Coherent Reflectometry from Space: Sensitivity to Sea-Surface Height and Atmospheric Disturbance

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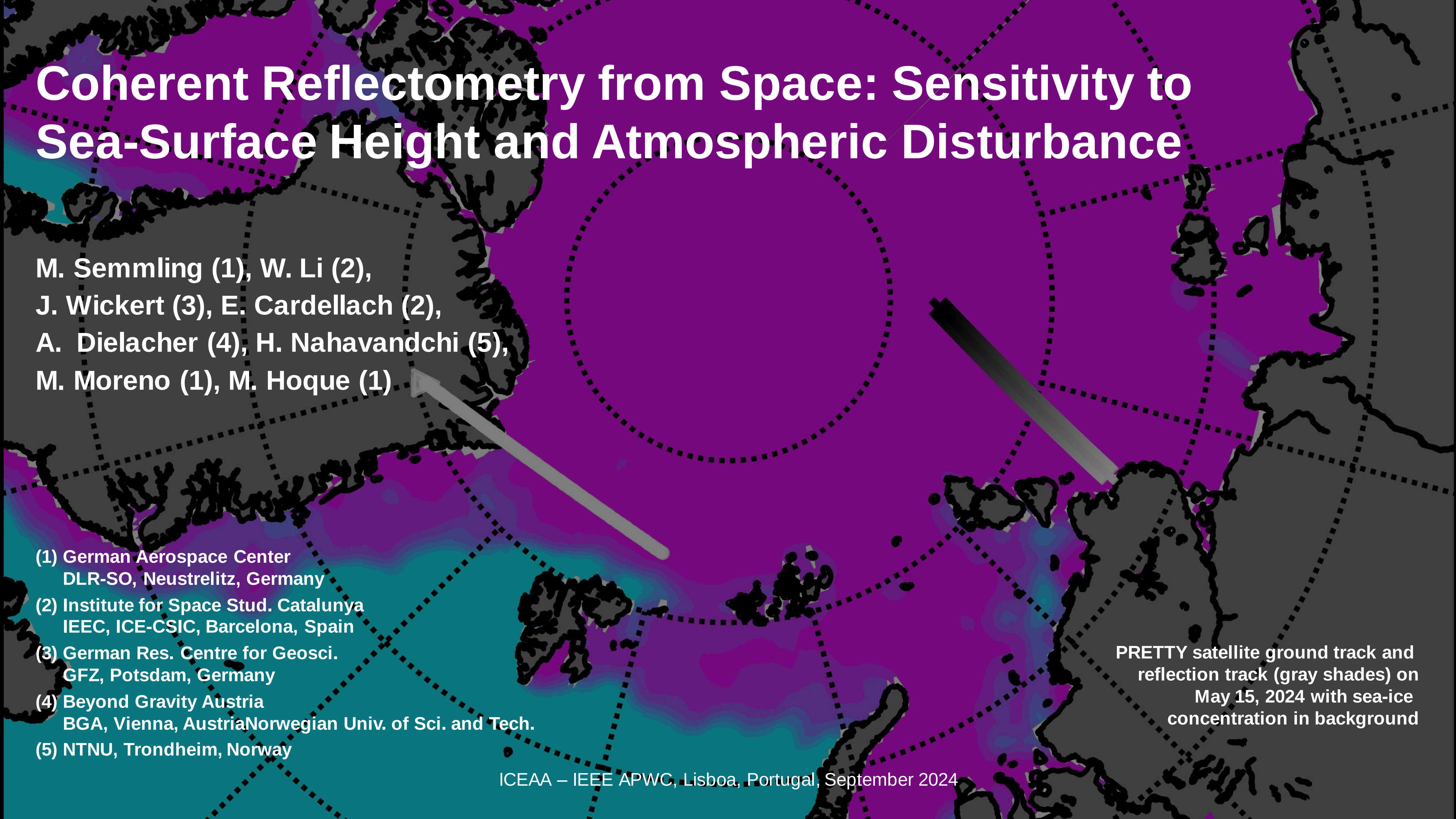


PRETTY satellite ground track and reflection track (gray shades) on May 15, 2024 with sea-ice concentration in background

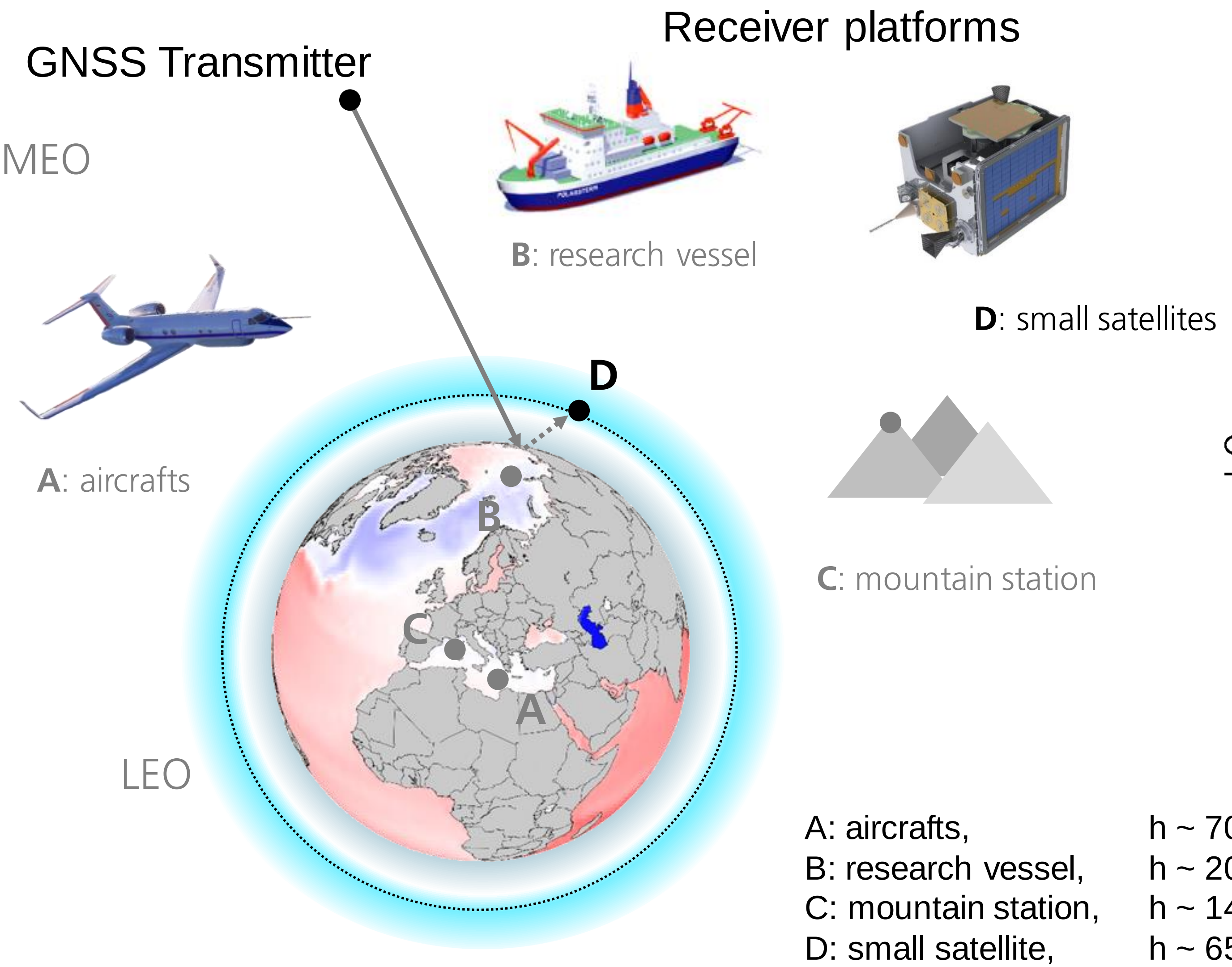
ICEAA – IEEE APWC, Lisboa, Portugal, September 2024

Outline

- Background and Motivation
- Data Sources and Processing Approach
- Results over …
  - Caribbean
  - Hudson Bay
  - Arctic Ocean
- Summary & Outlook

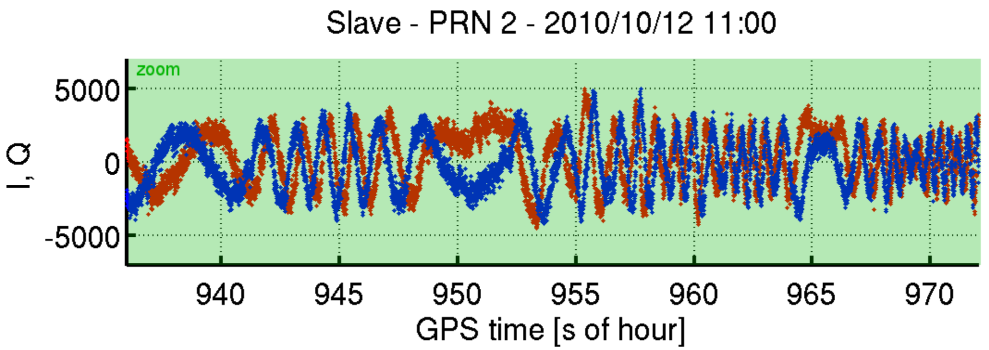
Background and Motivation

Scenarios of Coherent Reflectometry



Coherent Reflectometry:

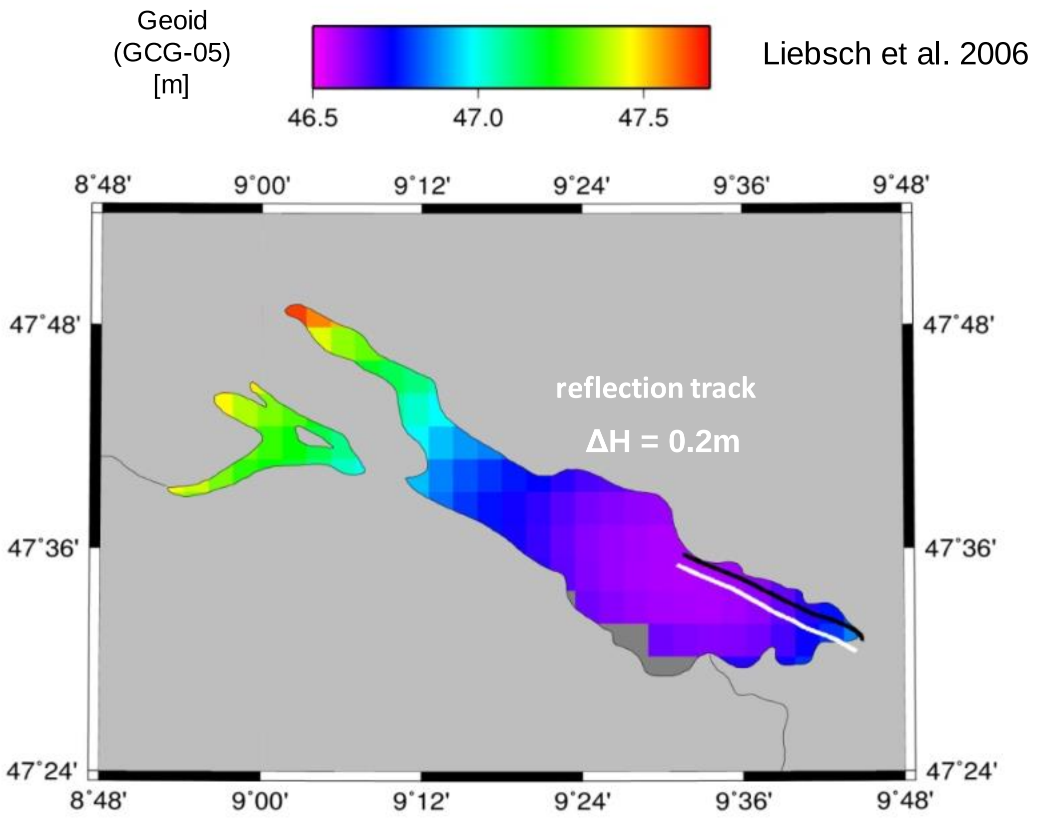
We have samples of the reflected signal that contain phase information over a reasonable time scale …

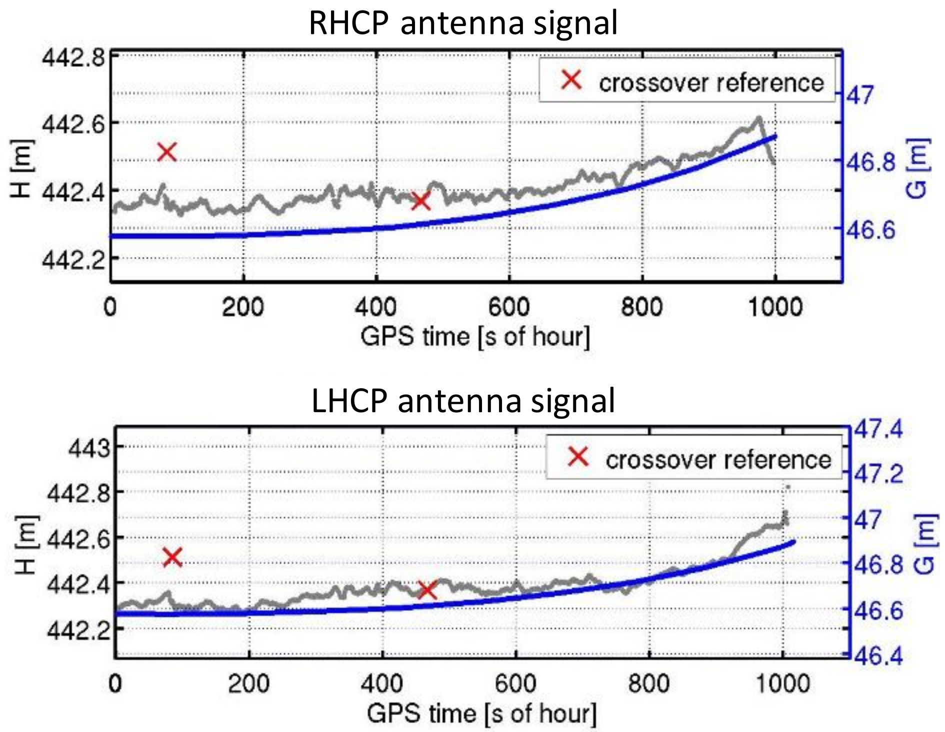


Coherent reflection event over lake Constance, airborne record (Zeppelin NT airship), Semmling et al. 2013.

A: aircrafts,	h ~ 700 … 3500 m	Semmling et al. 2014; Moreno et al. 2022
B: research vessel,	h ~ 20 m	Semmling et al. 2019, 2023
C: mountain station,	h ~ 1430 m	Fabra et al. 2011; Semmling et al. 2011
D: small satellite,	h ~ 650 km	Li et al. 2017; Cardellach et al. 2020

Altimetric Features from Reflectometry at lake Constance





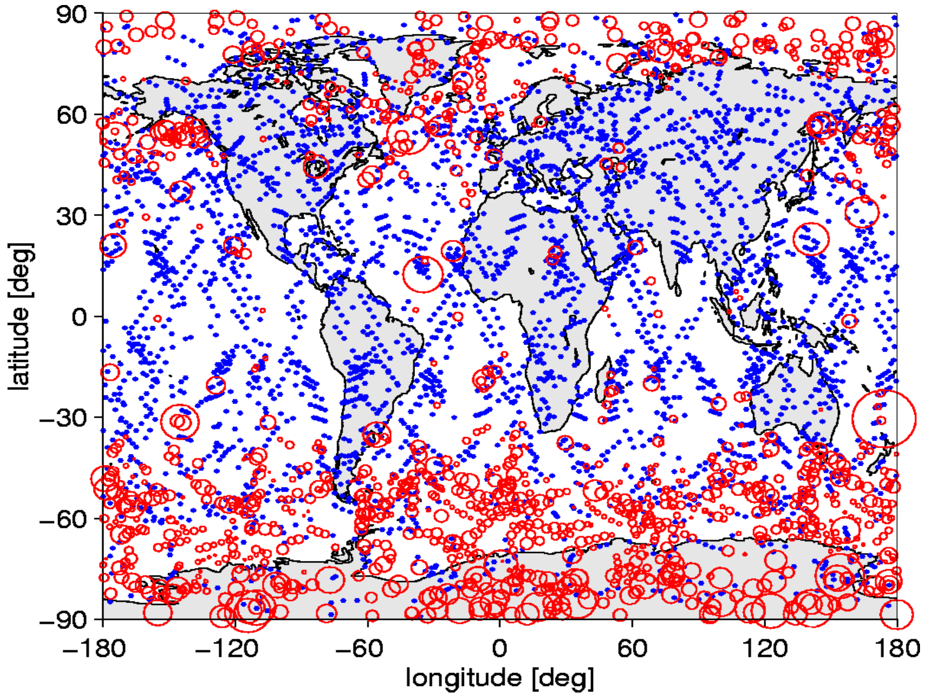
	mean bias	precision
H to G (RHCP)	7 cm	3 cm
H to G (LHCP)	5 cm	4 cm

Coherent phase obs. allow to retrieve water level variation e.g. geoid undulations with cm-precision.

Semmling et al. 2013, 2014

Opportunities and Challenges

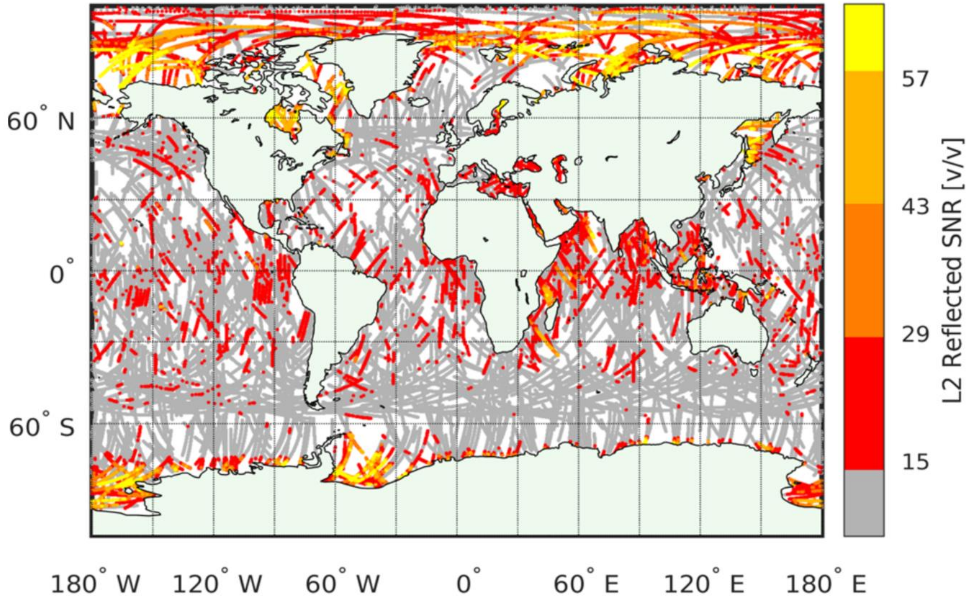
- **GNSS signal** are **freely available** with global coverage
- Coherent signature have been observed in various scenarios also from space
- **Main goal**: derive **altimetric products** (sea surface height) with centimeter precision
- **Disturbances** to be considered
  - Irregularities on Earth surface (land, ocean roughness)
  - Irregularities in Earth‘s atmosphere (ionosphere, troposphere)
- Best **Opportunities** for coherent reflectometry
  - Over **sea ice**, **calm ocean** and in coastal areas
  - At **gracing elevation** angles
- **Challenge** in this study
  - Study coherent observation from three different sat. missions
  - Conclude on sensitivity to **sea surface height** and **atmospheric effects**



Radio Occultation events recorded with CHAMP mission (one month)

red with reflection
blue w/o reflection

Beyerle et al. 2002



Reflectometry events recorded by Spire constell. (four months)

coherent obs. coincide with higher SNR

Roesler et al. 2021

Considerable Factors

Sea Surface

- Roughness (Sea State)
- Penetration (e.g. Sea Ice)
- …

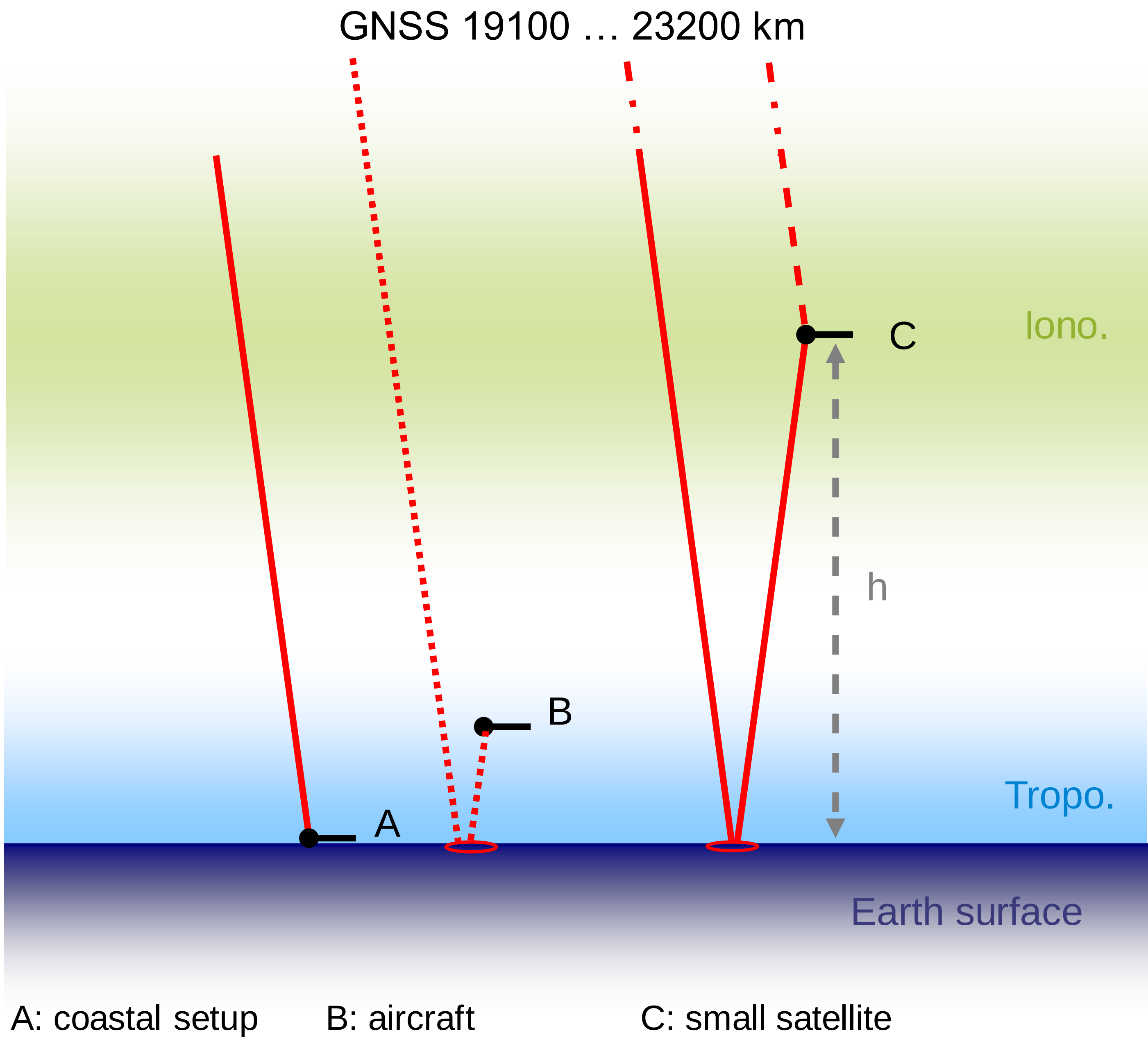
Atmosphere

- Refraction
  (neutral gas and ionosphere)
- Scintillation
  (Plasma Depletion, Space Weather)
- …

Receiver & Transmitter

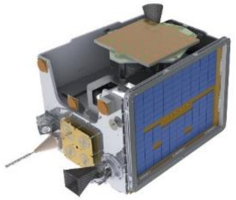
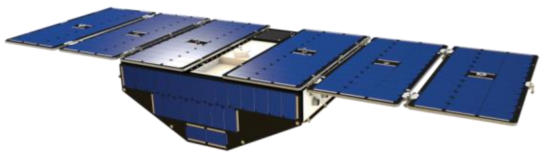
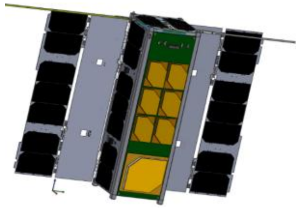
- Position & Attitude uncertainty
  (of vessel, aircraft or satellite)
- Antenna & Instrumental parameter
  (e.g. gain pattern)
- …

degree of disturbance



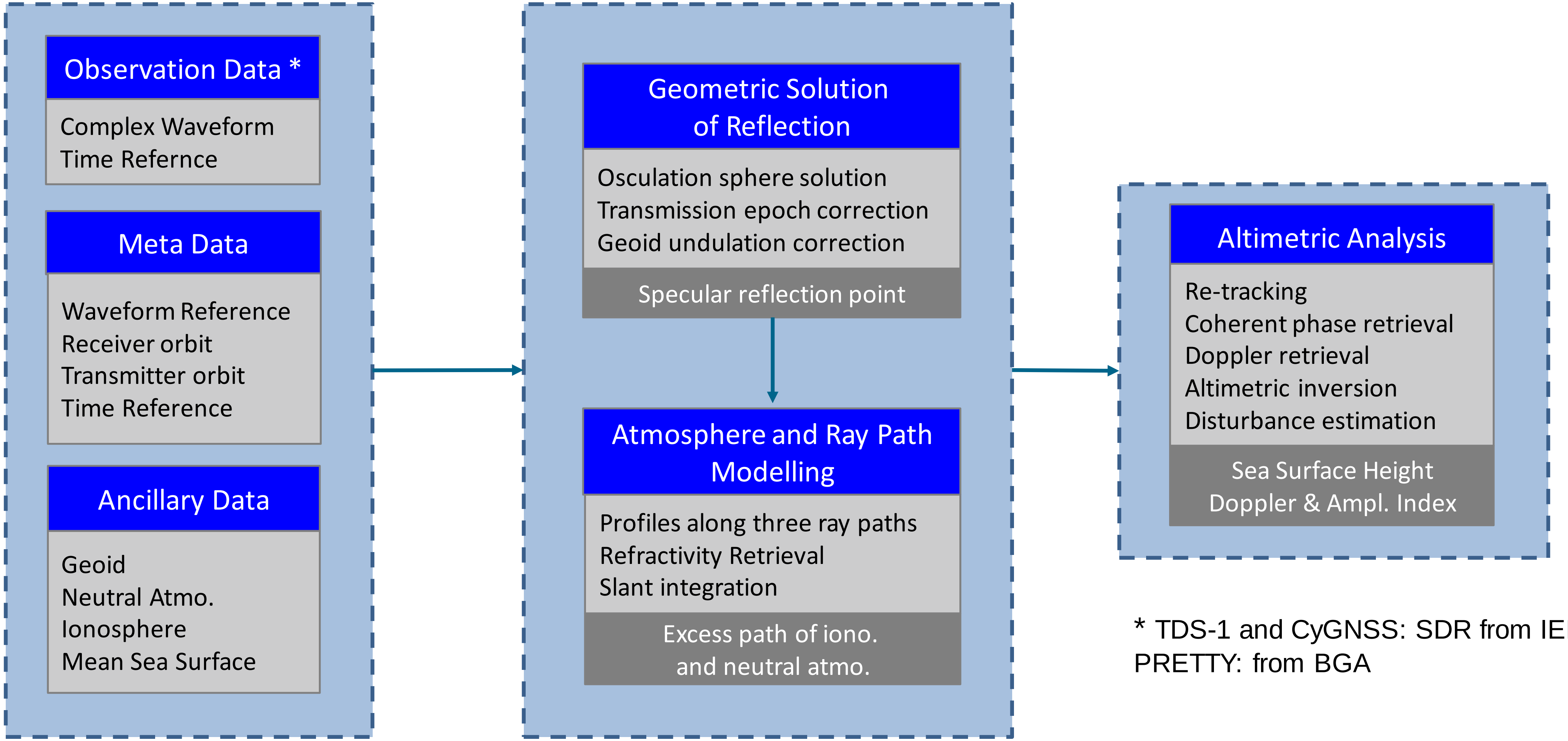
Data Sources and Processing Approach

Data from reflectometry missions

Mission:	TDS-1	CyGNSS	PRETTY
# of sats:	1 small sat	8 small sats	1 cube sat
Orbit height:	~ 650 km	~ 520 km	~ 560 km
Orbit inclination:	98.8°	35.0°	
Major field of view:	near-nadir	near-nadir	grazing
Supported signals:	GPS L1 C/A	GPS L1 C/A	GPS L5C & GAL E5
Select. area:	Hudson Bay, Canada	Caribbean Sea	Arctic Ocean
Time period:	Jan 2015	Sep 2017, Sep 2018	May – July 2024

Algorithm Theoretical Baseline Document for PRETTY



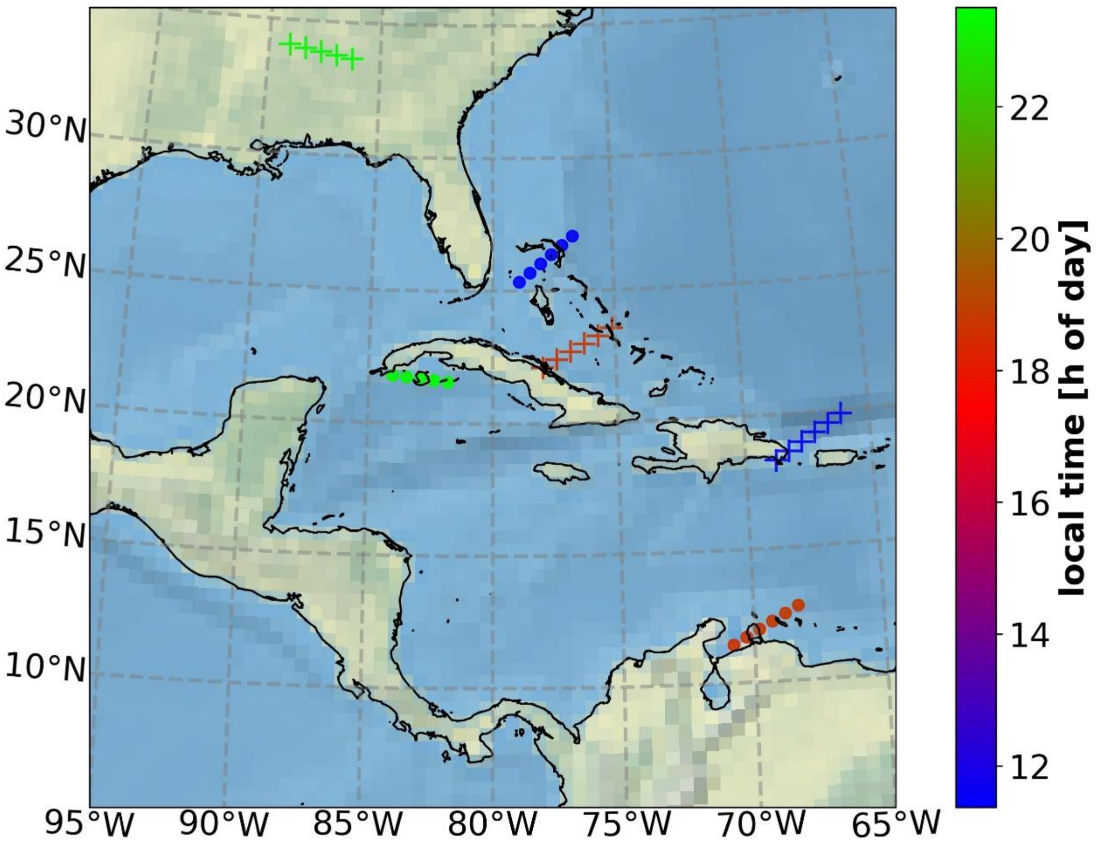
* TDS-1 and CyGNSS: SDR from IEEC
PRETTY: from BGA

Semmling et al. 2022

Results over Caribbean

Reflection Track Reference

Example Events of CyGNSS Mission



\+ receiver ground track

● reflection track

Venezuela Track

- GPS PRN 12 by CYG ID 4 on 2017/09/08 23h17 UTC
- local evening (equatorial plasma bubbles?)

Bahamas Track

- GAL PRN 1 by CYG ID 8 on 2017/09/20 16h37 UTC
- local noon

Cuba Track

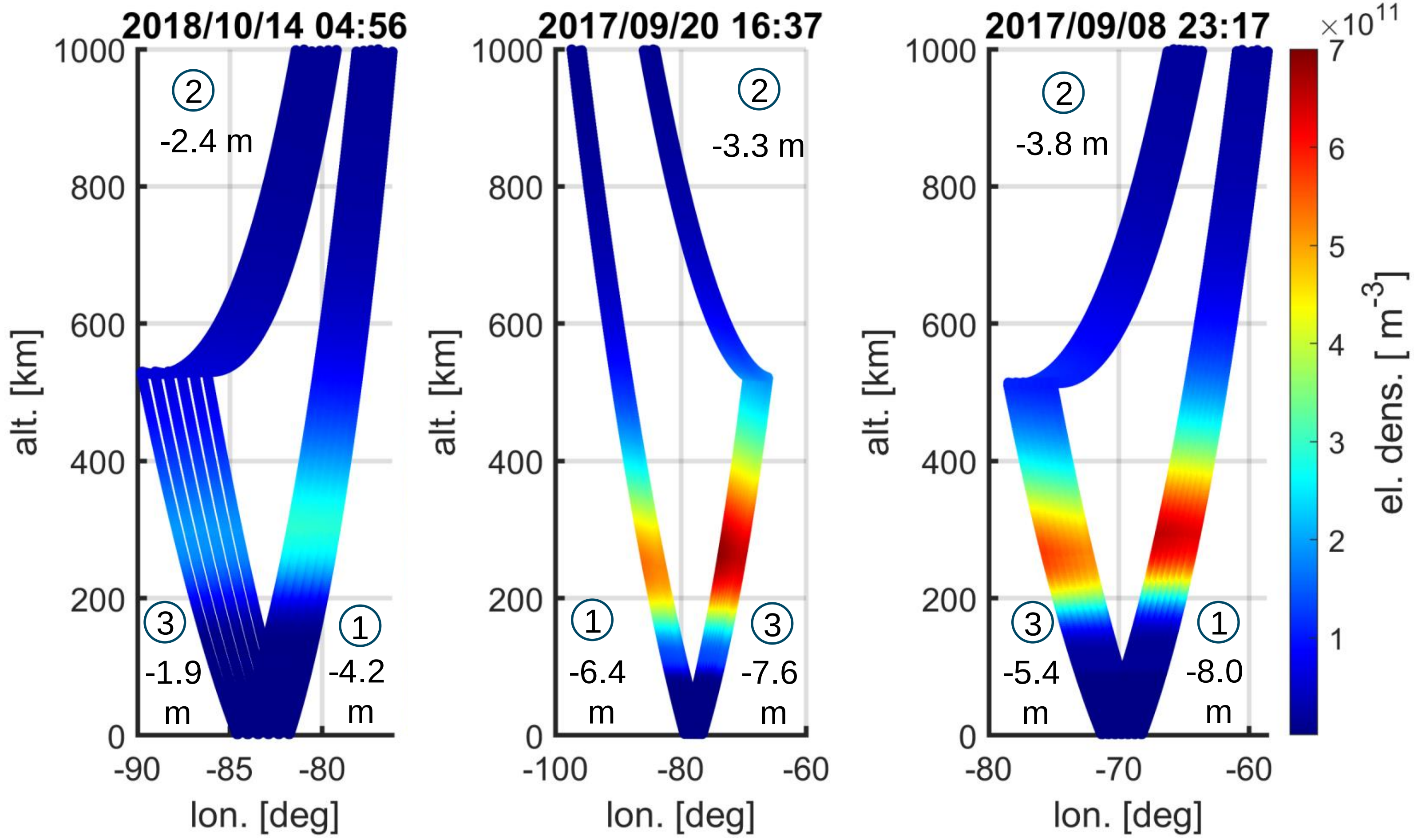
- GAL PRN 5 by CYG ID 5 on 2018/10/14 04h56 UTC
- local night

All three Tracks

- elev. angle between 13° … 15°

Cardellach et al. 2020

Ionosphere Reference Data



Cuba track
local night

Bahamas track
local noon

Venezuela track
local evening

NEDM model

- global, empirical climatology
- continuous in time and space
- smallest features 2.5° (TEC map based)
- temporal scale (down to semidiurnal)
- provider DLR-SO**
- Ionosphere parameter of interest:

  electron density *ne*

** German Aerospace Center,
Institute for Solar-Terrestrial Physics

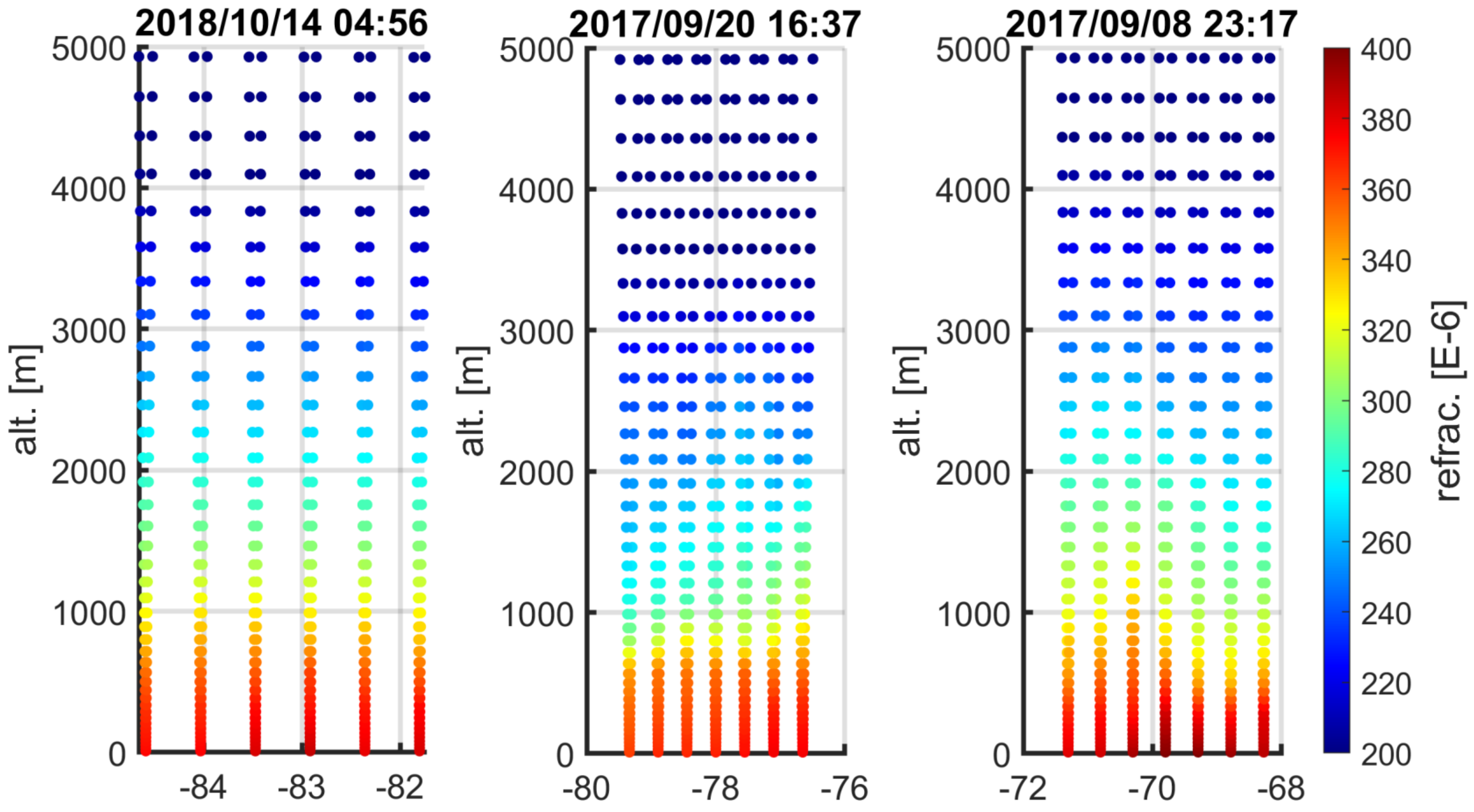
Jakowski & Hoque 2018

① phase excess path xmit to spc (1st ep.)

② phase excess path xmit to rcv (1st ep.)

③ phase excess path spc to rcv (1st ep.)

Neutral Atmosphere Reference Data



① 12.1 m ③ 12.0 m
Cuba track
local night

① 9.5 m ③ 9.5 m
Bahamas track
local noon

① 11.9 m ③ 11.9 m
Venezuela track
local evening

ERA5 model

- global, obs.-driven
- horizontal grid (res.: 30km)
- vertical levels (res.: 10m … ~6km)
- temporal scale (res.: 1h)
- provider ECMWF*
- Meteorological parameter of interest:

  air pressure p
  air temperature T
  specific humidity q

* European Centre of Medium-range Weather Forecast

Hersbach et al. 2020

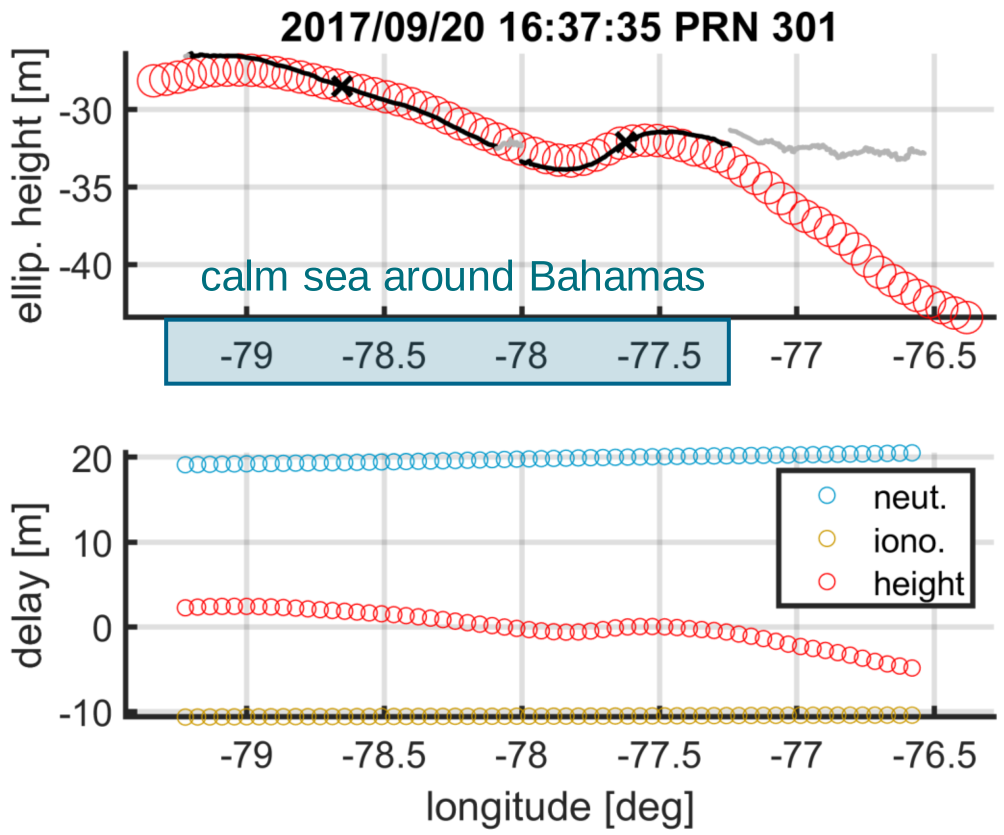
① phase excess path xmit to spc (1st ep.)

③ phase excess path spc to rcv (1st ep.)

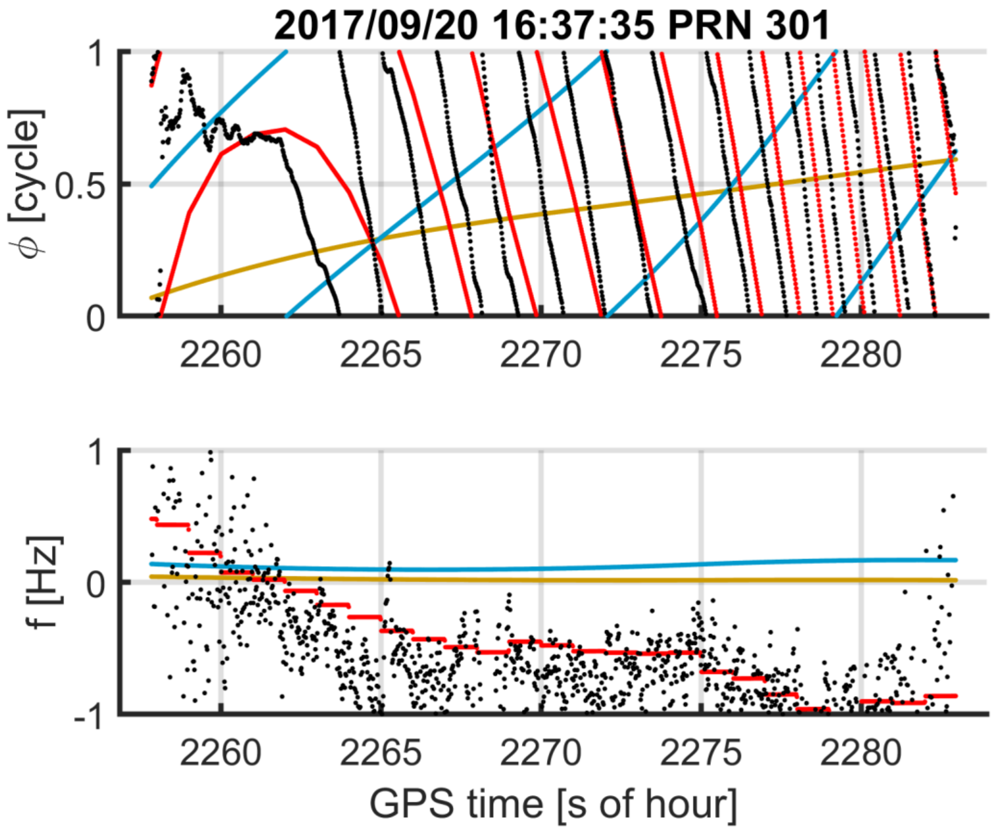
Bahamas Track

DLR

Retrieved Heights and Model corrections



Phase & Doppler of longest coherent track



○ Mean sea surface height from DTU 21

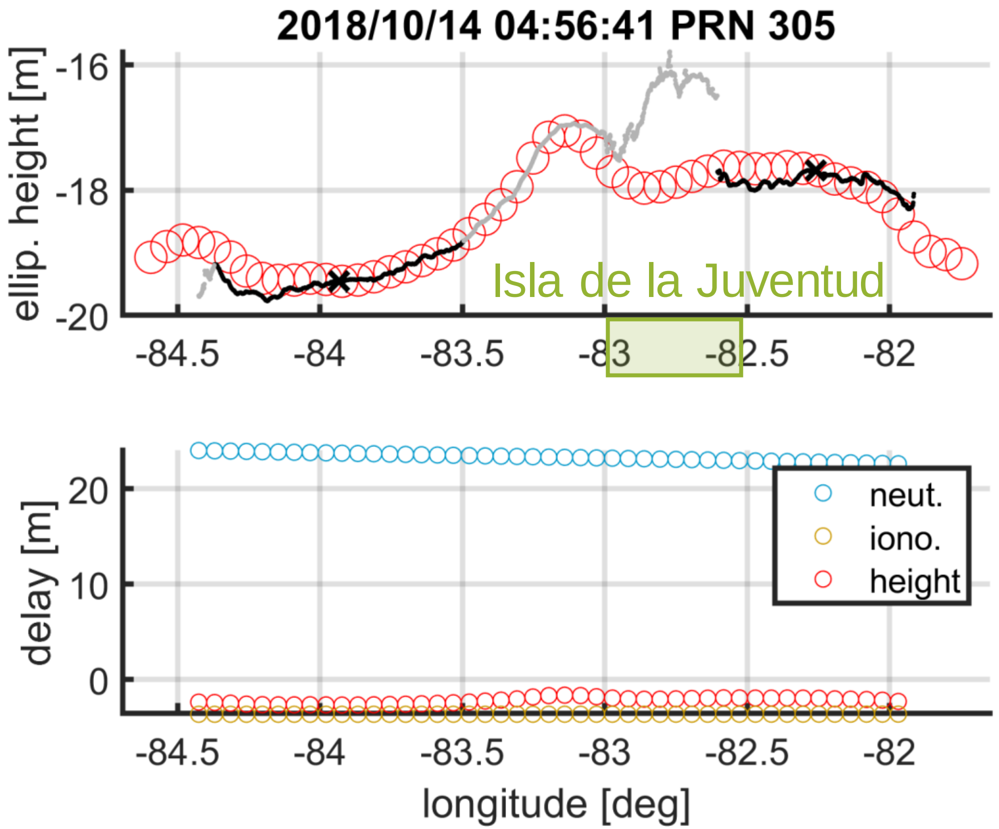
▪ Coherent observation/track   x reference epoch for amb. fix.

▪ Incoherent observation

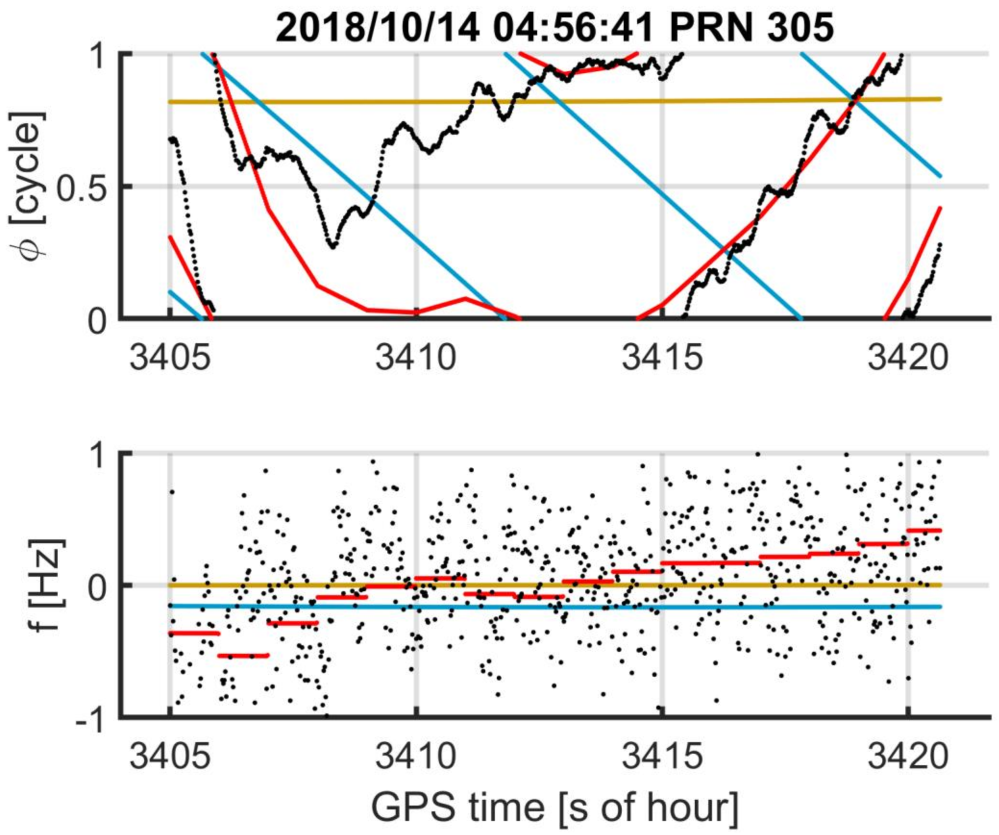
- long surface dominated track 25 s
- after surface correction std(f) = 0.94 Hz

Cuba Track

Retrieved Heights and Model corrections



Phase & Doppler of longest coherent track



○ Mean sea surface height from DTU 21

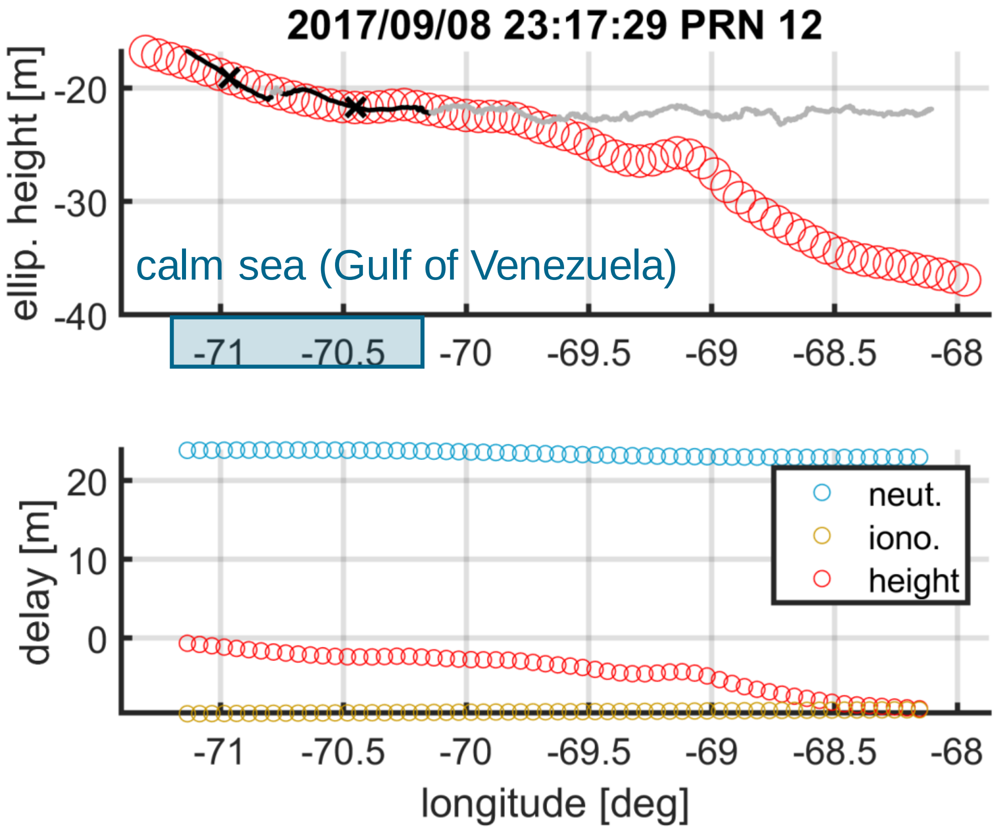
▪ Coherent observation/track x reference epoch for amb. fix.

▪ Incoherent observation

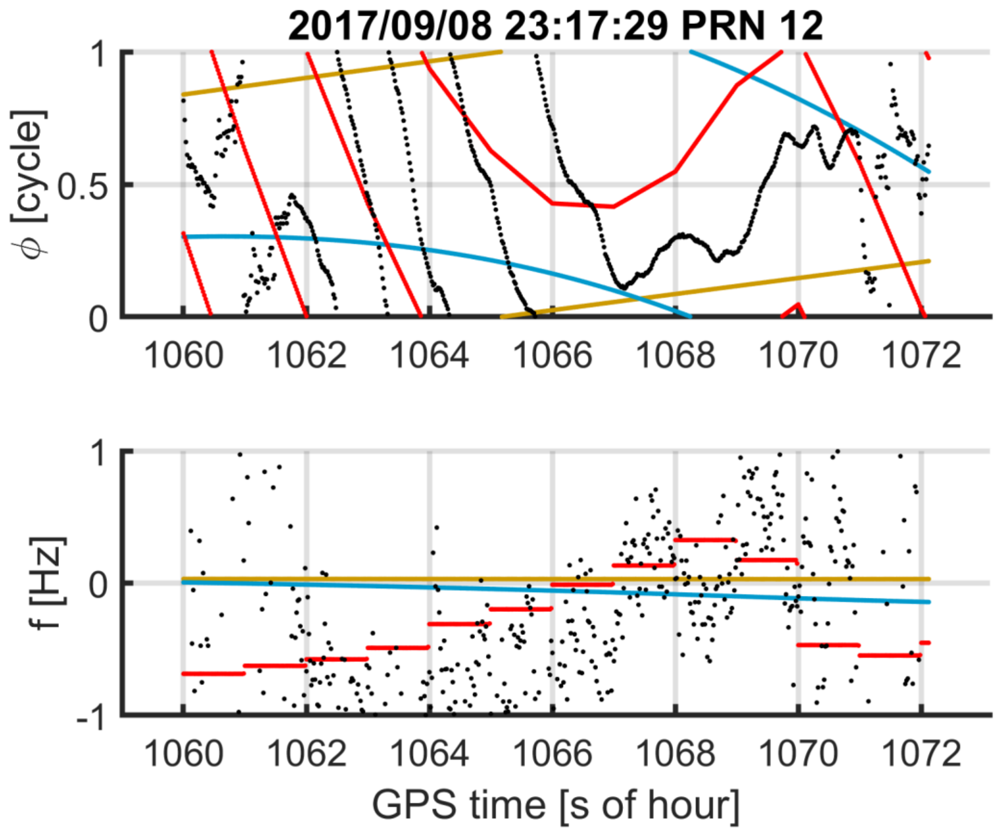
- short surface dominated track 16 s
- after surface correction std(f) = 0.49 Hz

Venezuela Track

Retrieved Heights and Model corrections



Phase & Doppler of longest coherent track



○ Mean sea surface height from DTU 21

▪ Coherent observation/track x reference epoch for amb. fix.

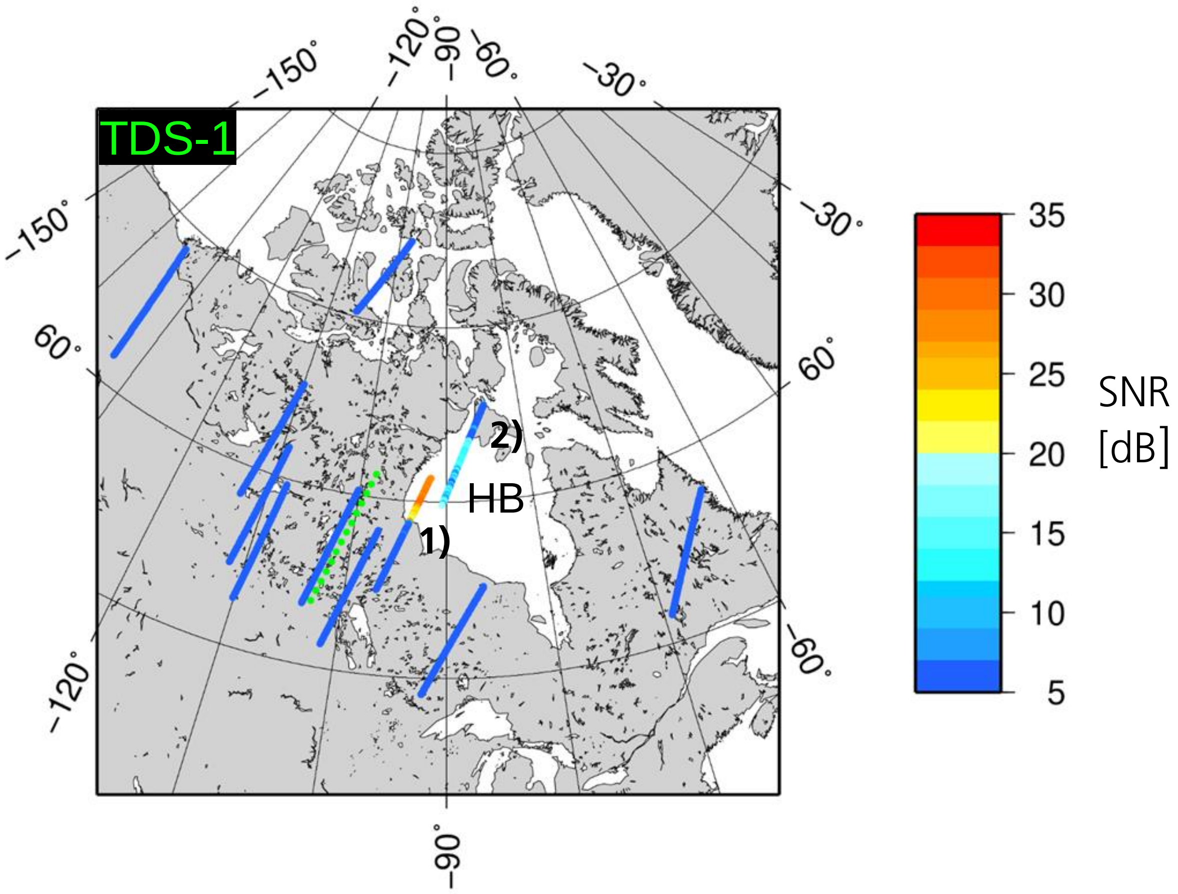
▪ Incoherent observation

- short surface dominated track 12 s
- after surface correction std(f) = 1.92 Hz

Results over Hudson Bay

Reflection Track Reference

Example Tracks of TDS-1 Mission



Two sea-ice tracks over Hudson Bay (HB) with rather high SNR selected for analysis.

Western HB Track 1)

- GPS PRN 15 by TDS-1 on 2015/01/18 17h20 UTC
- high elev. angle at spec. point (~ 58°)

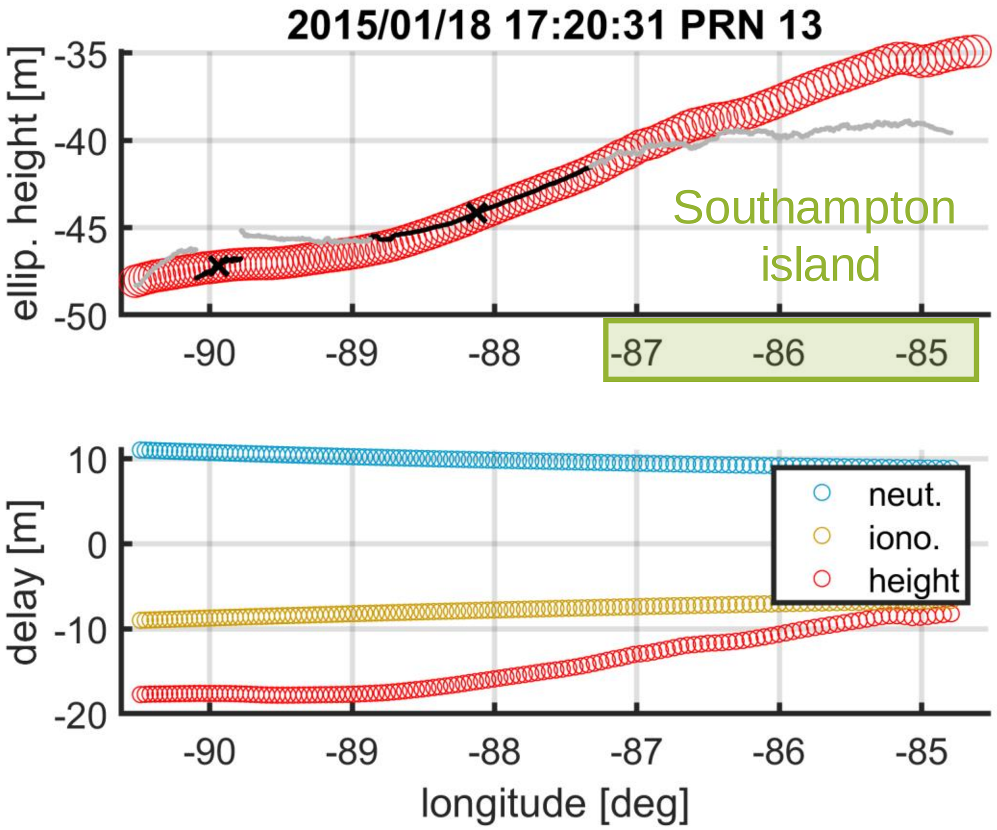
Eastern HB Track 2)

- GPS PRN 13 by TDS-1 on 2015/01/18 17h20 UTC
- moderate elev. angle at spec. point (~ 30°)

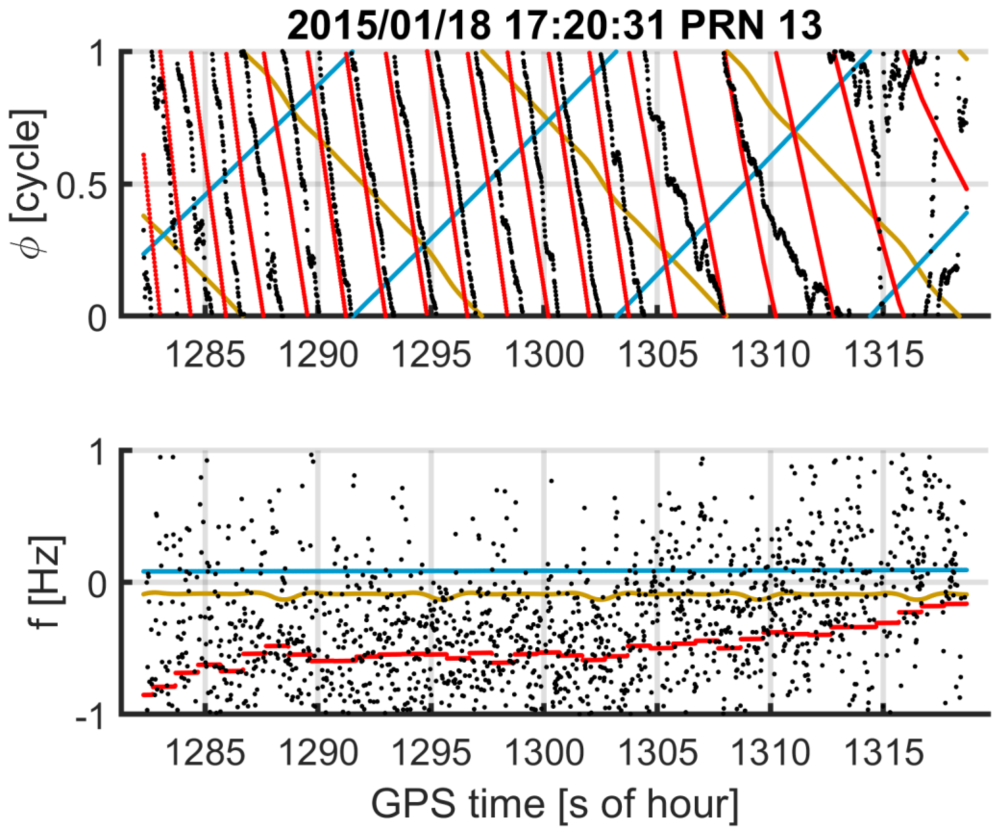
Li et al. 2017

Eastern Hudson Bay Track

Retrieved Heights and Model corrections



Phase & Doppler of longest coherent track

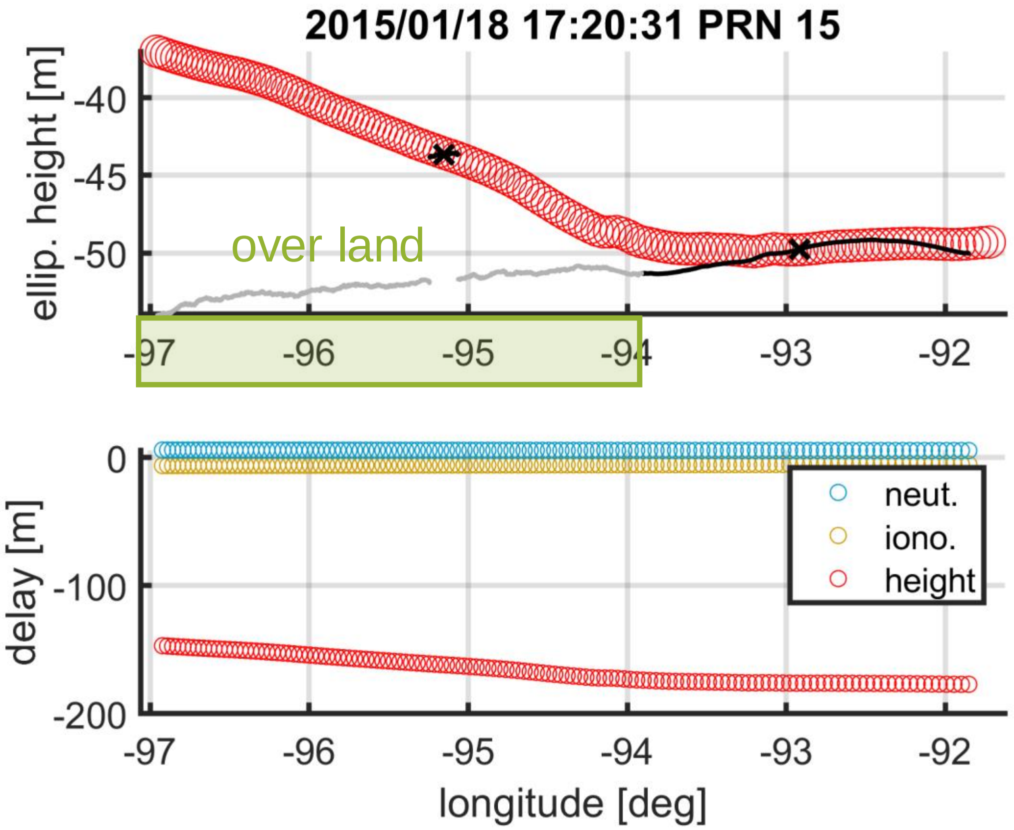


- ○ Mean sea surface height from DTU 21
- ▪ Coherent observation/track — x reference epoch for amb. fix.
- ▪ Incoherent observation

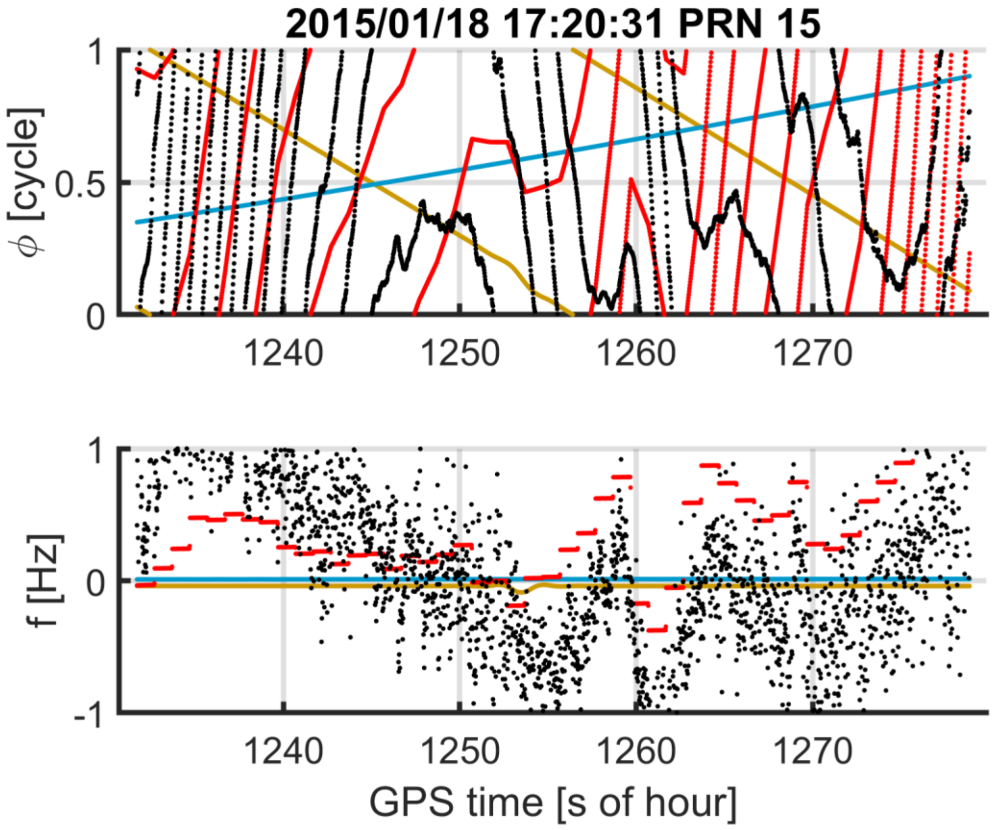
- ➢ very long surface dominated track 36 s
- ➢ after surface correction std(f) = 0.80 Hz

Western Hudson Bay Track

Retrieved Heights and Model corrections



Phase & Doppler of longest coherent track



○ Mean sea surface height from DTU 21

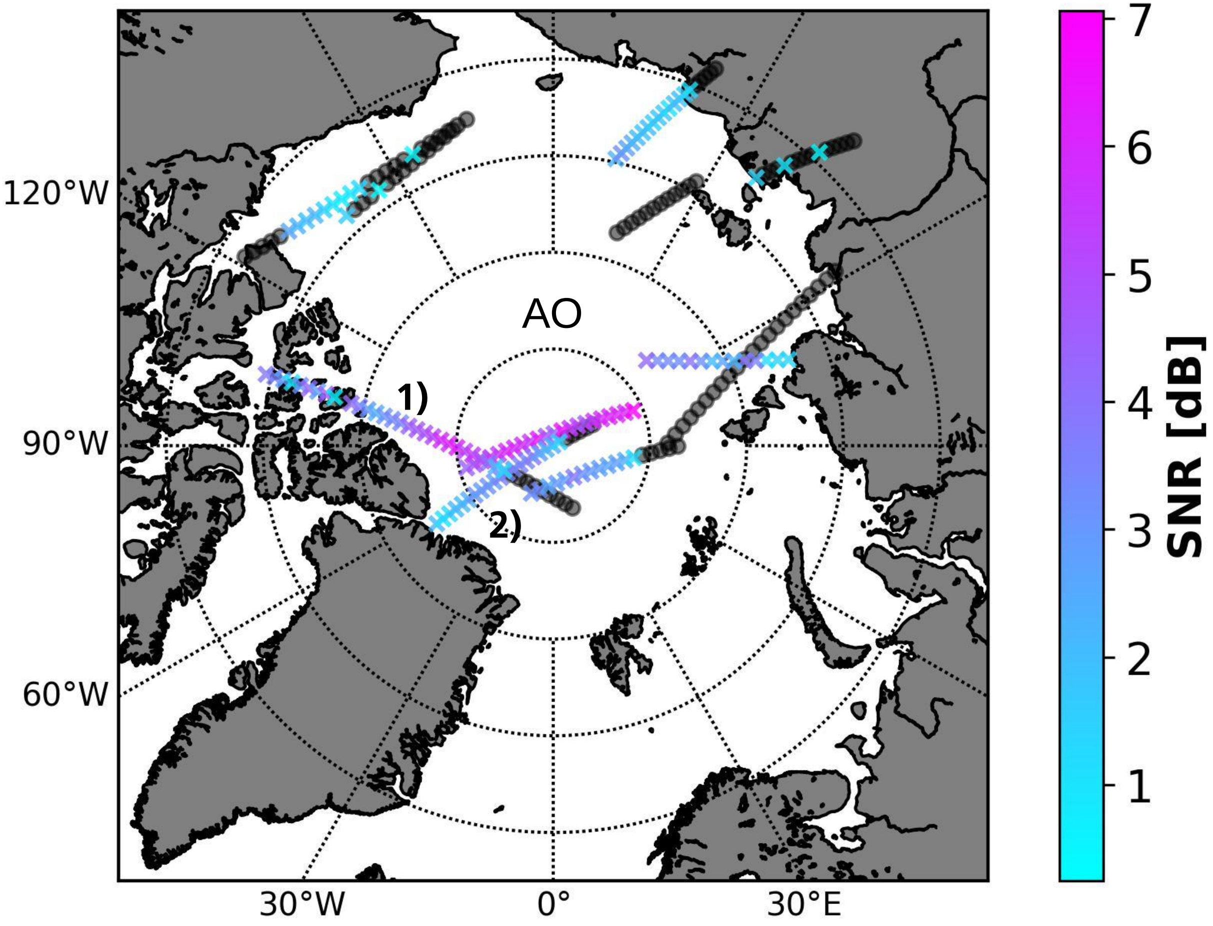
▪ Coherent observation/track x reference epoch for amb. fix.

▪ Incoherent observation

- longest surface dominated track (47 s) deviating from surface
- after surface correction std(f) = 1.04 Hz

Preliminary Results over Arctic Ocean

Reflection Track Reference



Nine sea-ice tracks over Arctic Ocean (AO) with reflection signature (rather low SNR). Doppler prec. Threshold applied (> 5 Hz disregarded, gray segment).

Western AO Track 1)

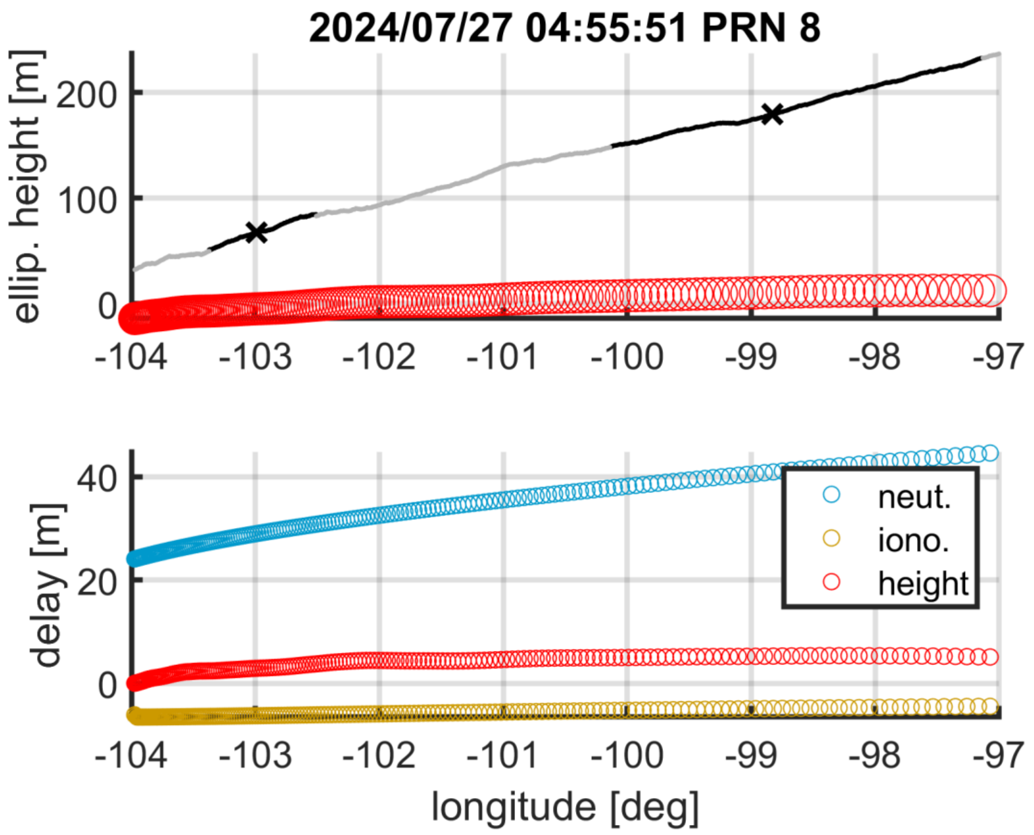
- GPS PRN 8 by PRETTY on 2024/07/27 04h55 UTC
- very low elev. angle at spec. point (0 … 11°)

Greenland Track 2) (to come)

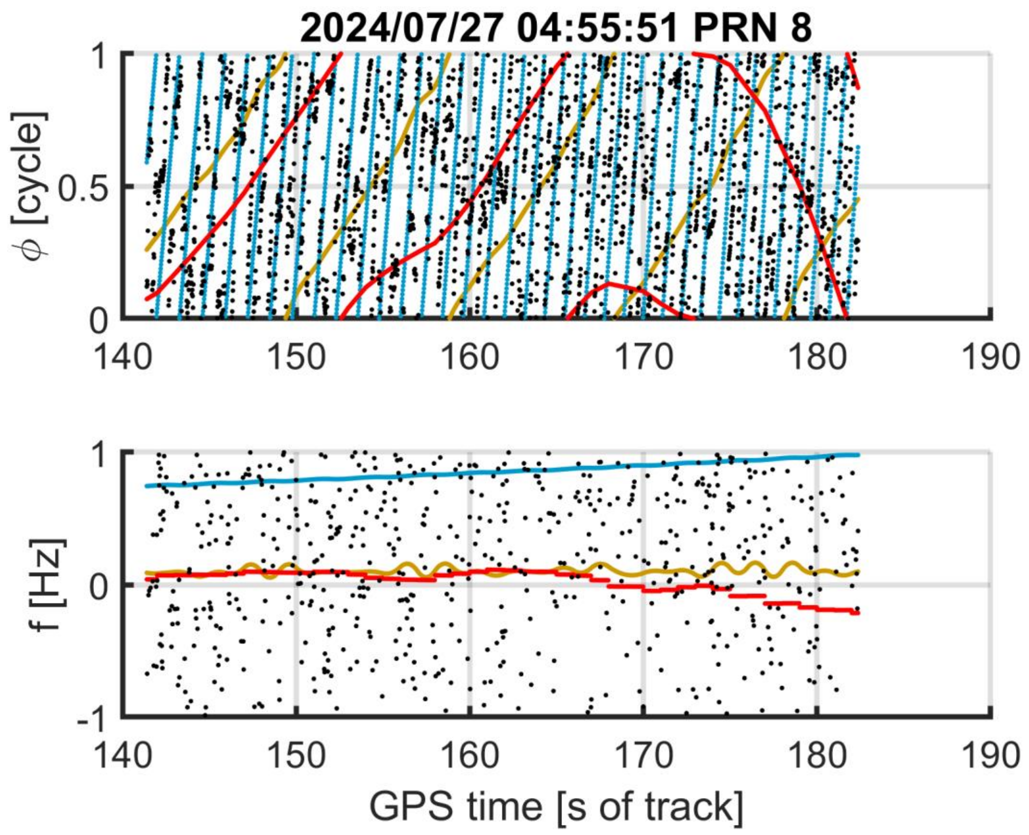
- GAL PRN 7 by PRETTY on 2024/07/16 00h55 UTC
- very low elev. angle at spec. point (1 … 10°)

Western Track

Retrieved Heights and Model corrections



Phase & Doppler of longest coherent track



○ Mean sea surface height from DTU 21

▪ Coherent observation/track x reference epoch for amb. fix.

▪ Incoherent observation

- ➢ long neutral atmo. dominated track
- ➢ after surface correction std(f) = 3.57 Hz

Summary & Conclusion

Summary of analysis after surface correction

	PRN G12	PRN E05	PRN E01	PRN G13	PRN G15	PRN G08
min. Elev. [°]	13	13	15	30	58	4
yyyy-mm-dd	2017-09-08	2018-10-14	2017-09-20	2015-01-18	2015-01-18	2024-07-27
UT [HH:MM]	23:17	04:56	16:37	17:21	17:20	04:58
LT [HH:MM]	18:35	23:19	11:21	11:32	11:13	22:18
track length [s]	12	16	25	36	47	41
resid. Dopp. [Hz]	-0,06	0,03	-0,21	0,06	-0,24	1.23
iono. Dopp. [Hz]	0,03	0,00	0,02	-0,09	-0,04	0.10
neut. Dopp. [Hz]	-0,04	-0,14	0,08	0,09	0,01	0.86
Dopp. Std [Hz]	1,92	0,49	0,94	1,04	0,80	3.57
ampl. Index	0,63	0,21	0,26	0,31	0,30	0.51
sig. wave hgt. [m]	0,74	0,36	0,81	n.n.	n.n.	n.n.

CyGNSS obs.* over Caribbean

TDS-1 obs.** over Hudson Bay

PRETTY obs.** over Arctic O.

Neutral atmo. correc.: * ERA5, ** Internat. Stand. Atmo.

Conclusion

- Complex waveforms for coherent analysis available for different missions
- Coherent tracks over calm water in the Caribbean (CyGNSS)
- Coherent tracks over sea ice in Hudson Bay (TDS-1) and Arctic Ocean (PRETTY)
- Surface-dominated tracks (i.e. useful for altimetry) down to 13° elev.
- Neutral-gas-dominated track at 4° elev. (altimetric value t.b.c.)

Acknowledgements

…

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Thank you for your attention

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Appendix

PRETTY Mission Main Payload

Passive **RE**flec**T**ometry and dosime**T**r**Y**

- GNSS-R instrument PACO (PARIS Correlator) for altimetry (interferometric and conventional sampling) at slant and grazing geometries
- Radiation dosimeter (total ionizing dose and single-event effects)

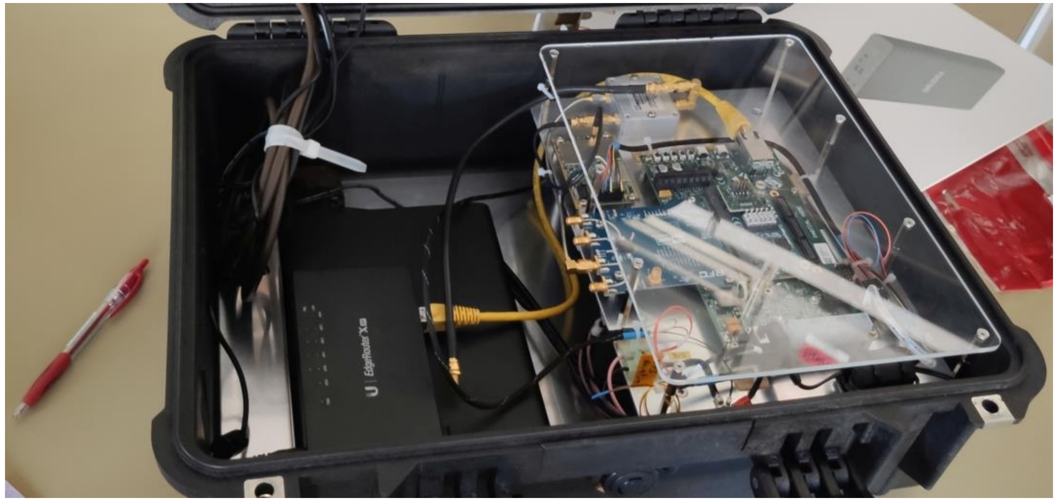
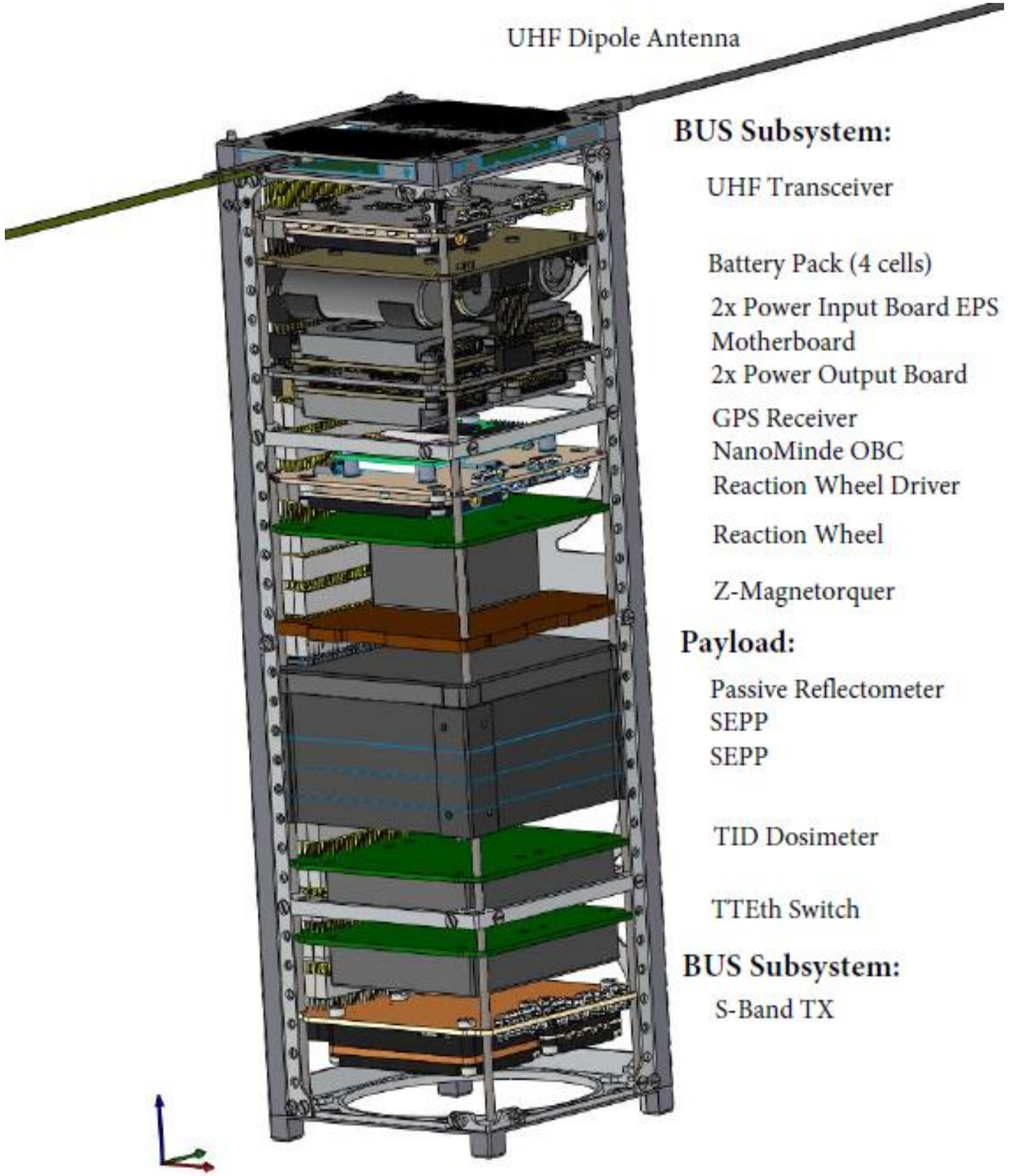


Photo: PACO Receiver unit for ground-based testing



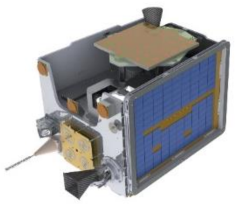
Scheme: PRETTY sat. layout

Dielacher et al. 2019

Coherent GNSS-R Measurements

- **C: Satellite**

  Wickert et al. 2016
  Li et al. 2017
  Cardellach et al. 2019
  Nguyen et al. 2020
  Roesler et al. 2021
  Wang et al. 2022



h: 500 … 640 km

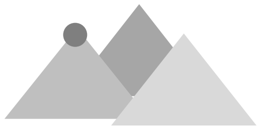
- **B: Aircraft**

  Semmling et al. 2014
  Moreno et al. 2021

h: 700 … 3500 m

- **A: Coastal Setup**

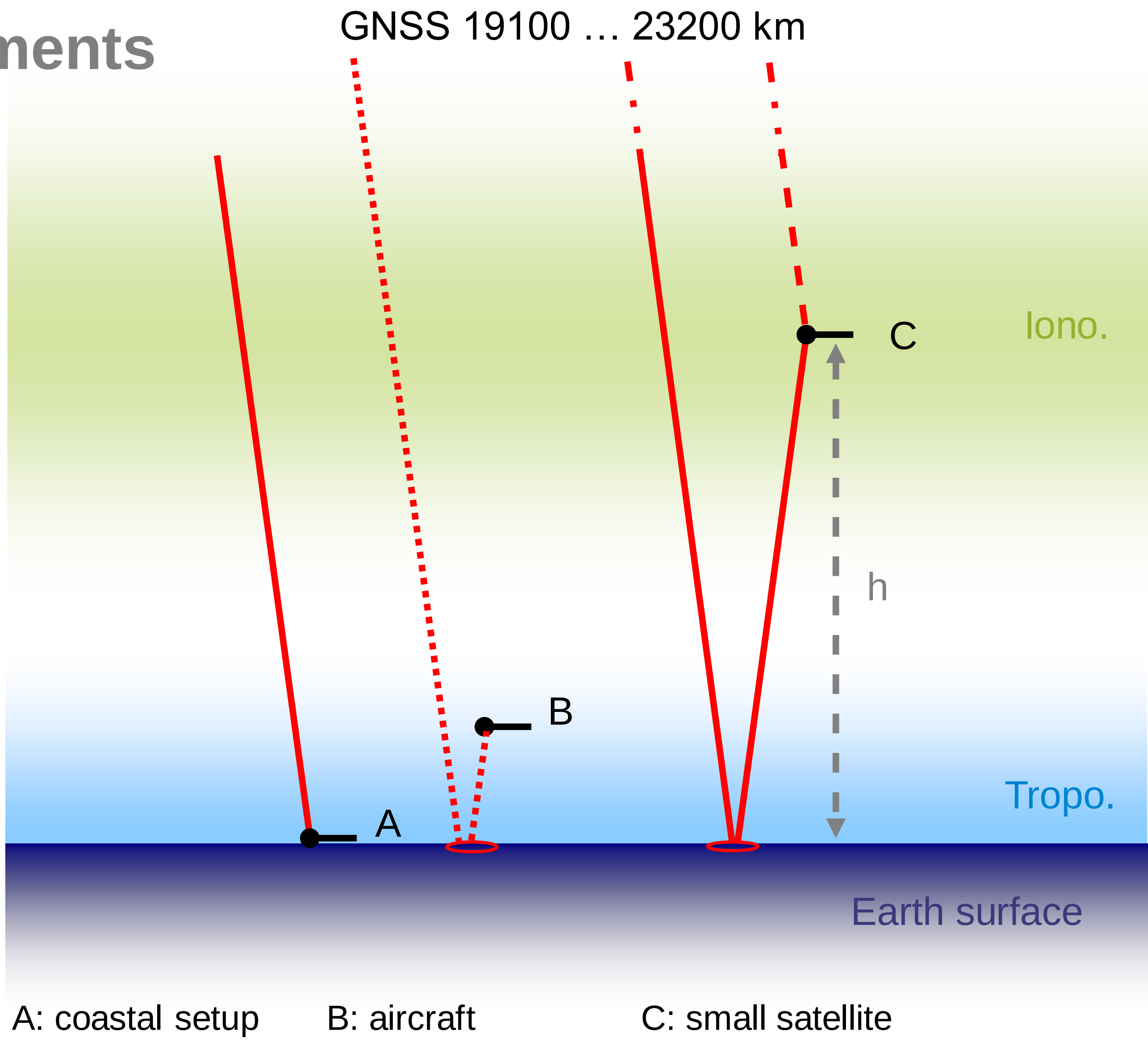
  Anderson 1999
  Fabra et al. 2011
  Semmling et al. 2011



h: 10 … 800 m

- **Application**

sea surface altimetry
sea-ice altimetry
atmosphere sounding
ionosphere sounding



First Step – Target Areas

- **Roughness Disturbance**
  - select targets/periods to maximize scientific outcome in limited duty cycle of PACO instrument

- **Simulation of coherent obs. probability**
  - Priority to areas with high probability of coherent reflections
  - More than three decades (1990 to 2021) analyzed Significant Wave Height (SWH) from the ECMWF ReAnalysis-5 (ERA5).
  - Several scenarios wind-driven waves, combined wind-swell waves and wind speed thresholds considered
  - Threshold set based on Rayleigh criterion
  - Average probability map on global scale for differents month are produced.