# Assessment of a CYGNSS Ocean Altimetry Product Using a Full DDM Approach

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GNSS+R 2019 – Benevento, Italy
May 21, 2019

# Background and Motivation

- CYGNSS ocean altimetry research is being performed as part of a ROSES proposal awarded in late 2016, 3 years duration: **“Assessing the Ability of CYGNSS to Provide Sea Surface Topography for Mesoscale Process Studies”, PI: Cinzia Zuffada**
- Goal is to develop algorithms to retrieve SSH from CYGNSS reflections and build SSH maps. Ingest retrieved topography into ROMS and assess the ability to constrain mesoscale features
- Jake Mashburn explored TDS-1 and CYGNSS SSH retrieval approaches using P70, delay waveform and full-waveform using Zavorotny model (shown in previous GNSS+R 2019 presentation)
- In this presentation, we are continuing this work by implementing a full-DDM approach to estimate SSH using the CYGNSS E2ES. We examine the predicted accuracy of the full DDM approach in comparison to other algorithms using simulations with realistic thermal and speckle noise

# Ocean Altimetry using GNSS-R

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- Current GNSS-R altimetry approaches use either a single tracking point on the DDM or a delay waveform fitting method
- A full DDM method can be used to incorporate extra information about the reflecting surface
- The full DDM retrieval algorithm uses the entire 11x17 CYGNSS DDM to make estimates of the ocean state
  - This method relies on an accurate full forward model
- The CYGNSS End-to-End Simulator (E2ES) has shown the ability to produce these accurate DDMs
- Next slide shows an example of the accuracy of E2ES

# Using CYGNSS E2ES for "Full DDM" Ocean Altimetry

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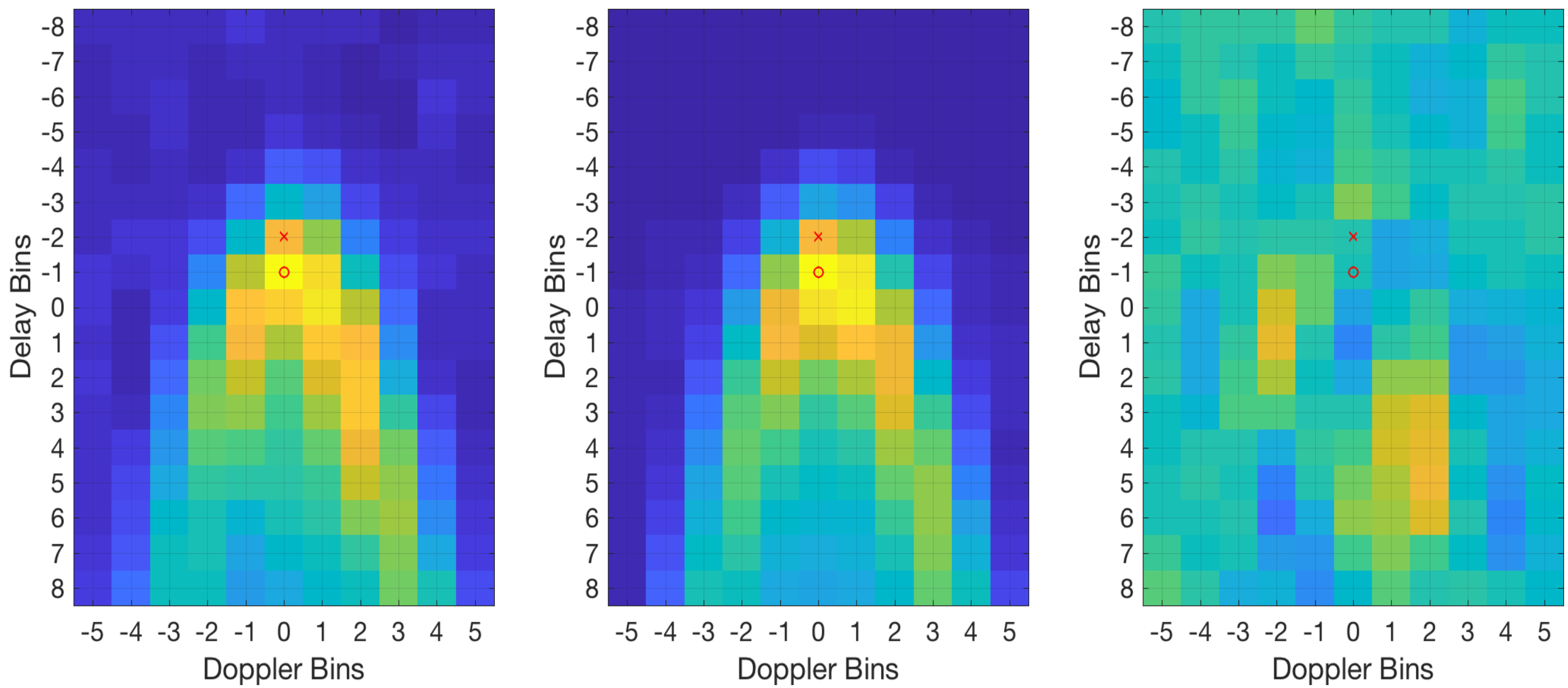
- CYGNSS End-to-End Simulator is accurate enough to provide full information about all DDM pixels

**CYGNSS On-Orbit Measurements** | **Simulated Match-Up** | **Difference**

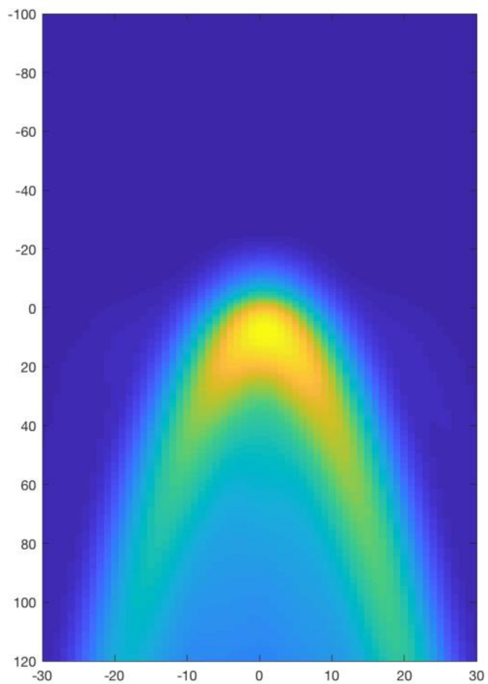


# Using CYGNSS E2ES for "Full DDM" Ocean Altimetry

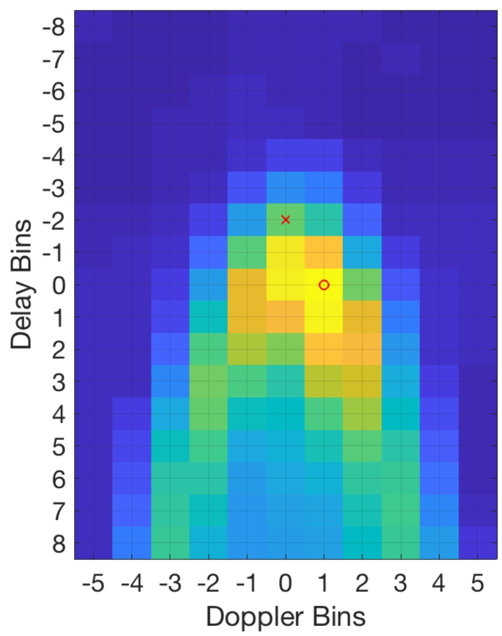


- For altimetry, the CYGNSS E2ES outputs high-resolution delay-Doppler maps. An optimal (MMSE) match-up is found by normalizing shape of DDM and searching over delay and Doppler space to find the minimum error as compared to a CYGNSS measurement
- Very fine delay and Doppler offset estimation is possible

**E2ES High-Res DDM**

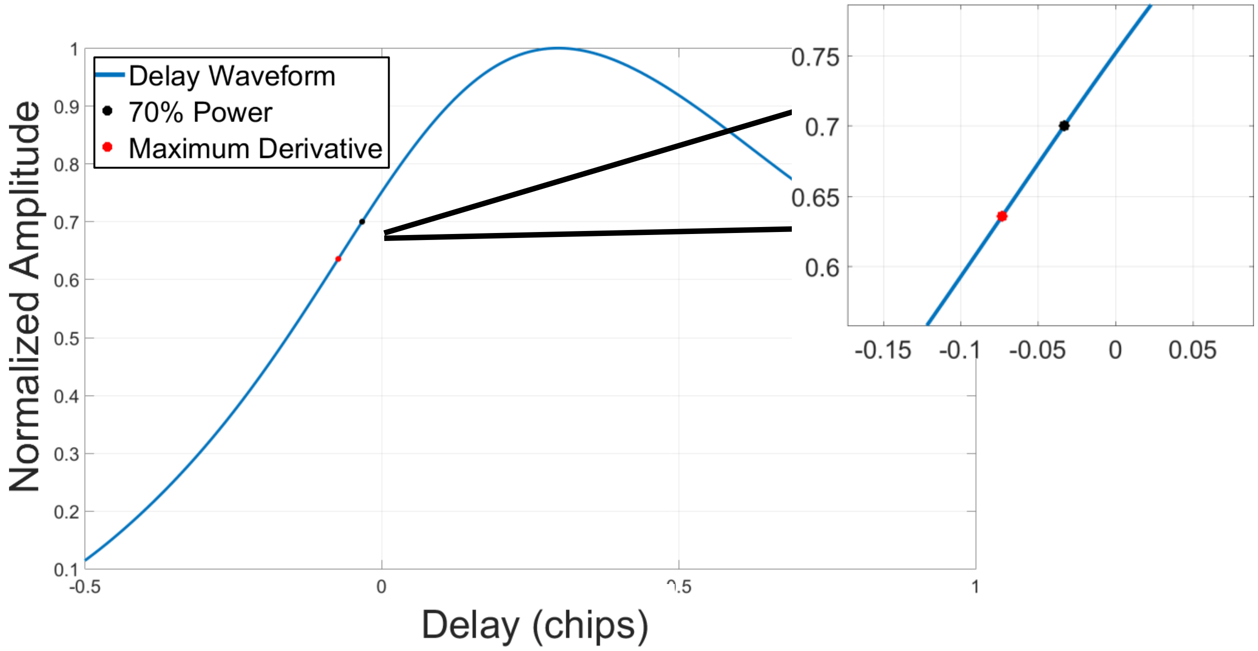



**E2ES Low-Res DDM**



# Using Point-Based Approaches for Ocean Altimetry

- A few single point tracking methods have been proposed such as maximum derivative [1] or 70% power value on the leading edge slope [2]
- Figure below shows an example delay retrieval



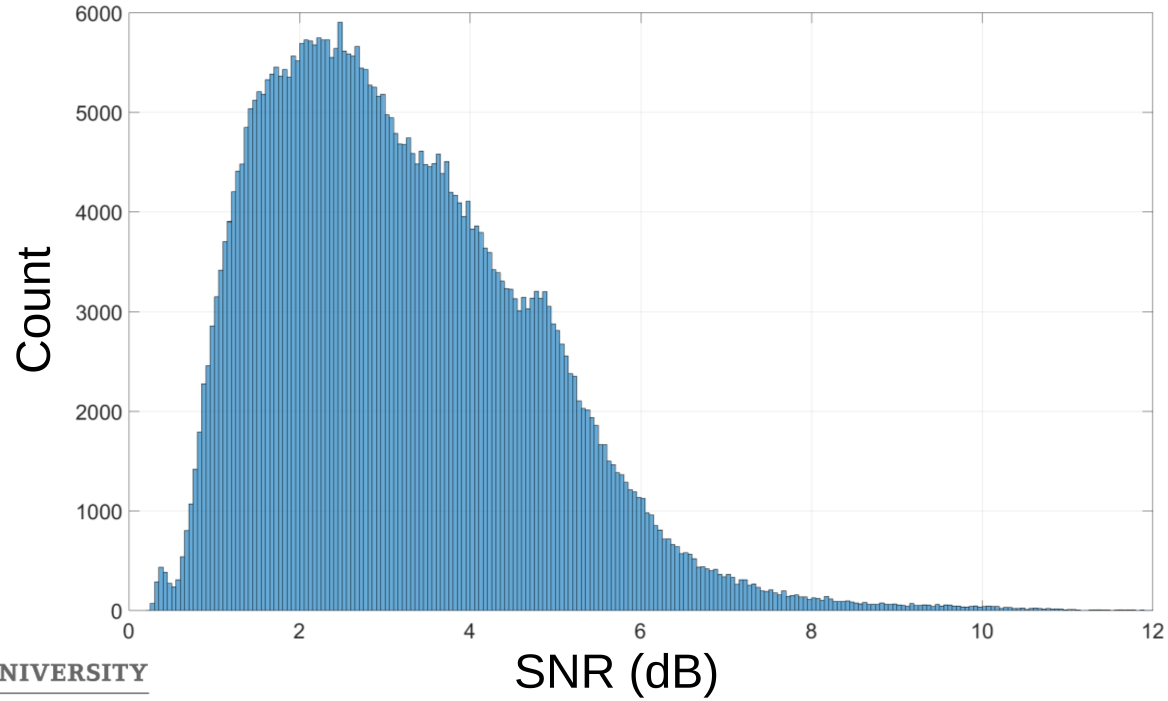


[1] W. Li, A. Rius, F. Fabra, E. Cardellach, S. Ribo and M. Martin-Neira, "Revisiting the GNSS-R Waveform Statistics and Its Impact on Altimetric Retrievals", IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 5, pp. 2854-2871, 2018. Available: 10.1109/tgrs.2017.2785343.

[2] J. Mashburn, P. Axelrad, S. T. Lowe, K. M. Larson, “Global Ocean Altimetry with GPS Reflections from TechDemoSat1”, IEEE Trans. Geosci. Remote Sens., 2018.

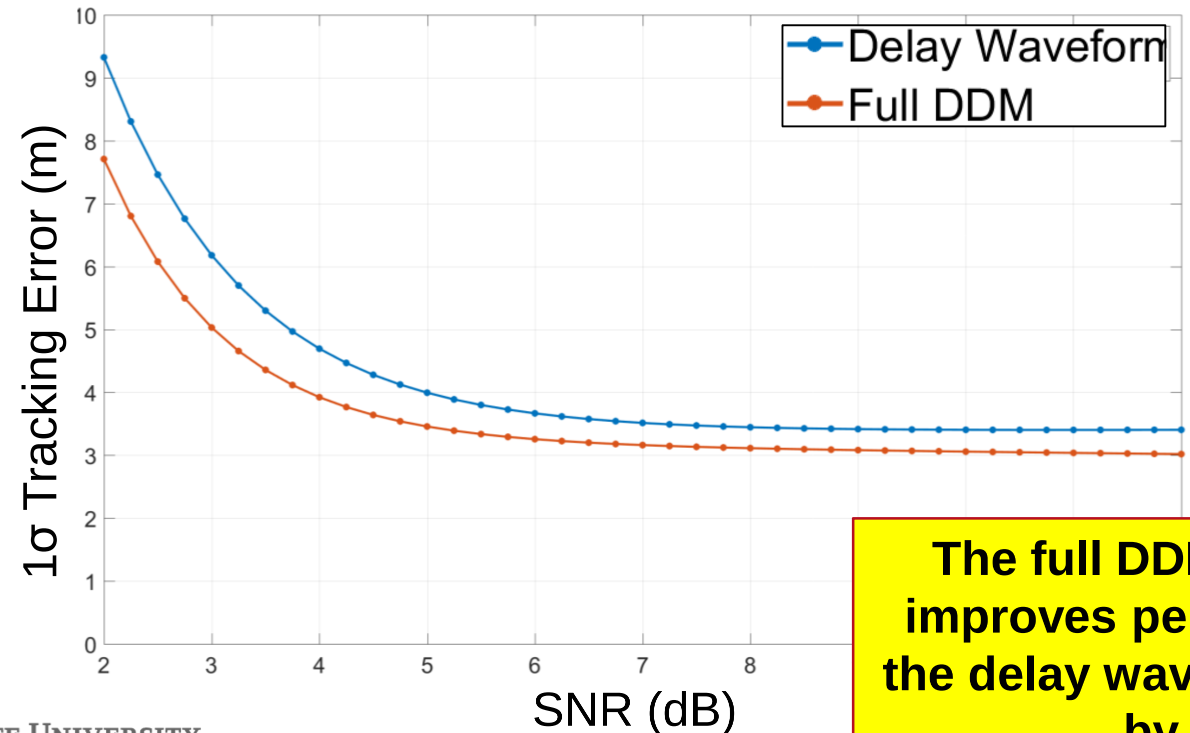
# Typical CYGNSS SNR

- We will quantify the delay estimation performance varies over different SNRs. (Note: in this work, we use the CYGNSS definition of SNR, which is really a peak-to-mean ratio)
- Figure below shows a histogram of CYGNSS SNR over a large section of the Pacific ocean over several days. Over the ocean, typical values range from 2-5dB
- Next, we will compare the estimated accuracy for the different algorithms



# Delay Estimation Performance – Full DDM

- In order to estimate the performance of the delay tracking algorithms, a large set of simulated DDMs were produced in the E2ES using CYGNSS metadata for the geometries and antenna patterns
- Thermal noise and speckle were added to the simulated DDMs, and retrievals were performed on the noisy DDMs.
- For each selected SNR value, 200 trials were evaluated




**The full DDM method has improves performance over the delay waveform approach by ~30%**

# Using a Weighted Least Squares Approach



- The current full-forward model approach use a least squares residuals minimization in order to make the estimates of delay
- This least squares method gives the same weight to every DDM bin, regardless of how much signal is present
- The delay estimation approach can be optimized by choosing weights in order to reduce the influence of noise in the match-up process
- The next slide shows an example of both the LS residual calculation, as well as the weighted LS

# Weighted Least Squares Match-Up Approach

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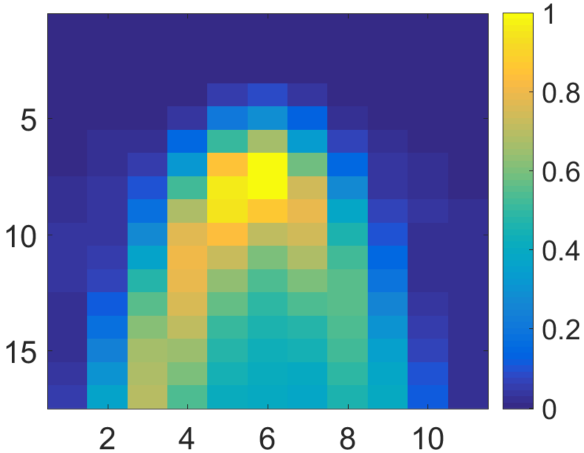
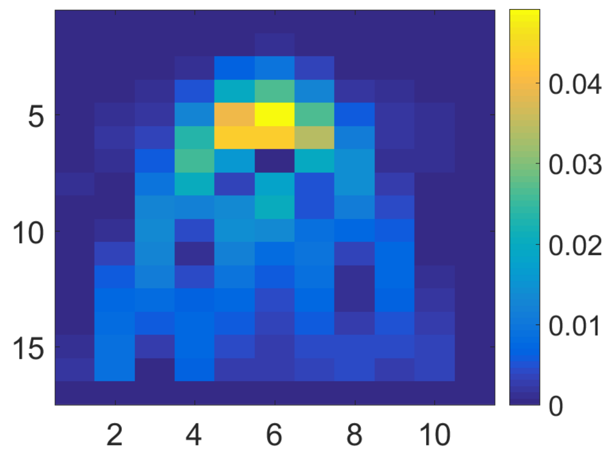
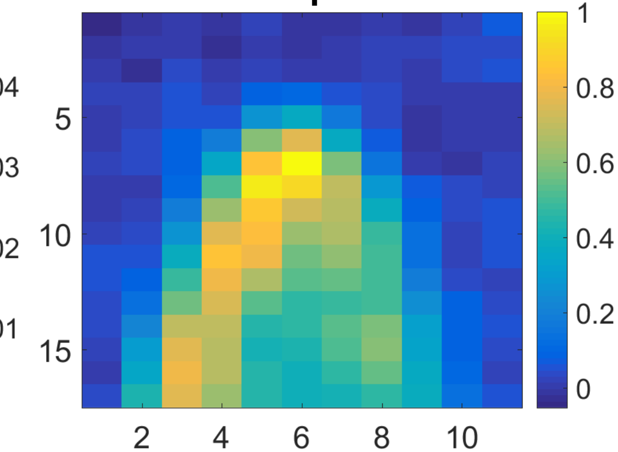
**Template DDM at CYGNSS resolution**



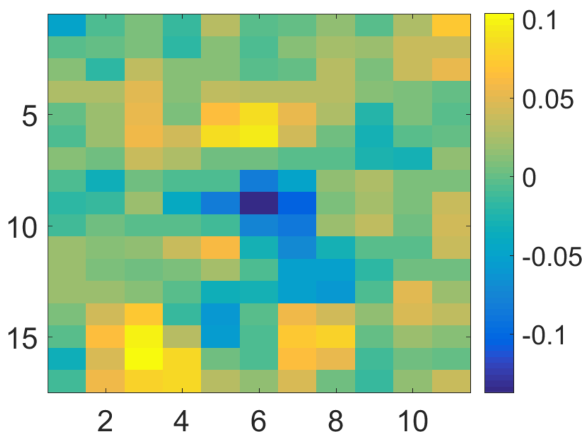

**Example Weights**



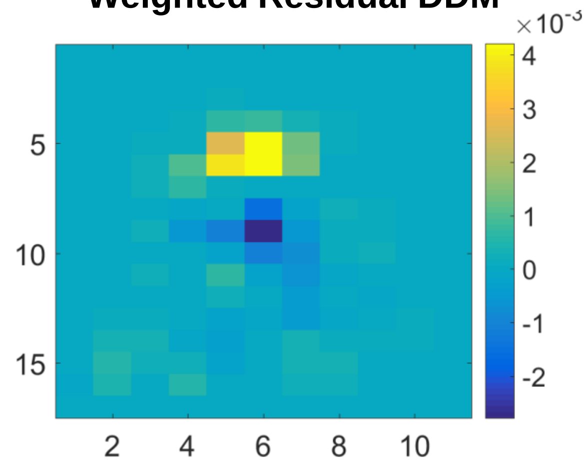

**Simulated DDM with thermal noise+speckle**




**Residual DDM**




**Weighted Residual DDM**




**The use of weights deemphasizes the noise and focuses more on the signal**

# Maximum Likelihood Approach



- Another way to implement a weighting scheme is to estimate the delay through the use of a Maximum Likelihood Estimator (MLE)
- The MLE is found by maximizing the log-likelihood function of the signal
- We can stack the measured DDM into a single vector, called X
  - The likelihood ratio is then:

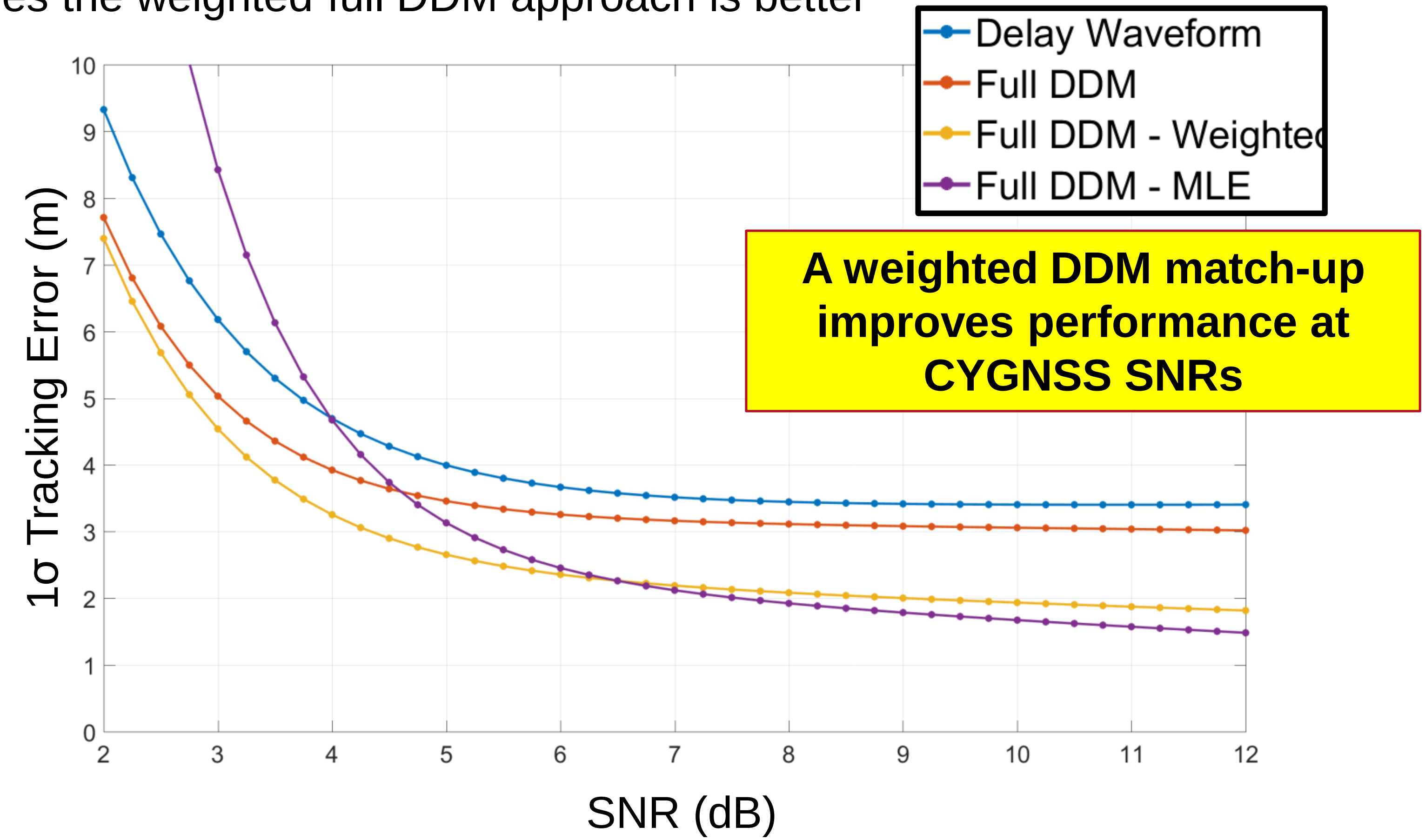
$$\mathcal{L}(X|\theta) = \frac{1}{(2\pi)^{\frac{N}{2}}|C_X(\theta)|^{\frac{1}{2}}} \exp\left[-\frac{1}{2}\left(X - \bar{X}(\theta)\right)^T C_X^{-1}\left(X - \bar{X}(\theta)\right)\right]$$

  - Where $C_X(\theta)$ is the covariance matrix, X is the measured waveform, $\bar{X}(\theta)$ is the mean waveform (expected value)
- The solution to this is then:
  - $\hat{\theta} = argmin_{\theta}[\ln|C_X| + e^T(\theta)\, C_X^{-1}\, e(\theta)]$
  - Where $e(\theta)$ is the residual vector
- This approach depends on having an accurate covariance matrix for each DDM, which may be computationally expensive in practice
  - In this presentation, we use an approximation for the estimated correlation between DDM bins as $\rho(\theta - \theta_0\,, f - f_0) \cong WAF$

# Delay Estimation Performance – Weighted Least Squares and MLE



- Figure below shows comparison of estimated tracking performance including both the weighted least squares retrieval approach and the MLE
- The simplified MLE is better at higher SNRs, but at typical CYGNSS SNR ranges the weighted full DDM approach is better



# Use of Full DDM Method to Retrieve Sea Surface Height

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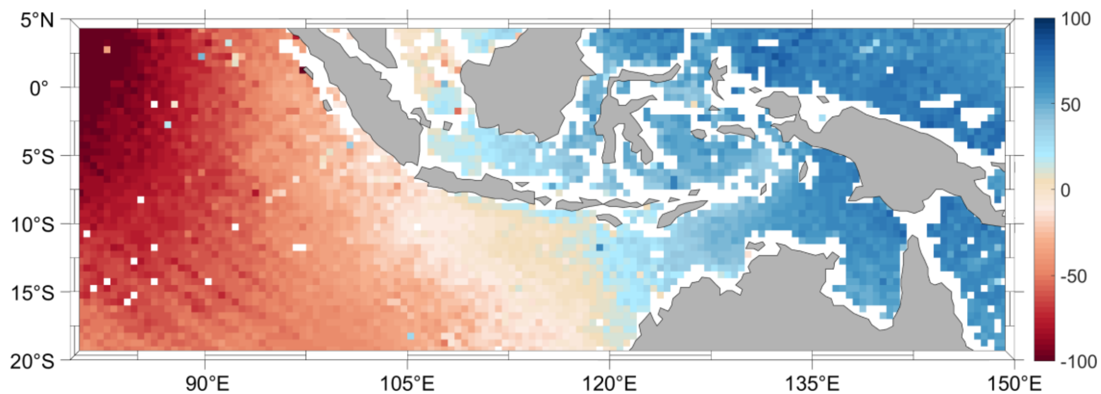
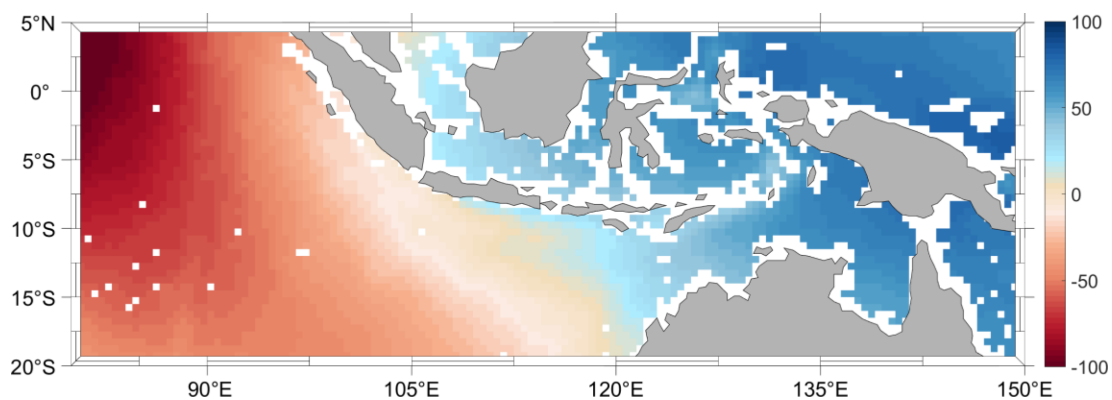
- The full DDM match-up approach was implemented in C for a large scale assessment of CYGNSS data over the Indonesian region
- Delay corrections were performed for the iono/troposphere, CYGNSS metadata variables, CYGNSS and GPS orbits, antenna lever arm, etc.
- Plots below show comparison of CYGNSS retrieved surface and the DTU10 "truth"

**CYGNSS retrieved Sea Surface Height**




**DTU10 Mean Sea Surface**



# CYGNSS Ocean Altimetry in Low Wind

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- A small, but non-negligible portion of CYGNSS ocean DDMs contain low-wind conditions.  Zavorotny & Voronovich have shown that the shape of the DDM waveform under these conditions can be quite different and a coherent component can also be present.
- We updated the CYGNSS E2ES to handle both the new low-wind diffuse scattering as well as a coherent component.  We ran the updated, low-wind SSA model and tabulated BRCS values versus incidence angle, scattering angle (theta, phi) and wind speed. These are now used to produce DDMs over all of the MSS regimes.
- Our simulated data has three independent components:  non-coherent (based on SSA tabulation), coherent, and a noise floor. We match E2ES with measured CYGNSS DDMs by finding the least mean square solution of these three components.

# CYGNSS Ocean Altimetry in Low Wind

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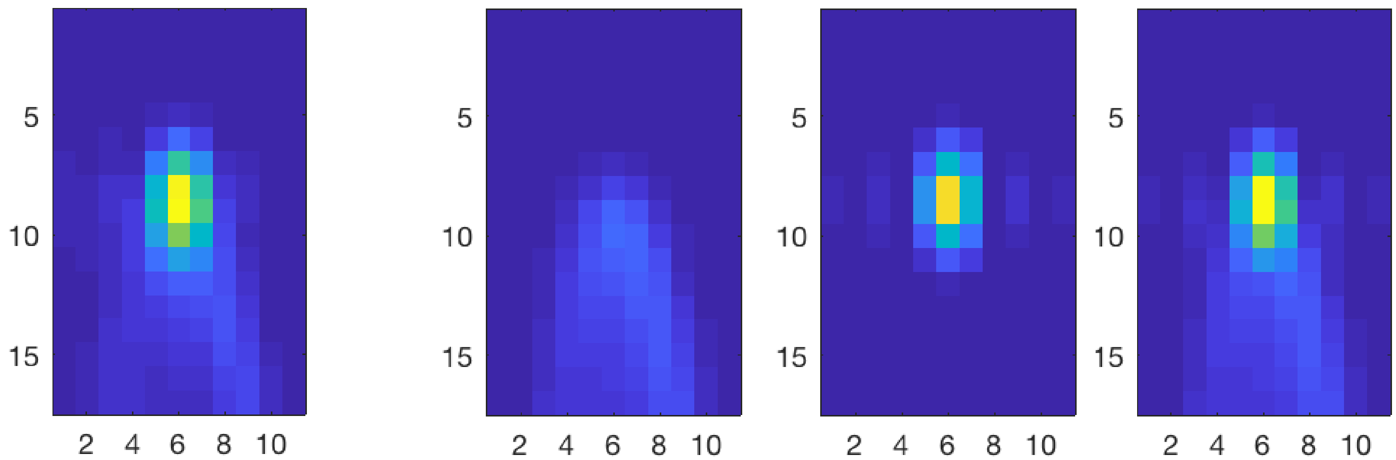
- During our ocean altimetry retrieval, the relative strengths of the non-coherent component, coherent component, and noise floor are all independently estimated
- Example below shows a low-wind DDM measured from CYGNSS over the Indonesian region. The E2ES is able to estimate the components separately to produce excellent agreement

**CYGNSS Measured**

**CYGNSS E2ES Simulated**

**Non-Coherent Component** | **Coherent Component** | **Total**



# Retrieval Performance in Coherent Regime

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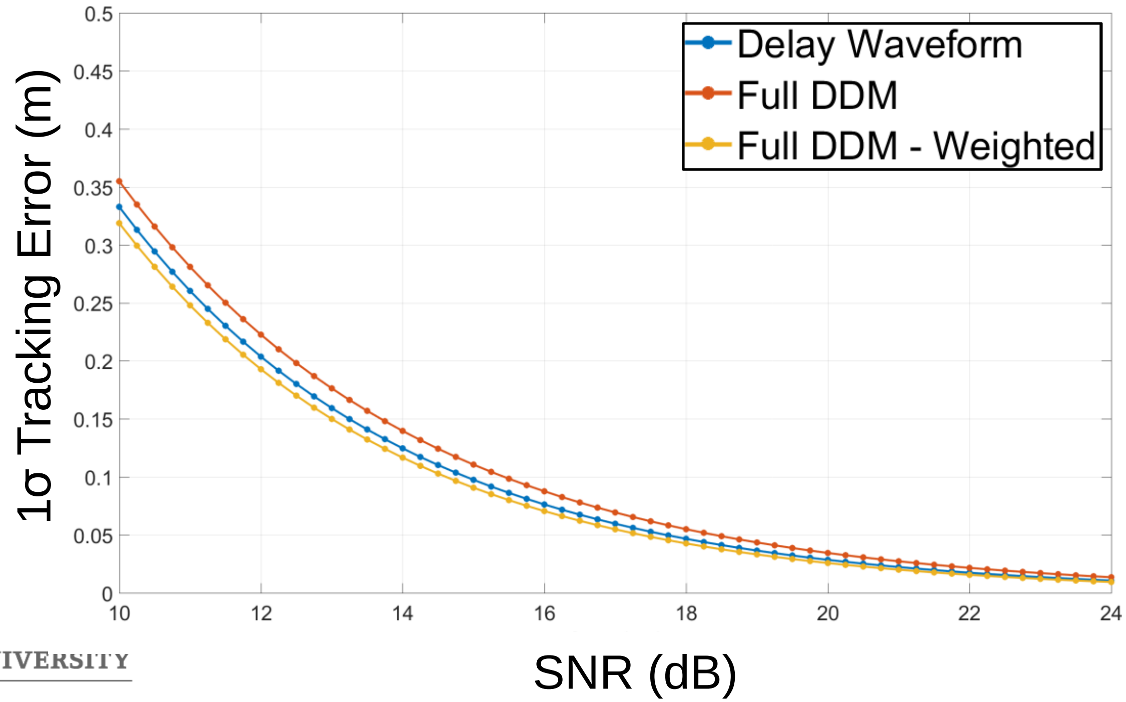
- Delay estimation using DDMs with coherent reflections performs much better than the non-coherent cases due to a few significant differences:
  - SNR is typically higher, known tracking points, and reduced speckle noise
- Figure below shows delay error for typical SNR values of coherent reflections seen by CYGNSS



# Conclusions

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- The CYGNSS E2ES has been modified to produce template DDMs for the purpose of estimating sea surface heights
- The use of a full DDM approach results in higher delay accuracy than either delay waveform or single point tracking methods
- We have also introduced a simple weighted least squares estimation approach to further improve the delay performance
- The E2ES is also capable of modeling reflections in low-wind scenarios where there is a mixture of coherent and diffuse power
- Tracking coherent reflections with CYGNSS can lead to significant improvements in delay estimation
- Future work would include evaluating similar retrieval algorithms for next-generation GNSS-R receivers utilizing other GNSS signals