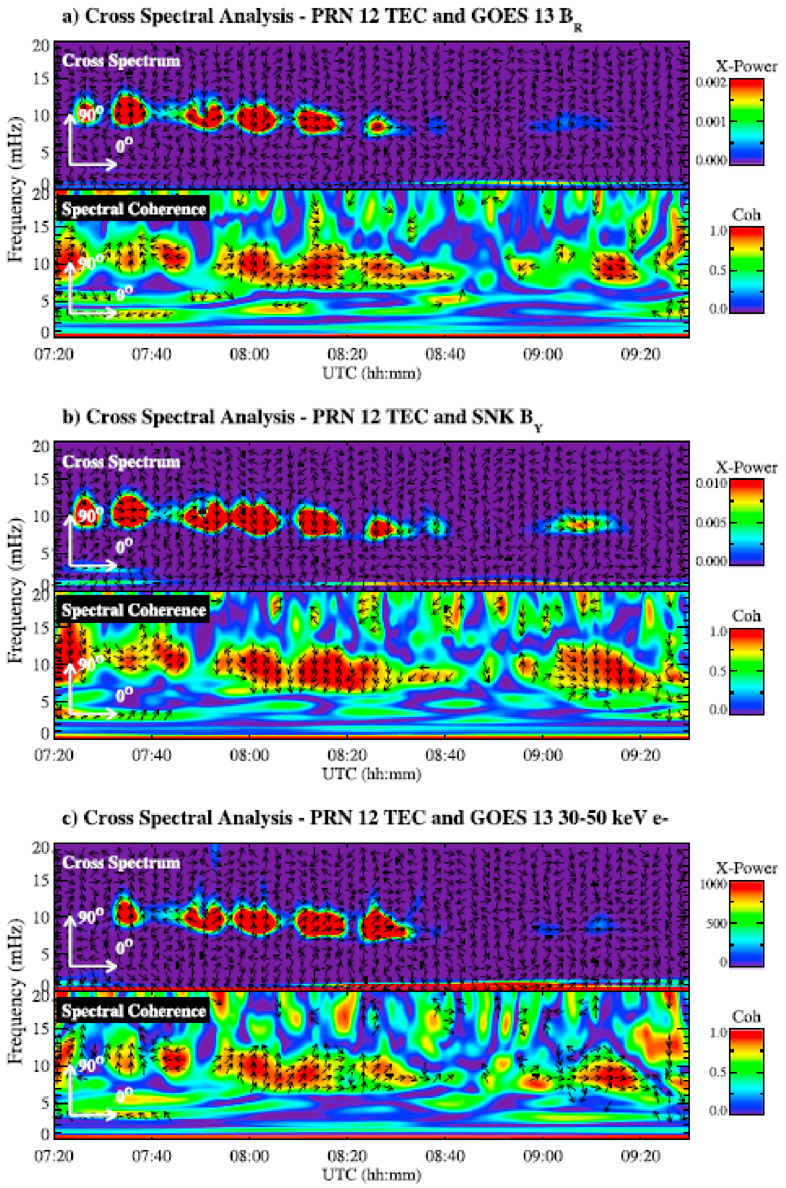
DATE	TIME (UTC)	e-POP Altitude (KM)	MSD e-POP VTEC (TECU)	GPS-CADI TEC (TECU)	CADI TEC (TECU)	Kp Index
02/27/2014	07:39:38-07:39:59	375.3-380.0	5.94±0.88	10.86	4.01 (good)	4-5
03/01/2014	07:38:57-07:39:13	354.9-357.4	5.11±1.99	12.11	3.38 (very patchy)	1-3
03/03/2014	07:38:03-07:38:14	342.5-343.5	5.09±2.26	11.31	3.15 (very patchy)	1-2
03/05/2014	07:36:55-07:36:56	337.4-337.4	9.12±0.56	10.89	3.72 (some patches)	1-2
03/07/2014	14:32:36-14:32:59	397.1-403.5	10.61±1.08	14.49	8.75 (good)	0-1
03/10/2014	05:48:00-05:48:03	337.1-337.1	5.85±2.13	8.90	3.23 (good)	1-2

Combined Ground-Occultation TEC Observations of High Latitude Ionization Structures

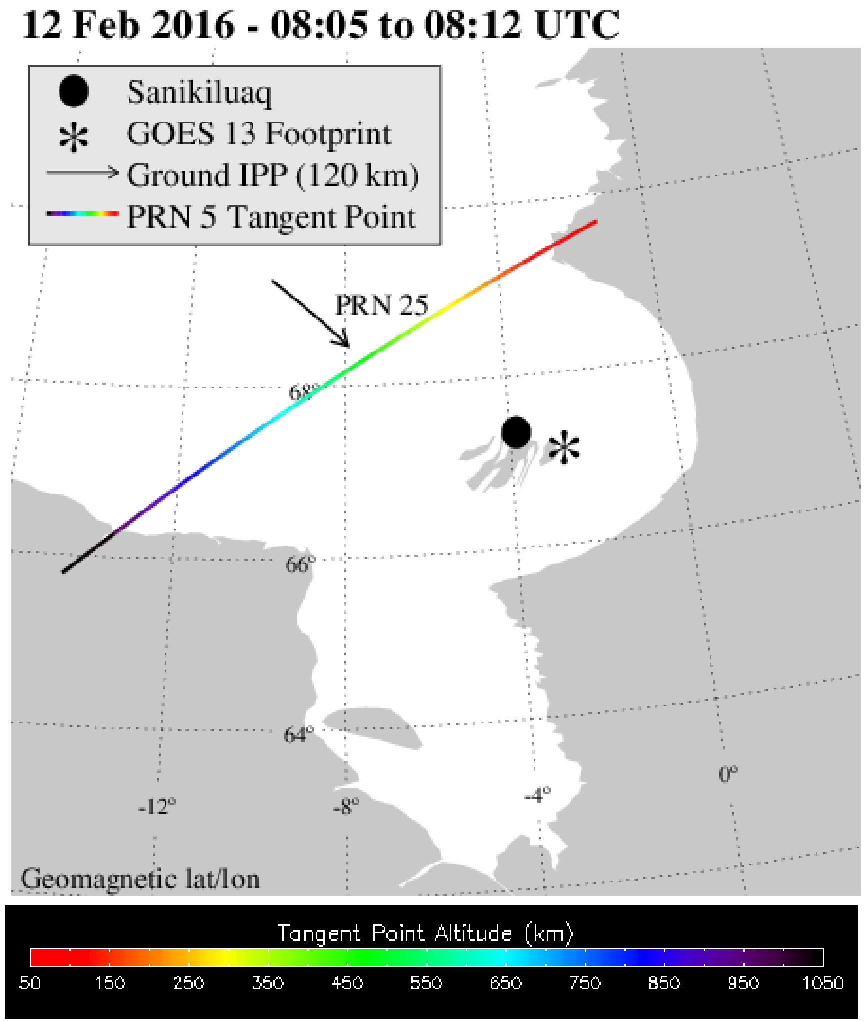
Watson et al [2016], GPS TEC response to Pc4 Giant Pulsations, JGR Space Physics



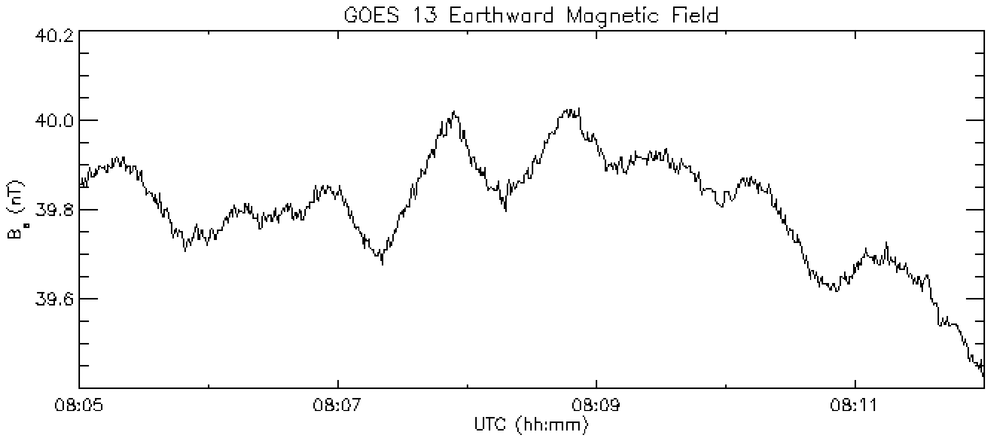




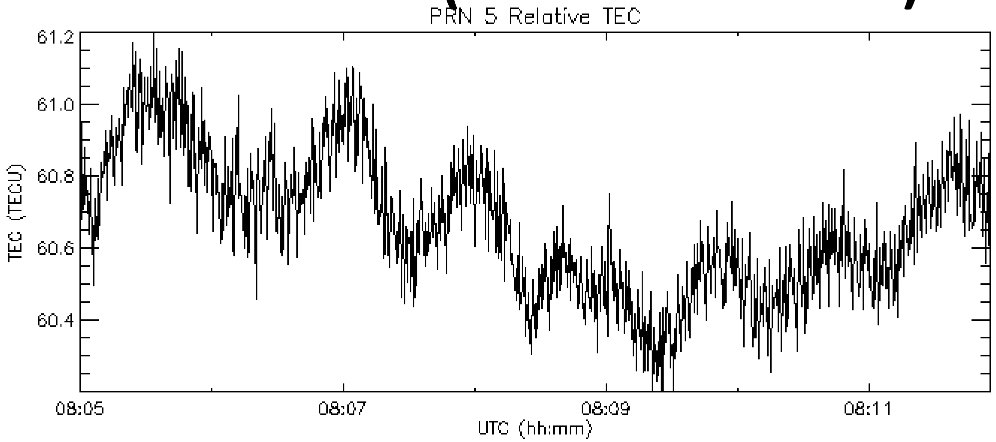
Combined Ground-Occultation TEC Observations of High Latitude Ionization Structures



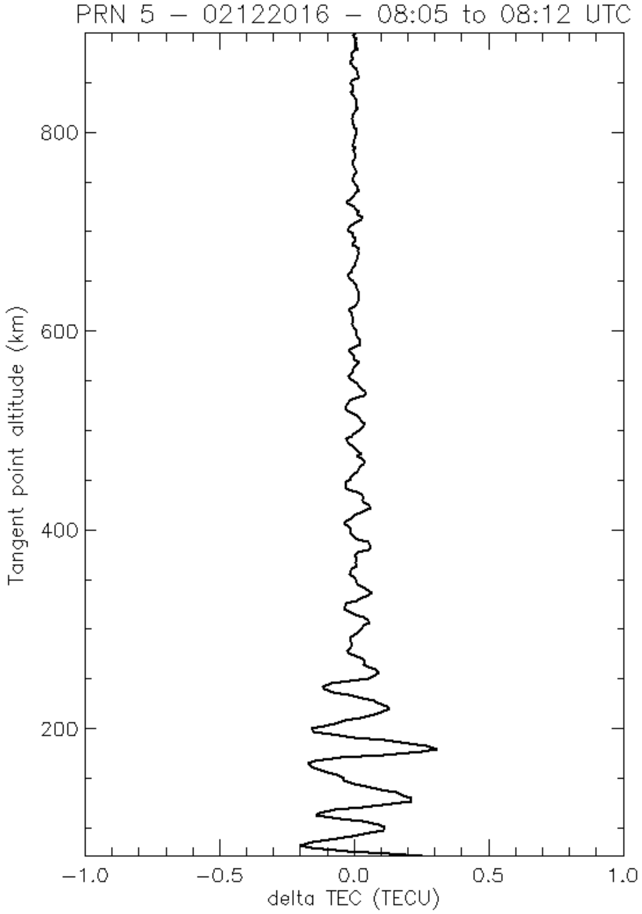
GOES 13 Magnetic Field



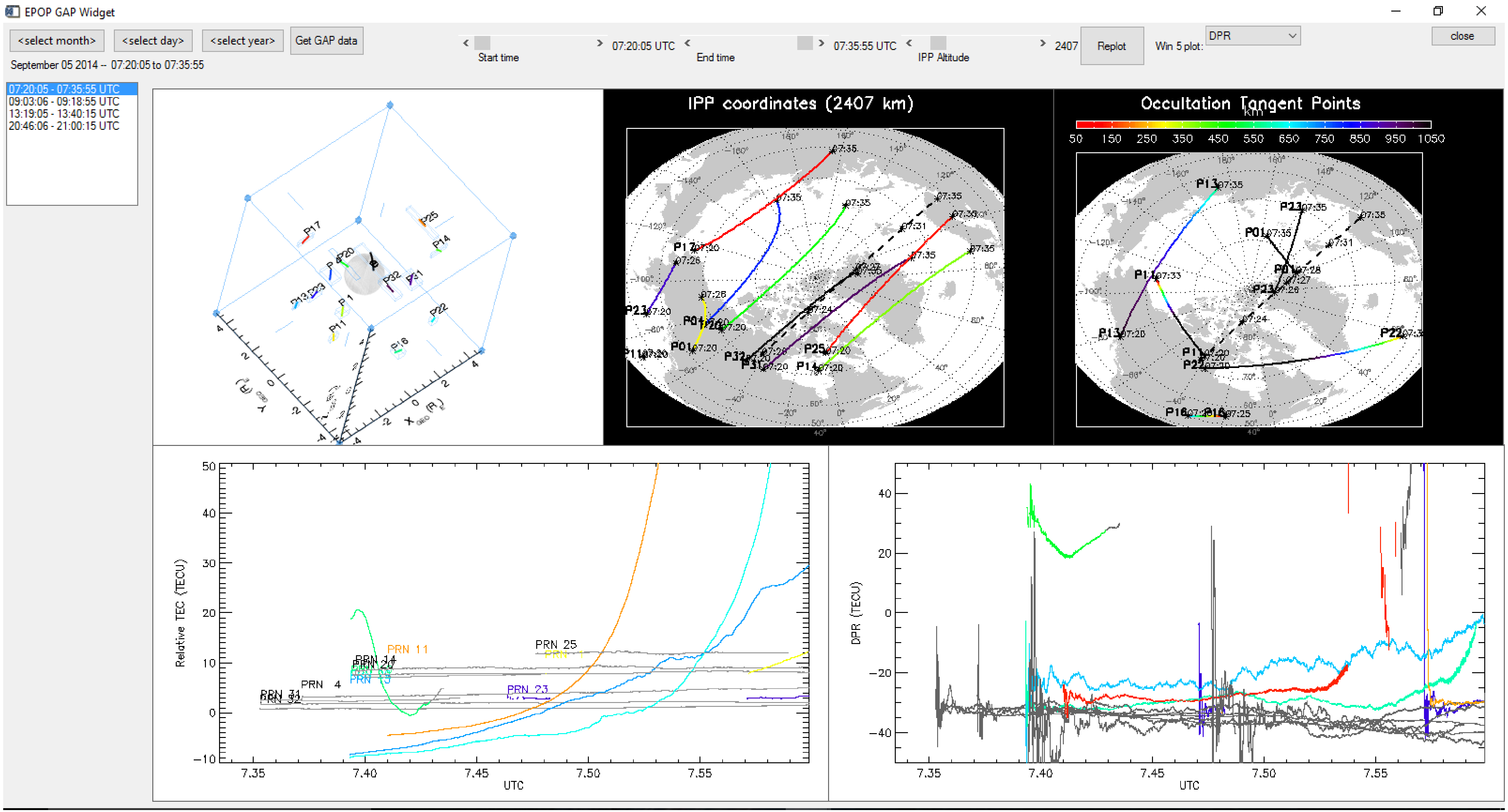
PRN 25 TEC (Ground Receiver)



PRN 5 TEC (Occultation)



GAP-O Data Availability and Visualization tools



GAP-O Data Availability and Visualization tools

- sFTP RINEX files via: http://epop-data.phys.ucalgary.ca/

- Research teams working on development of e-POP GAP data:
  - Richard Langley (University of New Brunswick)
  - Ionospheric Group at JPL (Esayas Shume, Attila Komjathy)
  - e-POP team at the University of Calgary

- My Email: Watson@phys.ucalgary.ca

Conclusions and Future Work

- Ionospheric density profiles inverted from GAP-O occultation TEC currently viable on a case-by-case basis.
- Automated TEC inversion for high latitude regions will require a more advanced method accounting for ionization structure & density gradients.

- Minimization of standard deviations (MSD) is currently the most reliable method for receiver DCB estimation.
- Further investigation required to determine whether temporal variations in rDCB are real or are due to errors inherent to the estimation technique.
- Comparison to CADI & ground based GPS TEC indicates that MSD method tends to underestimate receiver bias.

- Planned studies involving GAP-O data include combined occultation-ground TEC observation of high latitude ionization structures.

References

Kim, D. and R. B. Langley (2010), The GPS attitude, positioning, and profiling experiment for the enhanced polar outflow probe platform on the Canadian CASSIOPE satellite, *Geomatica, 64*(2), 233-243.

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