First Results of Grazing Angle GNSS-R Altimetry from Sea Ice and Ocean Surfaces Using the Spire CubeSat Constellation

Vu Nguyen[1], Takayuki Yuasa[2], Oleguer Nogués-Correig[3], Dallas Masters[1], Linus Tan[2], Timothy Duly[1]

1 Spire Global, Inc., USA
2 Spire Global Singapore PTE Ltd.
3 Spire Global UK Ltd., UK

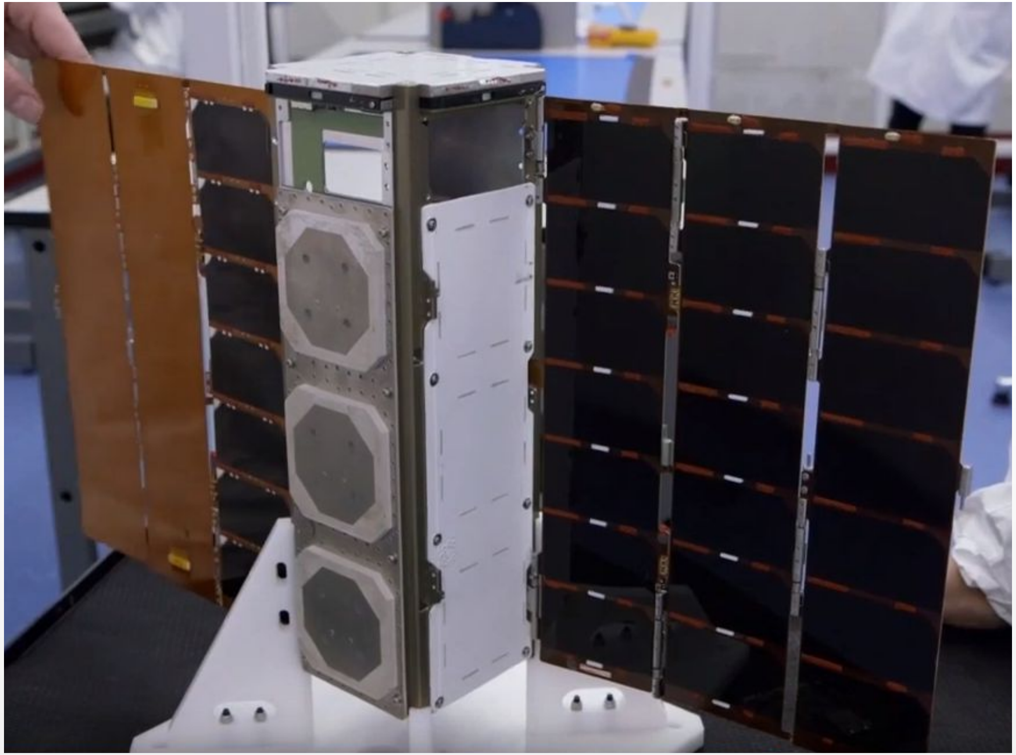
Who & What Is Spire?

We design, build, launch, and operate the **second largest constellation of nanosatellites** in the world.

We harness GNSS science and technology for Earth observation.

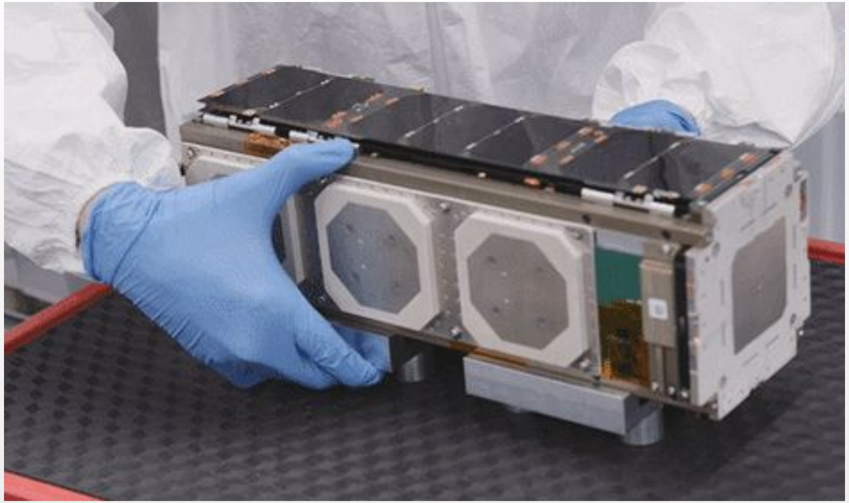
We also track ships (AIS broadcasts) and aircraft (ADS-B broadcasts) from space.

It's a **Spire product from start to finish** *(except for the rocket)*, and this allows us to innovate quickly (e.g., **first Galileo and QZSS radio occultations**, **phase-delay altimetry**, etc.).

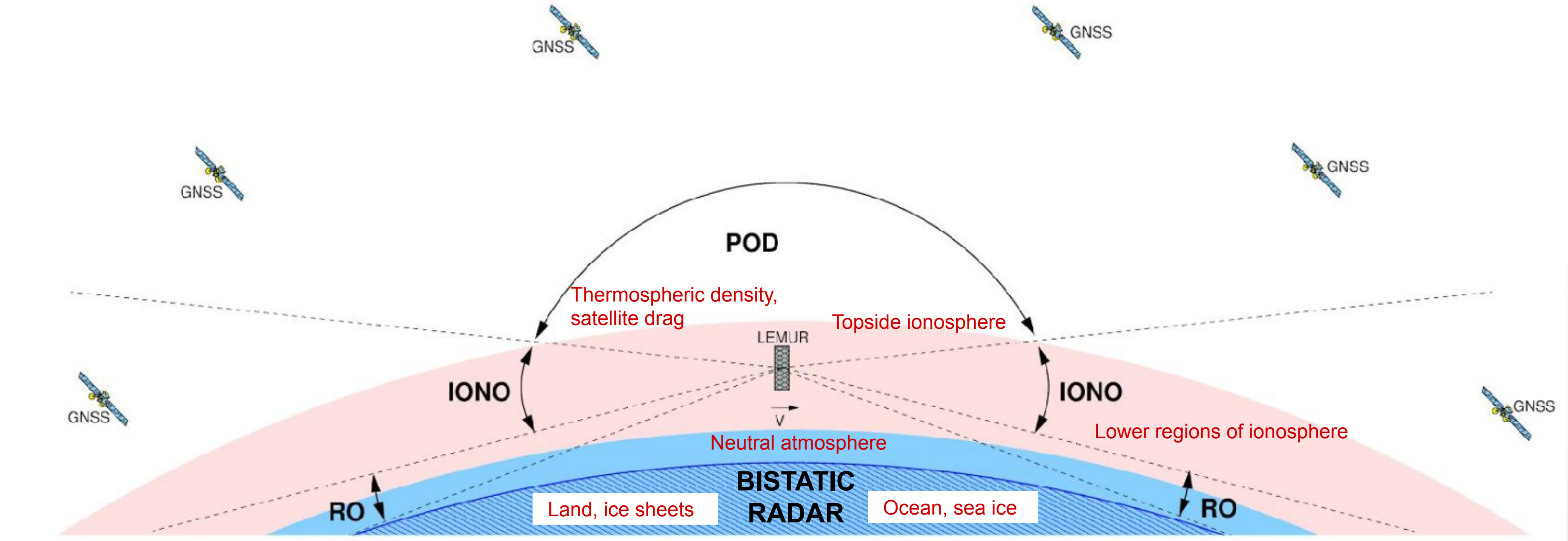


Spire Today

- Established and growing company with 150+ people across five offices
- **80+ LEO 3U CubeSats (10x10x30 cm) in orbit**
- 20 launch campaigns completed with 7 different launch providers
- 30+ globally distributed ground stations we own and operate
- **World's largest GNSS-based Earth observation (EO) constellation for weather/space weather/GNSS-R data collection**
- **Complete global coverage in multiple orbit inclinations**
- Can deploy new applications within 6-12 months
- Average launch of 4-8 satellites every 6 weeks
- World's largest ship tracking constellation
- ADS-B aircraft tracking product
- $150M+ raised with top institutional investors



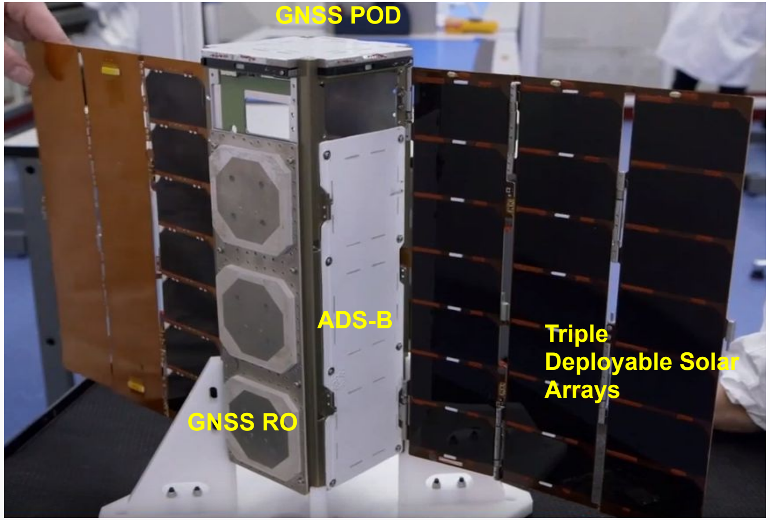
Earth Observations with GNSS



Spire leverages the ultra-stable, dual-frequency L-band signals broadcast by GNSS satellites to measure Earth properties that perturb these signals (e.g., refraction, **reflection**, etc.). These observations have various applications, such as NWP (radio occultation), space weather (TEC), **bistatic radar, altimetry.**

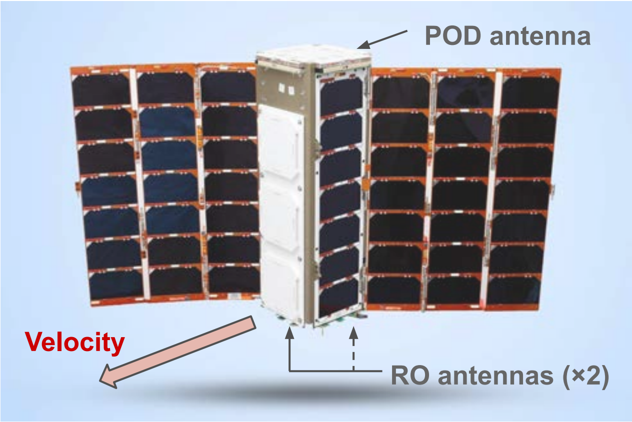
Spire EO Cubesat Technology

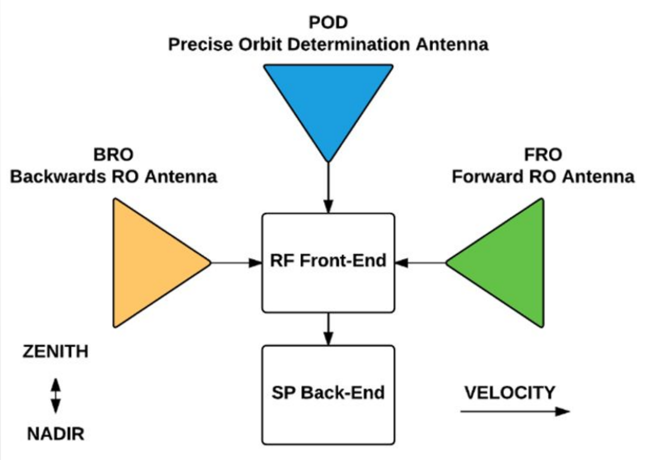
Parameter	Value	
Design Lifetime	2+ years	
Volume	10 x 10 x 30 cm (3U)	
Total Mass	4.7 +/- 0.1 kg	
Propulsion	None	
ADCS	3-axis stabilized (sun sensor, magnetometer, Earth-horizon sensor, 3 reaction wheels, magnetorquers)	
Orbit Average Power Usage	Triple-deploy solar arrays with batteries	
Transmitters	UHF	
	S-band, (X-band soon)	
Receivers	UHF, (S-band soon)	
Payloads	**GNSS**	**RO, TEC, POD, Scintillation, GNSS-R**
	AIS	Ship tracking
	ADS-B	Aircraft tracking



Spire designs and assembles nearly all of its satellite components in-house, ensuring expert-knowledge of the full satellite HW, SW, and processing stack

Spire GNSS Science Receiver

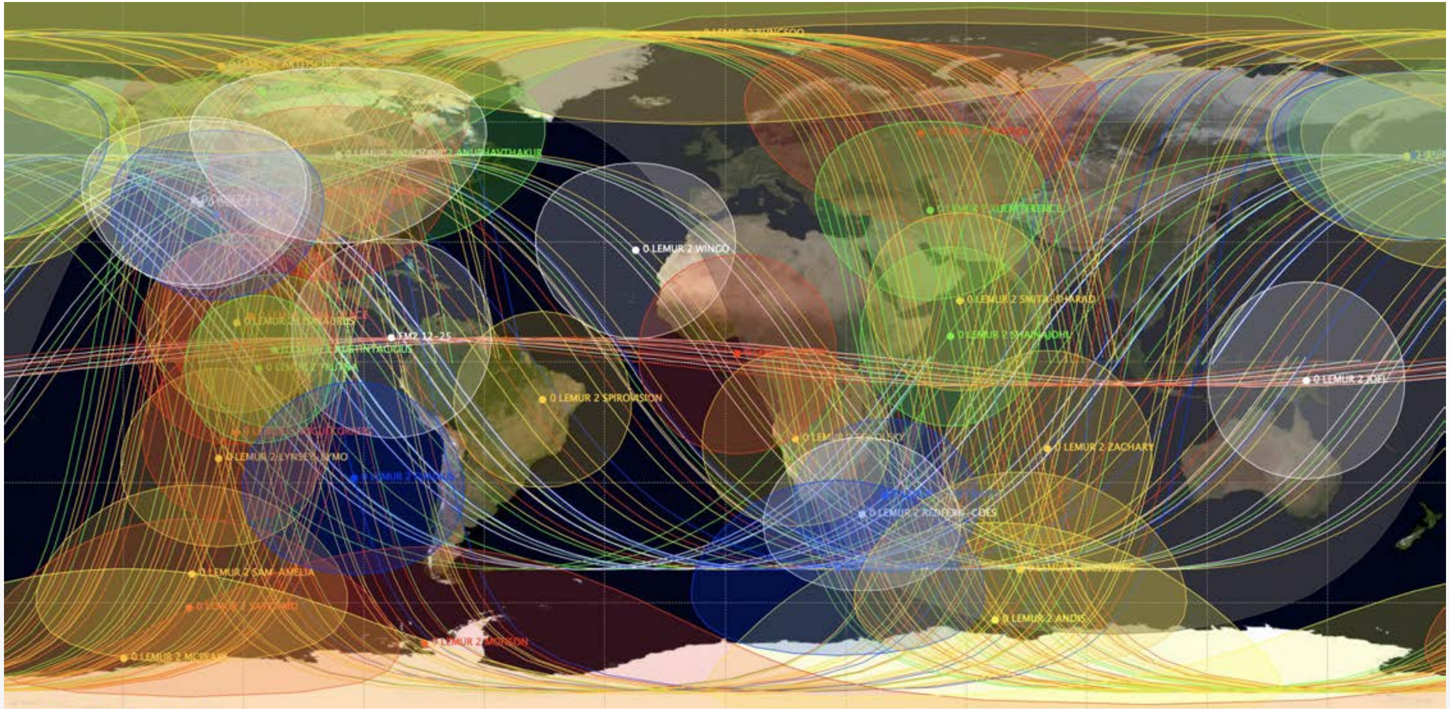




STRATOS is an advanced, software-defined, dual-frequency, low-power GNSS receiver for remote sensing and precise orbit determination (POD)

- SDR platform with FPGA-based acceleration of signal processing
- **Performs POD using zenith L1, L2 antenna** (orbits ~10 cm RMS from overlap analysis)
- Performs radio occultation (RO) on high-gain, forward (rising) and backward (setting) antennas
- Collects **GPS, GLONASS, QZSS, Galileo signals**
- Enables GNSS applications: atmospheric sounding, space weather monitoring, satellite drag, thermospheric density, **bistatic radar (GNSS-R)**

Spire Constellation & Orbits

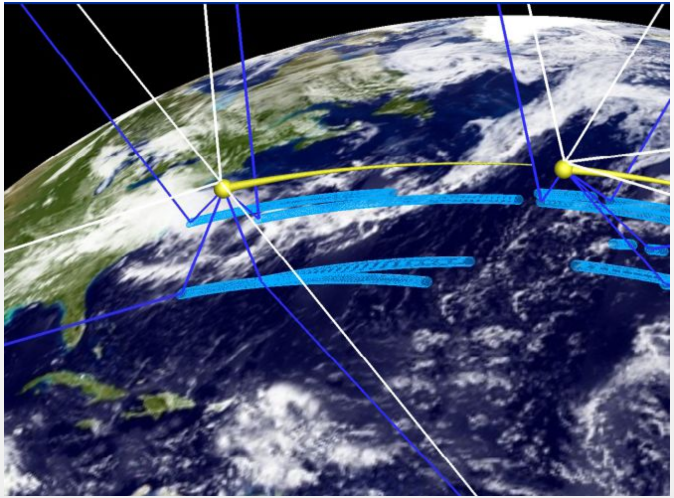


- Currently 80+ sats in 400-650 km orbits; **plans for 100+ operational EO sats**
- Varied orbits for dense global and temporal sampling with low data latency (10s minutes)
- Mainly sun synchronous (SSO) and 51.6 deg inc (ISS) orbits
- Some new launches at 85 deg and upcoming low inclination orbits

What is GNSS Reflectometry (GNSS-R)?

GNSS-R is a form of bistatic radar using GNSS signals of opportunity to perform Earth surface scatterometry (reflectivity and roughness, e.g. NASA CYGNSS mission) or **grazing angle phase delay altimetry**

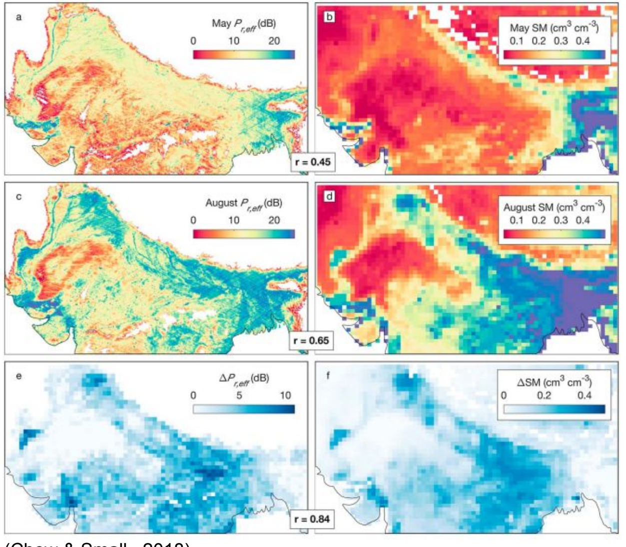
In 2019, Spire is **adding GNSS-R scatterometer satellites** to its EO fleet



(NASA CYGNSS Science Team)

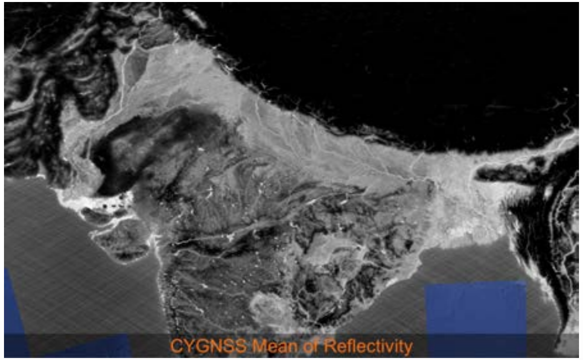
GNSS-R Scatterometry Applications

GNSS-R SMAP

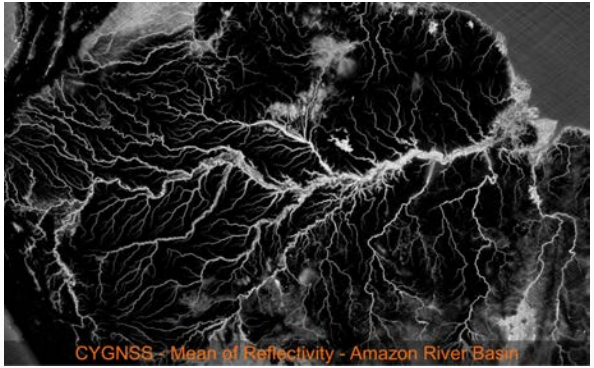


(Chew & Small., 2018)

Soil moisture measurements at potentially much finer (0.2-25 km) spatio/temporal resolution than SMAP



Surface water, flood mapping

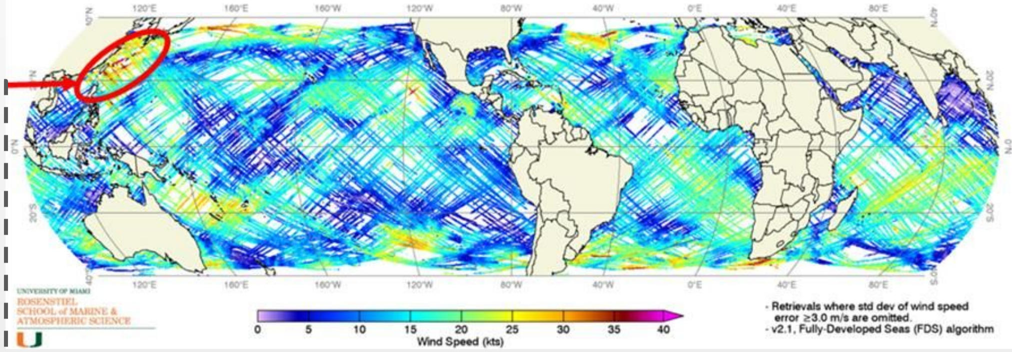


From Spire EO Team

Ocean L-band limited mean square slope or wind speed

(Ruf et al., 2019)

CYGNSS L3 WIND SPEED : 20180928 (0000Z-2300Z)



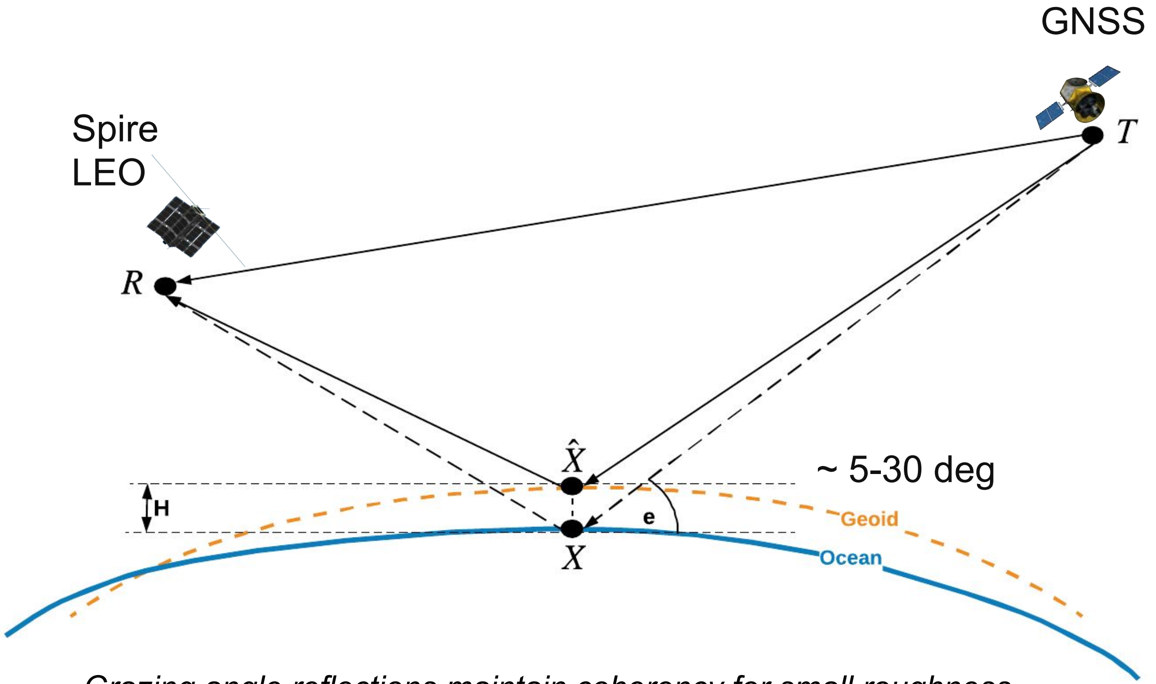
GNSS-R grazing angle altimetry?

Conventional waveform tracking of GNSS reflections yields coarse altimetry (~ meters)

Phase-delay altimetry is a type of GNSS-R that uses **coherent reflections of GNSS signals at low grazing angles (5-30 deg)** to estimate sea surface and sea ice heights **(~ cm)**

Renewed interest with TDS-1, CYGNSS data (recent work by Li, Cardellach, Semmling, etc.)

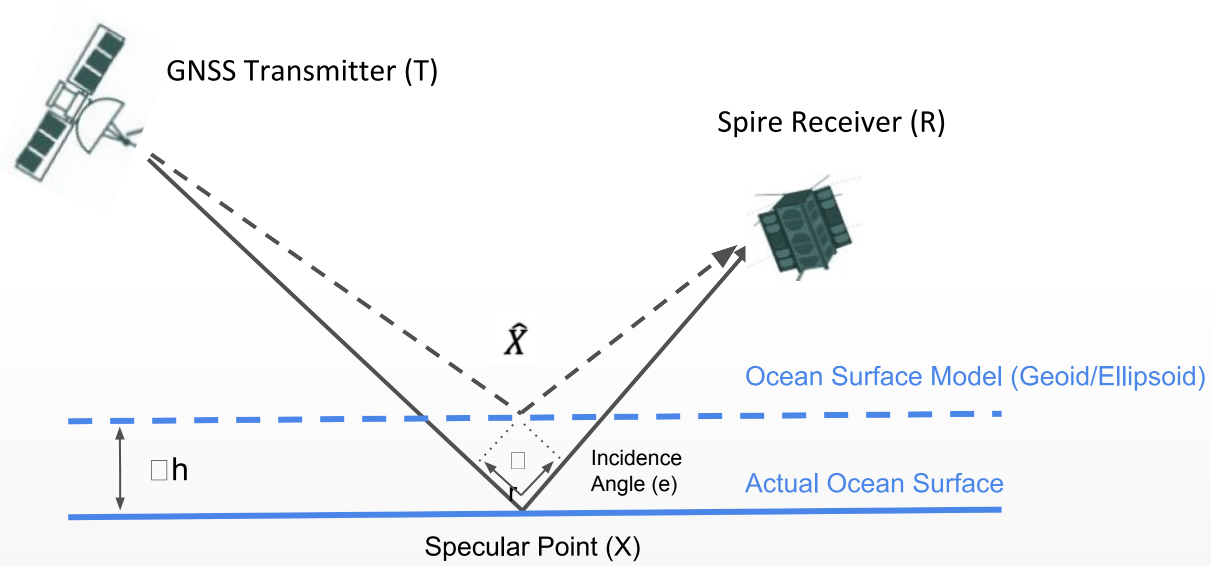
In Jan. 2019, **Spire reprogrammed RO sats open-loop tracker for dual-freq, grazing angle reflections**



Grazing angle reflections maintain coherency for small roughness

Funding: NOAA OPPA Technology Maturation Program (Spire) and NASA (with Nerem, Morton, Leben at CU)

Measuring Reflecting Surface Height



Target Measurement →

$$\delta h \equiv \frac{T\hat{X}R - TXR}{2 \cdot sin(e)}$$

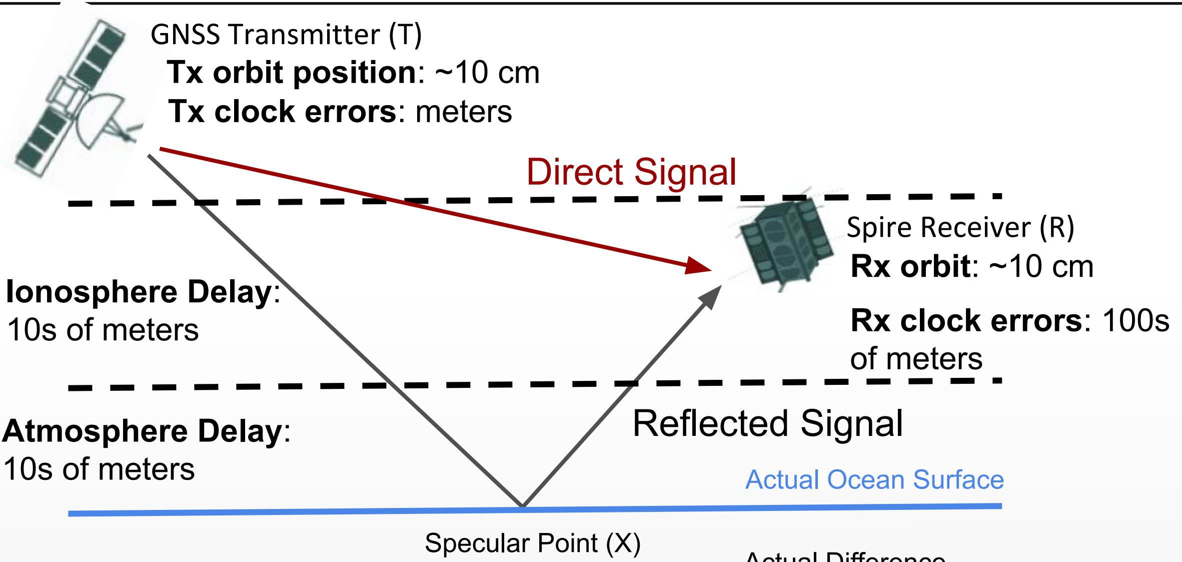
Modeled Signal Path $T\hat{X}R$

Computed distance based on transmitter, receiver positions and specular point on ellipsoid or geoid surface

Actual Signal Path TXR

Based on GNSS receiver measurements of pseudorange and phase

Reducing Error Sources



Modeled Reflected Signal Distance $\widehat{TXR}$

Measured Direct Signal Distance TR

Actual Difference Between Direct and Reflected GNSS Phase Measurement (corrected for iono/atm delays and biases) $\Delta\widehat{R}_v^{RD}$

Target Measurement → $\delta\widehat{h} = \frac{(\widehat{TXR}-TR)-\Delta\widehat{R}_v^{RD}}{2\cdot sin(e)}$

$$\Delta\widehat{R}_v^{RD} \equiv \frac{\Delta\phi_1^{RD}+\Delta\phi_2^{RD}-\Delta\widehat{K}_1^{RD}-\Delta\widehat{K}_2^{RD}+k\cdot\left(\frac{1}{f_2^2}+\frac{1}{f_1^2}\right)\cdot\widehat{TEC}^{RD}}{2} - \widehat{R}_n^R$$

GPS pseudorange and phase measurements provide approximation of signal travel distance based on timing

- Key error sources: Orbit/clock error, ionosphere, atmosphere, etc.
- Mitigate systematic Tx/Rx error sources using direct signal
- Ionospheric delay (dual frequency) and atmospheric delays (weather model) removed using observables rather than models

Initial Results from Spire RO Sats

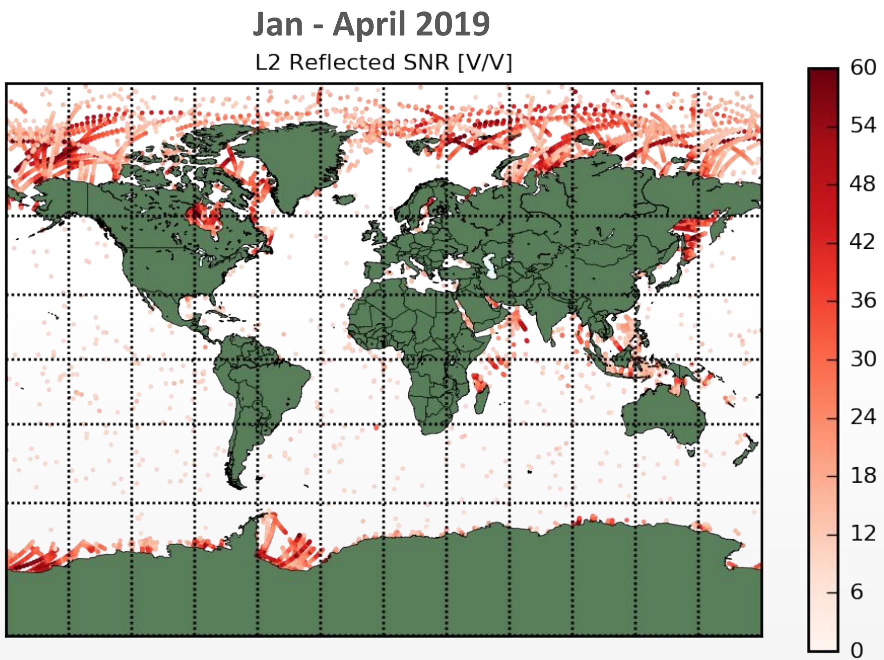
Data collection on orbit:

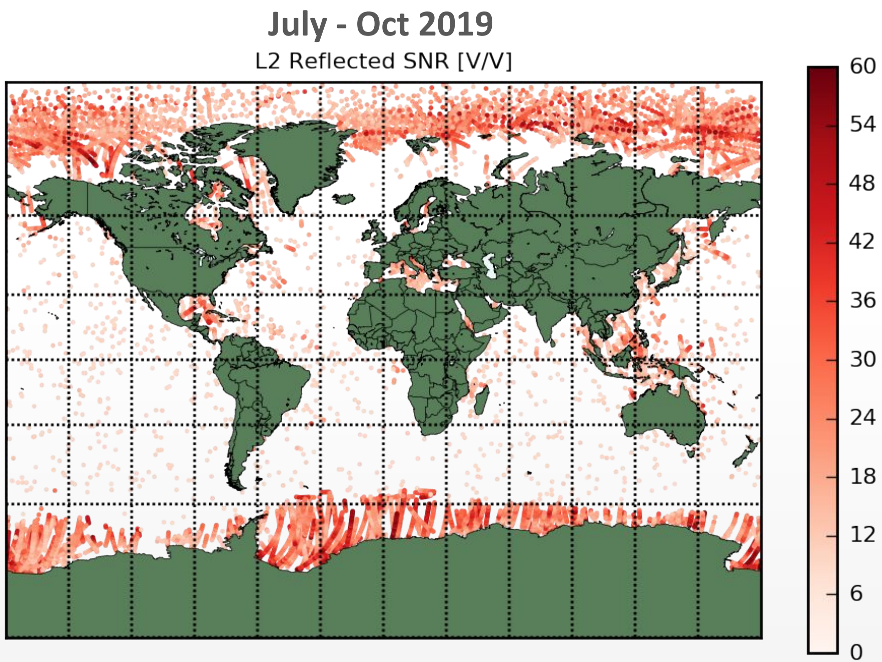
- Upload new software/firmware and modify RO open-loop tracking and tasking to add ocean reflection events (accomplished in 2 months)
- January 10-13, 2019: initial checkout and confirmation of results
- Between late January to present, altimetry collection has been performed on 2-3 satellites: **~10,000 collections** of ~180 to 240 sec reflection tracks
- **Limited to ocean areas, including sea ice covered areas**
- Currently, GNSS-R data **volumes are artificially constrained**

Altimetric processing:

- Estimation of ionospheric delay (no smoothing in most initial results)
- Estimation of tropospheric delay from computed slant paths (GFS model)
- Estimation of geometric delay and specular point location on WGS-84 ellipsoid
- Mean sea surface reference: DTU18
- Tide model removed: TPX09-atlas
- Other, smaller altimetric corrections ignored for now

Initial Spire Data Collections

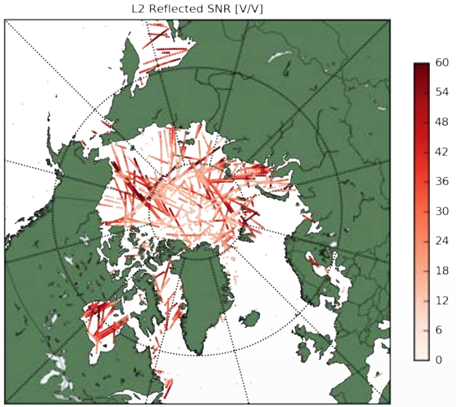


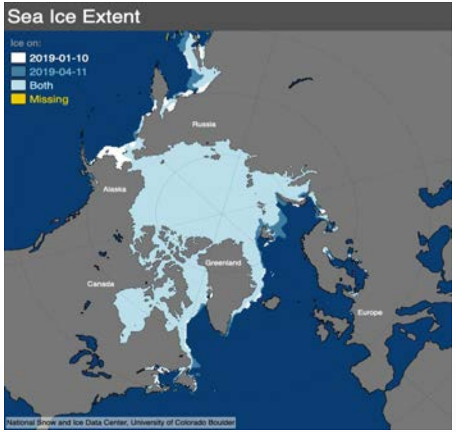


Summary of first data collected (Jan.-Oct., 2019) plotted as two seasons:

- Most sea ice reflections are coherent
- Frequent coherent ocean reflections in calm areas (Gulf of Mexico, Indonesia, inland seas)
- Seasonal sea ice extent is mapped

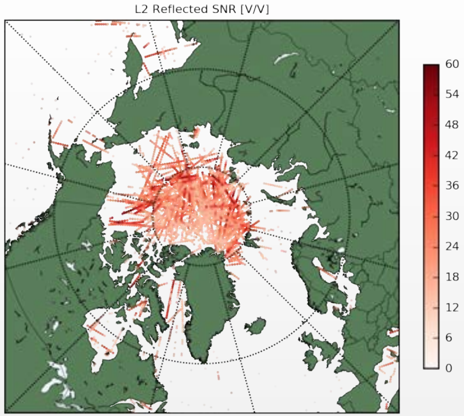
Sea Ice Extent Map: Arctic

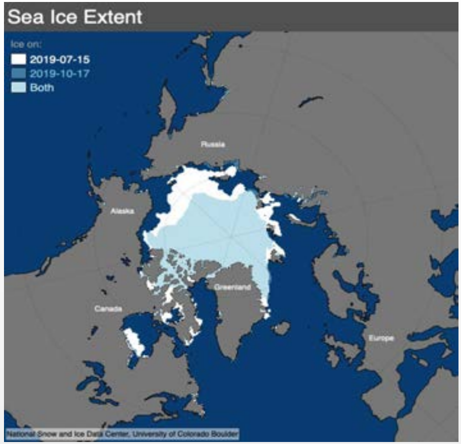




Arctic sea ice
Jan - Apr 2019

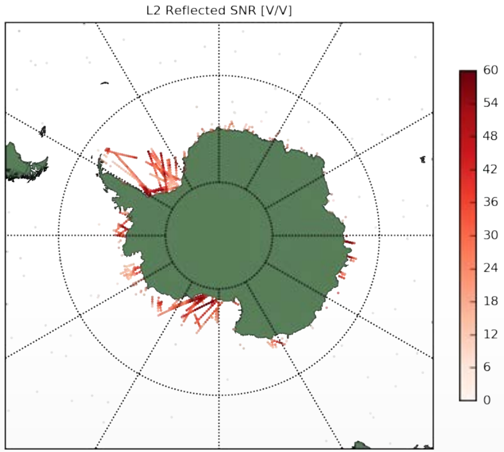
Arctic sea ice
Jul - Oct 2019





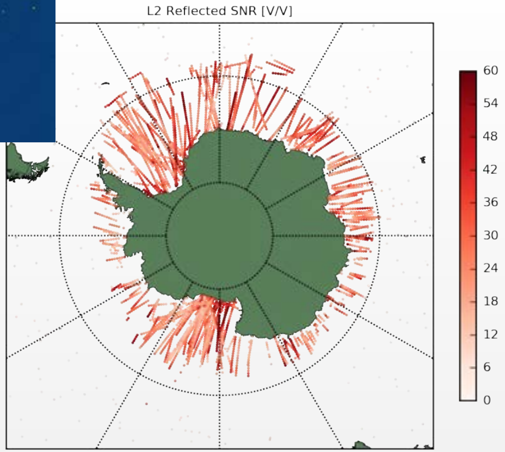
Mapping sea ice extent is possible with many RO sats, and perhaps ice age from SNR

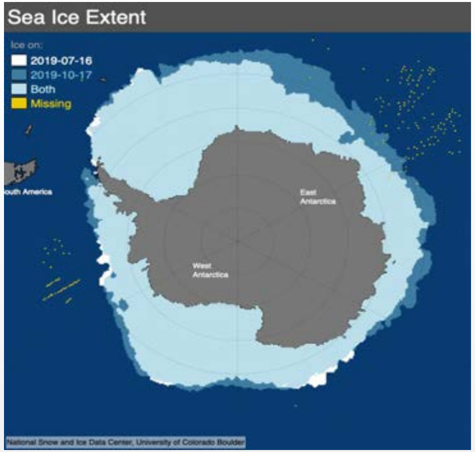
Sea Ice Extent Map: Antarctica



Antarctic sea ice
Jan - Apr 2019

Antarctic sea ice
Jul - Oct 2019



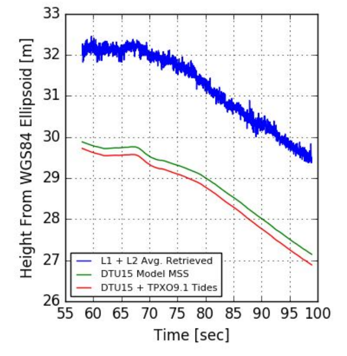


Mapping sea ice extent is possible with many RO sats, as well as ice age information

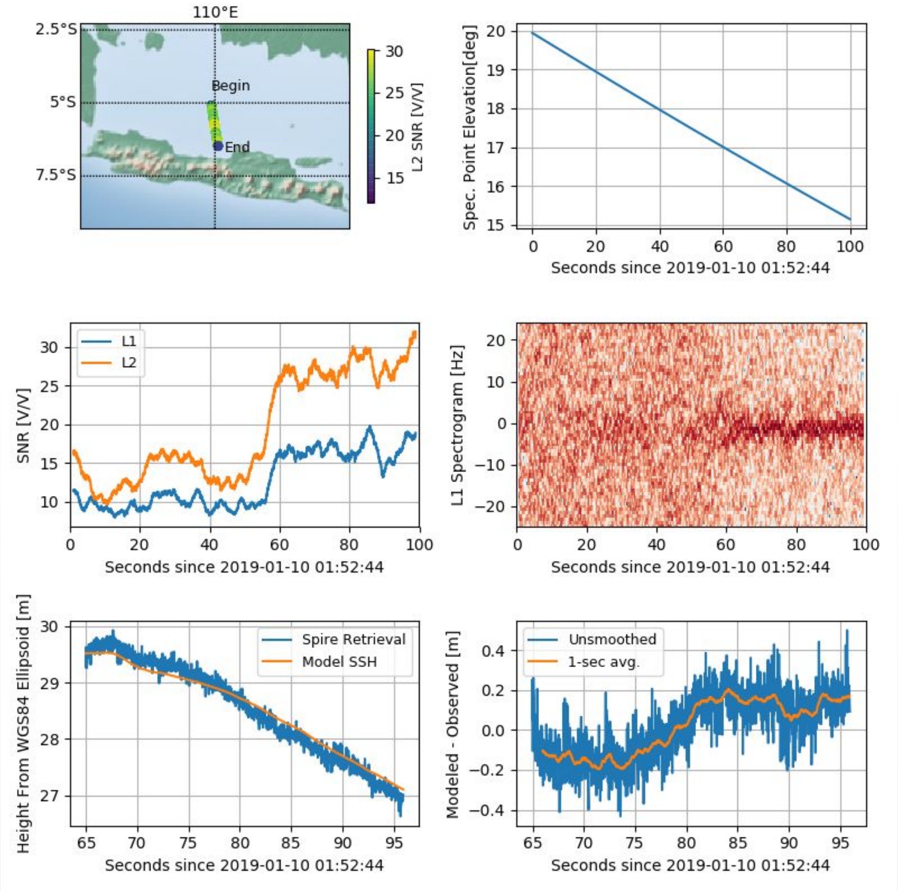
Ocean Altimetry: Java Sea

GNSS reflection event Java Sea

- Approximately 100 sec track between 20 to 15 deg grazing angle
- L1 & L2 SNR correlated
- Estimated reflector height follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Coherence is stronger over lower grazing angles (optically smoother)
- TBD: comparison with other altimeter data sets



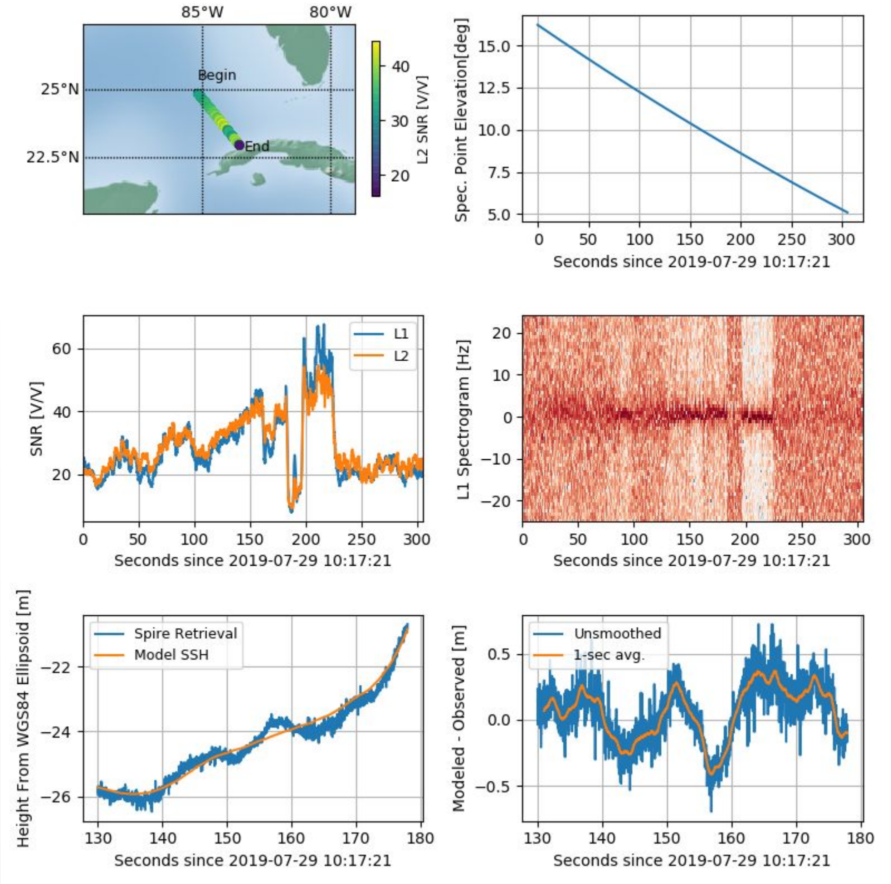
~ 2m bias removed



Ocean Altimetry: Gulf of Mexico #1

GNSS reflection event Gulf of Mexico #1

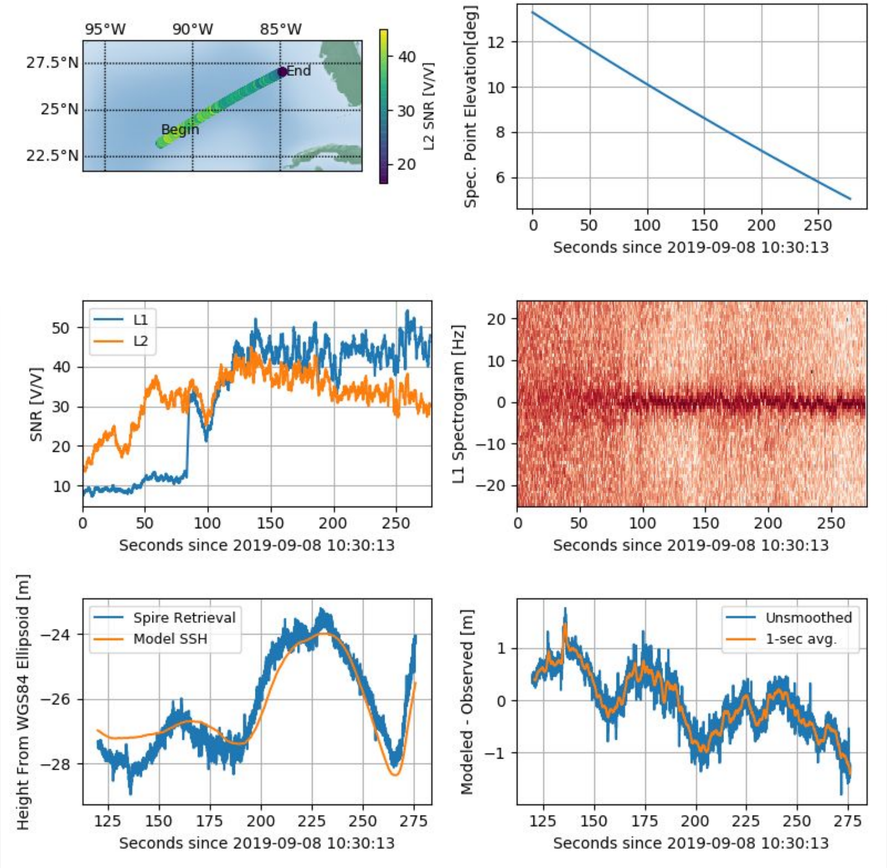
- Approximately 300 sec track between 17 to 5 deg grazing angle
- L1 & L2 SNR again correlated
- Estimated reflector height follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residual shows possible mesoscale features?



Ocean Altimetry: Gulf of Mexico #2

GNSS reflection event Gulf of Mexico #2

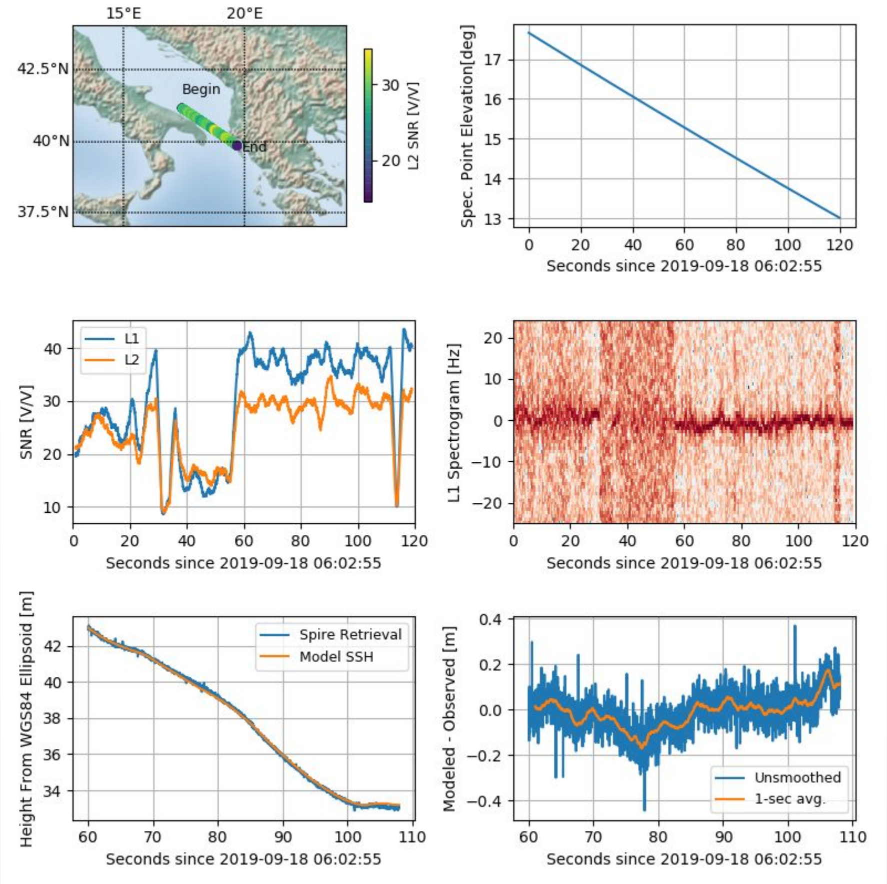
- Approximately 280 sec track between 14 to 5 deg grazing angle
- L1 & L2 SNR has weaker correlated
- Estimated reflector height follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed but departs at early part of track
- Residual shows possible mesoscale features?
- Gradient along the track (troposphere error?)



Ocean Altimetry: Adriatic Sea

GNSS reflection event Adriatic Sea

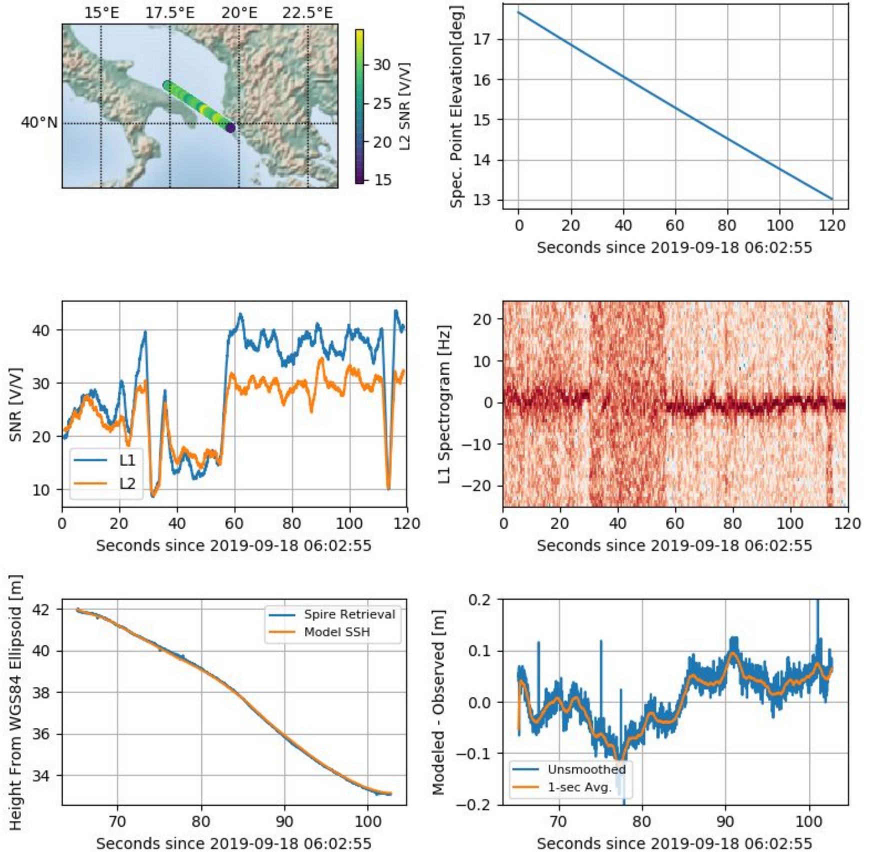
- Approximately 120 sec track between 18 to 13 deg grazing angle
- L1 & L2 SNR well correlated
- Estimated reflector height follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residuals flat (**8.5 cm RMS @ 50Hz)**



Ocean Altimetry: Adriatic Sea

GNSS reflection event Adriatic Sea

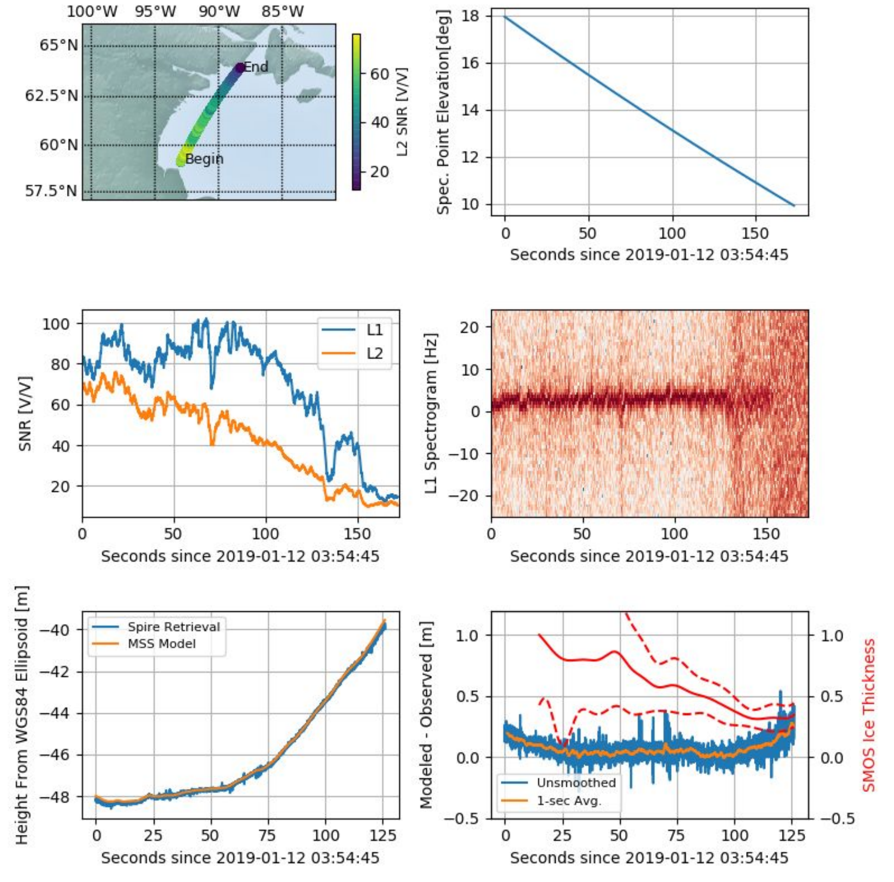
- Same as previous but ionosphere has been smoothed along track with 10 sec window
- Noise is reduced substantially by smoothing ionosphere correction
- Residuals flat (**5.4 cm RMS @ 50Hz)**



Sea Ice Altimetry: Hudson Bay #1

GNSS reflection event over Hudson Bay in early January 2019

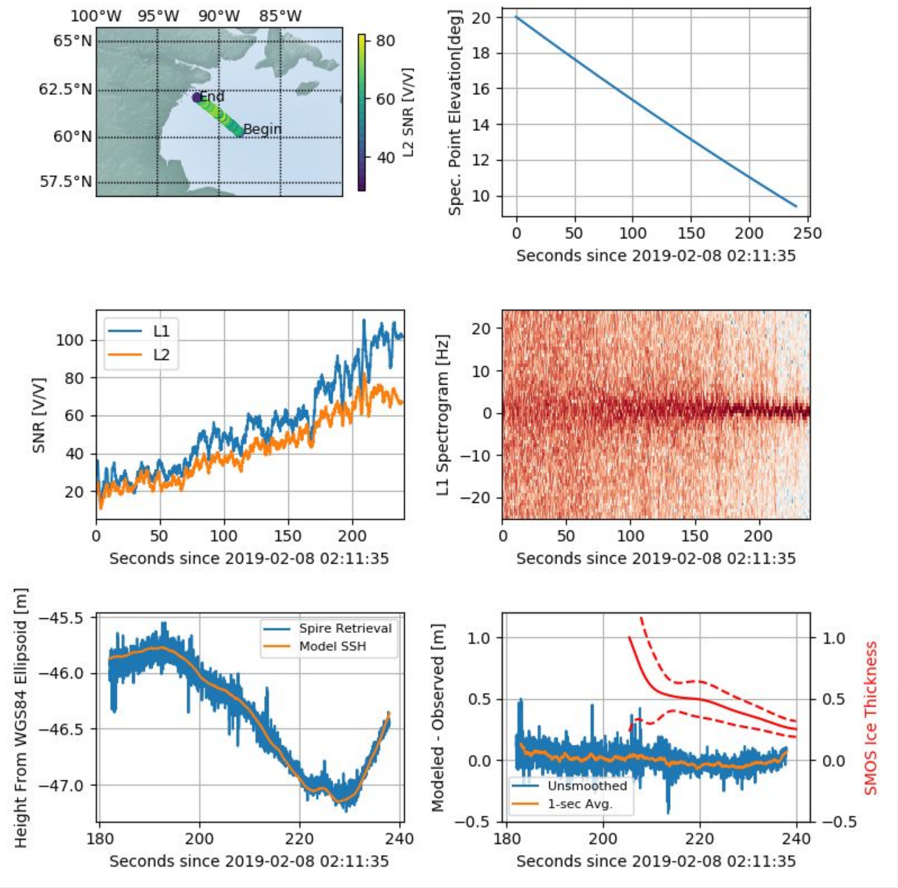
- Approximately 180 sec track between 18 to 10 deg grazing angle
- L1 & L2 SNR correlated with similar abrupt changes possibly showing ice features
- Estimated reflector height again follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residual shows slight gradient at ends of tracks near shorelines (tide model?)
- SMOS thickness estimate decreases along track



Sea Ice Altimetry: Hudson Bay #2

GNSS reflection event over Hudson Bay in early February 2019

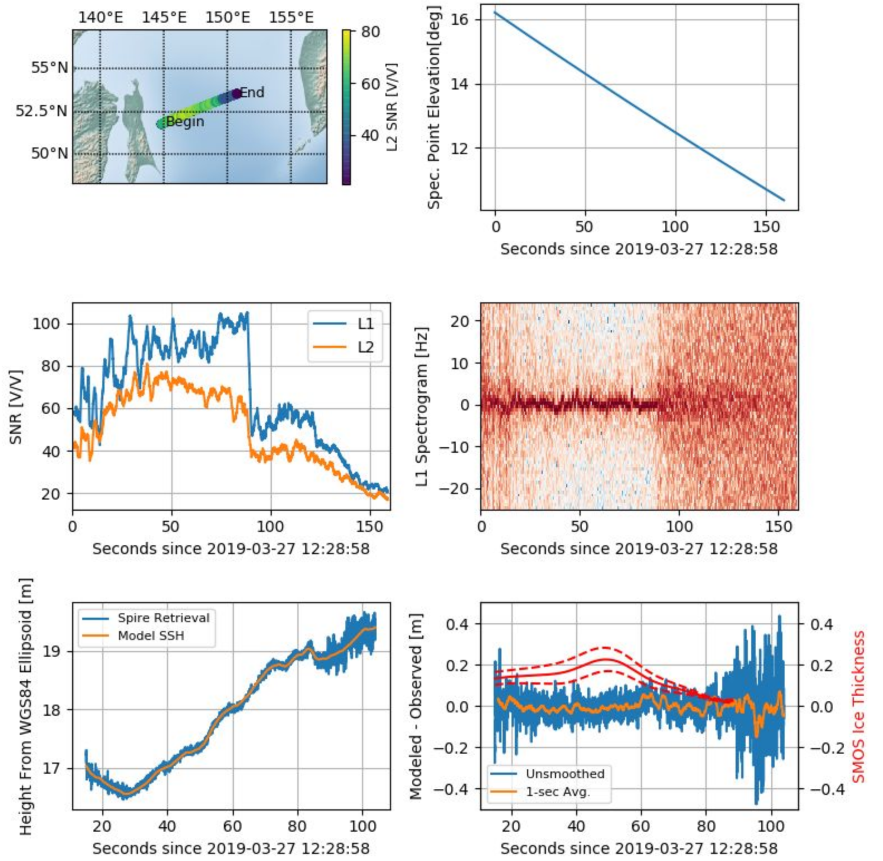
- Approximately 240 sec track between 20 to 8 deg grazing angle
- L1 & L2 SNR correlation is evidence of surface features
- Signal coherence is stronger at lower grazing angles
- Estimated reflector height follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residual shows slight gradient along track that might indicate freeboard
- Small negative gradient of 10 cm over 60 seconds in residual while the ice thickness (SMOS) changes from > 1 meter to 0.4 meters.



Sea Ice Altimetry: Sea of Okhotsk

GNSS reflection event over Sea of Okhotsk

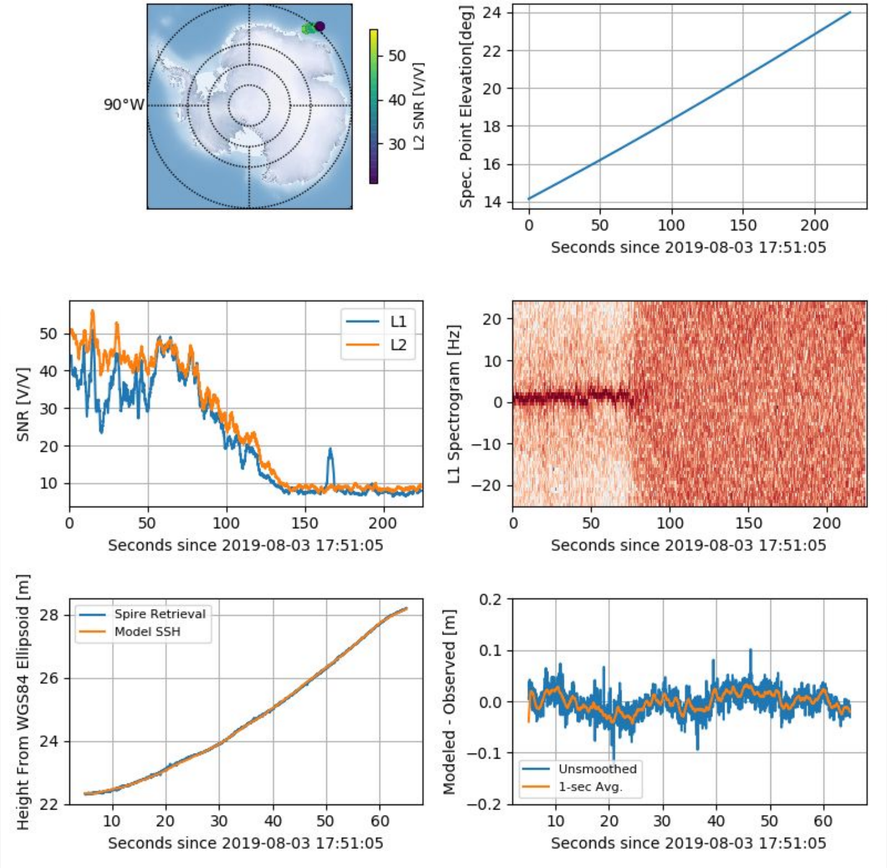
- Approximately 170 sec track between 16 to 10 deg grazing angle
- L1 & L2 SNR correlated and show transition from sea ice to open ocean around 80 seconds
- Estimated reflector height again follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residual shows little gradient along the track
- SMOS thickness estimate is larger in center of track
- Loss of coherence over open ocean (due to roughness)



Sea Ice Altimetry: Antarctica

GNSS reflection event over Antarctica sea ice

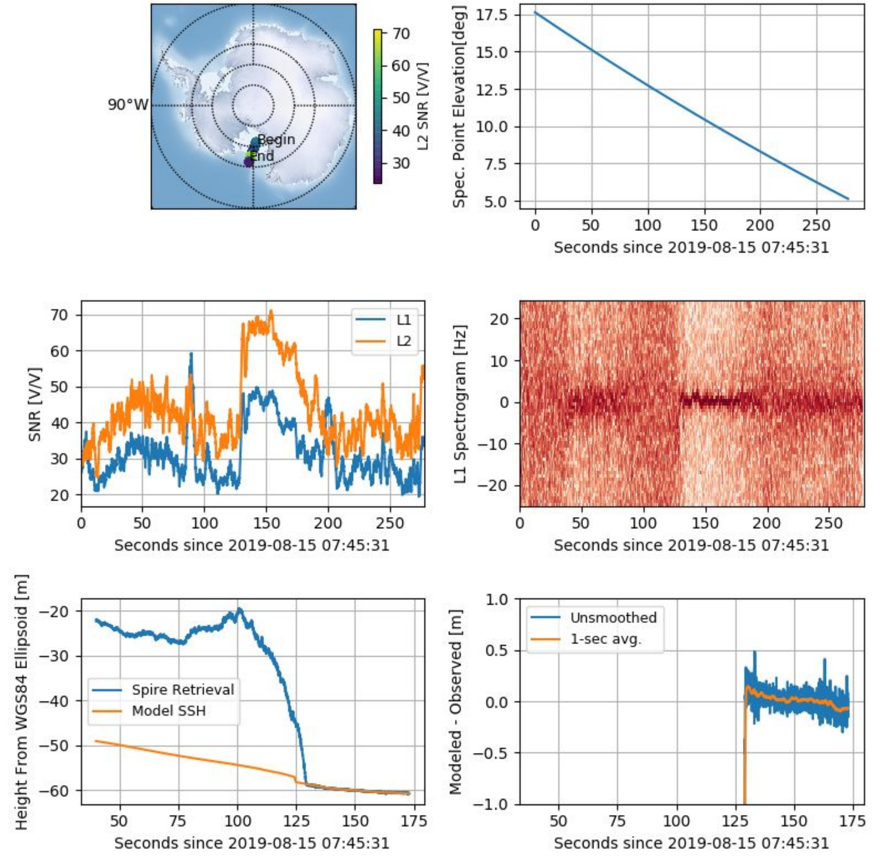
- **Ionosphere smoothed over 10 sec window**
- Approximately 220 sec track between 14 to 24 deg grazing angle (rising)
- L1 & L2 SNR correlated and show transition from sea ice to open ocean around 80 seconds
- Estimated reflector height again follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residual shows little gradient along the track
- **RMS 2.2 cm for 50 Hz data (1.6 cm for 1 sec smoothed)**

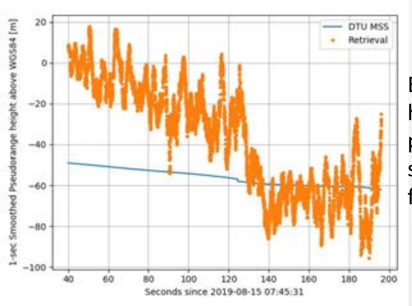


Sea Ice Altimetry: Antarctica

GNSS reflection event over Ross Ice Shelf and sea ice

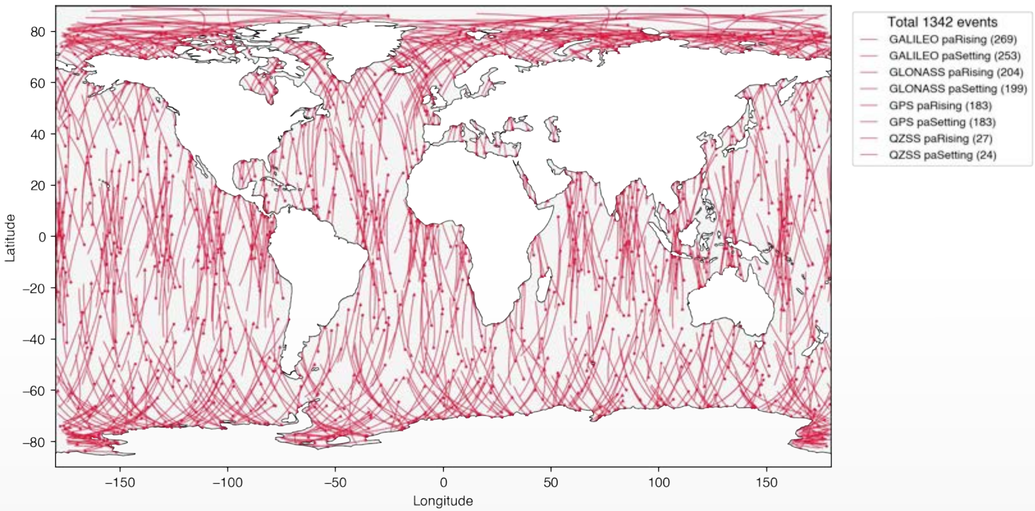
- Approximately 220 sec track between 17 to 5 deg grazing angle
- Track goes from ice shelf to sea ice to open water
- Estimated reflector height follows expected shelf magnitude (15-50 m) then mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Low RMS residuals in sea ice region with gradient

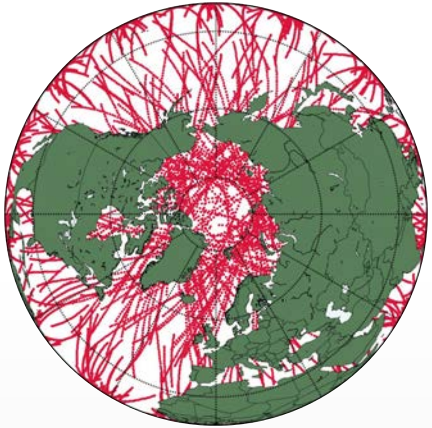


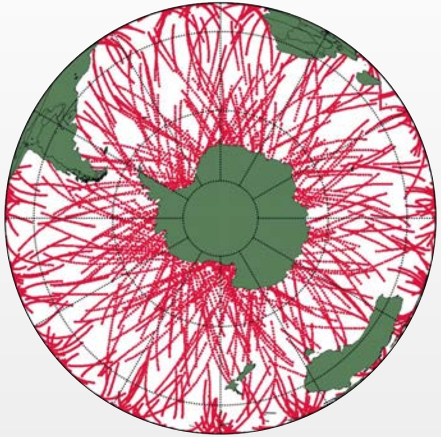


Estimation of height from pseudorange supports reflection from top of ice shelf

Coverage Analysis: 1 SSO sat, 1 day

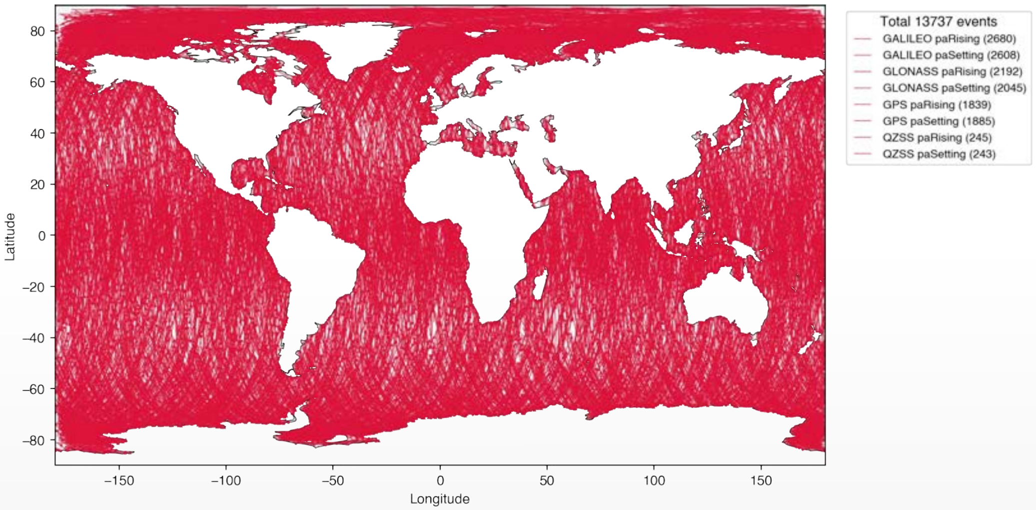


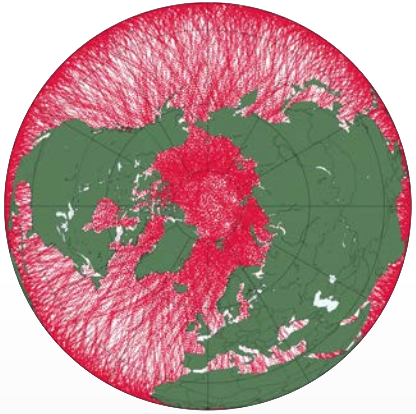


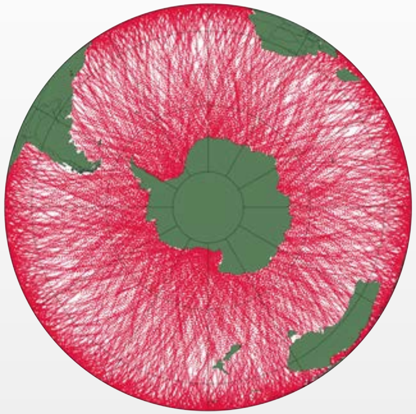


Coverage for 1 RO sat in sun synchronous orbit collecting GPS, GLONASS, Galileo, and QZSS reflections

Coverage Analysis: 1 SSO sat, 10 days

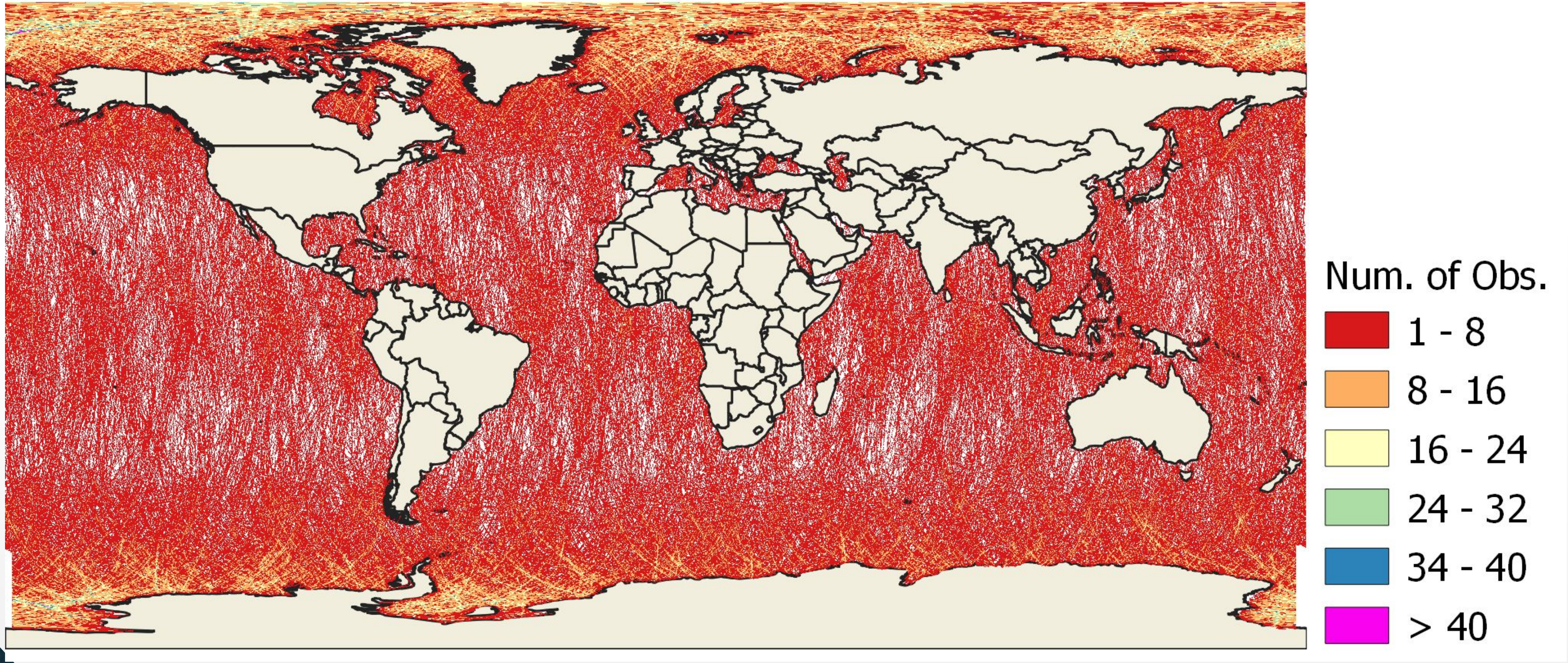






Coverage for 1 RO sat in sun synchronous orbit collecting GPS, GLONASS, Galileo, and QZSS reflections

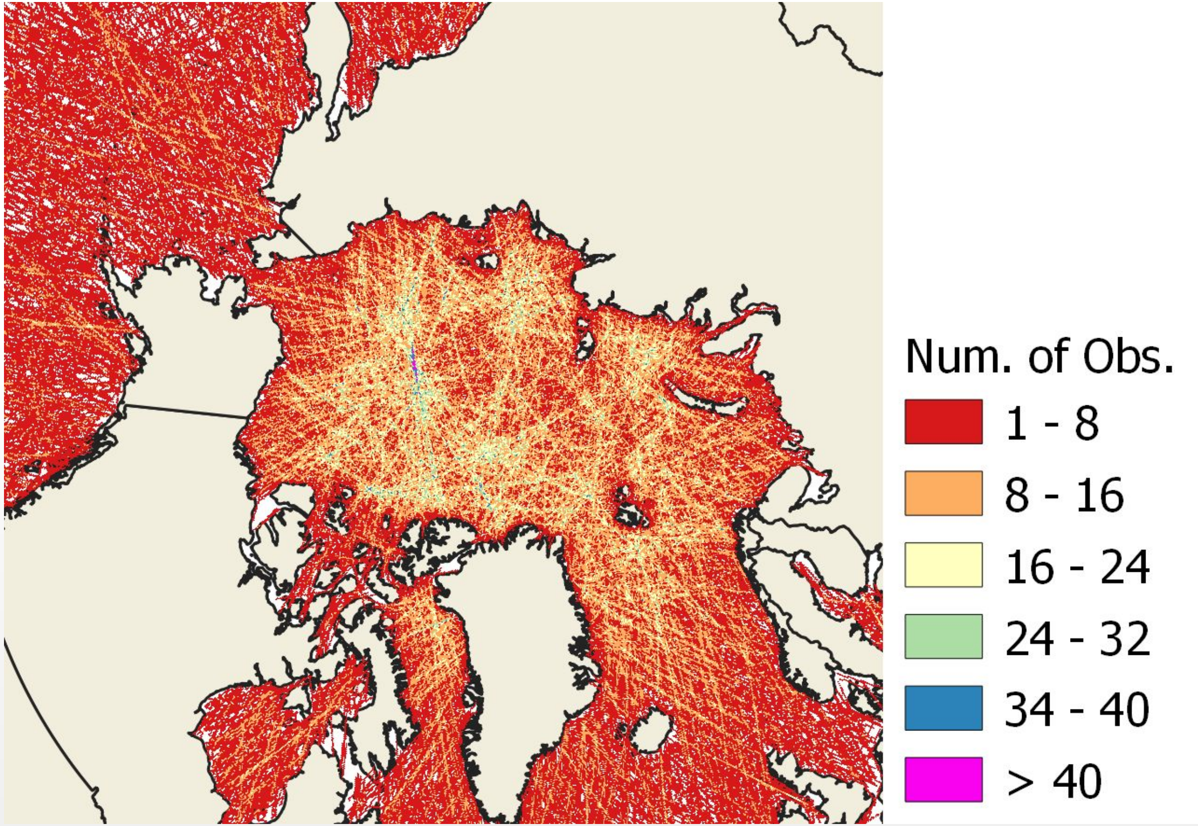
Coverage Analysis: Spire fleet, 1 day



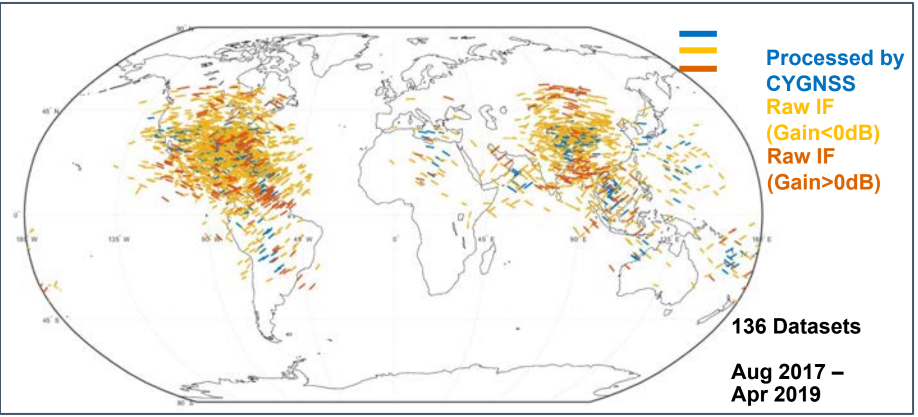
12 km gridded cells with number of observations in each grid cell in 1 day from current Spire RO sats

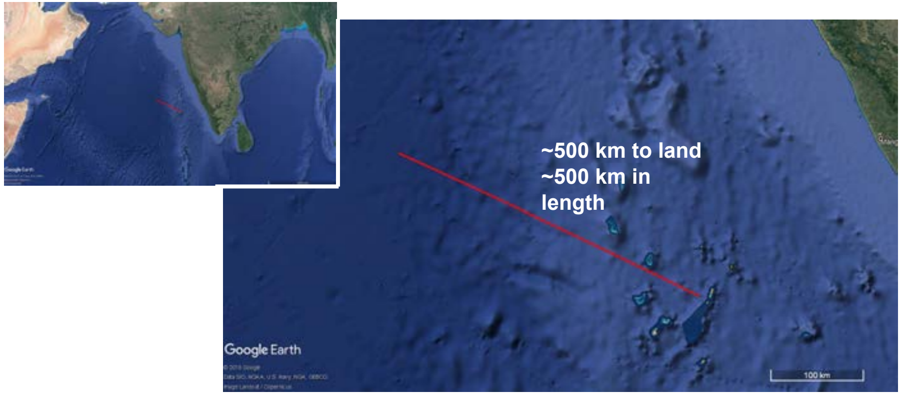
Coverage Analysis: Spire fleet, 1 day

12 km gridded cells with number of observations in each grid cell in 1 day from current Spire RO sats



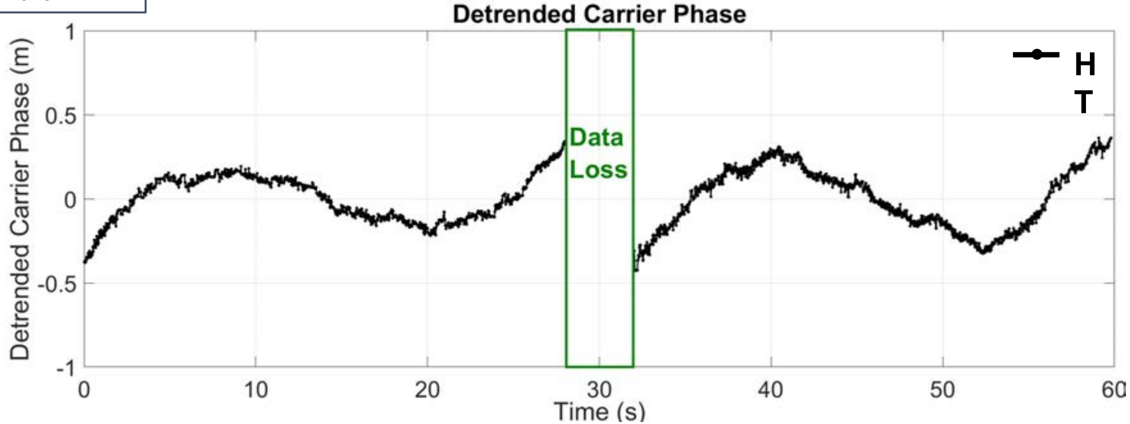
Results from University of Colorado (OSTST Project PI)





CU is processing raw IF data from CYGNSS and estimating carrier phase observables

Yang Wang, Carolyn Roesler, Jade Morton, Steve Nerem, Bob Leben



Key Takeaways & Next Steps

GNSS-R scatterometer missions

- First retasking of GNSS-RO satellites to perform operational GNSS-R grazing angle altimetry
- ~10K collections show **good coherence over sea ice and frequent coherence in calm seas**
- Ongoing data collection will be expanded to **ALL available reflections** and also over land and ice sheet surfaces and **with ALL Spire RO satellites**
- Initial results demonstrated < 10 cm RMSE height retrieval over sea ice and < 20 cm oceans
- Coverage analysis shows **great potential for high spatial and temporal sampling**

Next Steps

- Continue **productionizing altimetric processing** of data
- More validation with ancillary data sets
- **Collect raw IF data** for analysis by Spire, CU, and ESA partners

Spire data are available to PIS from NASA Purchase Program and soon ESA Earthnet

spire

Dallas Masters

Director of Earth Observations

dallas.masters@spire.com

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