# Ionospheric Scintillation Monitoring and Mitigation

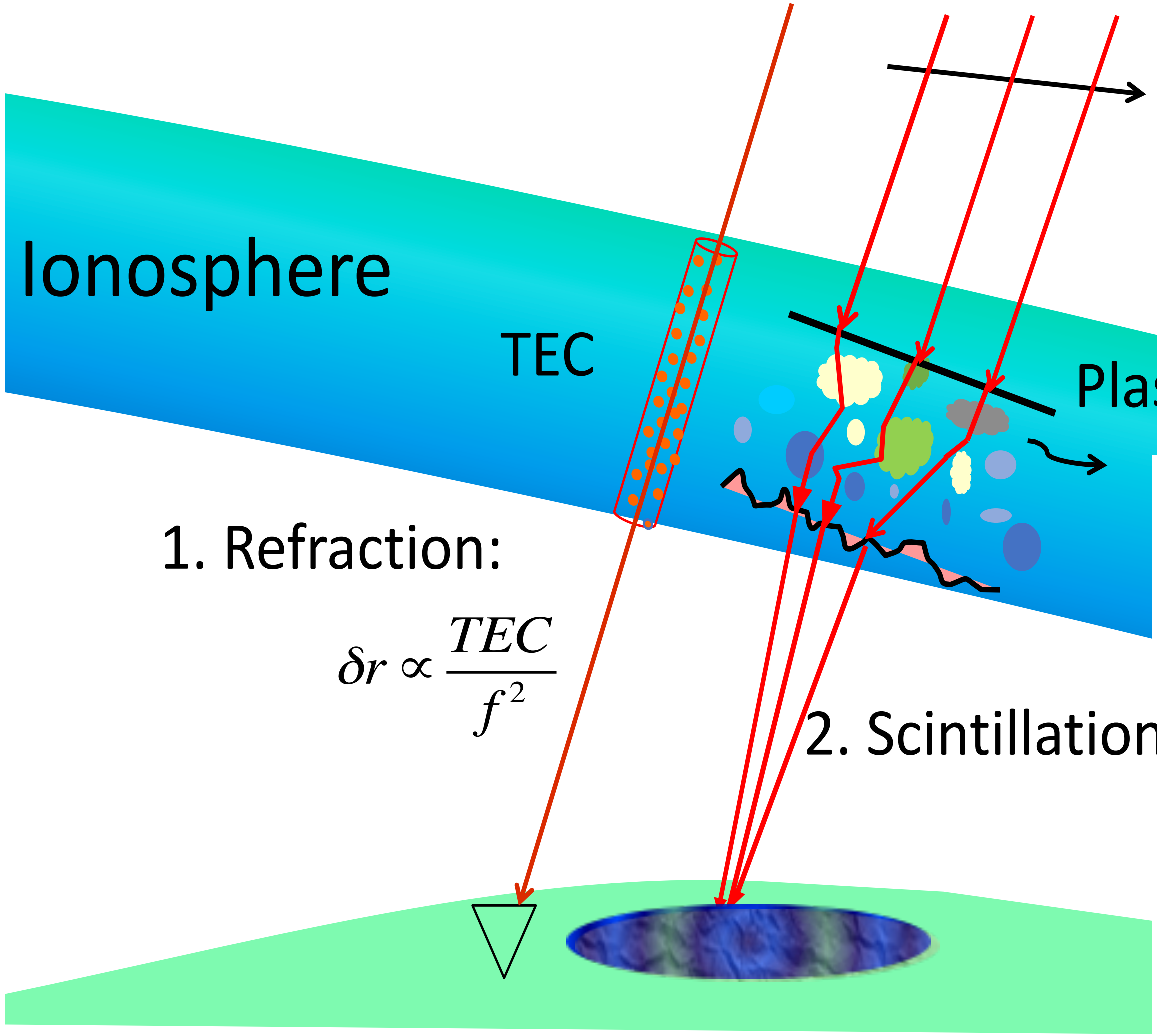
Jade Morton
University of Colorado at Boulder
Jade.Morton@Colorado.edu

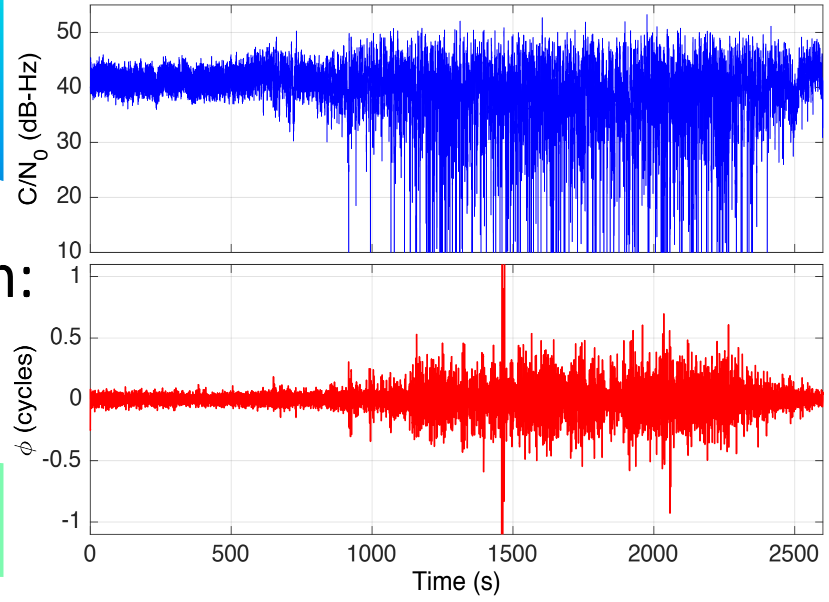
# Tutorial Outline

1. Background
2. Ionospheric Observations
3. Mitigation Techniques

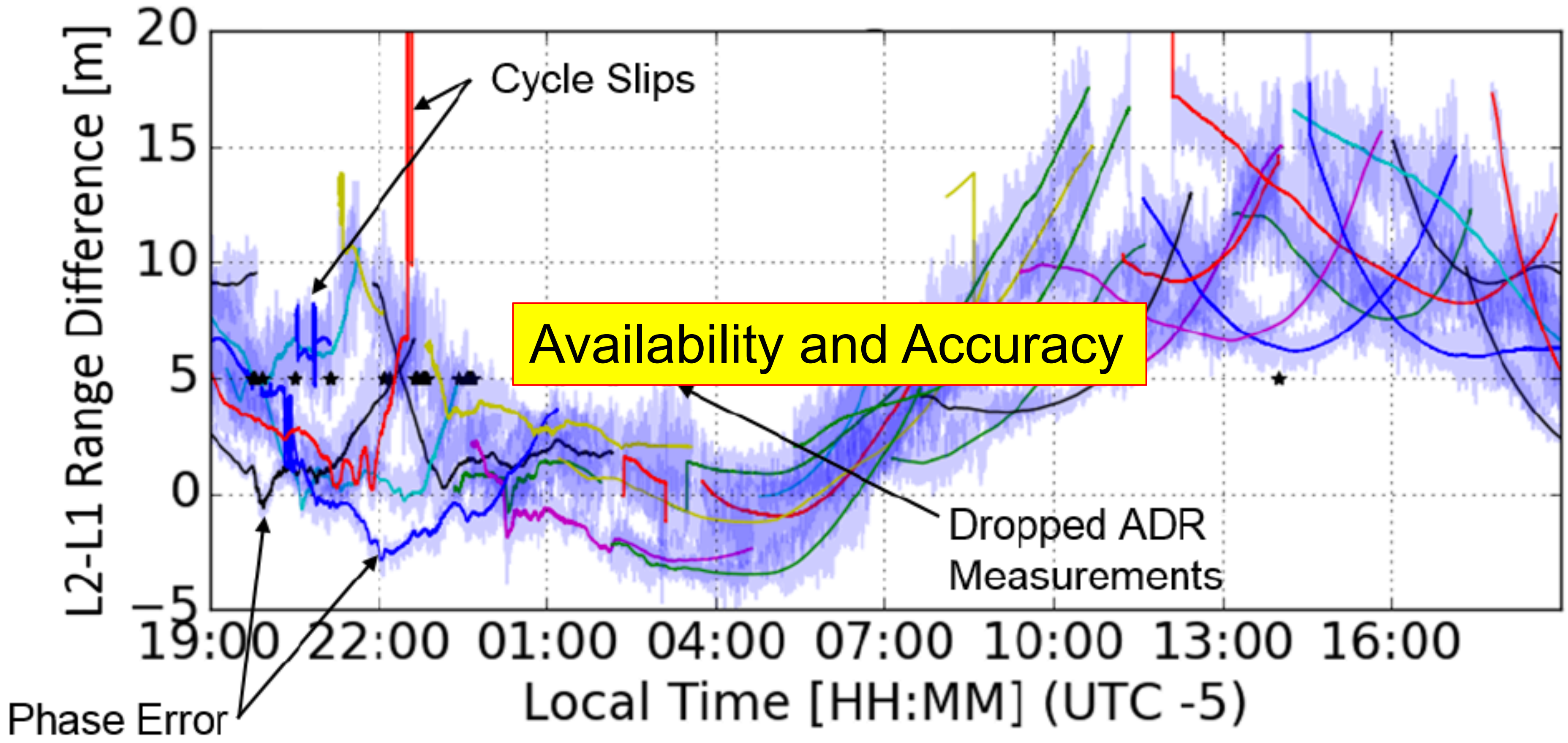
Some materials are from
Ch. 31 Ionospheric Effects, Monitoring, and Mitigation in Position, Navigation, and Timing Technologies in the 21st Century, edt. Y. Morton, F. van Diggelen, J. Spilker, and B. Parkinson, Wiley-IEEE Press, 2020.

# Diffractive Effects: Scintillation



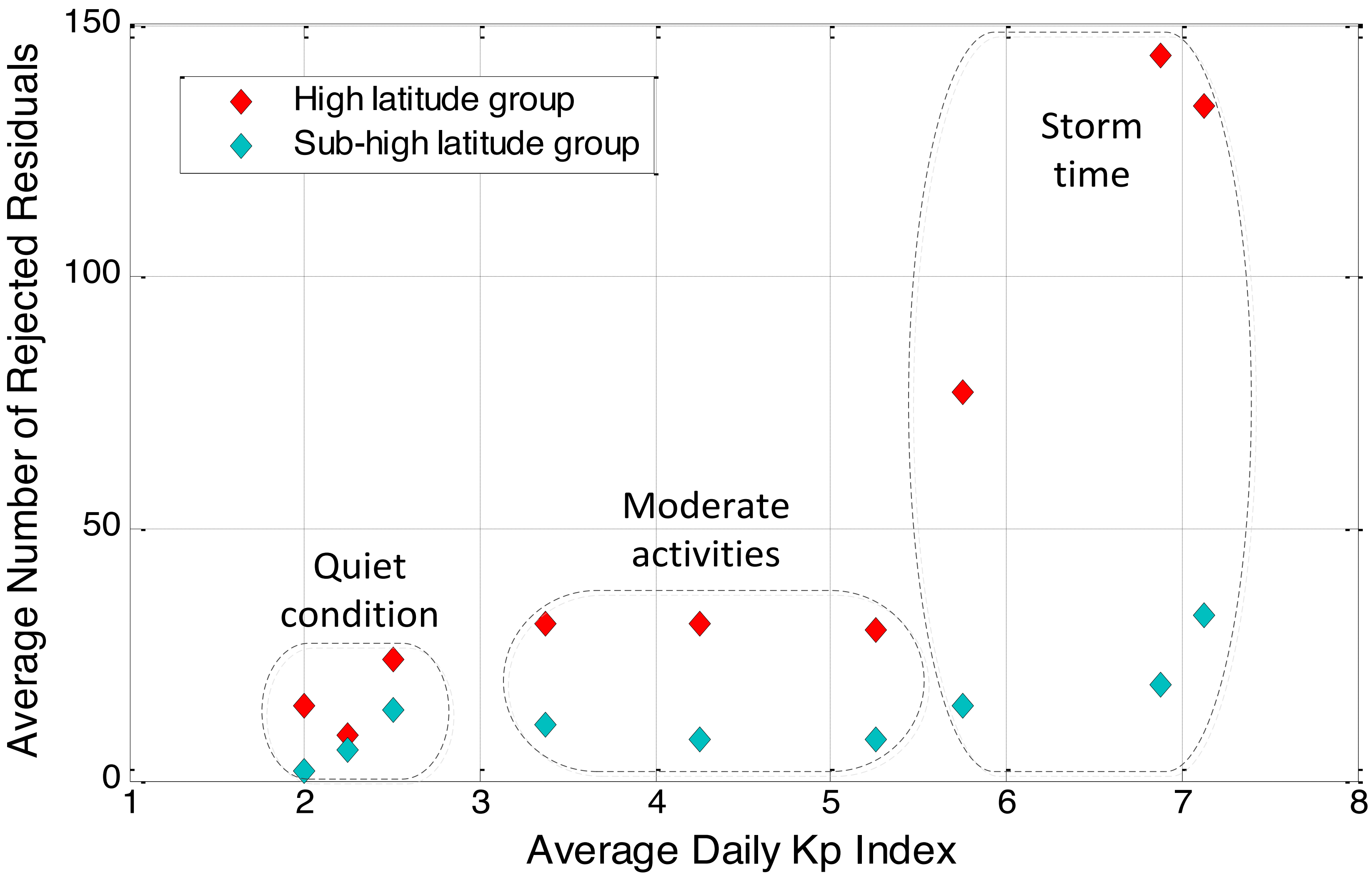



# Scintillation Effects



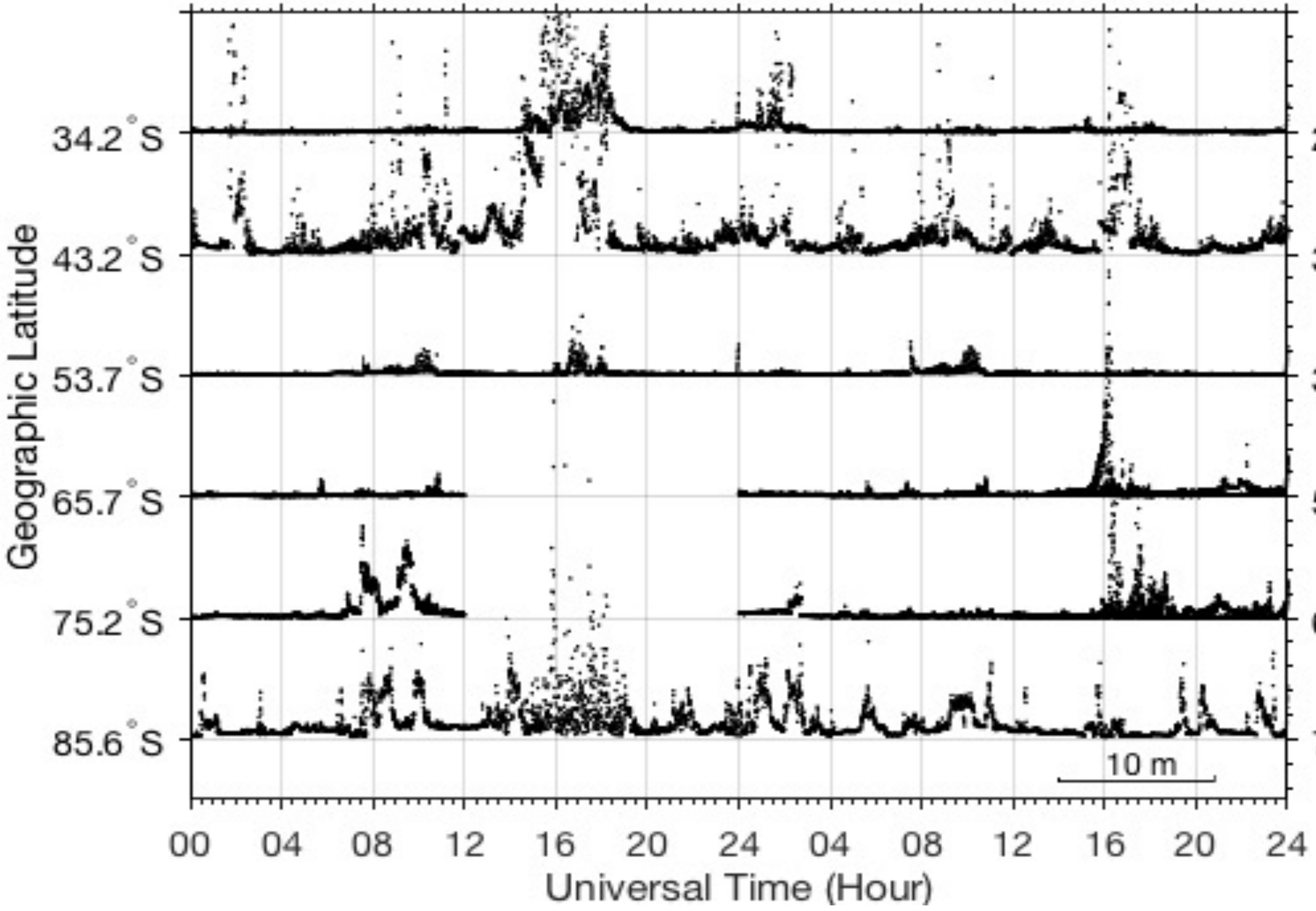

Myer, G. and Y. Morton, "Ionosphere scintillation effects on GPS measurements, a new carrier-smoothing technique, and positioning algorithms to improve accuracy," *Proc. of ION ITM*, Reston, VA, Jan. 2018.

# PVT Solution Availability Issue



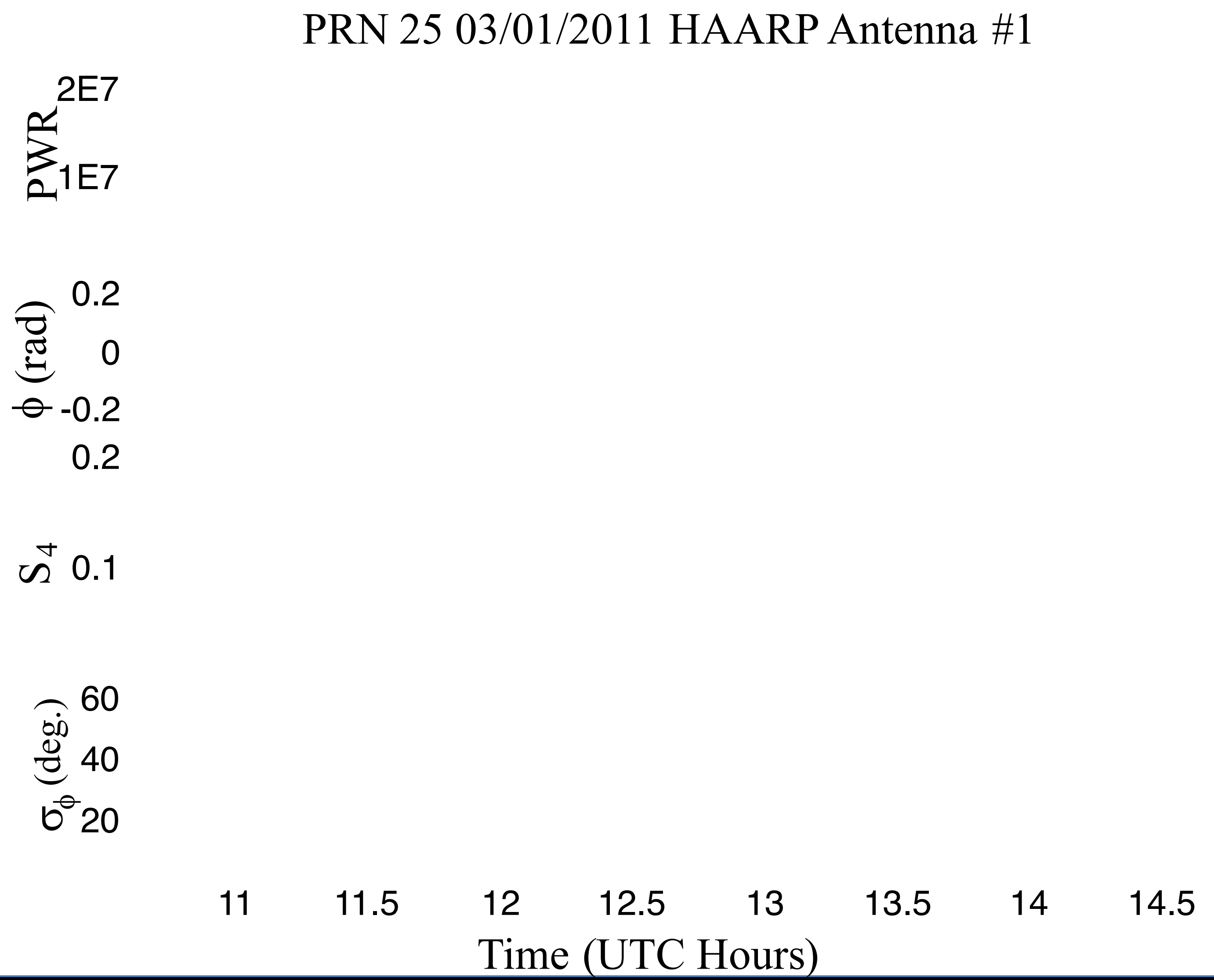

Morton, R.J., "Investigation of the impact of solar storms on the global positioning system receivers at high latitudes," *ION ITM,* 2014.

# Accuracy Issue: March 17-18, 2015 St. Patrick's Day storm

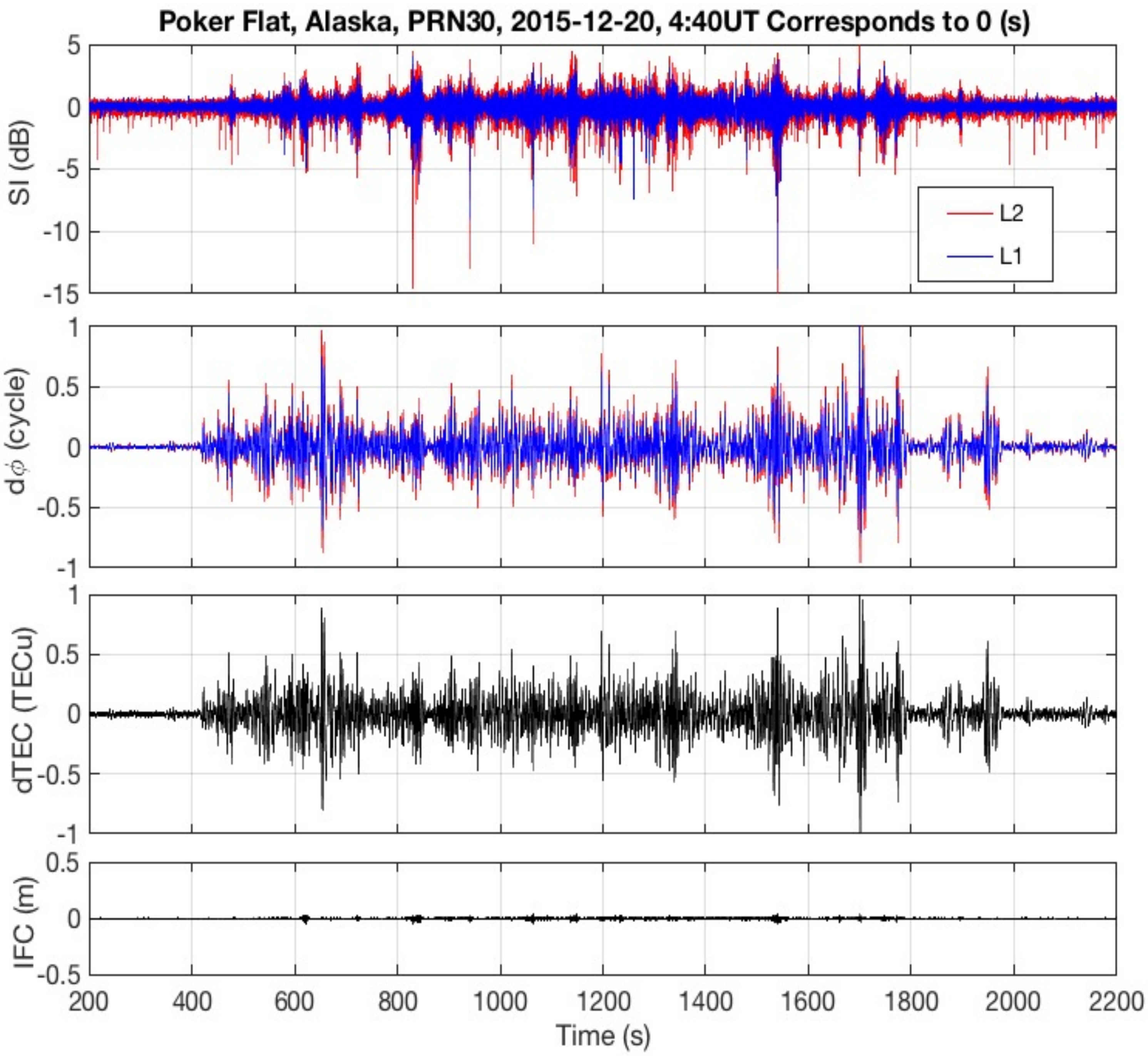



Yang, Z., Y. Morton, "Kinematic PPP errors associated with ionospheric plasma irregularities during the 2015 St. Patrick's day storm," *Proc. ION GNSS+*, 2019.

# High Latitude Scintillation Example

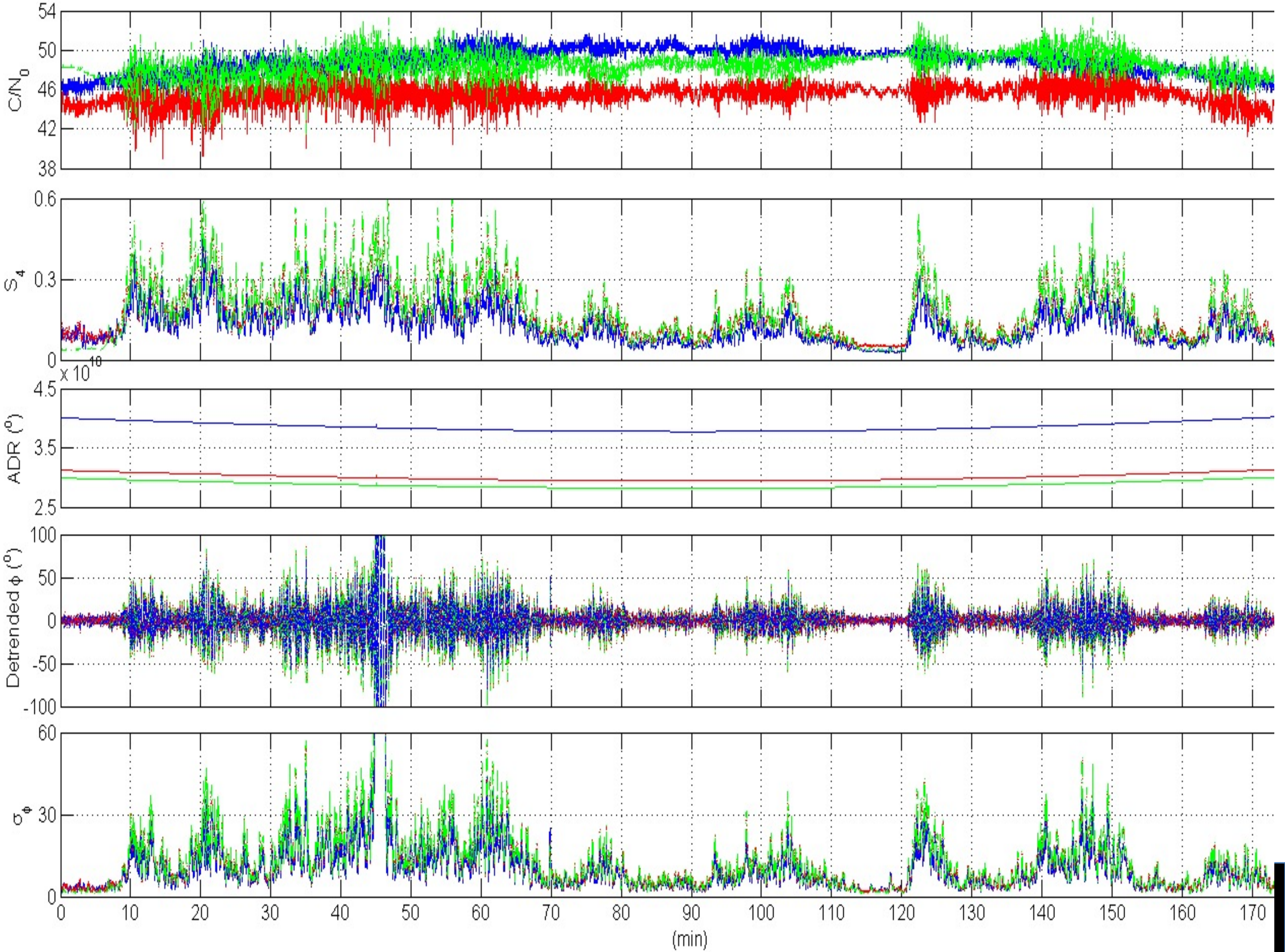


# High Latitude Scintillation: Mostly due to Refraction (TEC Variations)



# Low Latitude Scintillation Example

Peru
3/11/2013
13:30UTC

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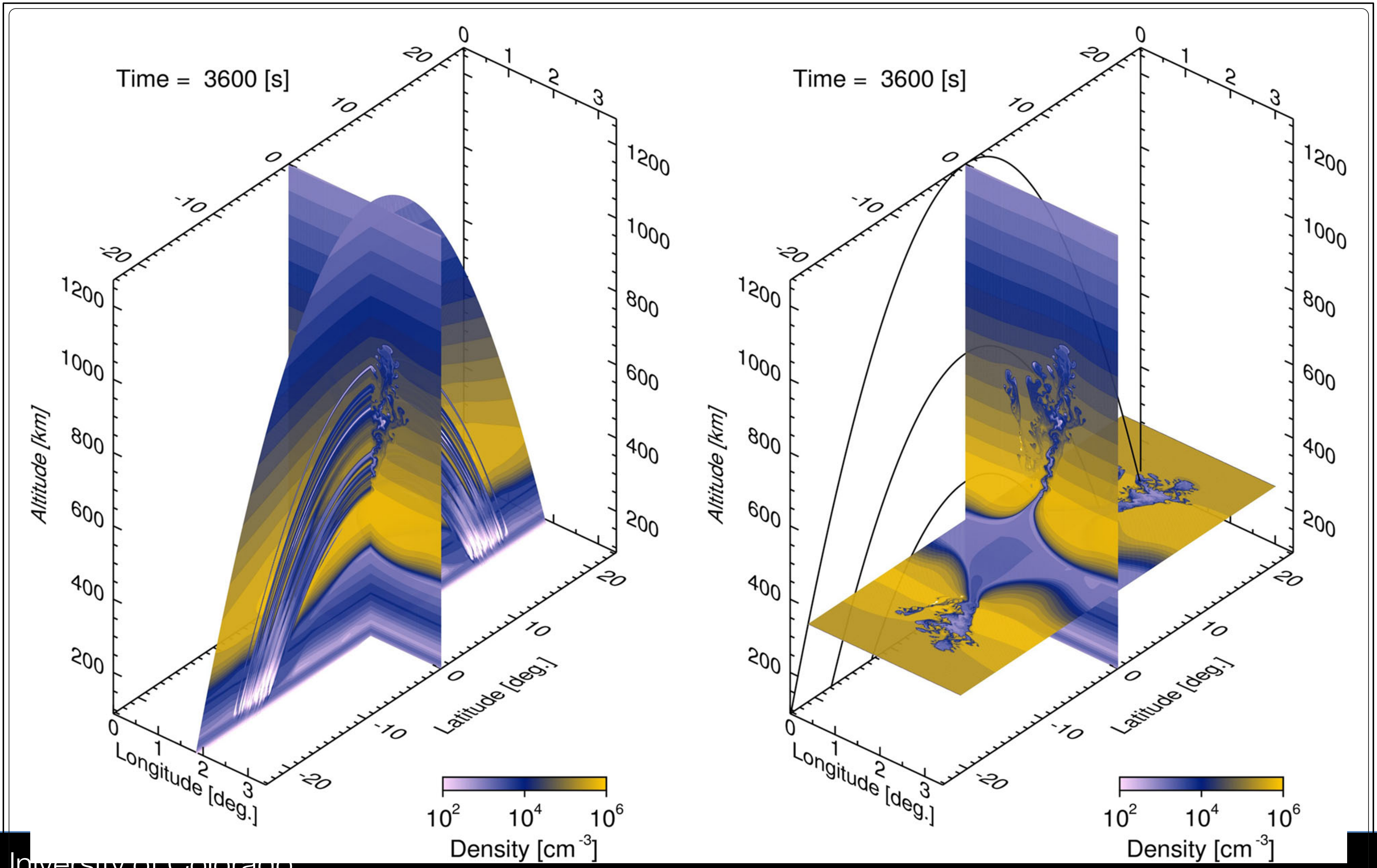
# Equatorial Plasma Bubbles




Yokoyama, T., "Hemisphere-coupled modeling of nighttime medium-scale traveling ionospheric disturbances," *Adv. Space Res.*, 54(3): 481–488, 2014.

# Scintillation Signal Model

Undisturbed signal model: $s_k = \alpha_k D(k\Delta t - \tau_k) C(k\Delta t - \tau_k) e^{j\phi_k}$

Scintillation signal model: $s_{s,k} = s_k \delta_{A,k} e^{j\delta_{\phi,k}} + \varepsilon_k$

Ignore code and nav data disturbance: $s_{s,k} = \alpha_k \delta_{A,k} e^{j\phi_{s,k}} + \varepsilon_k$

$\phi_{s,k} = \phi_k + \delta_{\phi,k}$: the composite carrier phase of the scintillation signal

# Scintillation Indices

Phase scintillation index: $\sigma_\phi = std\left(detrend(\phi_{s,k})\right)$

Amplitude scintillation index: $S_4 = \sqrt{\dfrac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2}}$

Signal intensity (power): $SI = \dfrac{SI_{raw}}{SI_{trend}}$ $\quad SI_{raw} = NBP - WBP$

Narrowband power: $NBP = \left(\sum_{i=1}^{M} I_i\right)^2 + \left(\sum_{i=1}^{M} Q_i\right)^2$

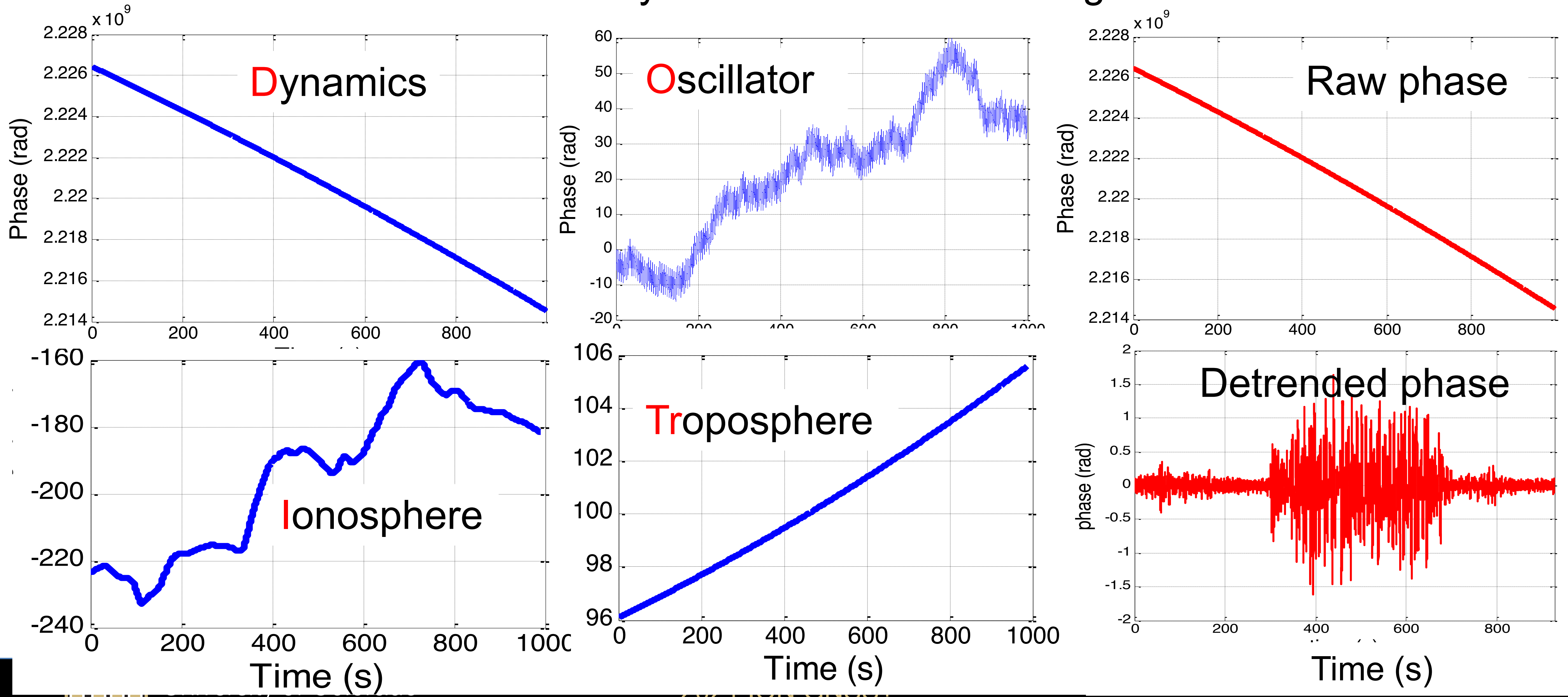
Wideband power: $WBP = \sum_{i=1}^{M} I_i^2 + \sum_{i=1}^{M} Q_i^2$

M: number of correlation blocks over a selected period

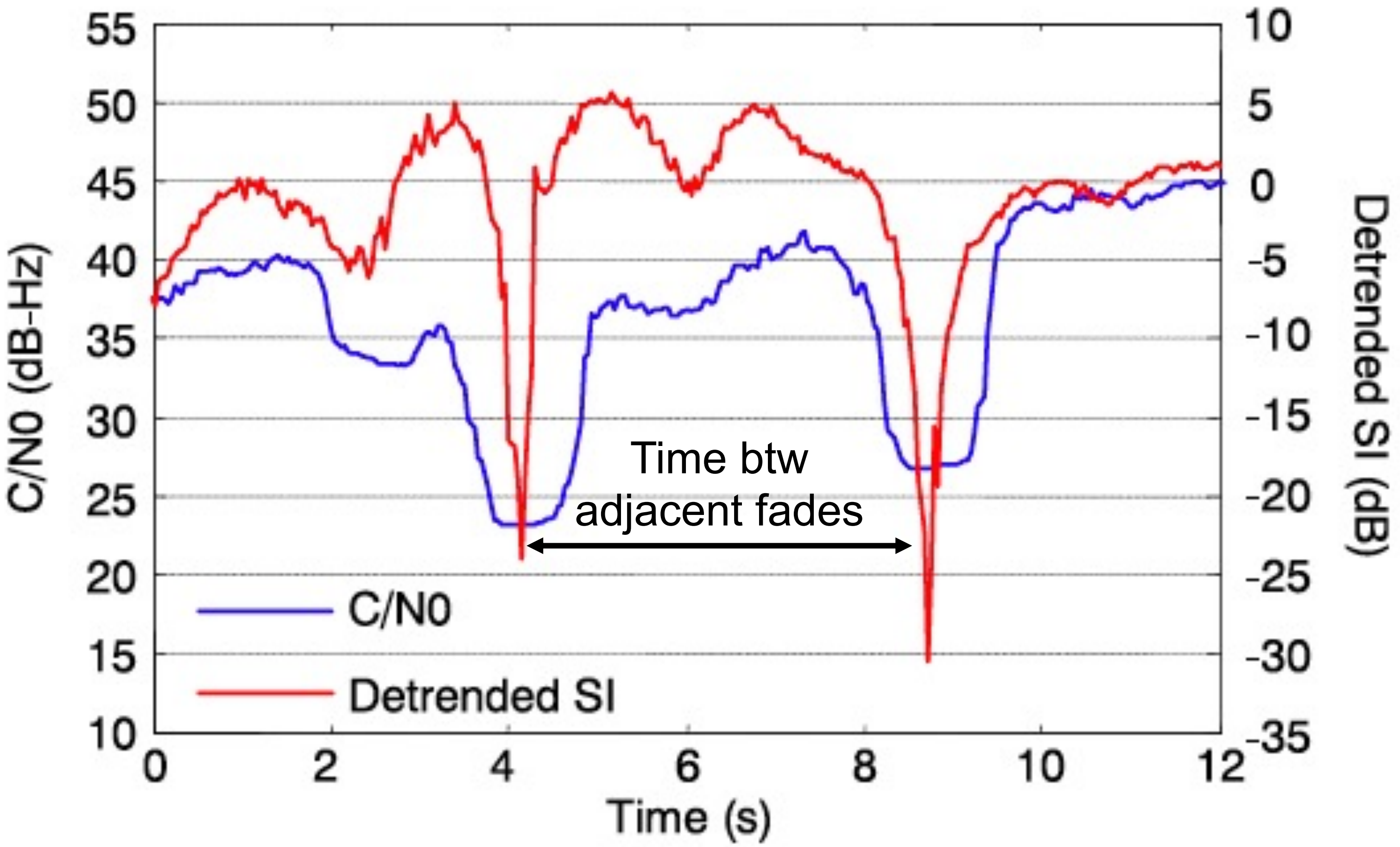
Typical setting: $T_I$ =1ms → M=20; $T_I$ =10ms → M=2

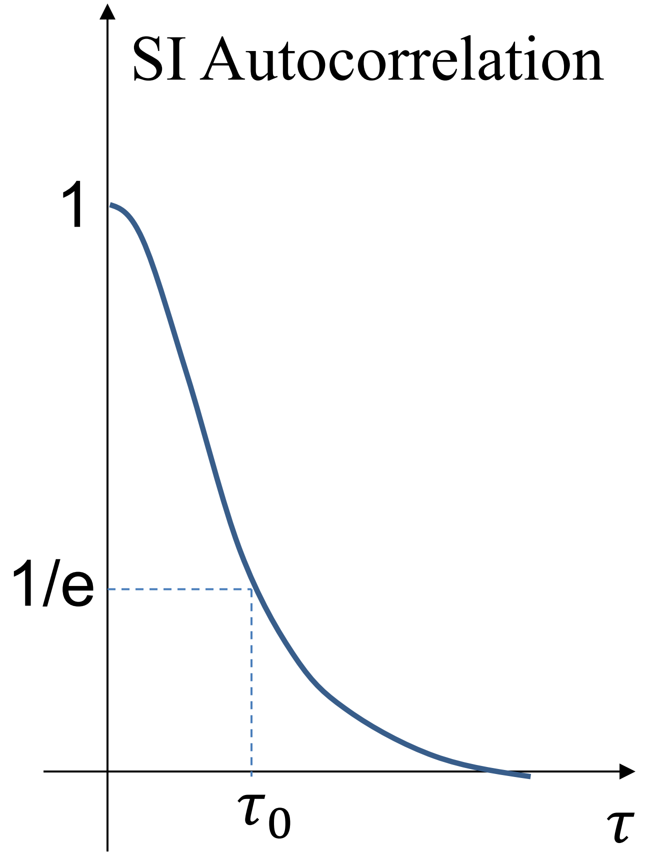
# Must Detrend Before Applying Scintillation Index Calculation

Scintillation effect is masked by other effects: detrending removes these effects



# Another Indicator: Decorrelation Time



# Rate of TEC Index: ROTI

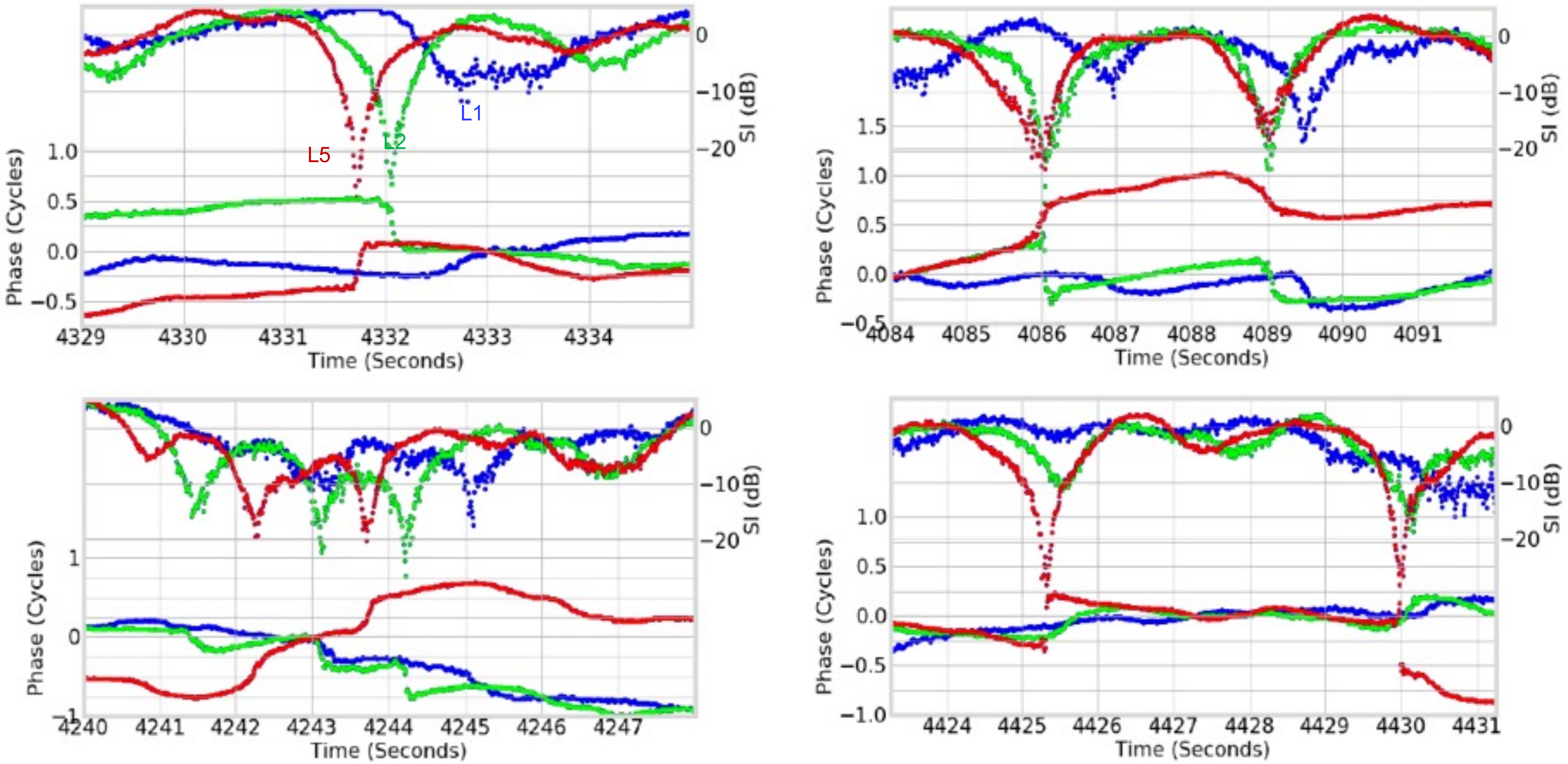
$$ROTI(\delta t) = \sqrt{E\left\{\frac{|TEC(t+\delta t) - TEC(t)|^2}{\delta t^2}\right\}}$$

- TEC must be first detrended to ensure that the TEC time series is zero-mean
- can be computed using low-rate TEC measurements
- Typical sample interval $\delta t$=1 or 30s
- Typical averaging window $\delta t_w$= 1 to 5 min
- ROTI and S4 are highly correlated if the signal propagation direction is near parallel with magnetic field lines.

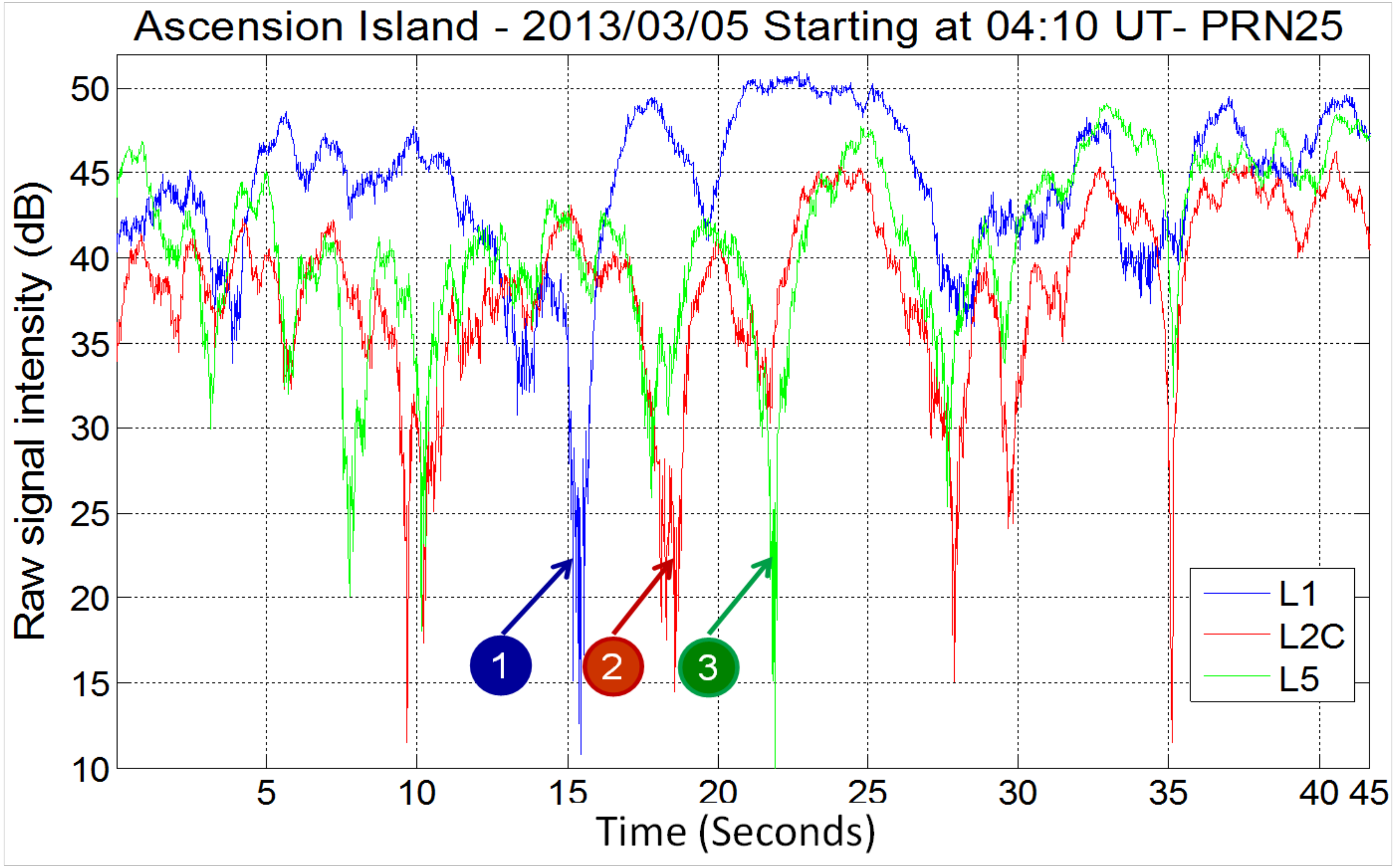
Carrano, C. S., Groves, K. M., & Rino, C. L. (2019). On the relationship between the rate of change of total electron content index (ROTI), irregularity strength (CkL), and the scintillation index (S4). *J. Geophy. Res.: Space Phy.*, *124*(3), 2099-2112.

# 2. Scintillation Observations

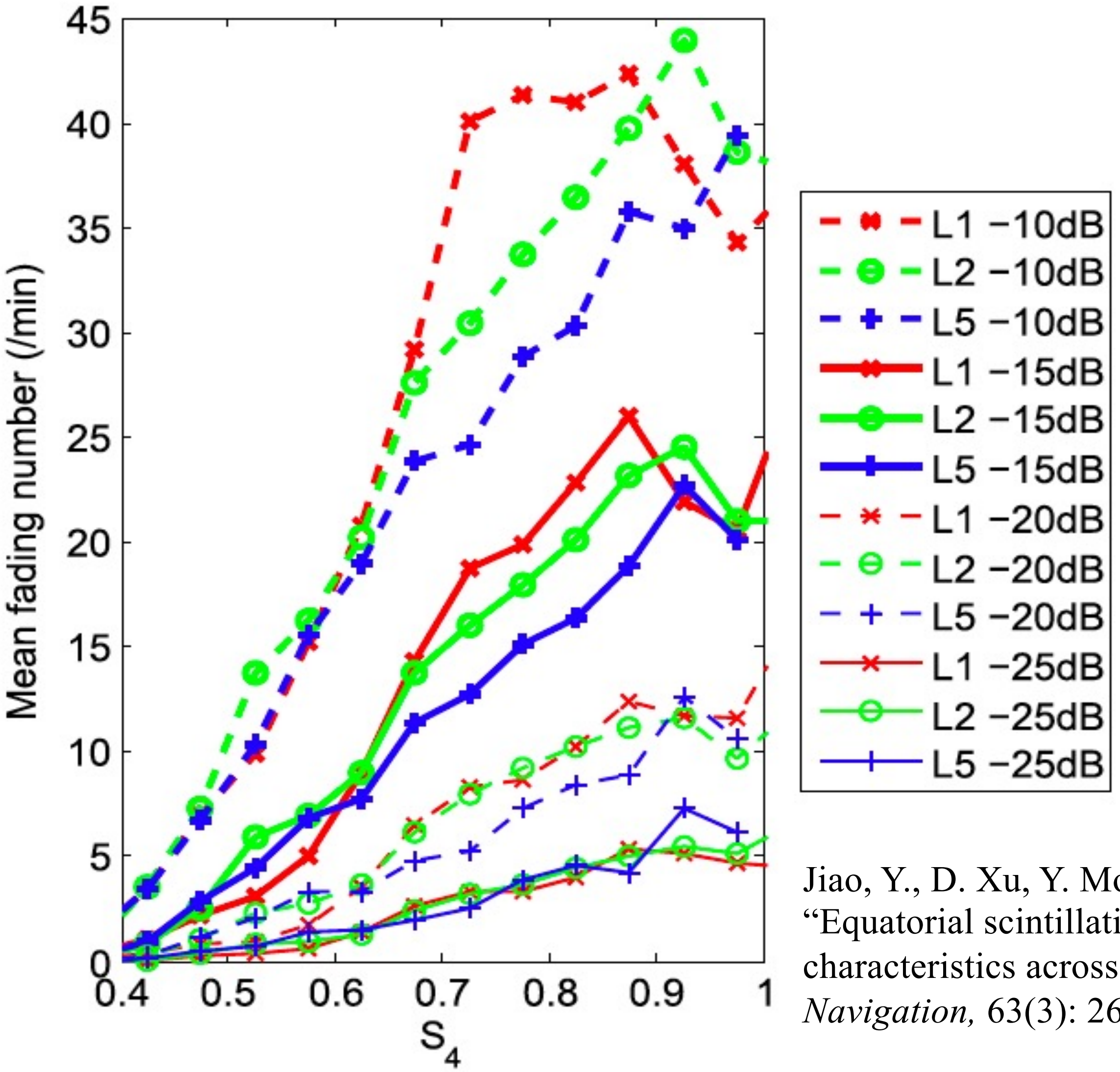
# Simultaneous Amplitude Fading and Phase Jumps



# Frequency Diversity: Selective Fading

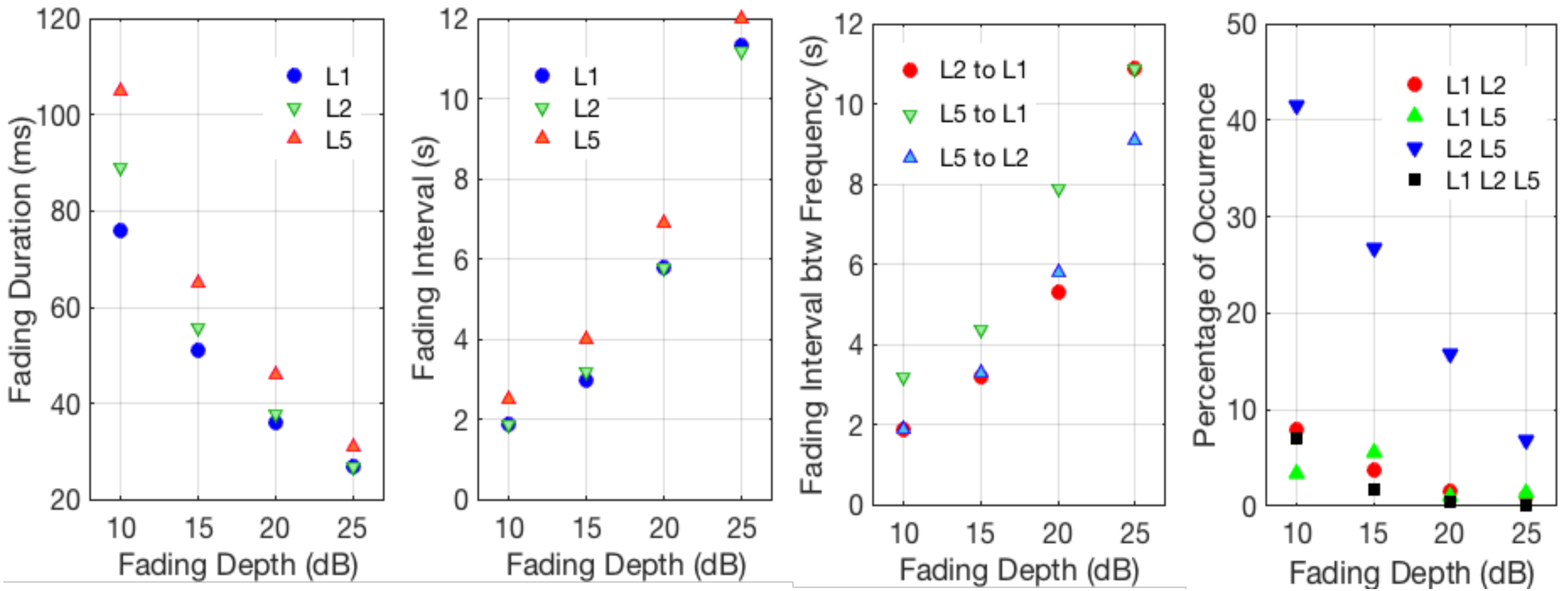


# Equatorial Fading Frequencies



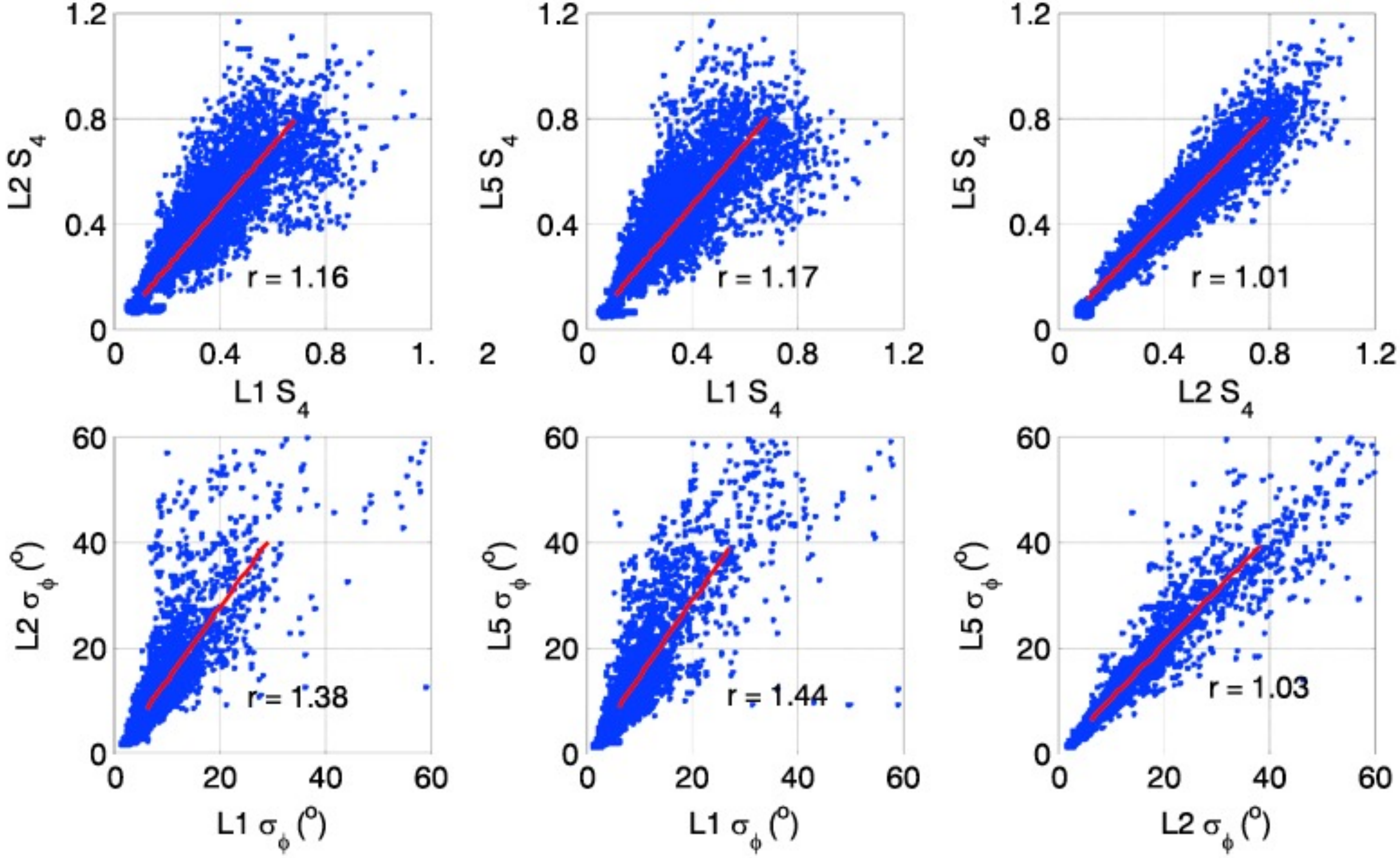

Jiao, Y., D. Xu, Y. Morton, and C. Rino, "Equatorial scintillation amplitude fading characteristics across the GPS frequency bands," *Navigation,* 63(3): 267–281, 2016.

# Fading Duration, Interval, Depth, and Rate of Occurrence



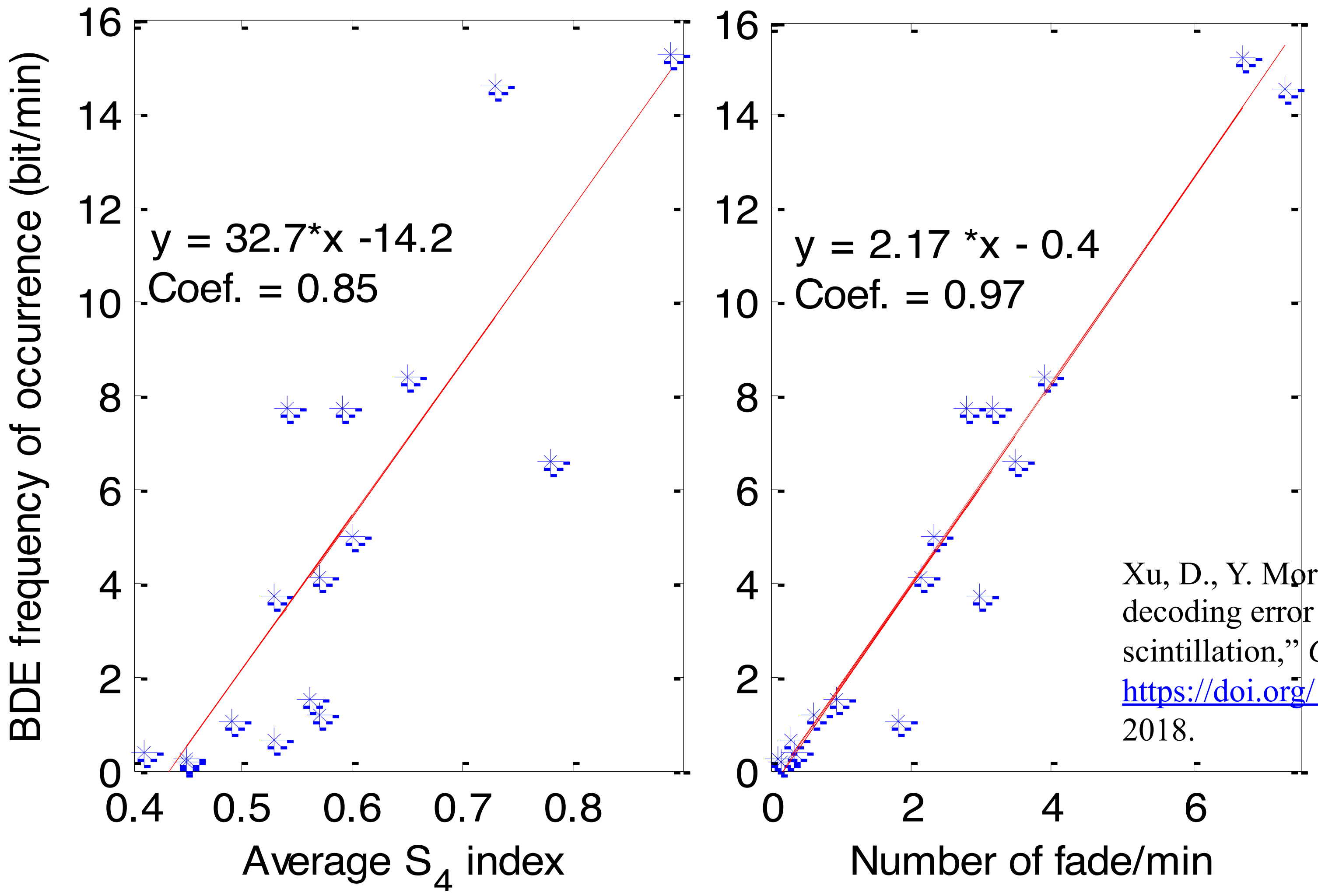

Jiao, Y., D. Xu, Y. Morton, C. Rino, "Equatorial scintillation amplitude fading characteristics across the GPS frequency bands," *Navigation,* 63(3): 267–281, 2016.

# Carrier Frequency Dependence



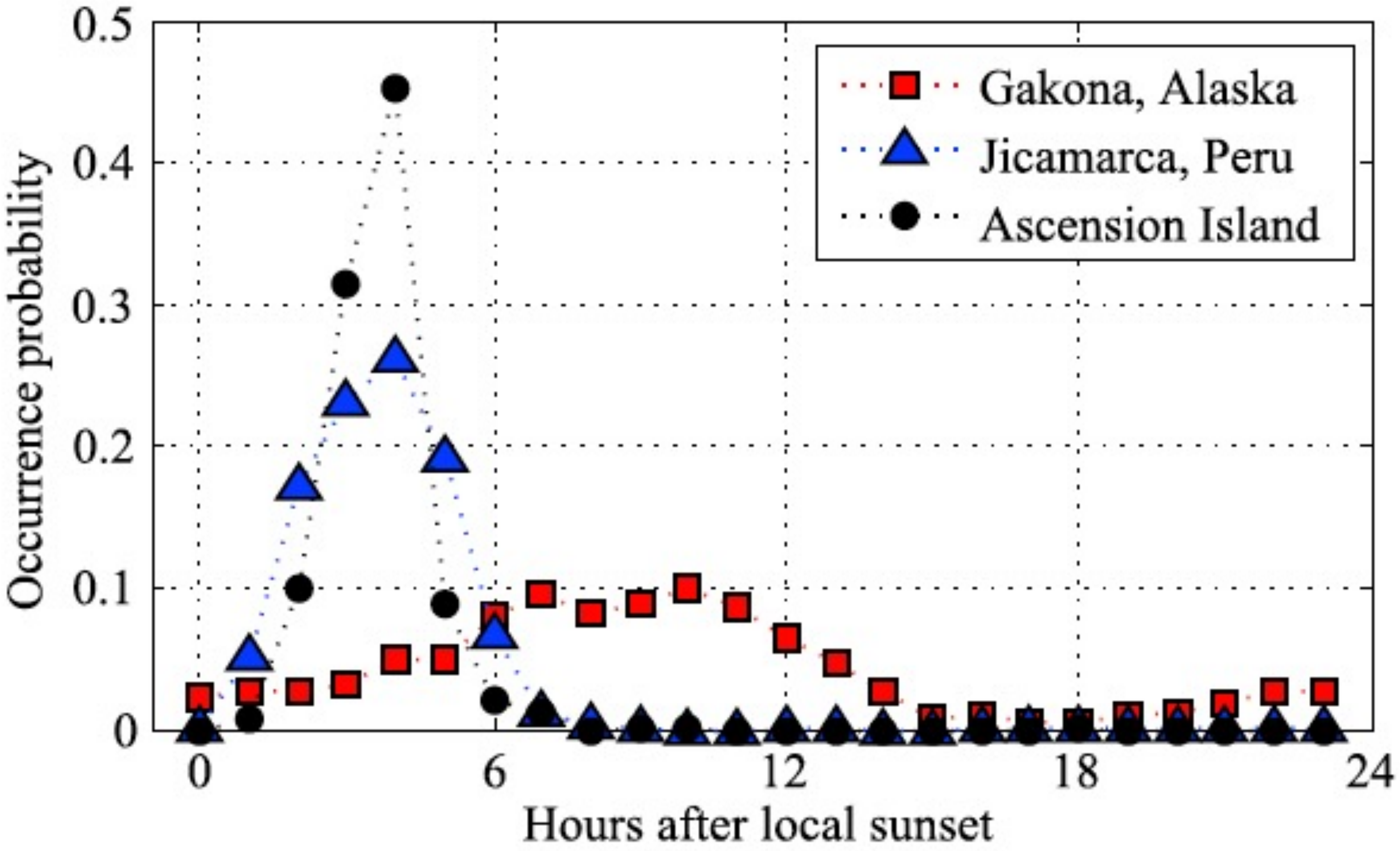

Jiao, Y., D. Xu, Y. Morton, C. Rino, "Equatorial scintillation amplitude fading characteristics across the GPS frequency bands," *Navigation,* 63(3): 267–281, 2016.

# Nav Bit Error Rate



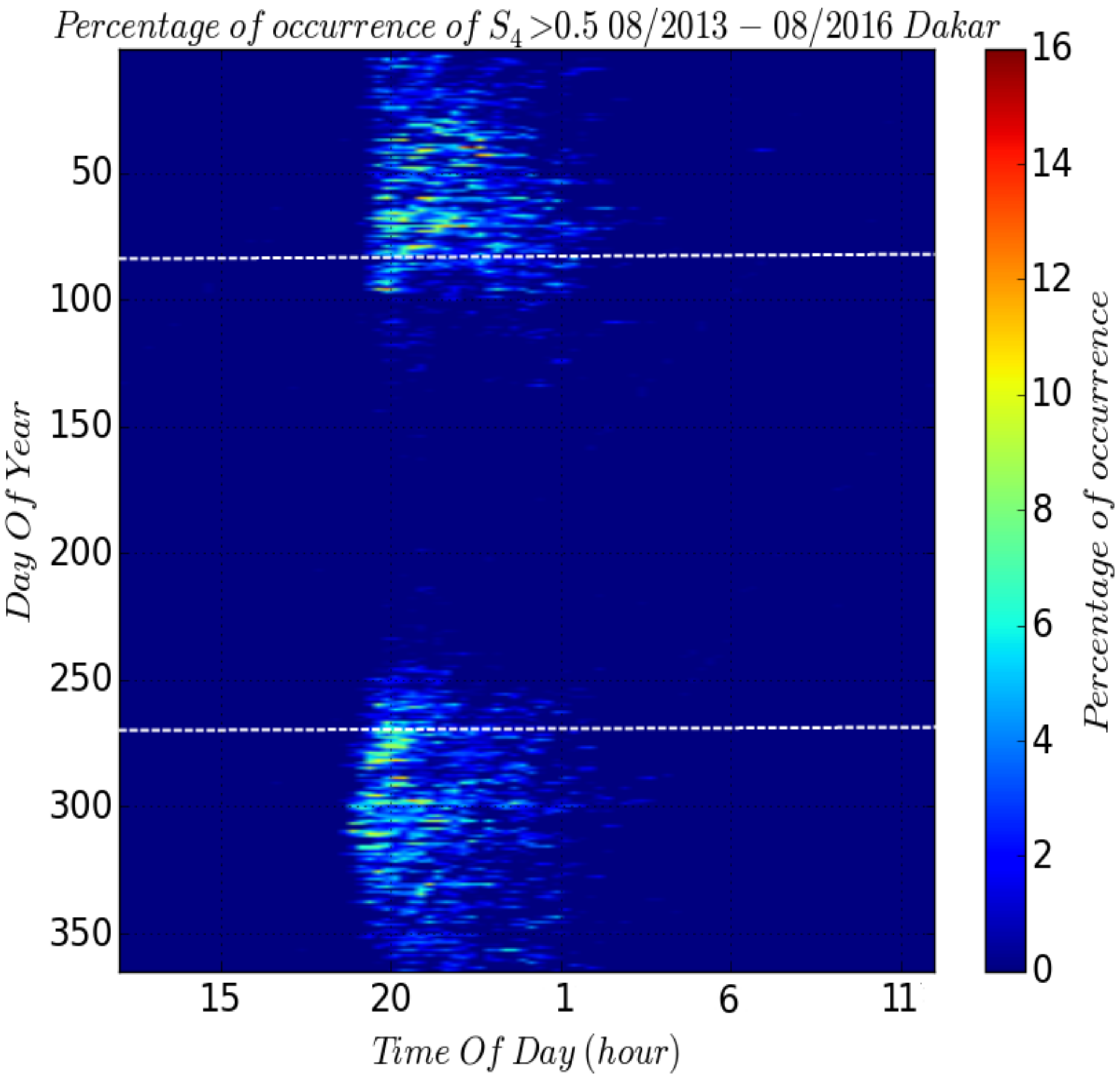

Xu, D., Y. Morton, “GPS navigation data bit decoding error during strong equatorial scintillation,” *GPS Solu.*, 22: 110, https://doi.org/10.1007/s10291-018-0775-1, 2018.

# Time of Occurrence



# Seasonal Behavior

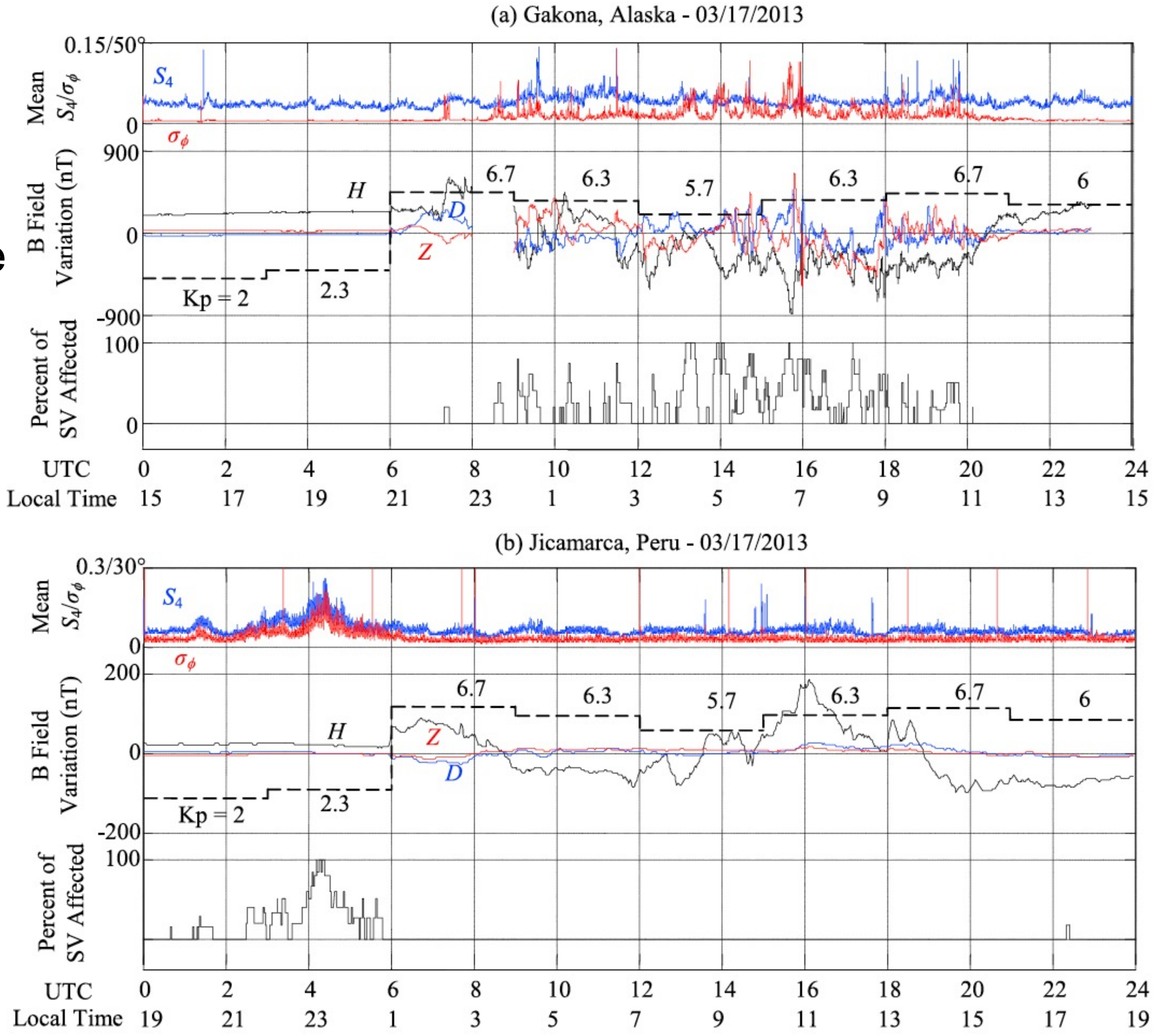
Galmiche, A., Vincent, F., Laurent, F., "Temporal and Geographical overview of the ionospheric amplitude scintillating variability in west Africa from a SAGAIE network GNSS database," *J. Space Weather & Space Climate*, 2019.



# Geomagnetic Storm Impact

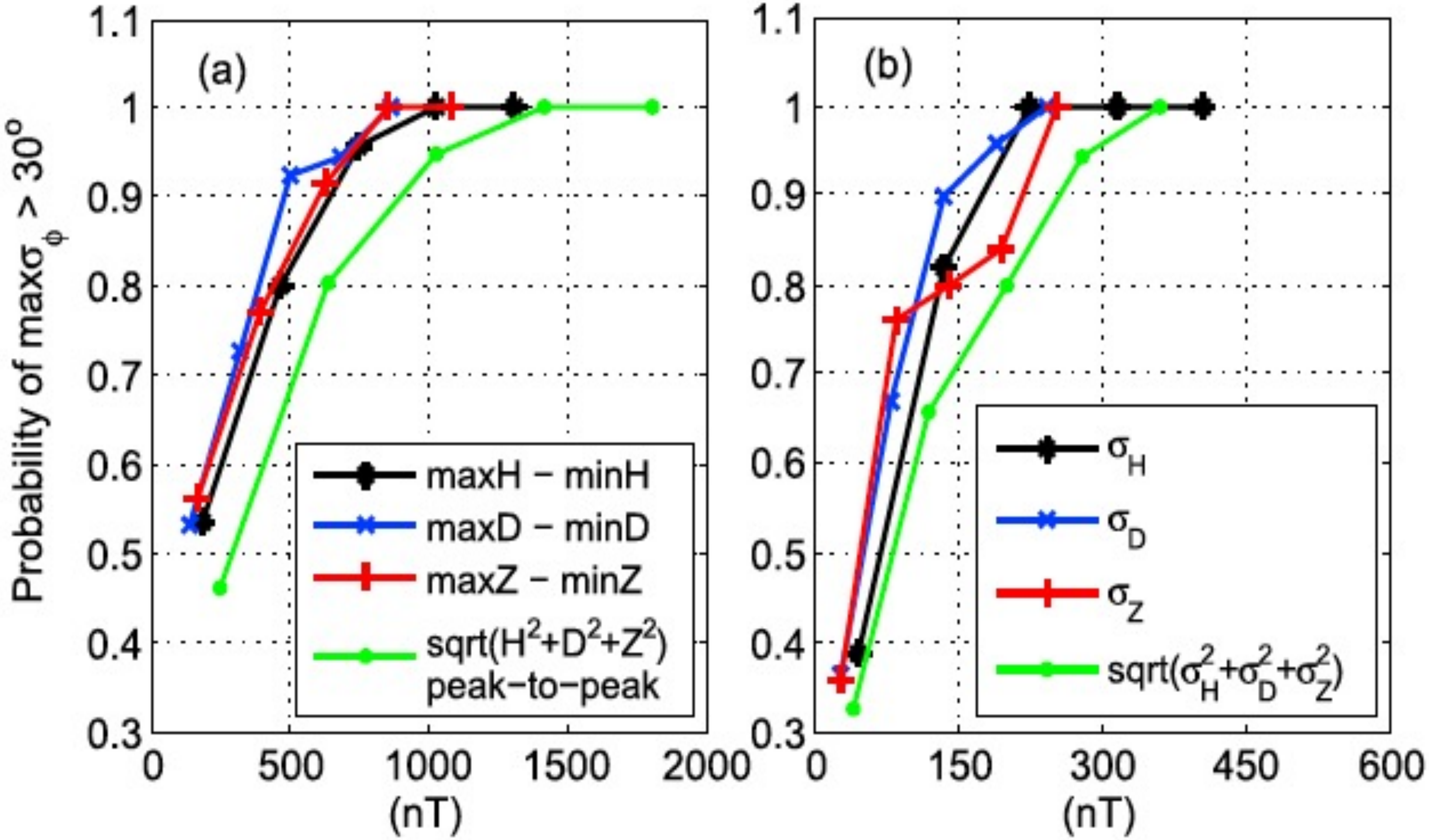
High latitude

Low latitude



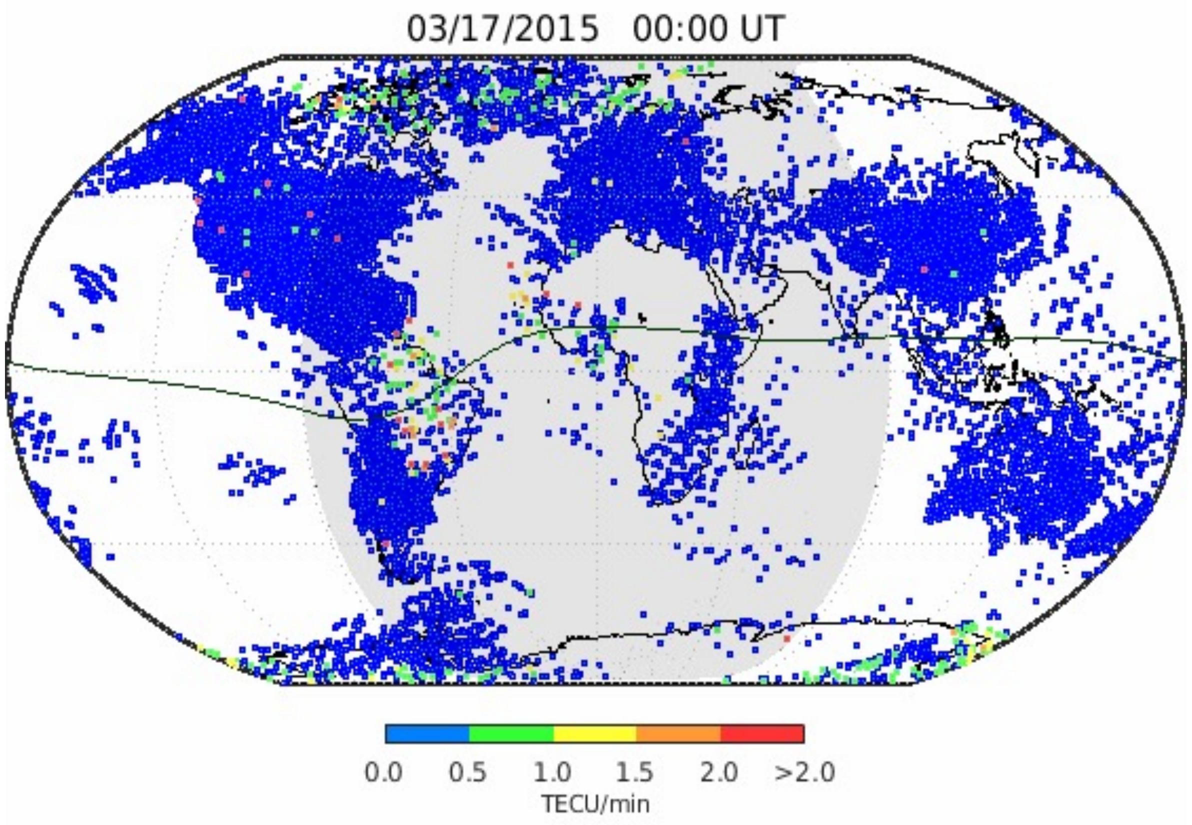

Jiao, Y. and Y.T. Morton, “Comparison of the effect of high-latitude and equatorial ionospheric scintillation on GPS signals during the maximum of solar cycle 24,” *Radio Sci.*, 50(9): 886–903, 2015.

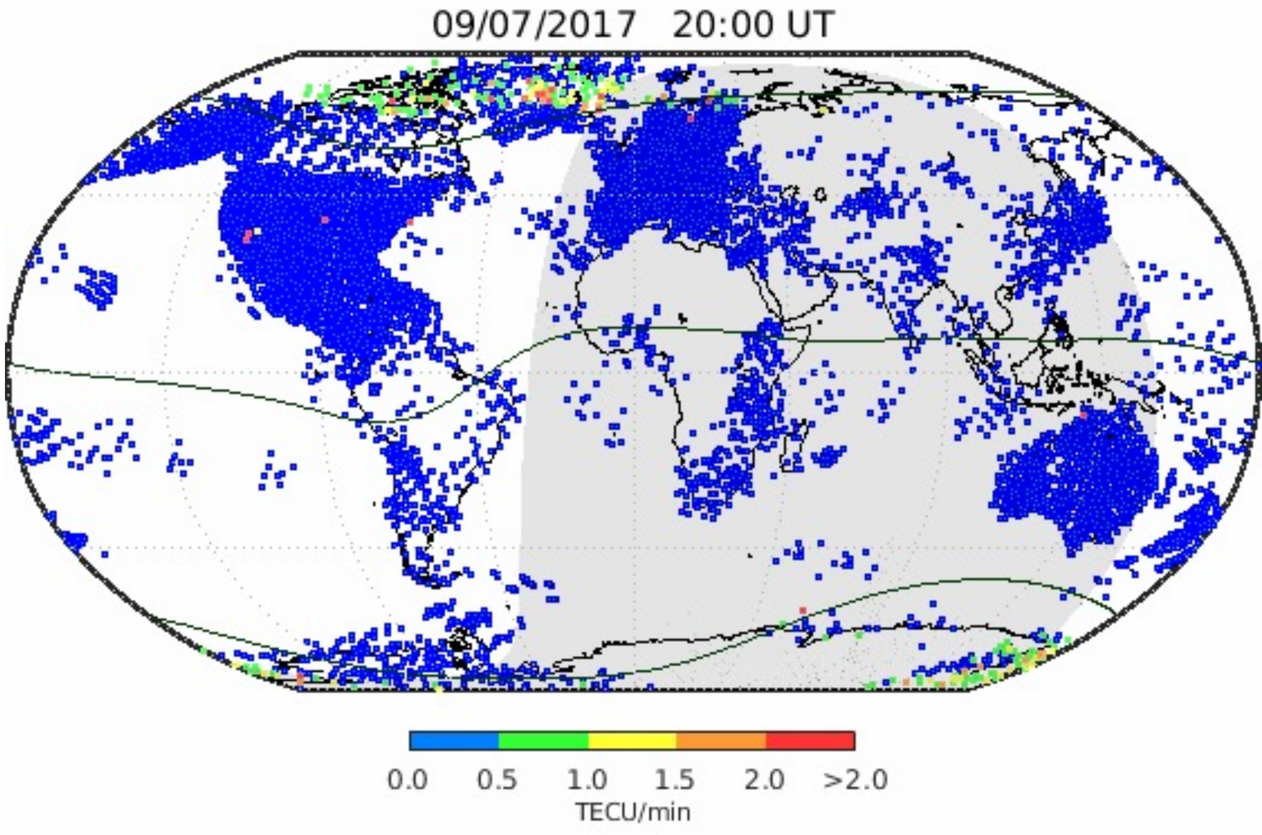
# Phase Scintillation Index Dependence on Magnetic Field Disturbance




Jiao, Y., Y.T. Morton, "Comparison of the effect of high-latitude and equatorial ionospheric scintillation on GPS signals during the maximum of solar cycle 24," *Radio Sci.*, 50(9): 886–903, 2015.

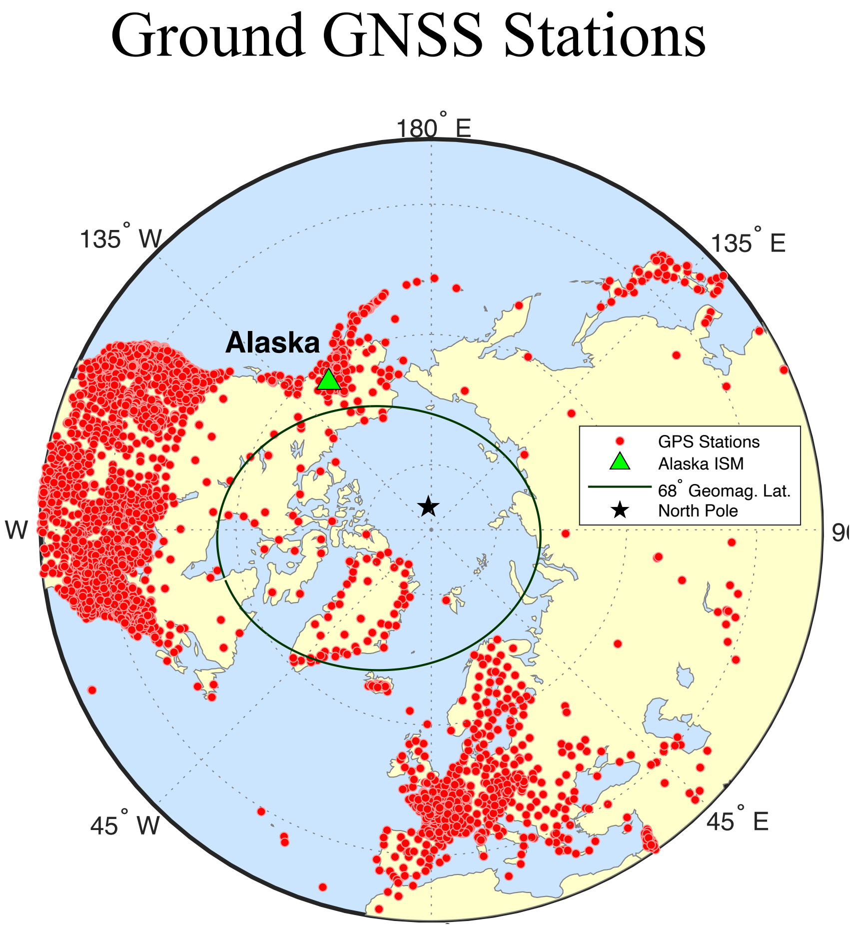
# Propagation in Space

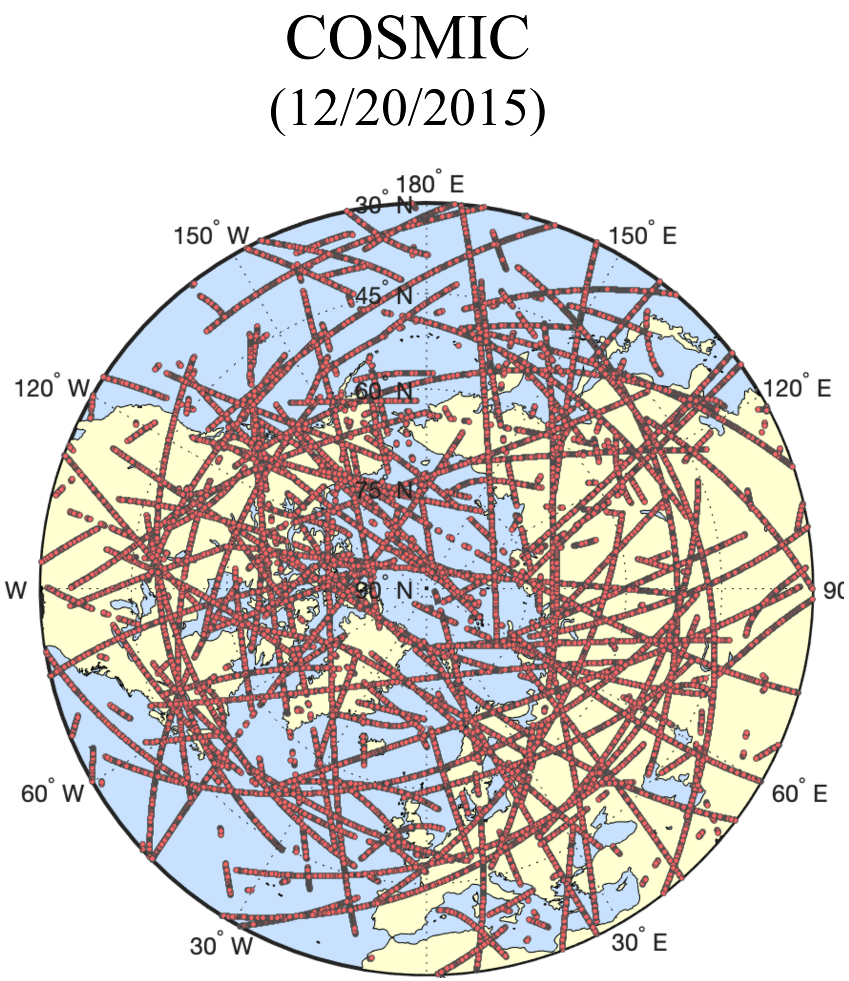


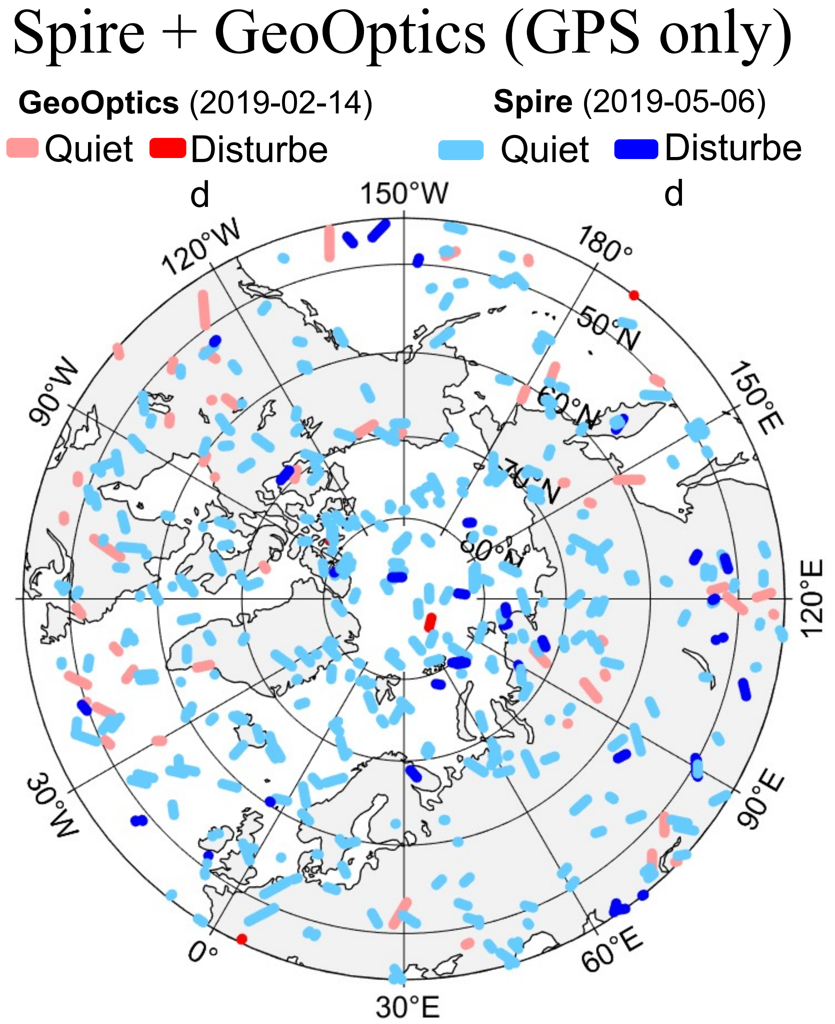




*Yang, Z.,* Y. Morton, I. Zakharenkova, I. Cherniak, S. Song, W. Li, "Global view of ionospheric disturbances impacts on kinematic GPS positioning solutions during the 2015 St. Patrick's Day storm," *J. Geophy. Res., Space Sci*., DOI: 10.1029/2019JA027681, 2020.

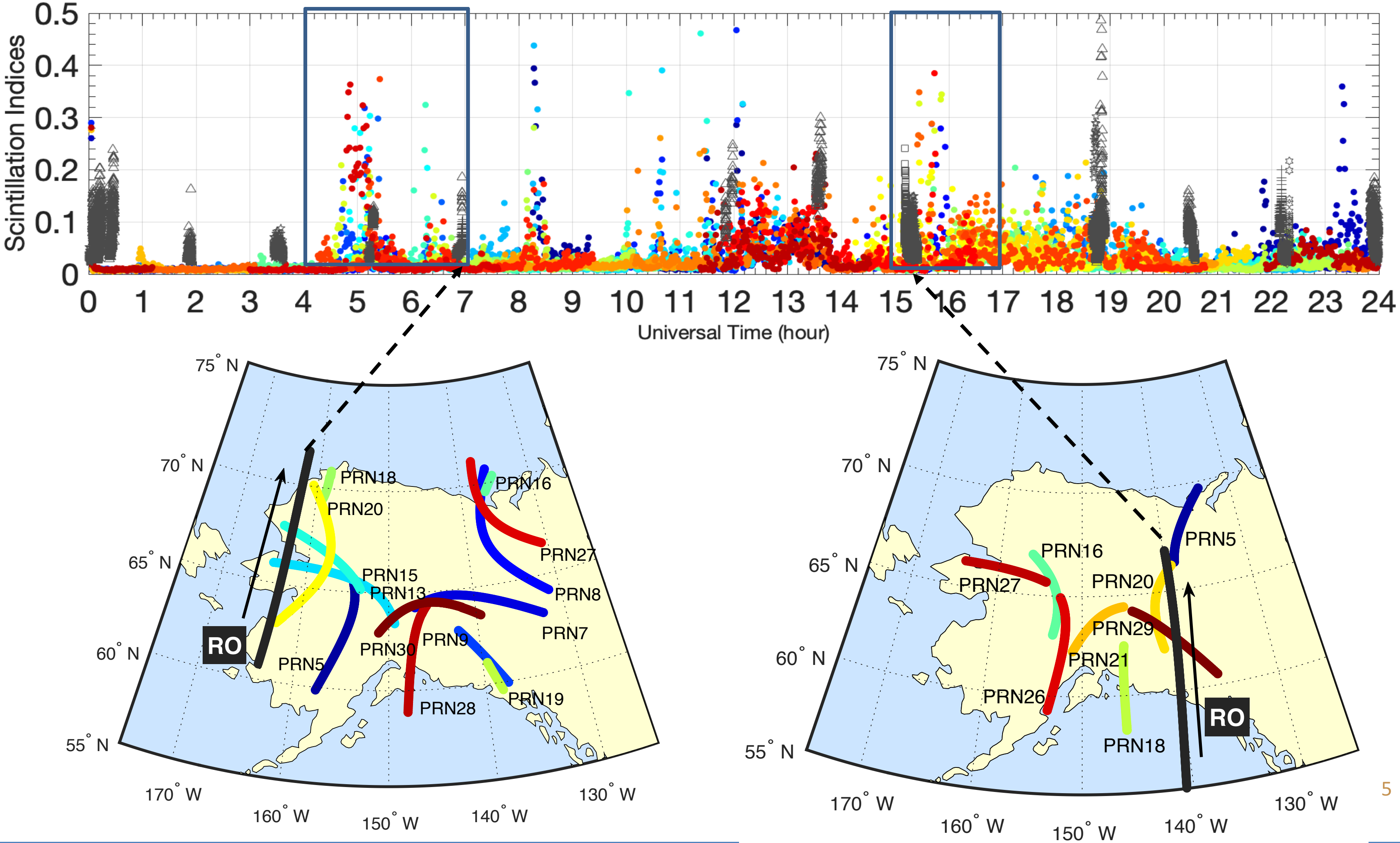
# Ground- and Space-based Observations



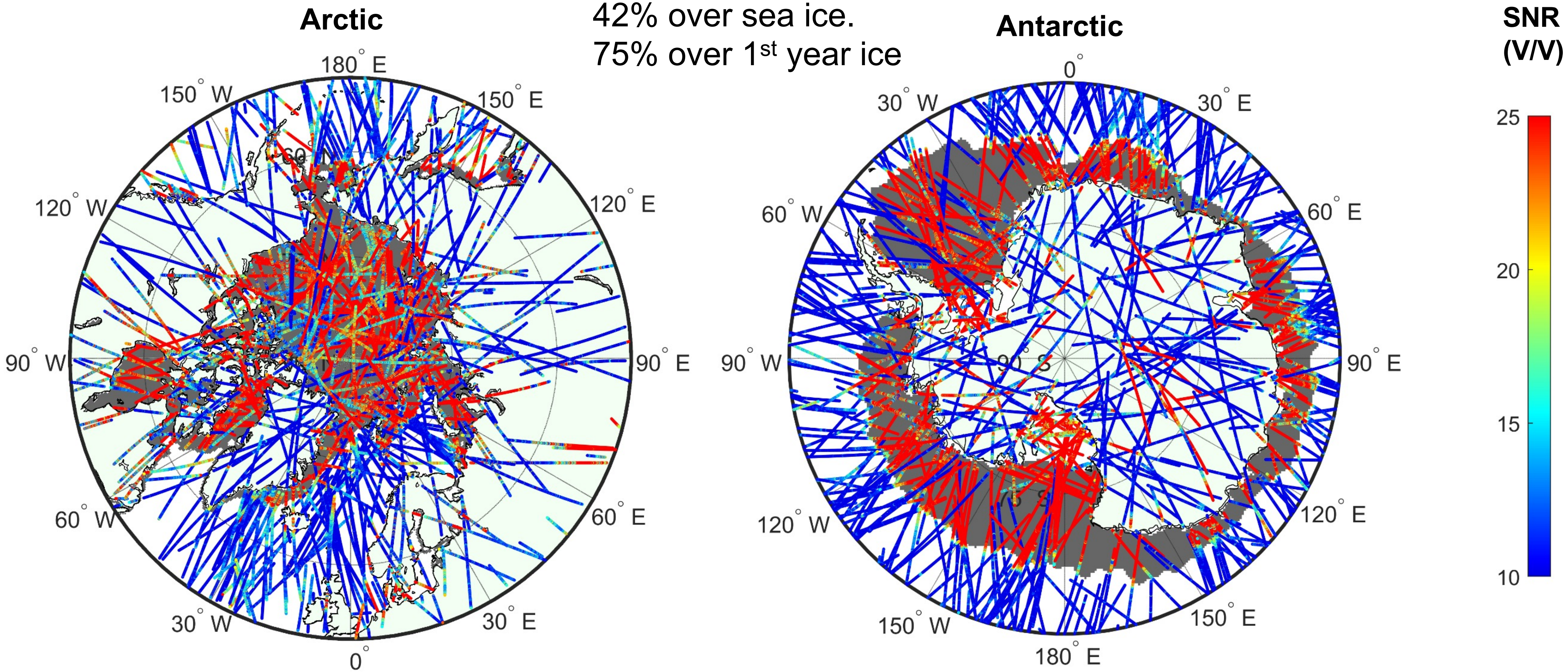
# CubeSat GNSS Radio Occultation Ionosphere Monitoring



# Coherent Reflection Tracks Over Arctic and Antarctica

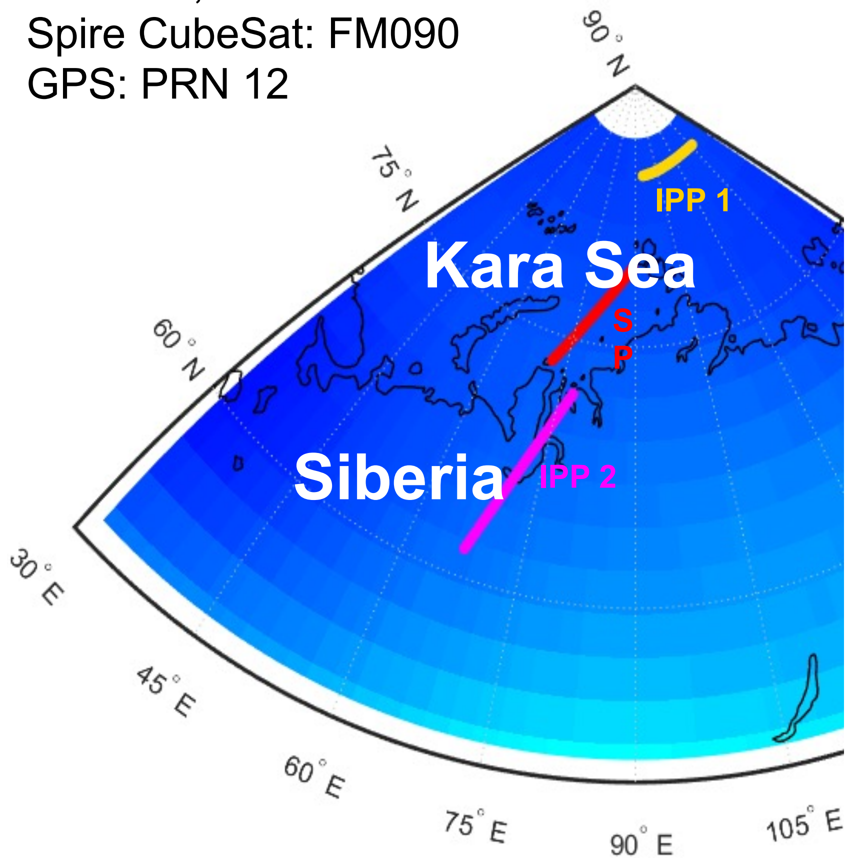
**Spire CubeSats Specular Point Tracks over one day (2021-05-12)**

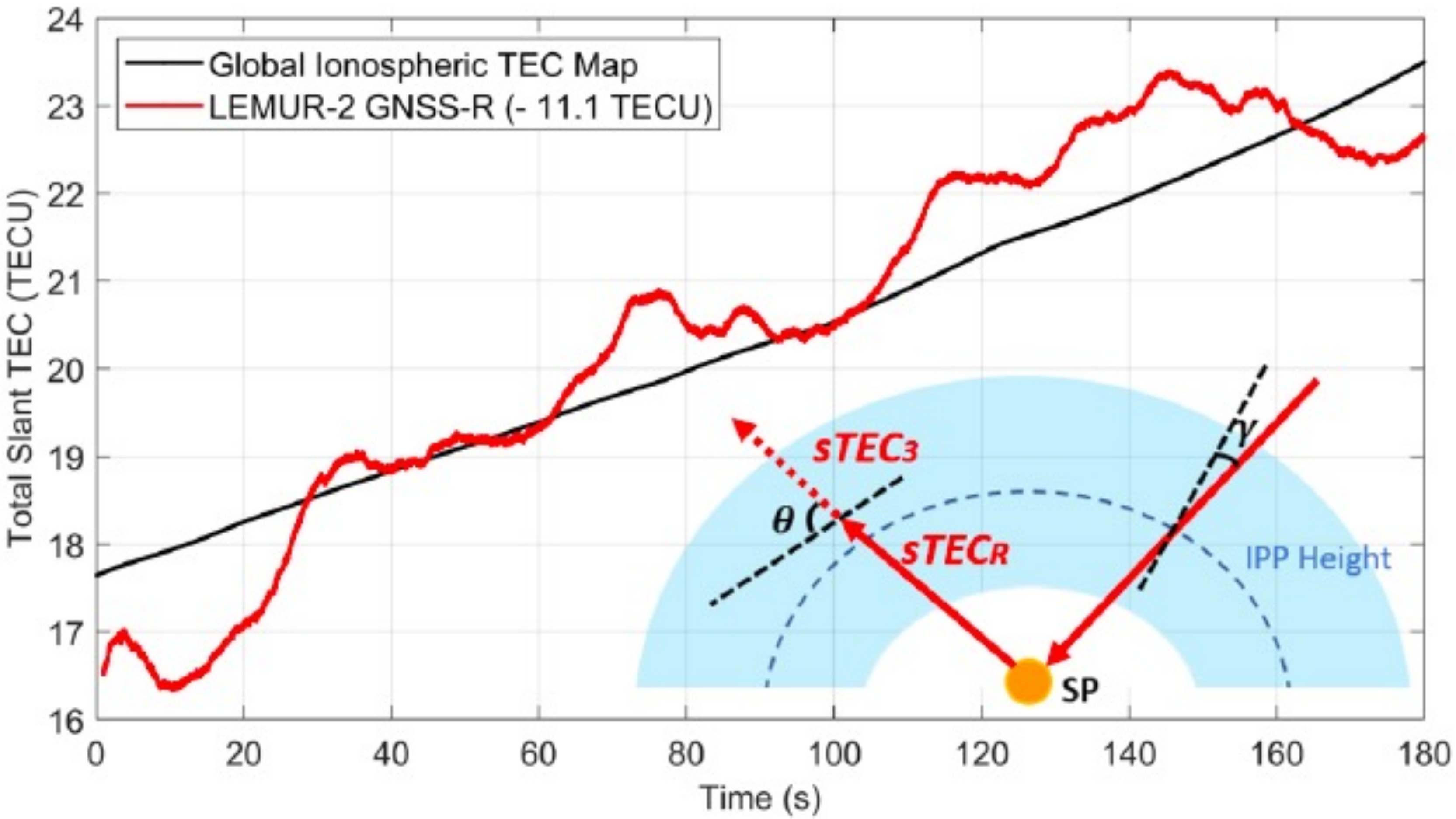
42% over sea ice.
75% over 1st year ice



# Example TEC Retrieval from Spire Data: Kara Sea

2/2/2019, 06:24:16 UTC
Spire CubeSat: FM090
GPS: PRN 12

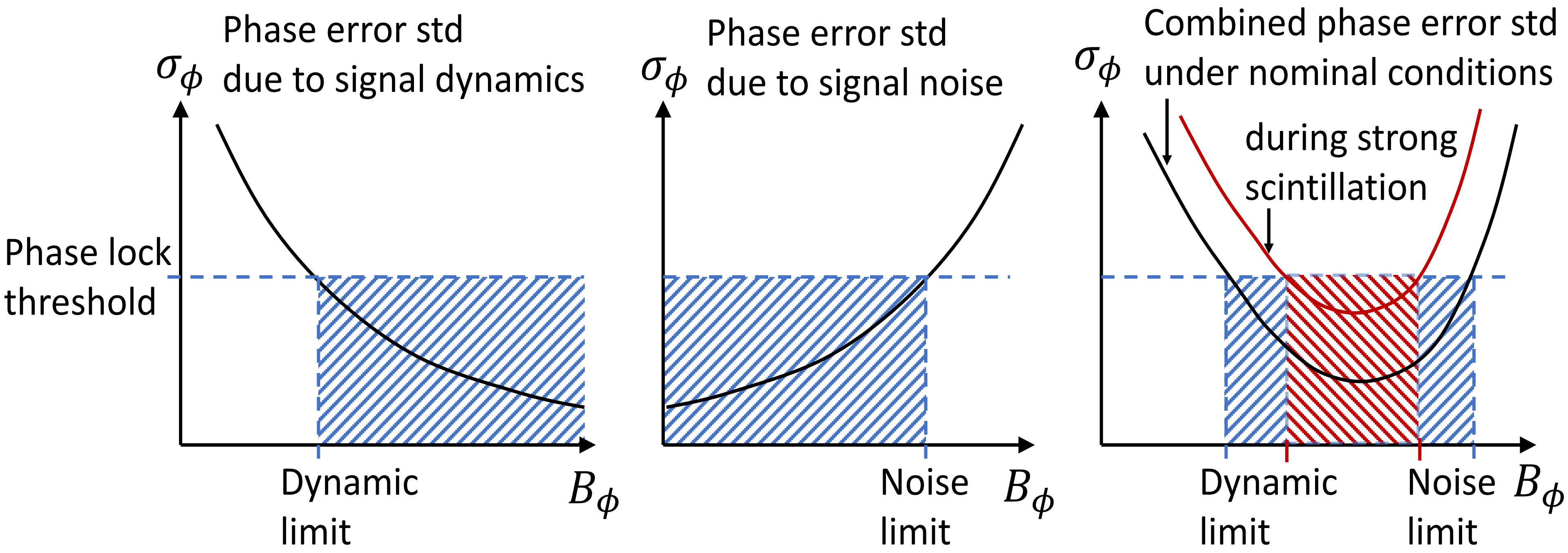


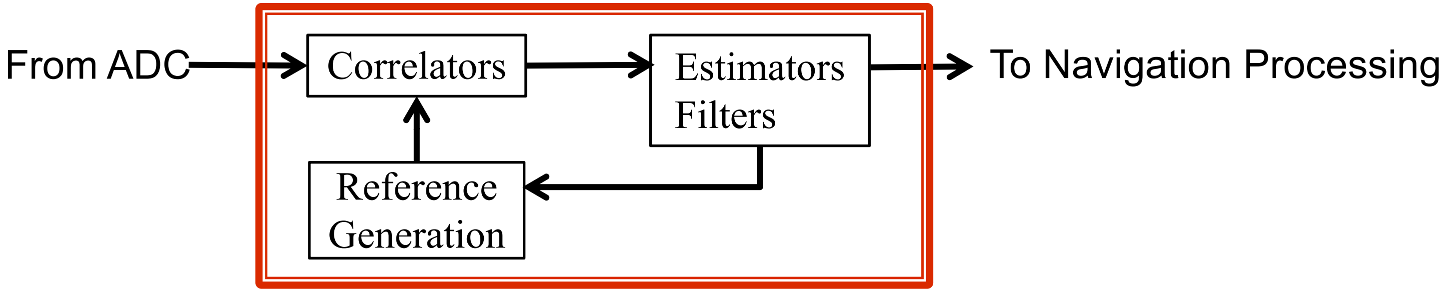

*Wang, Y.,* Y. J. Morton, "Ionospheric total electron content and disturbance observations from space borne coherent GNSS-R measurements," *IEEE Trans. Geosci. Remote Sensing,* doi: 10.1109/TGRS.2021.3093328, 2021.

# 4. Mitigation Techniques

# Why GNSS Receiver Lose Lock During Strong Scintillation?

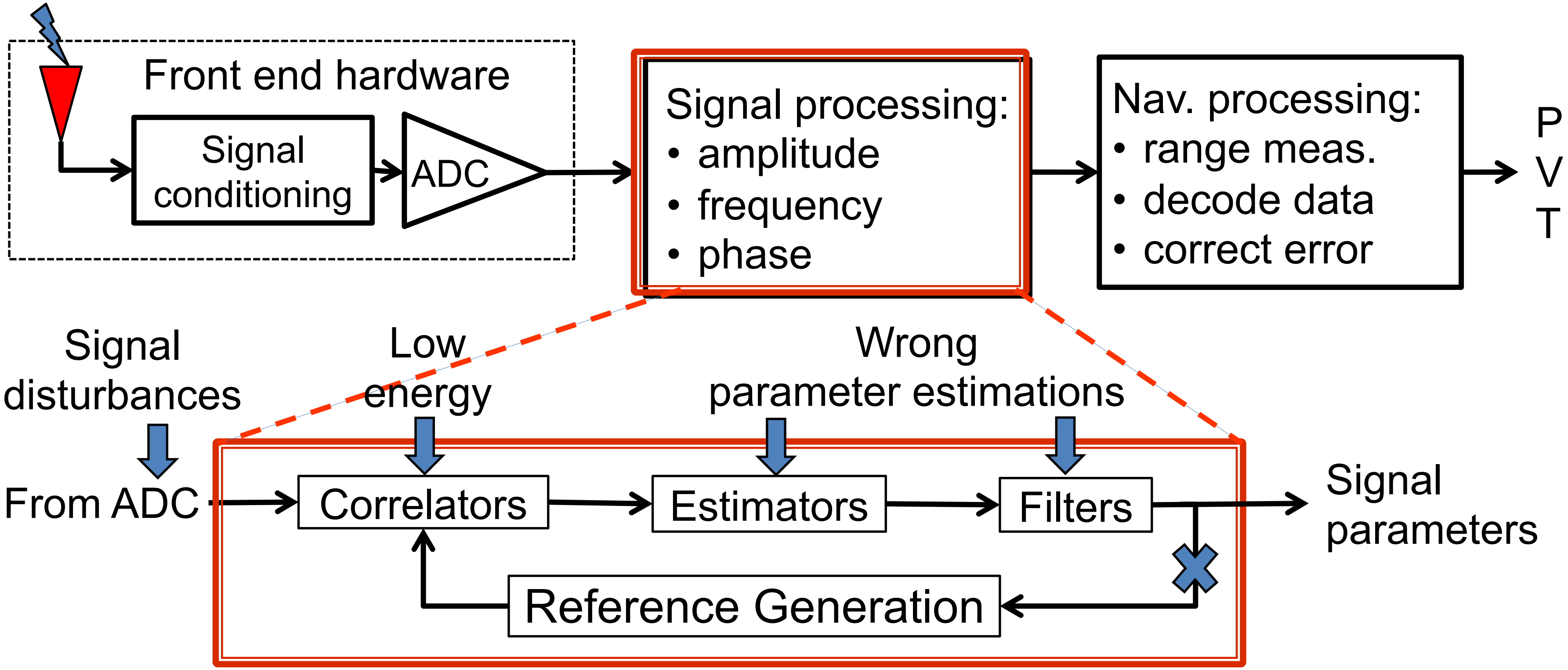


# Conflicting Demands for Weak Signal & Dynamic Signal For Strong Scintillation



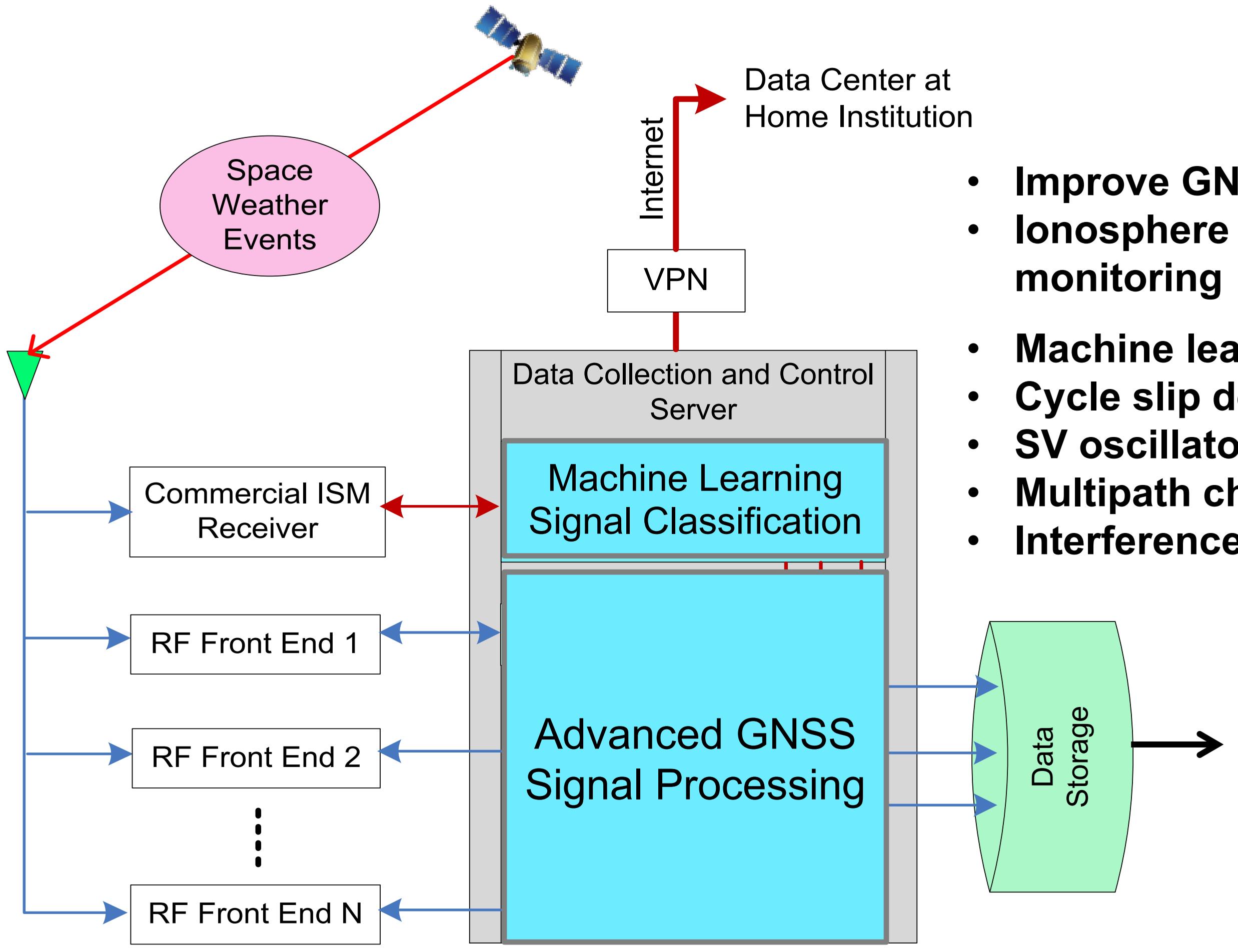

| Processing Component | Correlator | Estimator | Filter |
|---|---|---|---|
| Design Parameter | Integration Time | Estimator Type | Bandwidth |
| Weak Signal | Long | Phase | Narrow |
| Highly Dynamic Signal | Short | Frequency | Wide |

# A More Intuitive Way to Understand Why GNSS Receivers Lose Lock



# Q: Where Do We Get the “Raw” Data?

**E**vent-driven
**D**ata
**A**cquisition
**S**ystem

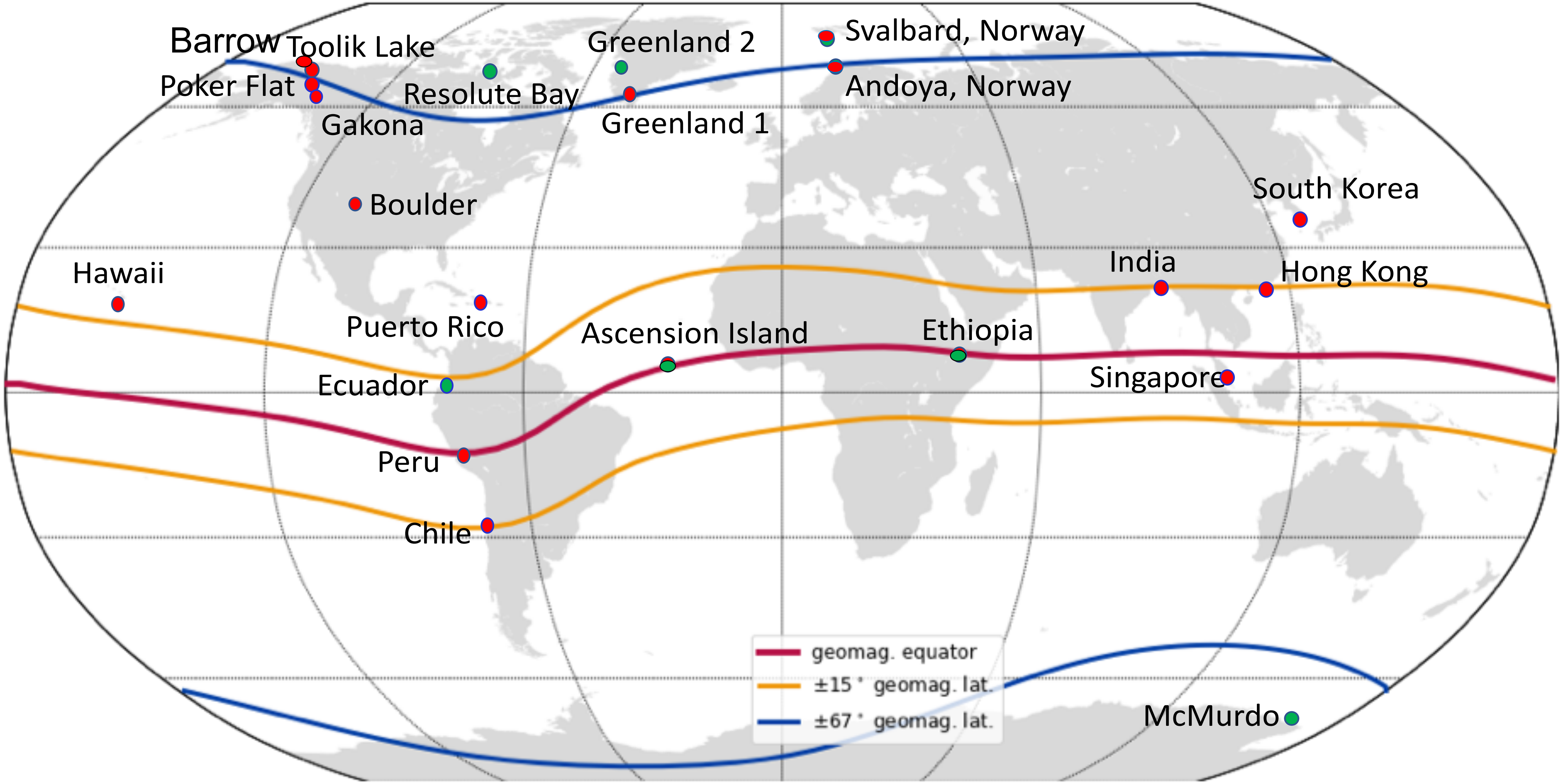



- **Improve GNSS Receivers**
- **Ionosphere and space weather monitoring**

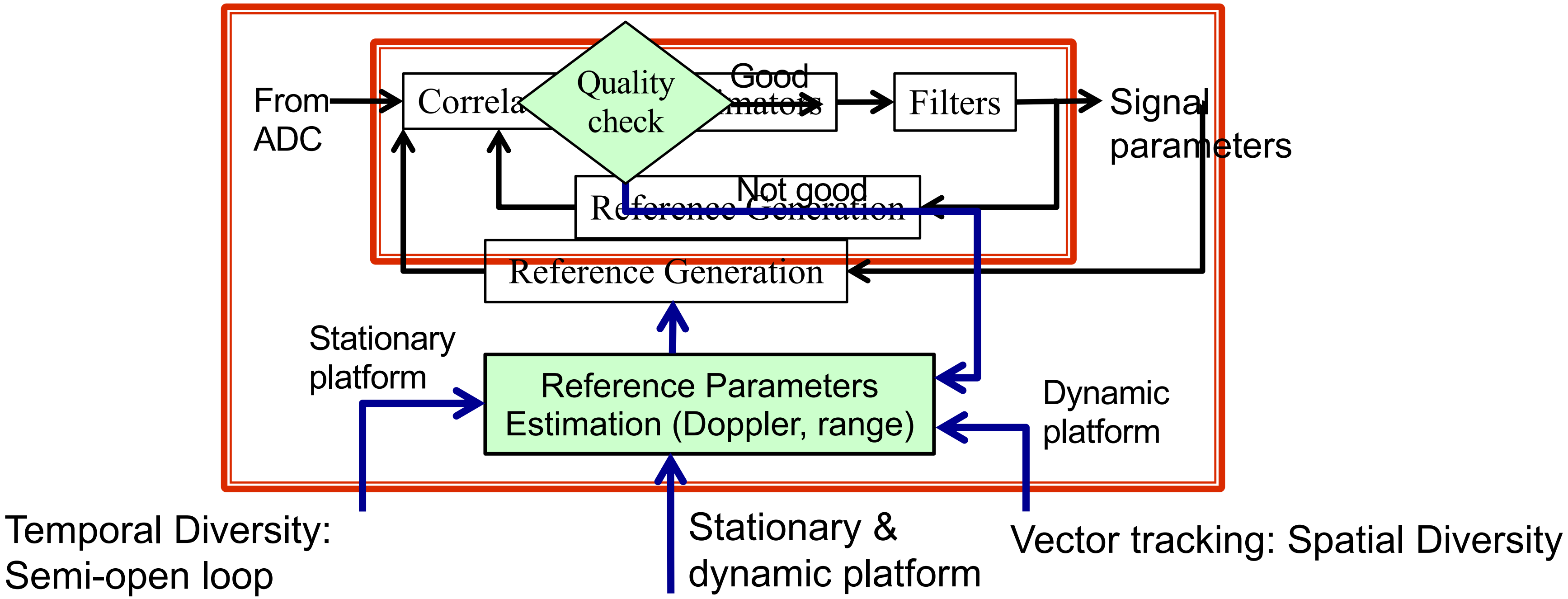
- **Machine learning**
- **Cycle slip detection/mitigation**
- **SV oscillator anomaly detection**
- **Multipath characterization**
- **Interference monitoring**

Receiver Signal Processing Algorithm Library

# Global SDR Data Collection Network



# Advanced Receiver Designs: Multi-Domain Processing

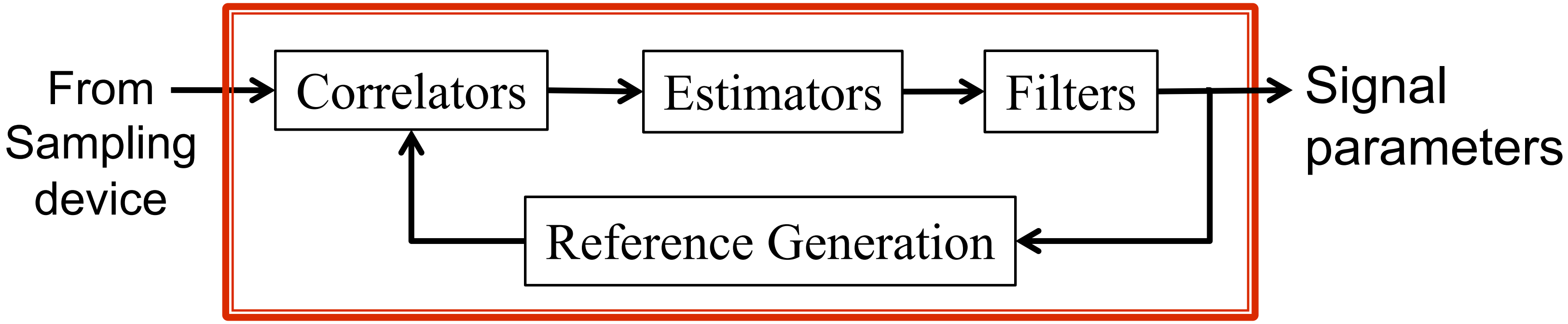



- Inter-frequency aiding: Frequency Diversity
- Open loop: Delay and Doppler Models

# Multi-Domain GNSS Receiver Processing

- Adaptive tracking → Parameter optimization
- Multi-carrier tracking → Frequency diversity
- Vector processing → Signal spatial diversity
- Semi-open loop → Temporal diversity
- Open loop → Models
- Adaptive hybrid tracking → Models + parameter optimization

# Adaptive Tracking: Parameter Optimization




- State-based framework
- Optimization: MMSE
- Low power + high dynamic signals

Correlator integration time: $T_{opt} = b_1 \left( C / N_0 \right)^{-\mu_1}$

Filter bandwidth: $B_{opt} = b_2 \left( C / N_0 \right)^{-\mu_2}$

$b_1$, $\mu_1$, $b_2$, $\mu_2$ are functions of receiver hardware qualities and platform dynamics


- Yang, R., K. Ling, E. Poh, Y. Morton, "Generalized GNSS signal carrier tracking in challenging environments: part I – modeling and analysis," IEEE Trans. Aero. Elec. Sys., 2017.
- Yang, R., Y. Morton, K. Ling, E. Poh, "Generalized GNSS signal carrier tracking in challenging environments: part II - optimization and implementation," IEEE Trans. Aero. Elec. Sys., 2017.

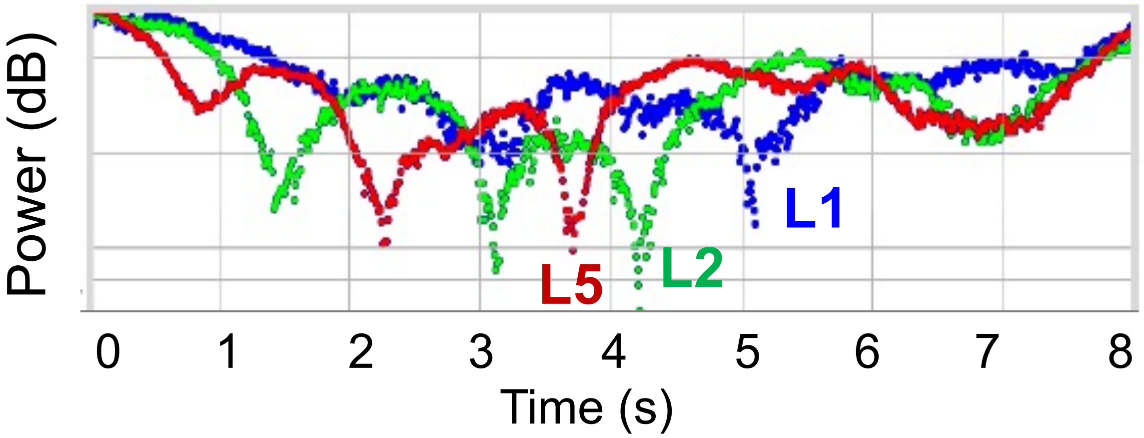
# Inter-Frequency Carrier Doppler Relationship

$$\underbrace{f_{L1} = 154 f_0 \qquad f_{L2} = 120 f_0 \qquad f_{L5} = 115 f_0}_{f_{Li} = a_i f_0}$$

$$f_{di} = \frac{v_{LOS}}{c} f_{Li} \longrightarrow f_{di} = a_i \boxed{\frac{v_{LOS}}{c} f_0}$$

Common for all carriers

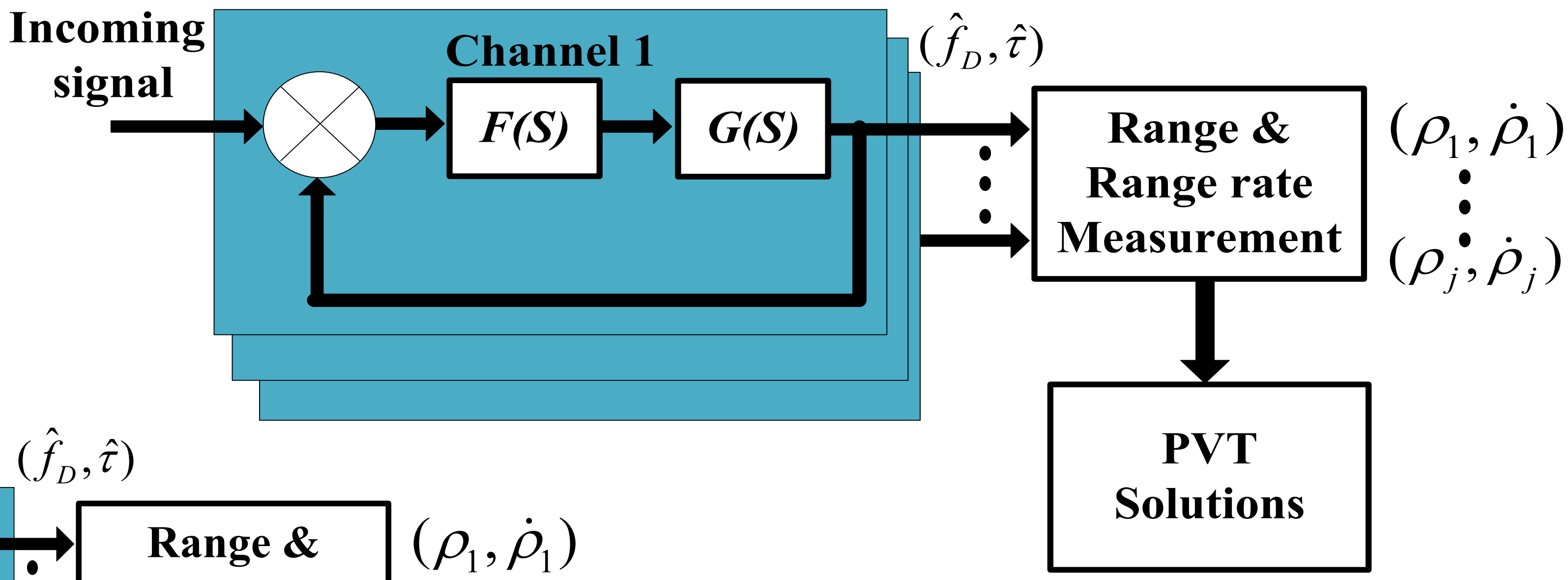
$$f_{di} = \frac{a_i}{a_j} f_{dj}$$



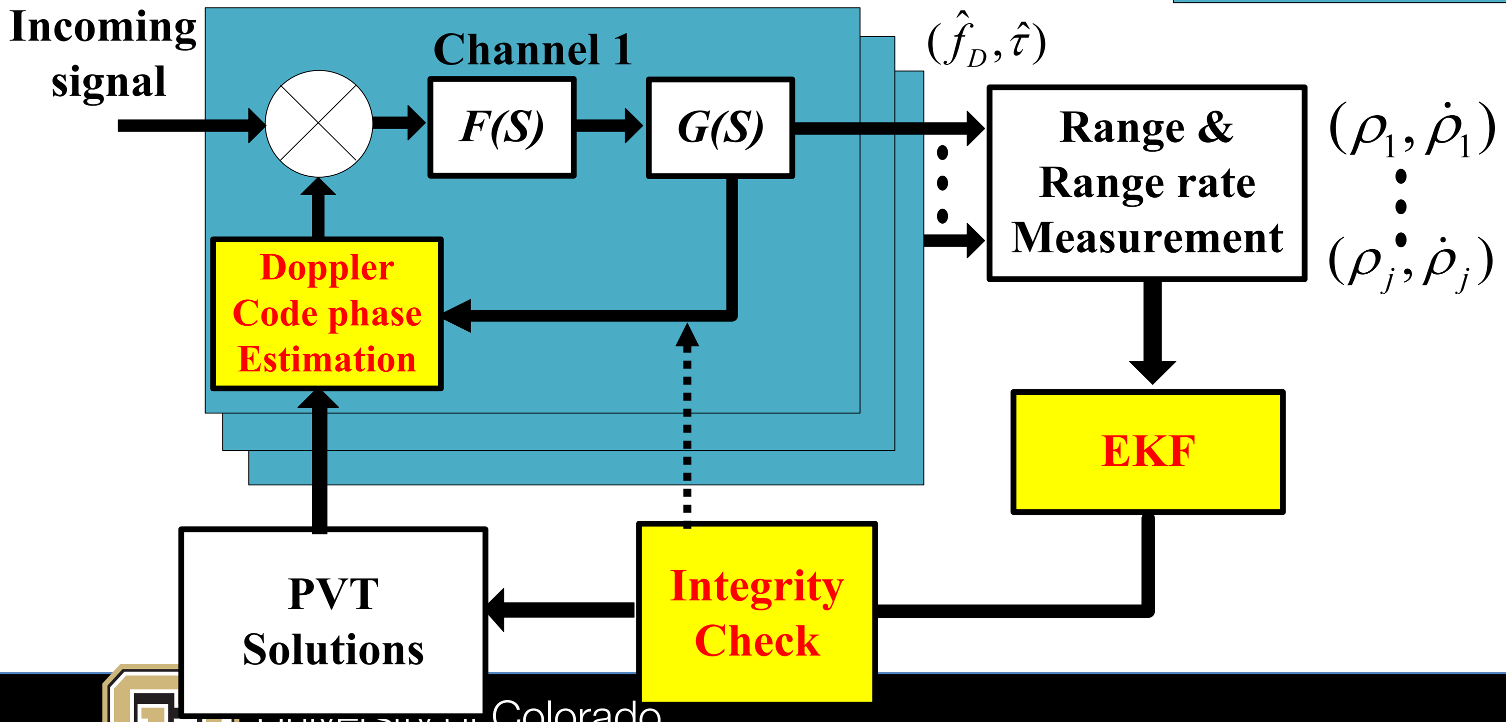

*Yang, R., D. Xu*, Y. Morton, "Generalized multi-frequency GPS carrier tracking architecture: design and performance analysis," *IEEE Trans. Aero. Elec. Sys.*, DOI:10.1109/TAES.2019.2948535, 2019.

# Vector Tracking vs. Scalar Tracking

## Scalar Tracking

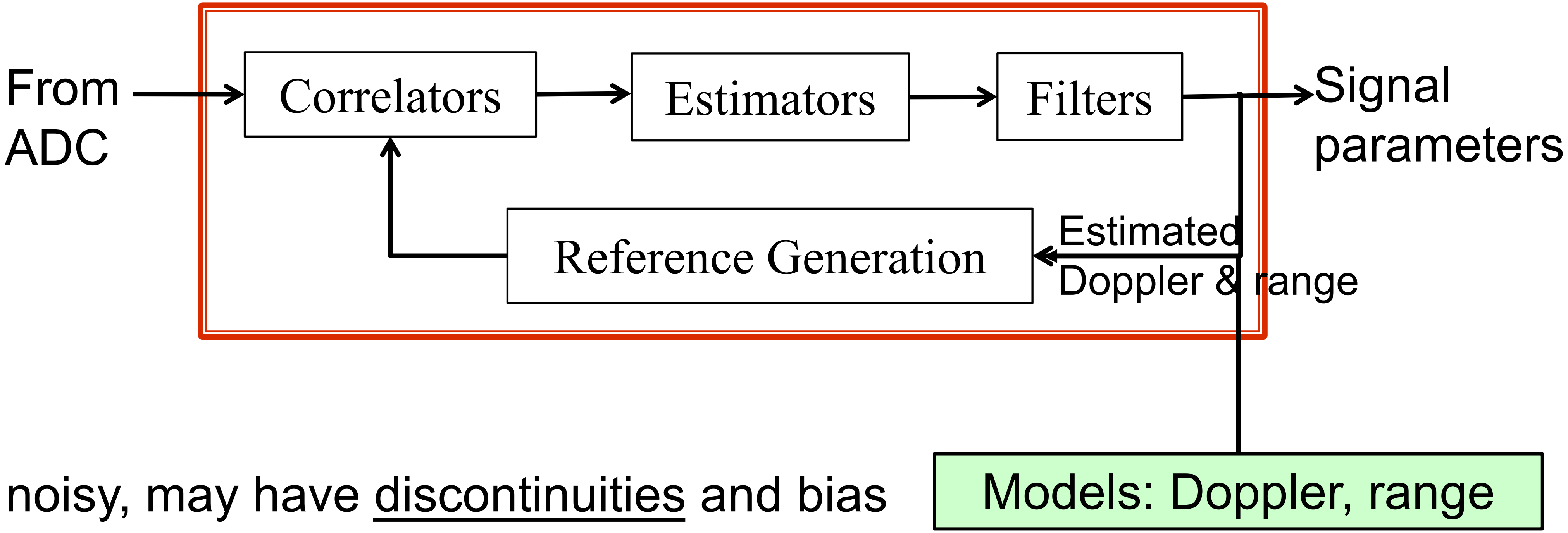



## Vector Tracking




*Peng, S.*, Y. Morton, *R. Di*, "A multiple-frequency GPS software receiver design based on a vector tracking loop," *Proc. IEEE PLANS*, Myrtle Beach, SC, April 2012.

# Open Loop Tracking (GNSS-RO, RNSS-R)




Can be noisy, may have discontinuities and bias

Cycle slips

# Conclusions

- Ionospheric scintillation affects GNSS signal propagation and limits receiver PVT solution availability and accuracy
- Ground-based and LEO satellite-based GNSS receivers have played a critical role in monitoring the state of the ionosphere and space weather activities
- Advanced GNSS receiver algorithms are necessary to provide reliable monitoring services for ionospheric scintillation
- New approaches such as GNSS-R have the potential to fill data gaps in ionospheric scintillation monitoring.