Sensing Ionospheric Irregularities with a GNSS Receiver Array

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Objective

Demonstrate the use of a closely-spaced array of Global Navigation Satellite System (GNSS) receivers as a single instrument

- Remotely sense the **horizontal drift motion** of ionospheric irregularities by examining multi-satellite scintillation events
- Compare the estimates and their **uncertainties** to existing co-located instruments

Background

Ionosphere: Modifies radio wave propagation

Irregularities: Non-uniform density variations measured by **drift speed**

Scintillation: Rapid fluctuation in signal amplitude or phase, related to time, season, solar activity and geomagnetic activity

Effects: Affect navigation operations or can be studied to understand the dynamics of the ionosphere

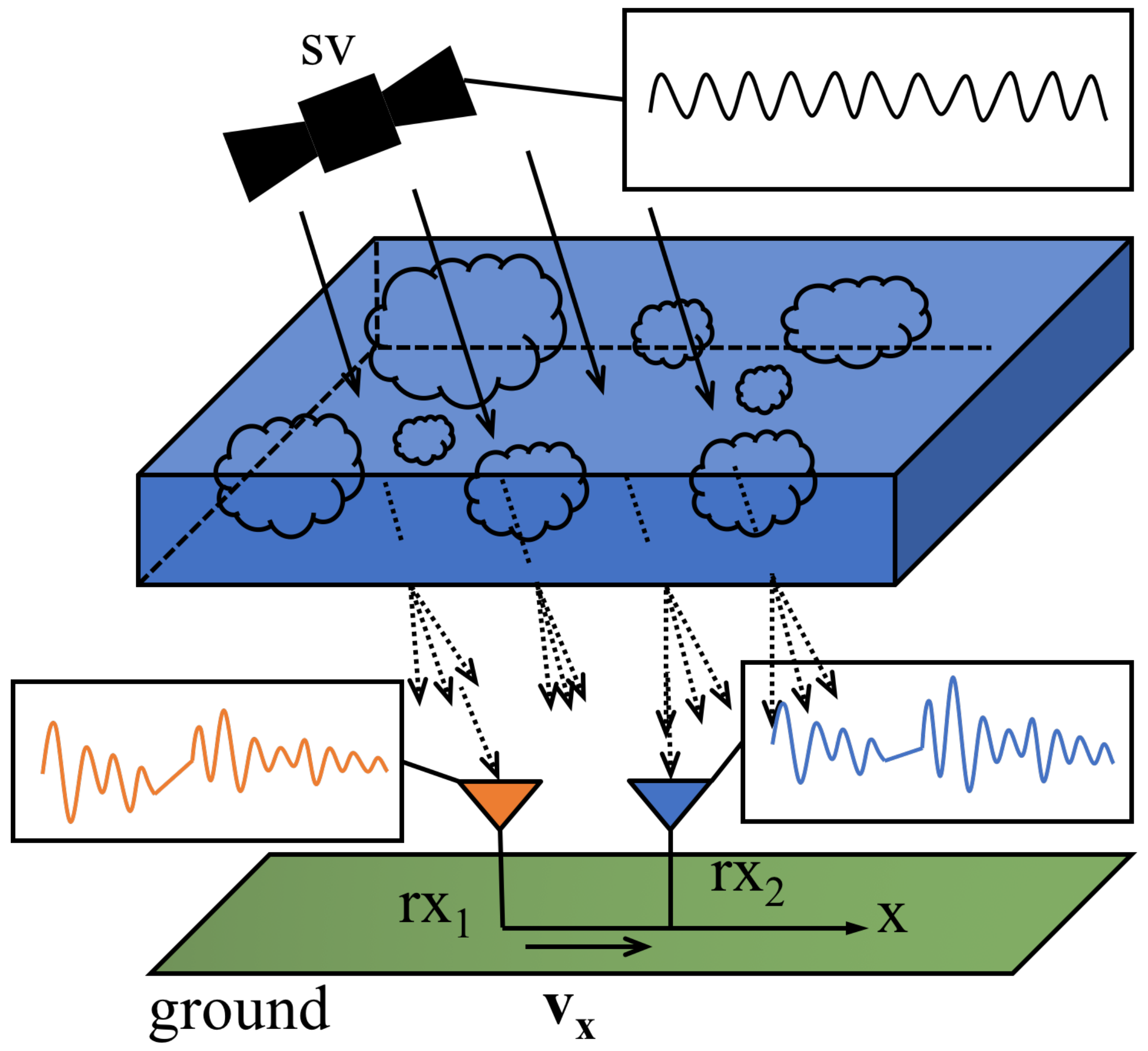

Figure: Scintillation caused by ionospheric irregularities.

Instrumentation

Scintillation Auroral GPS Array (SAGA)[1]

- Closely-distributed multi-receiver array sensitive to sub-kilometer irregularities
- Low cost and high mobility
- 0.01 Hz and 100 Hz scintillation database for space weather monitoring (available on `http://apollo.tbc.iit.edu/~spaceweather`).

Poker Flat Incoherent Scatter Radar (PFISR)[2]

- Existing Advanced Modular ISR (AMISR) structure with an array of antennas
- Larger-scale ionospheric measurements in multiple directions

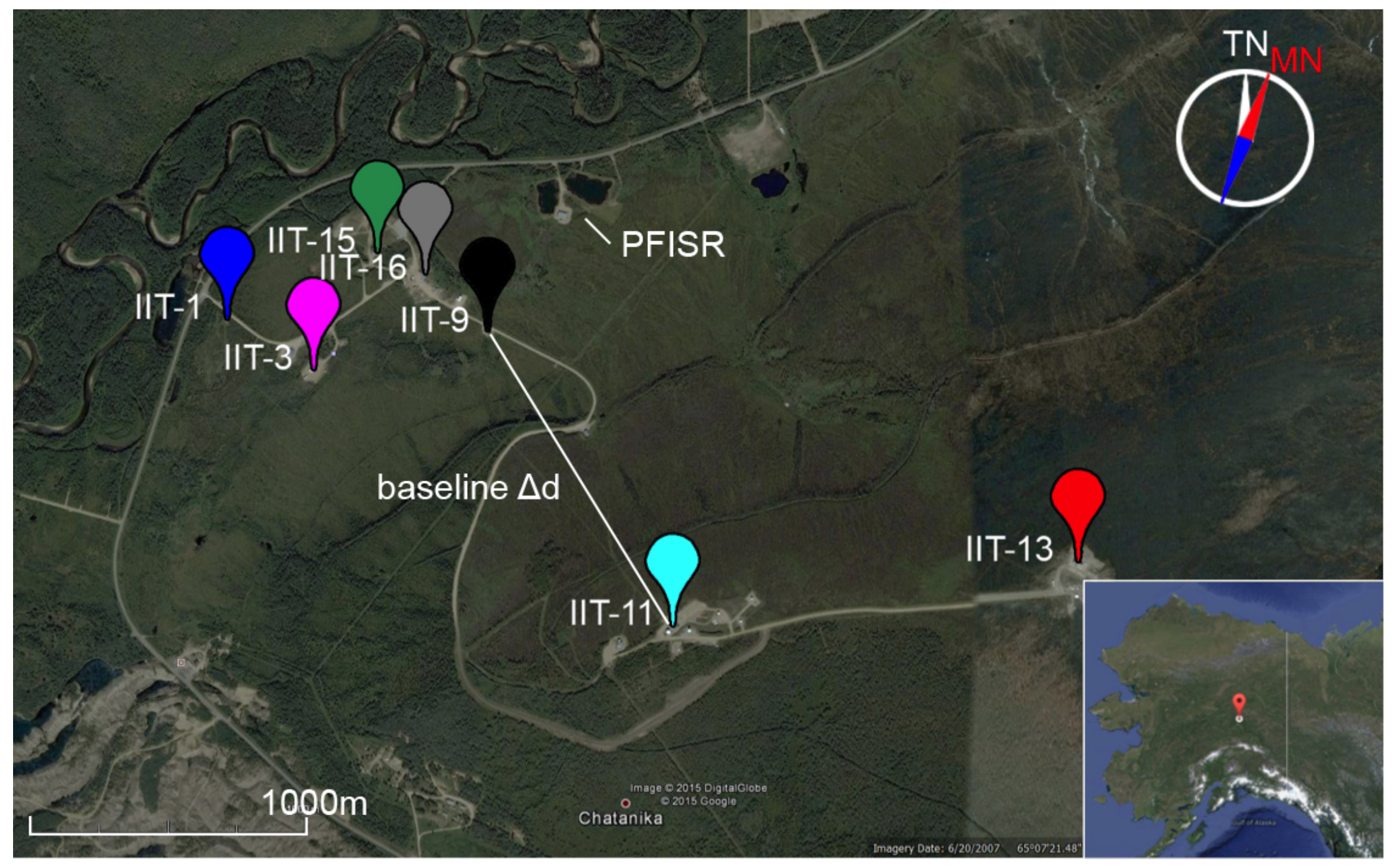

Figure: SAGA & PFISR at Poker Flat Research Range, Fairbanks, Alaska (geographic 65 ° N, 147 ° W), adapted from [1].

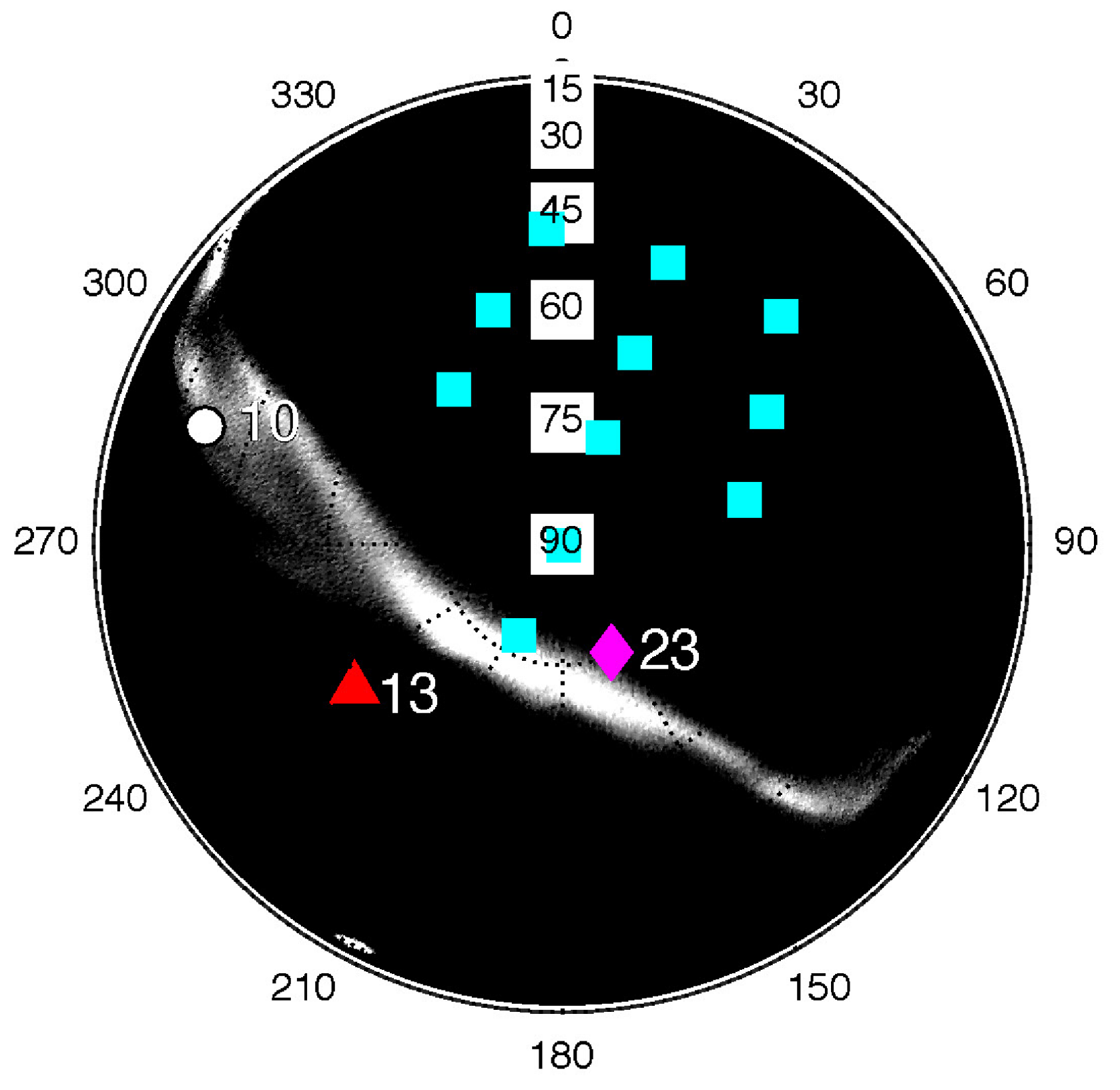

Figure: Locations of 3 scintillating satellites and PFISR radar beams (cyan) in the sky during a geomagnetic storm overlapped on the all-sky image of the auroral arc.

Measurements

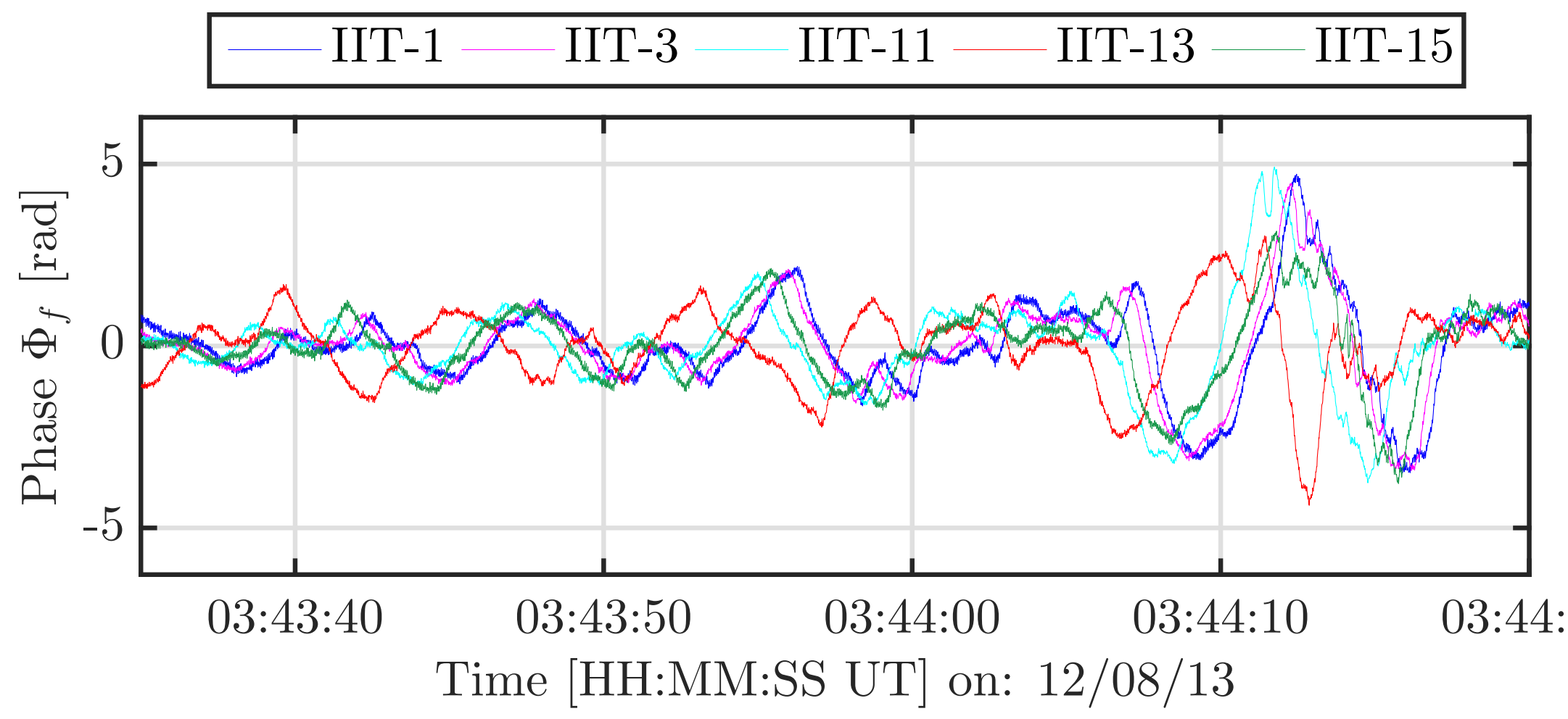

Figure: 45 s time series of SAGA 100 Hz received signal phase $\phi(t)$ for transmitter PRN23 from 5 operational receivers.

Spaced-receiver Technique [3]

Cross-correlate phase data pairs for time lags

$$\rho_{ij}(\tau) = \langle \phi_i(t), \phi_j(t+\tau) \rangle$$
$$\tau_{ii} = \arg\min_{\tau_{ii}} |\rho_{ij}(\tau_{ij}) - \rho_{ii}(\tau_{ii})|$$

Construct as follows

$$\mathbf{y} = \mathbf{R}(\boldsymbol{\tau}) = \boldsymbol{\tau}_{ii}^2 - \boldsymbol{\tau}_{ij}^2$$
$$\mathbf{y} = \mathbf{H}\mathbf{x}$$
$$\mathbf{v} = \mathbf{F}(\mathbf{x})$$

- **H**: mapping matrix based on baselines $\mathbf{r_{ij}}$
- **y**: observation array based on measurements $\phi(t)$
- **v**: horizontal drift, a non-linear function **F** of state **x**

Error Analysis [4]

To quantify errors on **v**, generate N noisy ensembles of original signal phase $\phi(t)$ via Monte Carlo simulation

$$\tilde{\phi}_{in}(t) = \phi_{in}(t) + w_{in}(t)$$

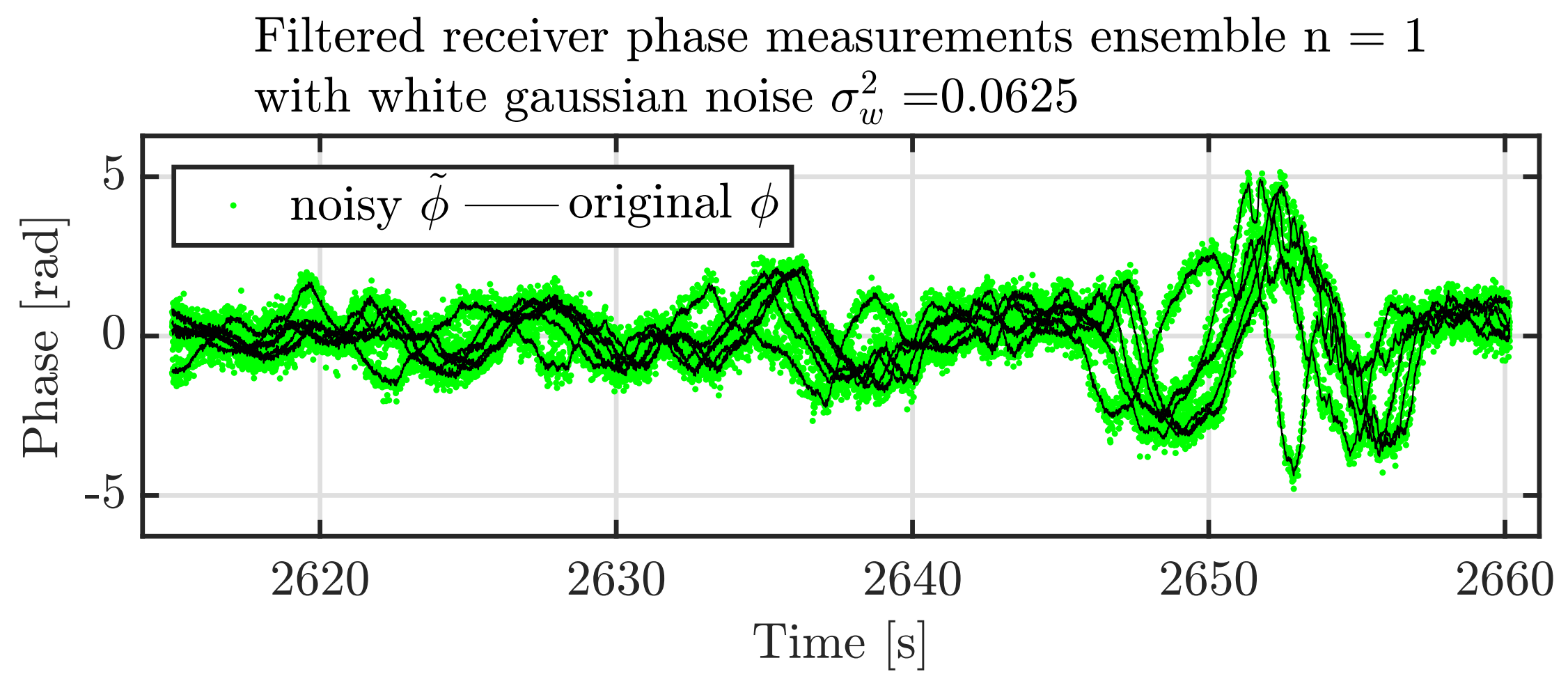

Figure: Original ϕ (black) and noisy $\tilde{\phi}$ (green) for all receivers.

Compute noisy $\tilde{\rho}$ and propagate errors through time lags $\tilde{\boldsymbol{\tau}}$, observations $\tilde{\mathbf{Y}}$, states $\tilde{\mathbf{x}}$ and drift estimates $\tilde{\mathbf{v}}$

$$\mathbf{R}(\tilde{\boldsymbol{\tau}}) = \tilde{\mathbf{Y}} = \mathbf{H}\tilde{\mathbf{x}}$$
$$\boldsymbol{\Sigma}_{\tilde{\mathbf{x}}} = (\mathbf{H^T H})^{-1}\mathbf{H^T}\boldsymbol{\Sigma}_{\tilde{\mathbf{Y}}}\mathbf{H}(\mathbf{H^T H})^{-1}$$
$$\tilde{\mathbf{v}} = \mathbf{J}\tilde{\mathbf{x}}$$
$$\boldsymbol{\Sigma}_{\tilde{\mathbf{v}}} = \mathbf{J}\boldsymbol{\Sigma}_{\tilde{\mathbf{x}}}\mathbf{J^T}$$

- **J**: Jacobian, first-order expansion of function **F** at $\tilde{\mathbf{x}}$

For quantitative comparison, compute "root-mean-squared error" ϵ with PFISR drifts $\mathbf{v_p}$ as "true" values

$$\epsilon = \sqrt{\mathbf{E}\left[\frac{(\tilde{\mathbf{v}} - \mathbf{v_p})^2}{\mathbf{v_p}^2}\right]}$$

Acknowledgments

- Space Weather Lab members.
- PFISR data are available on `http://isr.sri.com/madrigal/`.
- All-sky camera data are available on `http://optics.gi.566alaska.edu/realtime/data/MPEG/PKR_DASC_256/`.
- NSF grants AGS-1261369, AGS-1311922.

Results and Discussions

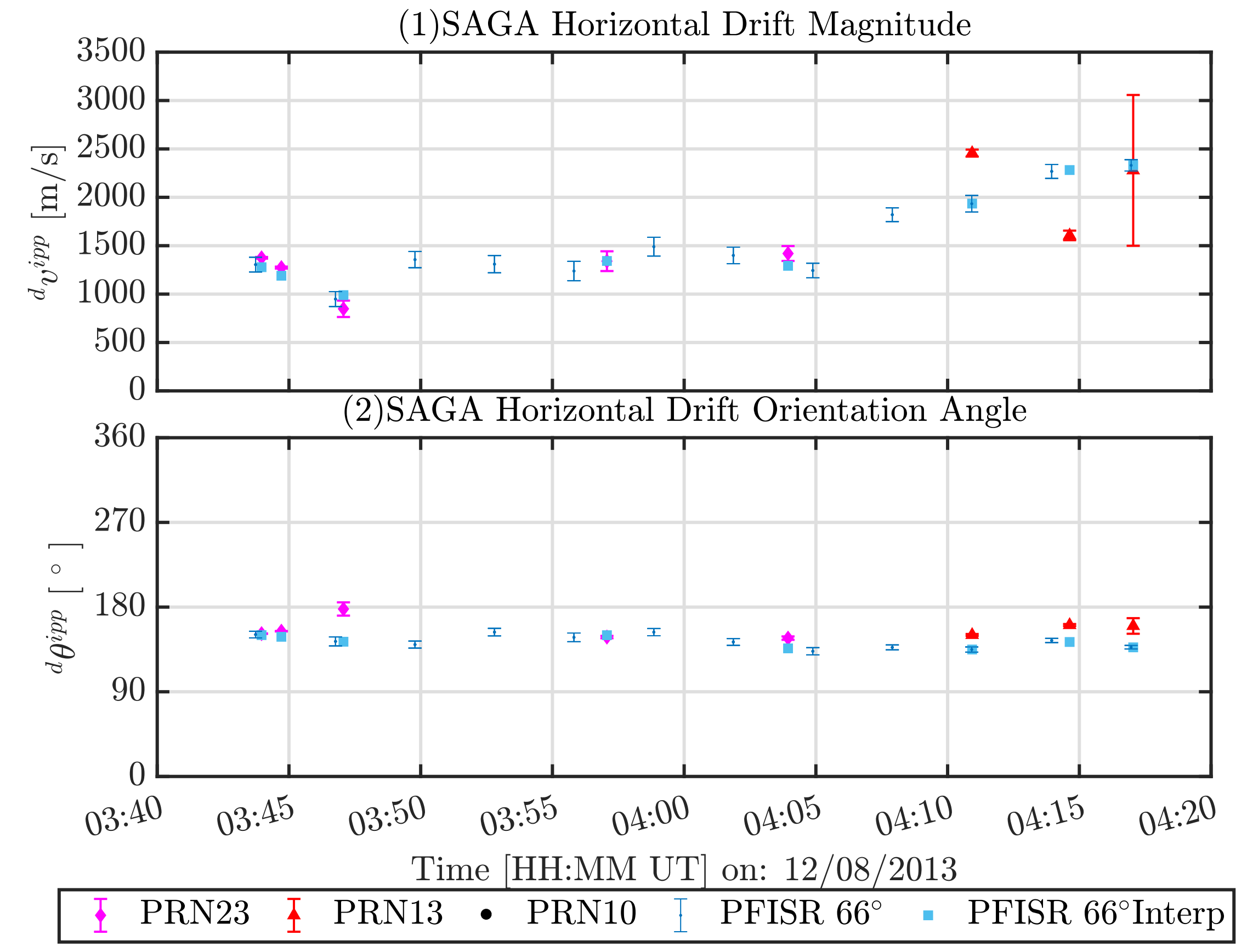

Figure: 30-minute SAGA drift estimates computed every 60 s for three simultaneously scintillating satellites, compared to PFISR ion drifts measured at 66 ° N, $\epsilon_v, \epsilon_\theta \leq 25\%$.

Differences

- Measuring technique
- Transmitting frequency
- Sensing region

Summary and Future Work

- Estimated horizontal drifts with uncertainties
- Observed fair agreement between SAGA drift estimates and PFISR
- Found correlation between auroral activity and scintillation in the F-region

- Scintillation forecasting
- Further estimation of spectral properties

References

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