GNSS Reflectometry for Earth Remote Sensing

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Invited Presentation

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Outline

• Basic Principles of Reflectometry
• Early oceanographic applications
• Spaceborne reflectometry
• Research directions: Data assimilation
• Other variables
• Future work – beyond GNSS
• Conclusions
GNSS Basic Principles

\[ c\tau_1 = \sqrt{(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2 + ct_b} \]
\[ c\tau_2 = \sqrt{(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2 + ct_b} \]
\[ c\tau_3 = \sqrt{(X - X_3)^2 + (Y - Y_3)^2 + (Z - Z_3)^2 + ct_b} \]
\[ c\tau_4 = \sqrt{(X - X_4)^2 + (Y - Y_4)^2 + (Z - Z_4)^2 + ct_b} \]

4+ Observations

4 Unknowns

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GNSS Basic Principles

- Ideal navigation signal – infinitely-long sequence of random pulses (in reality – Pseudorandom noise (PRN))

- Received and local signals not aligned

- Received and local signals partially aligned
• **Cross-correlation** of $(\infty$-long) sequence of random pulses – large values for narrow range of delay
GNSS-R Basic Principles

Receiver

glistening zone

glistening zone

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Rough Surface Scattering

Phenomenon observed in visible light at sunset:
(water is calm inside the red ellipse)

(From Chapron and Ruffini, 2003 GNSS-R workshop, Barcelona. Photo taken at Le Conquet, Brittany)
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Early Airborne Experiments

Ca. 1997

Surface Wind Speed
(Assumed wave spectrum model)

Measured Waveform

Best Fit of Model Waveform

Brightness Temperature


[ Garrison, et al. GRSL 2011 ]

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Why GNSS-R from Space?

Simulated Coverage of Hurricane Frances: ASCAT vs. CYGNSS

Going to Space ...

Maximum Delay for 25 km resolution
• Spaceborne observation – 2D “delay-Doppler Map” (DDM)
• 25 km resolution requirement: 3 X 5 pixels used in L2 retrieval
• Downloaded to the ground: 17 x 11 pixels around specular point
CYGNSS

- 8 satellite GNSS-R constellation

Improved forecast of tropical cyclone intensification:

1. Better penetration of rain (L-band vs K-band)
2. Higher revisit rate (2.8 H med. vs 11-35 H)
Cyclone GNSS (CYGNSS) Launch 12-Dec-2016

[University of Michigan]

https://www.youtube.com/watch?time_continue=1&v=rRBqn6JPtv8

[Ruf, et al. JSTARS, 2018, DOI:10.1109/JSTARS.2018.2833075]
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Let’s return to this picture ...

Example of E2ES DDM

Surface area covered

- Delay (chips)
- Doppler (kHz)
- x (km)
- y (km)

- 25 km resolution cells, i.e. 3x5 pixels
- 50 km resolution cells, i.e. 17x11 pixels
- Current DDM size, i.e. 36 x 20 pixels
As an equation ...

\[ P_R(\tau, f_D) \propto \int_S |\chi(\tau, f_D)|^2 \times G_R \times \frac{1}{R_R^2} \times P_{ij} \left( \frac{\vec{q}_+}{q_z} \right) \times \frac{1}{R_T^2} dA \]

- Delay-Doppler Map (DDM)
- Integral over surface
- Masking of Surface by delay-Doppler mapping
- Path loss Surface-receiver
- Masking of Surface by Receiver antenna
- Cross-section: Proportional to Probability of slope scattering in correct direction
- Path loss Trans-surface

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Data Assimilation

True Wind field

Wind speed
Wind direction
Waves
Antenna Pattern, S/C Attitude
GPS EIRP ...

Observed DDM

Wind Speed Retrieval (point)
Observable

(Data is just for illustration – not actual observations)

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Data Assimilation

True Wind field

- Wind speed
- Wind direction
- Waves
- Antenna Pattern
- S/C Attitude
- GPS EIRP ...

Model Wind field

Forward Model

Adjustment

Observed DDM

Model DDM

Diff

(Data is just for illustration – not actual observations)

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Data Assimilation

- Experience from GNSS Radio-occultation (GNSS-RO):
  
  \[
  N_d(0) = 77.64 \frac{P_0}{T_0} \\
  N_w(0) = 3.73 \times 10^5 \frac{e_0}{T_0^2}
  \]

  \[
  \alpha(a) = 2a \int_a^{\infty} \frac{dn}{n dx} \frac{dx}{\sqrt{x^2 - a^2}}
  \]

- Direct inversion (bending angle -> refractivity) assumes uniform properties over area covered by the integral

- Alternative: assimilate bending angle directly into weather models.
DDM forward model

- Sensitivity of DDM sample to surface wind speed

![DDM bins and Sensitivity to surface grid points](image)

Delay-Doppler ambiguity
DDM forward model

“Delay-Doppler Ambiguity” – Have you heard this before?

Synthetic Aperture Radar (SAR) (Monostatic) [history.nasa.gov]

Bistatic Reflectometry [Zavorotny & Voronovich, 2000]
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Other Variables

Soil Moisture [1]

Post-Hurricane Flood Inundation [1]

Mapping inland waterways under dense biomass [1]

Freeze-Thaw State [2]

[2] Scientific Reports DOI: 10.1038/s41598-018-27127-4
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Why GNSS?

- Continuous global coverage
- L-band good penetration of atmosphere, vegetation, rain, etc ... (but not good penetrating soil)
- Pseudorandom noise (PRN) code – designed for ranging
- My career began with GNSS!
  (not radiometry, radar or communications)
What about other signals?

- Approximately 400 communication satellites in GEO
- High-powered (~30 dB above GNSS) signals
- Allocations in most bands used for remote sensing: L, S, C, Ku/Ka
- **Designed for data transmission – Not ranging!**
- **Assumption:** Compression & Encryption are very efficient at filling available spectrum
  - Data is nearly random
  - Direct signal can be used as reference
Signals of Opportunity (SoOp)

Self-Ambiguity Function
(Defined in: [Baker, et al., 2005, DOI: 10.1049/ip-rsn:20045083])

\[ |\chi(\tau, f_c)|^2 = \left| \frac{1}{T_I} \int_0^{T_I} s(t)s^*(t - \tau)e^{-j2\pi f_c t} dt \right|^2 \]
Why would SoOp be useful?

NTIA Spectrum Allocations: Very Valuable “Real Estate”
Two New Applications

P-band: Long wavelength, Better Penetration (RZSM & SWE)

Ku/K-band: Wide bandwidth “For free” (coastal altimetry)
Root Zone Soil Moisture (RZSM)

- Water in top ~1m of soil
- Essential for understanding water cycle & agricultural forecasts
- Global RZSM from model assimilation (e.g. SMAP L4)

5 cm

100 cm

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Wideband SoOp Altimetry

- Improved spatial-temporal sampling & coverage from SoOp Altimetry
  (Example: 9 days, Monterey Bay)

SSH Signature  
Altimeter (e.g. Jason-2/3) 10-day repeat  
8-satellite W-SoOp constellation

[Data from R. Shah, JPL]
Future Mission Concept

The “Virtual Swath”
SoOp as the “Third Way”

Conservation of Energy: $\Gamma = 1 - \epsilon$
Conclusions

- Spaceborne GNSS-R wind retrievals successfully demonstrated under *some conditions*.
- Perhaps wind speed is not the best variable?
  - Wind/Wave coupling
  - Direct DDM Assimilation
- Other geophysical variables can be retrieved
- **GNSS-R just the beginning - many other signals are out there!**
  - Diversity of frequencies in a crowded spectrum
  - High EIRP (+30 dB Vs. GNSS)
  - Broadly – “Signals of Opportunity” may introduce a “third way” of microwave remote sensing.
Data Sources

- CYGNSS (at the JPL PO.DAAC): https://podaac.jpl.nasa.gov/CYGNSS
- UK TDS-1: http://merrbys.co.uk/