BOSTON COLLEGE ISR INSTITUTE FOR SCIENTIFIC RESEARCH

Ionospheric Effects Symposium
9-11 May 2017

Alexandria, VA

Characterization of HF Perturbations and Drift Velocity with GPS

K. Groves, V. V. Paznukhov, C. S. Carrano, C. Bridgwood, D. Decker
Institute for Scientific Research, Boston College
Boston, MA, USA

C. Rago, S. Haron, R. Argo, A. Douglass
Systems Technology Research
Woburn, MA USA

This work was funded by the Intelligence Advance Research Projects Activity (IARPA) under contract FA8650-15-C-9105, United States Air Force

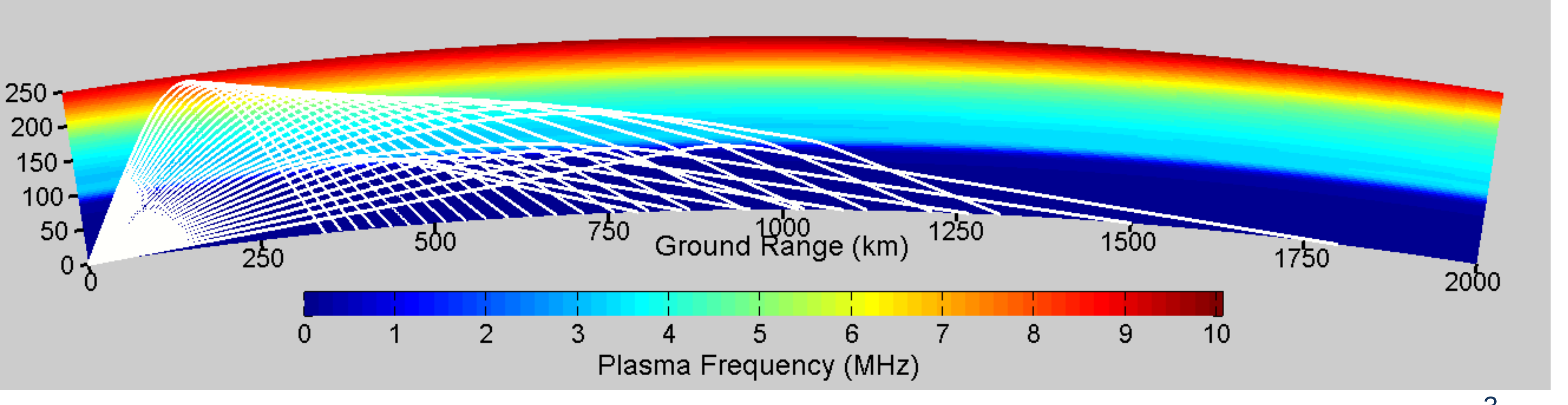
keith.groves@bc.edu

Acknowledgment

Special thanks to R. Todd Parris, Jack Hines and Eugene Dao from AFRL for supporting the GPS observations

Outline

- Motivation
- The Correlation of GNSS and HF Effects
- Extracting the Velocities
- Preliminary Results
- Summary & Way Ahead



Motivation

- Disturbances in the ionosphere can often be the limiting factor in the performance of high frequency (HF) systems
- Current techniques to detect, characterize and compensate such disturbances require dedicated active sensors
- The goal of this effort is to detect and characterize disturbances with GPS sensors for comparison with effects on HF propagation
- The results will help us better understand the nature of traveling ionospheric disturbances and improve our ability to interpret their signatures on specific sensors

Technical Approach

1. Monitor high frequency (HF) propagation channels using available broadcasts on appropriate paths
2. Collect and correlate GPS total electron content (TEC) data to detect and characterize TID spectrum and dynamics
3. Determine suitability of GPS observations for meaningful prediction of HF propagation effects

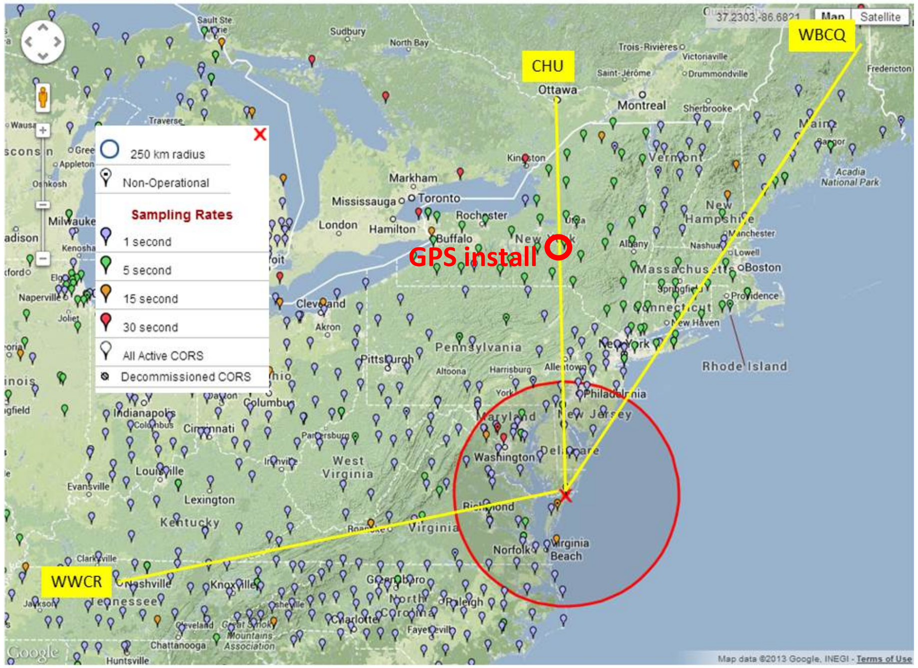
Implementation

A. Use the VIPIR ionosonde at Wallops Island, VA as the primary HF receiver capable of measuring angle-of-arrival
B. Use CORS and other available GPS receivers to measure TEC signatures along the HF raypaths
C. Install a compact (baseline < ~10 km) three GPS rx array to test performance for TID characterization

Correlating GPS Signatures with HF

HF and GPS data were collected in 2014 and 2015 to compare signatures in both sensors

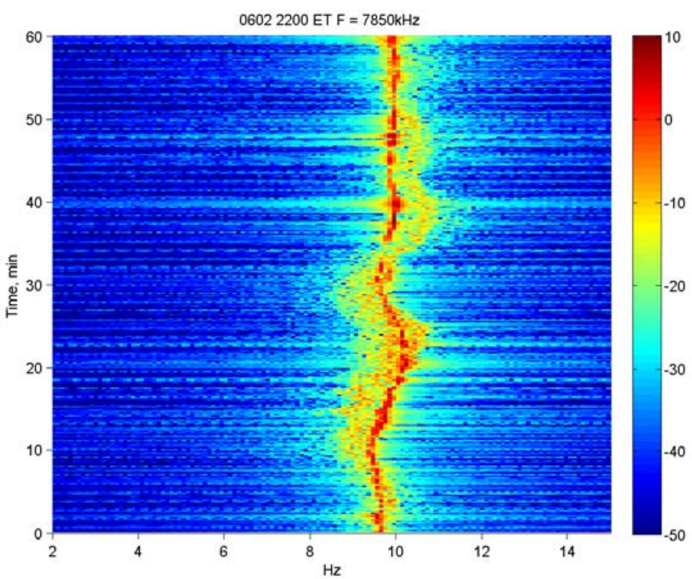
- Primary HF link was CHU (Ottawa), a Canadian time reference station. Very stable and reliable operation.
- GNSS receivers were installed at Rome, NY to obtain data near the mid-point of the link
- HF signals were received at Wallops Island, VA approximately 1000 km from CHU

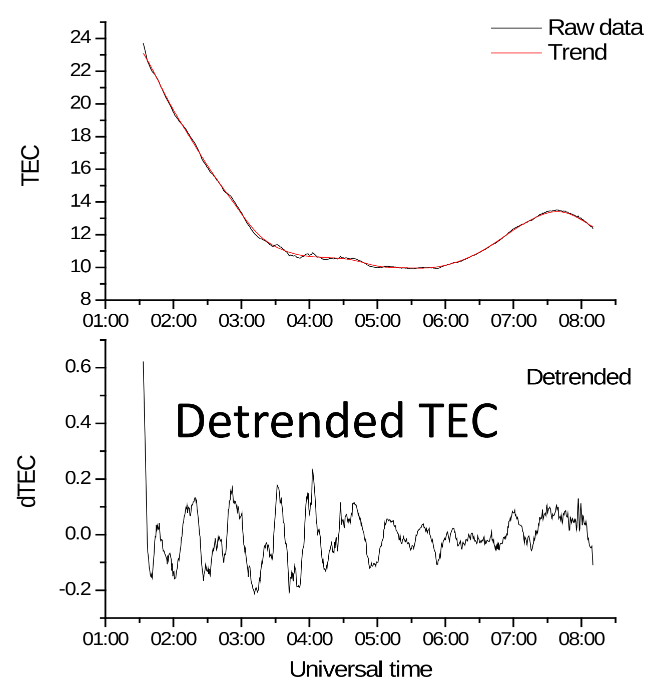


HF signal amplitude & phase

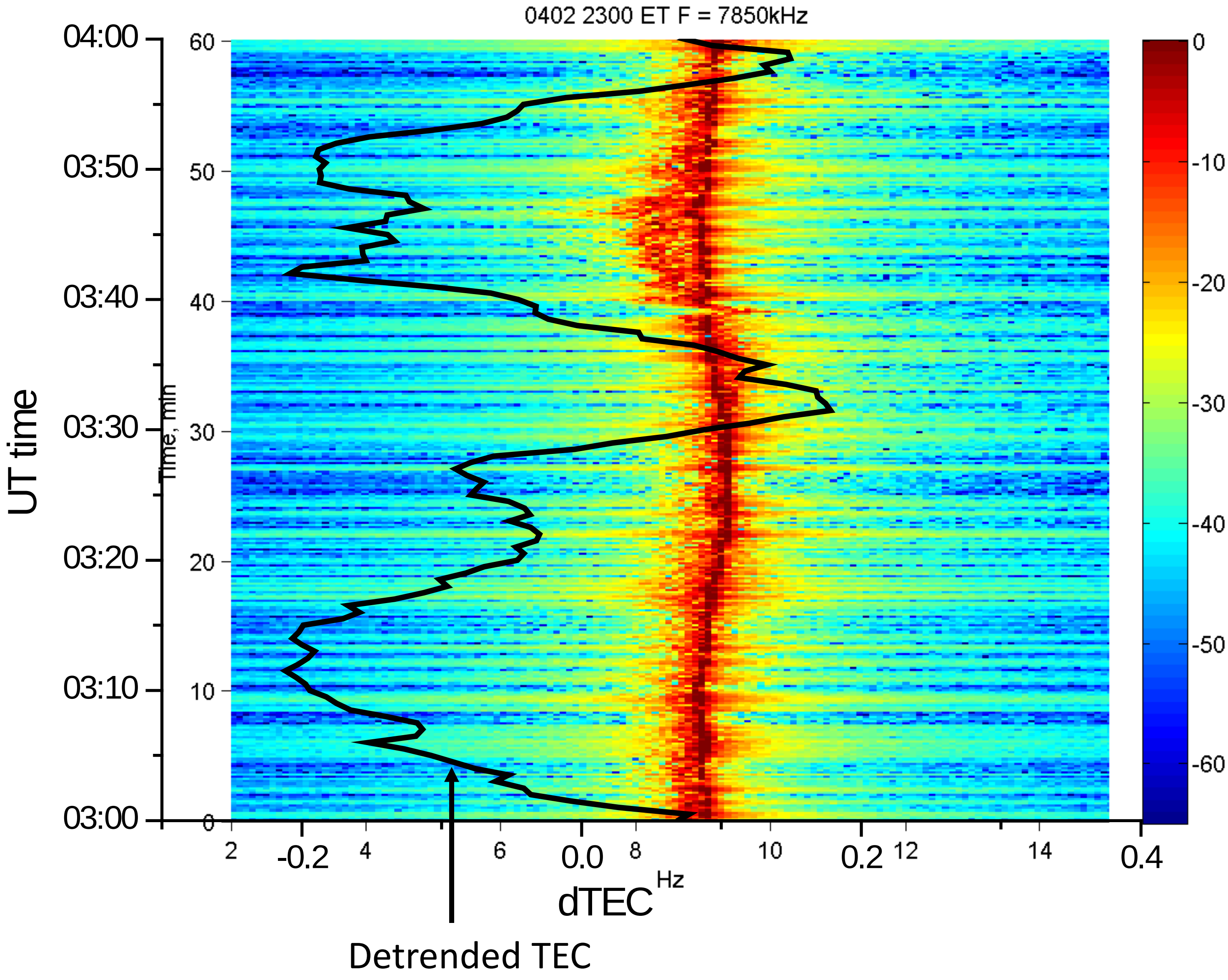
Analysis Approach

- Generate HF Disturbance Index based on Doppler variations in signal
- Generate GPS Disturbance Index based on the amplitude of detrended TEC residuals

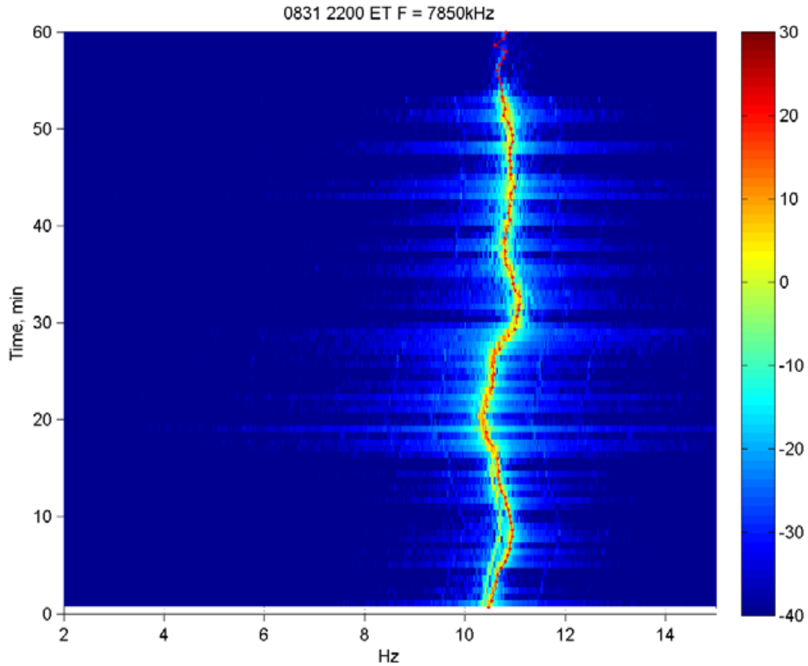


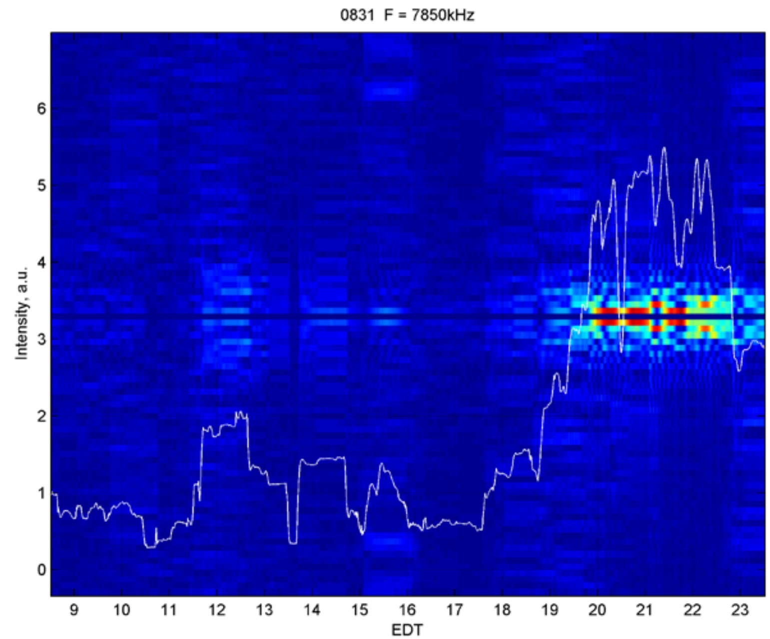


HF Doppler and GPS TEC Correlation



HF Link TID Detection Processing





- Track principal frequency in a given HF channel
- Extract Doppler variations and take real FFT to detect TID "power"
- Automated processing applied to reduce all HF data
- Reduction of GPS data performed separately

Activity on September 12, 2014

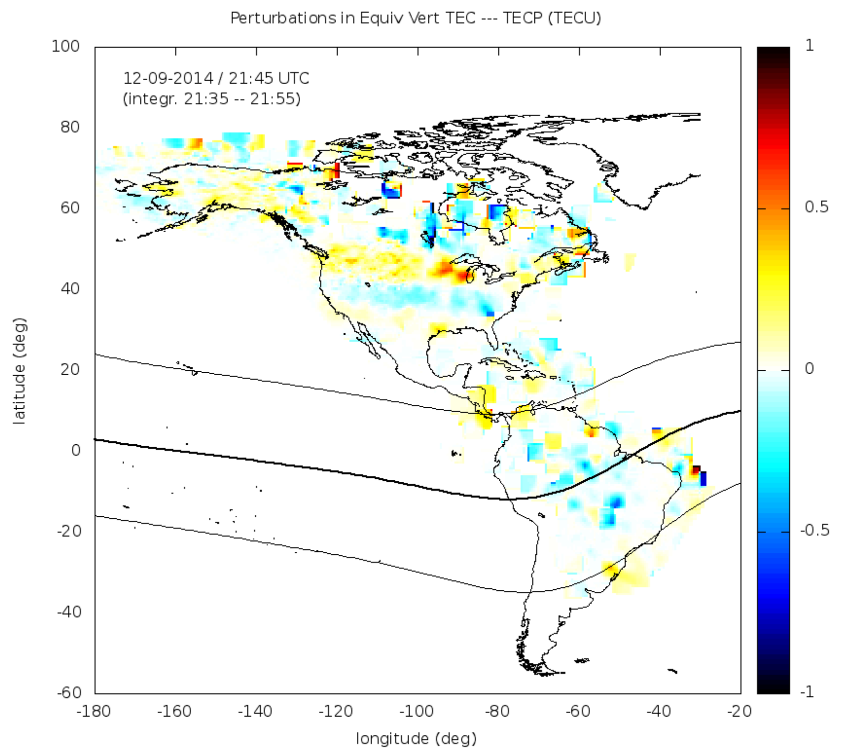
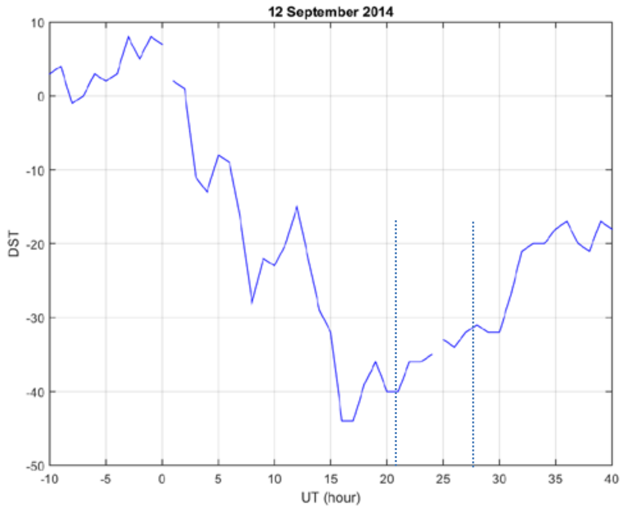
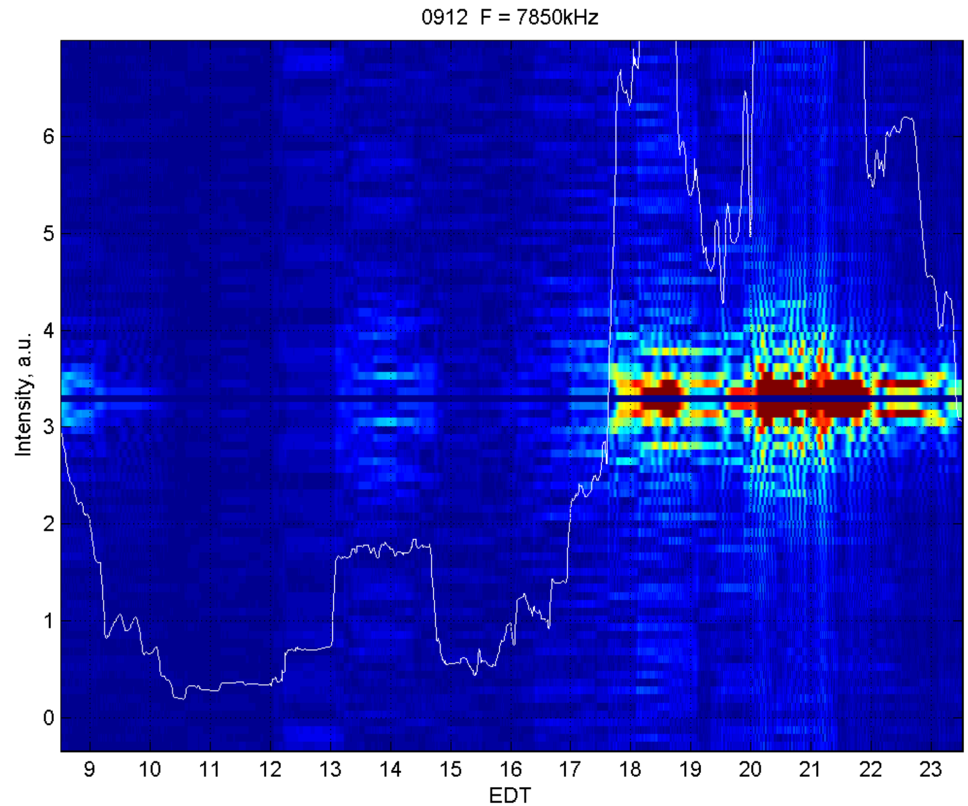


Image courtesy of R. Predipta

- Minor storm activity on 12 September resulted in significant large and medium scale TID generation observed by GPS
- Signatures were also observed on HF links

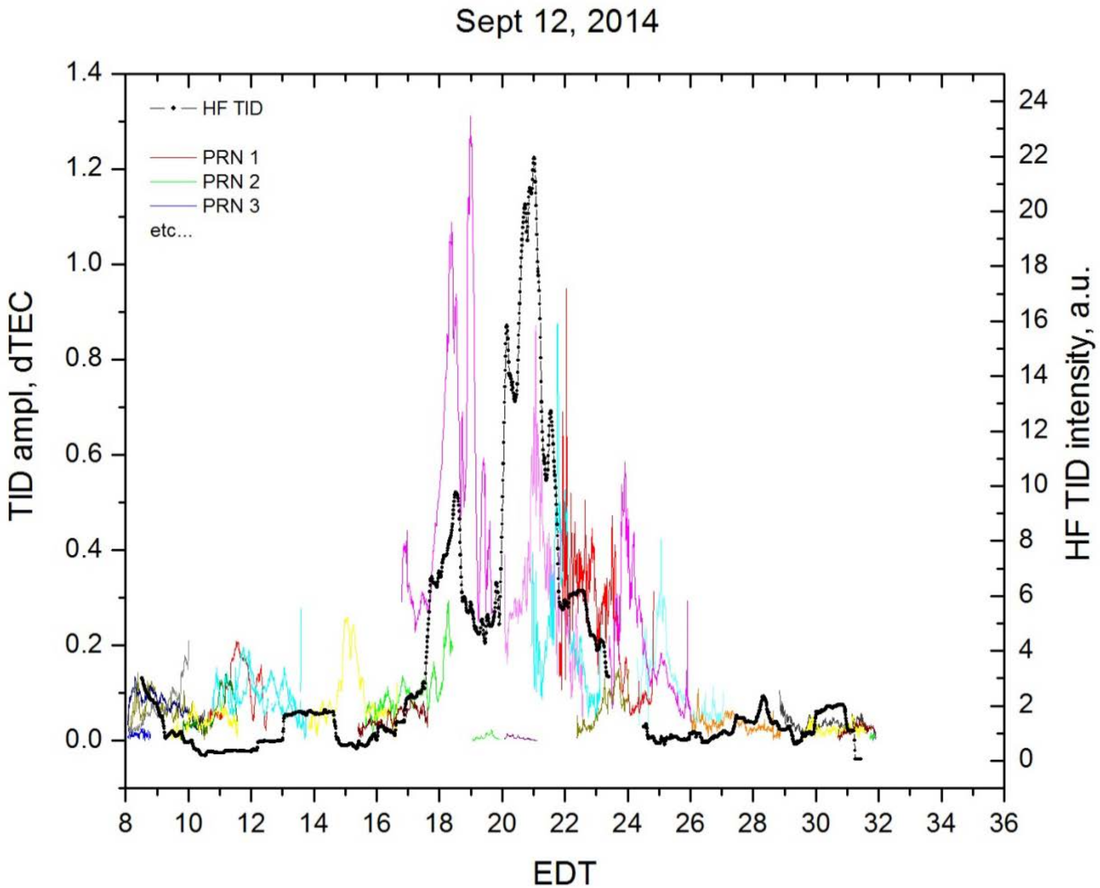
12 September HF TIDs





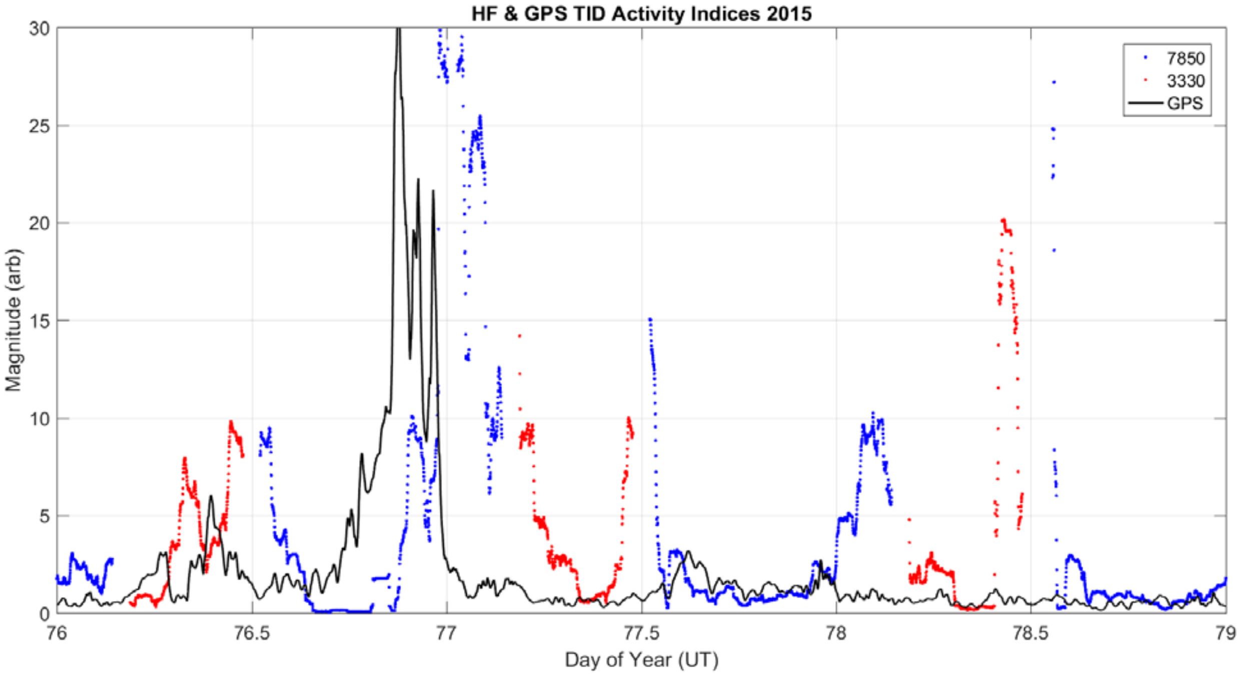
- TIDs show a fairly abrupt "turn-on" on 12 Sep, during recovery from negative DST excursion
- These are the strongest TID events observed through the period 28 Aug-16 Sep

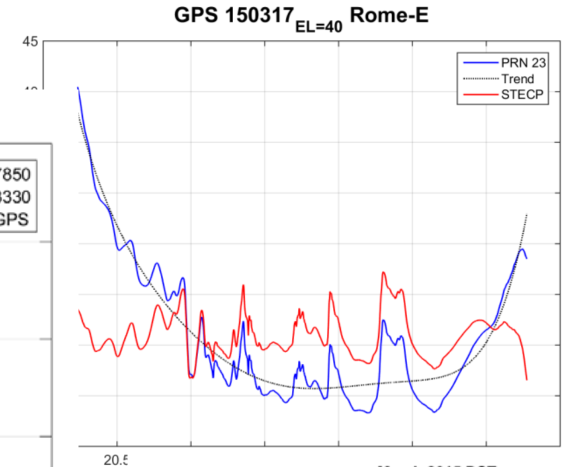
HF and GPS Data Comparison

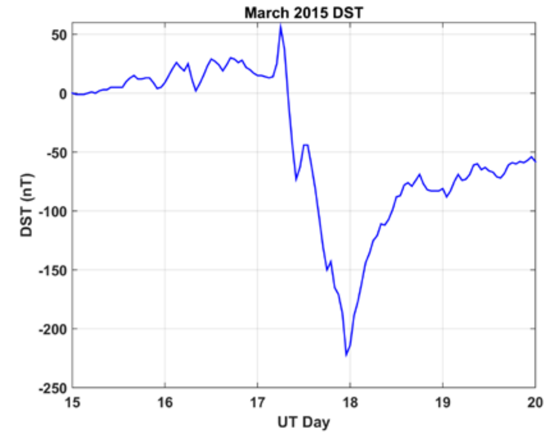


- Ratio of responses on GPS and HF varies significantly
- Note large GPS signature at 19:00 corresponds to relatively modest signature on HF; conversely, at 21:00 HF response exceeds GPS

Another Example:
St. Patrick's Day 2015

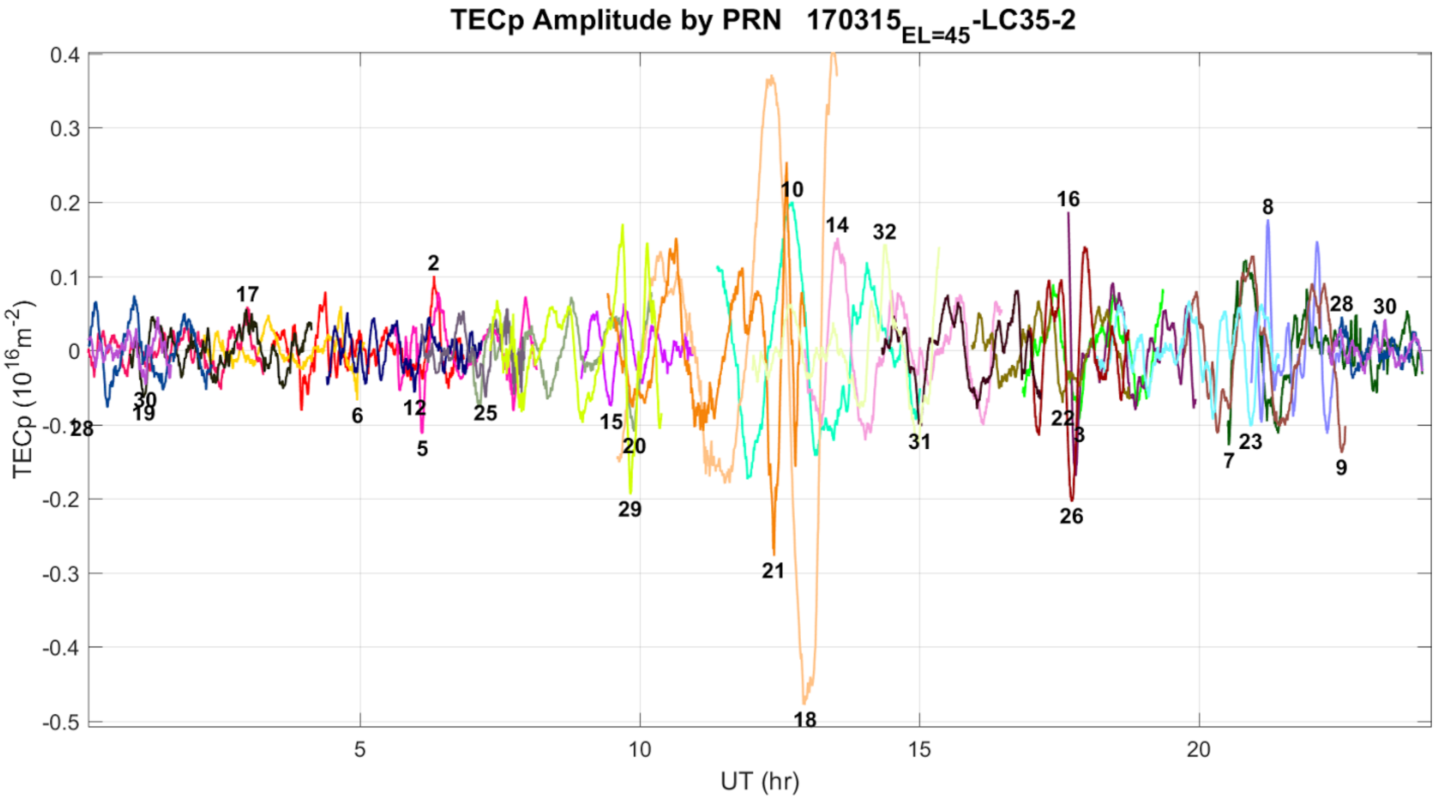






- Corresponds to on-set phase declining period of DST
- Real data is often not "Hooke-like" or even wave-like
- HF channel

“TID” Variations in GPS

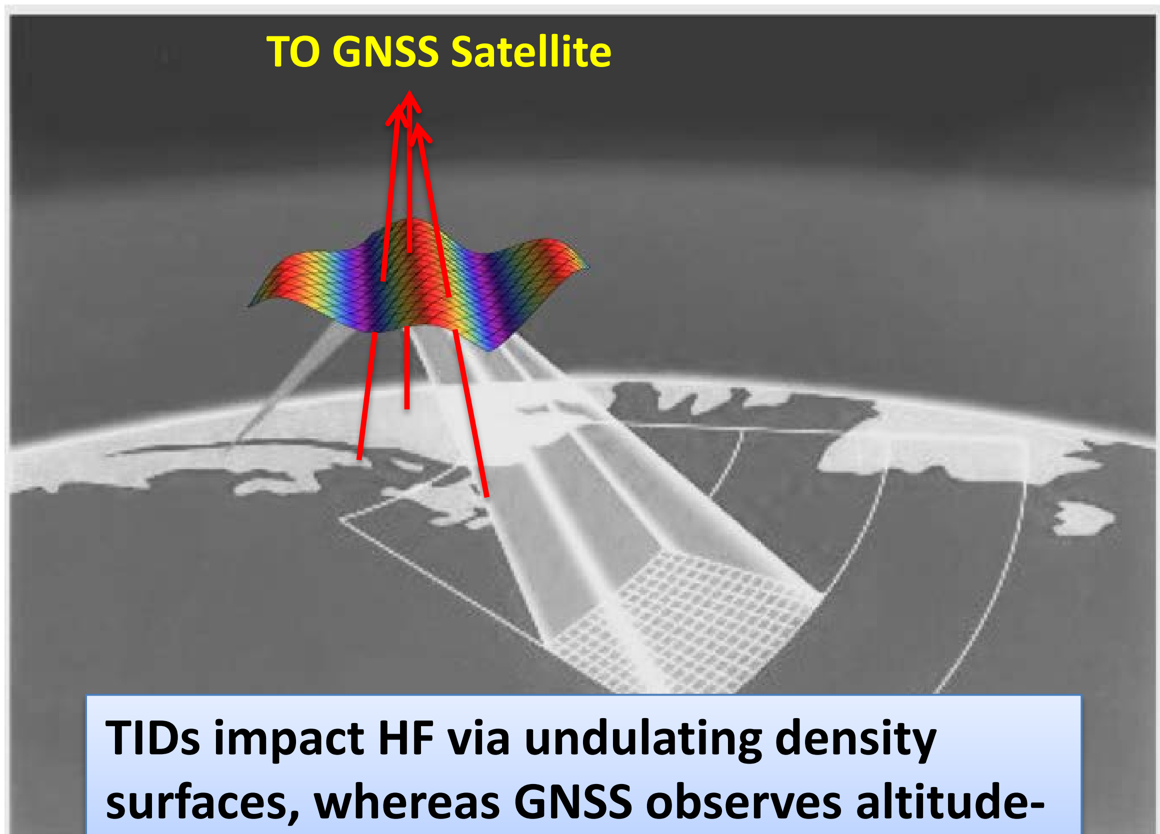


- Larger amplitude fluctuations do not necessarily correlate with HF variations
- Coherence/periodicity between multiple satellites may be a better indicator

Extracting Velocity Parameter

- An array of at least three GNSS receivers can be used to measure TEC variations from which TID parameters such as phase speed and propagation direction can be inferred.

- A number of different analysis approaches considered, including:
  - Afraimovich [1998]; statistical angle of arrival and Doppler method
  - Galushko [2012]; generalization to non-plane wave perturbations
  - Temporal cross-correlation approach

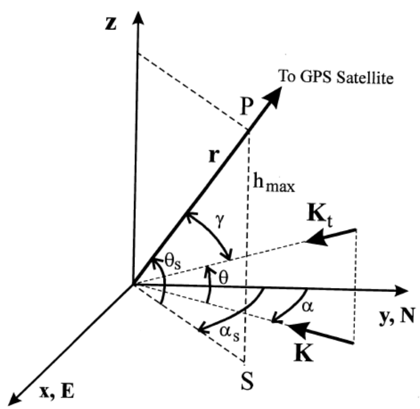


TIDs impact HF via undulating density surfaces, whereas GNSS observes altitude-integrated effects

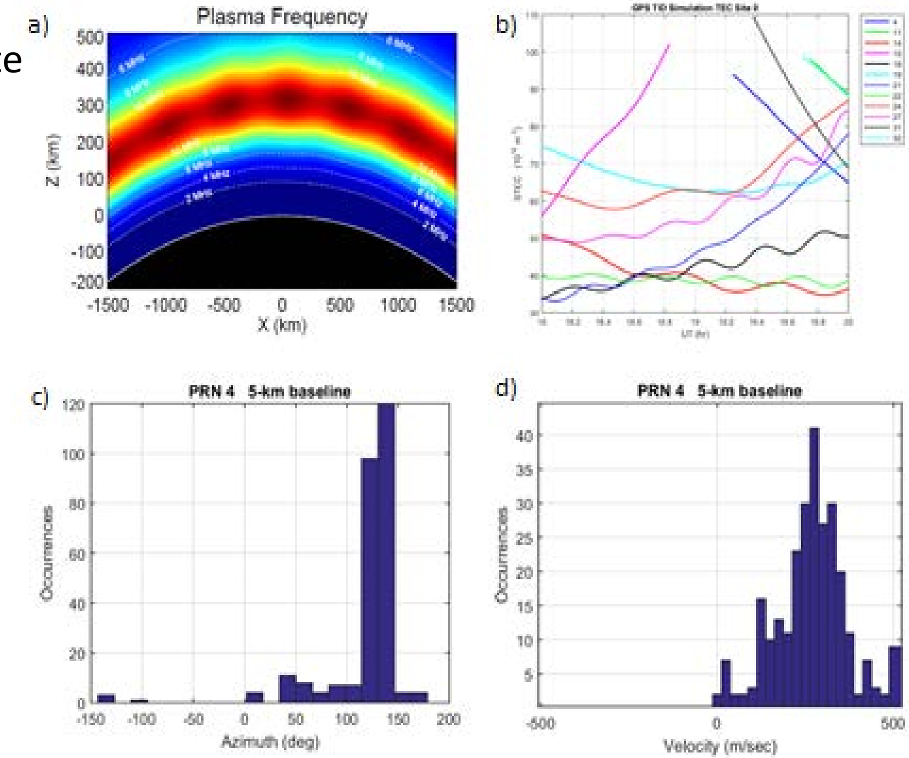
TID GNSS Simulation

- Afraimovich [1998] was employed to estimate propagation angle and velocity for a simulated TID assuming three GPS receivers on 5-km baselines

E.L. Afraimovich et al./Journal of Atmospheric and Solar-Terrestrial Physics 60 (1998) 1205–1223



Then the phase differences $\Delta\phi$ between the receivers, spaced along the axes x and y, are proportional to the values of the horizontal components $G_x = I'_x$ and $G_y = I'_y$ of the TEC gradient; primes denote derivatives with respect to variables specified by a lower index. For convenience of presentation, we will be using values of phase as well as TEC. Phase differences $\Delta\phi$ are used to calculate its spatial derivatives $\phi'_x(t) = \Delta\phi/\Delta x$ and $\phi'_y(t) = \Delta\phi/\Delta y$ where Δx and Δy are distances between receivers spaced along the x and y axes.



Plane wave

$$\Delta\phi(t,x,y) = \delta \sin(\Omega t - K_x x - K_y y + \varphi_0)$$

Propagation Azimuth

$$\alpha(t) = \arctan(G_x(t)/G_y(t)) = \arctan(\phi'_x(t)/\phi'_y(t))$$

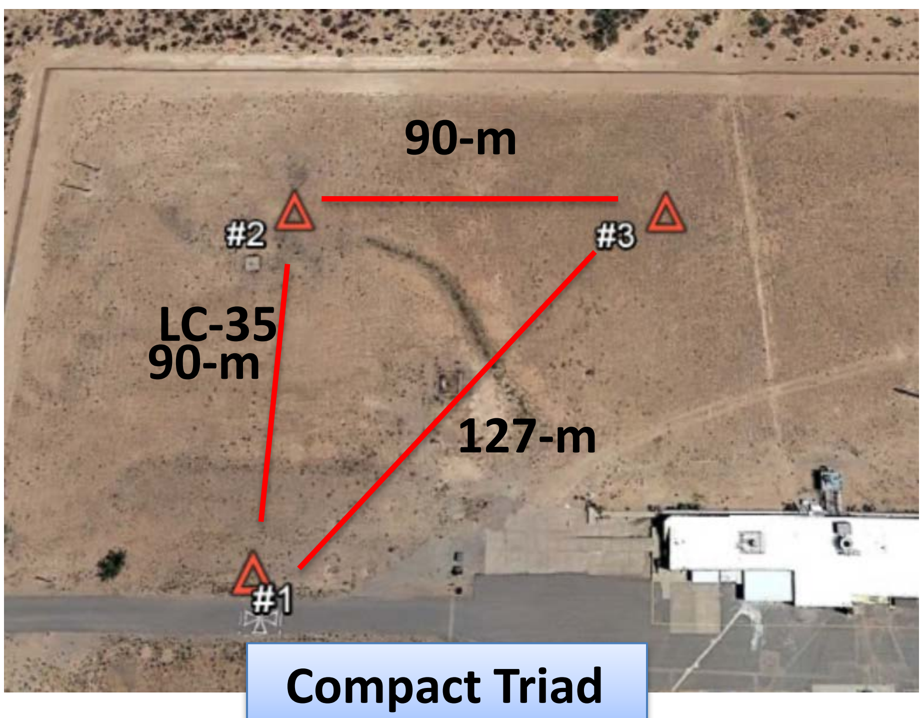
Velocity

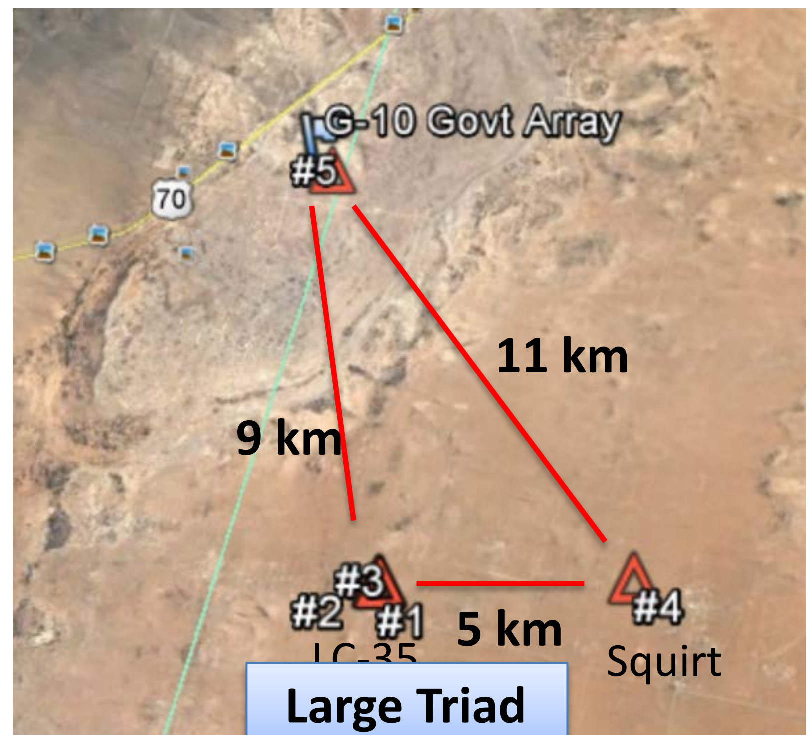
$$u_x(t) = \phi'_t(t)/\phi'_x(t) = \Omega/K_x \qquad u_y(t) = \phi'_t(t)/\phi'_y(t) = \Omega/K_y$$

$$V_h(t) = u(t) + w_x(t)\sin\alpha(t) + w_y(t)\cos\alpha(t),$$

Triad Observations Mar 2017

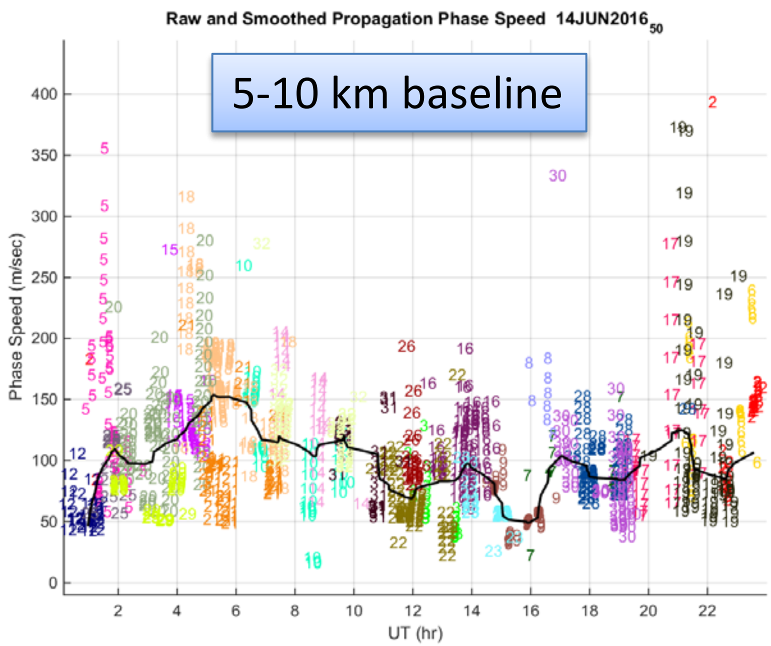
- Deploy three GNSS systems on short baselines and two additional systems on longer baselines
- Add *phase-coherent* GNSS systems to compact array; understand limitations imposed by phase noise

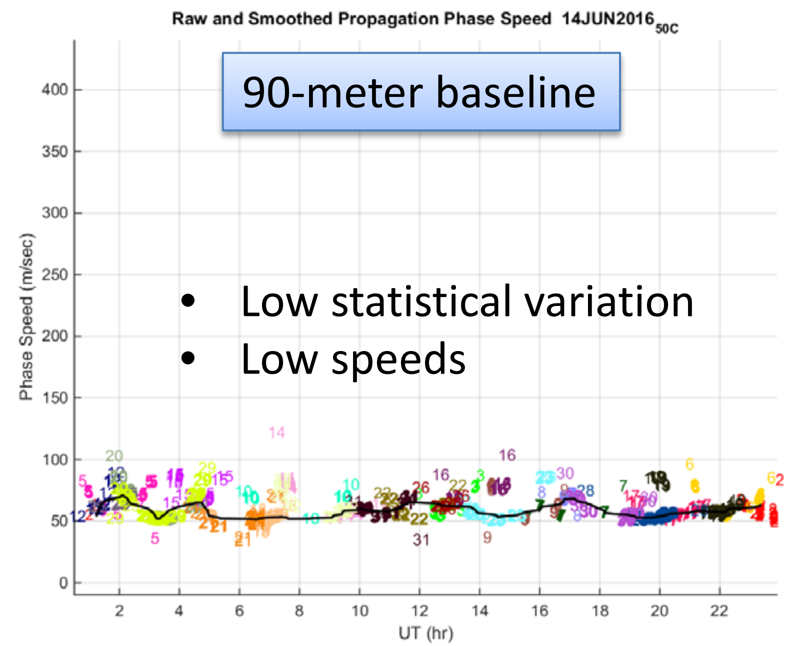




Phase Speed Estimation with GNSS: Compact vs Large Array Results

14 June 2016

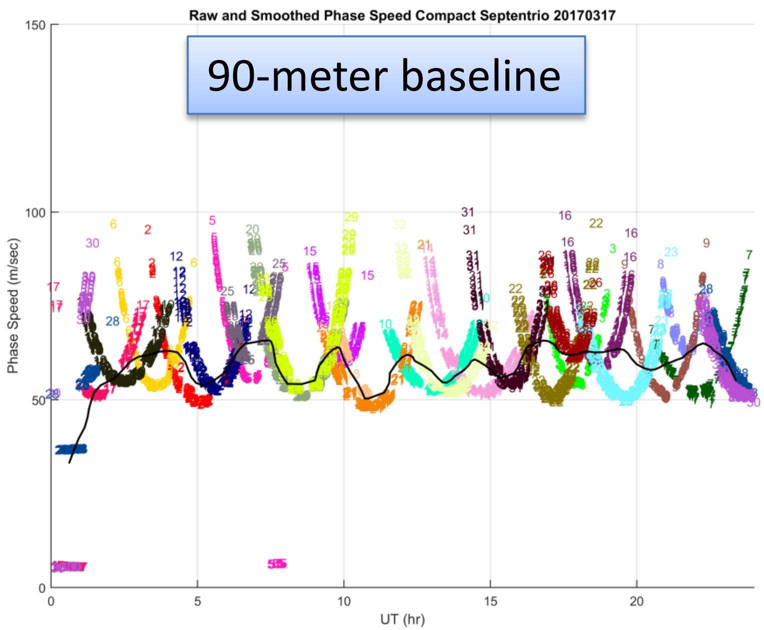


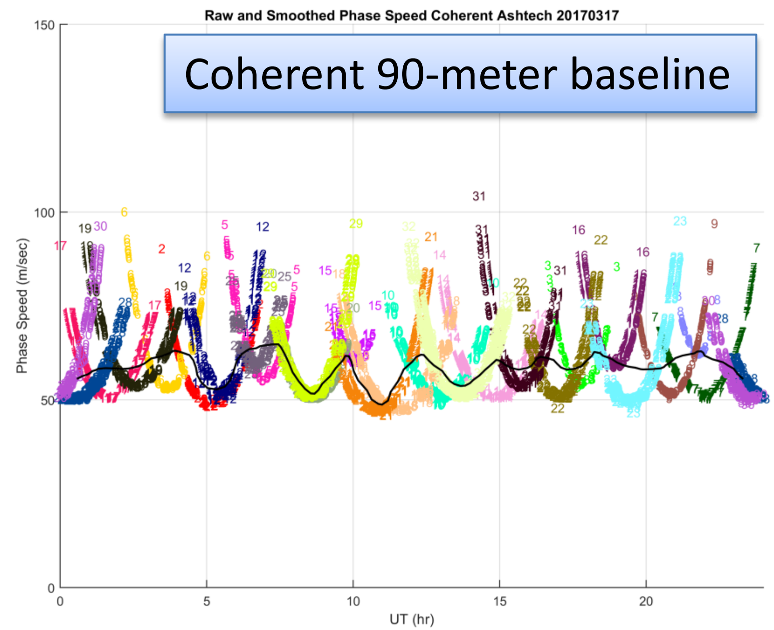


- Interferometric velocity estimates from compact array typically less than estimates from larger baseline array
- Compact array sensitivity impacted by phase noise

March 2017 Comparisons

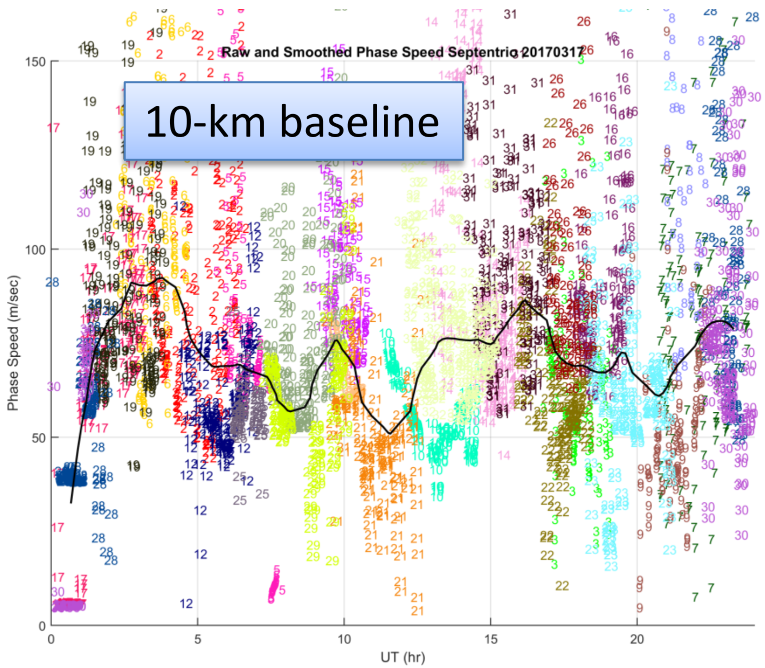
17 March 2017

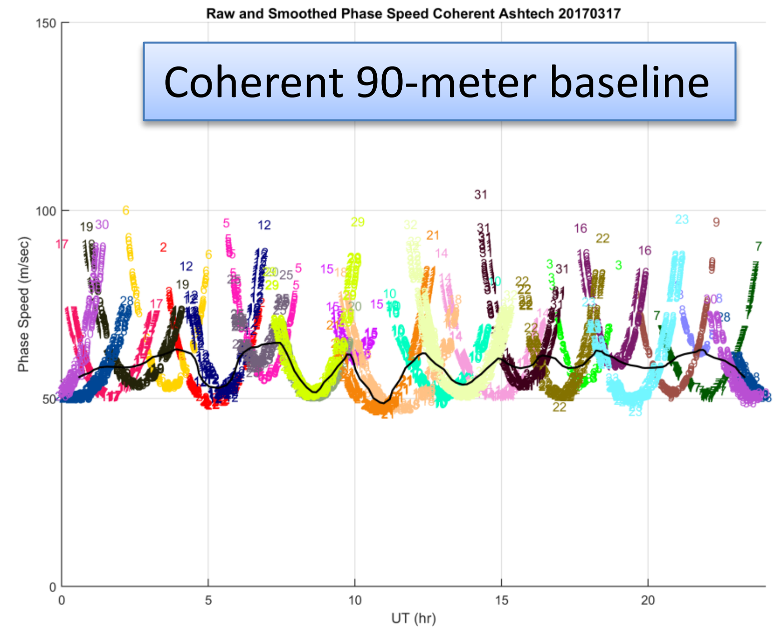




- Virtually identical results from coherent and incoherent array
- Very little diurnal variation evident

March 2017 Comparisons





- 10-km baseline data extremely noisy during this period
- Phase speeds similar after 05:00 UT
- Modest/weak TID amplitudes observed

Summary

- Clear qualitative correlation between strong HF TIDs and GNSS TEC perturbations; less evident for moderate to weak events.
- The relationship between the amplitudes of the responses is nonlinear and not well-understood; coherence may be more important than amplitude
- Signatures may not occur simultaneously due to spatial separation of region being sampled – probable that GNSS can provide some predictive behavior due to wider coverage area
- Results from both coherent and incoherent compact arrays essentially identical; phase noise does not appear to be an issue
- Speeds derived from large array much noisier but similar in magnitude to compact array data
- Multi-constellation GNSS observations should improve sensitivity further and provide additional information on TID characteristics

Way Ahead

- Validation of real world results is badly needed
  - Conduct dedicated measurement campaign with appropriate diagnostics (multiple digisondes, HF links) for several days at least
- Realistic simulations may be one way to resolve questions regarding the algorithm
- Explore parameters other than perturbation amplitude that may better signal correlations between HF and GNSS (e.g., coherence across multiple satellites, geometric factors, etc.)
- Conversely, identify periods when GNSS does not contribute to understanding HF propagation
- Investigate the utility of GNSS gradients to model HF tilts
- Integrate true GNSS observations (GLONASS, Beidou, Galileo, etc); 2X improvement in resolution per site particularly useful when applying high elevation angle filters