Method and Validation for Determining Hooke TID Parameters from GNSS Data

Jacob Schofield,
Dave Rainwater, Thomas Gaussiran

ARL:UT

9 May 2017

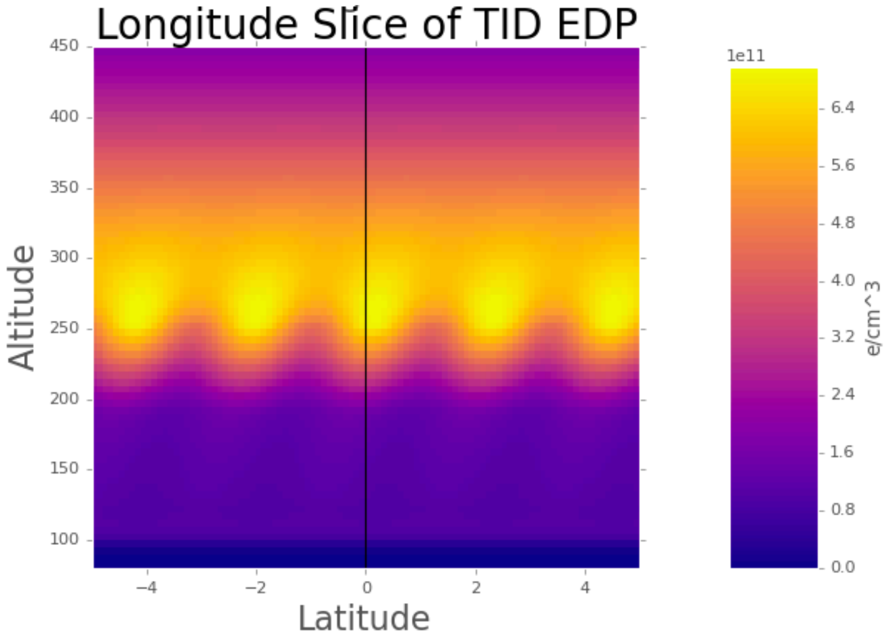
Medium Scale TID

Estimate Medium Scale TIDs (MS-TID) using GNSS data

- Multiple types of MS-TIDs
  - Acoustic Gravity Wave (AGW) – physical model by Hooke, 1967
  - We determine amplitude and phase phenomenologically

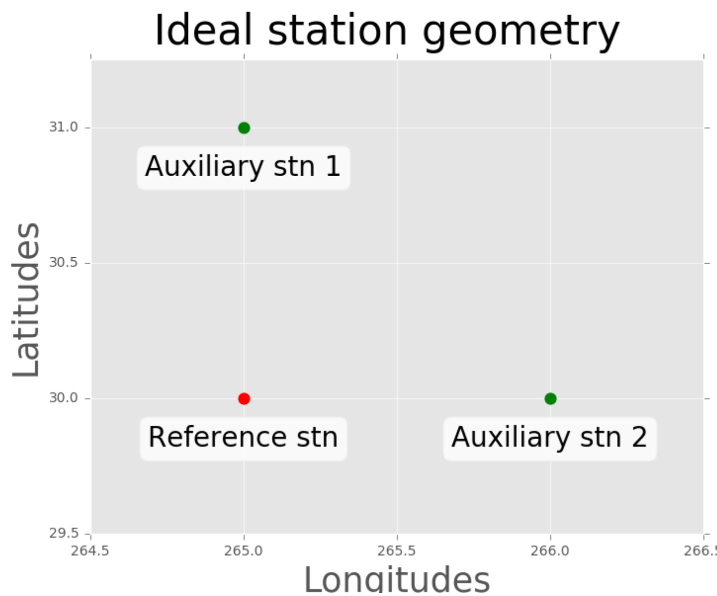
$$N_e' = AN_e^0 \sin(I) \exp(k_{zi}(z-z_0))\omega^{-1}\sqrt{\left(\frac{1}{N_e^0}\partial_z N_e^0 + k_{zi}\right)^2 + \left(\frac{k_{br}}{\sin(I)}\right)^2} \cos\left[\omega\Delta t - \mathbf{k}_r \cdot \mathbf{\Delta x} + \frac{\pi}{2} - \arctan\left(\frac{k_{br}}{\sin(I)\left(\frac{1}{N_e^0}\partial_z N_e^0 + k_{zi}\right)}\right) + \phi\right]$$

  - ‘Non-classical’ electrodynamics-driven TIDs
- Define MS-TID:
  - Period: 5 < T < 45 minutes
  - Velocity: 100 < v < 400 m/s
- TID parameters to estimate
  - k_E: wave vector east component
  - k_N: wave vector north component
  - k_z: wave vector vertical component
  - ω: angular frequency
  - A: amplitude
  - t_0: phase zero (time, alt, lat, lon)



TID parameter estimation - Input data

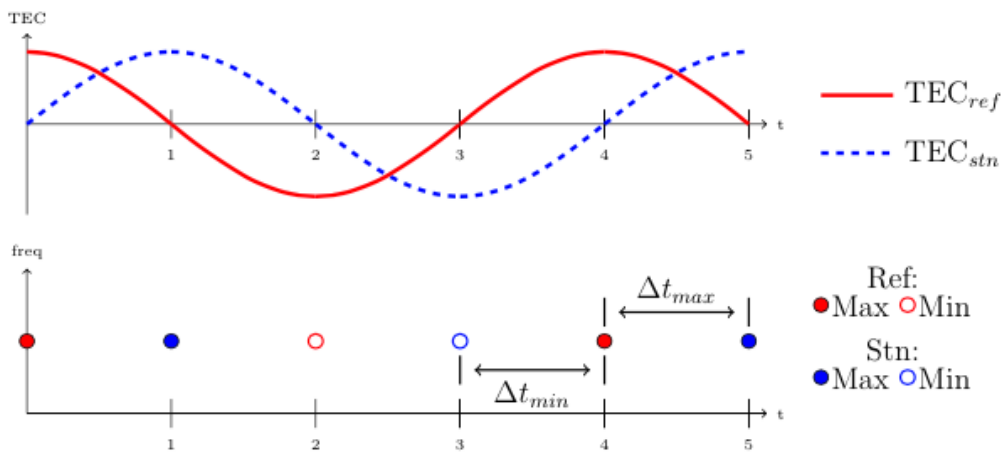
1. GNSS data
   - L1-L2 geometry-free phase or STEC
   - Minimum of 3 receivers in a non-collinear arrangement, optimally orthogonal legs
     - Separations 30-75 km
     - Separation ratio max of 2
     - Opening angle 75°-105°
   - Minimum pass length 90 min. (Nyquist)
   - Satellite elevation angle >45°

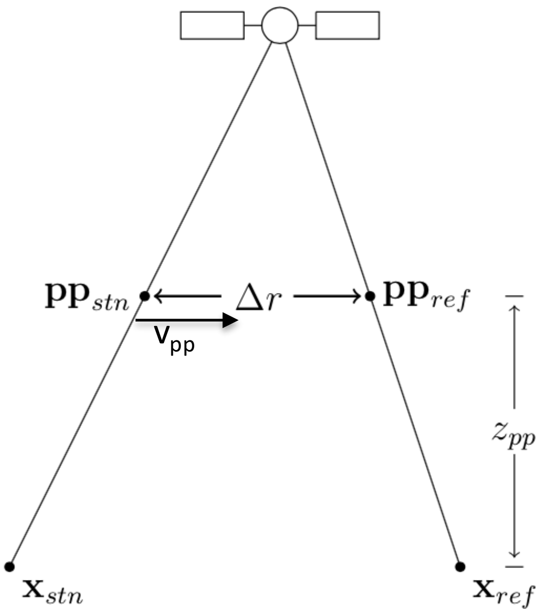


2. Ionospheric model
   - Full 3D EDP
     - Used to normalize Amplitude
   - Need yF_2 and h_mF_2
     - yF_2 used as k_{zi} (scale height in Hooke model)
     - h_mF_2 used as reference altitude (semi-arbitrary)

TID parameter estimation – Pajares defined parameters

- Method based on: *"Medium-scale traveling ionospheric disturbances affecting GPS measurements: Spatial and temporal Analysis",* M. Hernández-Pajares, J.M. Juan, J. Sanz, JGR **111** A07S11, 2006.
- Defines how to calculate k-vector and frequency
  - Uses STEC measurements from 3 GNSS receivers
  - Correlates bandpass-detrended STEC data to obtain time delays
  - We assume k_{zr} = 0 and use iono scale height yF2 for k_{zi}
- Variables required to solve for k-vector, ω





Δt_{max}: Time of maximum correlation
Δt_{min}: Time of maximum anti-correlation

Δr_{pp}: Ionosphere Pierce Point (IPP) separation
v_{pp}: IPP velocity

TID parameter estimation – Pajares defined parameters

- K-vector linear equations:

$$\Delta t_{max1} = (\Delta \mathbf{r}_{pp1,E} + \Delta t_{max1} \cdot \mathbf{v}_{pp1,E}) \cdot \mathbf{s}_\mathbf{E} + (\Delta \mathbf{r}_{pp1,N} + \Delta t_{max1} \cdot \mathbf{v}_{pp1,N}) \cdot \mathbf{s}_\mathbf{N}$$
$$\Delta t_{max2} = (\Delta \mathbf{r}_{pp2,E} + \Delta t_{max2} \cdot \mathbf{v}_{pp2,E}) \cdot \mathbf{s}_\mathbf{E} + (\Delta \mathbf{r}_{pp2,N} + \Delta t_{max2} \cdot \mathbf{v}_{pp2,N}) \cdot \mathbf{s}_\mathbf{N}$$

  - Subscript 1 (2) indicates reference to 1^{st} (2^{nd}) auxiliary station

- Angular frequency equation:

$$\omega = \frac{\pi}{|\Delta t_{min} - \Delta t_{max}| \cdot (1 - \mathbf{s} \cdot \mathbf{v}_{pp})}$$

  - We compute omega for velocity of each auxiliary station's IPP
  - Final ω is the average of the two individual values

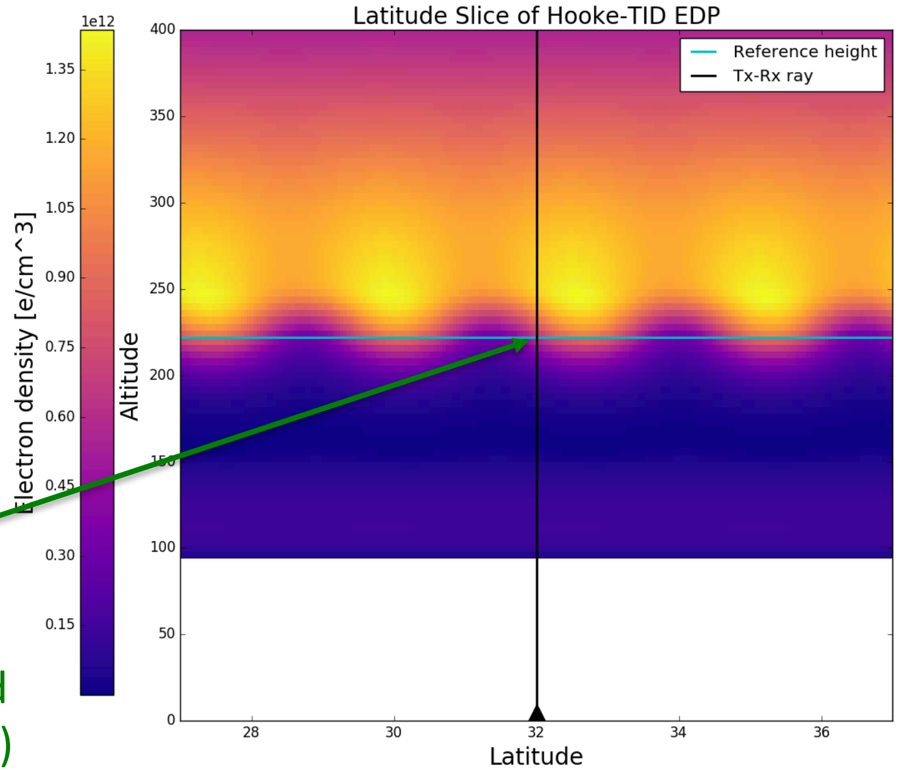
- Connect slowness vector and k-vector

$$\mathbf{k} = \mathbf{s} \cdot w$$

TID parameter estimation – ARL parameters

ARL:UT method to obtain Phase

- Determined observationally from GFP or STEC data
- Locate null (effective zero crossing) in data



Hooke input:
Phase zero at time t_0 and
IPP location (z_0, lat_0, lon_0)

ARL:UT method to obtain Amplitude

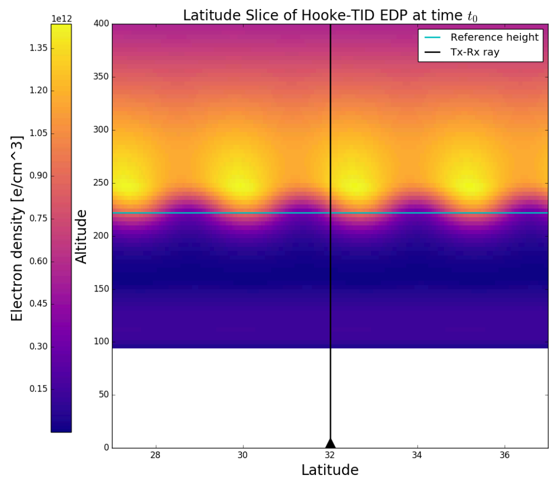
- Dependent on other variables (k-vector, ω, ϕ_0)
- Uses steady-state ionosphere EDP (best available) to normalize TID amplitude
- STEC value definition: $S(\mathbf{x},t) = S^0(\mathbf{x},t) + \beta = \oint_s N(\mathbf{x},t)d\mathbf{s} + \beta$
- Hooke electron density perturbation:

$$N(\mathbf{x},t) = N_e^0(\mathbf{x},t) + N_e'(\mathbf{x},t) = N_e^0(\mathbf{x},t) + A(z_0)N_e''(\mathbf{x},t)$$

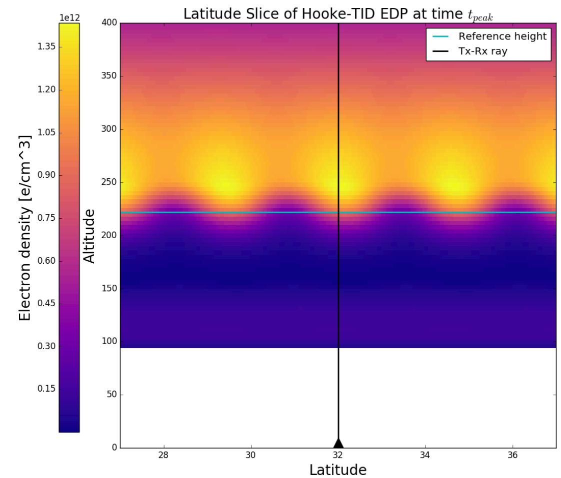
- For two time points, we can solve the matrix

$$\begin{bmatrix} S(\mathbf{x_1},t_1) - \oint_s N_e^0(\mathbf{x_1},t_1)d\mathbf{s} \\ S(\mathbf{x_2},t_2) - \oint_s N_e^0(\mathbf{x_2},t_2)d\mathbf{s} \end{bmatrix} = \begin{bmatrix} \oint_s N_e''(\mathbf{x_1},t_1)d\mathbf{s} & 1 \\ \oint_s N_e''(\mathbf{x_2},t_2)d\mathbf{s} & 1 \end{bmatrix} \times \begin{bmatrix} A \\ \beta \end{bmatrix}$$

t_1 taken at ϕ_0

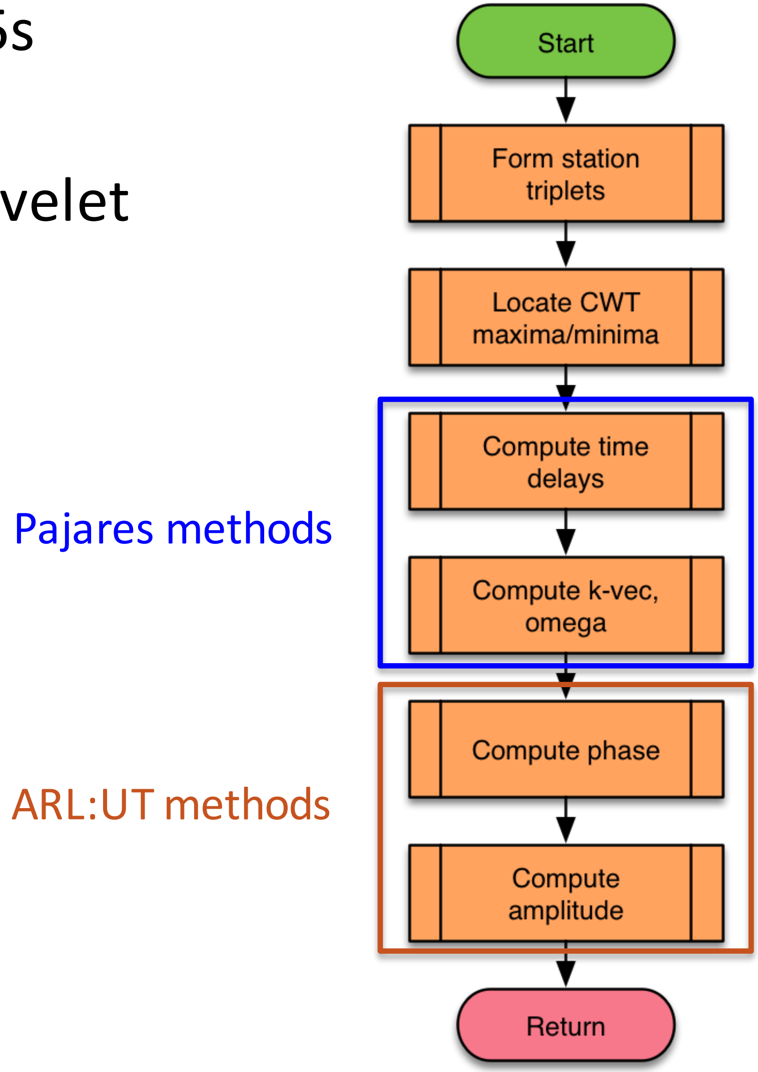


t_2 taken at peak



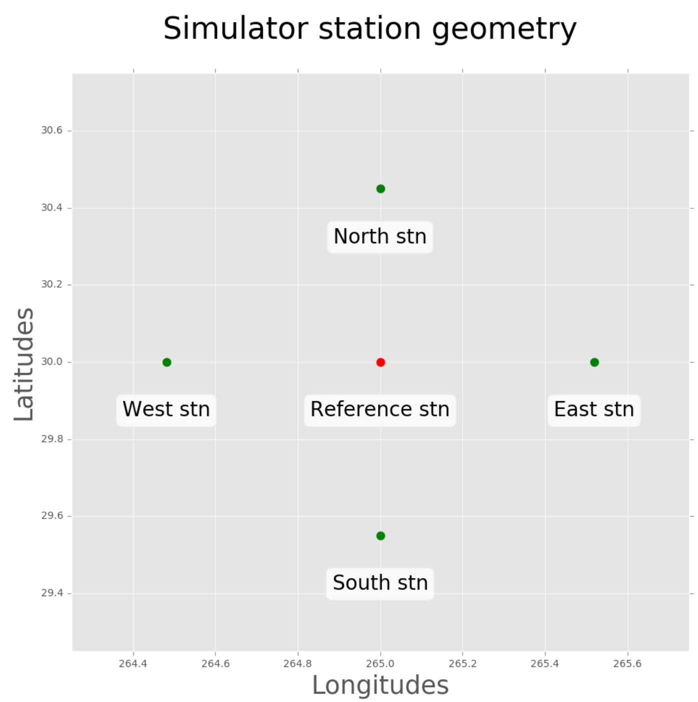
TID parameter estimation – High-level algorithm

- Typical GNSS data rate: 5s
  - We interpolate to 1s
- Compute continuous wavelet transformation (CWT)



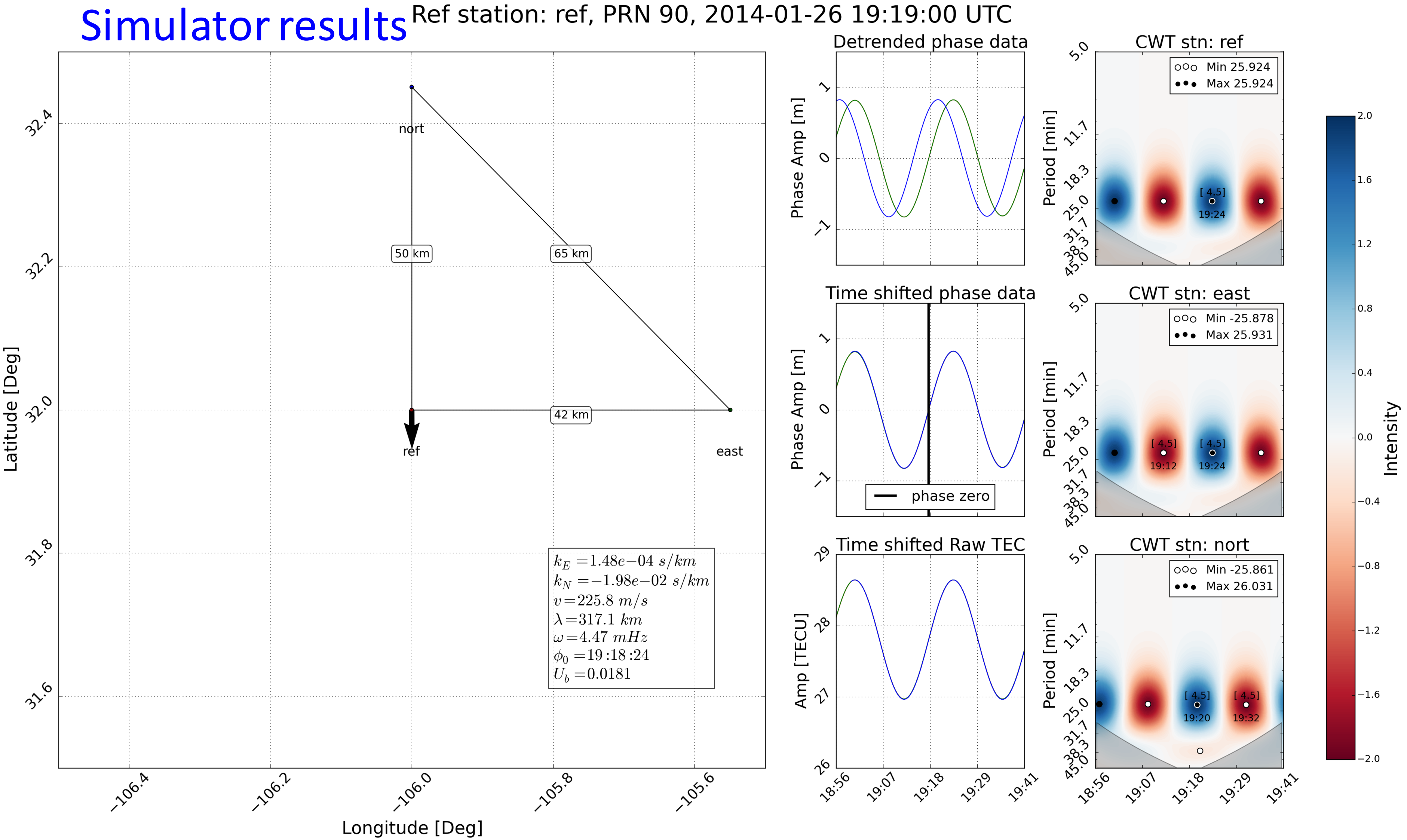
TID parameter estimation - Simulator

- The GNSS data simulator
  - Hooke TID
  - Ideal station geometry
  - Stationary or moving satellites
  - Strider (ARL:UT Jones-Stephenson type) 3D full-physics ray tracer



TID parameter estimation – Sample output

Simulator results

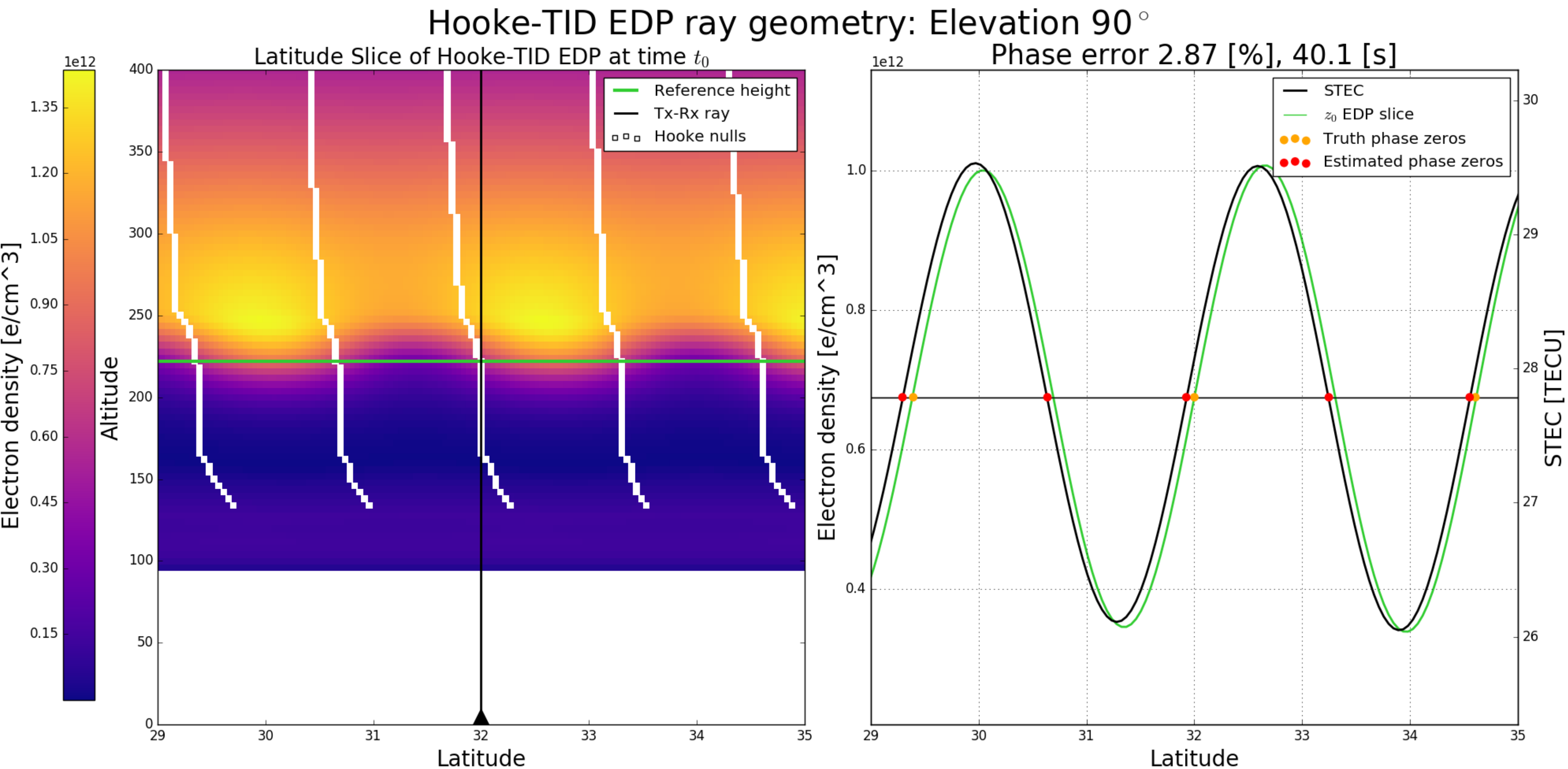


Algorithmic error due to look angle (El/Az)

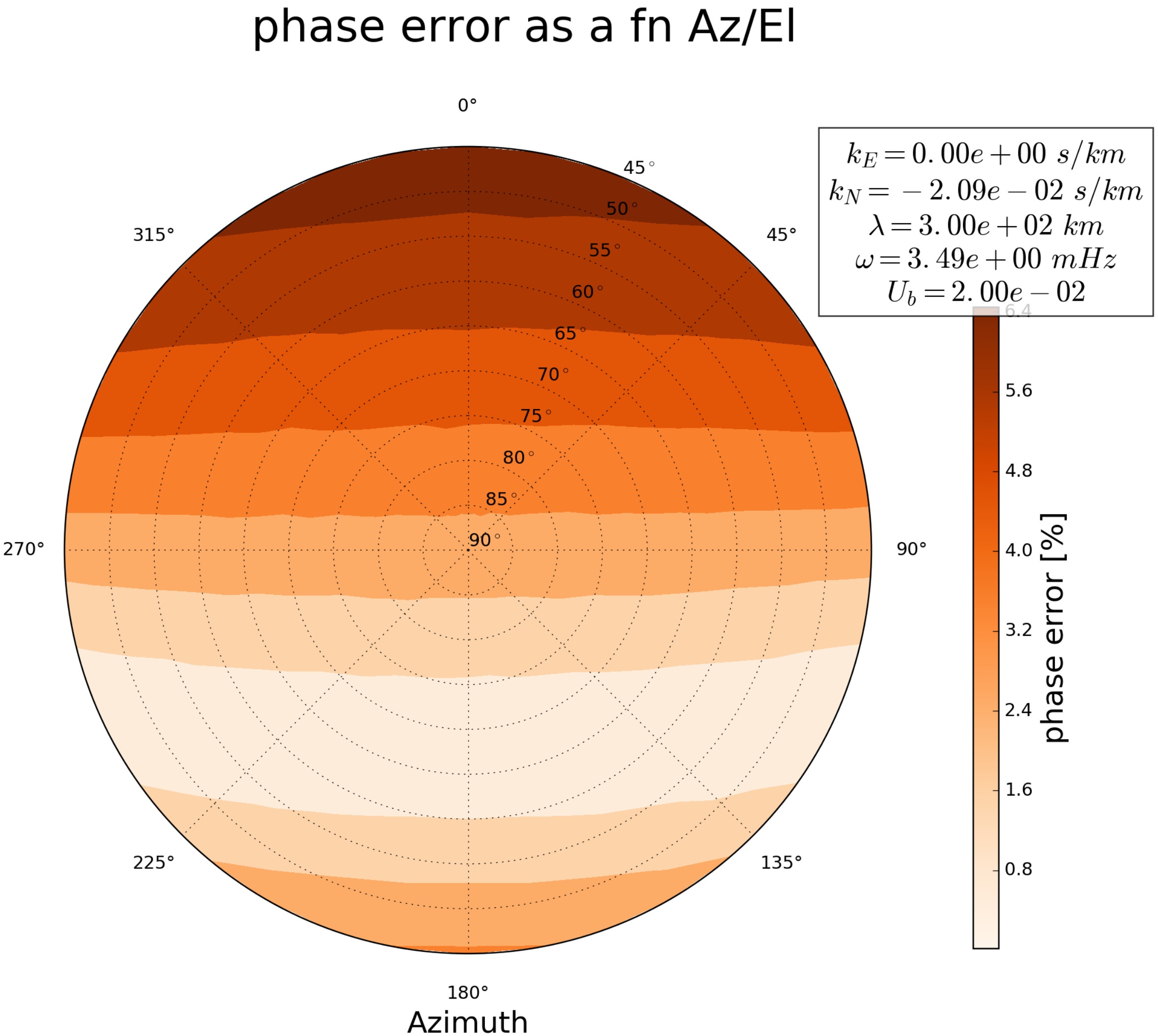
- Eliminate satellite motion effects by using non-moving GNSS satellites
  - This yields a IPP velocity of zero; simplifies the Pajares k-vector equation
  - Done to disassociate geometric effects from satellite motion effects
- Employ our Hooke TID model to simulate GNSS data
- Spherically symmetric ionosphere formed with single IRI vertical profile
- Use same data rate discretization to mimic binning limitations
  - Generate data at 5s cadence (typical GNSS data rate)
  - Interpolate to 1s

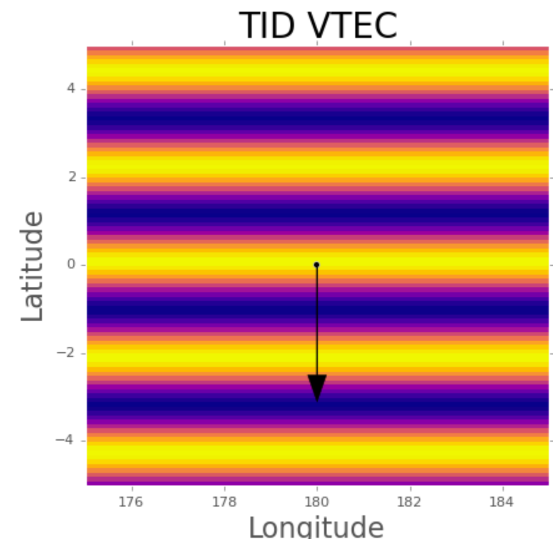
Geometric error analysis

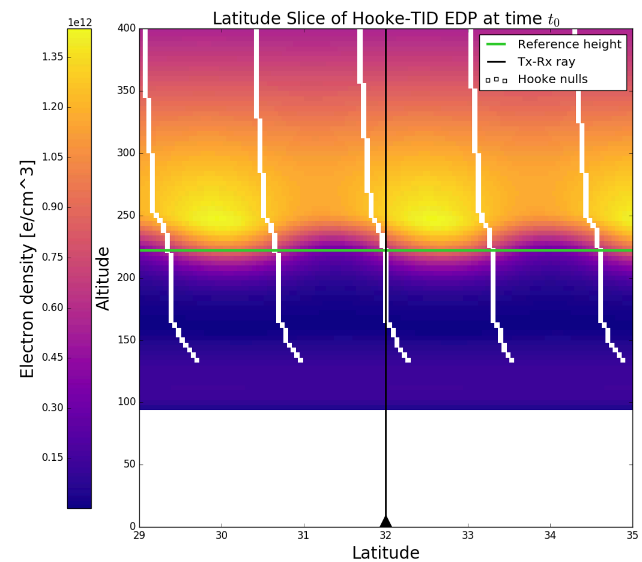
- TID amplitude: 0.04 km/s
- Phase zero is a fn of altitude



Geometric error analysis – Phase Error

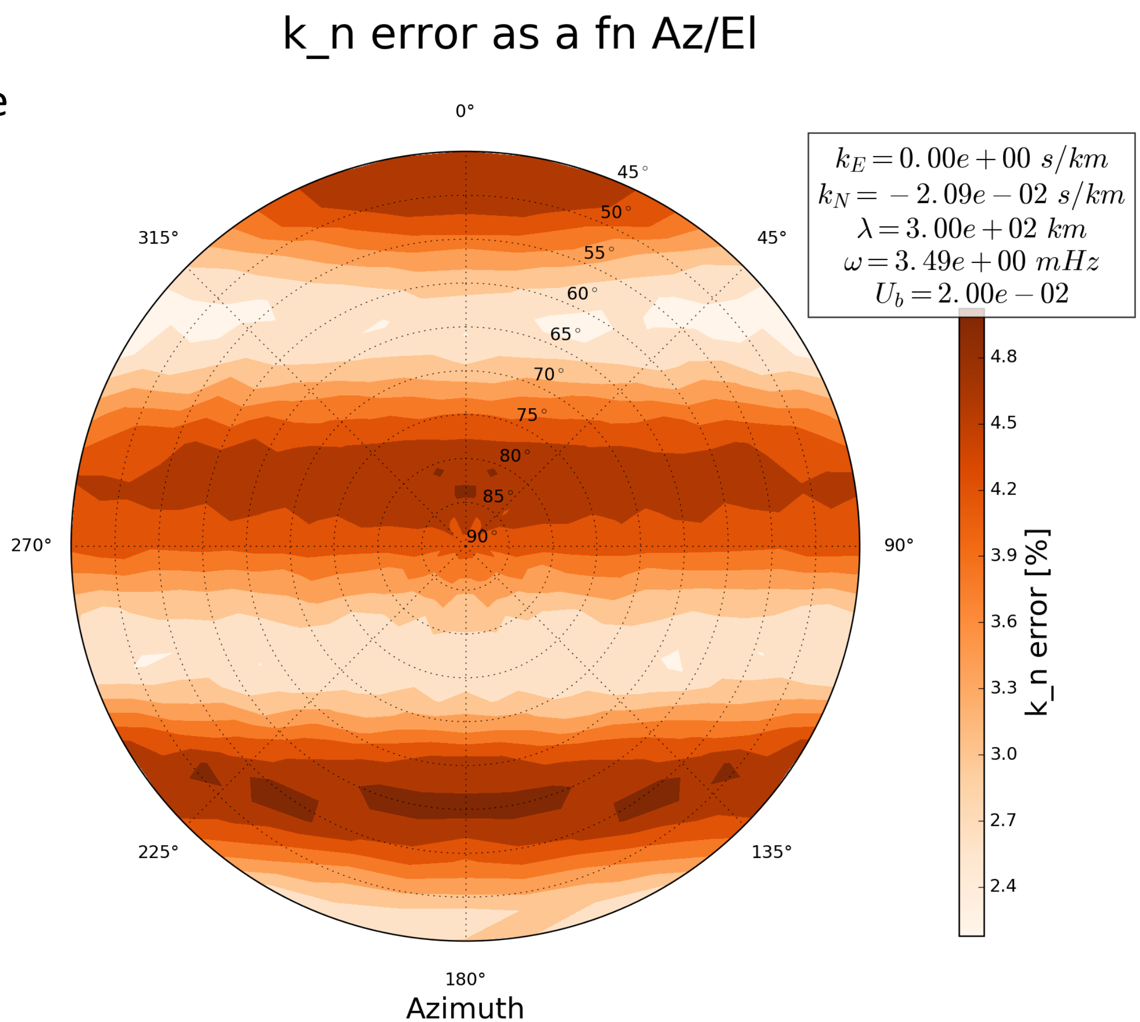






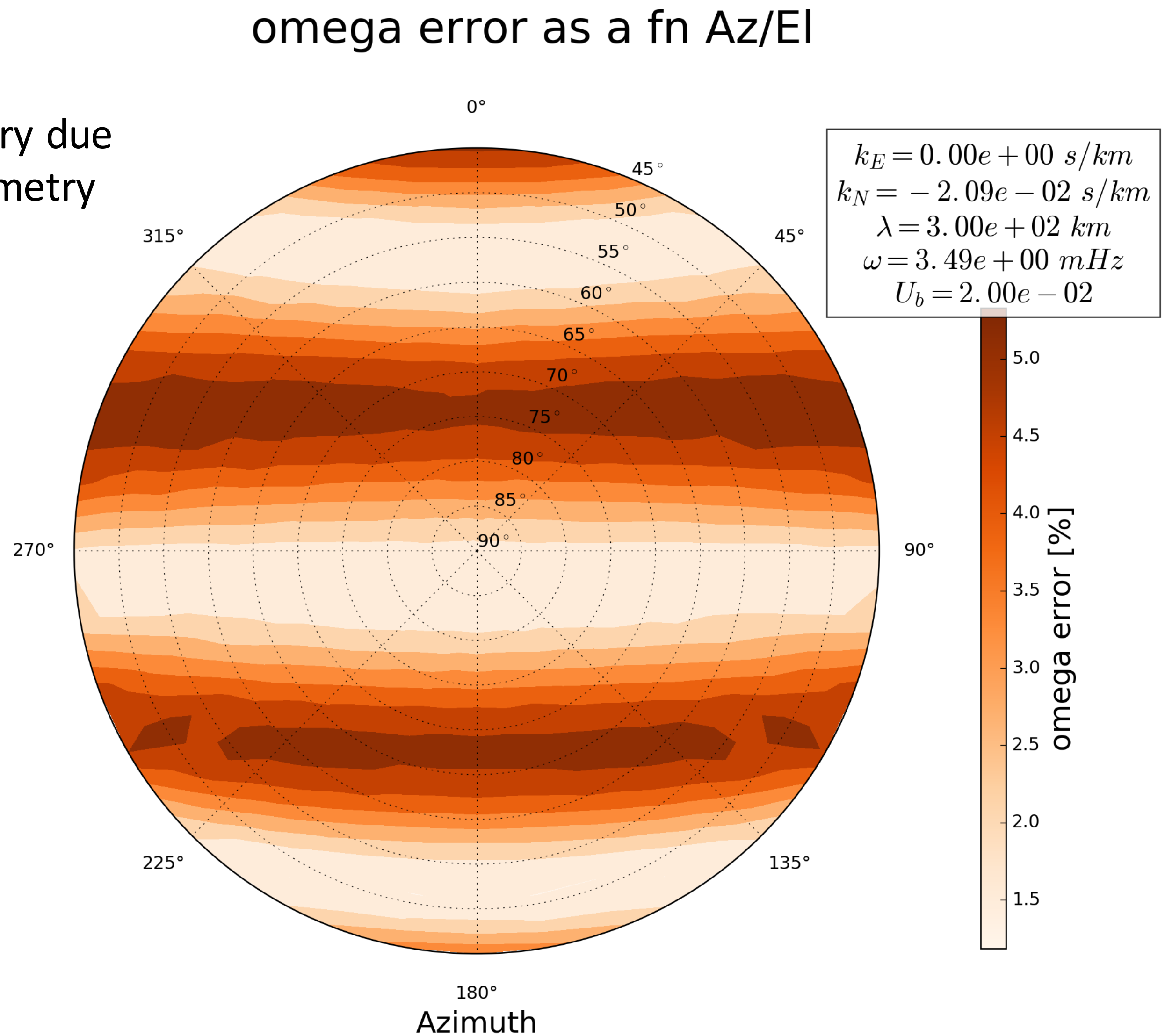
Geometric error analysis – k_N Error

Minor asymmetry due to station asymmetry



Geometric error analysis – Omega Error

Minor asymmetry due to station asymmetry



Geometric error analysis - Results

- We establish a new method to determine Hooke parameter error as a function of GNSS ray geometry
- We found significant geometry-induced errors in GNSS data-derived TID parameters
  - Impacts precision HF ray propagation applications
- Next efforts:
  - Determine effects of satellite motion
  - Explore ways to compensate for TID parameter errors, knowing the GNSS ray geometry, as part of processing

Backup – k_E Error

Result is zero since k_e is defined as zero for this scenario