Improved Ocean Altimetry Methods with CYGNSS Observations in Indonesia

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Outline

- Altimetry with GNSS-R
  - Background and description of measurement
1. Model Based Re-tracking Methods
   - Utilizing Voronovich and Zavorotny 2018
2. Improved Ionospheric Modeling and Evaluation
   - Data driven GIM estimates
3. Improved Orbit Determination
   - Kalman filtering the CYGNSS OD solutions
- SSH Retrievals in Indonesia
- Conclusions and Next Steps

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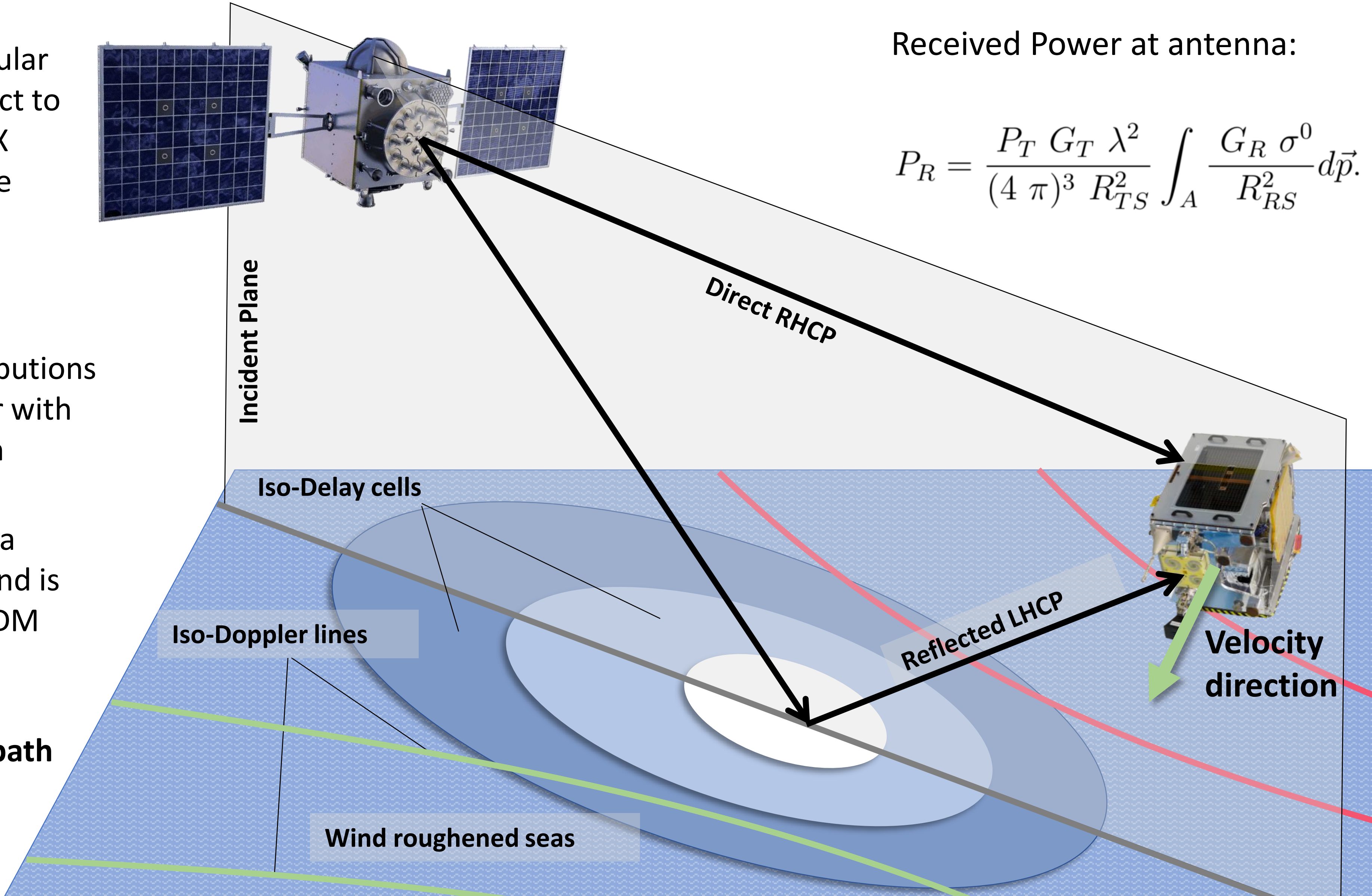
GNSS-R - Description of Altimetry Measurement

- For altimetry, we track the specular reflection path delay with respect to the direct signal and relate to RX height above a reference surface
- **Delay anomaly**
  $\Delta\delta = (\delta_{measured} - \delta_{modeled})$
- Received power contains contributions from the specular path together with those from an area of the ocean around it, the glistening zone
- Received power is measured as a function of delay and Doppler and is output as delay Doppler map DDM
- **The altimetry measurement is dependent on the accurate determination of the specular path delay from the DDM**

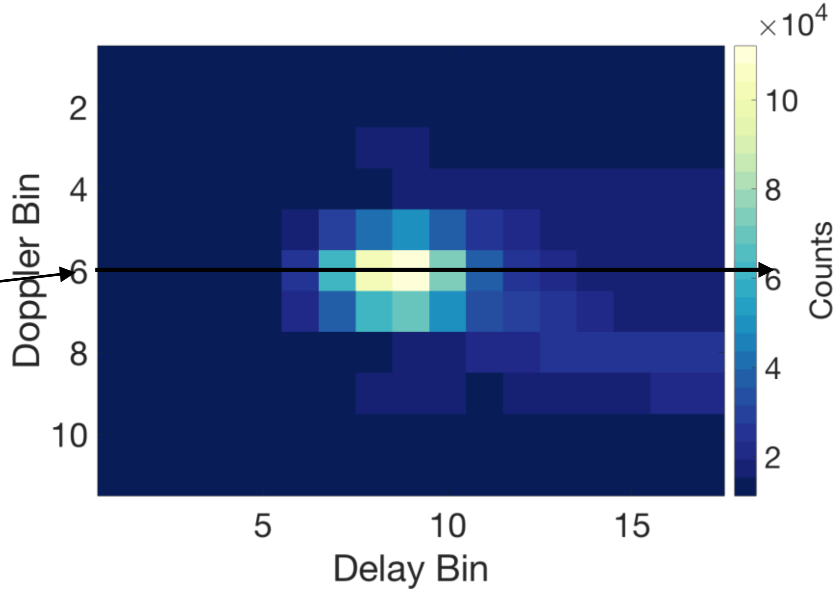
Received Power at antenna:

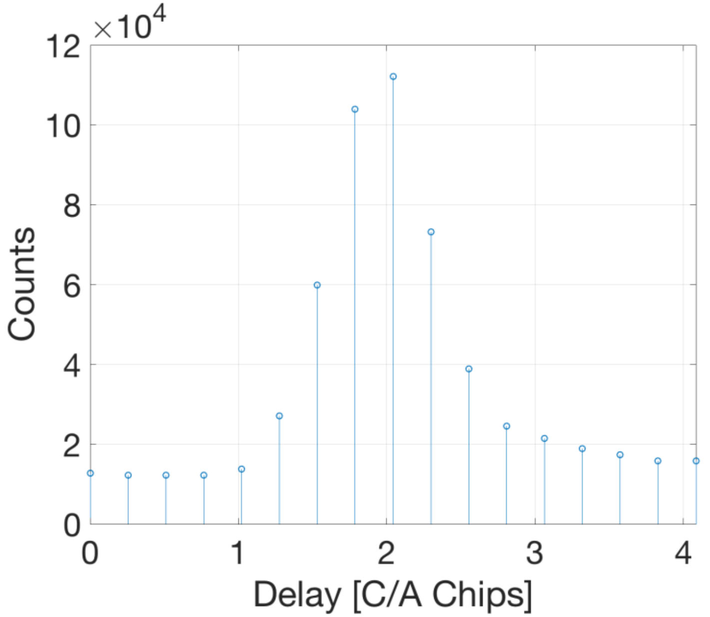
$$P_R = \frac{P_T\ G_T\ \lambda^2}{(4\ \pi)^3\ R_{TS}^2} \int_A \frac{G_R\ \sigma^0}{R_{RS}^2} d\vec{p}.$$

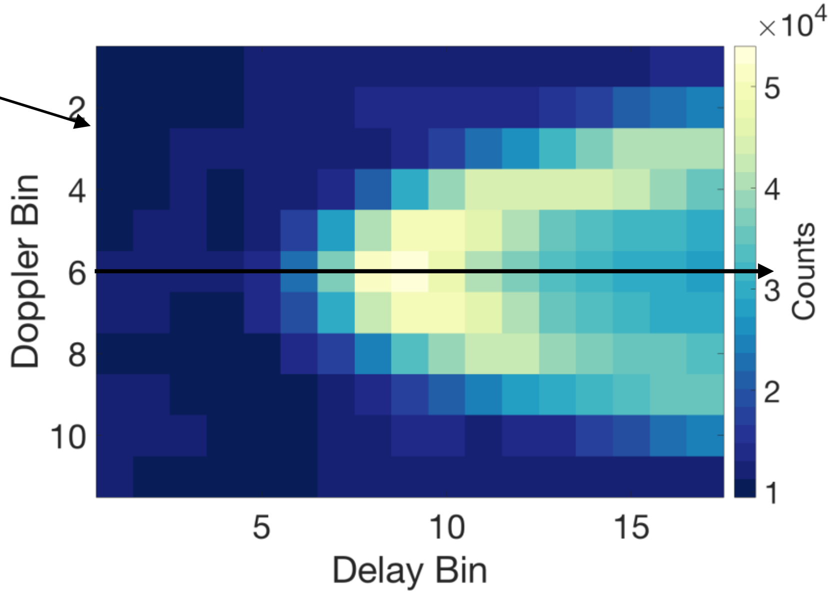


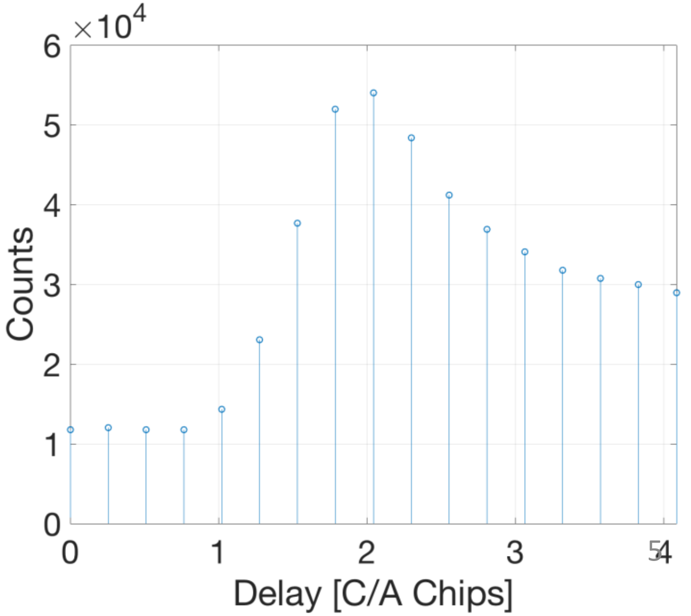
GNSS-R – DDMs from CYGNSS

- Illustrate the different characteristics of observations from the coherent and incoherent cases.
- Coherent specular reflection dominates when surface conditions are smooth
  - Waveform looks similar to direct signal
- Typically, ocean surface winds are high enough that diffuse scattering over a large area resulting in an incoherent return
- For altimetry we need to re-track these observations to determine the signal path delay but the tracking point is different in each of these DDMs



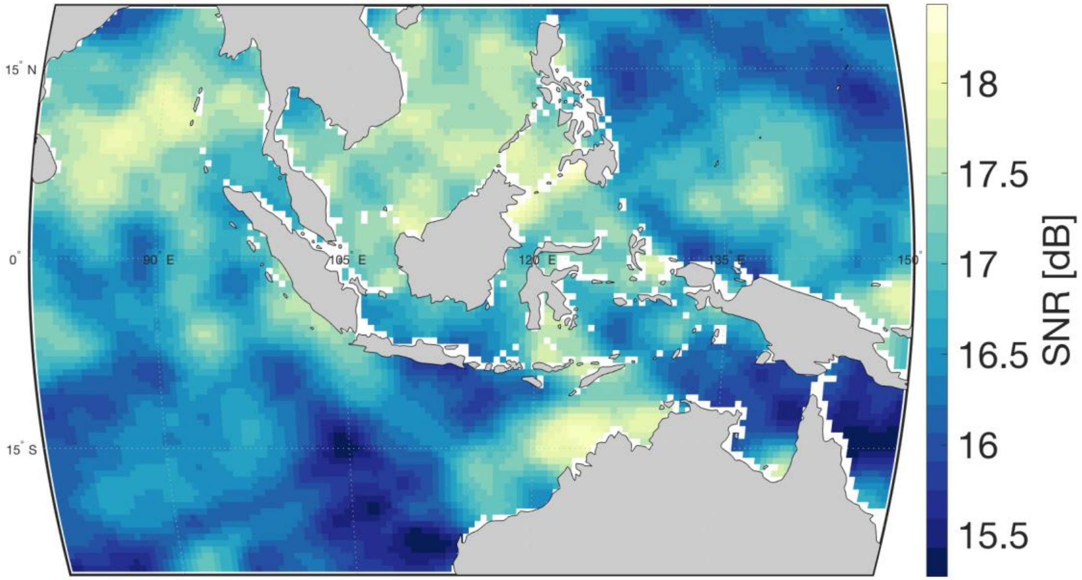


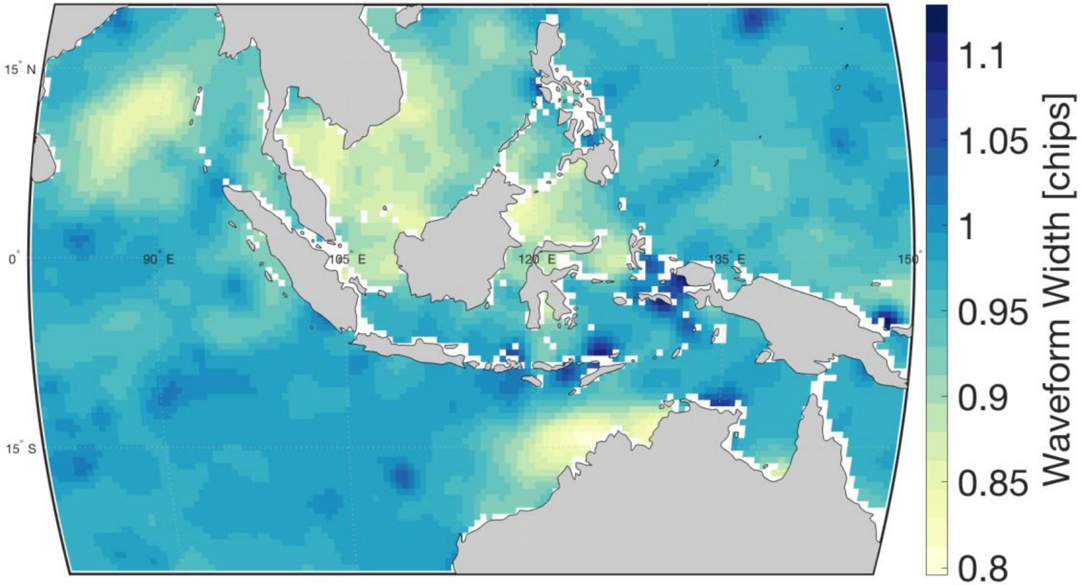




Indonesia Case Study

- We select the region around Indonesia to perform a case study
- A relatively large percentage >2% of observations exhibit coherent characteristics in this area
- This area provides a good testing ground to develop our methods and is also oceanographically interesting due to the seasonal SSH signals





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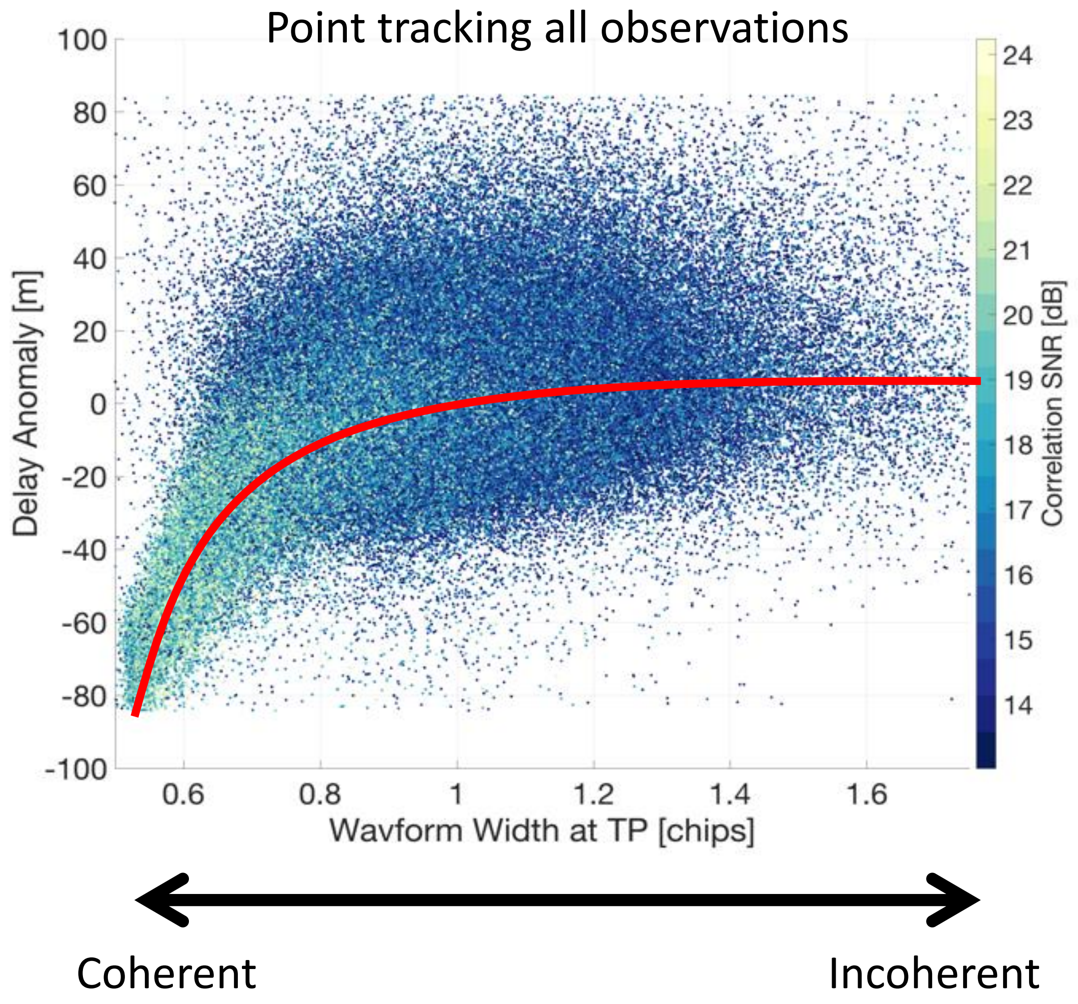
Altimetry – Delay Re-Tracking Algorithms

Point Tracking

- **P70** – Track 70% of peak power on waveform leading edge (Leads to systematic tracking errors)

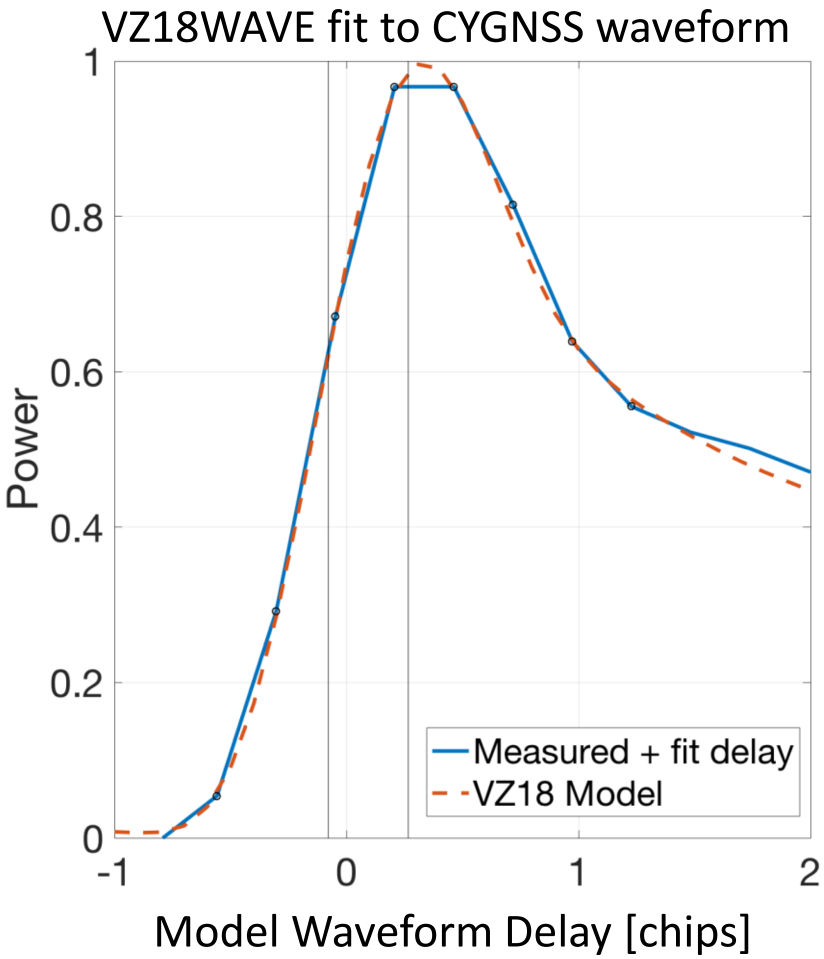
Model Based Tracking

- **VZ18WAVE** – Fit measurements to simulated delay waveforms from 0Hz Doppler bin *Voronovich and Zavorotny (2018)*
- **VZ18DDM** – Fit measurements to simulated DDMs *Voronovich and Zavorotny (2018)*



VZ18 Model Tracking

The recent Voronovich and Zavorotny (2018) GNSS-R model now considers **diffuse AND coherent scattering** and is used to simulate CYGNSS ocean observations



2 methods are tested…

- **VZ18WAVE** – LS fit of modeled waveforms to observed waveforms from 0Hz Doppler bin
- **VZ18DDM** – LS fit of modeled DDMs to observed DDMs. Fits the Doppler asymmetry in the observations

- 1-sec and 10-sec integrated observations are tracked with the VZ18 algorithms

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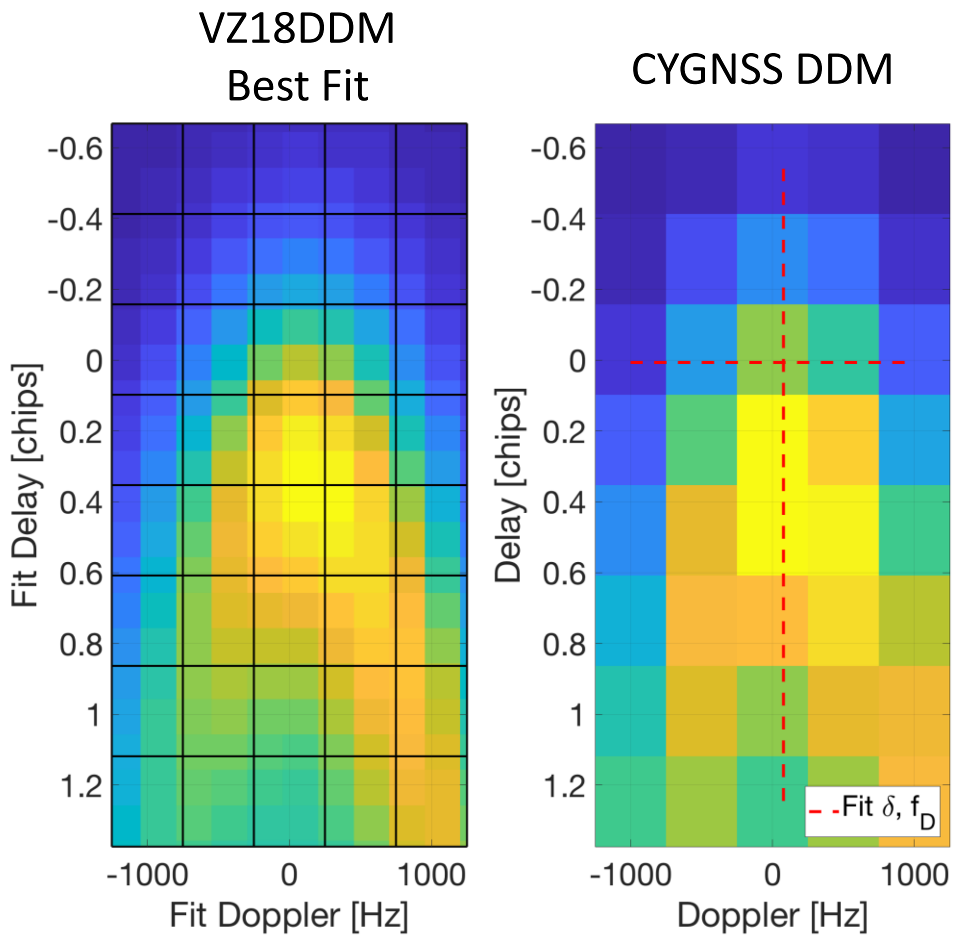

2x methods are tested

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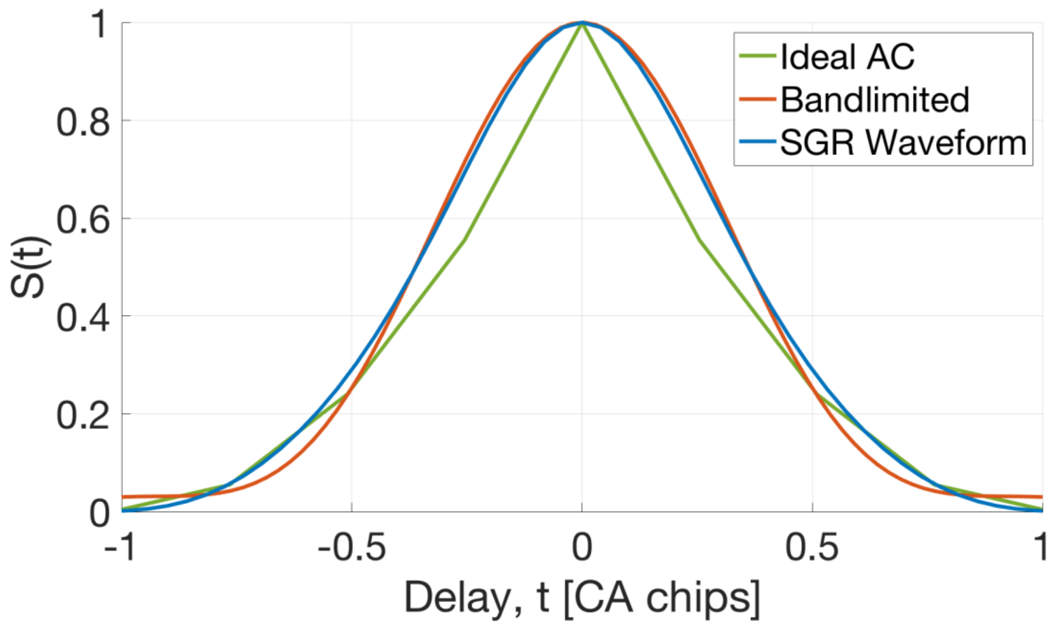
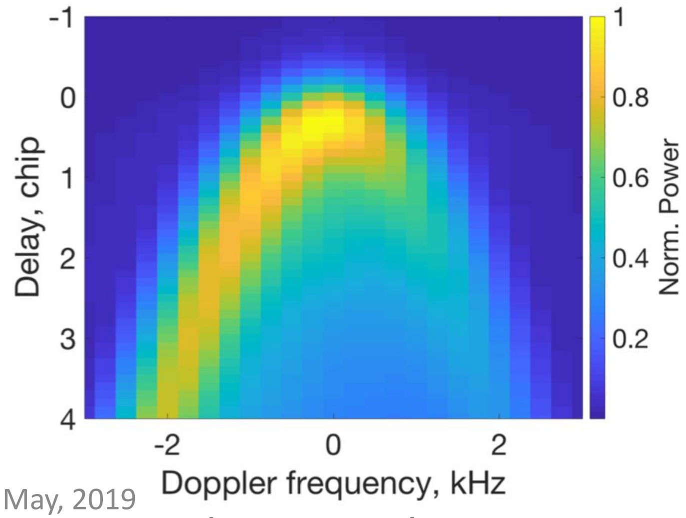
VZ18 Model Tracking

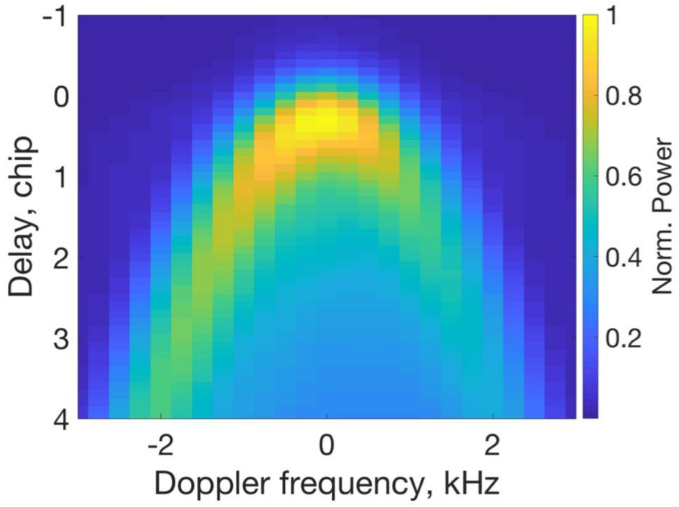
We account for…

- Measured CYGNSS antenna pattern
  - 1 pattern for all 8 CYGNSS
- Continuous satellite geometries to capture Doppler asymmetry
  - 360deg azimuth wrt. velocity direction
- Bandlimited sampling effects on the correlation function

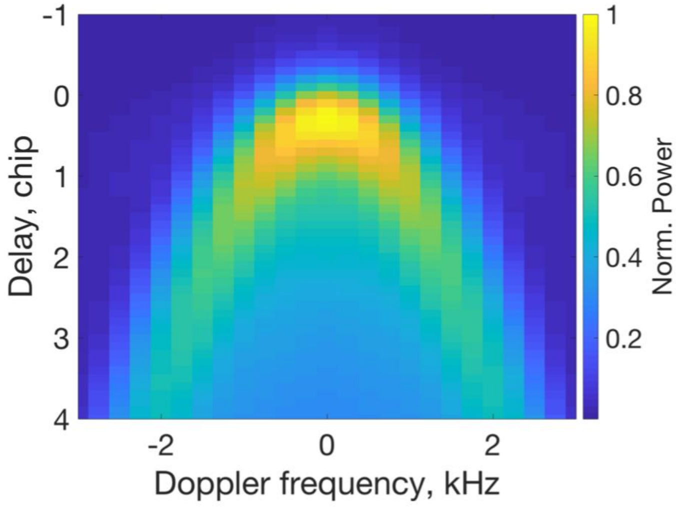




0deg azimuth



60deg azimuth

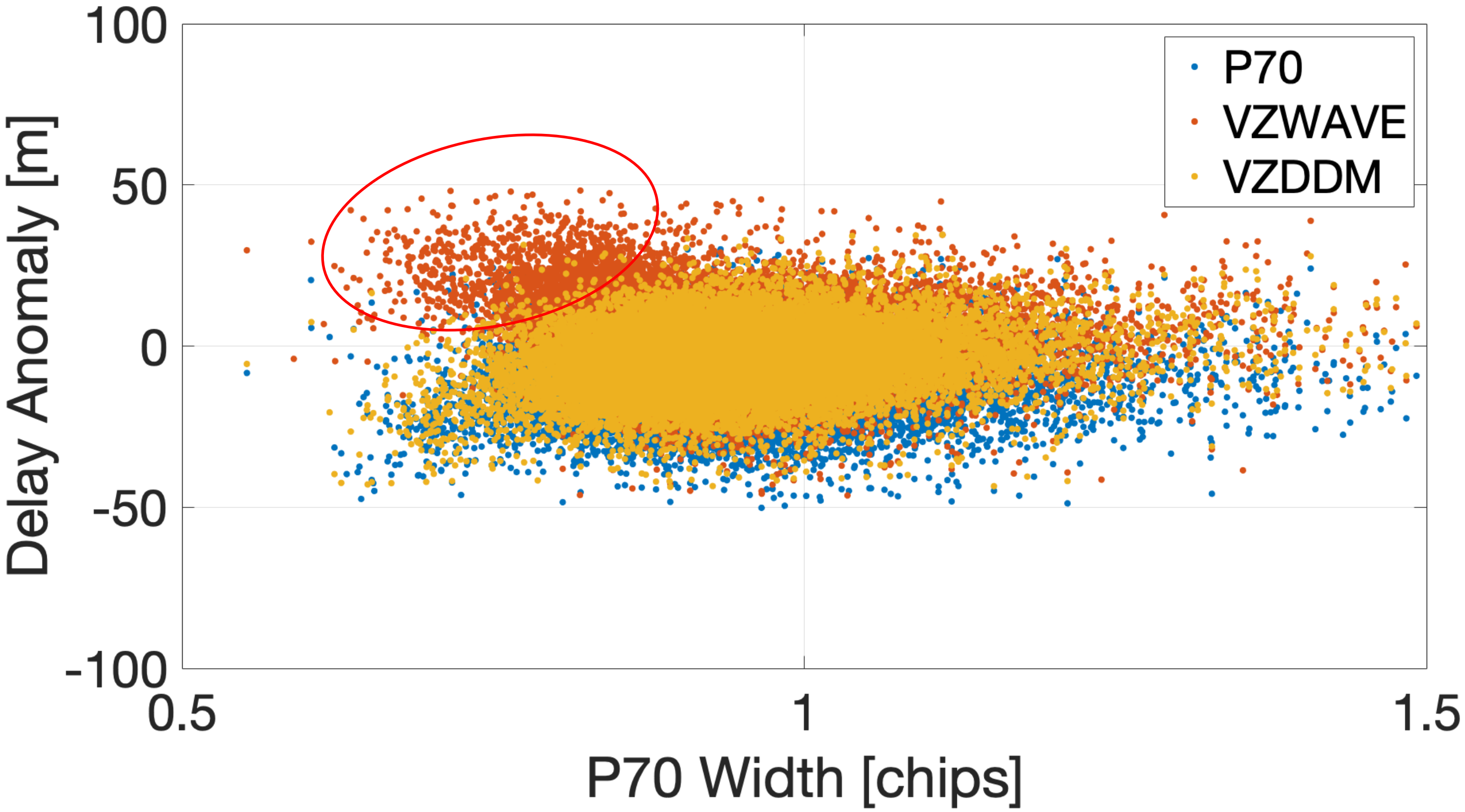


90deg azimuth

Retracking Coherent Observations

- VZ18WAVE tends to over-compensate for measurements with **width 0.6-0.8 chips**
  - Possible Doppler mis-alignment between observation and model
- VZ18DDM shows less biased behavior and comparable precision to P70

P70	VZ18DDM
mean = -10m	mean = -4.4m
σ = 9.9m	σ = 9.5m



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Improved Ionosphere Modeling

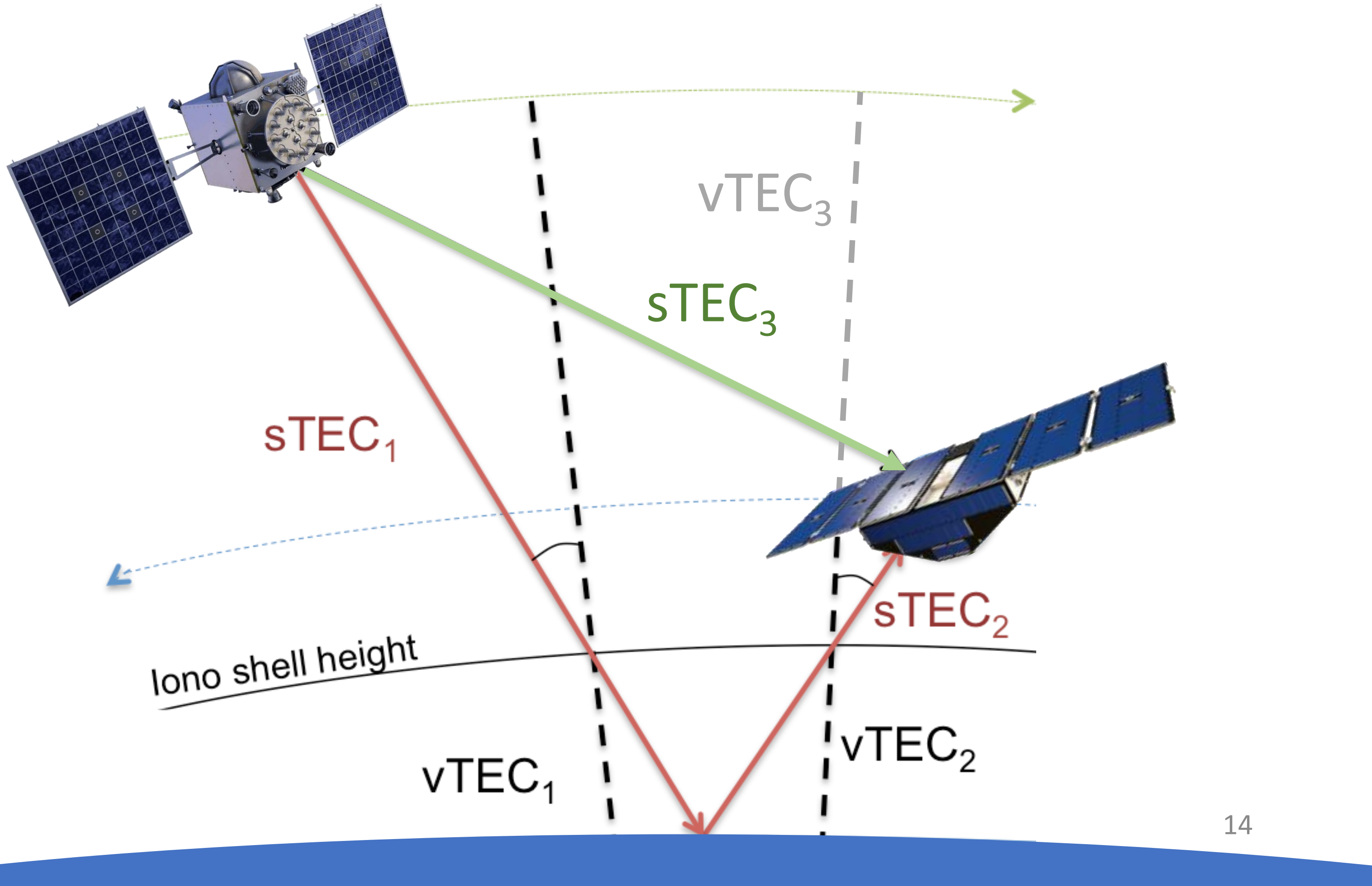
- IGS Global Ionosphere Maps (GIMs) used to estimate vertical TEC columns
  - Assimilated GNSS observations of the ionosphere from IGS network
- Map direct path effect to slant angle with Montenbruck model for LEO spacecraft

$$M(\gamma) = \frac{\alpha}{sin(\gamma)}, \ \alpha = \frac{e - exp(1 - exp(-z_{IP}))}{e - exp(1 - exp(h_0/H))}$$

- Map reflection path effects to slant angles with Komjathy mapping

$$M(\gamma) = \frac{1}{\sqrt{1 - \left(cos(\gamma)\frac{R_E}{R_E+h}\right)^2}}$$

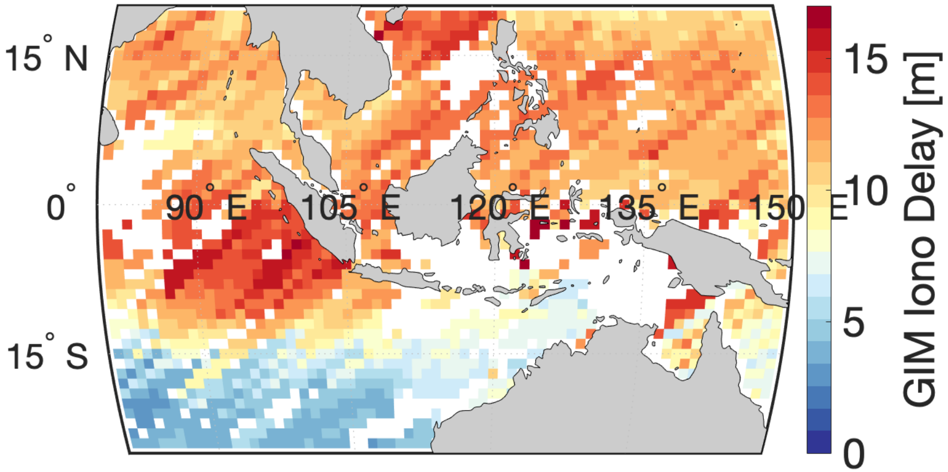
$$\delta_{iono} = (\delta_1 + \delta_2) - \delta_3$$



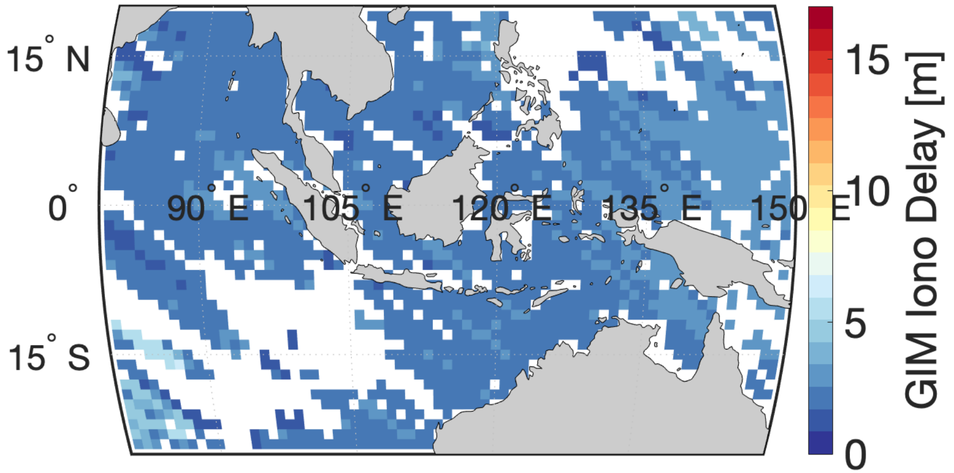
Residual Ionospheric Errors

- Monthly average of estimated ionosphere effect is >10m over most of Indonesia region
- Nightly average is <2m

Monthly AVG Day time

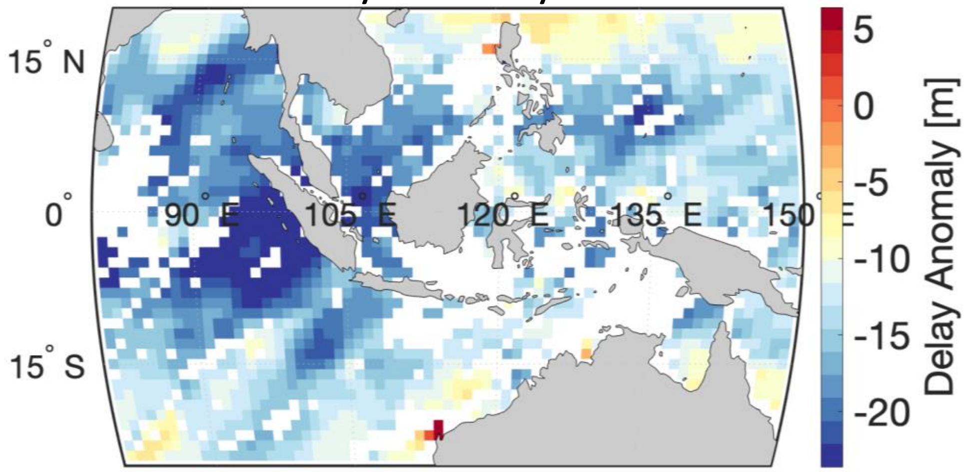


Monthly AVG Night time

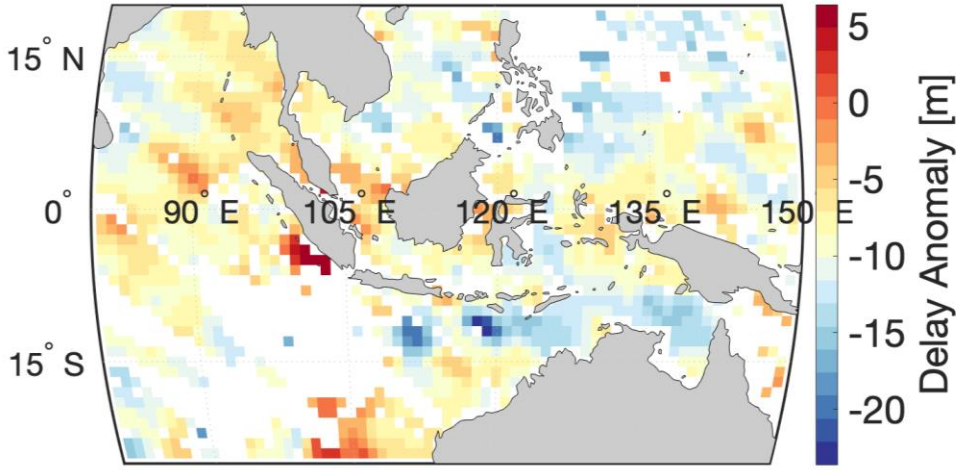


- **Average day-time delay anomaly is biased -5m wrt average night-time delay anomaly**

Monthly AVG Day time



Monthly AVG Night time



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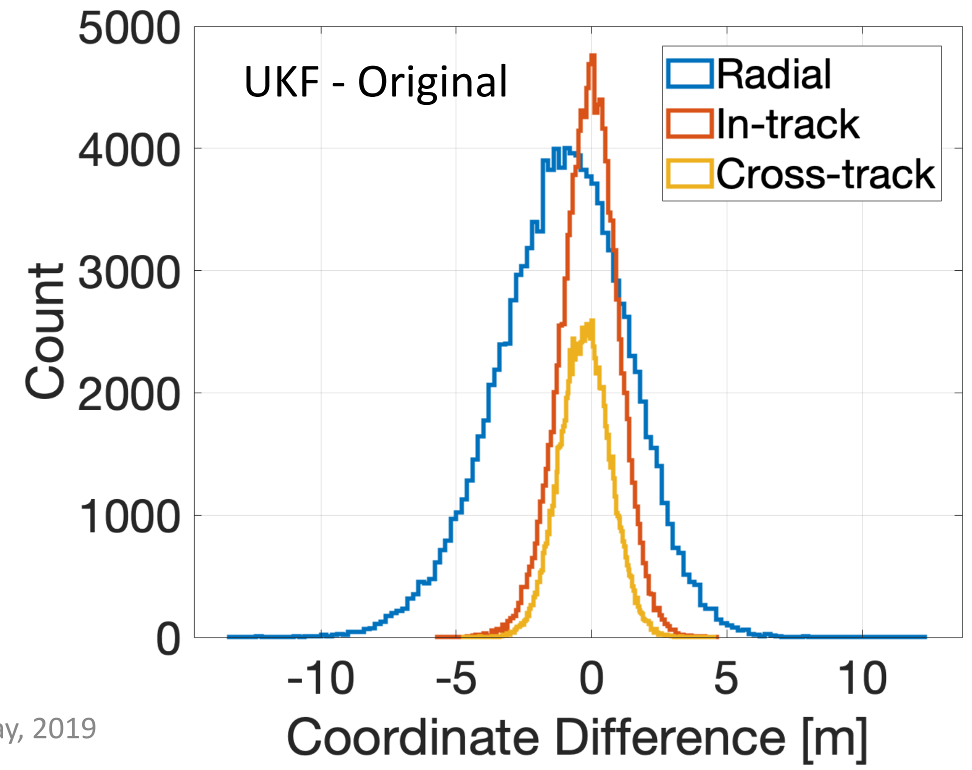
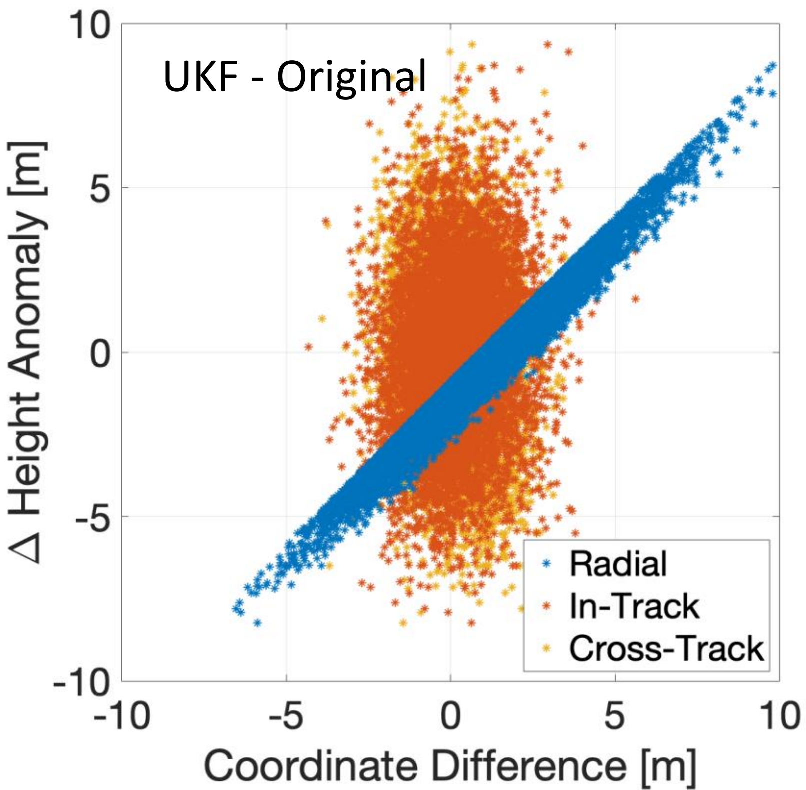
Improved Orbit Determination

- An Unscented Kalman Filter is used to smooth the CYGNSS OD solutions
  - Original solutions are 1Hz real-time GPS L1C/A navigation solutions
- UKF smoothed orbit reduces significant random error in the orbit-radial direction
  - Errors in the orbit-radial component will map directly into SSH errors





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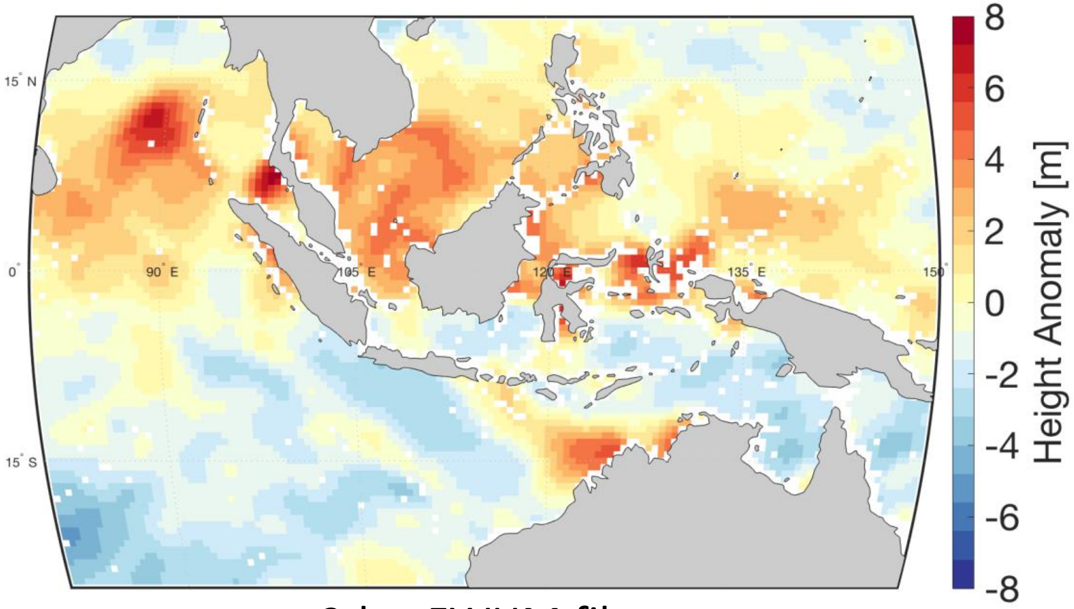
SSH Retrieval in Indonesia

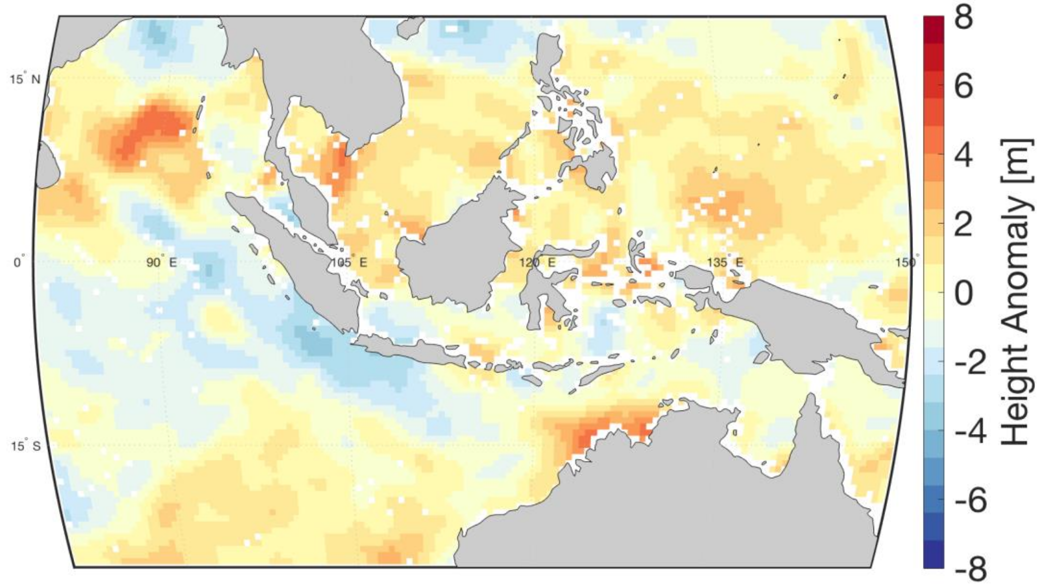
Tracking Method	Single Sample, σ_H [m]	Gaussian Smoothed, σ_H [m]
P70 (1 sec)	6.7	1.9
VZ18WAVE (1 sec)	10.9	3.2
VZ18DDM (1 sec)	5.8	1.9
P70 (10 sec)	3.6	1.3
VZ18DDM (10 sec)	3.8	1.3

P70 – 1s obs



2deg FWHM filter

VZ18DDM – 10s obs



2deg FWHM filter

Altimetry Results – CYGNSS

Error Budget

- **Models and considerations**
  - UKF filtered orbits
  - DTU10 MSS
  - GIM Ionosphere estimates
  - CYG predicted delay correction
  - QC to remove outliers

Name		Uncorrected Magnitude	Residual Error
CYG orbit error		3 m position	0.03 m (1σ Gipsy) 0.70 m (1σ UKF)
TX orbit error		1 m position	0.03 m position (1σ)
DTU10 MSS		100 m height	0.1 m height (1σ)
Ionosphere delay		$<$ 15 m delay (day) $<$ 7 m delay (night)	$<$ 3.5 m delay (RMS) $<$ 2 m delay (RMS)
Troposphere delay		6 m delay	0.05 m delay (1σ)
Antenna baseline		1 m delay	0.001 m delay (1σ)
add_range_to_sp truncation		$\pm$ 15 m delay	4.6 m delay (1σ)
Open loop delay-Doppler smearing		$\leq$ 1 m delay	$\leq$ 1 m delay
Tracking error (at mean SNR = 15dB)	P70 (1s obs) VZ18WAVE (1s obs) VZ18DDM (1s obs)		10 m 5.5 m 2 m
		RSS_{P70}	= 11.6 m delay
		$RSS_{VZ18WAVE}$	= 7.9 m delay
		$RSS_{VZ18DDM}$	= 5.9 m delay

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Conclusions and Next Steps

Continue to improve ionosphere modeling

- Residual ionosphere bias is still several meters between average day and night observations
- Local GNSS receivers across Indonesia can be utilized to produce regional, time-varying ionosphere density estimates
- Improved understanding of local ionospheric activity will help produce better corrections

Model-based retracking

- VZ18WAVE and VZ18DDM retracking show improvement over point-tracking techniques
- Transition zone observations are still difficult to capture well
- More detailed along-track analysis and comparison between strongly coherent and incoherent observations will help improve our modeling and retracking algorithms