Earth Remote Sensing using Surface-Reflected GNSS Signals (Part II)

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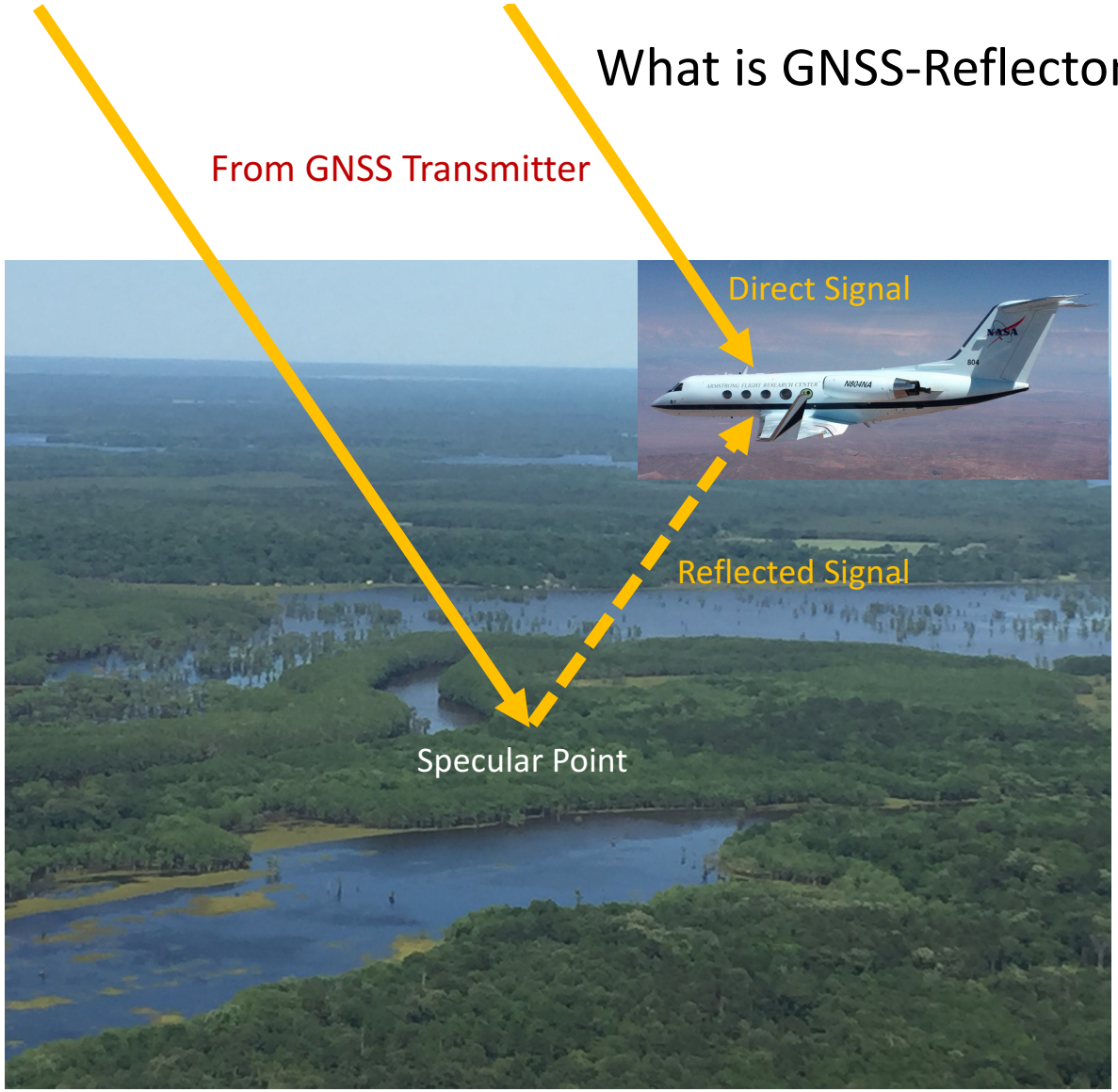
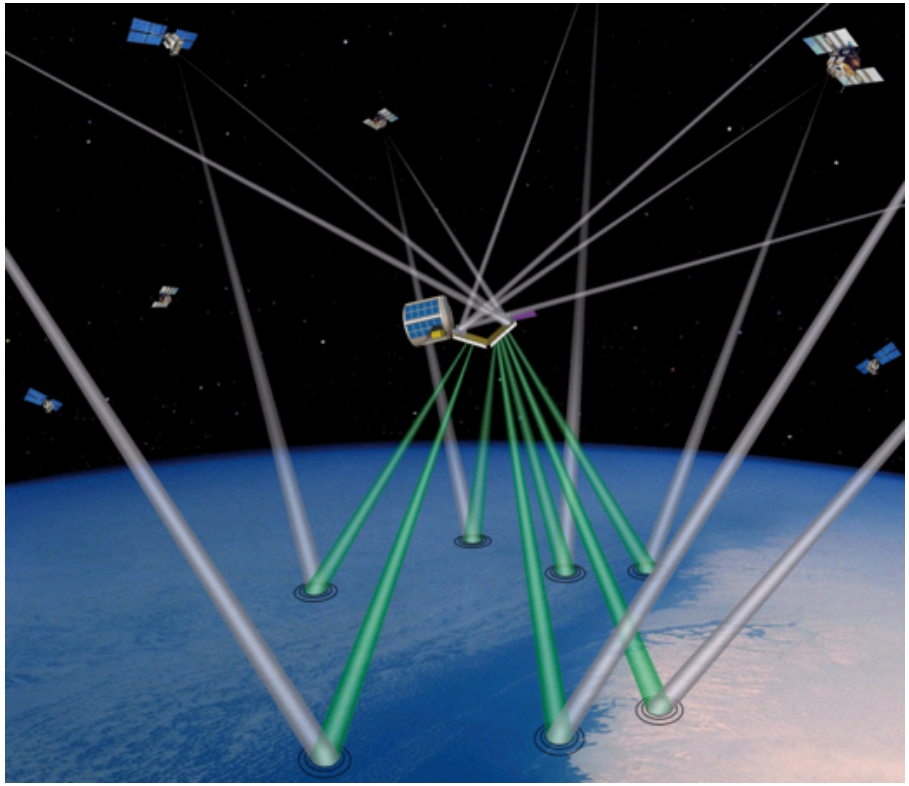
What is GNSS-Reflectometry (GNSS-R)?



GNSS-R

- Radar with separate transmitter and receiver (bistatic radar)
- Forward-scattering
- Specular Point: Earliest arrival at receiver

Space-Based GNSS-R System



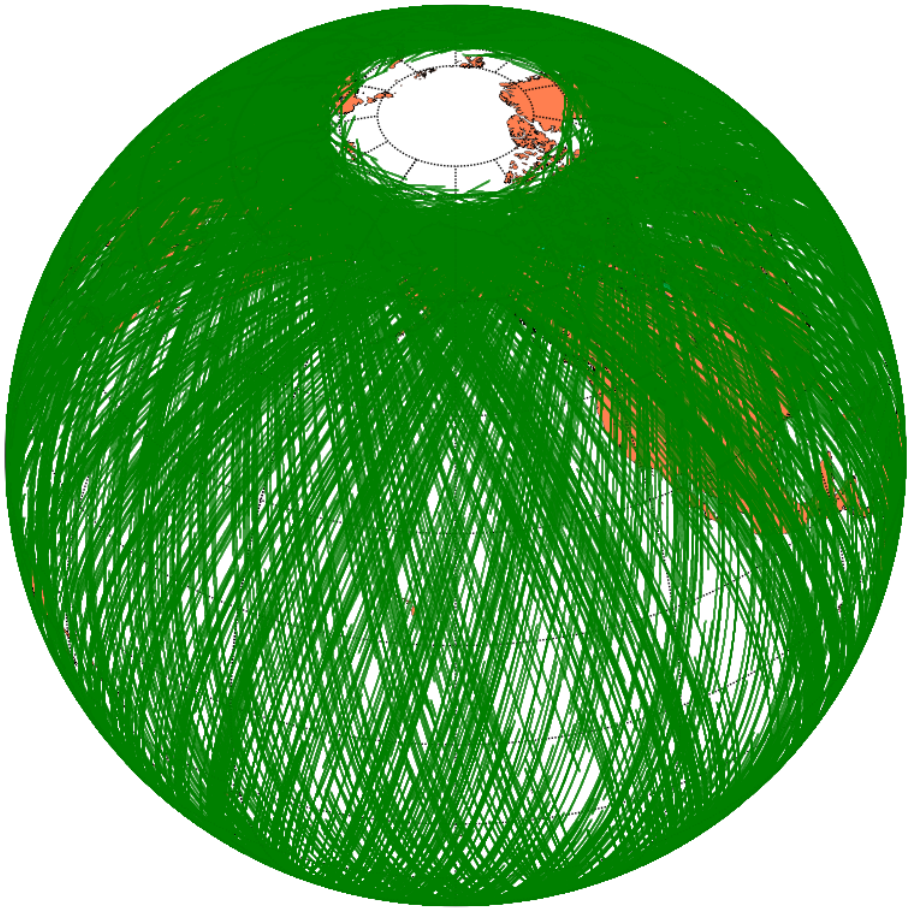
GNSS-R

- Multi-bistatic
- Next few years: >100 GNSS transmitters
- Dense surface coverage

Many Advantages

- Multiple, simultaneous observations
  - High spatial / temporal resolution
- Free high-quality signals
- Leveraging huge global infrastructure
- No transmitter
  - Relatively low cost, low power
  - Constellation possibilities (CyGNSS)
- Forward scattering (where the power goes)
- ~Same hardware as Radio-Occultations'

Surface Coverage

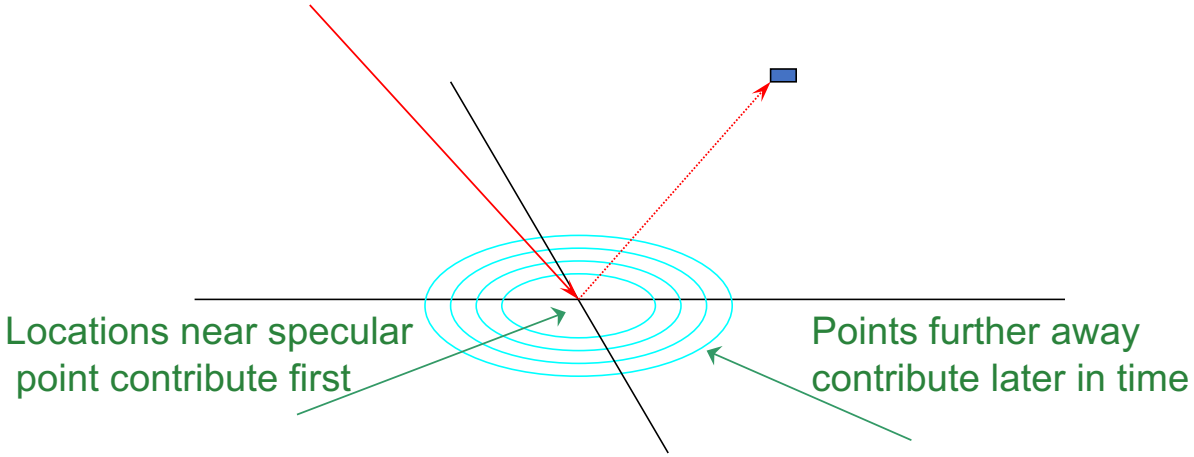


Coverage Simulation:

- 6-satellite constellation
- High inclination orbit (72 deg)
- 1 day
- GPS + Glonass + Galileo

Signal Effect: Autocorrelation Function

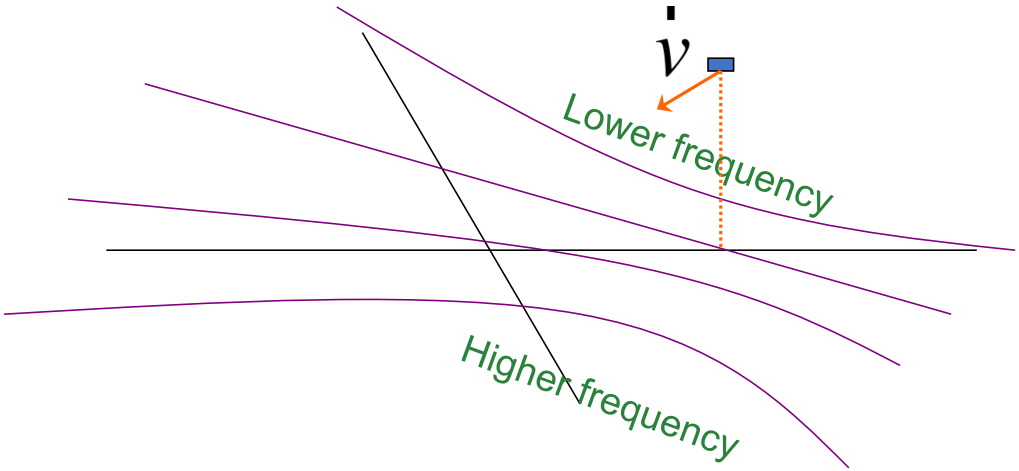
Iso-Delay Ellipses



- For delays of order λ => Fresnel Zone
- For delays of order τ (chip) => Iso-Delay Ellipses (code)
  - 1 MHz chip rate (GPS C/A code) => 293 m

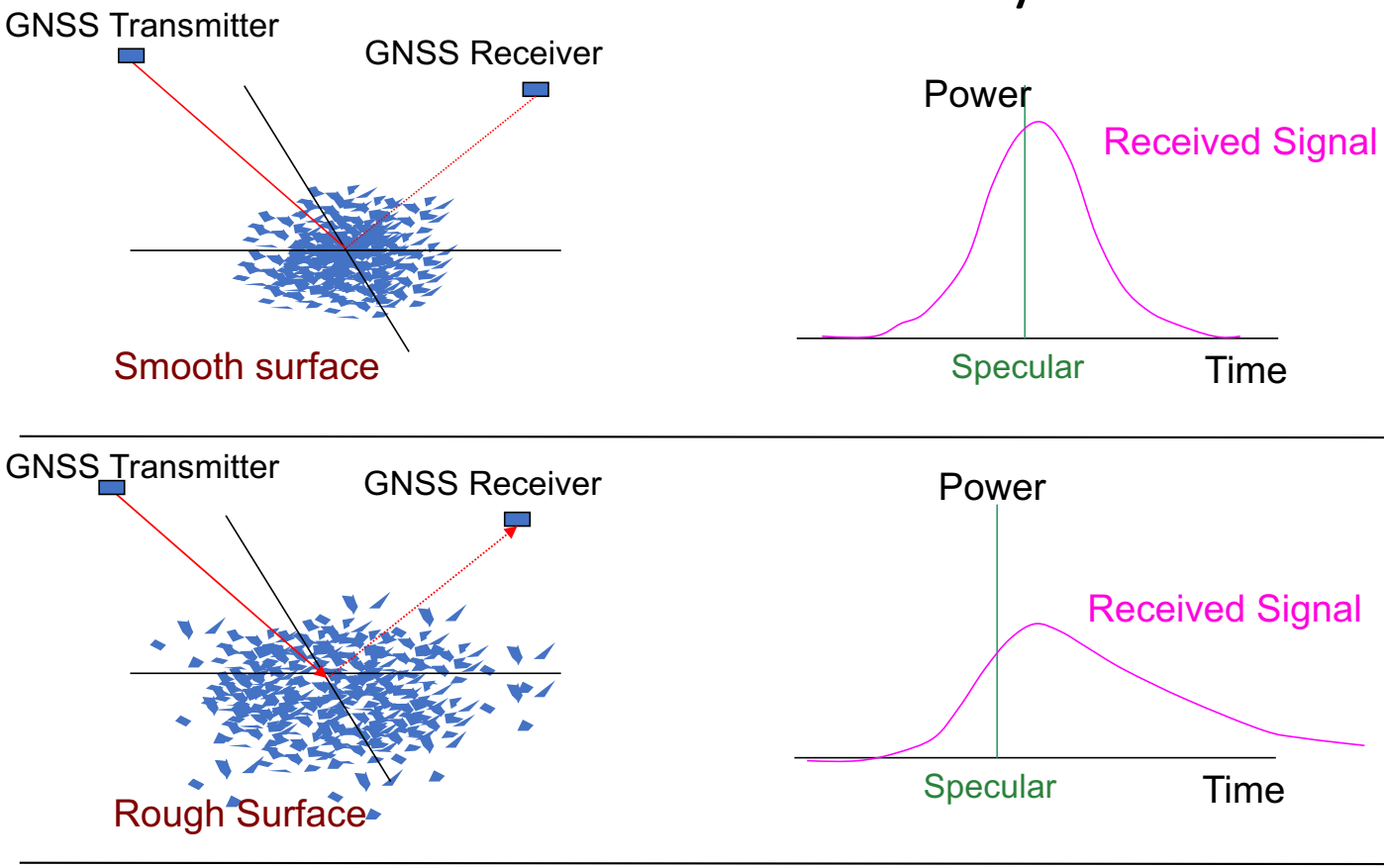
Receiver Effect: Velocity, Model Frequency, τ_{int}

Iso-Doppler Hyperbolas



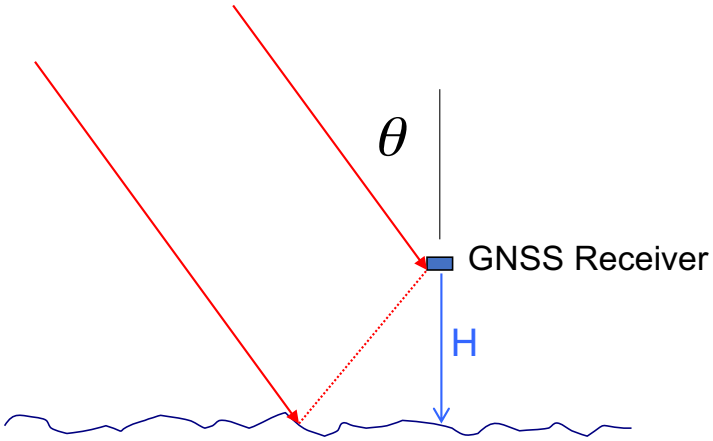
Signals arriving from forward direction arrive with higher frequency

GNSS-R Scatterometry

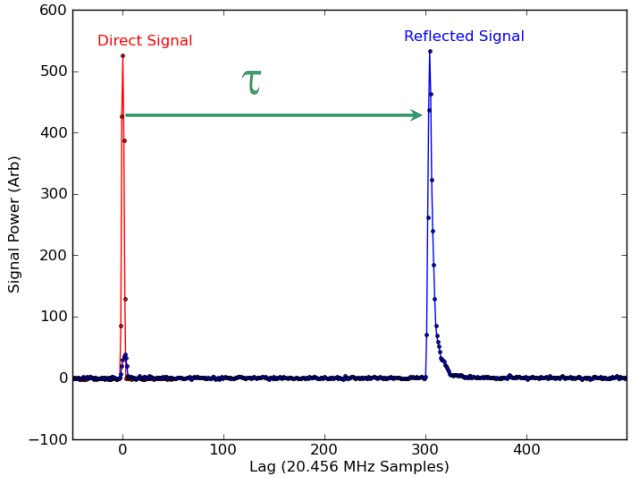


Smooth surface: Higher peak, faster rise
Rough surface: Lower peak, slower rise

GNSS-R Altimetry

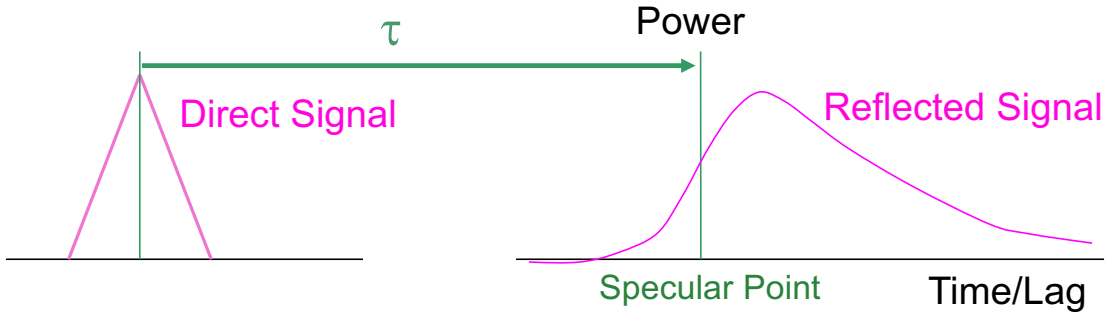


$$\tau = 2H\cos\theta$$

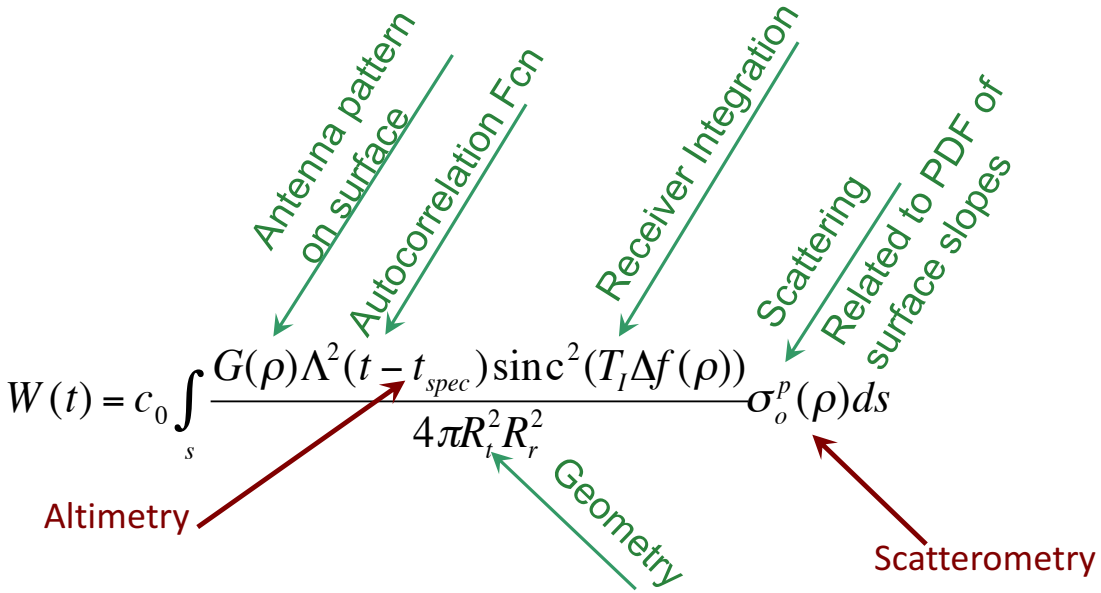


JPL 2003 Monterey-Bay aircraft test

Time delay (τ) between direct and ocean-reflected signal gives information on receiver height over surface



GNSS-R Bistatic Radar Equation



Zavorotny, V. U. and A. G. Voronovich, Scattering of GPS Signals from the Ocean with Wind Remote Sensing Application, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 2, 951-964, 2000.

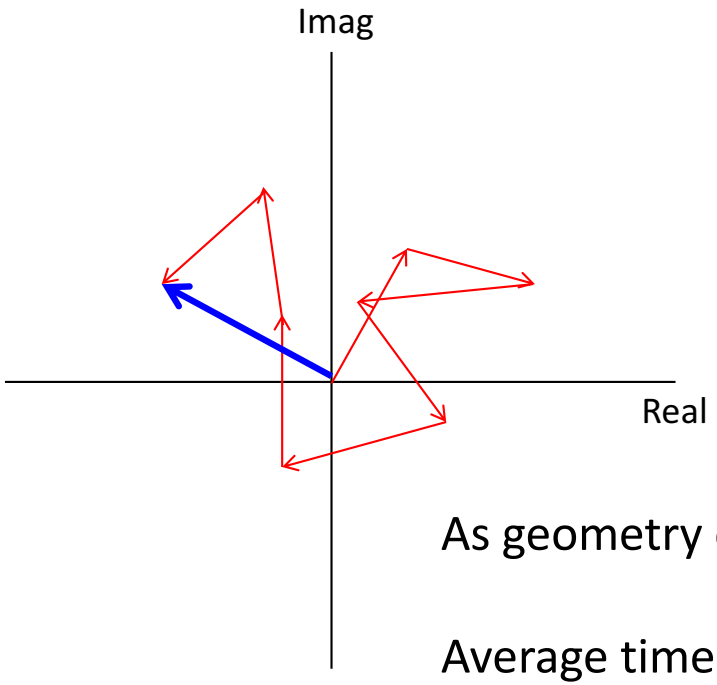
Scatterometry (oceans)

- This technique measures surface Mean-Squared Slopes (MSS)
- MSS related to wind speed through empirical model

Altimetry

- Specular timing relative to direct-signal reception

Signal Incoherence



- Received signal is sum over all surface facets
- Rough surface: resulting phasor has random phase
- Resulting power is exponentially distributed

  => Power SNR = 1 (speckle)

As geometry changes (receiver movement) the phasor sum changes.

Average time for phasor sum to be uncorrelated to previous sum is the signal's correlation time.

Aircraft: ~10 msec
Spacecraft: ~1 msec

What Measurements Can GNSS-R Make?

Red: Demonstrated from space

Green: Ground, aircraft experiments

Oceanography

- Surface winds (CyGNSS Mission: Cyclones)
- Mesoscale topology
- Tsunami science/warning
- Geoid / Mean Sea Surface

Land

- Soil Moisture
- Wetland Extent
- Freeze/Thaw State
- Vegetation Characteristics

Cryosphere (assuming high-inclination orbit)

- Sea-Ice Extent
- Ice freeboard
- snow depth
- Ice roughness / age

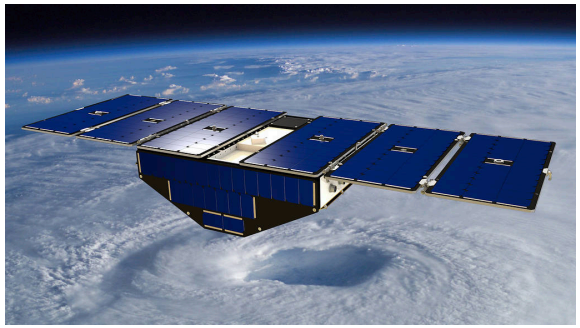
What's Happening in the GNSS-R Field?

Mission/Satellite	Year	# Space GNSS Reflections
SIR-C	2003 (obtained)	2
SAC-C	2003	~6
UK-DMC	2007	22
TechDemoSat1	2015-2017	~100M
SMAP (GNSS-R)	2015-present	>2.3M + 2900/day
CyGNSS (8 sats)	2017-present	>125M + 0.5M/day

Explosion of data in last 2 years

What's Happening in the GNSS-R Field?

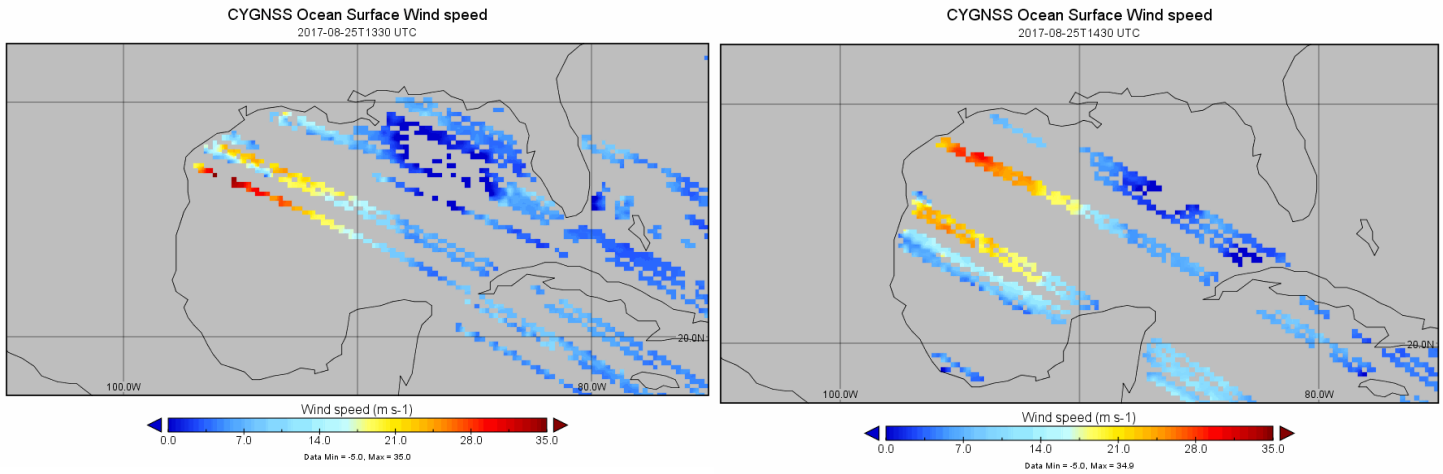
CyGNSS Satellite



CyGNSS: NASA Earth Venture Mission

- $157M to study Cyclone Science
- Goal: Improved cyclone intensity forecast
- 8 small-sats
- Observe GPS L1 C/A signals after reflecting from the ocean

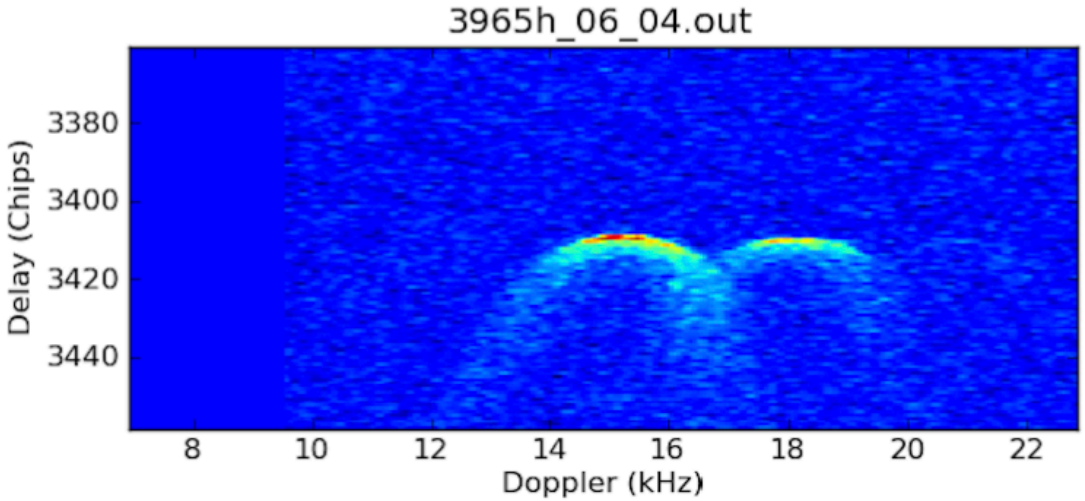
Observations of Hurricane Harvey Prior to Landfall on August 25, 2017



Courtesy Chris Ruf (PI)

CYGNSS Level 3 gridded surface wind speed data product (v1.1) at
1300-1400 and 1400-1500 UTC on 25 Aug 2017, prior to landfall at ~0300 UTC on 26 Aug 2017

What's Happening in the GNSS-R Field?



Delay-Doppler Map (DDM) has aliased images due to data blanking

NASA's Soil Moisture: Active & Passive (SMAP)

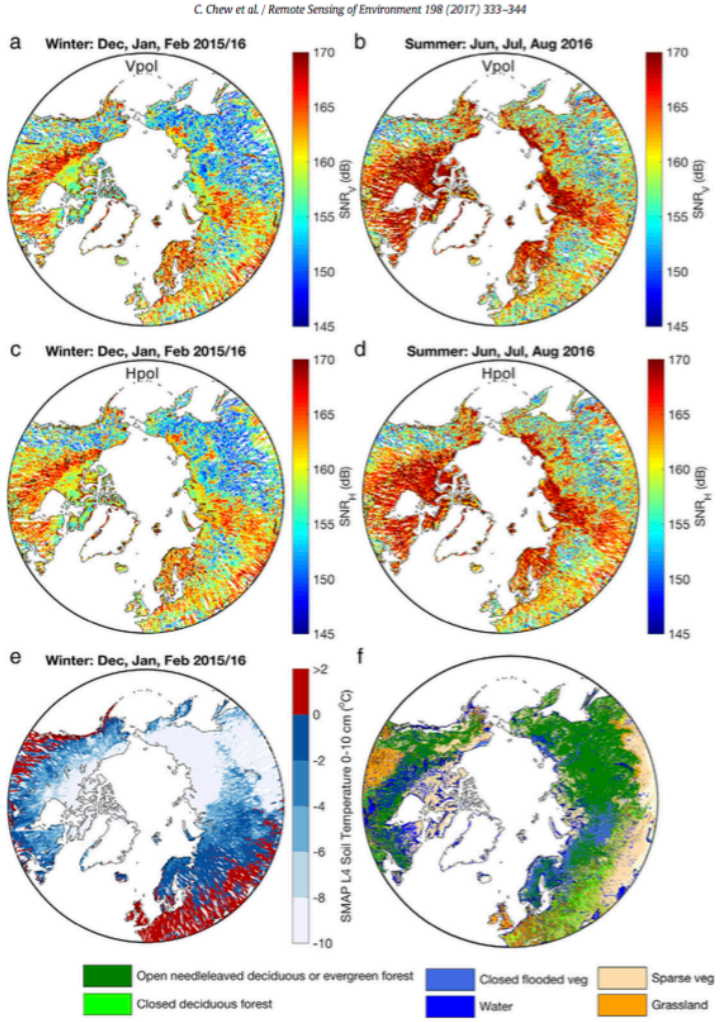
- Dedicated soil-moisture mission
- Active L-band radar + passive radiometer
- Radar transmitter failed 7/7/15
- On 8/20/15, radar receiver moved to collect GPS L2

Unique GNSS-R data set

- High gain antenna (~30 dB)
- Dual polarization (H/V)
- Raw sampled data downloaded
  - Look at phase, coherence, integration times, etc.
- Hope to make DDM + metadata public soon

Created unique GNSS-R data set from failed radar system

What's Happening in the GNSS-R Field?



SMAP GNSS-R Observes Freeze/Thaw

Vertical Polarization

Winter Summer

Horizontal Polarization

Winter Summer

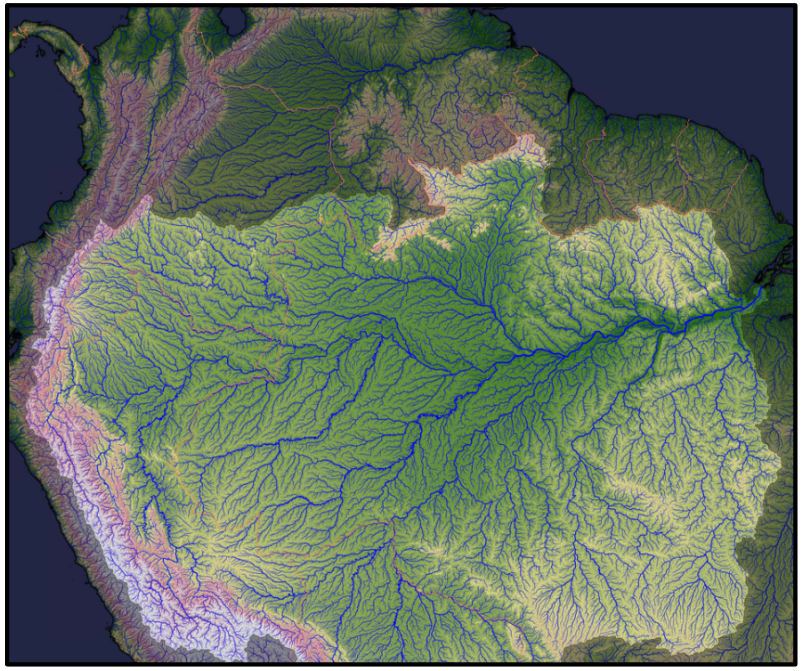
Winter Temp (blue frozen)

Vegetation Type

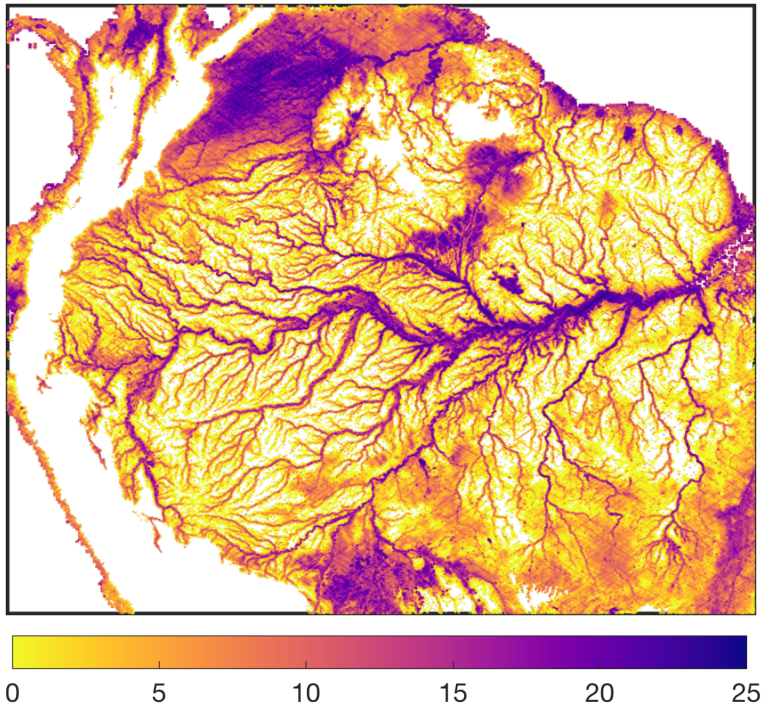
From Chew et al, Remote Sen Env 198, 2017

What's Happening in the GNSS-R Field?

HydroSheds Database



CyGNSS Data: SNR vs location



White: Outside CyGNSS delay window

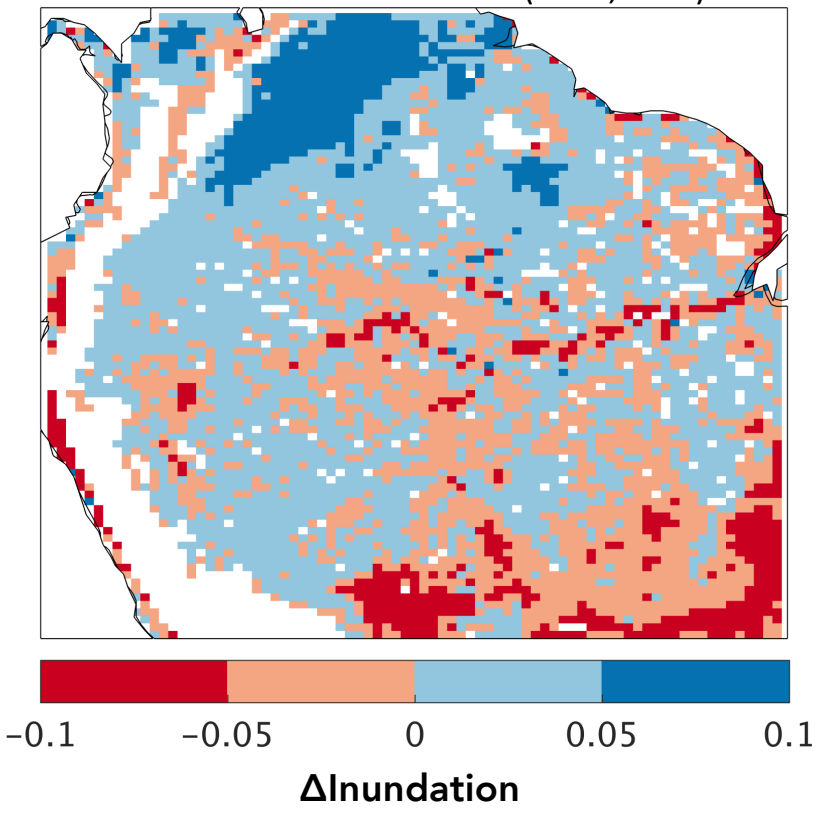
Amazon Rainforest

Courtesy Clara Chew (UCAR)

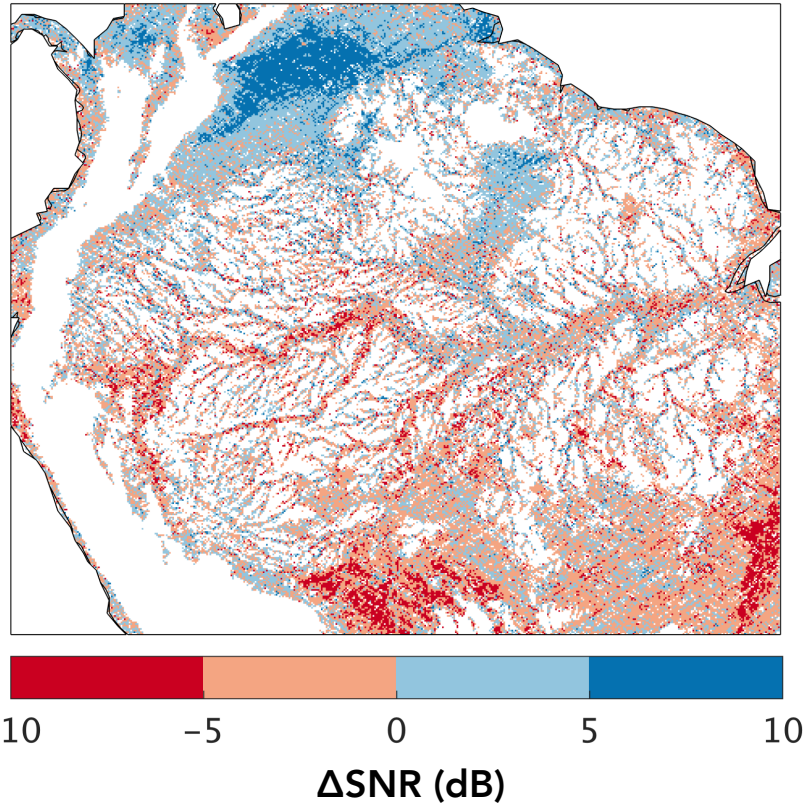
What's Happening in the GNSS-R Field?

Change in SNR: Aug - Mar

SMAP Radiometer (J. Du, et al)



CyGNSS Data



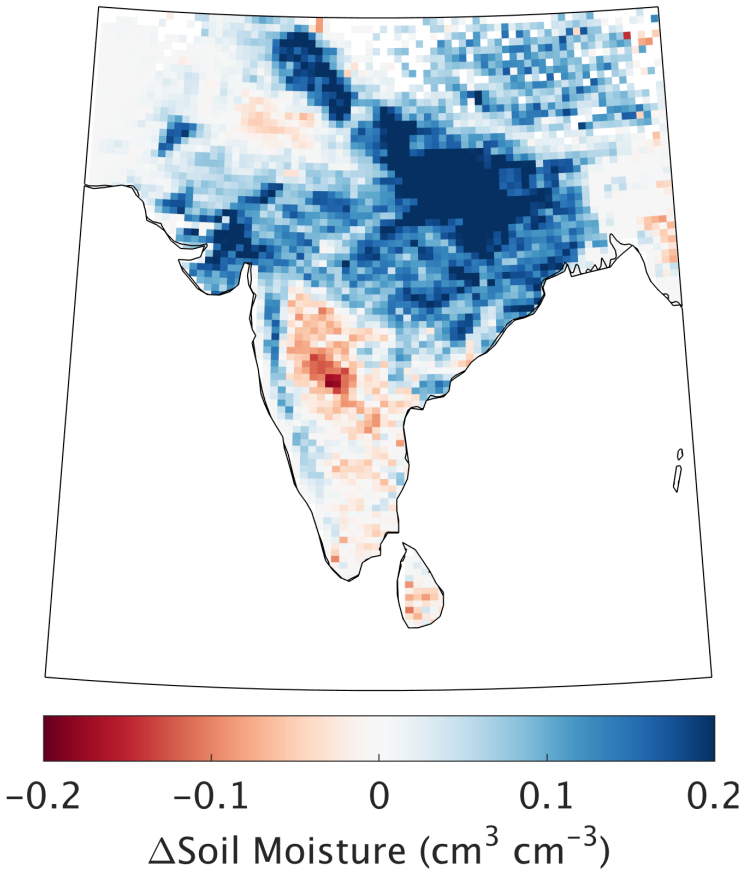
Amazon Rainforest

Courtesy Clara Chew (UCAR)

What's Happening in the GNSS-R Field?

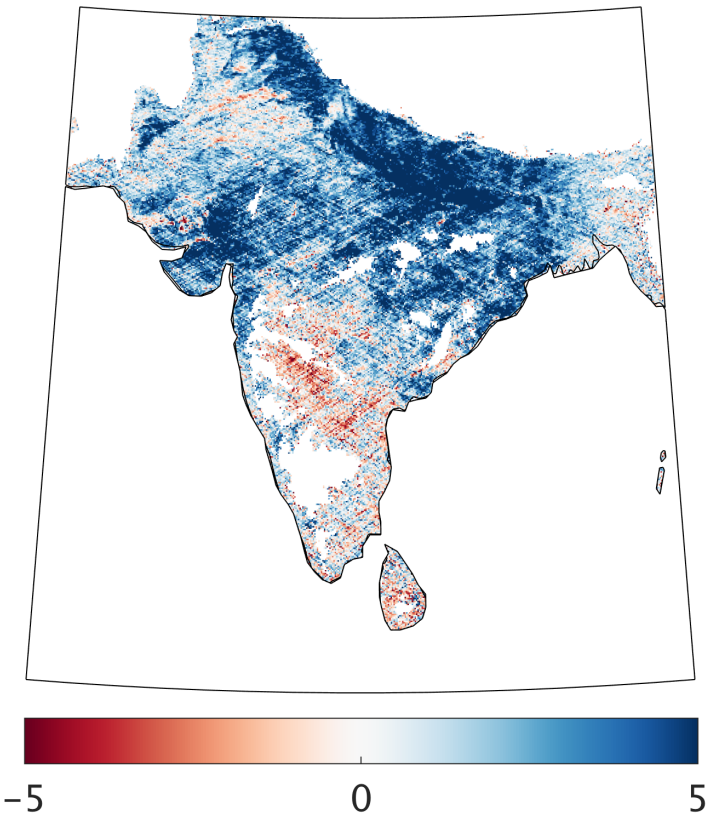
Change in SNR: Apr - Mar

SMAP Radiometer: Level 3



India

CyGNSS Data: SNR Change



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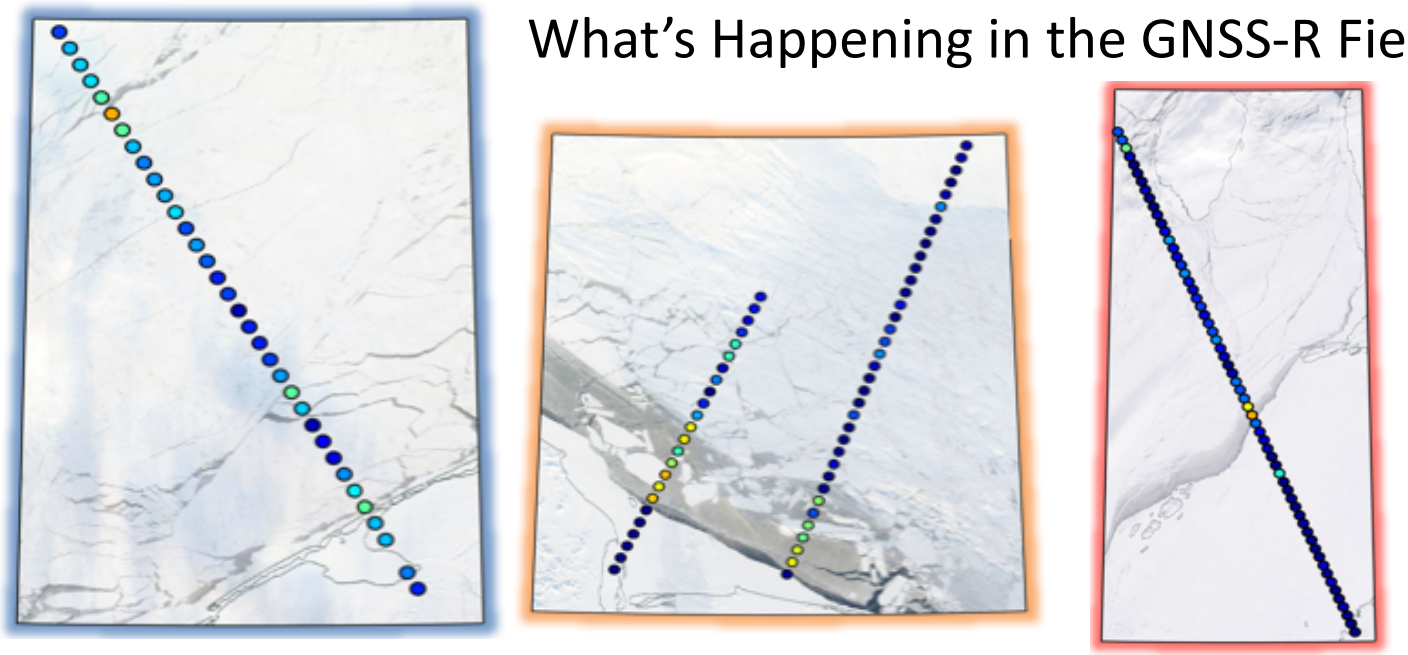
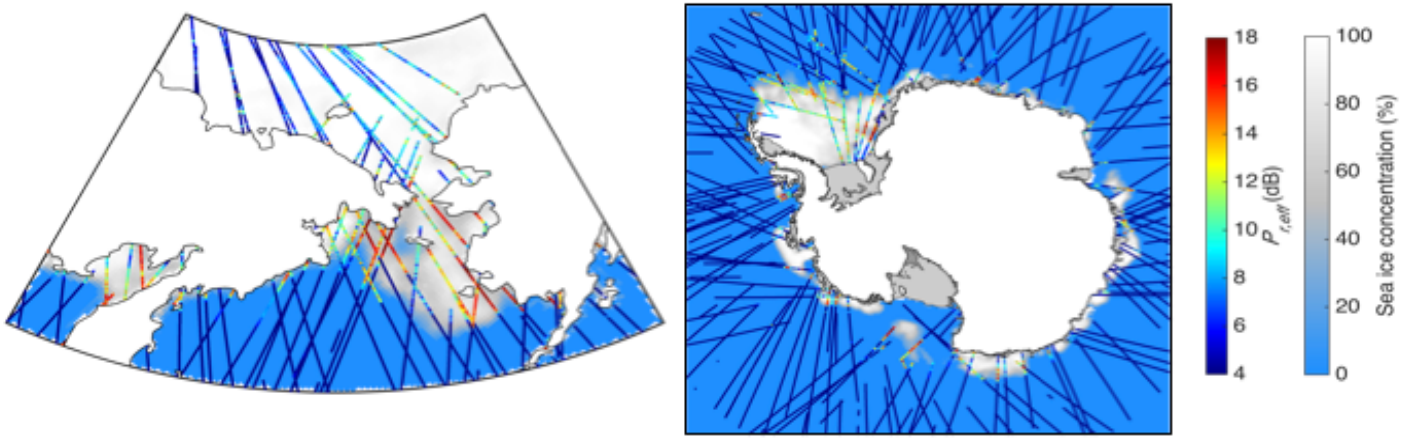




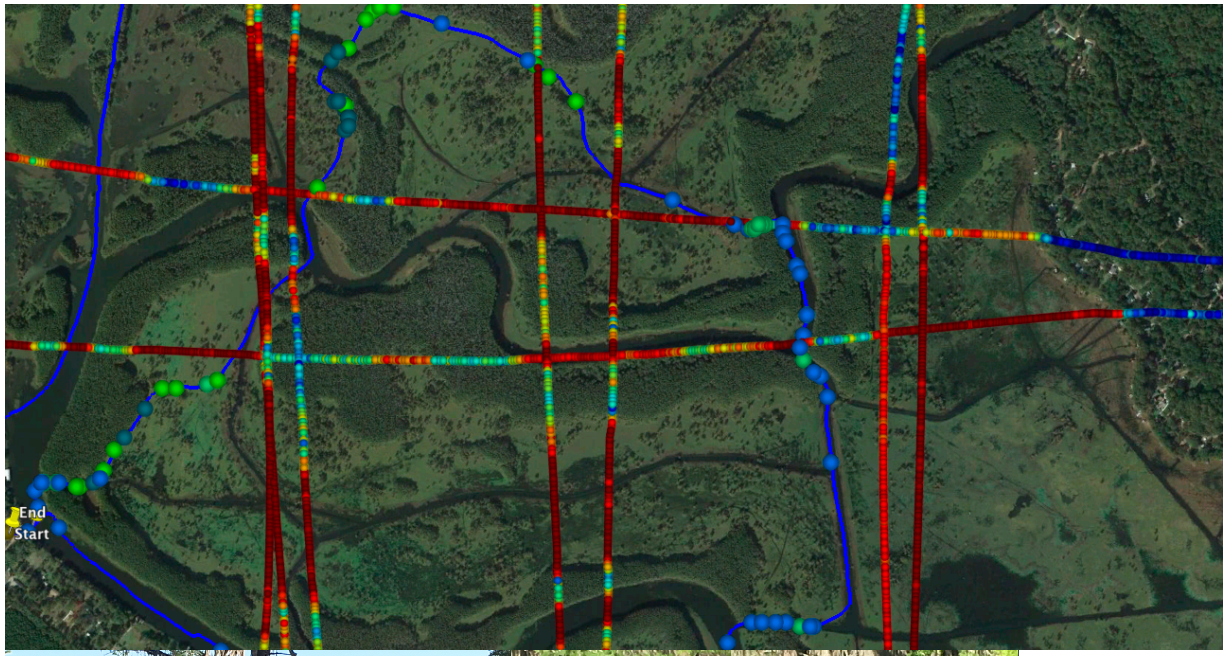
TechDemoSat-1 Data

- Higher power over ice leads and polynyas
- Up to 10 dB increase
- Not seen in passive microwave

- Increased P on ice edges
- Highest P intermediate sea ice conditions

Courtesy Clara Chew (UCAR)

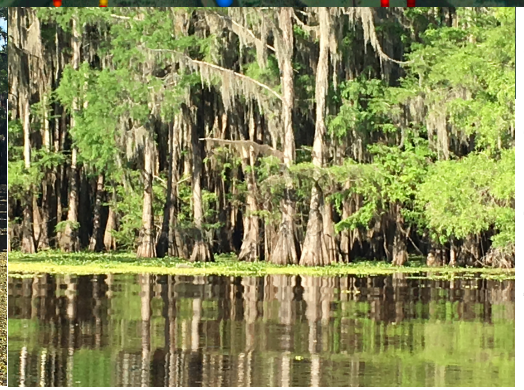
What's Happening in the GNSS-R Field?

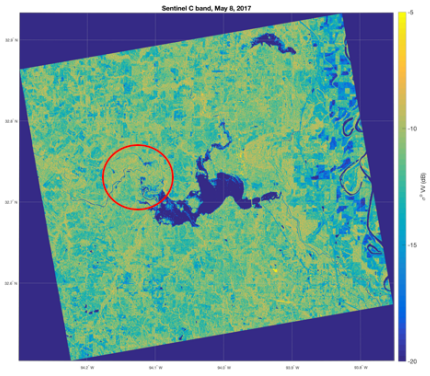


<u>Wetland Inundation Extent</u>

- Connection to methane production
  - Potent greenhouse gas
- Can forward-scattered GNSS-R signals penetrate vegetation to sense underlying inundation?

- May 2017 aircraft experiment: Caddo Lake LA
  - 20 dB blue to red scale
  - Light green: Giant Salvia
  - Dark green: Cypress
  - Backscatter radar shows little water



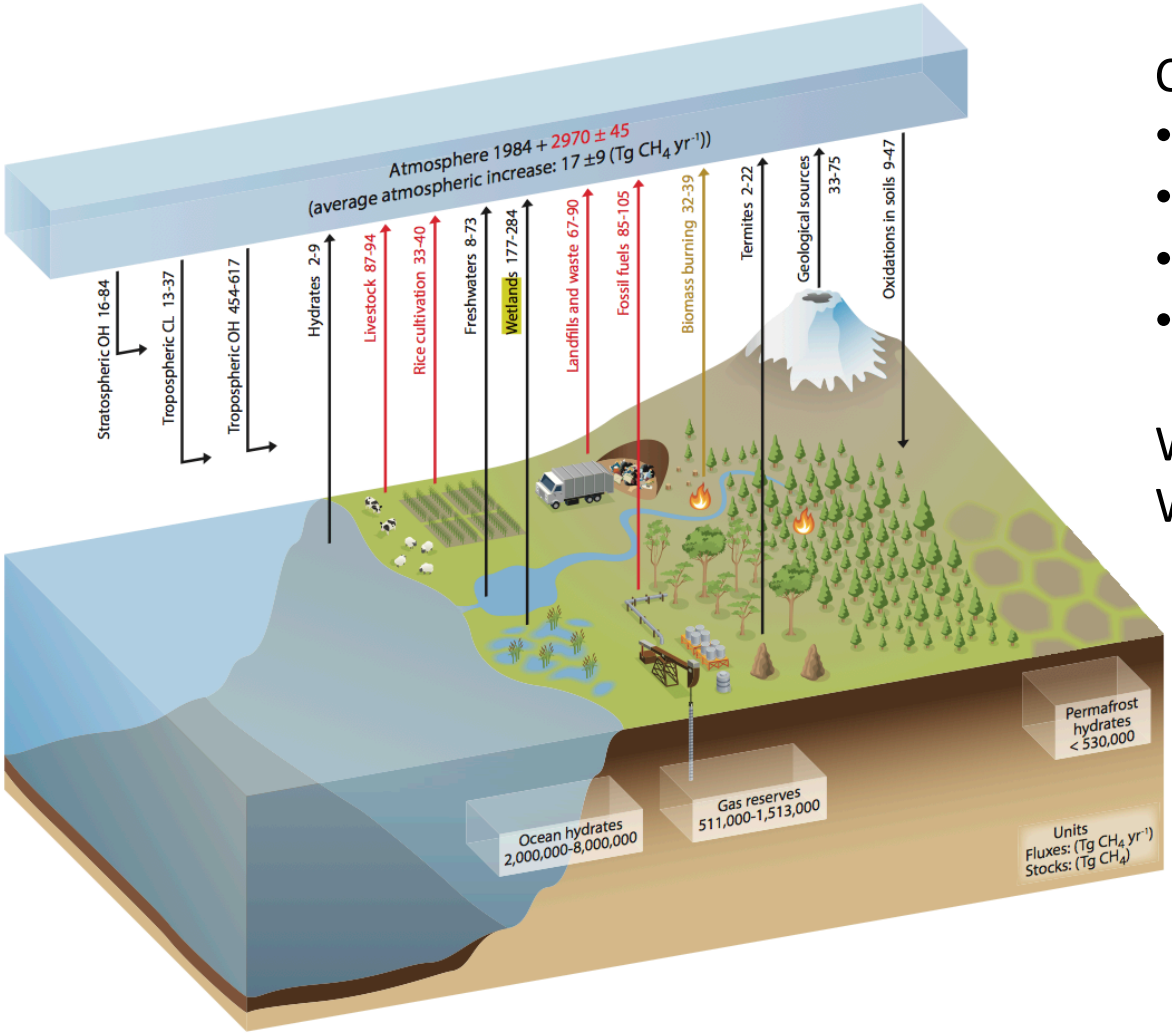


Summary

- GNSS-Reflectometry is a new Earth-remote sensing technique
- Explosive growth since 2015: TDS-1, SMAP, CyGNSS
- Many unique advantages compared to other remote sensing techniques
  - High spatial/temporal coverage, forward scattering, GNSS-RO-compatible, long-term SI-traceable signals
- Active research underway:
  - Ocean winds, soil moisture, wetland extent, freeze-thaw state, sea ice extent, ocean altimetry

Backup Slides

Global Methane Cycle



Contributions to Atmospheric Methane

- Wetlands (177-284 Tg/yr)
- Fossil Fuels (85-105 Tg/yr)
- Livestock (87-94 Tg/yr)
- Landfills (67-90 Tg/yr)

Wetlands has largest contribution
Wetlands has largest uncertainty range

IPCC (2013), Climate Change 2013: *The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change