Improved Ocean Altimetry Methods with CYGNSS Observations in Indonesia
IEEE GNSS+R 2019 – Benevento, Italy, 20-22 May, 2019

Jake Mashburn, Penina Axelrad
University of Colorado Boulder

Andrew O’Brien, Eric Loria
The Ohio State University

Cinzia Zuffada, Bruce Haines, George Hajj
NASA Jet Propulsion Laboratory
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
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
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**

\[ \Delta \delta = (\delta_{\text{measured}} - \delta_{\text{modeled}}) \]

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.
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

20-22 May, 2019
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.

[Maps showing SNR and waveform width in Indonesia region]
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
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
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.

2x 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.
VZ18 Model Tracking

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

<table>
<thead>
<tr>
<th></th>
<th>P70</th>
<th>VZ18DDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>-10m</td>
<td>-4.4m</td>
</tr>
<tr>
<td>σ</td>
<td>9.9m</td>
<td>9.5m</td>
</tr>
</tbody>
</table>
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
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
  \[ M(\gamma) = \frac{\alpha}{\sin(\gamma)}, \quad \alpha = \frac{e - \exp(1 - \exp(-z_{FP}))}{e - \exp(1 - \exp(h_0/H))} \]
- Map reflection path effects to slant angles with Komjathy mapping
  \[ M(\gamma) = \frac{1}{\sqrt{1 - \left(\cos(\gamma) R_E / H \right)^2}} \]

\[ \delta_{\text{iono}} = (\delta_1 + \delta_2) - \delta_3 \]

20-22 May, 2019
Residual Ionospheric Errors

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

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

20-22 May, 2019
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
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
• 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
SSH Retrieval in Indonesia

<table>
<thead>
<tr>
<th>Tracking Method</th>
<th>Single Sample, $\sigma_H$ [m]</th>
<th>Gaussian Smoothed, $\sigma_H$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P70 (1 sec)</td>
<td>6.7</td>
<td>1.9</td>
</tr>
<tr>
<td>VZ18WAVE (1 sec)</td>
<td>10.9</td>
<td>3.2</td>
</tr>
<tr>
<td>VZ18DDM (1 sec)</td>
<td>5.8</td>
<td>1.9</td>
</tr>
<tr>
<td>P70 (10 sec)</td>
<td>3.6</td>
<td>1.3</td>
</tr>
<tr>
<td>VZ18DDM (10 sec)</td>
<td>3.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

![P70 – 1s obs](image1.png)

![VZ18DDM – 10s obs](image2.png)
Altimetry Results – CYGNSS

Error Budget

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Uncorrected Magnitude</th>
<th>Residual Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYG orbit error</td>
<td>3 m position</td>
<td>0.03 m (1σ Gipsy)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.70 m (1σ UKF)</td>
</tr>
<tr>
<td>TX orbit error</td>
<td>1 m position</td>
<td>0.03 m position (1σ)</td>
</tr>
<tr>
<td>DTU10 MSS</td>
<td>100 m height</td>
<td>0.1 m height (1σ)</td>
</tr>
<tr>
<td>Ionosphere delay</td>
<td>&lt; 15 m delay (day)</td>
<td>&lt; 3.5 m delay (RMS)</td>
</tr>
<tr>
<td></td>
<td>&lt; 7 m delay (night)</td>
<td>&lt; 2 m delay (RMS)</td>
</tr>
<tr>
<td>Troposphere delay</td>
<td>6 m delay</td>
<td>0.05 m delay (1σ)</td>
</tr>
<tr>
<td>Antenna baseline</td>
<td>1 m delay</td>
<td>0.001 m delay (1σ)</td>
</tr>
<tr>
<td>add_range_to_sp truncation</td>
<td>± 15 m delay</td>
<td>4.6 m delay (1σ)</td>
</tr>
<tr>
<td>Open loop delay-Doppler smearing</td>
<td>≤ 1 m delay</td>
<td>≤ 1 m delay</td>
</tr>
<tr>
<td>Tracking error</td>
<td>P70 (1s obs)</td>
<td>10 m</td>
</tr>
<tr>
<td>(at mean SNR = 15dB)</td>
<td>VZ18WAVE (1s obs)</td>
<td>5.5 m</td>
</tr>
<tr>
<td></td>
<td>VZ18DDM (1s obs)</td>
<td>2 m</td>
</tr>
</tbody>
</table>

\[
RSS_{P70} = 11.6 \text{ m delay}
\]
\[
RSS_{VZ18WAVE} = 7.9 \text{ m delay}
\]
\[
RSS_{VZ18DDM} = 5.9 \text{ m delay}
\]
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
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