

GNSS Reflectometry For Ionospheric Observation

East African Capacity Building Workshop on
Space Weather and Low Latitude Ionosphere

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10/9/2023

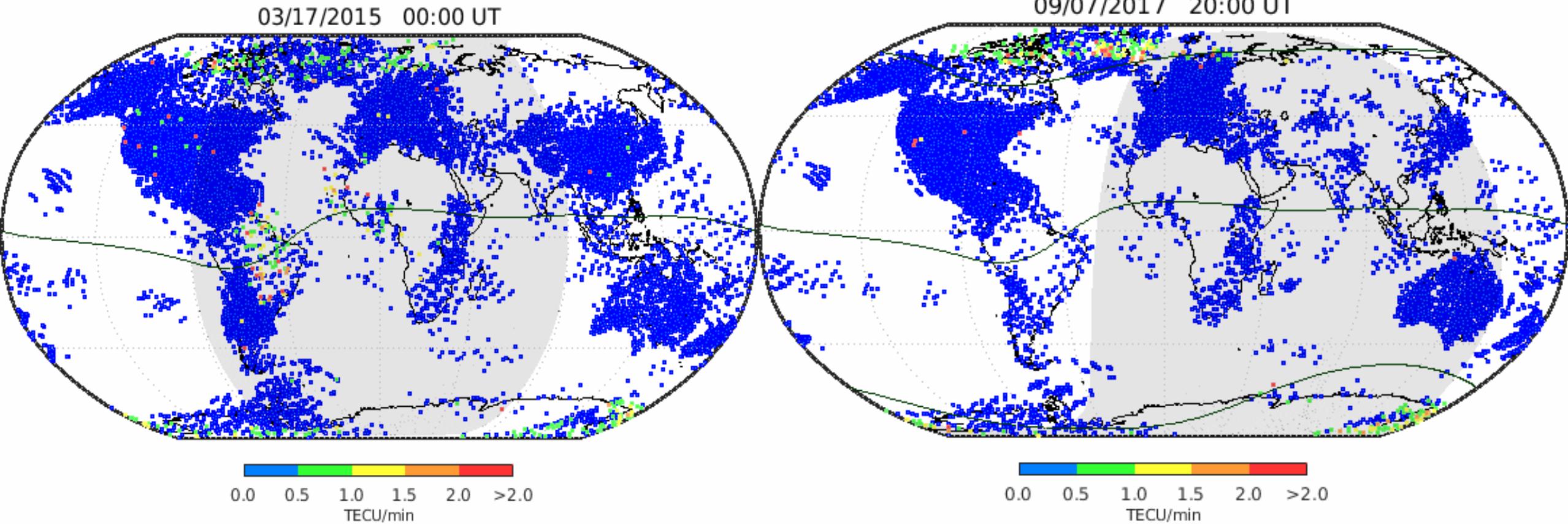
Outline

1. Background and Motivation
2. Fundamentals of GNSS-R
3. GNSS-R Ionosphere Observations
4. Challenges and Opportunities



GNSS for Ionosphere Monitoring

Rate of TEC Index (ROTI)



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. Geophys. Res., Space Sci.*, DOI: 10.1029/2019JA027681, 2020.

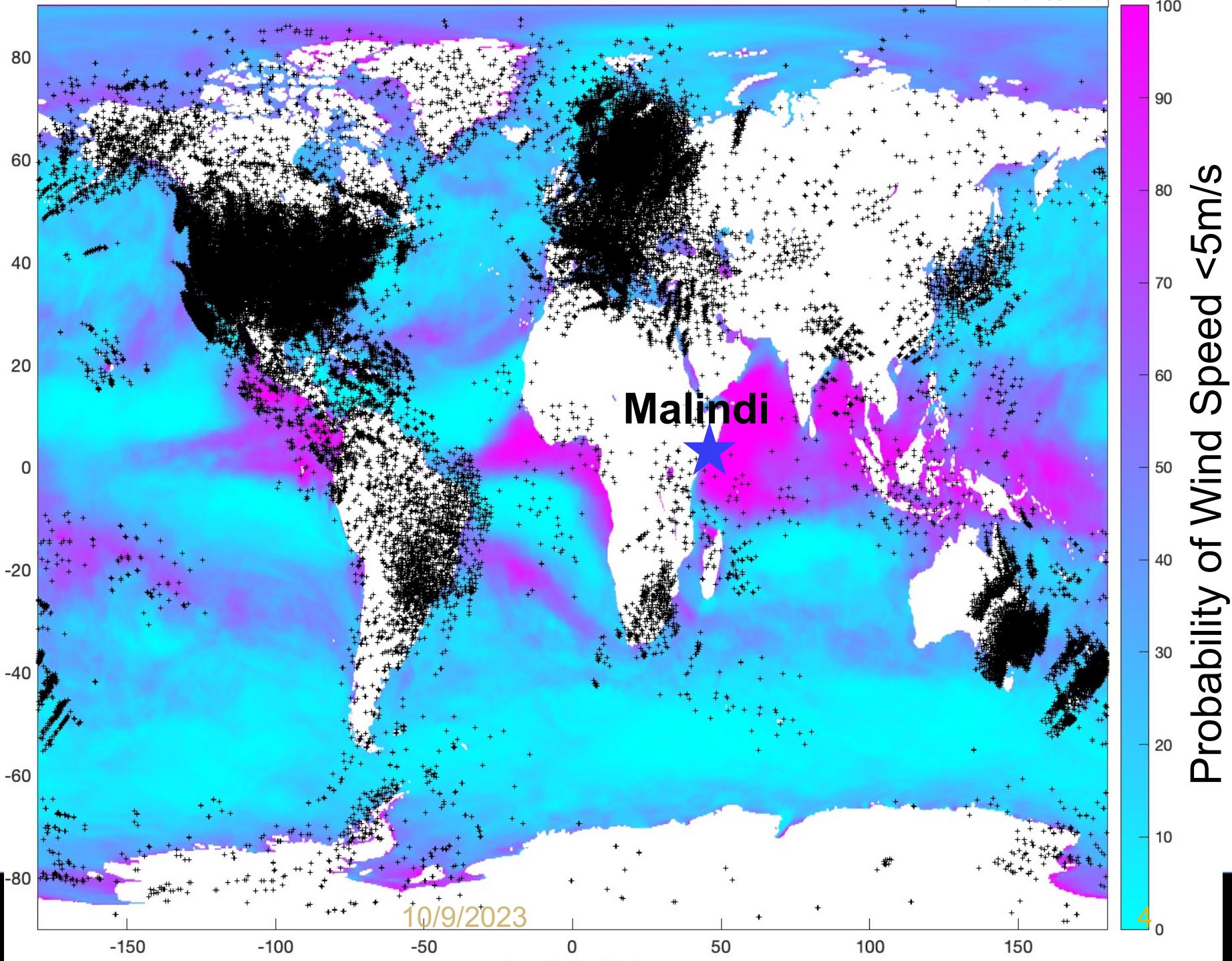


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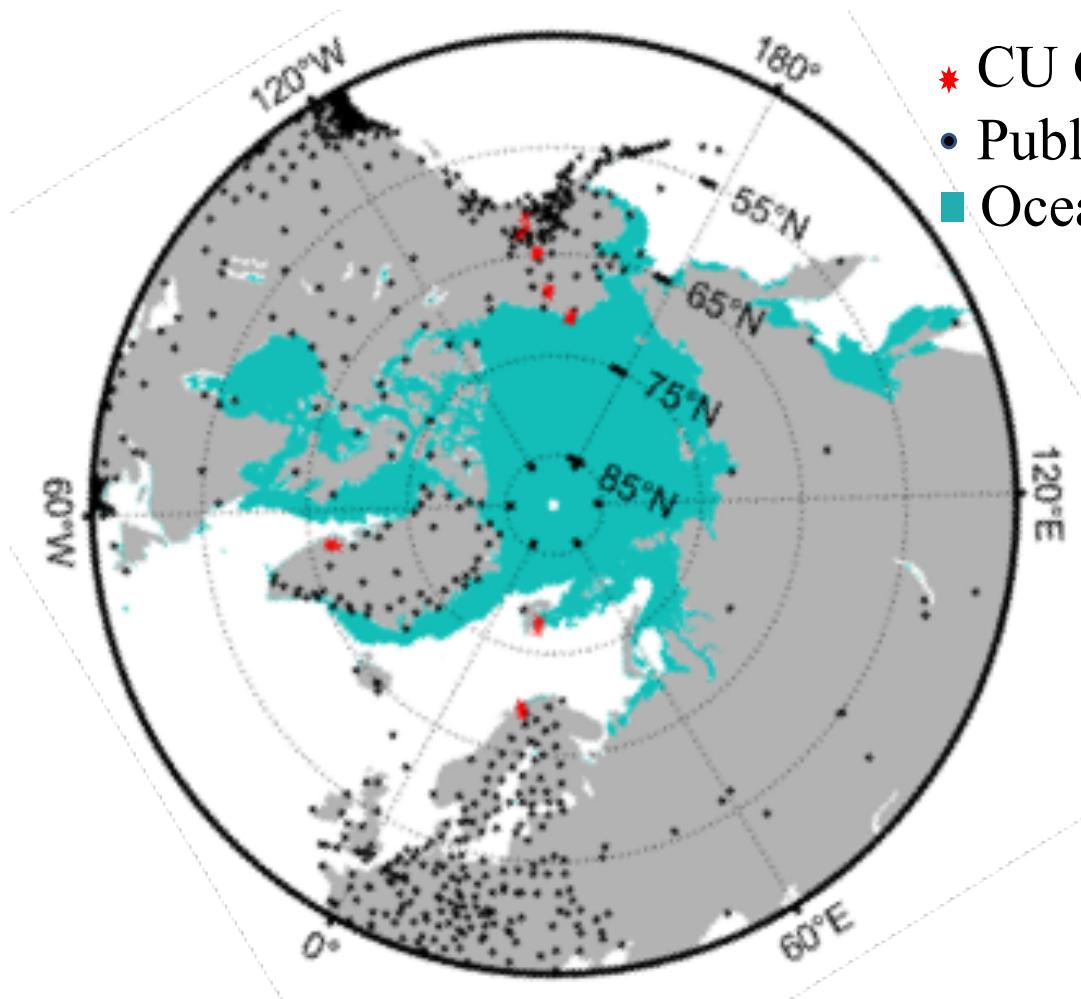
Data Gap Over the Oceans



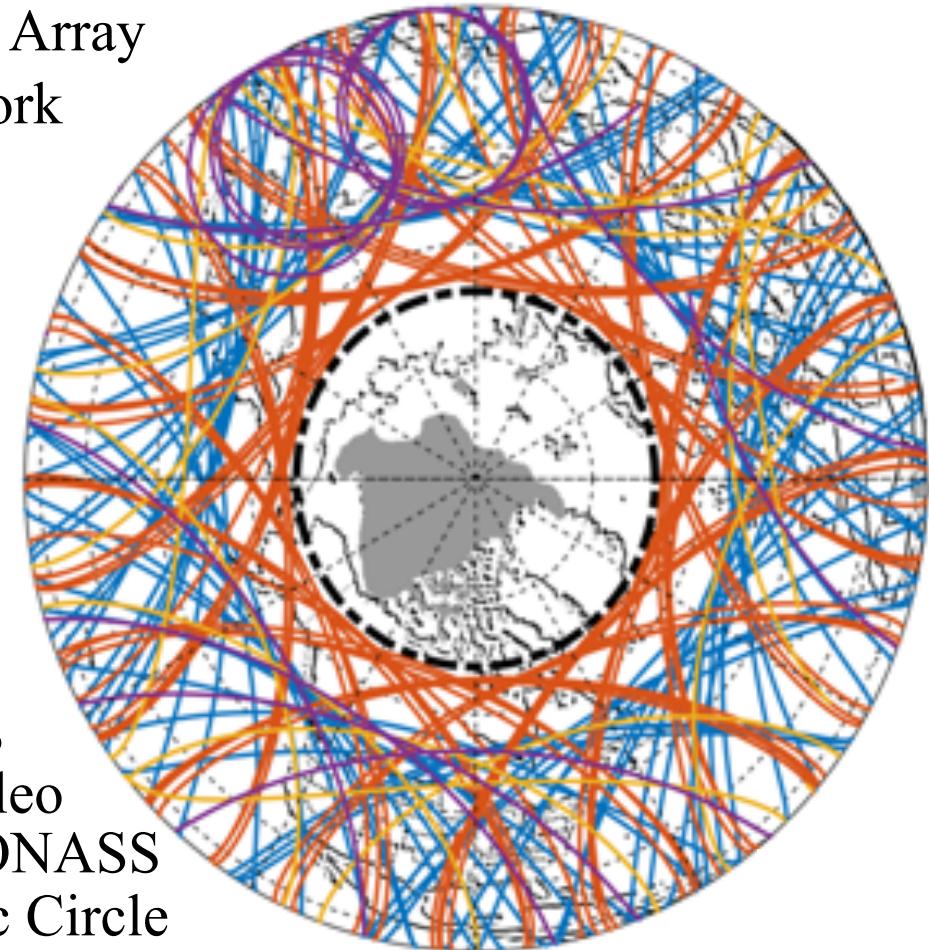
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Data Gap Over Polar Regions



- ★ CU GNSS Receiver Array
 - Public GNSS Network
 - Ocean/Sea Ice
-
- GPS
 - BDS
 - Galileo
 - GLONASS
 - - - Artic Circle



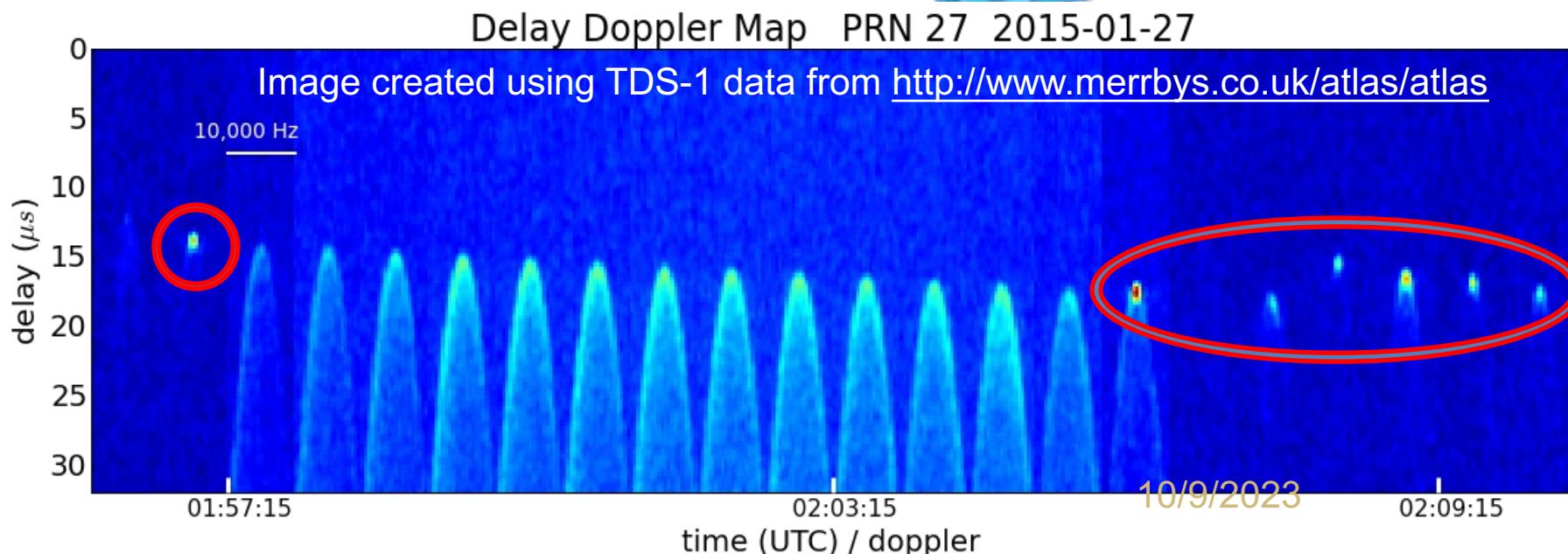
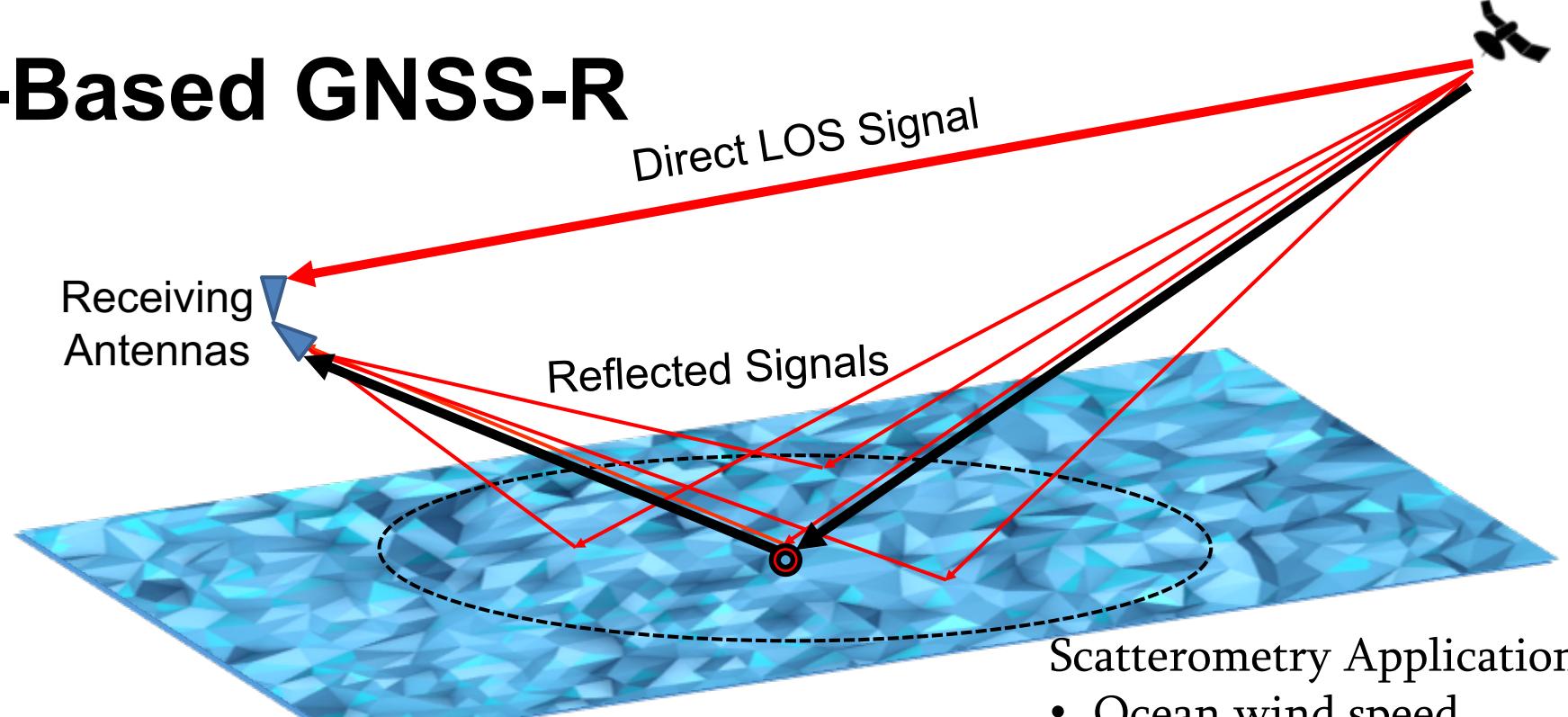
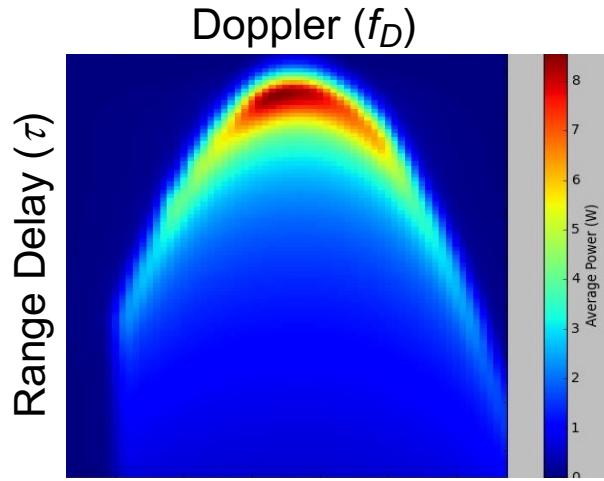
Fundamentals of GNSS-R



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LEO Satellite-Based GNSS-R



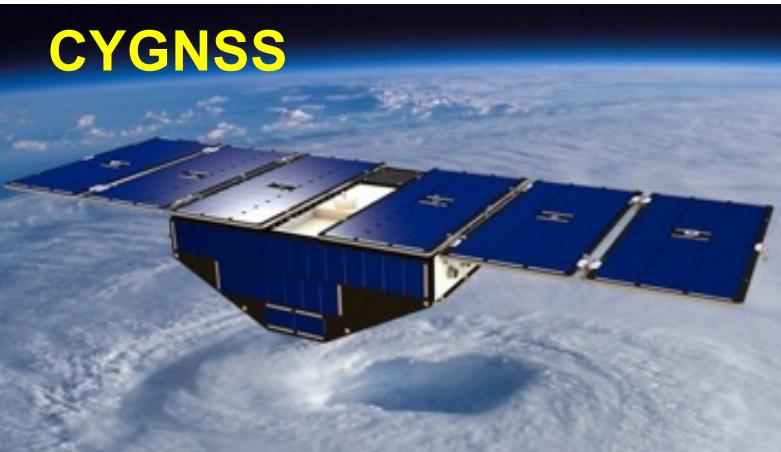
- Scatterometry Applications
- Ocean wind speed
 - Land surface water content
 - Ionosphere scintillation

- Altimetry Applications
- Sea/sea ice surface height
 - Rivers, lakes, glacier surface topography
 - Ionosphere retrieval



GNSS-R Data Sources

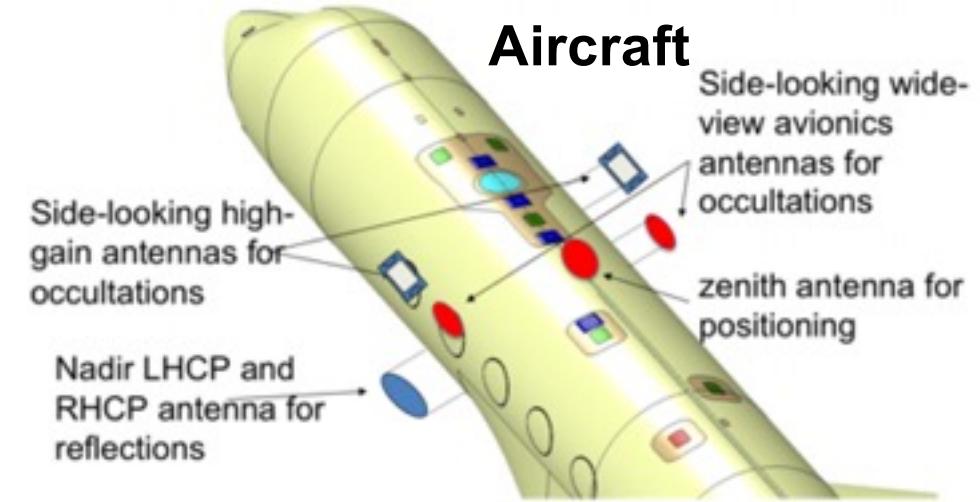
CYGNSS



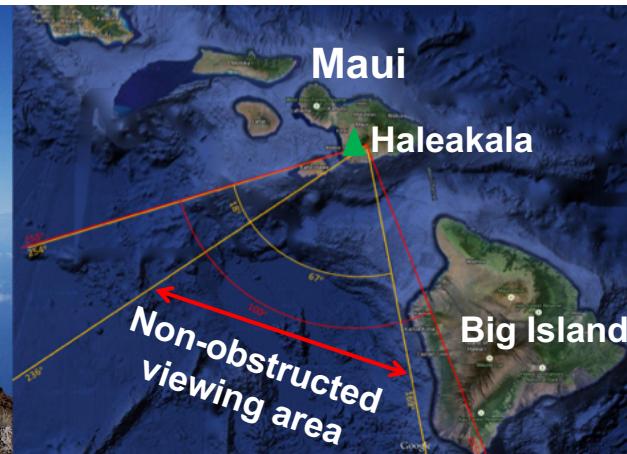
Spire Global



Aircraft



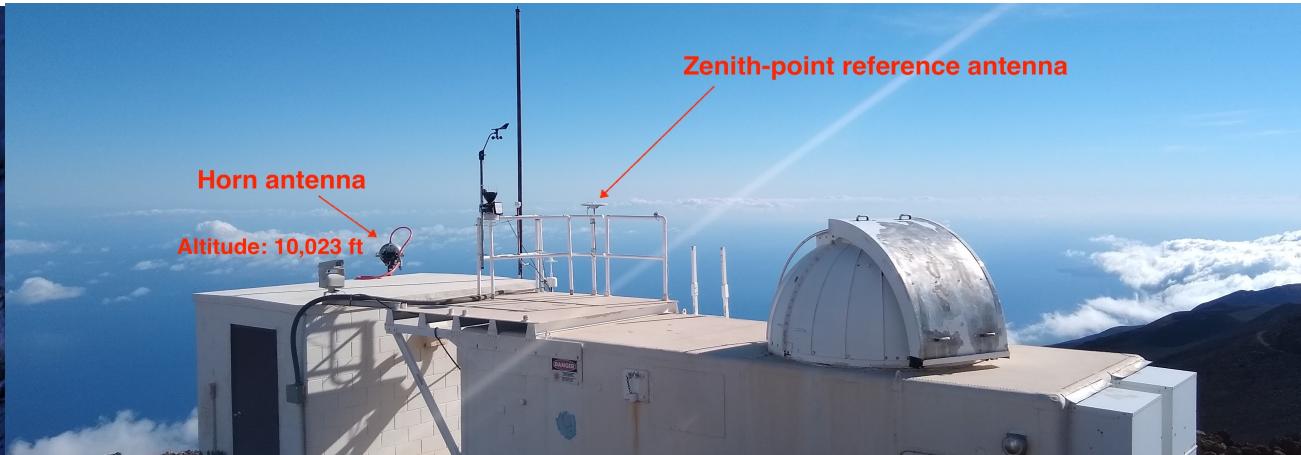
Steerable high-gain antenna



Horn antenna

Altitude: 10,023 ft

Zenith-point reference antenna



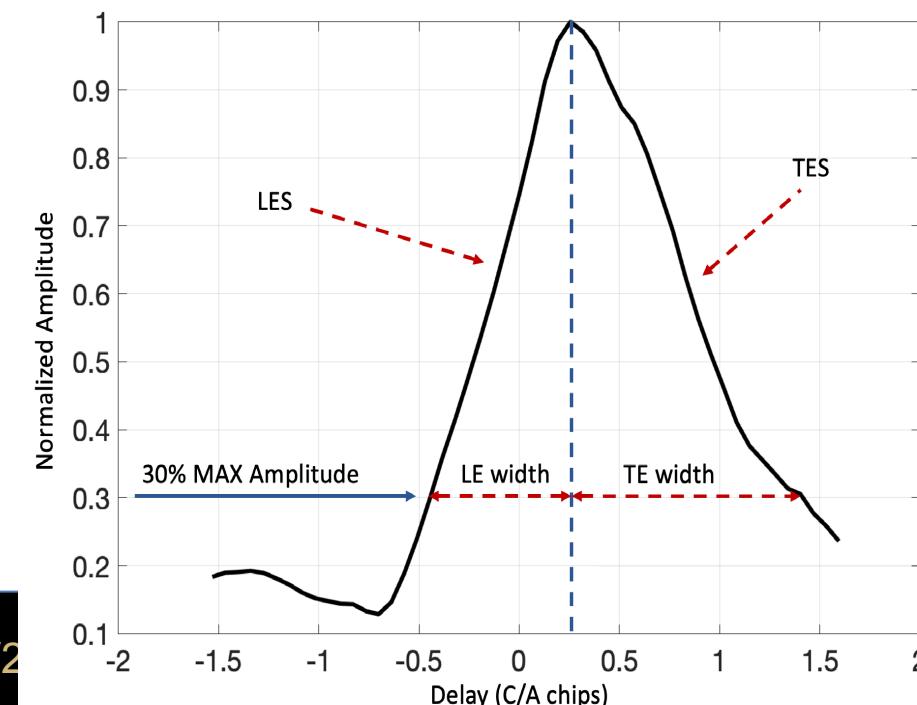
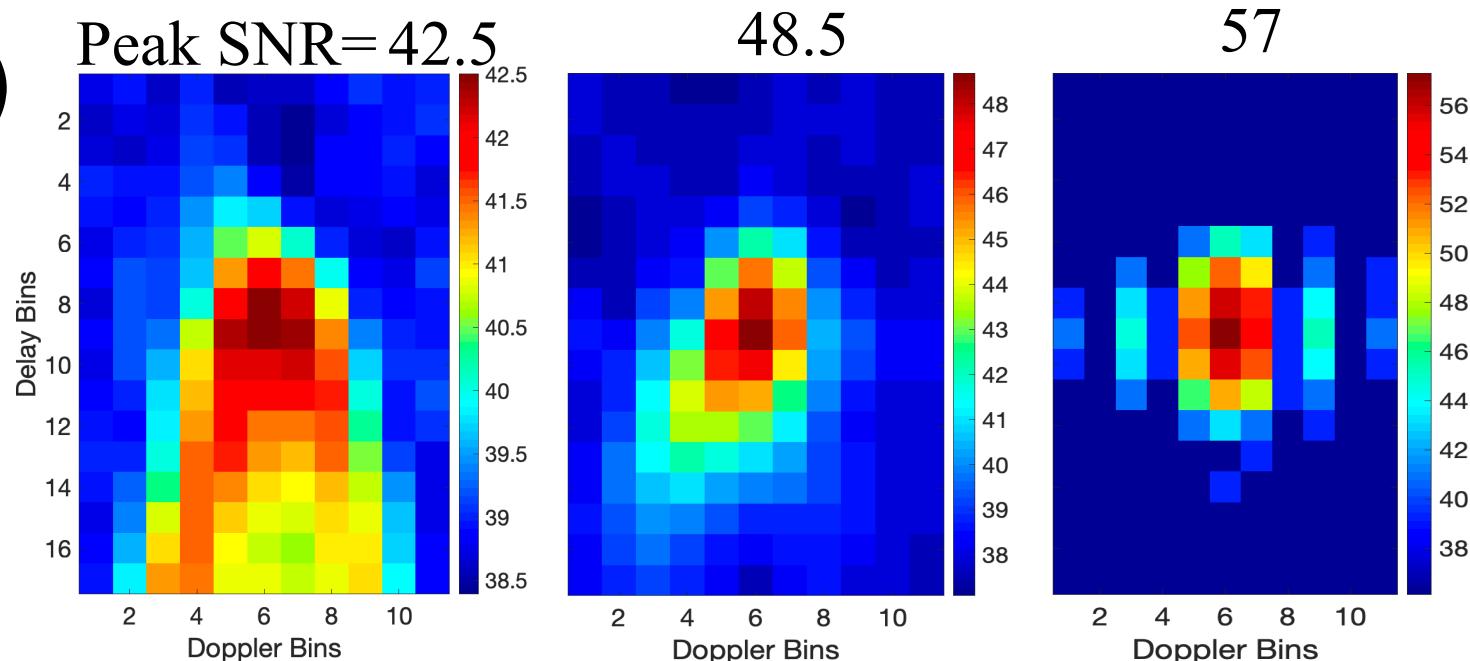
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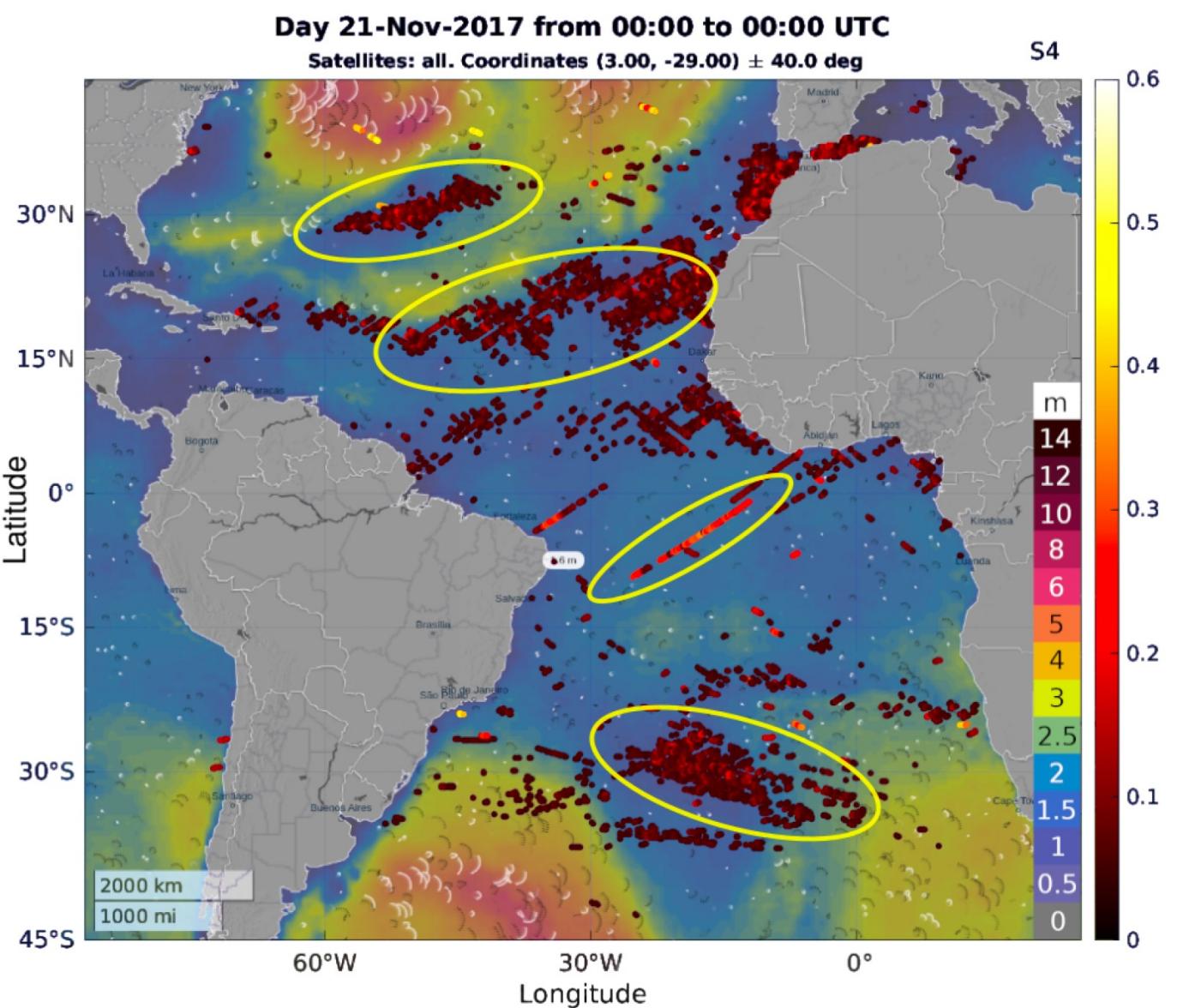
Delay Doppler Map (DDM)

- Depends on Surface Conditions
 - Peak amplitude
 - DDM power spread
 - DDM waveshape
 - Leading Edge Slope
 - Trailing Edge Slope
 -

Loria, E., Russo, I., Wang, Y., Giangregorio, G., Galdi, C., Di Bisceglie, M., Wilson-Downs, B., Lavalle, M., O'Brien, A., Morton, Y., Zuffada, C. (2023). Comparison of GNSS-R Coherent Reflection Detection Algorithms Using Simulated and Measured CYGNSS Data. IEEE Trans. Geosci. Remote Sensing, DOI: 10.1109/TGRS.2023.3277411, 2023.



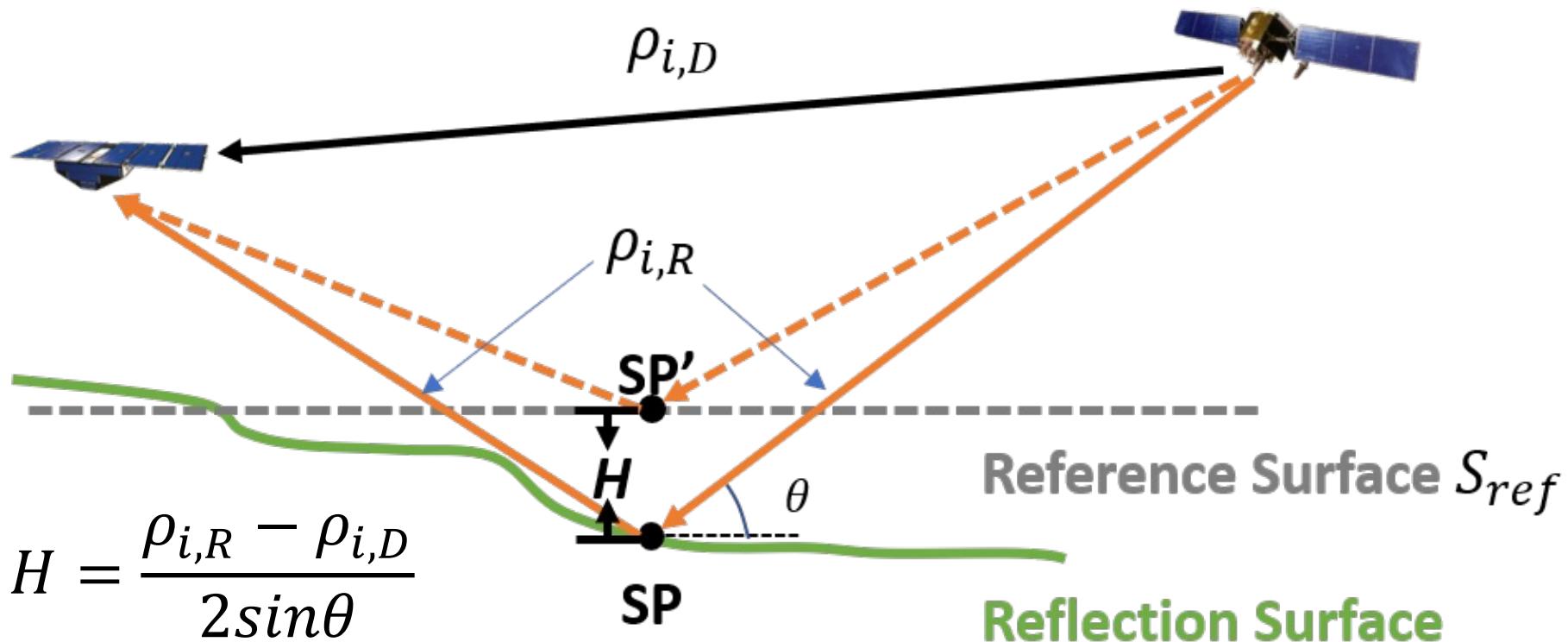
If the Ocean is **Calm**,
DDM Distortions
can be interpreted
as due to
**Ionospheric
Disturbances**



Molina, C., Boudriki Semlali, B. E., Park, H., & Camps, A. (2022). A Preliminary Study on Ionospheric Scintillation Anomalies Detected Using GNSS-R Data from NASA CYGNSS Mission as Possible Earthquake Precursors. *Remote Sensing*, 14(11), 2555.

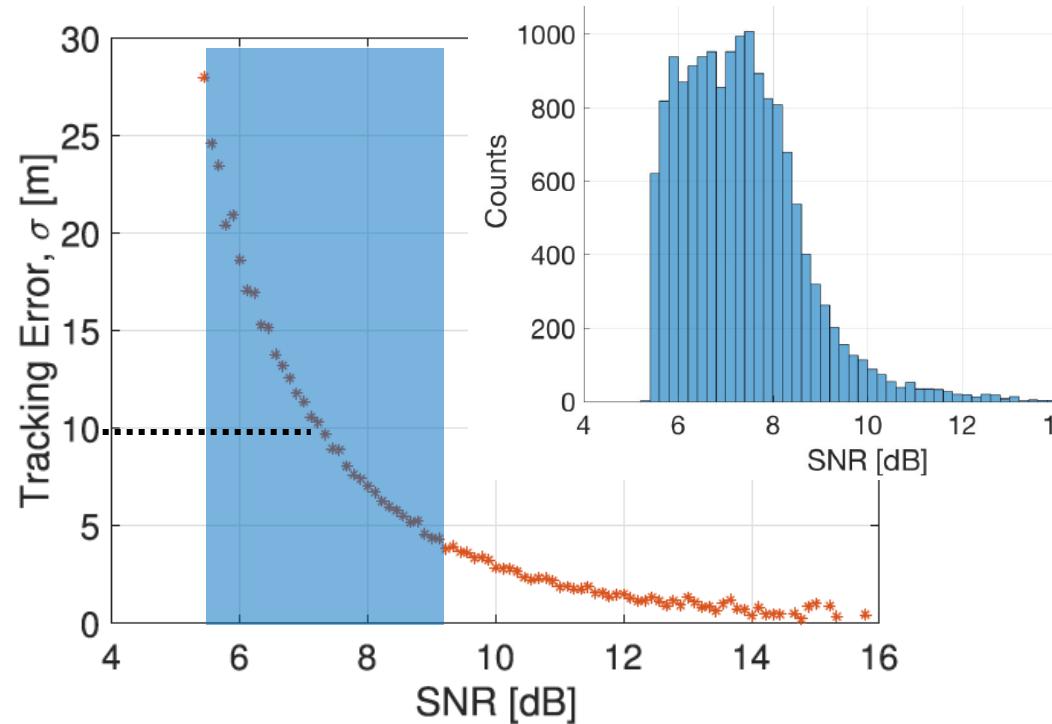
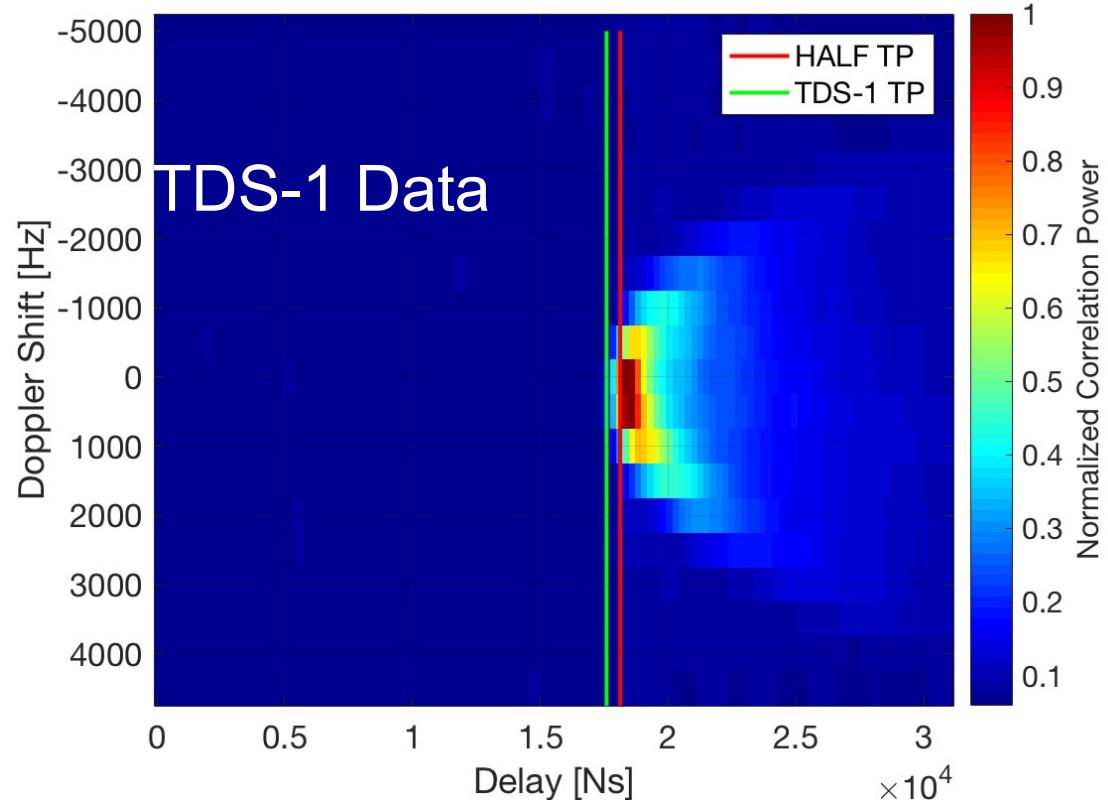


Space-borne GNSS-R Altimetry



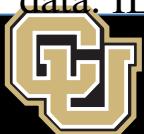
2 types of range measurements: code phase and carrier phase

Code Phase-Based Altimetry



- J. Mashburn, P. Axelrad, S. Lowe, K. Larson (2018). Global Ocean Altimetry With GNSS Reflections From TechDemoSat-1. IEEE Trans. Geosci. Remote Sen., 56(7), 4088-4097.
- Li, W., Cardellach, E., Fabra, F., Ribó, S., Rius, A. (2019). Assessment of spaceborne GNSS-R ocean altimetry performance using CYGNSS mission raw data. IEEE Trans. Geosci. Remote Sen., 58(1), 238-250.

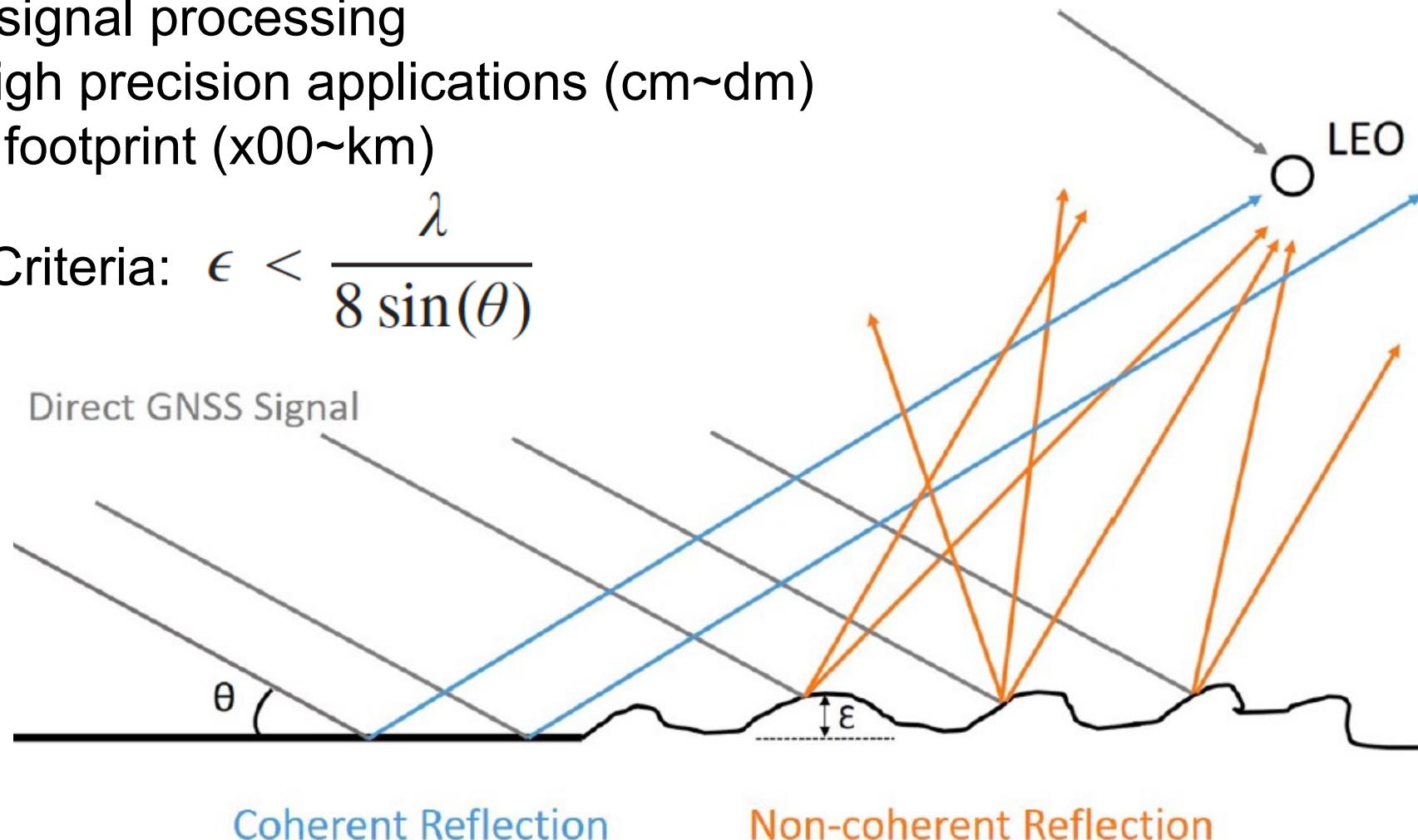
Error Source	Residual Error
TDS-1 Orbit	2.6 m position (1σ)
GPS Orbit	0.03 m position (1σ)
Tides	0.1 m height (1σ)
Ionosphere	4 m delay (day, RMS)
Troposphere	2.2 m delay (night, RMS)
Antenna Baseline	0.05 m delay (1σ)
Tracking Error	0.001 m delay (1σ)
RSS	10 m delay (1σ)
	11.1 m (day)
	10.6 m (night)



Carrier Phase-Based Altimetry: Coherent GNSS Reflections

Coherent signal processing
enables high precision applications (cm~dm)
and small footprint (x00~km)

Rayleigh Criteria: $\epsilon < \frac{\lambda}{8 \sin(\theta)}$



Range Measurement Error: Sea Ice vs Calm Ocean

Track #	Surface	Duration (s)	EL ($^{\circ}$)	ZTD Corr. (cm)	RMS (cm)
1	ice	85	14 - 18	-2.30	5.94
2	ice	80	16 - 20	3.12	7.41
3	ice	75	17 - 20	6.80	7.14
4	ice	93	5 - 9	-0.60	8.49
5	ice	148	10 - 17	7.84	3.48
6	ice	70	17 - 20	0.80	4.01
7	ice	100	12 - 17	-6.54	8.15
8	ice	112	9 - 14	2.78	6.15
9	ice	140	13 - 20	3.90	3.44
10	ice	120	13 - 19	-7.48	7.06
11	ice	115	15 - 20	-1.54	3.37
12	ice	140	11 - 17	4.34	6.32
13	ice	94	14 - 18	-10.00	4.56
14	ice	200	9 - 17	0.98	6.71
15	ice	180	9 - 16	-4.70	4.17
16	water	100	15 - 20	6.16	8.72
17	water	60	12 - 14	6.12	10.17
18	water	200	7 - 16	-2.46	26.31

Wang, Y., Breitsch, B., & Morton, Y. (2020). A state-based method to simultaneously reduce cycle slips and noise in coherent GNSS-R phase measurements from open-loop tracking. *IEEE Trans. Geosci. Remote Sen.*, 59(10), 8873-8884.



Coherent Reflection Statistics

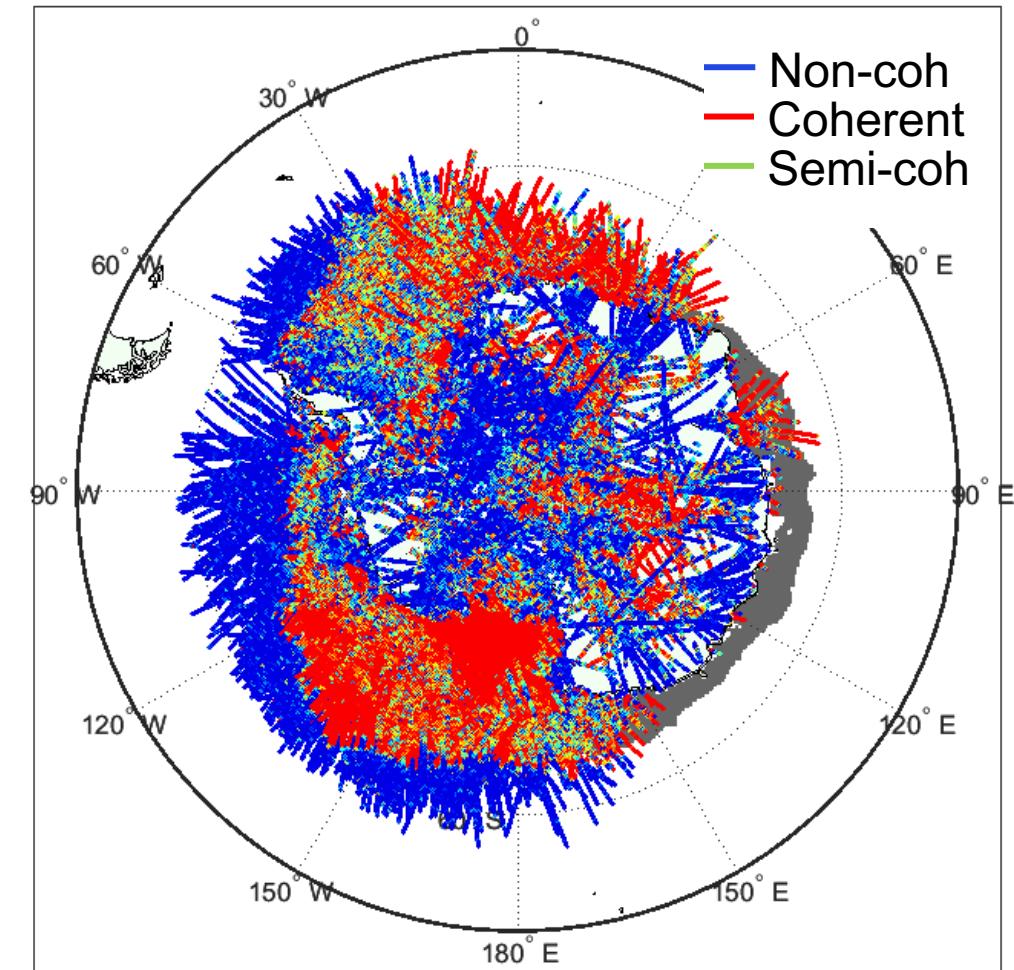
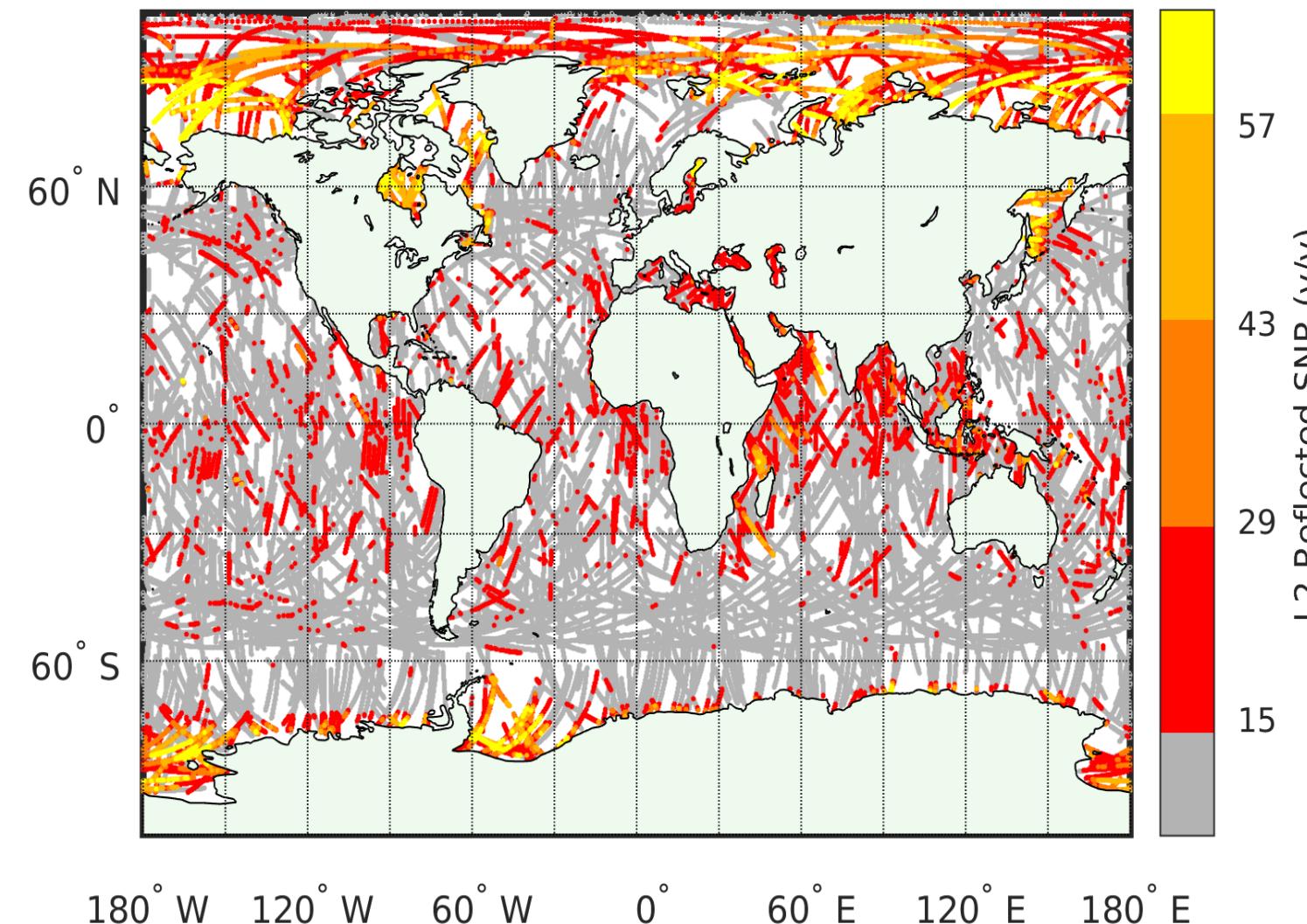
	Surface type	% coherent reflections
Ocean	Global average	1%
	Wind speed < 5m/s	15%
	Within 200km of coast lines	5.5%
	Indonesia Archipelago	23%
Sea Ice	Global average	44.3%
	Multi-year ice	32%
	First year ice	75%

Roesler, C., Y. J. Morton, Y. Wang, R. S. Nerem, "Coherent GNSS-reflections characterization over ocean and sea ice based on Spire Global CubeSat data," IEEE Trans. Geosci. Remote Sensing, DOI: 10.1109/TGRS.2021.3129999, 2021.



Spire GNSS-R Data:Jan-Apr 2019

Oct. 2021



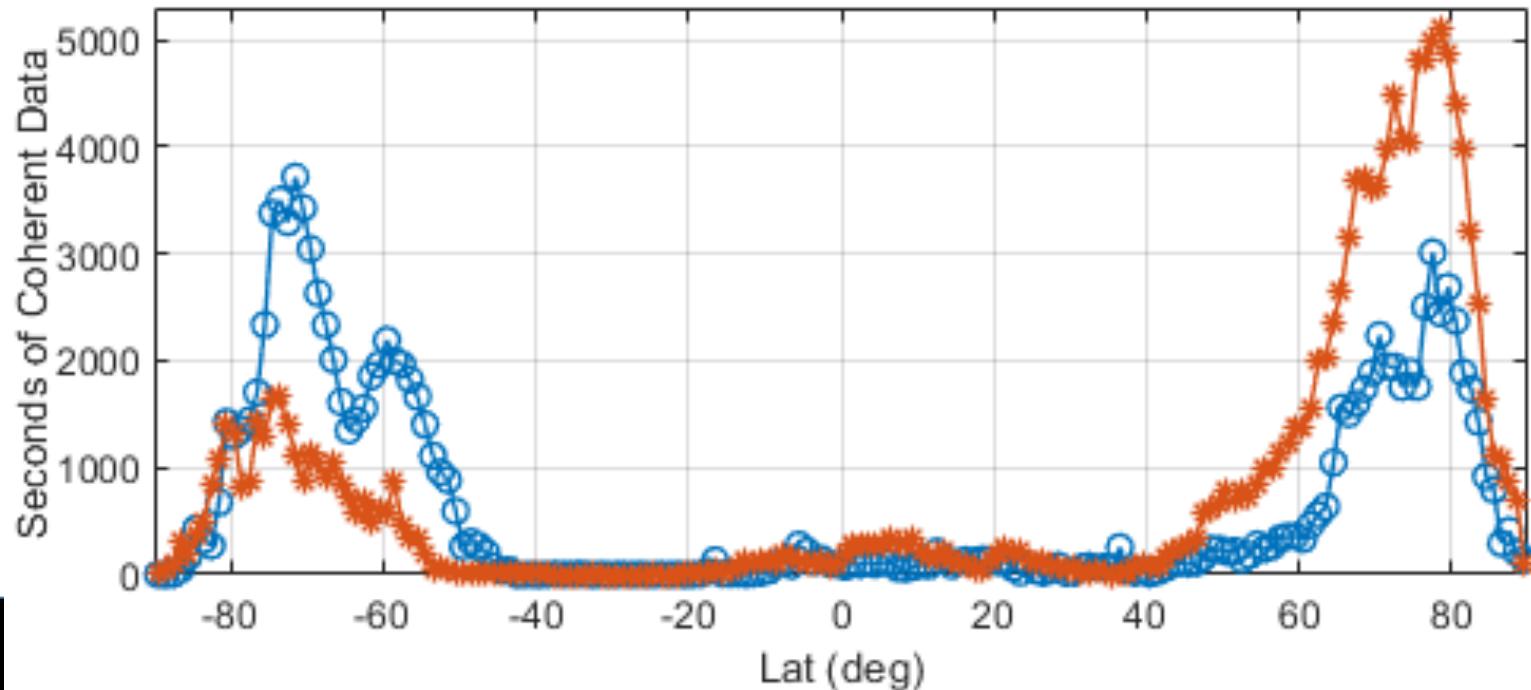
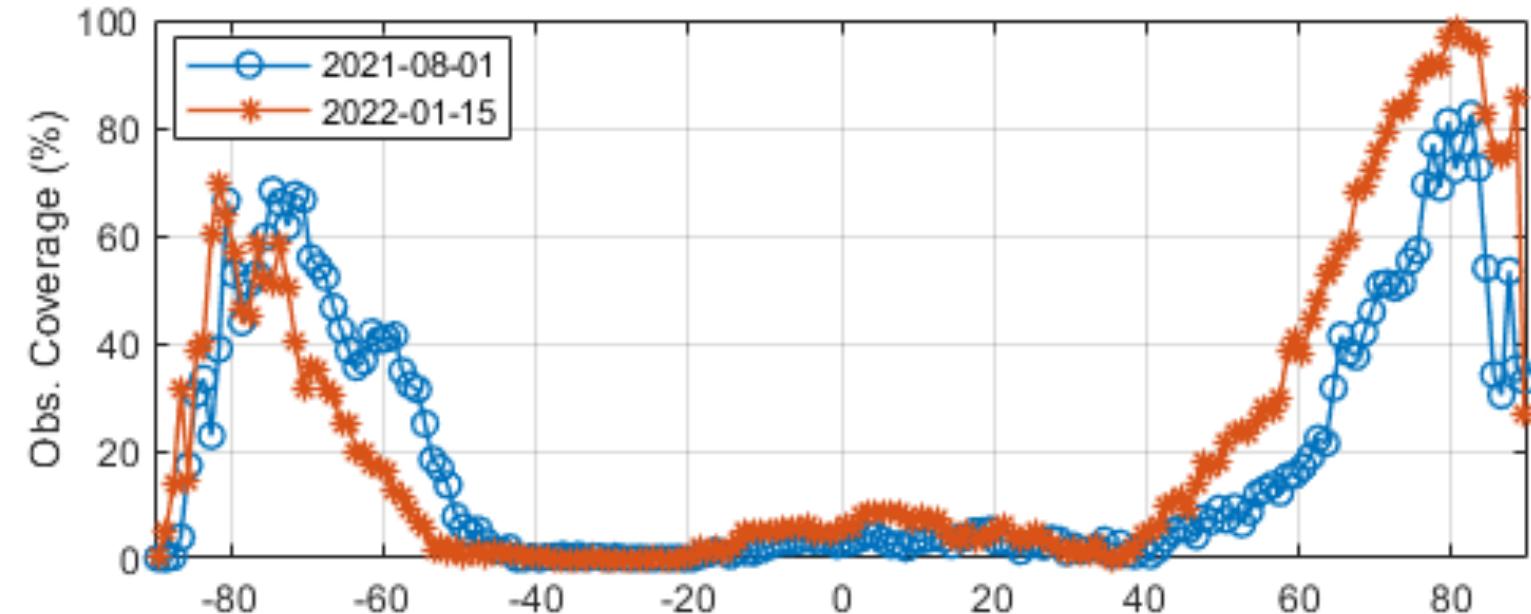
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Sample Coherent Reflection Observation Distributions

Obs. coverage at 1-degree resolution



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GNSS-R Altimetry for Ionosphere Observations

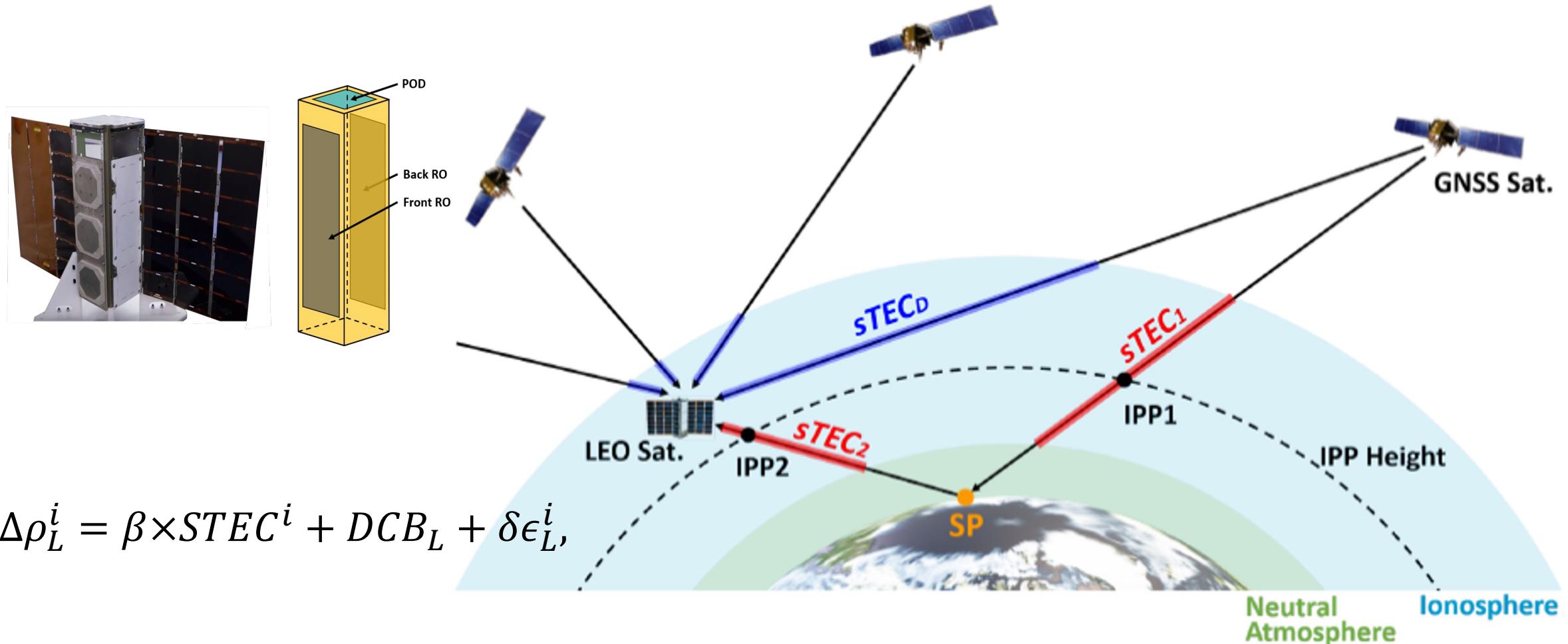


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Spire Global CubeSat Dual-Frequency Measurements for Ionosphere Monitoring



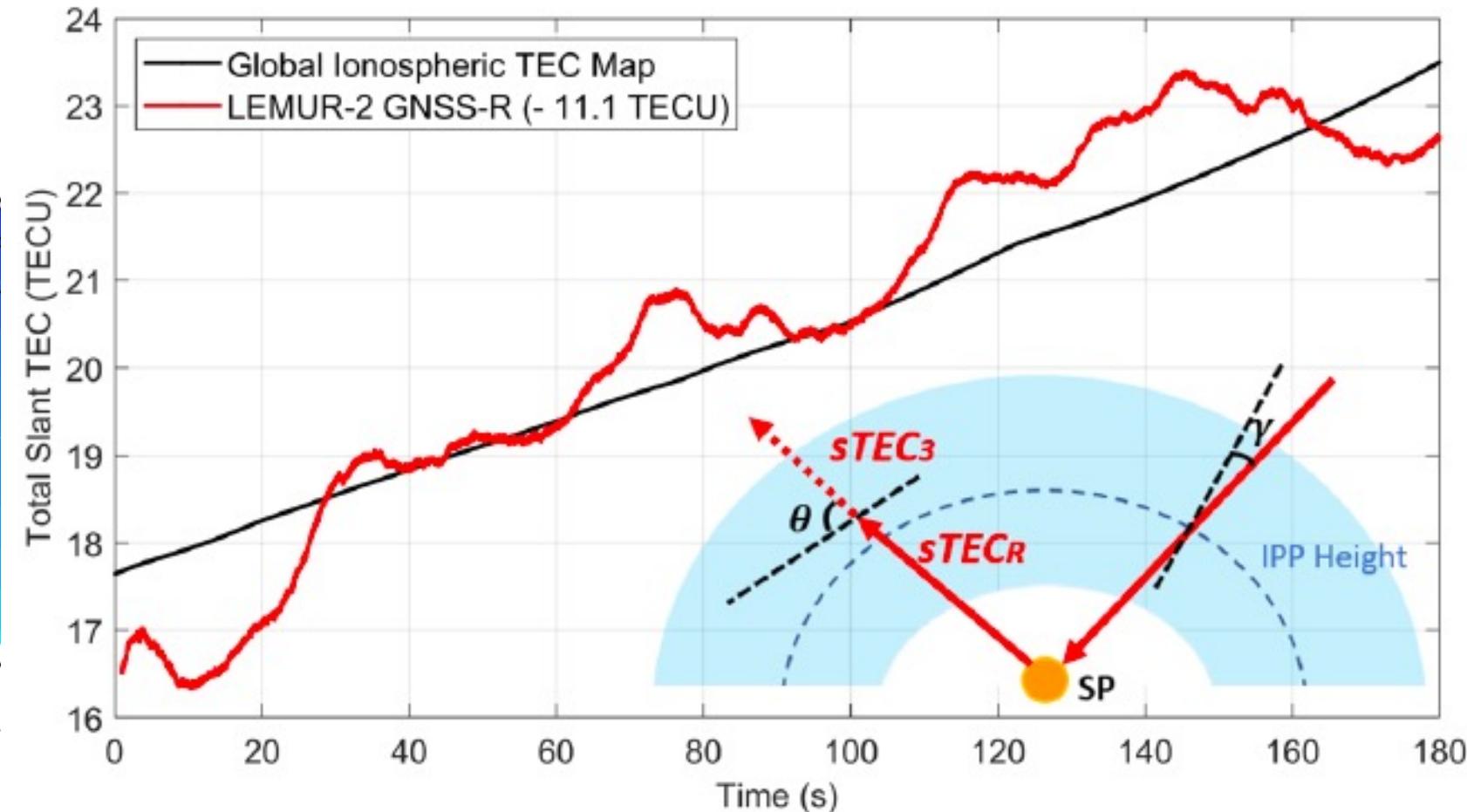
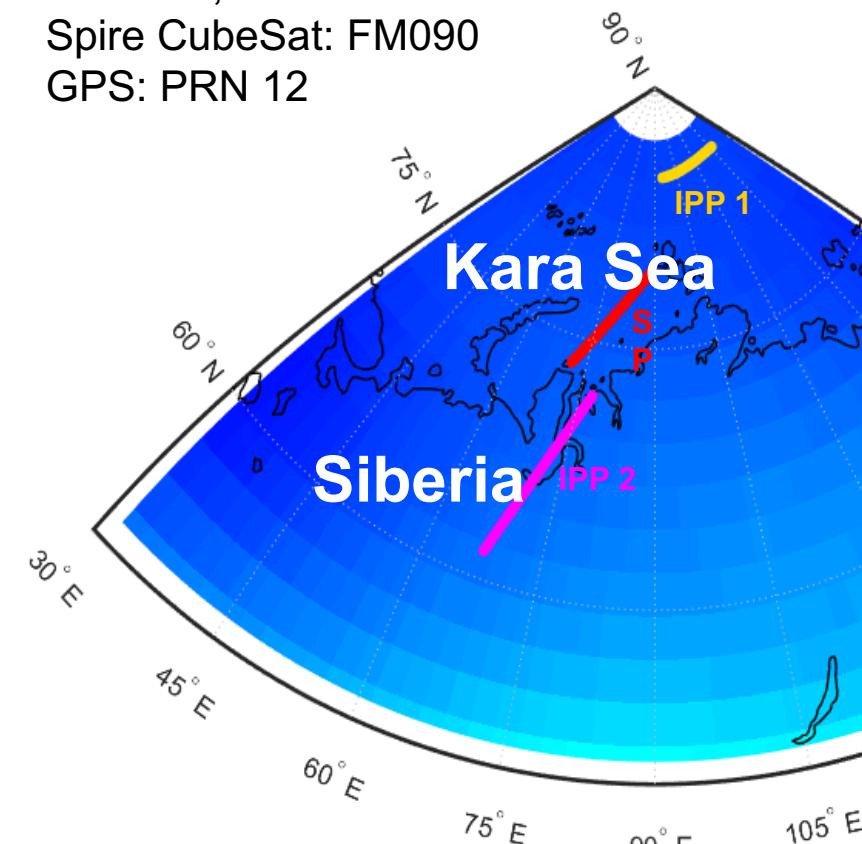
Wang, Y., Y. J. Morton, "Ionospheric total electron content and disturbance observations from space borne coherent GNSS-R measurements," *IEEE Trans. Geosci. Remote Sensing*, DOI: 10.1109/TGRS.2021.3093328, 2021.



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TEC Retrieval

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.

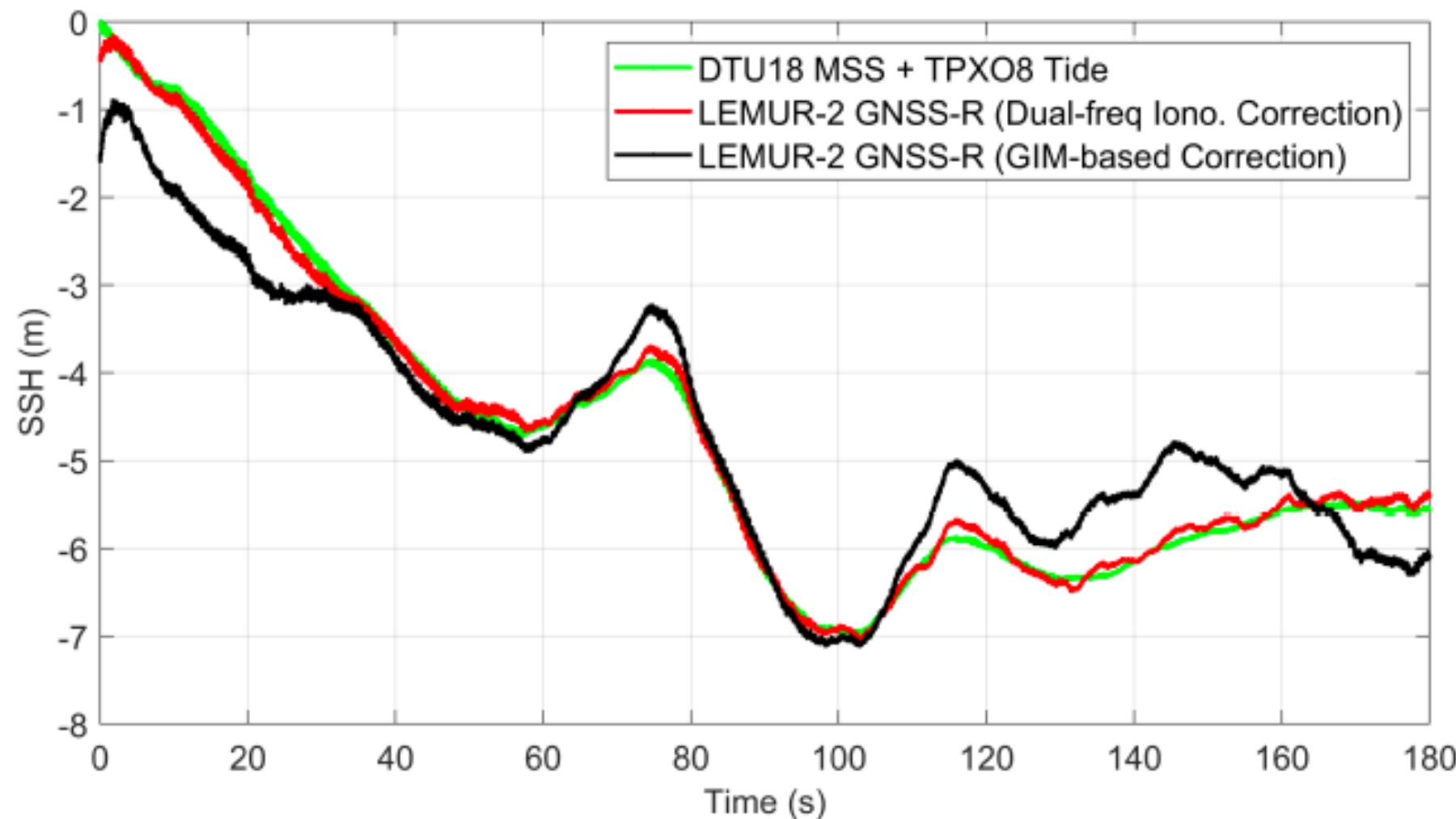


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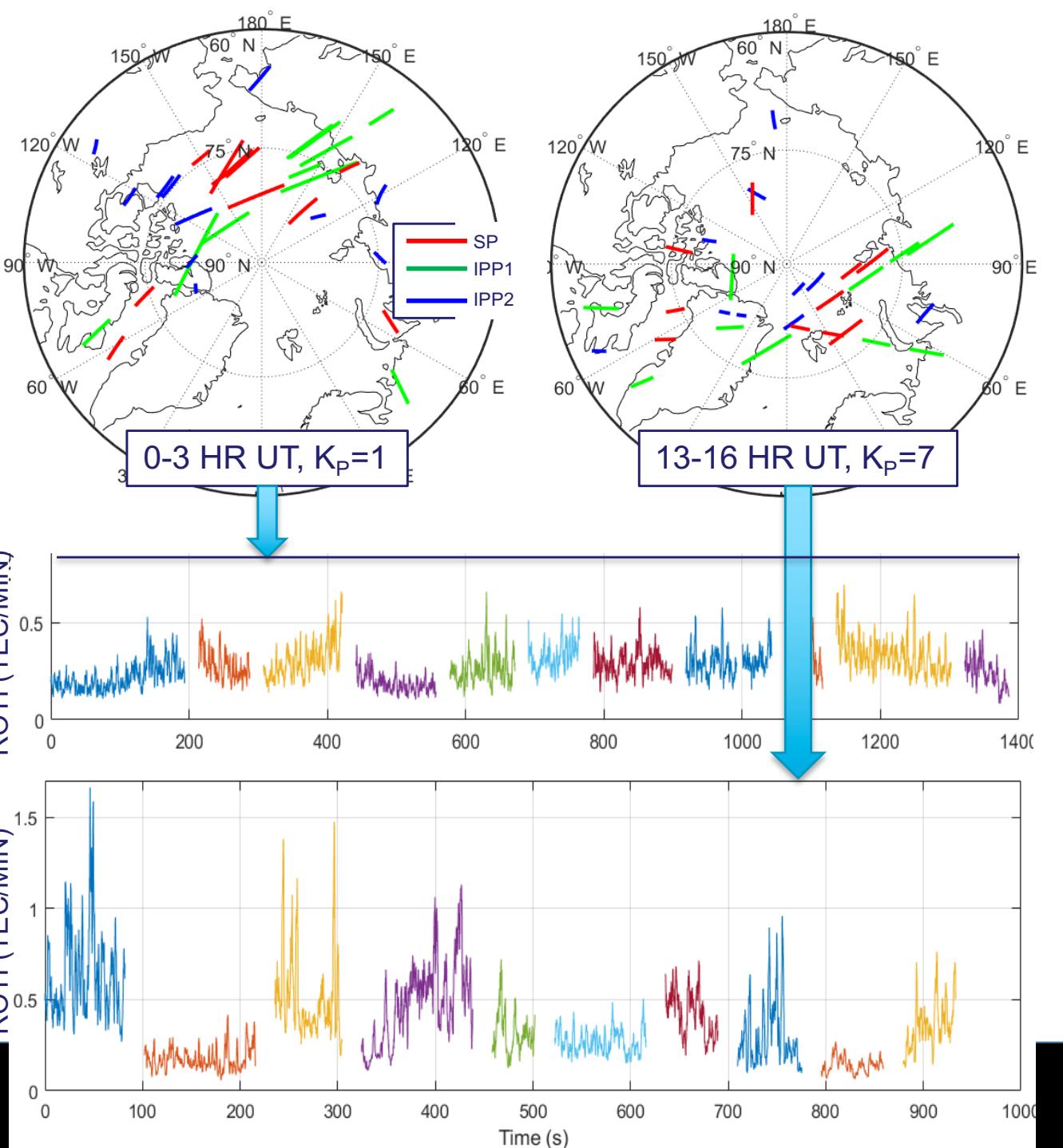
Validation Based on Sea Surface Model: GNSS-R TEC vs. IGS GIM



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.



Ionospheric Disturbances Observation

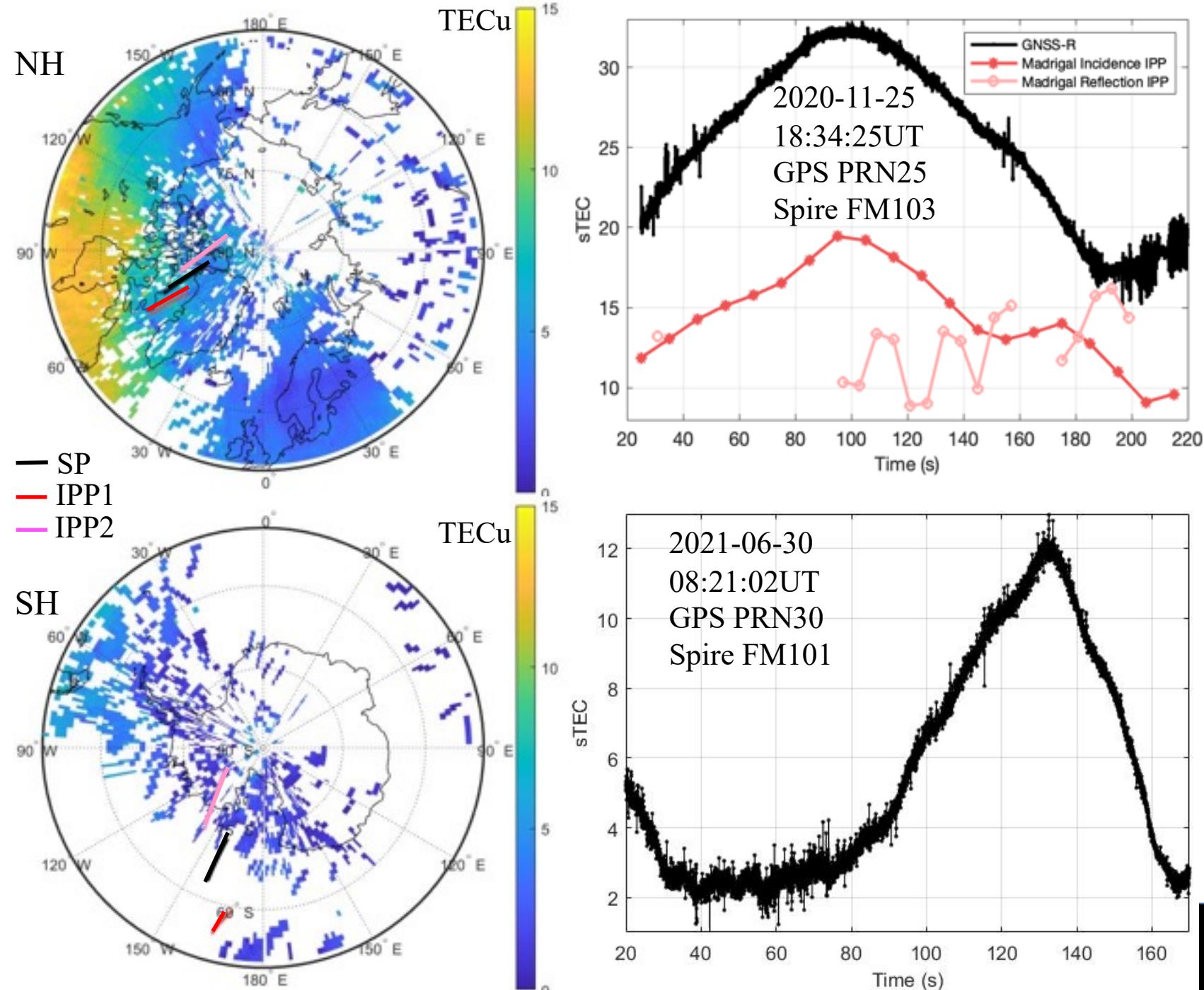


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TEC Enhancement

Arctic 11/25/2011

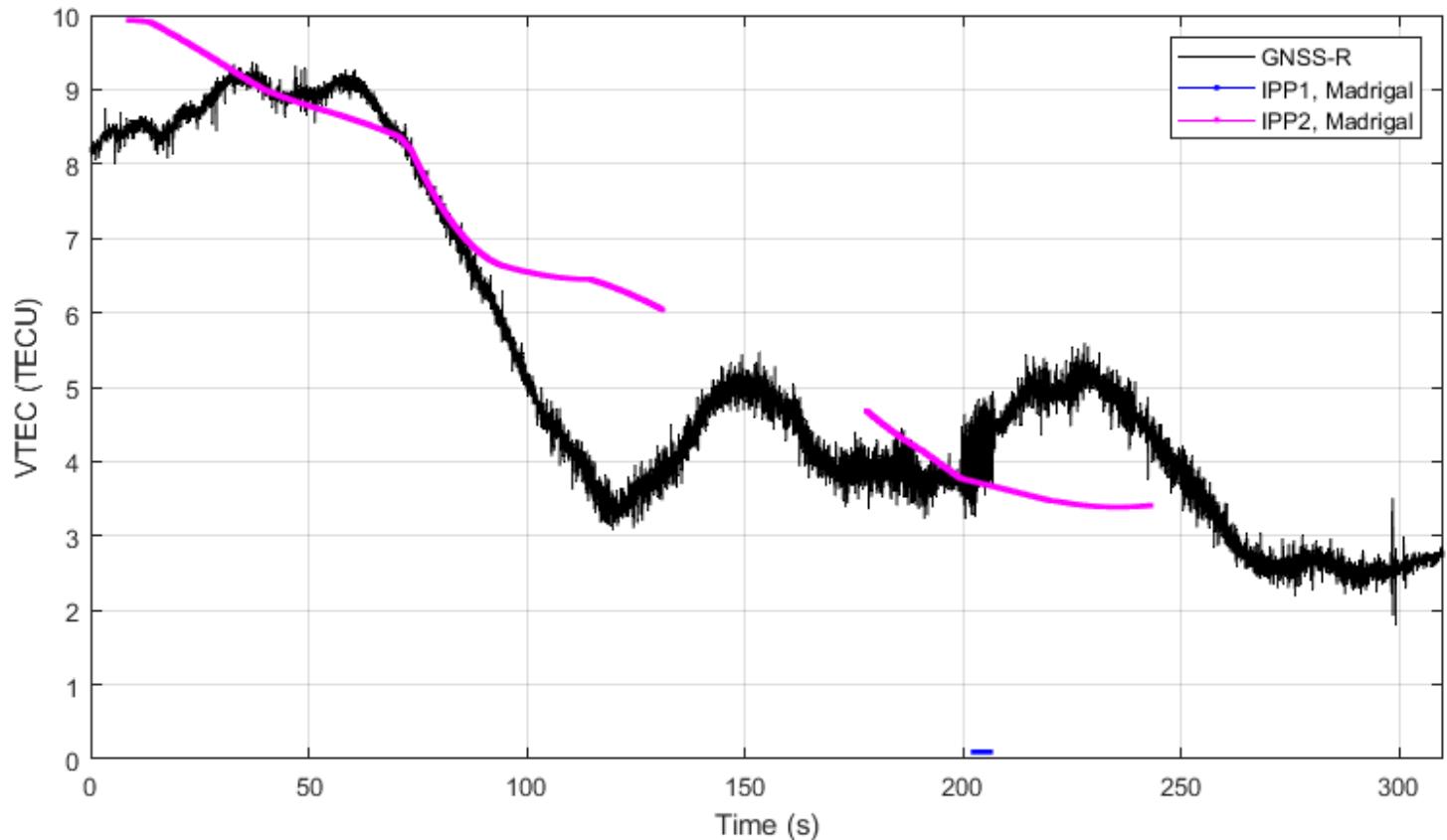
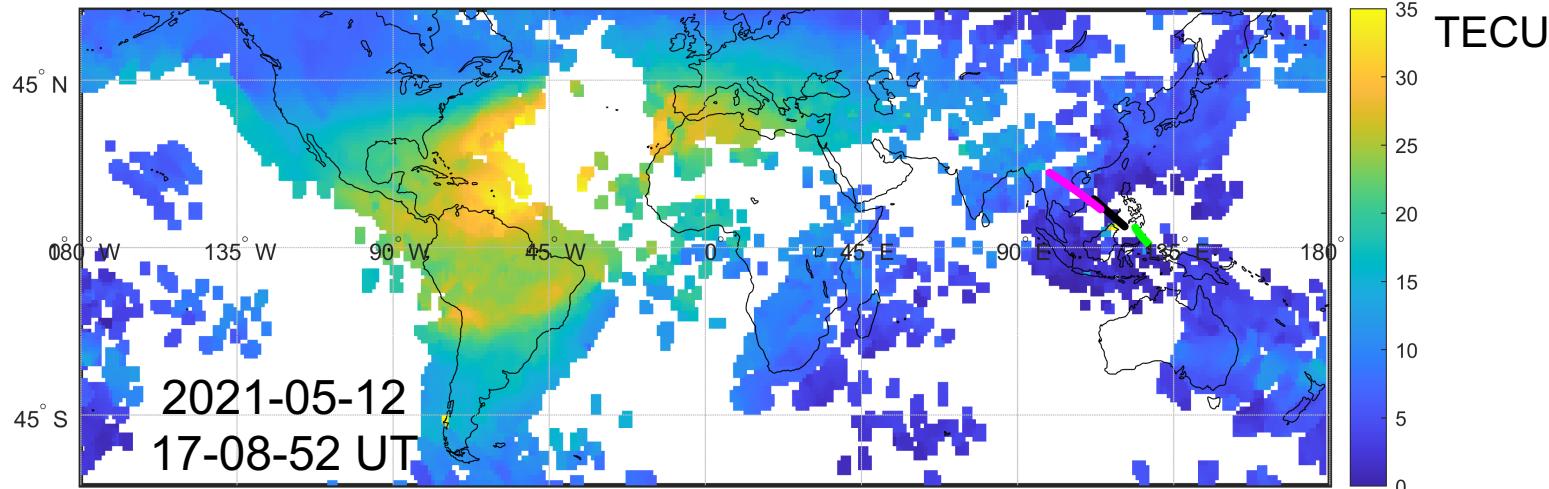
Y. Wang, Y., Morton, "Polar Ionospheric TEC Enhancement Observation Using GNSS-R," Proc. URSI GASS, 2023



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Ionosphere Observation Over Ocean

Y. Wang, Y. Morton, "Observation of Low-latitude Ionospheric Structures from LEO Satellite-based GNSS-R Measurements," 2022 AGU.

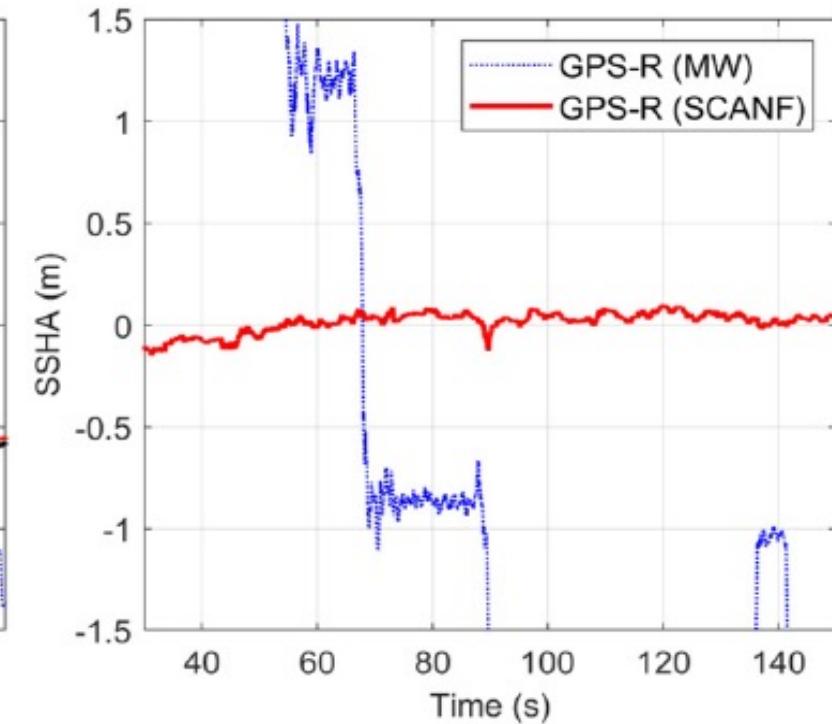
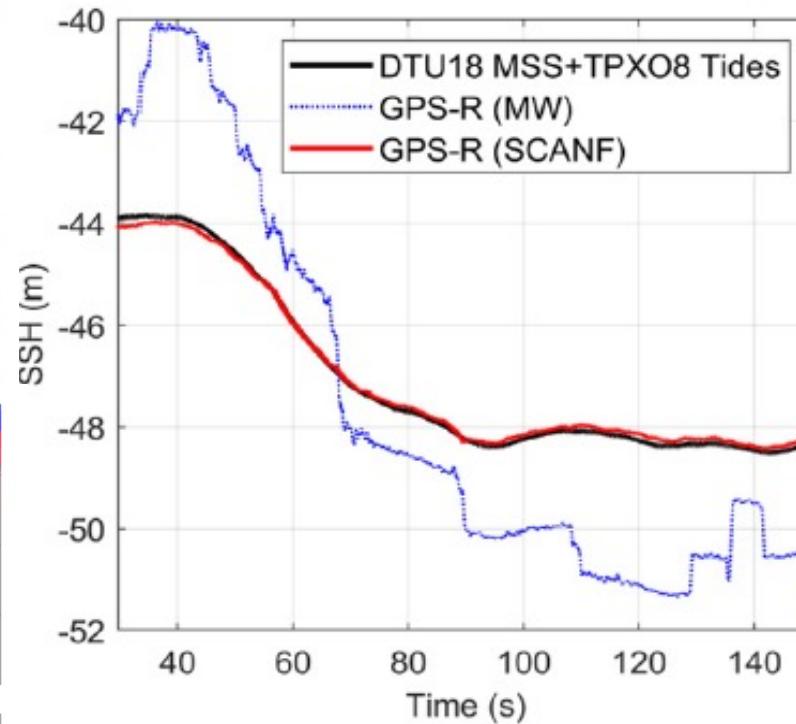
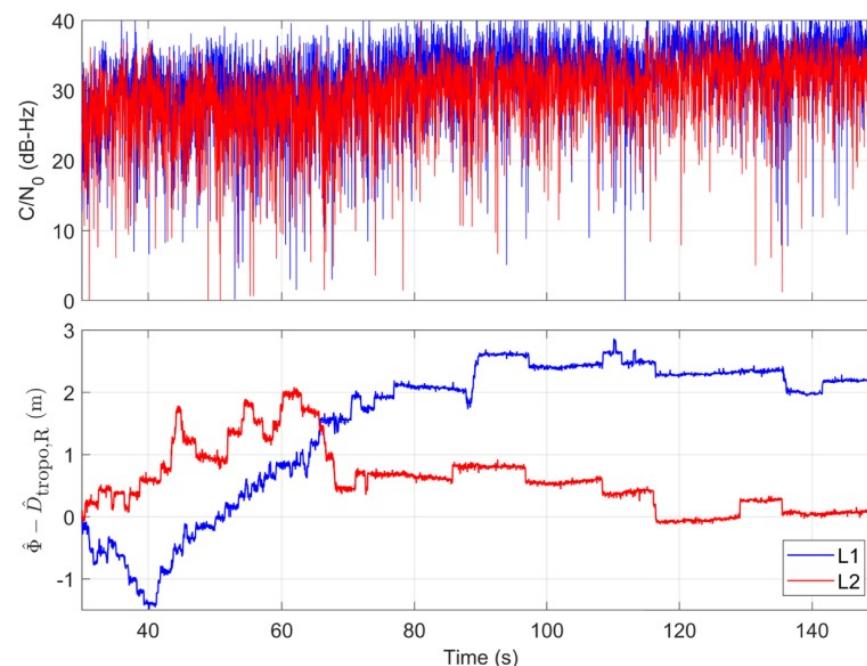
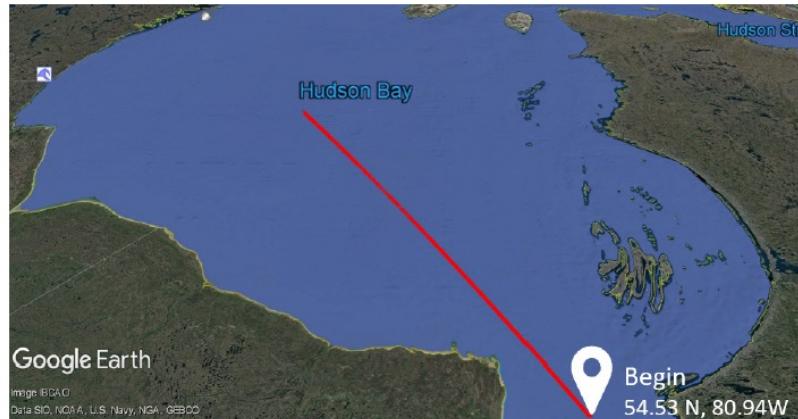


GNSS-R Ionosphere Monitoring Challenges

- Coherent reflection signal carrier tracking and cycle slip mitigation
- GNSS-R receiver hardware bias calibration
- Incidence and reflection ray contribution separation



Sea Ice Surface Height (SSH) Variations



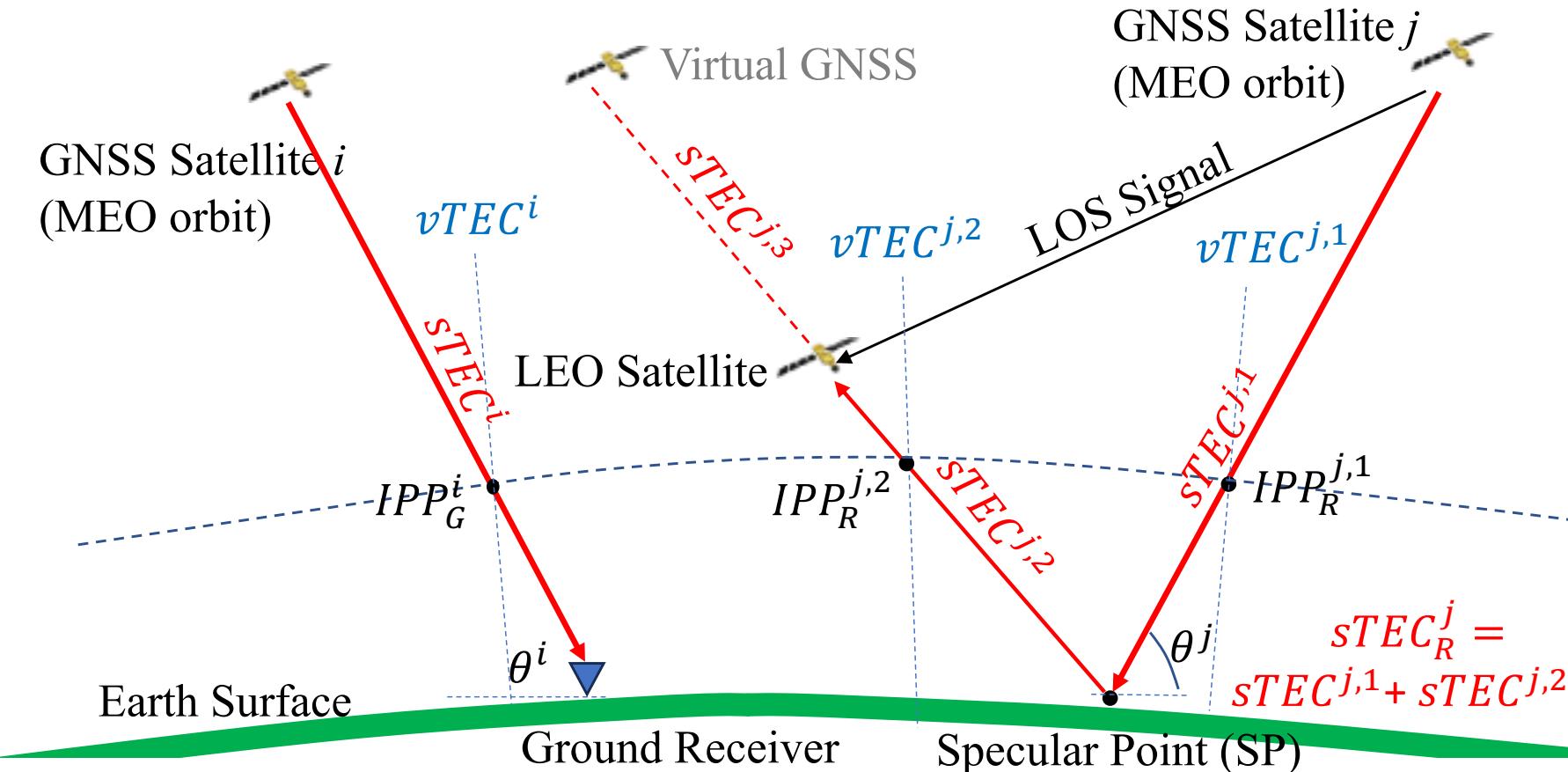
Wang, Y., Breitsch, B., & Morton, Y. (2020). A state-based method to simultaneously reduce cycle slips and noise in coherent GNSS-R phase measurements from open-loop tracking. *IEEE Trans. Geosci. Remote Sen.*, 59(10), 8873-8884.



GNSS-R Receiver Hardware Bias Estimation

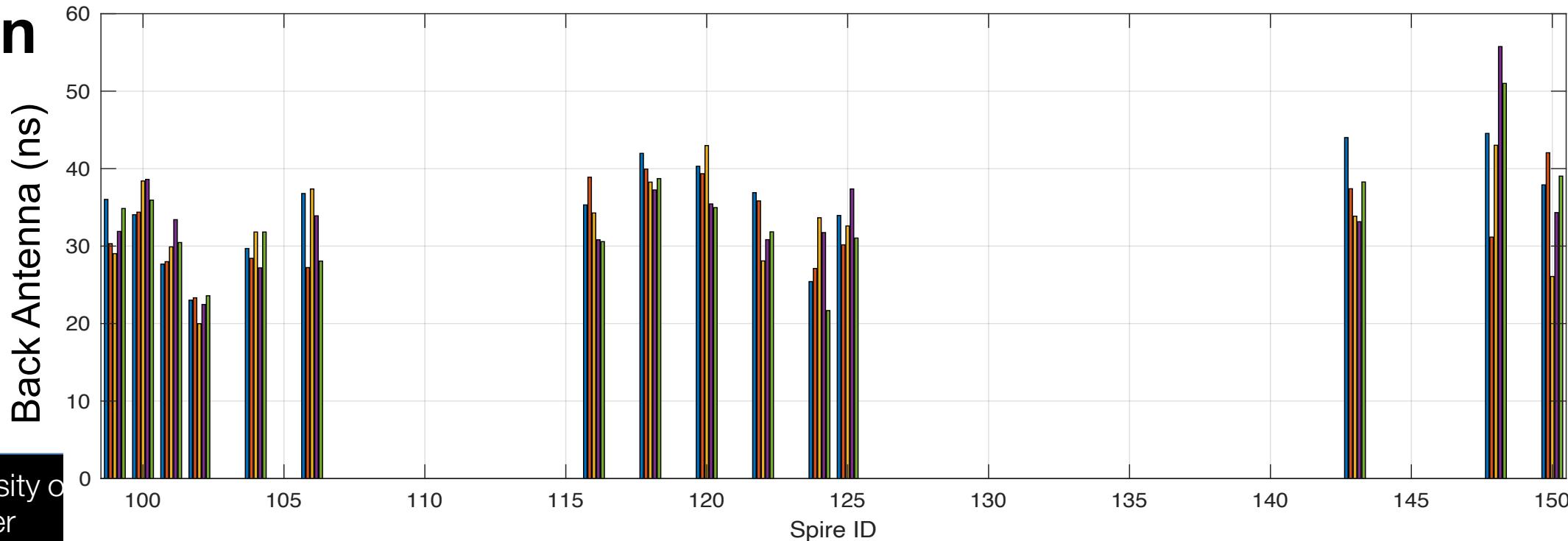
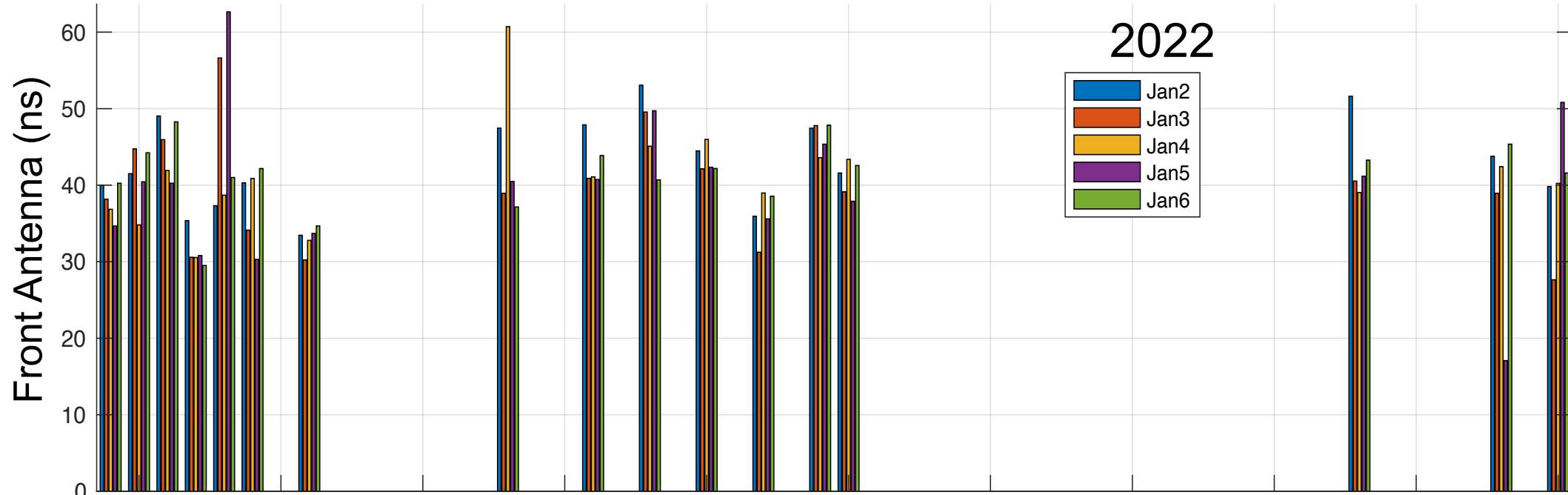
$$\Delta\rho_G^i = \beta \times M_G(\theta^i) \times vTEC^i + DCB_G + \delta\epsilon_G^i, i = 1, 2, \dots, N_G$$

$$\Delta\rho_R^j = \beta \times M_R(\theta^j) \times (vTEC^{j,1} + vTEC^{j,2}) - \beta \times sTEC^{j,3} + DCB_R + \delta\epsilon_R^j, j = 1, 2, \dots, N_R$$



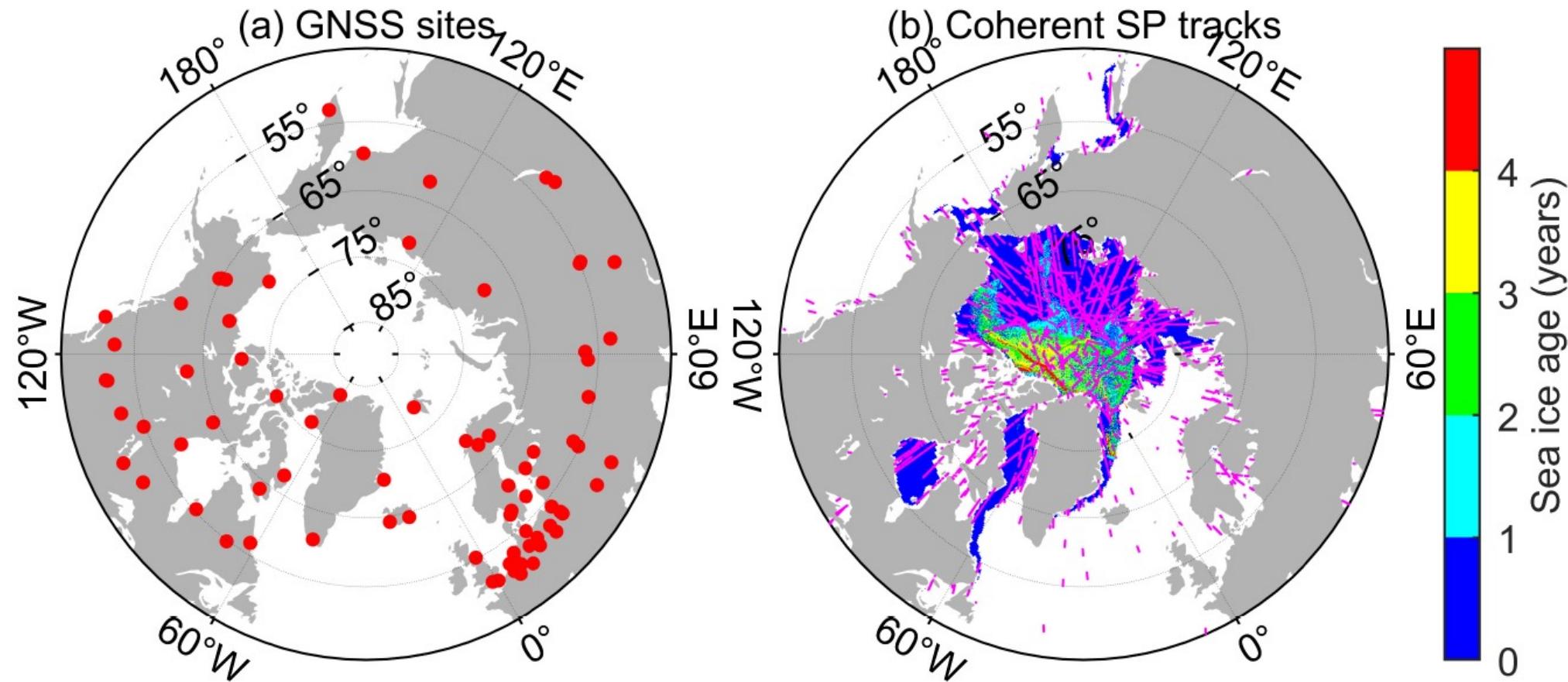
GNSS-R Receiver DCB Estimation

2022



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Separating Incident and Reflection Ray Contributions: Simulation Studies



Liu, L., Y. J. Morton, Y. Wang, "Arctic TEC mapping using integrated LEO-based GNSS-R and ground-based GNSS observations: a simulation study," *IEEE Trans. Geosci. Remote Sensing*, DOI: 10.1109/TGRS.2021.3138692, 2021.

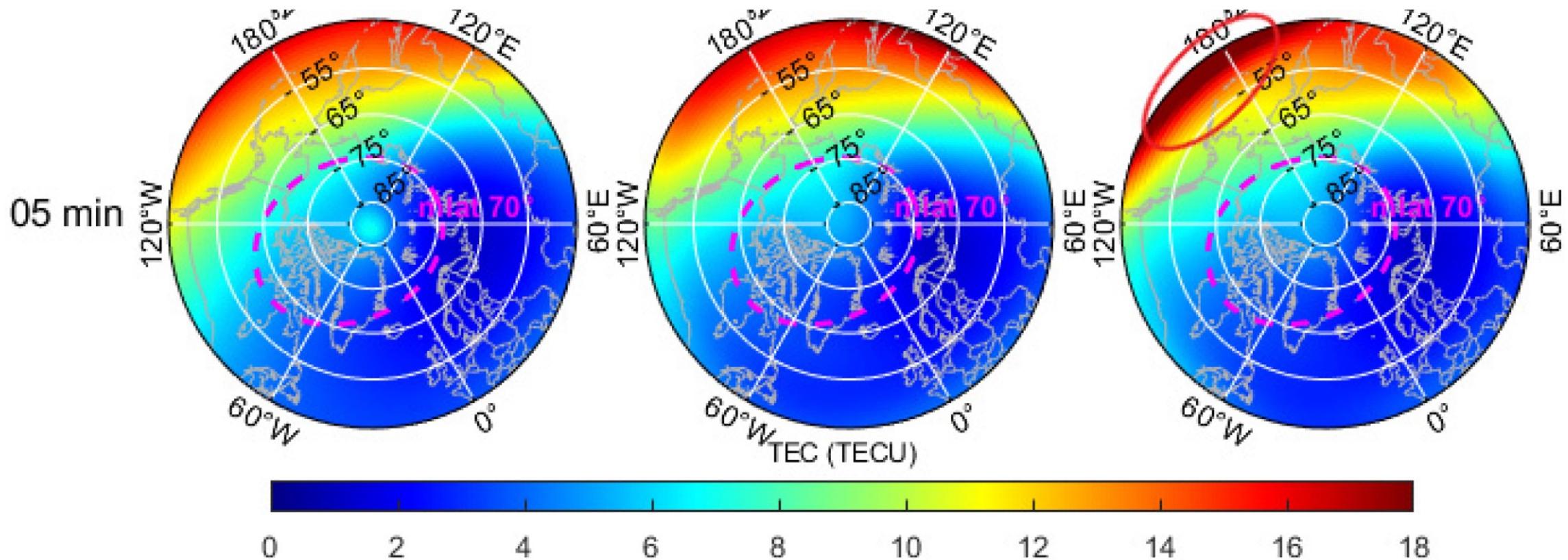


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TEC Map Construction: Using 5 Minutes Data



Liu, L., Y. J. Morton, Y. Wang, "Arctic TEC mapping using integrated LEO-based GNSS-R and ground-based GNSS observations: a simulation study," *IEEE Trans. Geosci. Remote Sensing*, DOI: 10.1109/TGRS.2021.3138692, 2021.



Conclusions

- GNSS-R has the potential to fill data gaps at critical regions (equatorial and high latitudes)
- GNSS-R offers nearly frozen-in time view of the ionosphere due to its rapid scan velocity
- There are challenges that need to be addressed. Potential methods under implementation.

Funding support:

NASA 80NSSC21K1553, 80NSSC20K1738, DARAP AWD-102938-G3, ONR N00014-23-1-2145



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