Interfacing ionospheric propagation model with plasma instability model for GNSS scintillation studies

Kshitija Deshpande and Matt Zettergren (ERAU)

CEDAR 2017 Workshop

21 June 2017

SIGMA: GNSS FORWARD PROPAGATION MODEL

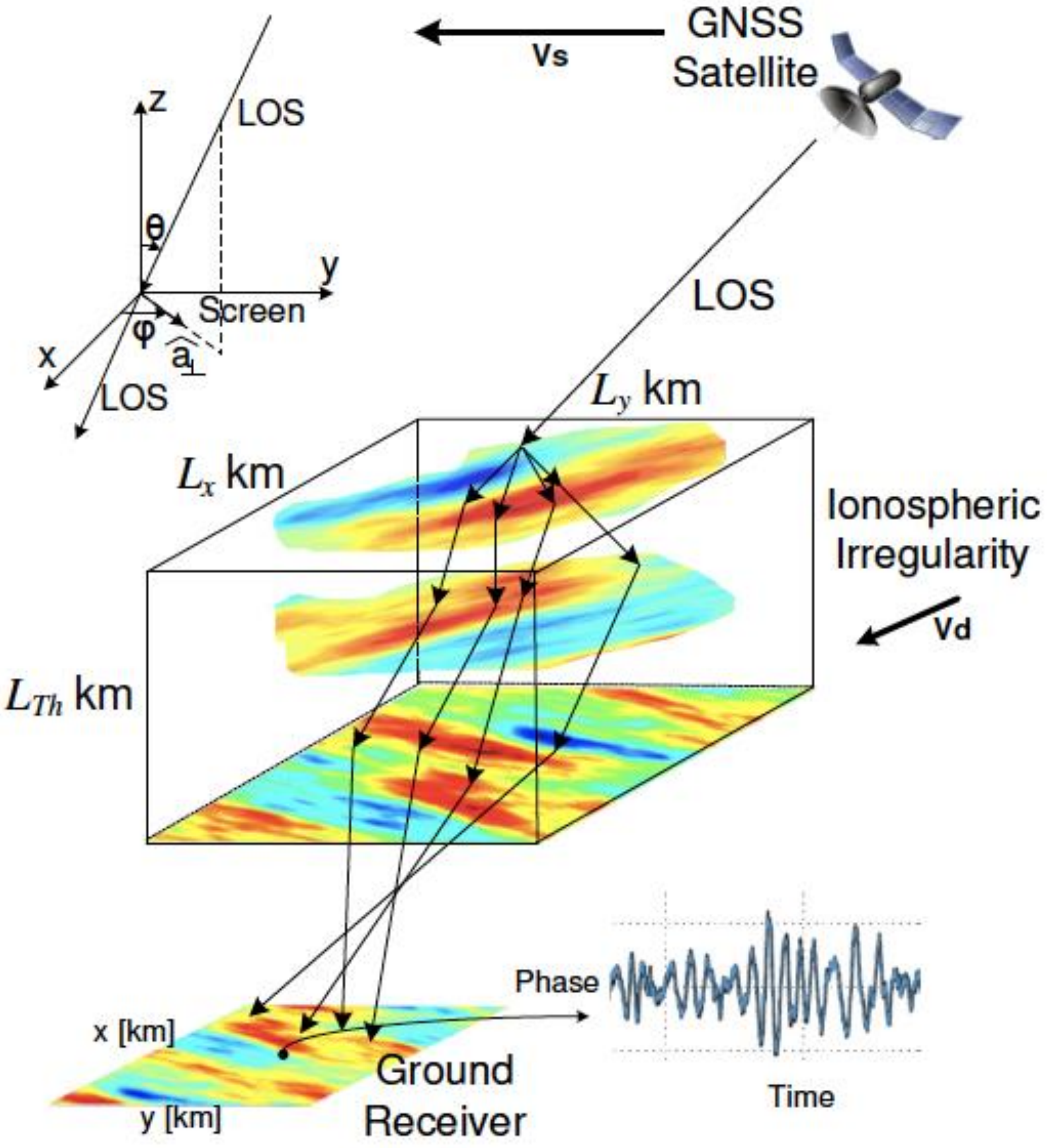
Satellite-beacon Ionospheric-scintillation Global Model of the upper Atmosphere (SIGMA)

- SIGMA can be used to study the propagation of the EM waves through the electron density structures **anywhere on the globe, and at any altitude -> unique.**
- To simulate GPS scintillations on ground we need to:
  1. Simulate ionospheric irregularities.
  2. Propagate a signal from a moving satellite through the irregularity.
  3. Propagate the signal to the ground at a given receiver location.

[Deshpande et al. 2014, 2016; Chartier et al. 2016]

Input parameters:

- Spectral index
- Axial ratio
- Outer scale
- Thickness of irregularity
- RMS of density fluctuations
- Drift velocity
- Irregularity Altitude



Outputs:

- Peak to peak phase and power variation
- $S4$ and σ_ϕ
- Period of scintillations
- 2D phase & power spectrum on ground

SOME MORE ABOUT SIGMA

- SIGMA is based on MPS hybrid split-step method - an **exact numerical implementation of the propagation** equations with density structure realizations for **higher fidelity.**
- SIGMA considers **complex high latitude geometries**. —> perfect to study generators of irregularities, even magnetosphere - ionosphere interactions in high latitudes based on abundant GNSS and multi-instrument data and **Inverse modeling** techniques [Deshpande et al. 2016]

SIGMA FORMULATION, GIVEN IRREGULARITY SPECTRUM

- Phase at the bottom of the irregularity in geomagnetic coordinates.

$$\begin{aligned}\widetilde{\Phi}(k_x,k_y) &= \sqrt{|P_{NH}(k_x,k_y)|}\lambda r_e L \\ &\quad \sec\theta \exp(i2\pi\theta_n)\end{aligned}$$

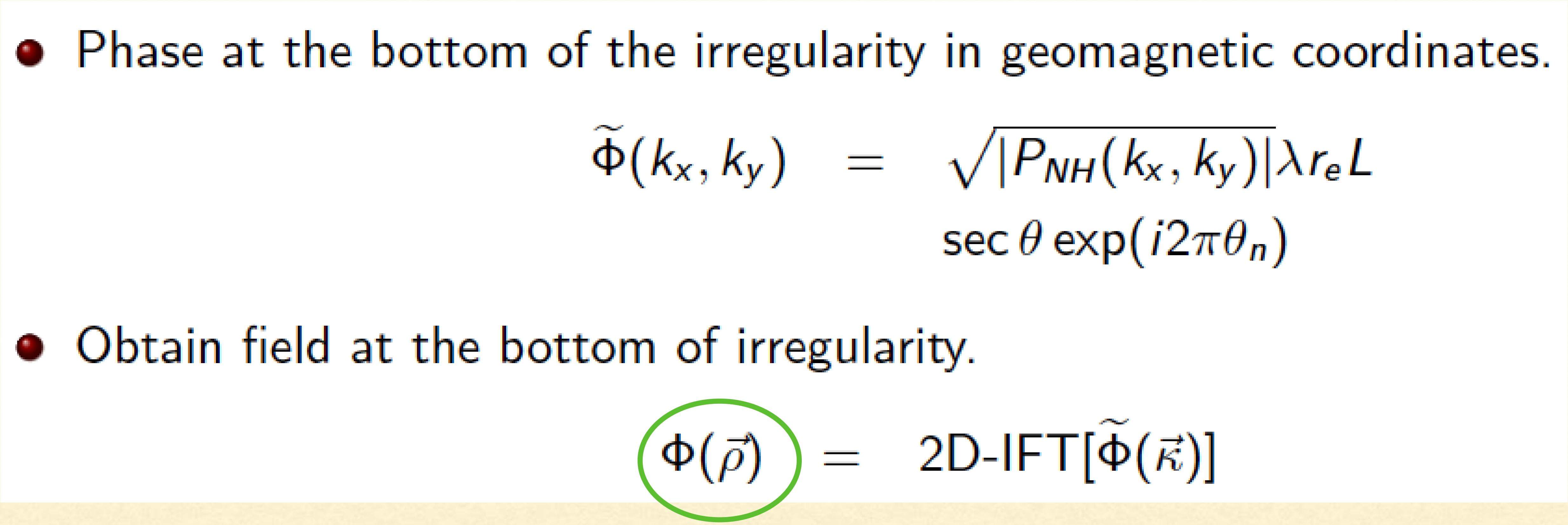
- Obtain field at the bottom of irregularity.

$$\begin{aligned}\Phi(\vec{\rho}) &= \text{2D-IFT}[\widetilde{\Phi}(\vec{\kappa})] \\ \vec{E}_{lb}(\vec{\rho}) &= \vec{E}_{la}(\vec{\rho})\exp(-j\phi(\vec{\rho})) \\ \widetilde{E}(\vec{\kappa}) &= \text{2D-FT}[\vec{E}_{lb}(\vec{\rho})]\end{aligned}$$

- Add drift velocities and propagate to next layer or ground using forward propagation equation.

$$\begin{aligned}f(\vec{\rho},z) &= \int \widetilde{E}(\vec{\kappa})\exp(ikg(\vec{\kappa}+\vec{k_\perp})(z-z_0)) \\ &\quad \exp(-i\tan\theta\widehat{\mathbf{a}_\perp}.\vec{\kappa}(z-z_0)) \\ &\quad \exp(i\vec{\kappa}.\vec{v_d}t)\exp(i\vec{\kappa}.\vec{\rho})\,d\vec{\kappa}\end{aligned}$$

SIGMA FORMULATION WITH NUMBER DENSITY



- Phase at the bottom of the irregularity in geomagnetic coordinates.

$$\begin{aligned}\widetilde{\Phi}(k_x, k_y) &= \sqrt{|P_{NH}(k_x, k_y)|}\lambda r_e L \\ &\quad \sec\theta \exp(i2\pi\theta_n)\end{aligned}$$

- Obtain field at the bottom of irregularity.

$$\Phi(\vec{\rho}) = \text{2D-IFT}[\widetilde{\Phi}(\vec{\kappa})]$$

- What if we skip these steps and obtain the phase at the bottom of irregularity layer directly? — If we know electron number density distribution Ne(x,y,z) of the irregularity, we can integrate along z to get the phase directly. **This is where GEMINI comes in…**

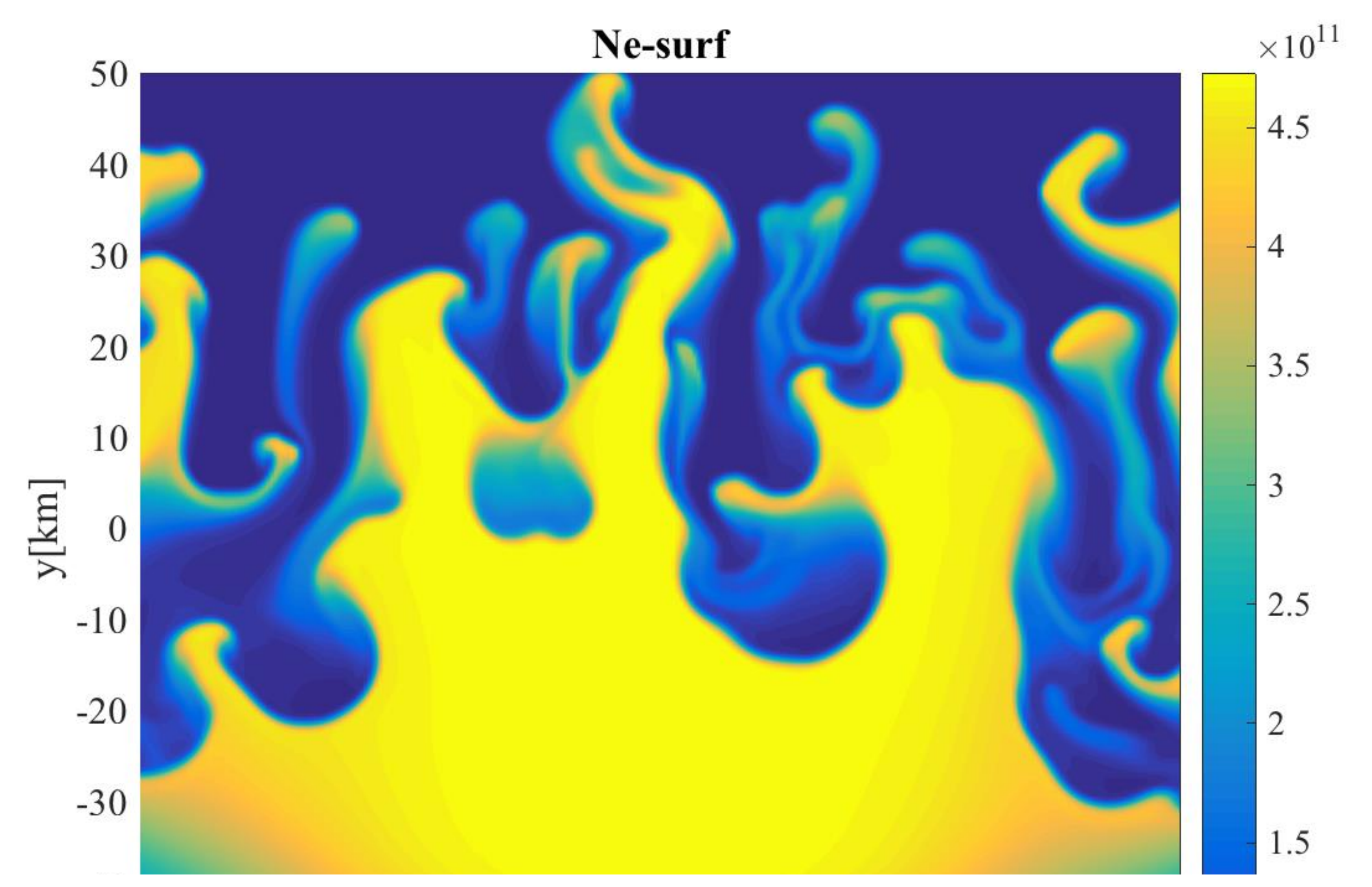
GEMINI: PHYSICS BASED PLASMA INSTABILITY MODEL

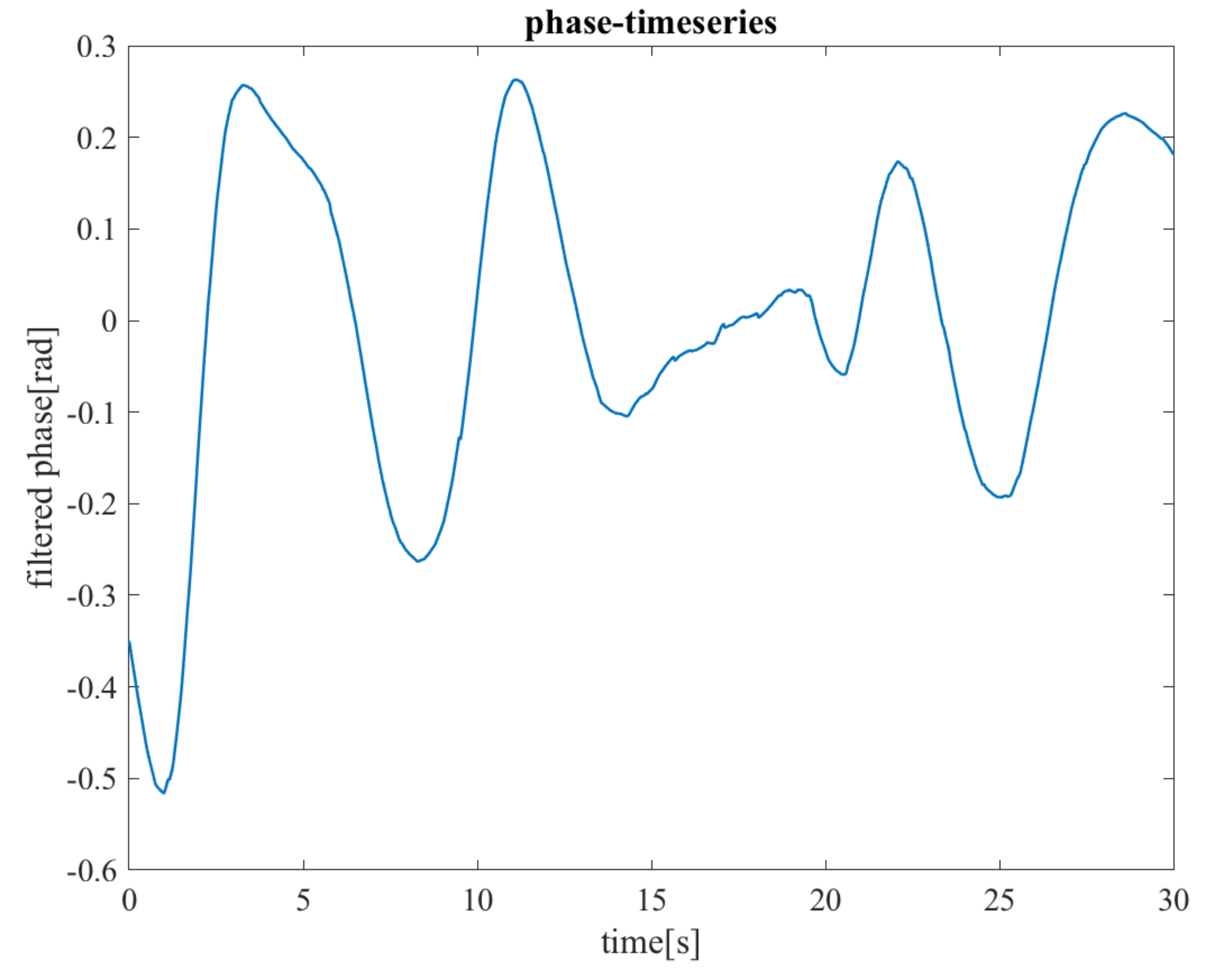
- **GEMINI**: **Geospace Environment Model of Ion-Neutral Interactions** [Zettergren et al. 2012]
- **First principles plasma physics model**
- Solves standard fluid system of equations
- Equipotential field line (EFL) formulation with polarization current (e.g. Mitchell et al, 1985)
- **Gives SIGMA Ne (x,y,z, [t])** for Gradient drift instability (**GDI**) and Kelvin Helmholtz (**KHI**) instabilities

RESULTS OF COMBINING SIGMA AND GEMINI

- Testing with GDI and KHI instabilities (assuming as dominant phenomena driving the irregularity)
- Rx location: Resolute Bay, Date: March 2012, Frequency: GPS L1 (1.57 GHz), Varying incidences, drift velocity 500 m/s in geomagnetic west, Height: 350 km, Irregularity thickness: 50 km.

GDI


Ne-surf
×10^11
4.5
4
3.5
3
2.5
2
1.5
y[km]
50
40
30
20
10
0
-10
-20
-30


phase-timeseries
filtered phase[rad]
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
5
10
15
20
25
30
time[s]

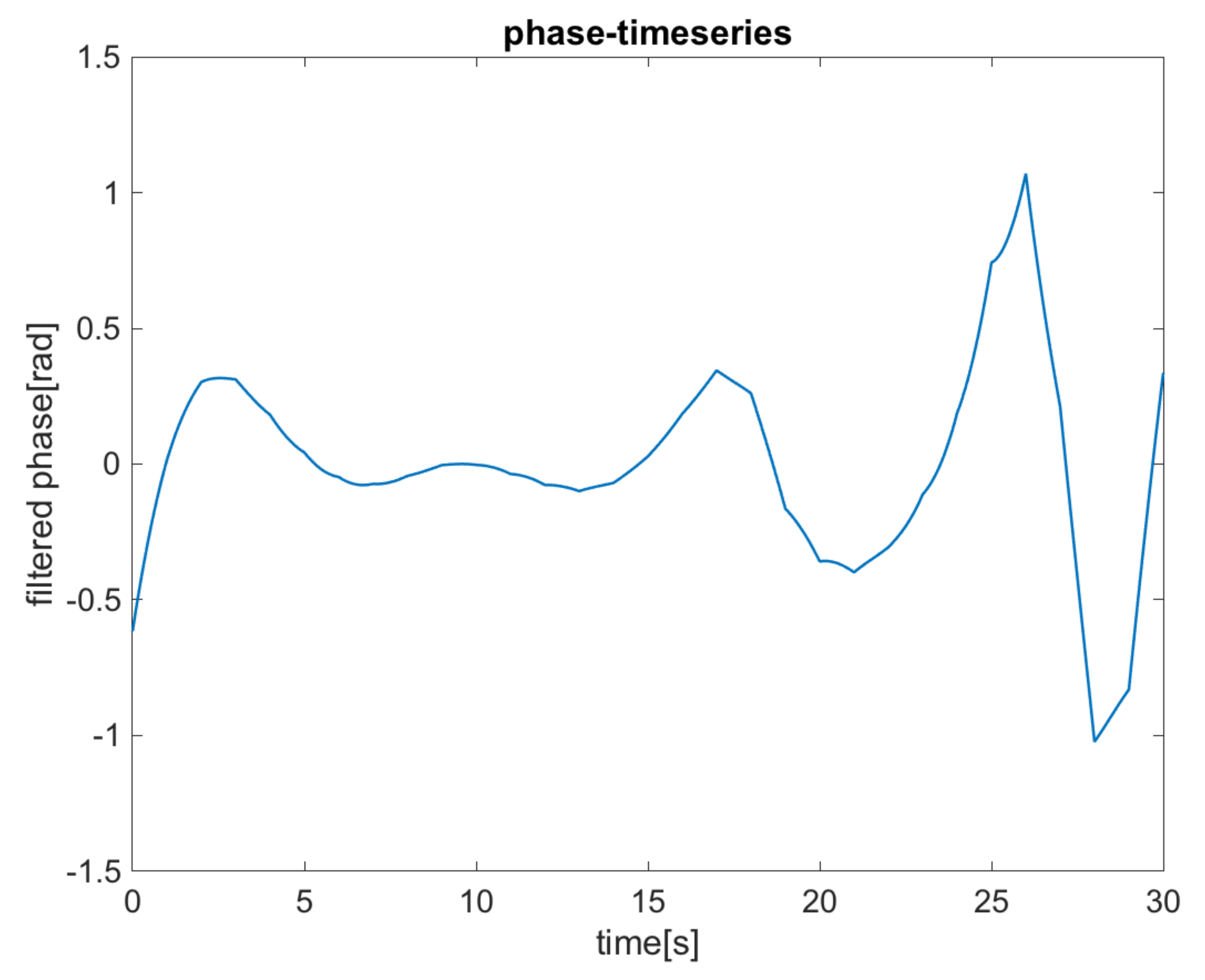
ADD DRIFT VELOCITY THROUGH GEMINI

- Previously: Take one “snapshot” Ne (x,y,z) and add drift later in SIGMA assuming **constant drift velocity**.

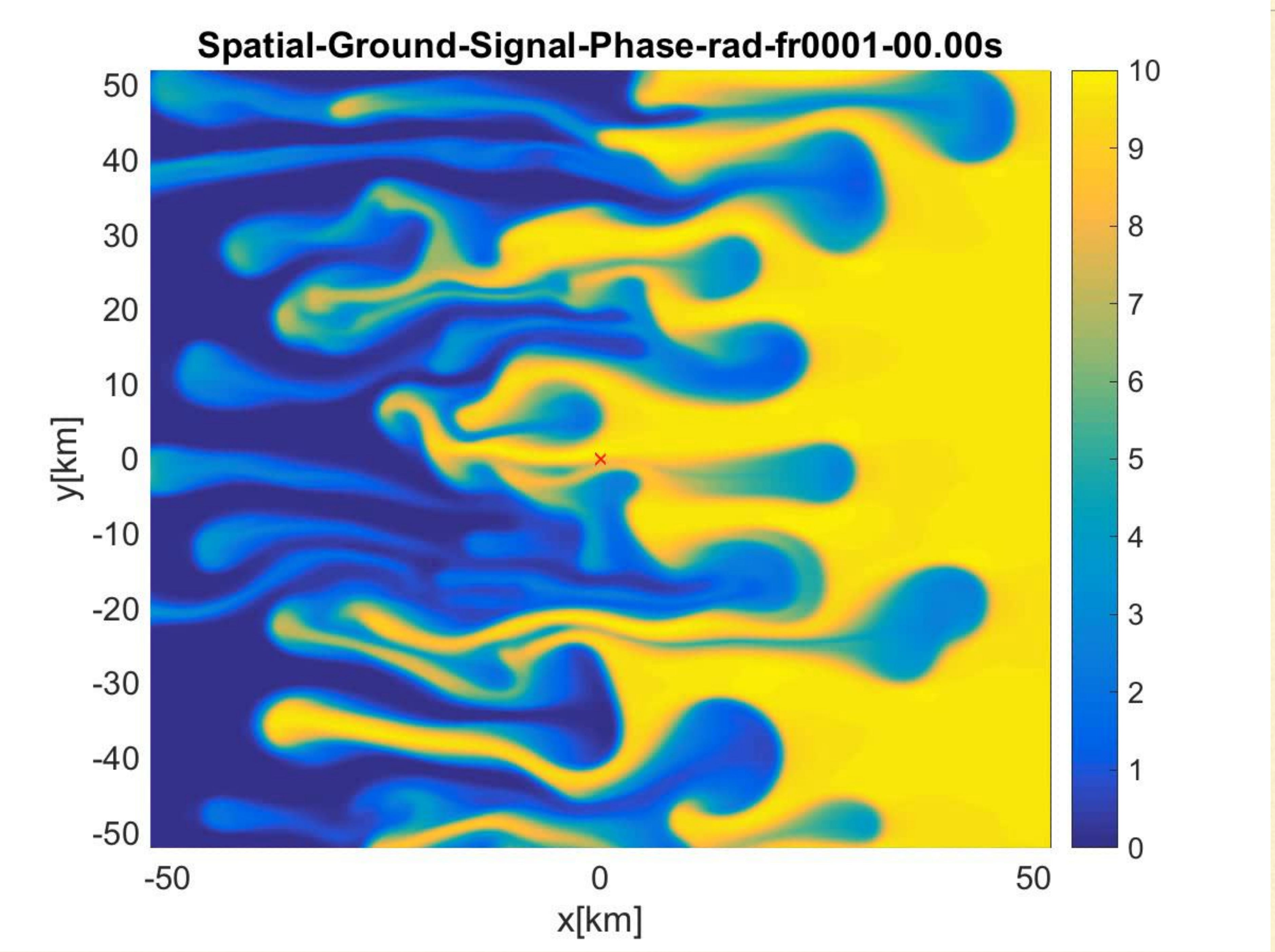
- Adding drift through GEMINI allows **variable drift velocity** as a function of space and time to be added.

- Use Ne (x,y,z,t) in SIGMA — Called for some modifications in SIGMA in order to keep it computationally viable. We are talking about 3D FFTs and IFFTs for a matrix of size ~500x500x500 at 1500 different instances (In simulating 30 second GNSS time series on ground with 50 Hz sampling rate)…

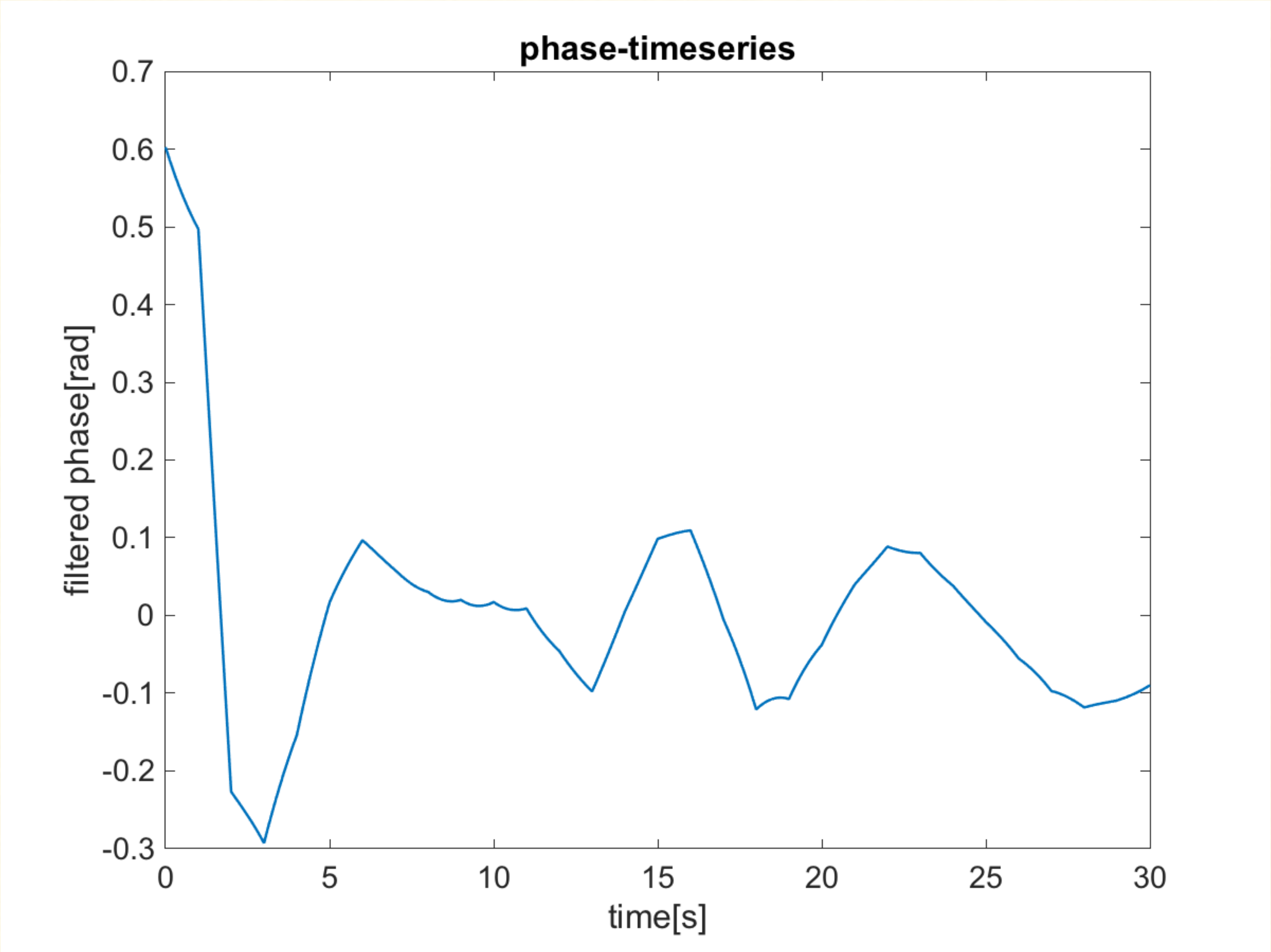
GDI WITH VARIABLE DRIFT (ZENITH INCIDENCE)



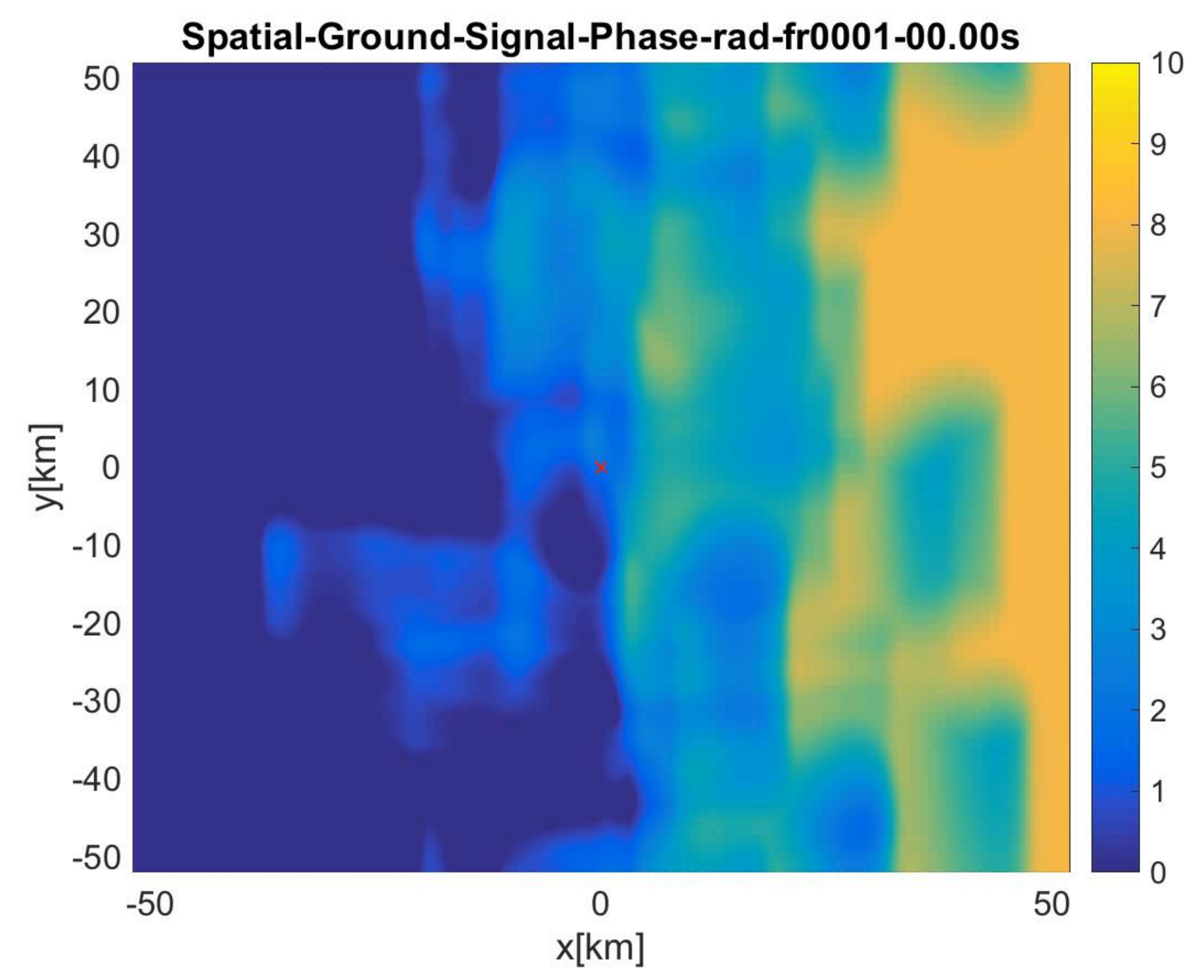
PHASE ON GROUND (ZENITH INCIDENCE) MOVIE

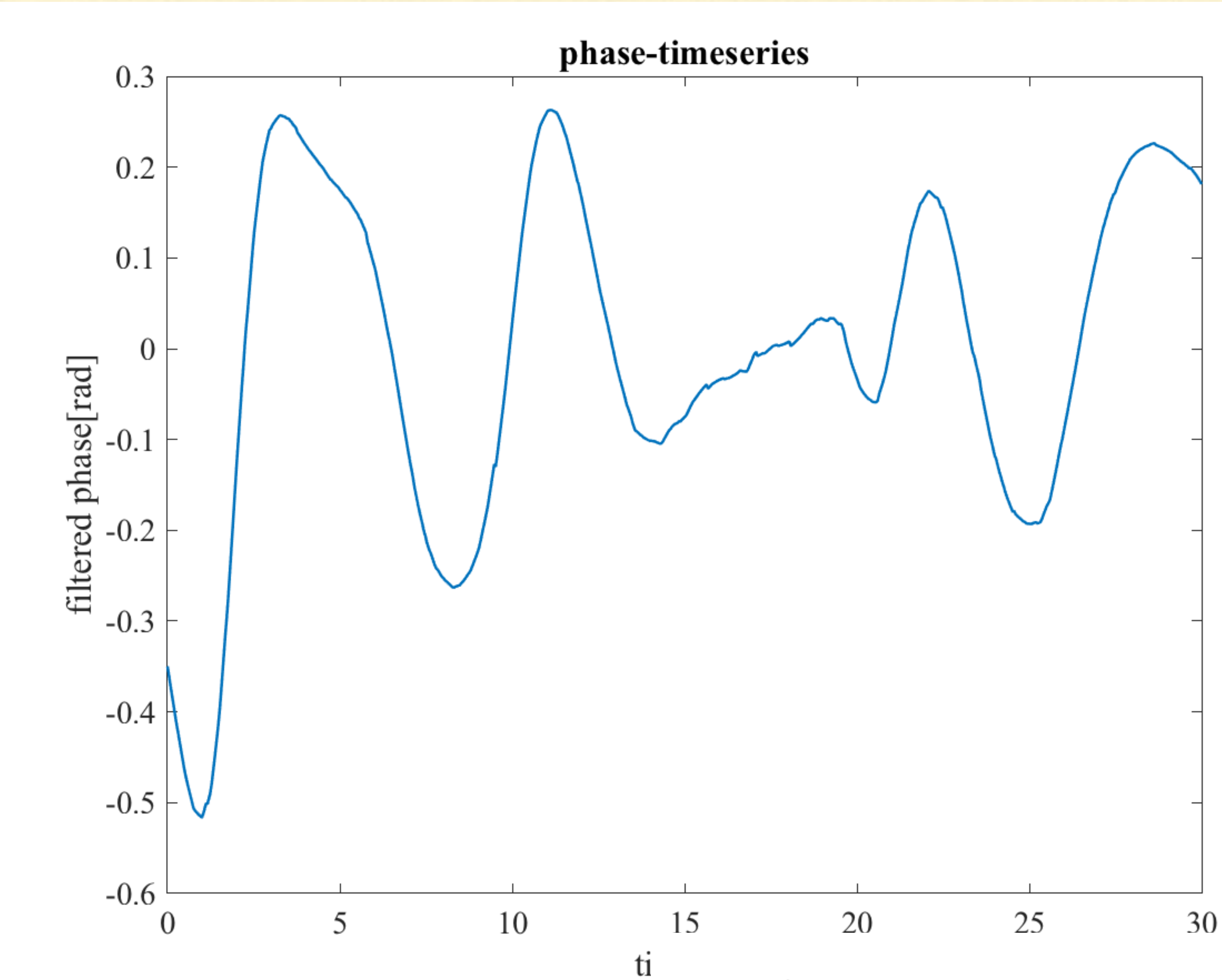


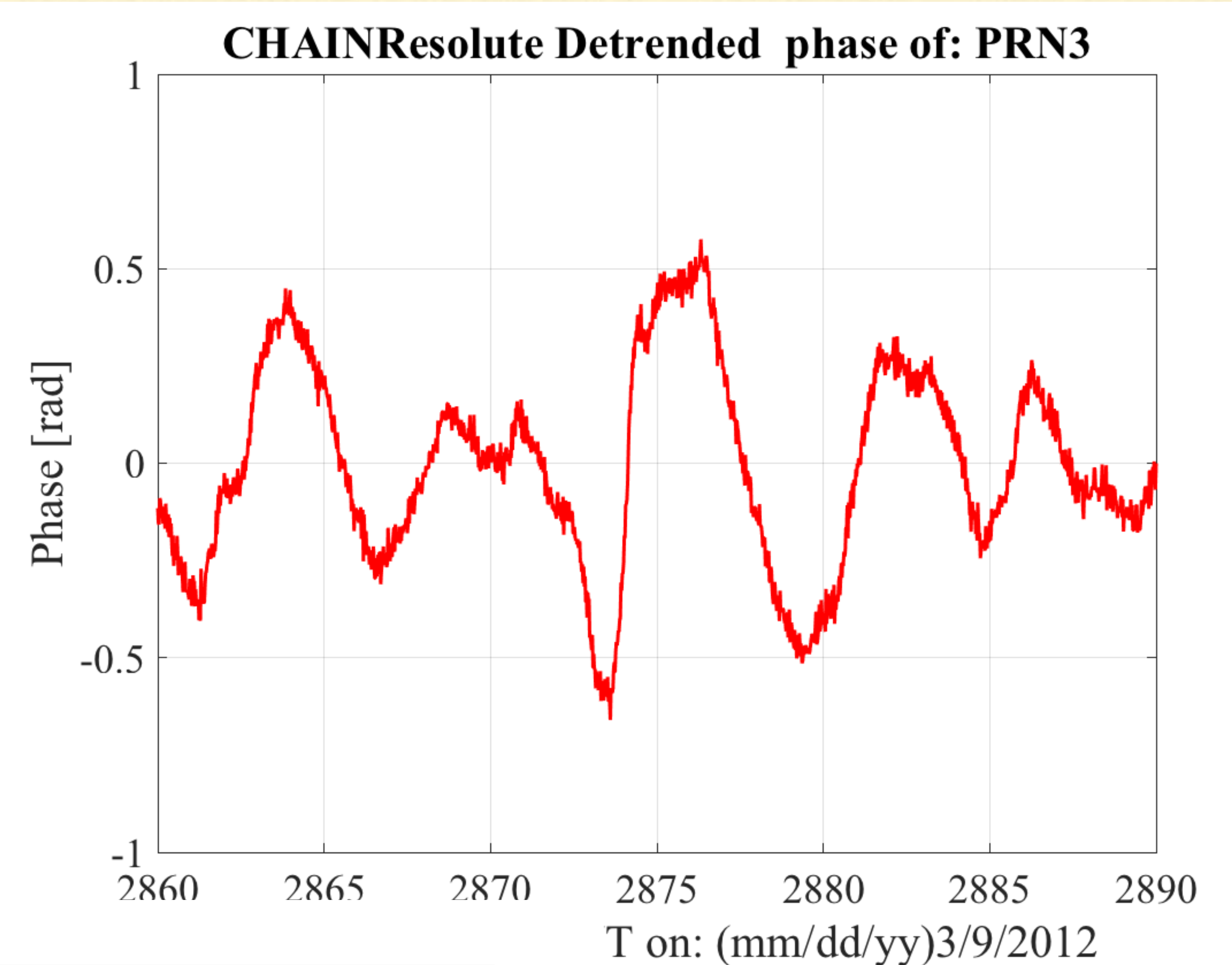
GDI WITH VARIABLE DRIFT (30 DEG INCIDENCE)

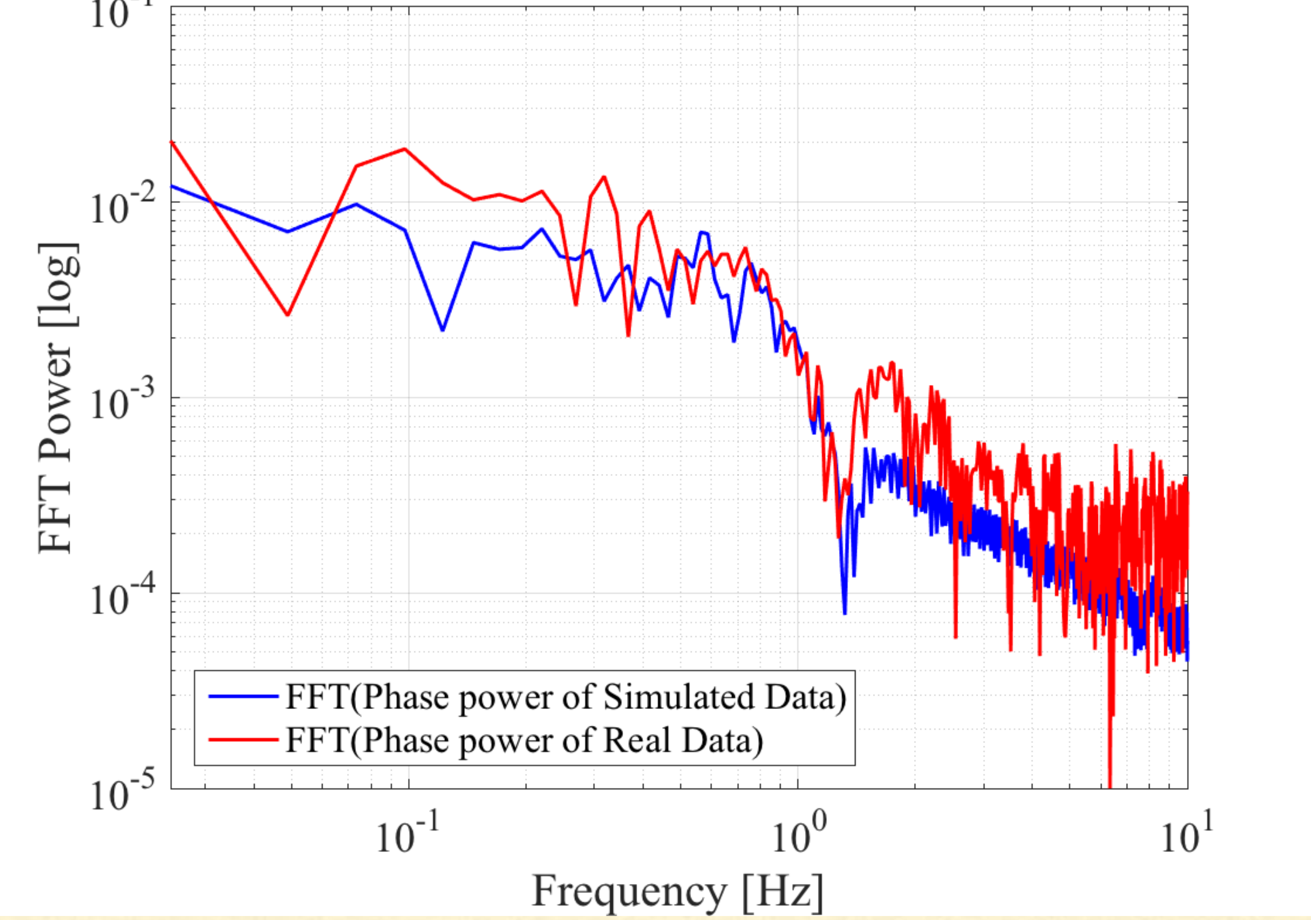


PHASE ON GROUND (30 DEG INCIDENCE) MOVIE




phase-timeseries
filtered phase[rad]
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
5
10
15
20
25
30
ti


CHAINResolute Detrended phase of: PRN3
Phase [rad]
1
0.5
0
-0.5
-1
2860
2865
2870
2875
2880
2885
2890
T on: (mm/dd/yy)3/9/2012


FFT Power [log]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
10^{0}
10^{1}
Frequency [Hz]
FFT(Phase power of Simulated Data)
FFT(Phase power of Real Data)

- p.s. We are ignoring satellite motion in these Nxyzt cases. That’s our next task to figure out how to correctly include it through SIGMA (without any other drift).

SCIENCE QUESTIONS:

- How often does GDI or KHI occur in the auroral regions or under what conditions?
- What are the observable signatures of GDI, KHI in GPS data?
- What observational constraints can be placed on instabilities (and other processes?) leading to GPS scintillation?
- To what degree might scintillation data and the proposed forward modeling framework be used as a remote sensing diagnostic for studying fundamental plasma processes (ionization, depletion, instability)?

FUTURE PLAN

- Run plasma simulations for a set of specific conditions in auroral ionosphere and obtain electron density distributions.
- Run SIGMA for those density distributions and predict GPS outputs/ scintillations for different LOS angles.
- Quantify how the predicted GPS scintillations differ with each set of plasma simulations.
- Obtain ISR, GNSS data. From GNSS data, form geometries etc. for SIGMA. Predict plasma properties and simulate densities for this case from GEMINI. Inverse modeling of SIGMA with densities from GEMINI.