Spaceborne Carrier Phase Altimetry Using GNSS Reflected Signals At Grazing Angles Of Observation Over Open Sea Water

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GRAZING ANGLE (GA) CARRIER PHASE ALTIMETRY (CaPA)

CyGNSS RAW DATA SET

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EFFECTS OF TROPOSPHERIC BENDING (BENT vs STRAIGHT PROPAGATION)

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- **GNSS-R grazing angle (GA) observation:** when the elevation angle at the specular point is low, e.g. $e < 30^{o}$.

- **Carrier Phase Altimetry (CaPA)**: altimetric retrievals resulting from range measurements or range variation measurements obtained from the tracking of the phase of the carrier EM signal → it requires **COHERENT** signal/scattering.

- GNSS signals reflected off sea surface waters are generally not-coherent (diffuse scattering).

At GA, the delays of the signals scattered at the troughs of the waves w.r.t. the ones scattered at the crests is shorter than in near-nadir geometry → better conditions for coherence (**smoother effective roughness**).

- **Advantages of GNSS-R GA CaPA observations:**
  - Fine precision of the range measurements: the signal noise of each coherent observation (several millisecond) is only a fraction of the EM wavelength → several cm level range precision at millisecond rates.
  - Higher number of observations possible (potential for high spatio-temporal coverage).
  - Simple/small/cheap GNSS-R payloads, e.g. radio occultation payloads, TDS/CyGNSS-like payloads, PRETTY…
- **Disadvantages of GNSS-R GA observations**:
  - Lack of coherence impairs CaPA, it reduces the final number of retrievals.
  - Atmospheric effects are larger → accurate atmospheric corrections required.

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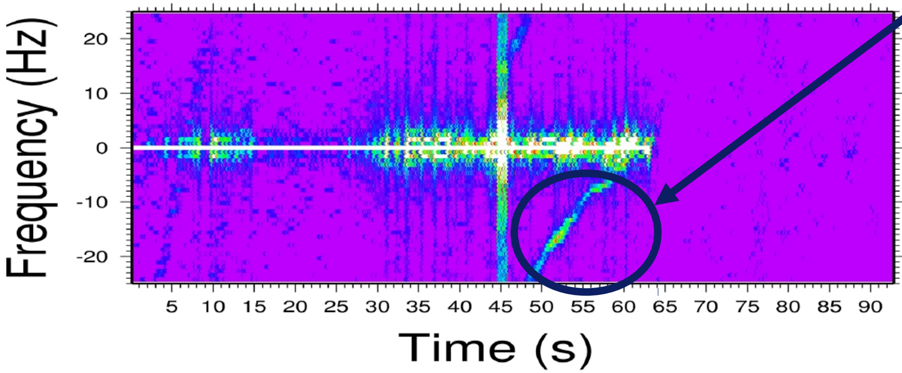
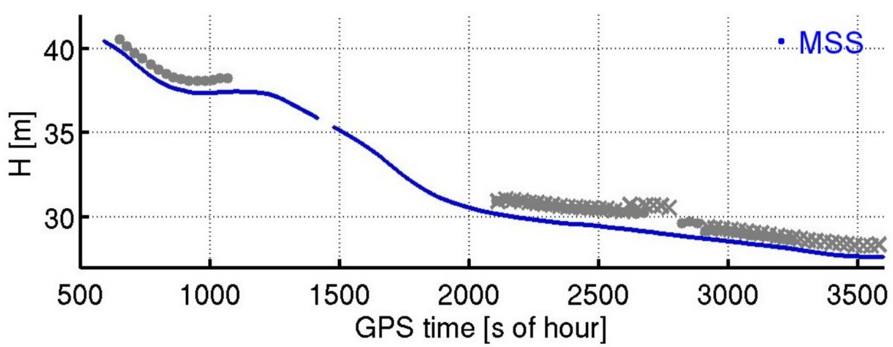
- **Empirical examples:**



70% of the GNSS radio occultation (atmospheric sounding) profiles **over the Oceans** present reflected signals, a clear tone, **irrespectibely of the sea surface roughness conditions** (coef. correlation with SWH 0.04) [Cardellach et al. 2004, Aparicio et al., 2018]. **Elevation angles 0º-1º**.

GA CaPA was possible in a diversity of roughness conditions over open sea waters across the Mediterranean from an airborne at 3km altitude [Semmling et al. 2014]. Both RHCP and LHCP polarizations presented coherence. **Elevation angles up to 30º**.



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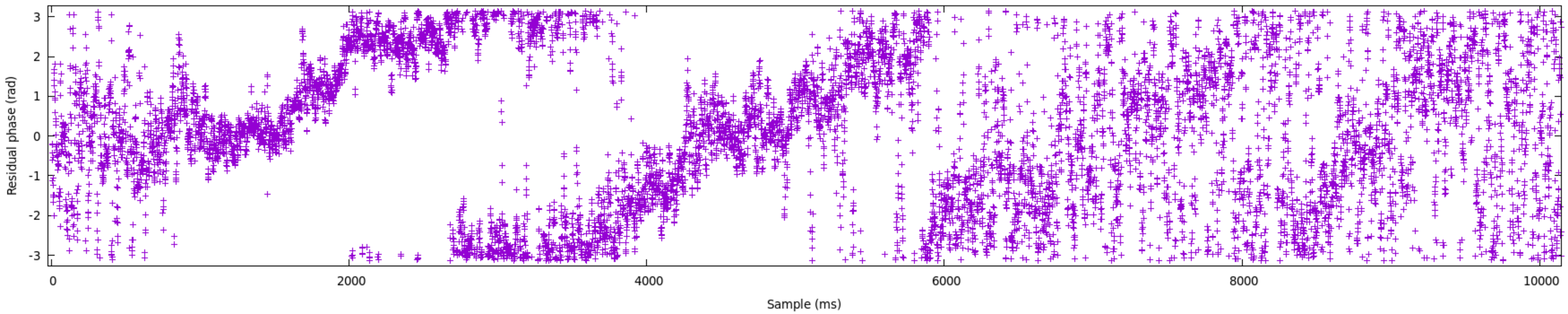
- **CyGNSS raw data:** GNSS signals captured at any of the satellites' antennas, down-converted to intermediate frequency and sampled at 16.0362 MHz.
- We have analyzed all CyGNSS raw data sets available over the region of **Central America**.
- We have applied our 'software receiver' on the ground to obtain tracks of GNSS reflected signals. Coherent integration time: 50 ms.
- The tracks consist of complex waveforms at 20 Hz sampling.
- The phase of the peak-phasor is extracted (here Tc=10 ms):



- **Summary of processed data:**

Number of acquisition sets:	24 different days, 11 periods (hurricane passes? Sep-Oct 2017 and 2018)
Number of reflected tracks at GA geometries:	63
Range of antenna gain values:	-22 to 12.4 dB
Range of elevation angles:	2^0 to 26^0
Range of wind speed conditions (ERA-5 co-location):	1 to 11 m/s
Range of SWH conditions (ERA-5 co-location):	0.2 to 2.4 m

CyGNSS data set:

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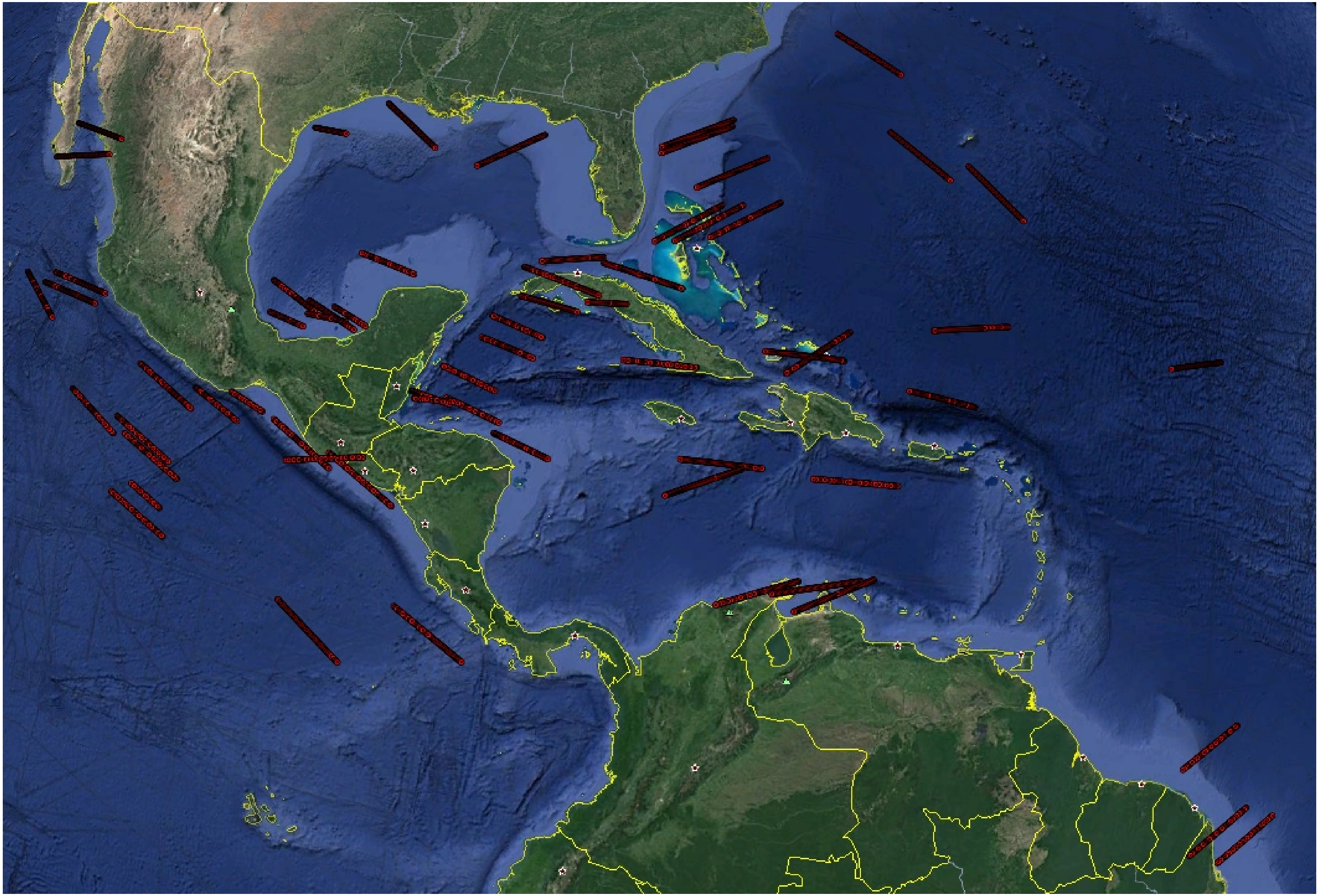

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GA CaPA retrievals:

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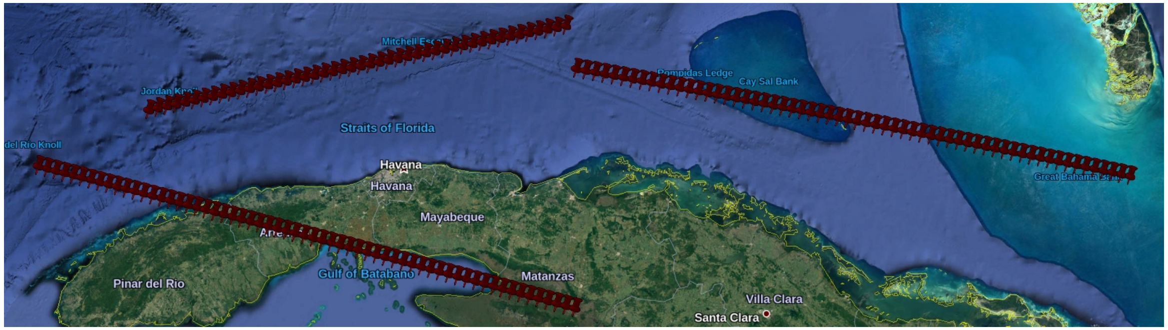
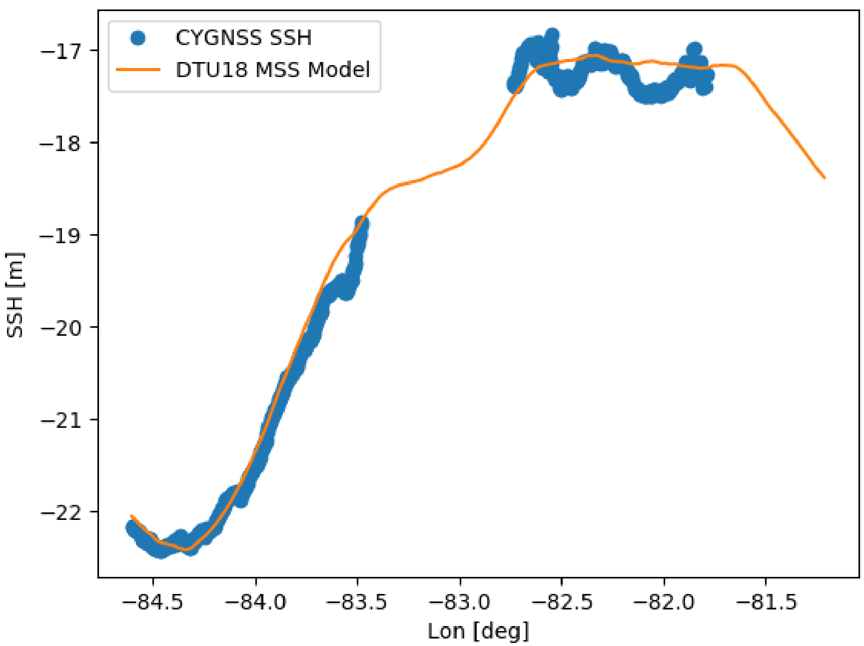
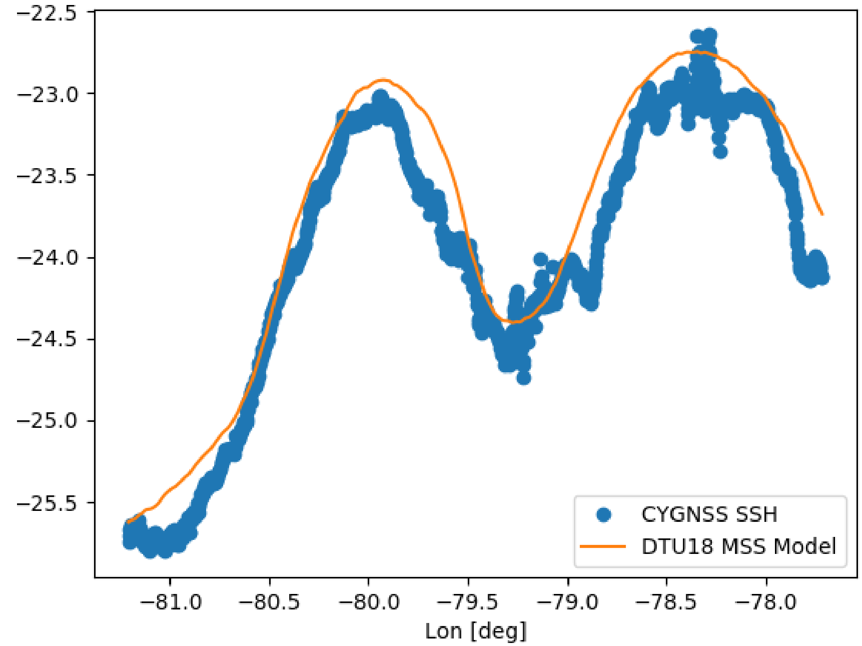




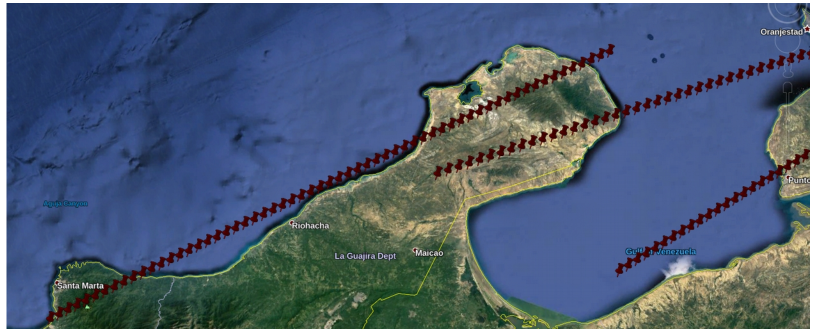


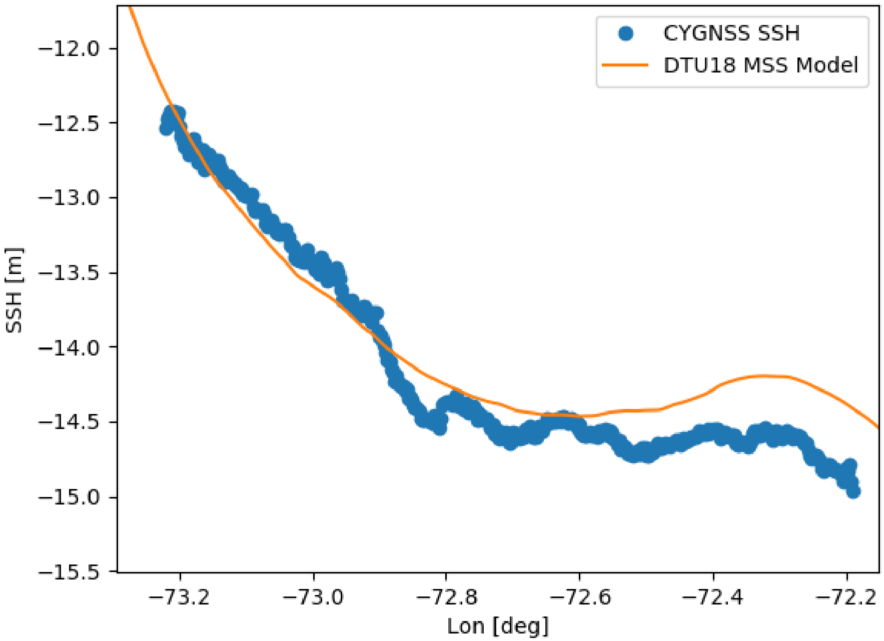
-81.16^0 22.40^0 2018-09-15 12:29

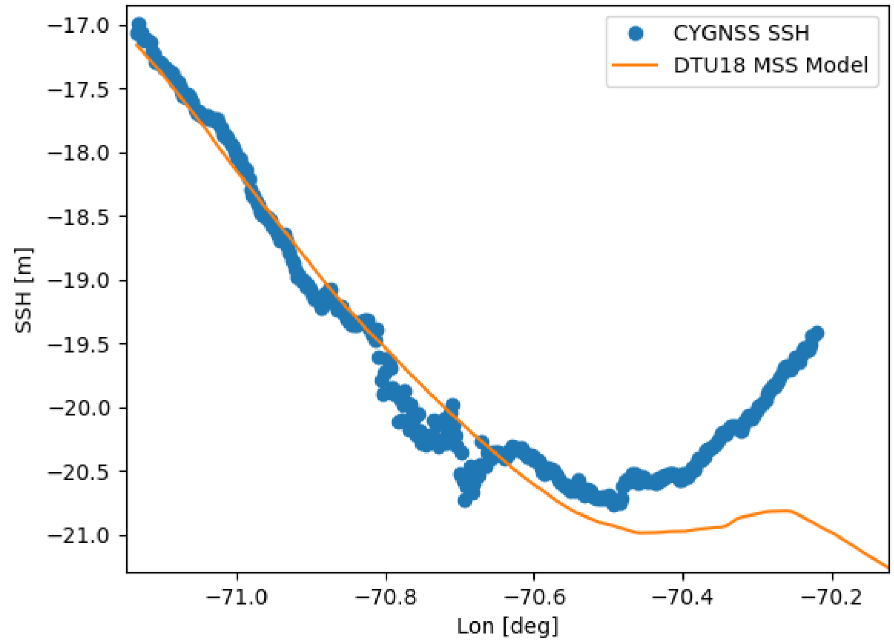
-77.65^0 23.26^0 2018-09-15 12:43

- 50 msec solutions, no further smoothing
- Systematic errors partially corrected: no tide, no atmospheric load...

GA CaPA retrievals:







-71.15^0 12.42^0 2017-09-08 18:32

-68.10^0 12.89^0 2017-09-08 18:44

GA CaPA retrievals:

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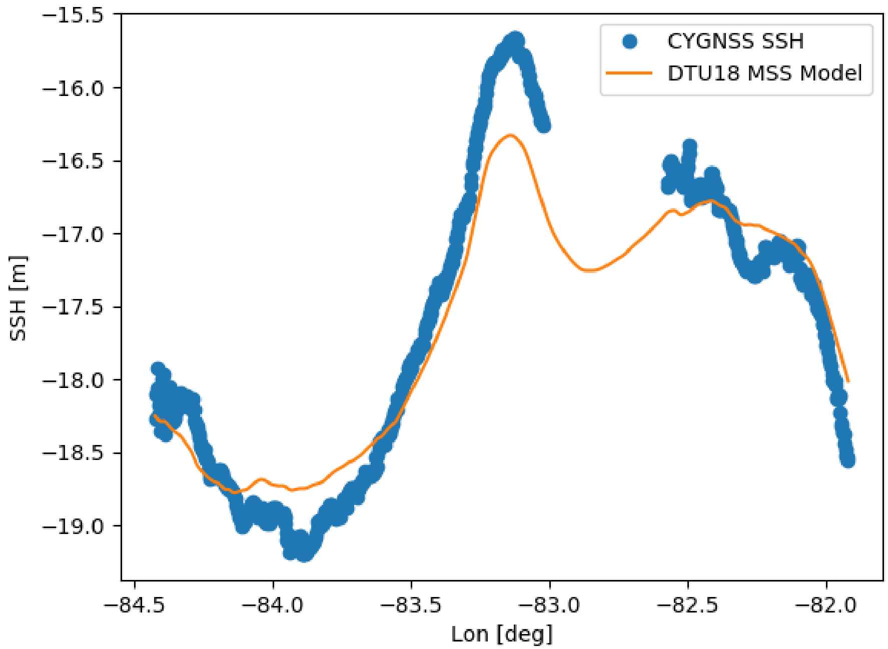

-81.91^0 21.57^0 2018-10-14 23:28

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PRECISION ANALYSIS:

The **precision error due to noise in the range measurements** is very small <λ/4 (< 5 cm) at 50 ms integration.

However, other systematic effects such as residual ionospheric and tropospheric miscorrections, orbit and clock errors, etc, might induce larger errors.

A **coarse combined precision figure** (noise+residual systematic effects) is provided as the RMSE between the DTU18 mean sea level and GNSS-R solutions. Please note that we did not correct for all effects (e.g. tides) and only approximate models were used for ionospheric corrections:

0.15 m to 0.5 m with 50 ms coherent integration

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Tropospheric bending:

- The tropospheric effects increase with incidence angle. Maximum effect at low elevation angles : **~1/sin(e)**.
- Moreover, at grazing angles, the ray trajectory could bent due to vertical gradients of the refractive index!
- 'Ray tracers' are numerical tools to compute the atmospheric ray path, including bending.
- Range and Doppler differences between straight-path and bending-path (ray tracer) computations in the examples we analyzed are small enough to be neglected in the OPEN LOOP tracking model → **tracking receivers can use straight-line propagation models**.

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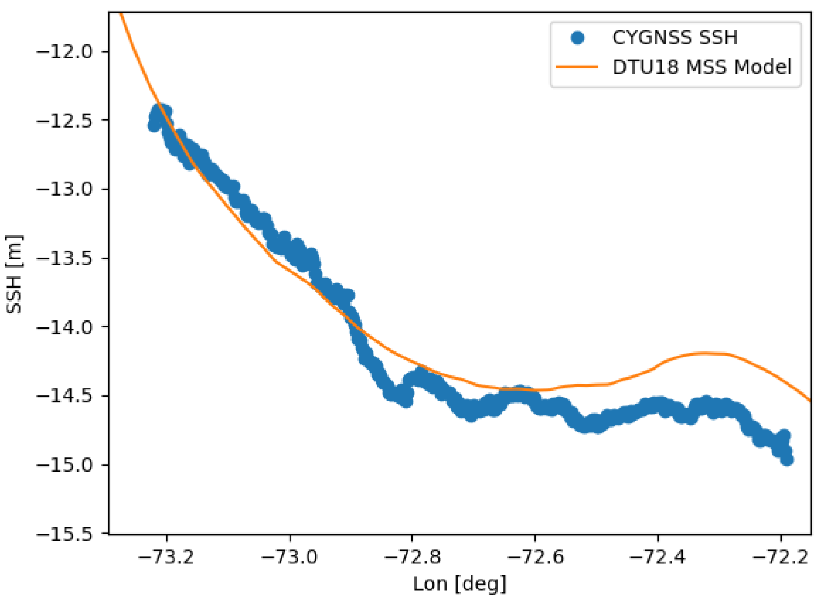
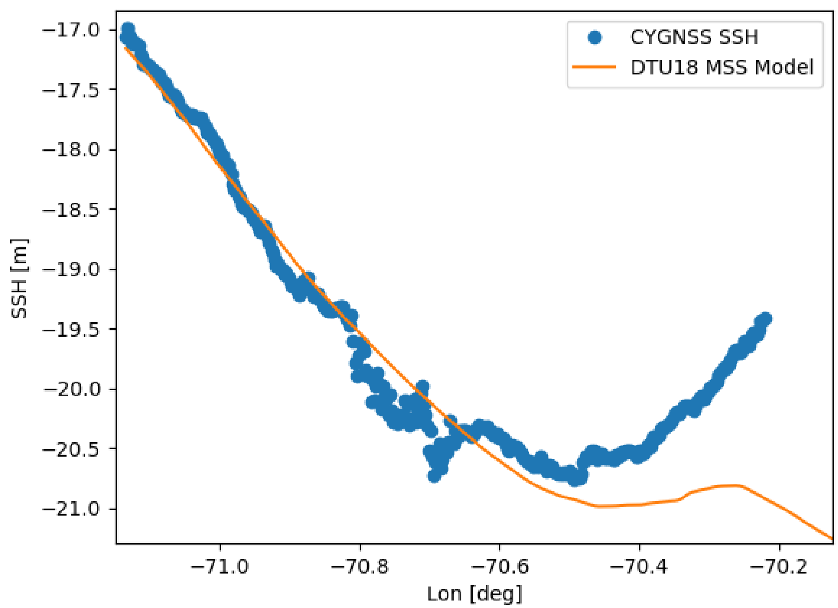
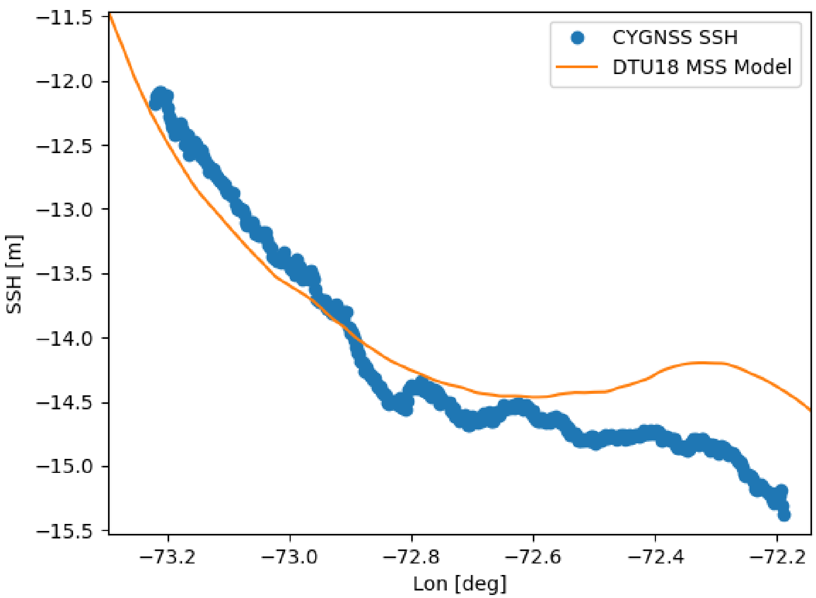
- However, the altimetric retrieval might present large differences if the tropospheric are corrected from straight-line or bended models:

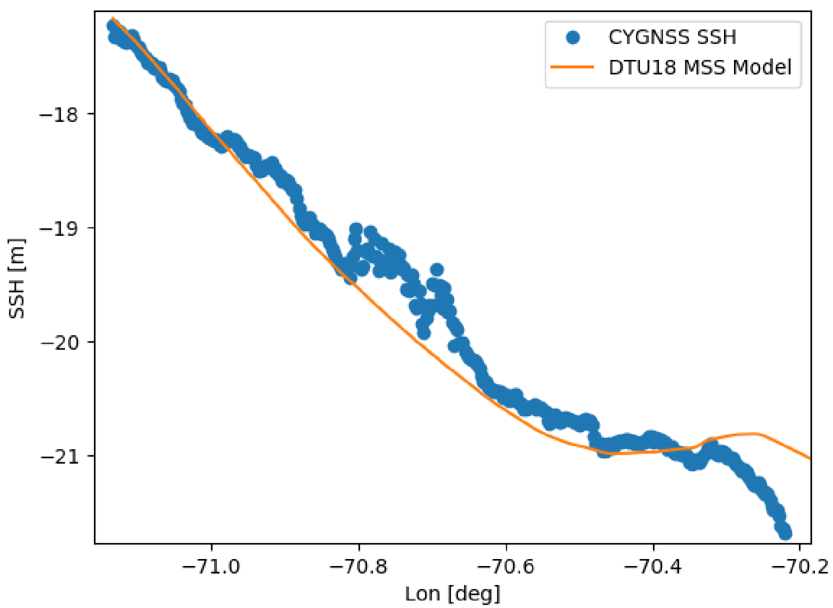




Straight-line atmospheric corrections

- However, the altimetric retrieval might present large differences if the tropospheric are corrected from straight-line or bended models:





Ray tracer/bended rays atmospheric corrections

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Conditions for coherence:

- This data sets is too small for strong conclusions → preliminary conditions.
- We **only** found **coherent signals** when:

Antenna gain:	> -15 dB
Elevantion angle:	< 25^0
Wind speed (ERA-5):	< 6 m/s
SWH (ERA-5):	< 1.5 m
Mean square slope (ERA-5):	< 0.004
Steepness:	< 0.021

These are **necessary conditions**, but not sufficient (tracks fulfilling these conditions not necessary present coherence)

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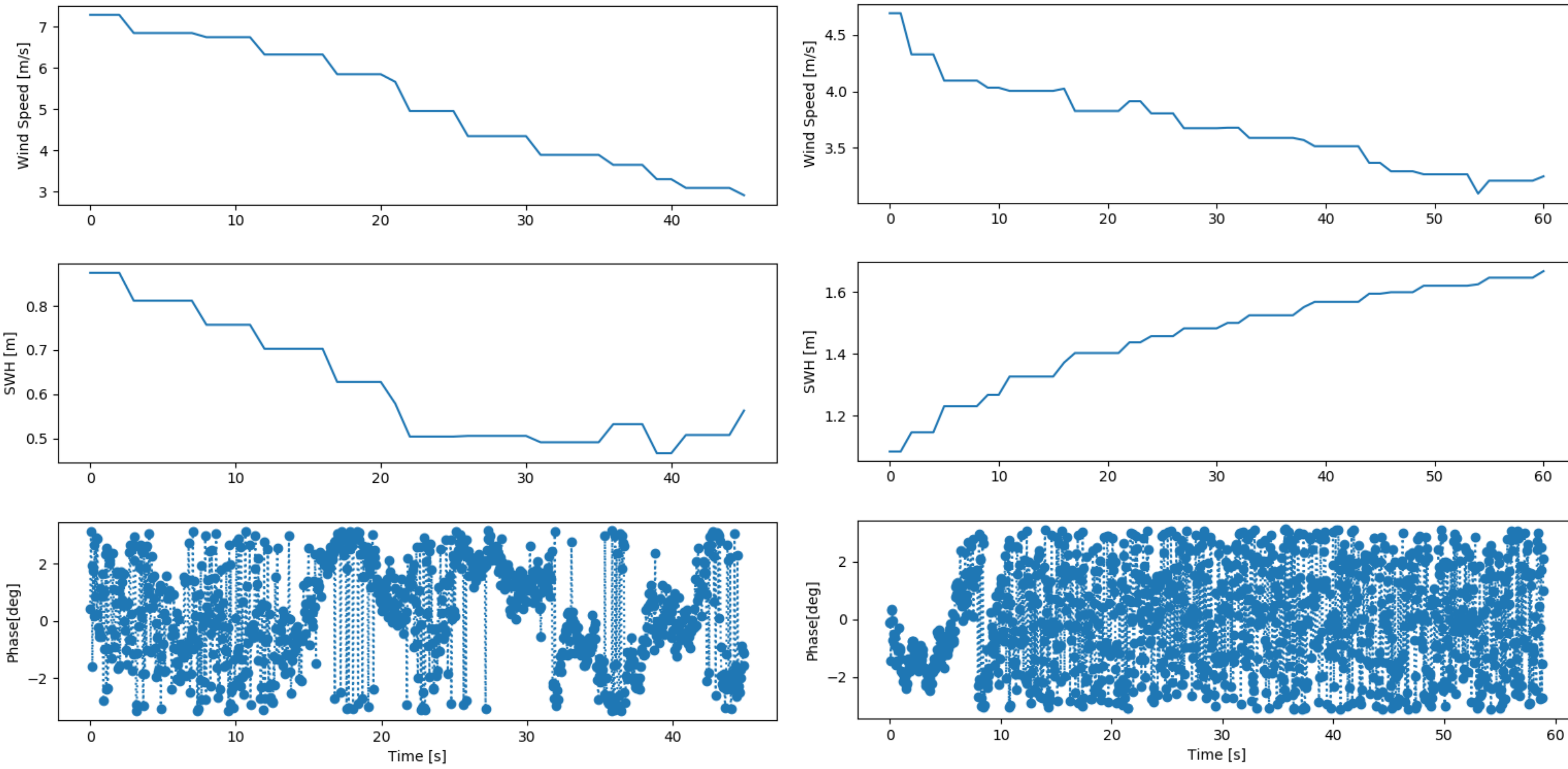
Examples of coherence and noisy measurements:



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- The number of reflected tracks that fulfill the necessary ‘calm’ conditions are 36.
- Among them, 12 present coherence (33%).

OPEN QUESIONS: why some tracks do not present coherence under the same conditions? Why GEOHALO airborne experiment presented much relaxed coherence conditions?

- Dynamics of the Fresnel zone? (e.g. airborne vs spaceborne; within spaceborne, direction of the Fresnel ellipse w.r.t. direction of velocity)
- Direction of the roughness features w.r.t. observation azimuth?
- Ionospheric disturbances (strong scintillation)?
- Insufficiently smart processing?

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Which is the potential use of these coherent reflections?

- Simulated tracks as obtained for the CyGNSS mission, assuming its HW was also designed to collect grazing angle GNSS-R tracks between 10^0-20^0 elevation, with antenna gain values larger than -15 dB.
- GNSS constellations: GPS, Galileo, BeiDou-3 & Glonass.
- **3 days simulation:** 11, 12, 13 Oct 2018 & 1, 2, 3 Feb 2019.
- Each track is co-located with ERA-5 wind and SWH. **Only tracks that fulfill 'needed conditions'** are selected.
- Among these, **only 33%** (randomly chosen) are finally displayed.

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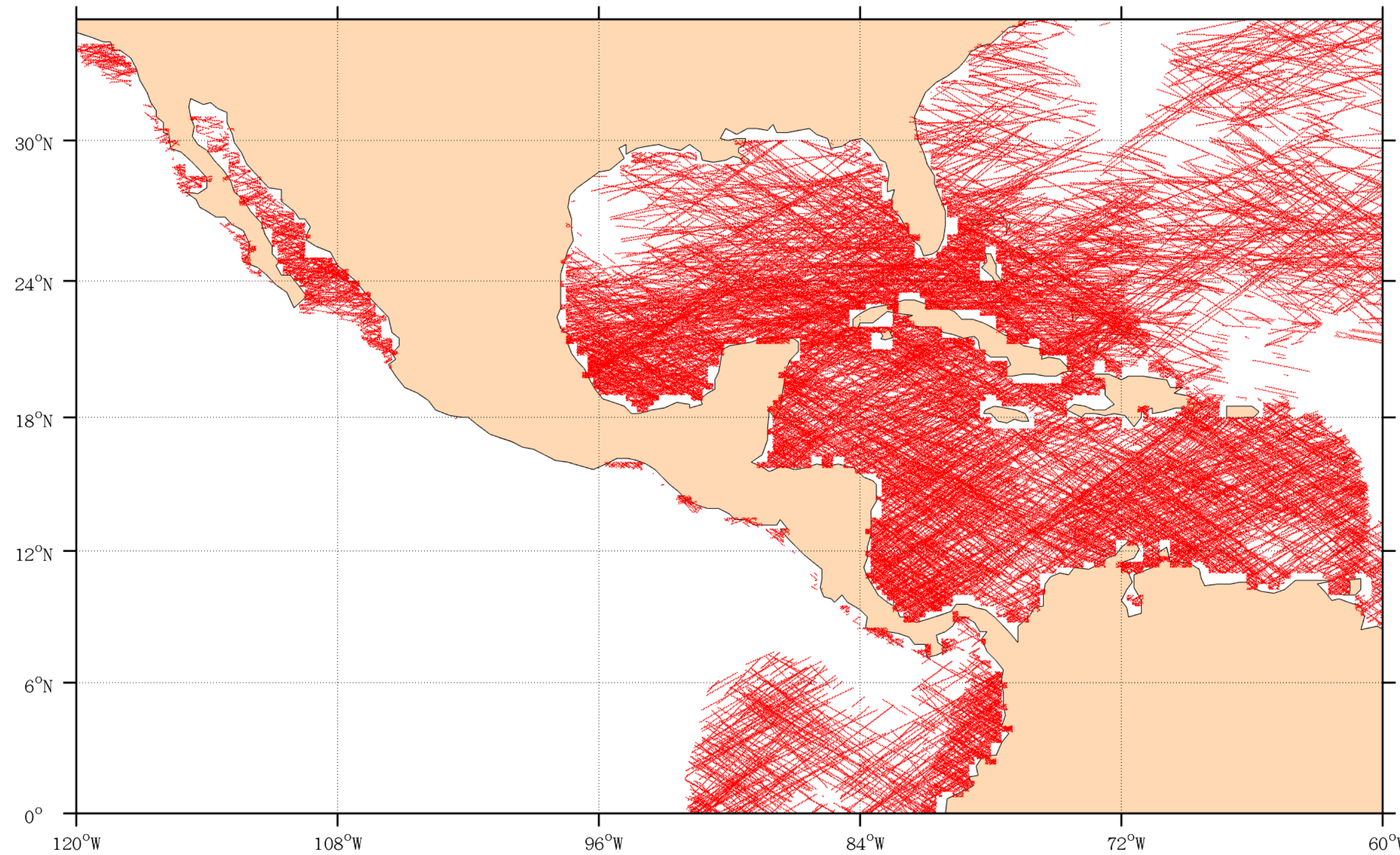
Tracks along ‘required conditions’ 11-13 Oct 2018:



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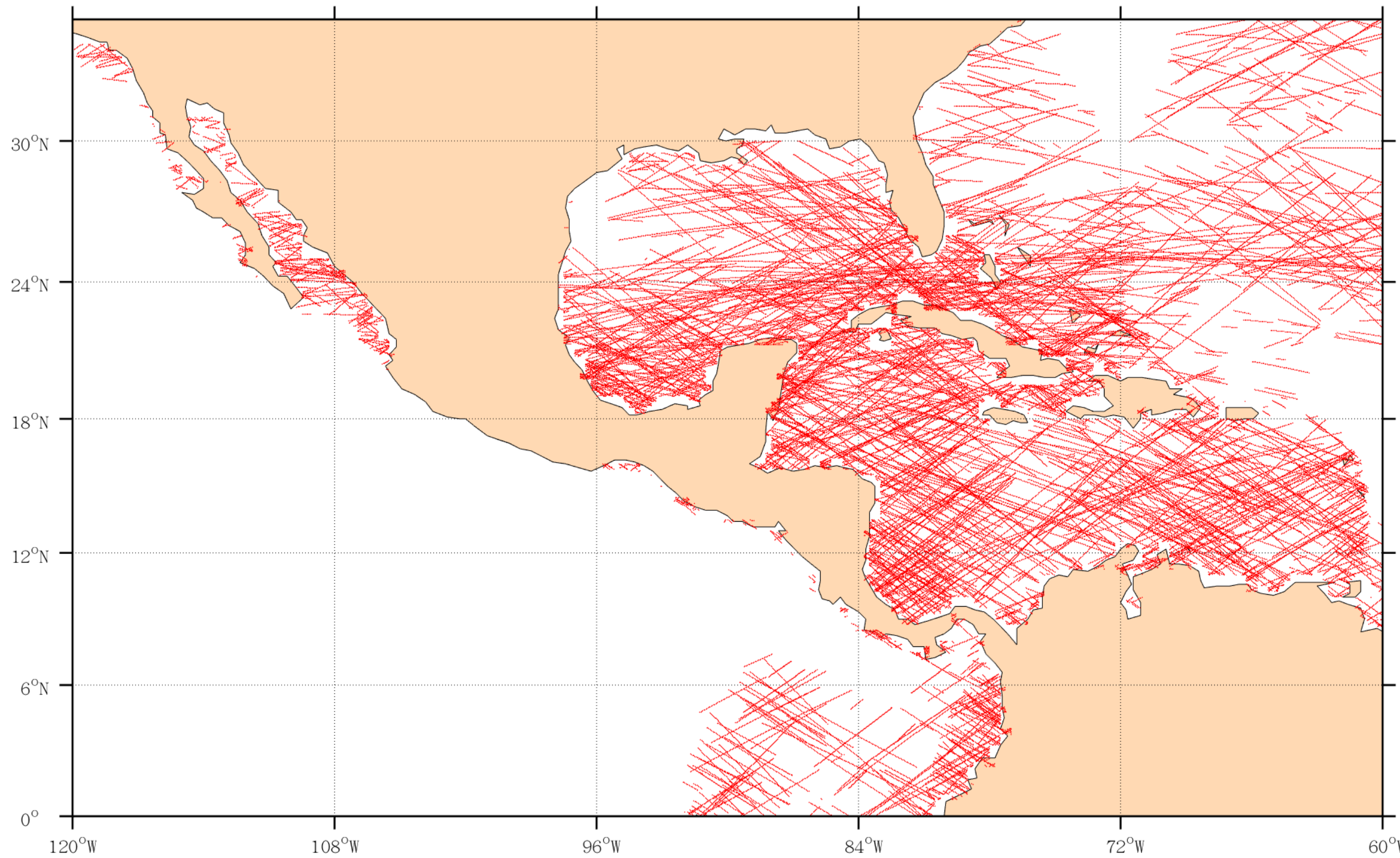
33% of tracks along ‘required conditions’ 11-13 Oct 2018:



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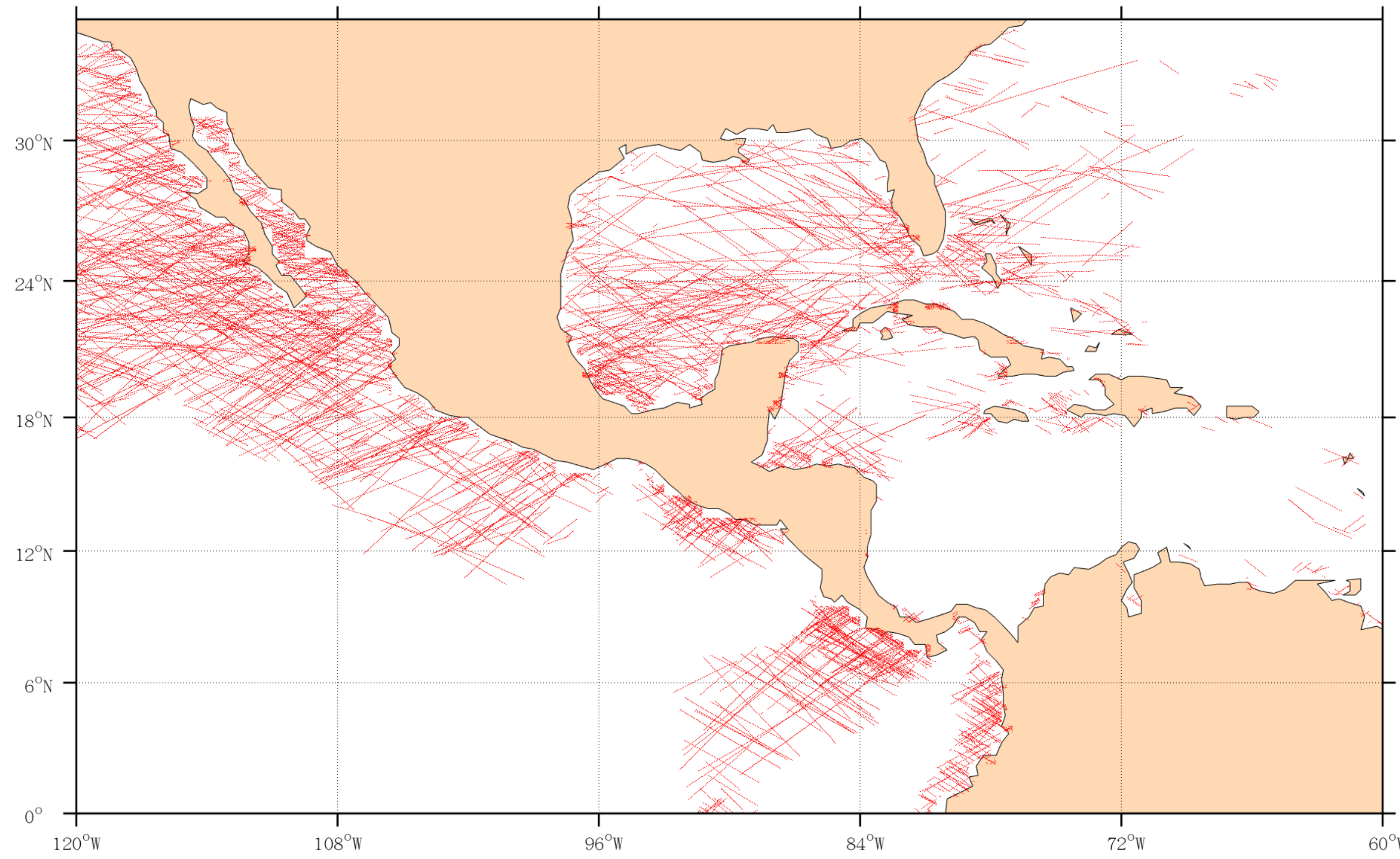
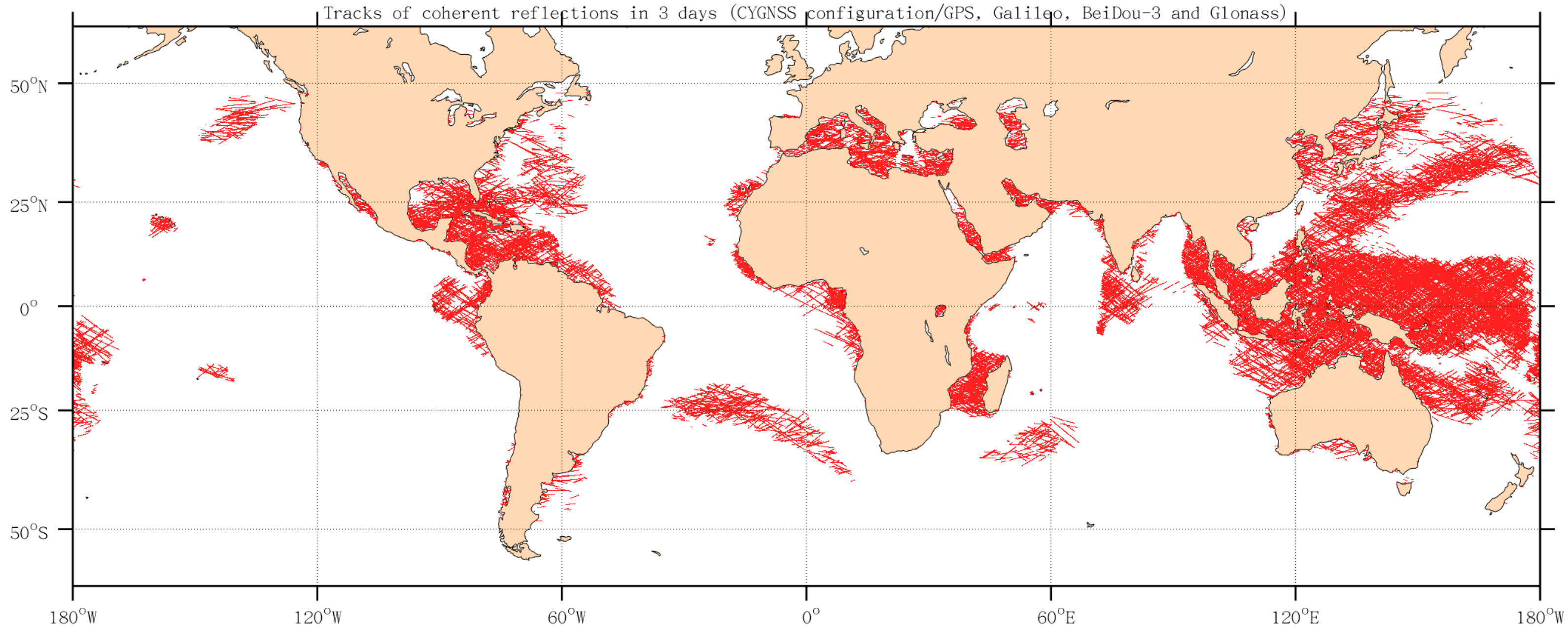
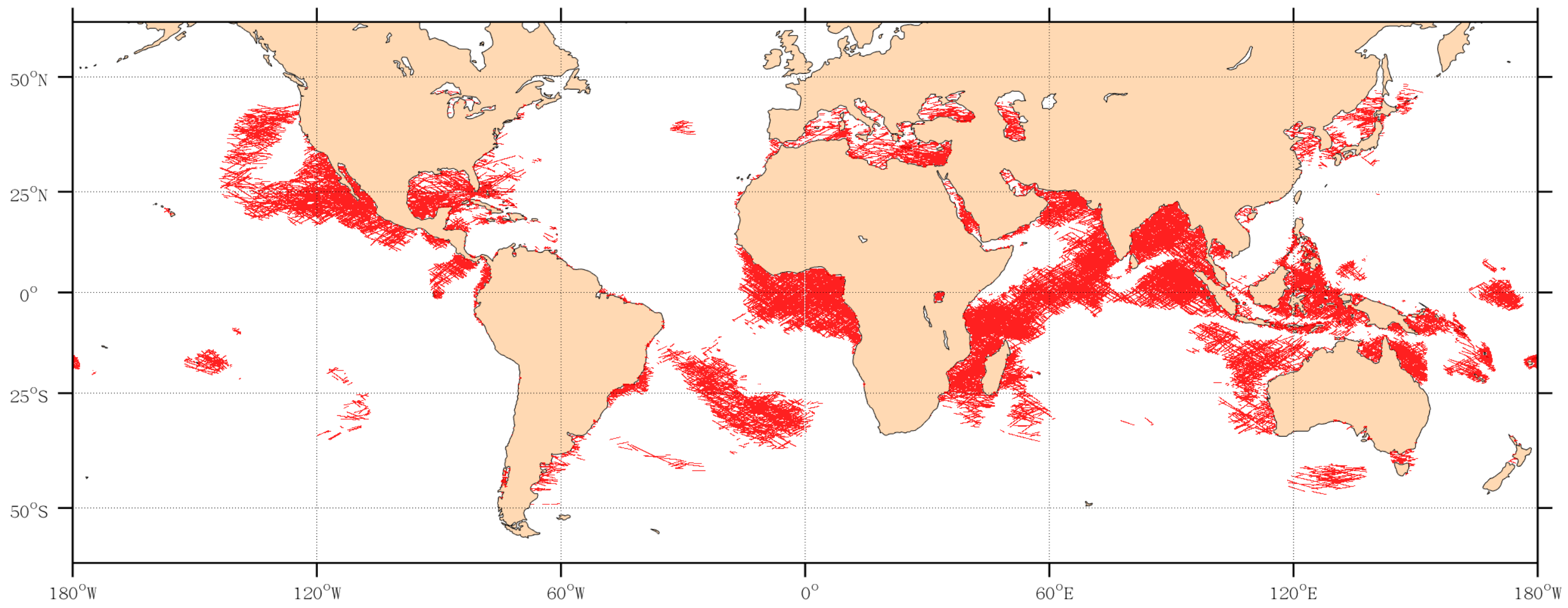
33% of tracks along ‘required conditions’ 1-3 Feb 2019:



33% of tracks along ‘required conditions’ 11-13 Oct 2018:



33% of tracks along 'required conditions' 1-3 Feb 2019 Global:



Discussion:

- Moreover, GA CaPA could be easily activated in many GNSS atmospheric radio occultation (RO) missions:
  - >10 agency satellites currently in orbit;
  - 6 more to be launched June 2019;
  - >50 commercial cubesats in orbit.
- GNSS RO missions have some advantages:
  - They work at 2 frequencies (**ionospheric corrections**),
  - They are a key element of operational weather forecast, **plans to expand and maintain large meta-constellations** of GNSS RO,
  - Firmware-only changes required!
  - Commercial companies currently deploying GNSS RO satellites.

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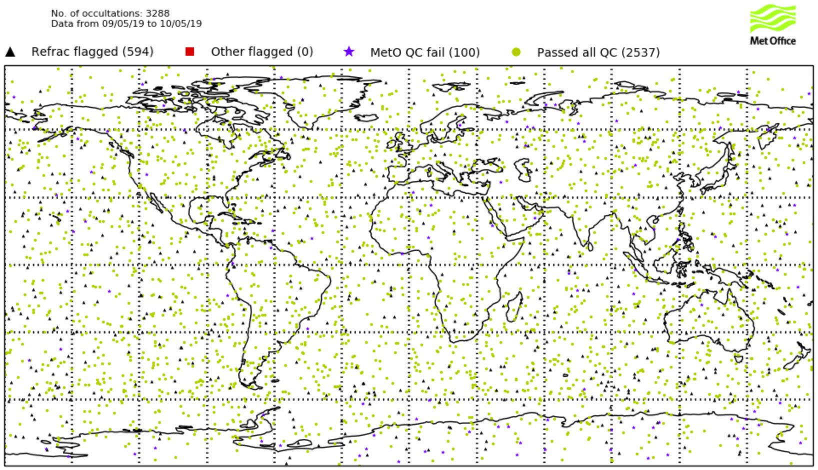
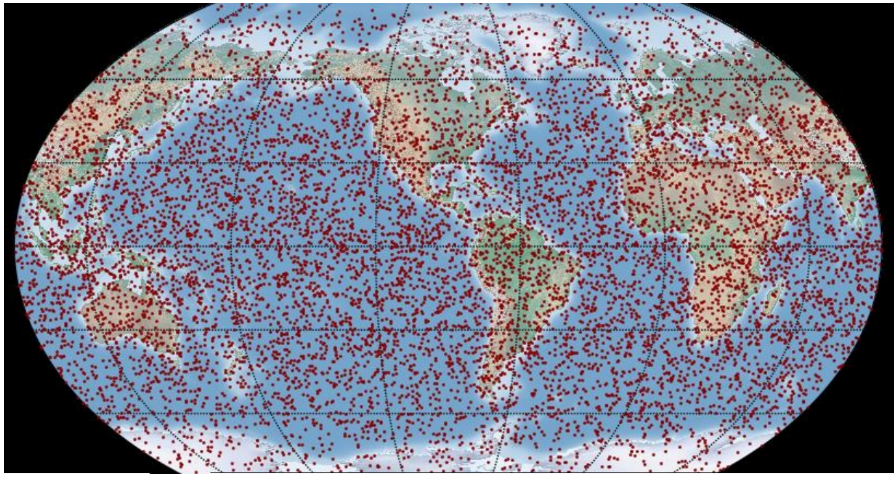
Current daily radio occultation coverage:



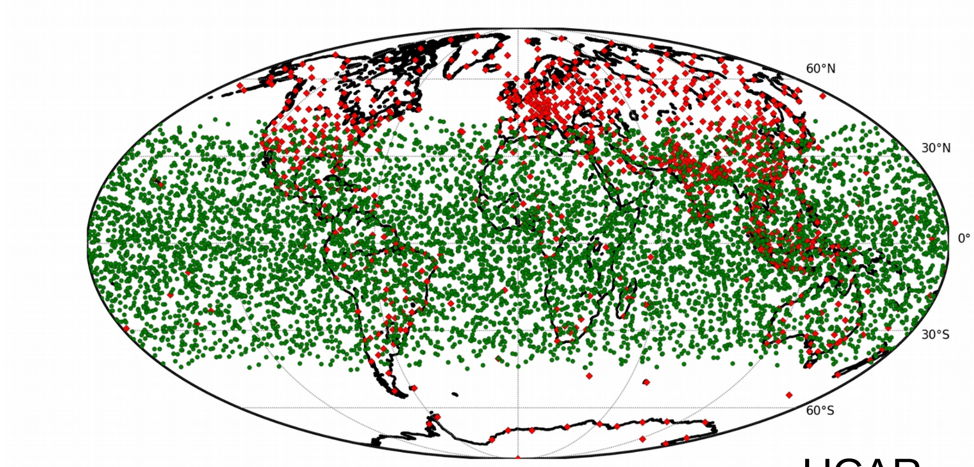
EUMETSAT ROM SAF 8 agencies' LEO

Plotted at 09:00, 10 May 2019



Spire's commercial LEOs

Daily radio occultation coverage of COSMIC-2 (Launch June):



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Conclusion:

- GA CaPA over open seas has been **first tested from spaceborne platform in the range up to 25^o elevation**.
- CyGNSS raw data sets analyzed across the Central America region: **63 GNSS-R tracks** found below 25^o elevation.
- **Sea surface** GA CaPA is possible, with **fine precision figures**.
- GA CaPA over open sea waters seems to be only possible under certain conditions (roughness, instrument).
- However, these conditions are not sufficient. In this data set 33% of the tracks under 'required conditions' present coherence.
- **WHY? Open question to be solved** (future work)
- Even if these numbers are confirmed, 3-day simulations with CyGNSS like constellations show that **the resulting coverage could be useful for sub-mesoscale altimetry** over certain regions.
- Implementation on GNSS RO mission would be feasible, providing unprecedented coverage.