# Towards precise synoptic altimetry by means of GNSS-R


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ESTEC

**GNSS-R altimetry**: use of GNSS signals to estimate sea surface height

**Synoptic**: multistatic system with several specular points

→ High spatio-temporal coverage

→ Complement monostatic Radar by monitoring mesoscale ocean signals (30-300 km evolving in days-week)

**Precise**: use of interferometric approach (iGNSS-R)

→ Cross-correlation of direct and reflected GNSS signals to take profit of all codes

→ Increase of effective bandwidth and thus altimetry precision

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**Challenge**

Synoptic **and** precise: not enough with best-case results → we need **consistency** among **different signals** in a **wide elevation range**

Hardware development

## GOLD-RTR

GPS L1 C/A **clean-replica** receiver

10 correlation channels
3 front-ends
64-lag complex waveforms (msec rate)
20 MHz (15 m)

Employed in **12 experimental campaigns** (so far)

Multiple remote sensing applications

Data publicly available (gold-rtr-mining)

Nogués-Correig et al., “A GPS-reflections receiver that computes Doppler/delay maps in real time.”, *IEEE Transactions on Geoscience and Remote Sensing*, **2007**.

Cardellach et al., “GNSS-R ground-based and airborne campaigns for ocean, land, ice, and snow techniques: Application to the GOLD-RTR data sets.”, *Radio Science*, **2011**.

## Hardware development

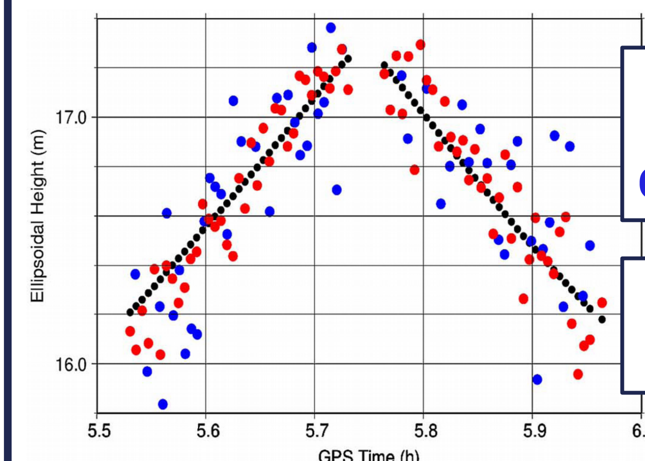
| GOLD-RTR | PIR |
|---|---|
| GPS L1 C/A clean-replica receiver | First **Interferometric** Receiver (L1) |
| 10 correlation channels<br>3 front-ends<br>64-lag complex waveforms (msec rate)<br>20 MHz (15 m) | 1 correlation channel<br>2 front-ends<br>512-lag complex wav. (msec rate)<br>**80 MHz (3.75 m)** |
| Employed in 12 experimental campaigns (so far)<br><br>Multiple remote sensing applications<br><br>Data publicly available (gold-rtr-mining) | **Proof of concept** of **iGNSS-R** altimetry from a 18-m bridge over estuary waters |

Rius et al., “Altimetry with GNSS-R interferometry: first proof of concept experiment.”, *GPS Solutions*, **2012**.

## Hardware development

**GOLD-RTR** → **PIR** → **PIRA**

| GOLD-RTR | PIR | PIRA |
|---|---|---|
| GPS L1 C/A clean-replica receiver | First Interferometric Receiver (L1) | Adaptation of PIR to **aircraft** scenario (displacement of acquisition window) |
| 10 correlation channels<br>3 front-ends<br>64-lag complex waveforms (msec rate)<br>20 MHz (15 m) | 1 correlation channel<br>2 front-ends<br>512-lag complex wav. (msec rate)<br>80 MHz (3.75 m) | **Assessment** of altimetry **precision** from an altitude of 3 km |
| Employed in 12 experimental campaigns (so far)<br><br>Multiple remote sensing applications<br><br>Data publicly available (gold-rtr-mining) | Proof of concept of iGNSS-R altimetry from a 18-m bridge over estuary waters | A **single** PRN acquired (high elevation)<br>Not **absolute** retrieval (accuracy not evaluated) |




Results 10 sec
**PIRA 17 cm**
**GOLD-RTR 36 cm**

Height gradient
**EGM96**

Cardellach et al., "Consolidating the Precision of Interferometric GNSS-R Ocean Altimetry Using Airborne Experimental Data.", *IEEE Transactions on Geoscience and Remote Sensing*, **2014**.

## Hardware development

GOLD-RTR → PIR → PIRA → **SPIR**


Software PARIS Interferometric Receiver

Raw data recorder of each front-end (320 MB/sec) → **software receiver** in post-processing

*N correlation channels*
**L1, L2 and L5** operation modes
**16 front-ends**
*512-lag complex waveforms (msec rate)*
80 MHz (3.75 m)

Allows to explore different data/signal processing techniques (here we focus in iGNSS-R)

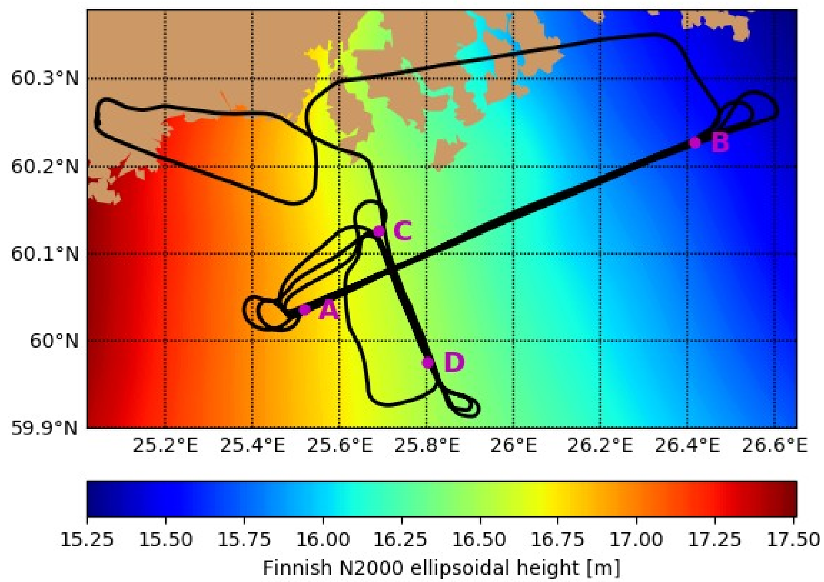
Up (RHCP) and down-looking (LHCP) antenna arrays of 8 elements are employed

**→ Digital beamforming**

Ribó et al., “A Software-Defined GNSS Reflectometry Recording Receiver with Wide-Bandwidth, Multi-Band Capability and Digital Beam-Forming.”, *Remote Sensing*, **2017**.

Same scenario as in PIRA campaign (onboard Aalto's Skyvan at 3 km altitude)

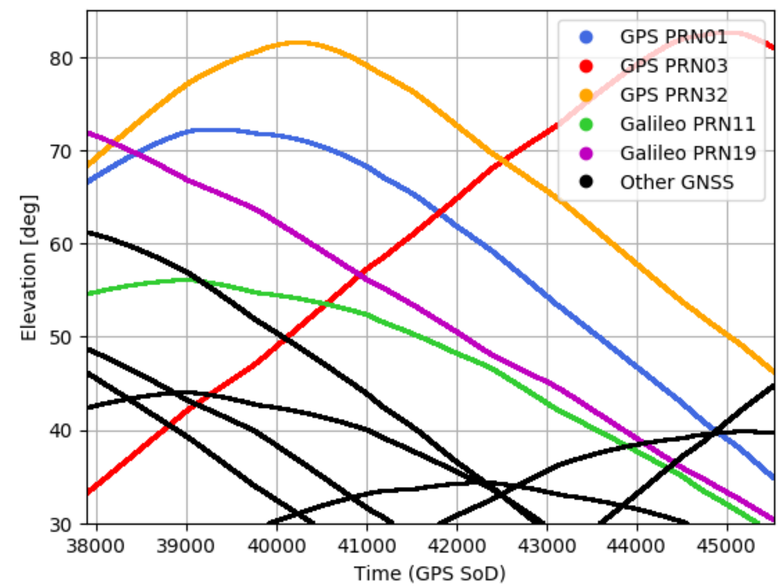
## Trajectory




**9** straight **segments** analyzed:

0-BA **L5**
1-AB **L1**
2-BA
3-CD
4-DC
5-AB
6-BA
7-CD
8-DC

## GNSS visibility



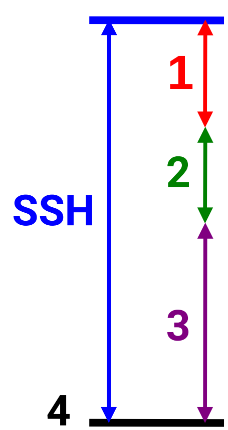

Elevation range between 28 and 83 deg

GPS PRN32 without M-code → discarded

**8 signals**: 2 GNSS, 2 PRN each and 2 frequency bands (L1/L5)

## Ground truth

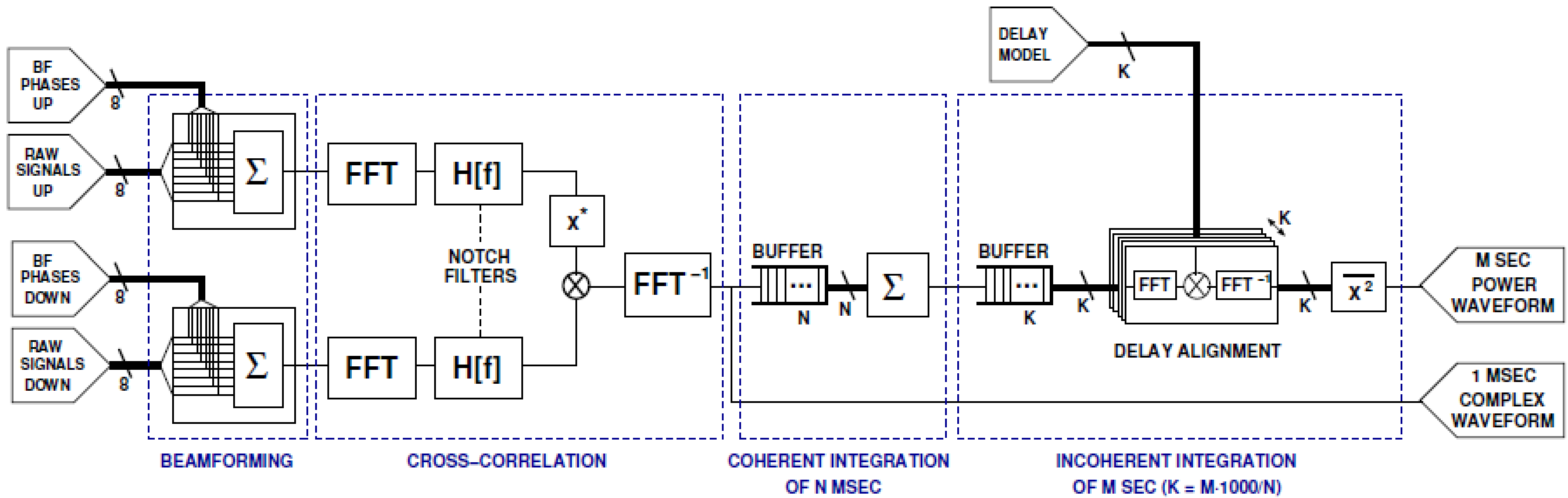
(1) Surface level measured by buoys*
(2) Mean sea level*
(3) Finnish N2000 local height system
(4) WGS84 ellipsoid




*Provided by Finnish Meteorological Institute

**>2 hours of data collected (3 TB)**

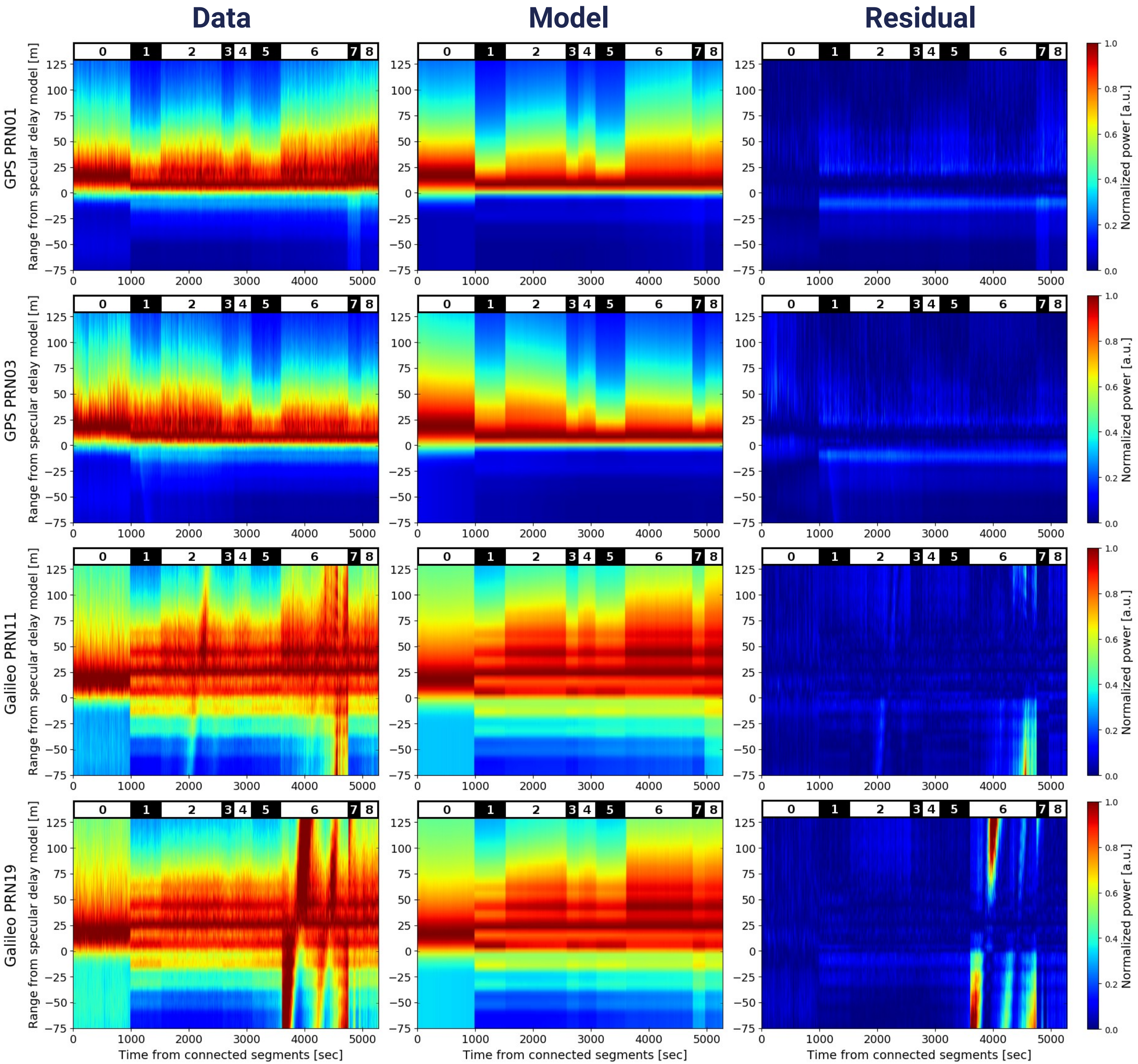
## Methodology




**Integration time:** 10 msec coherent and **10 sec** incoherent

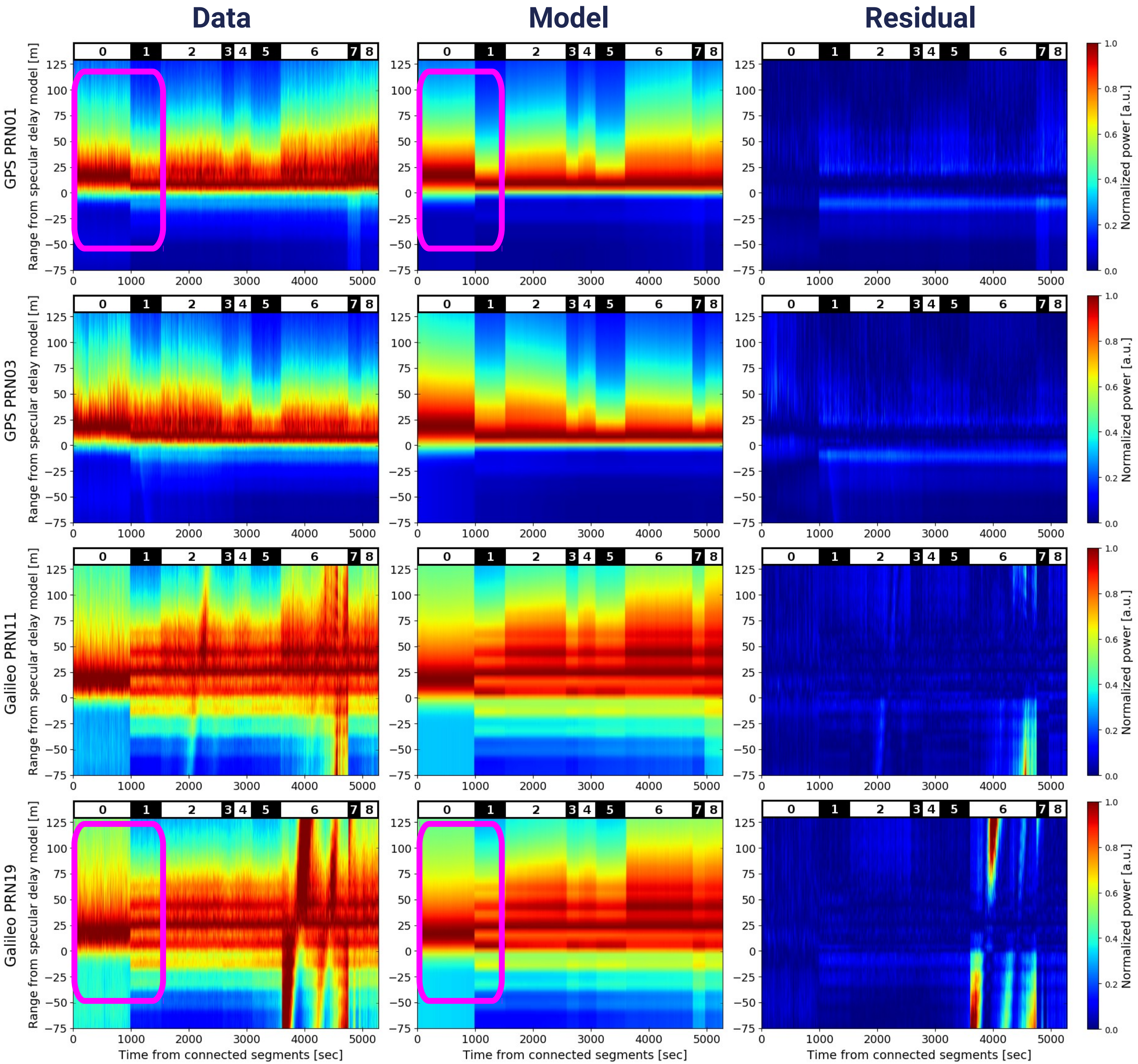
For each power waveform, its corresponding **model** is generated

# WAVEFORMS



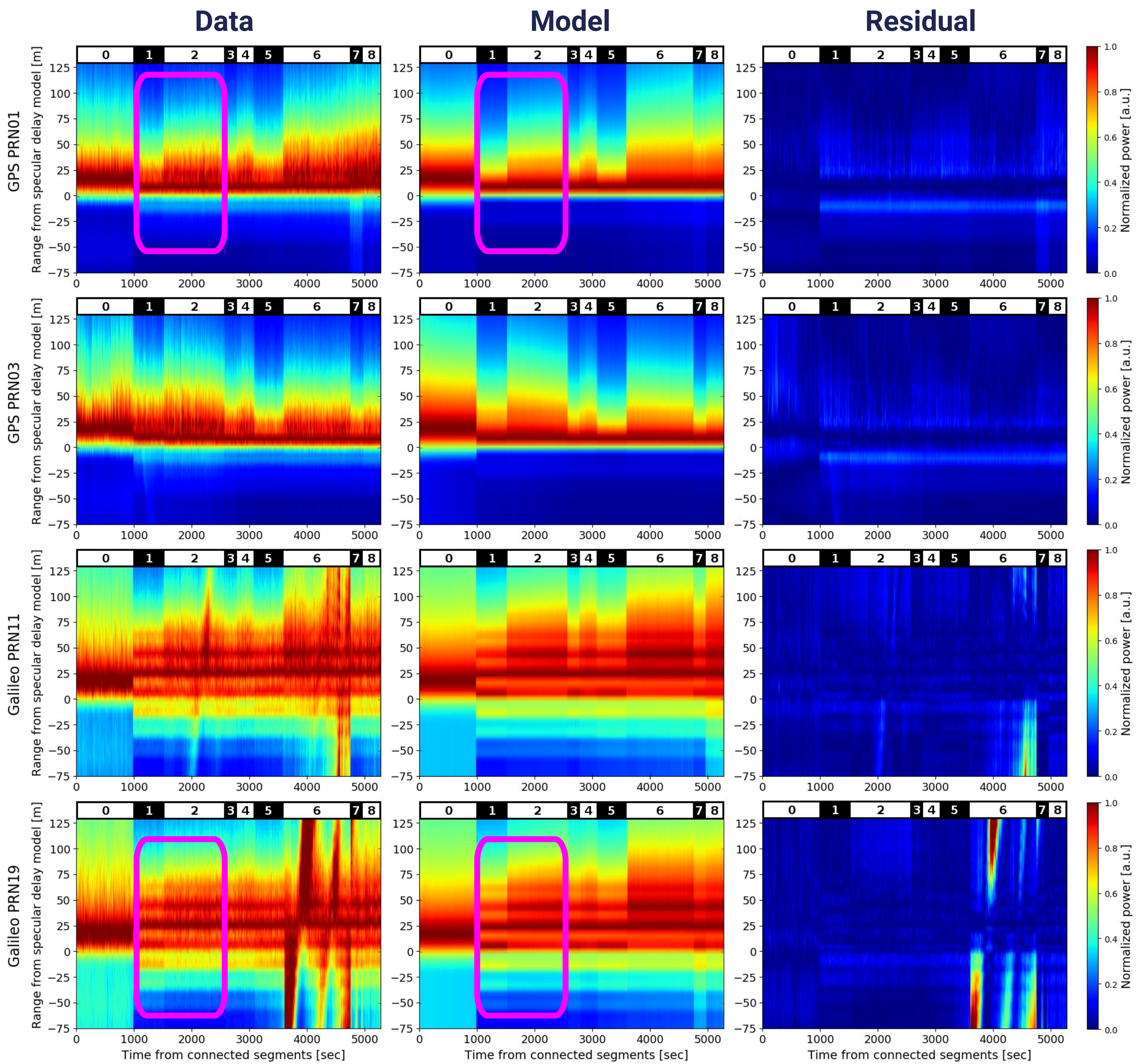

## To point out

# WAVEFORMS




## To point out

(1) Good agreement with model and clear differences between systems and frequency bands (different codes)

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(1) Good agreement with model and clear differences between systems and frequency bands (different codes)

(2) Relevant impact of changes in aircraft velocity (given a fixed integration time)

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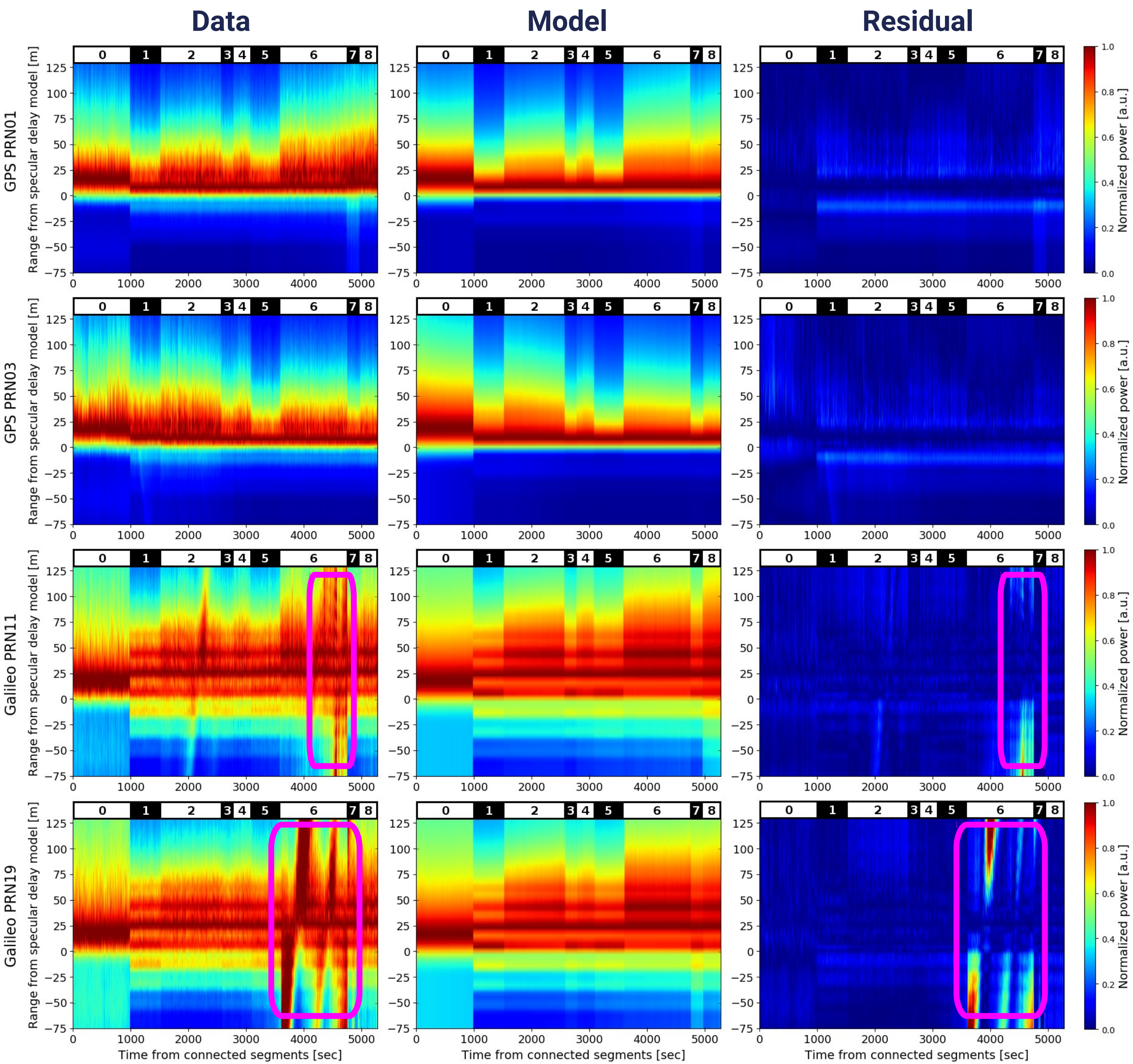


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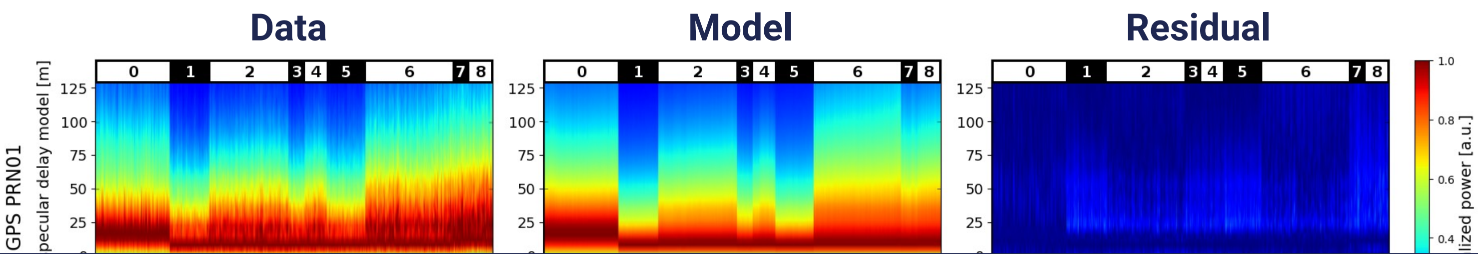
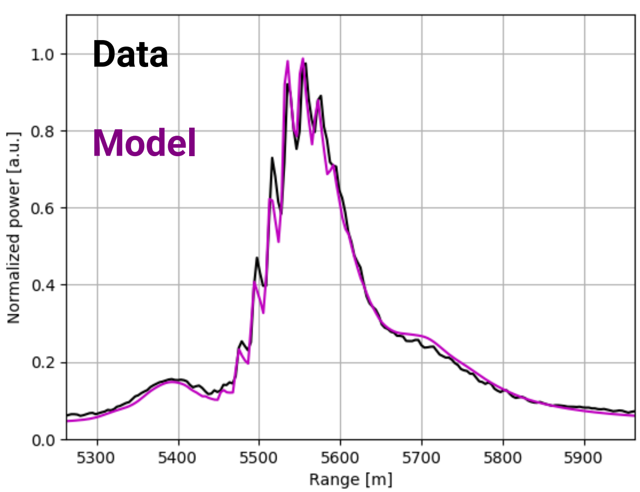
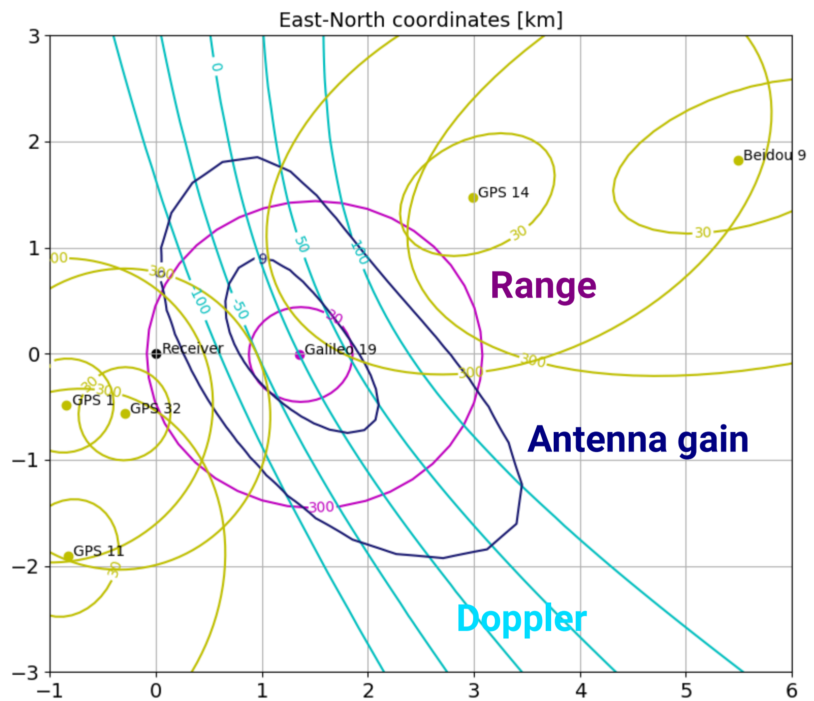
(3) Cases with clear inconsistencies → crosstalk from other GNSS signals

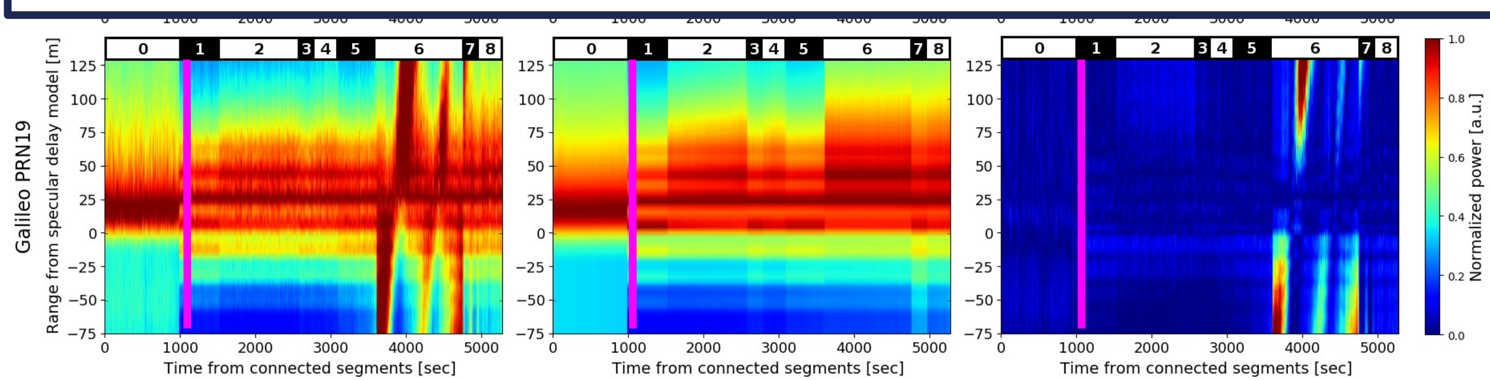



## Clean case

Galileo PRN19 sec #1070

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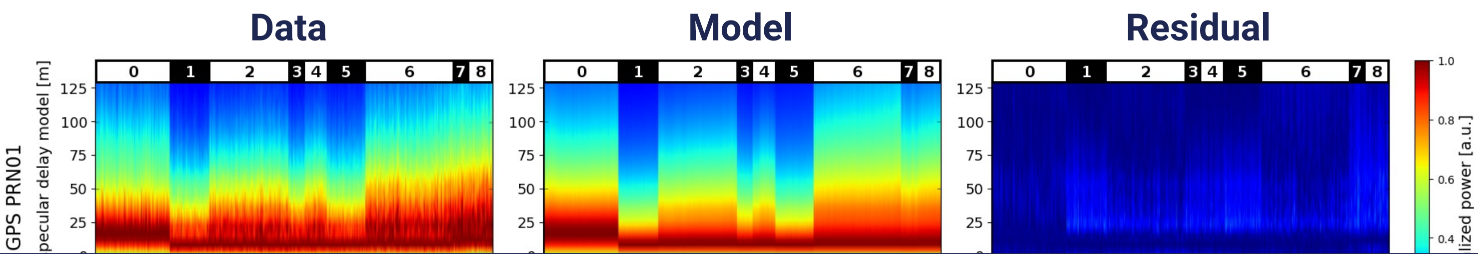
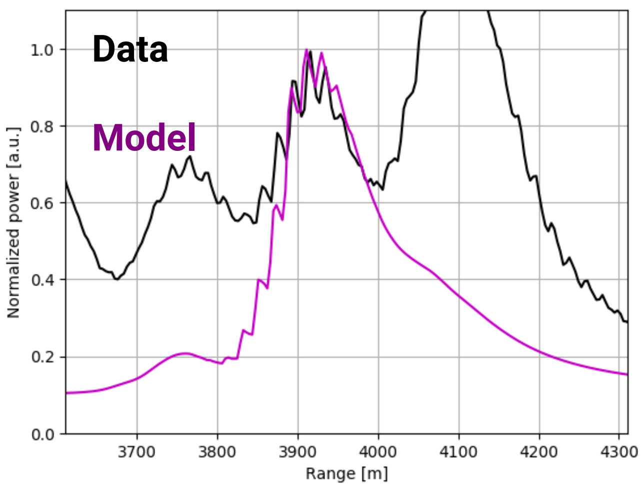
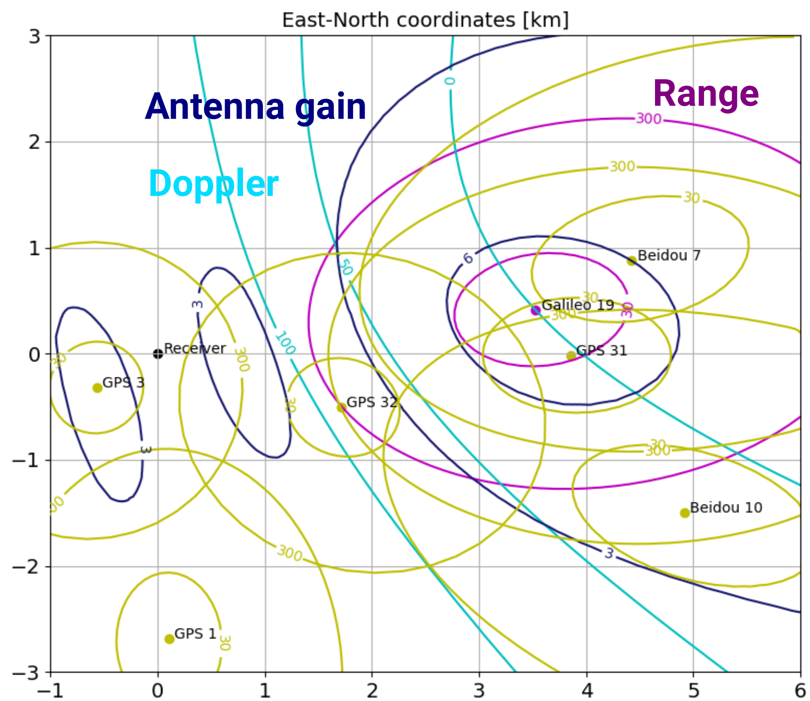
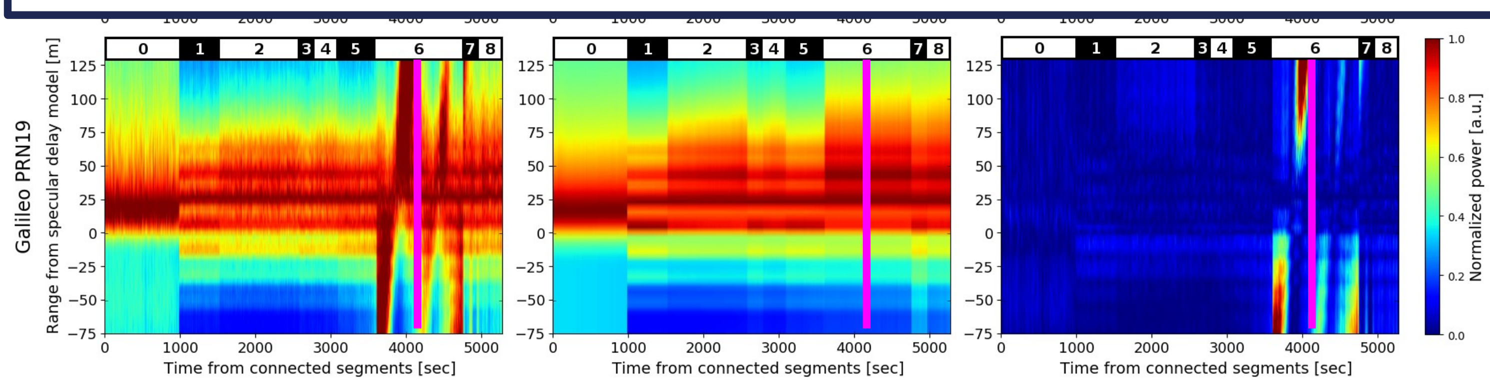



## Crosstalk case

Galileo PRN19 sec #4110

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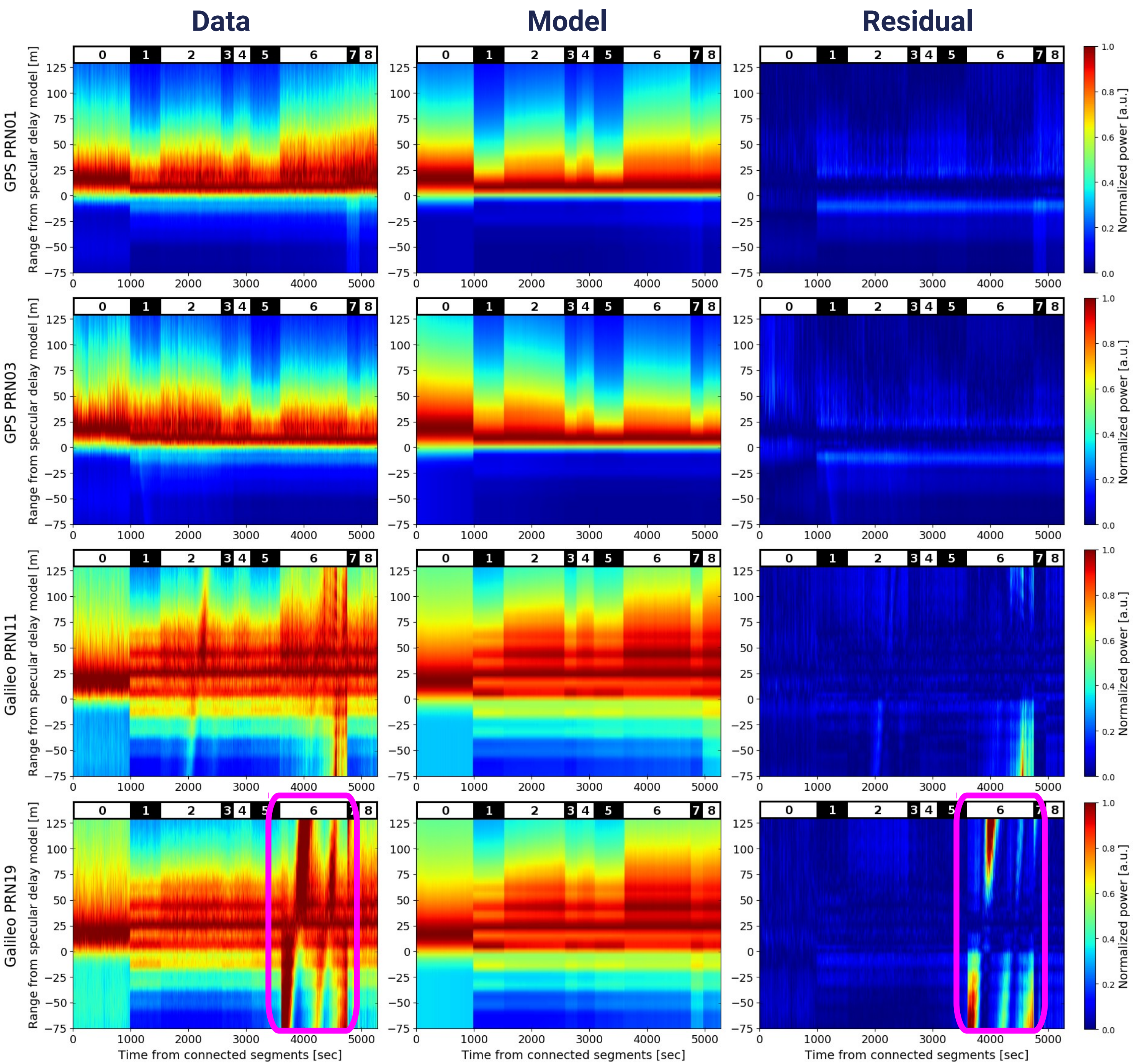


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→ Segment #6 from Galileo PRN19 removed from analysis due to (3)

## Delay estimation

**Retracking** method: DER (first derivative) → Simpler to be applied against different GNSS signals

Applied to both data and model waveforms: $\Delta\rho = \rho_{data} - \rho_{model}^{\mathbf{FinN2000}}$

→ Delay model includes **tropospheric** and **antenna baseline** corrections

Estimation of remaining **instrumental delay offset** from delay residuals:

$$\Delta\rho = 2\Delta H\,\sin(elevation) + \mathbf{K_{inst}}$$

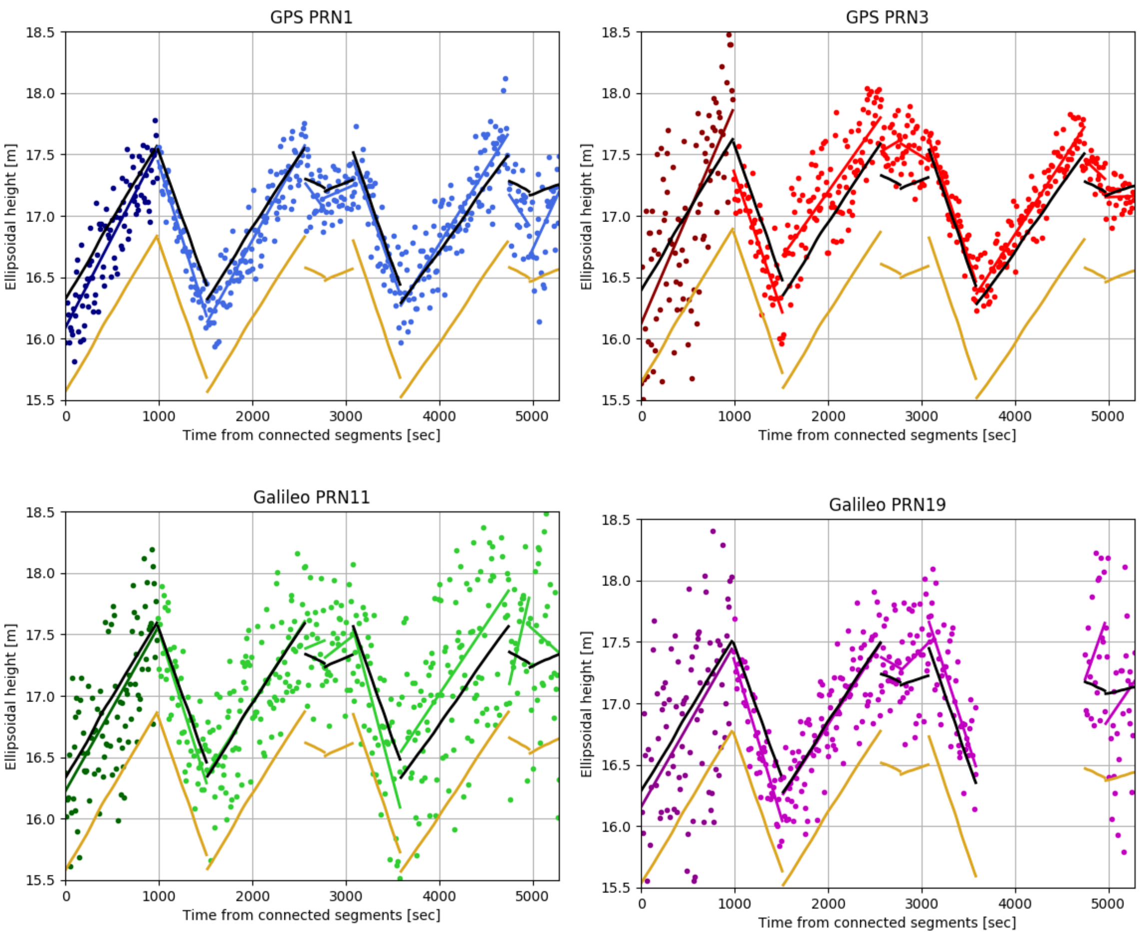
Final delay estimation is obtained after removing such instrumental offset:

$$\overline{\rho_{data}} = \rho_{data} - K_{inst}$$

## Altimetry inversion

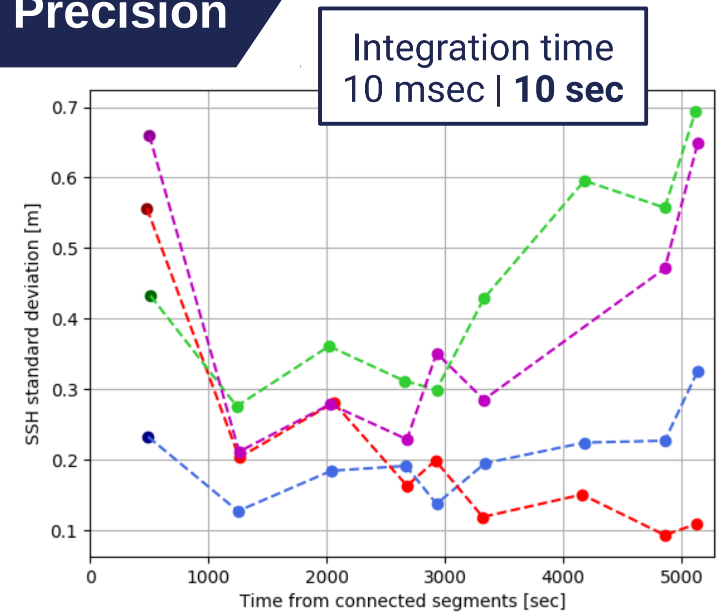
Computed with respect to ellipsoid WGS84: $SSH_{data} = (\rho_{model}^{\mathbf{WGS84}} - \overline{\rho_{data}})/2\sin(elevation)$

## Sea surface height retrieved ($SSH_{data}$)




The results follow the height gradient and are at the same height level as the **ground truth**, both being above **Finnish N2000**

## Precision




The evolution of $\sigma_{SSH}$ depends on three main factors:

- **SNR/elevation** → general trend
- **Sensitivity** → L5 has worse results
- **Effective integration** → segments with higher velocity perform better

Good agreement with precision models*

Galileo not yet operational (lower SNR)

*Li et al., "Revisiting the GNSS-R Waveform Statistics and Its Impact on Altimetric Retrievals", *IEEE Transactions on Geoscience and Remote Sensing*, **2018**.

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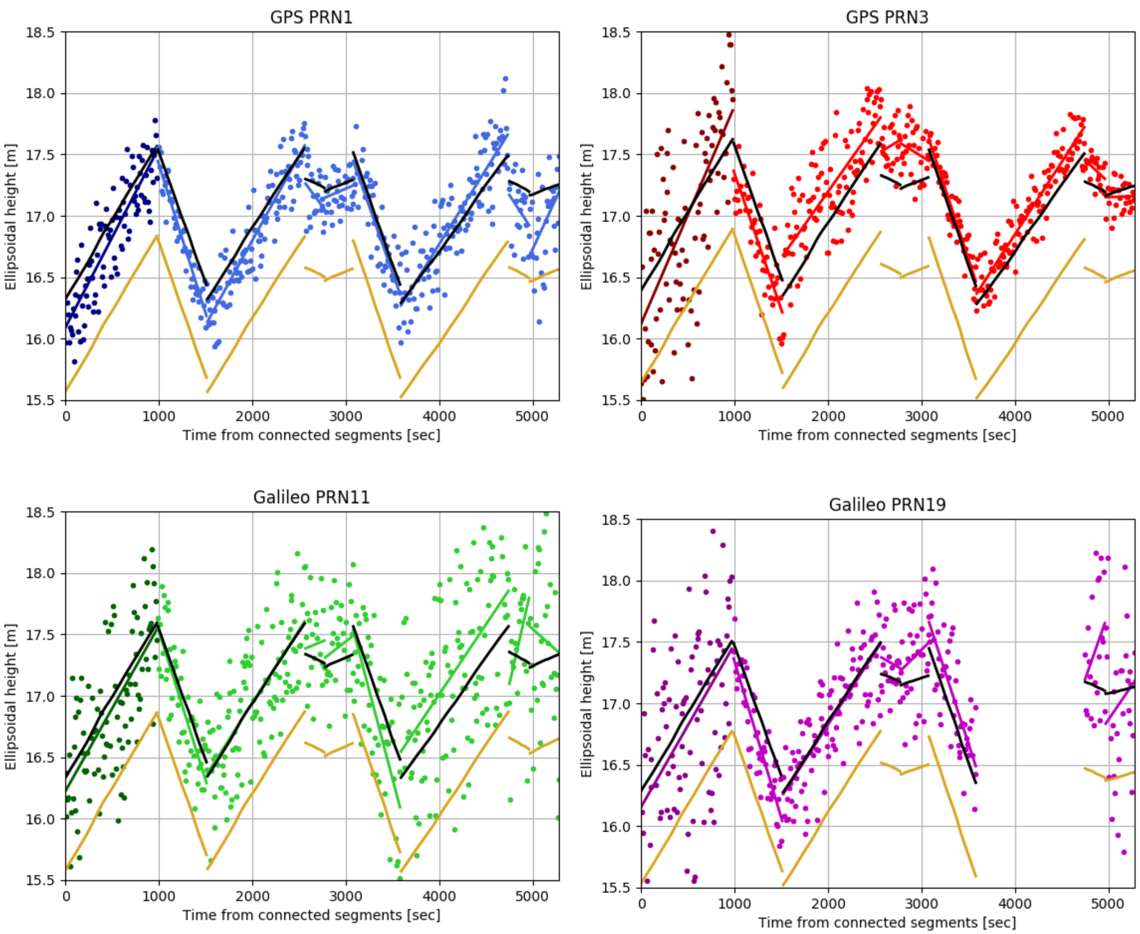


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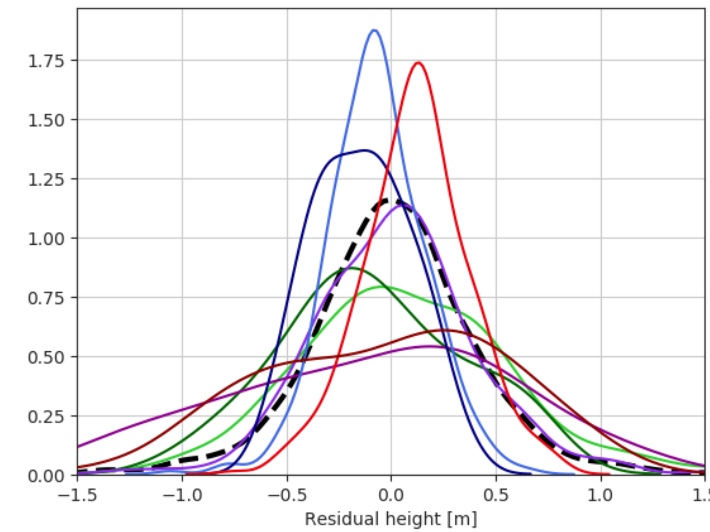
## Accuracy

PDF from ΔSSH



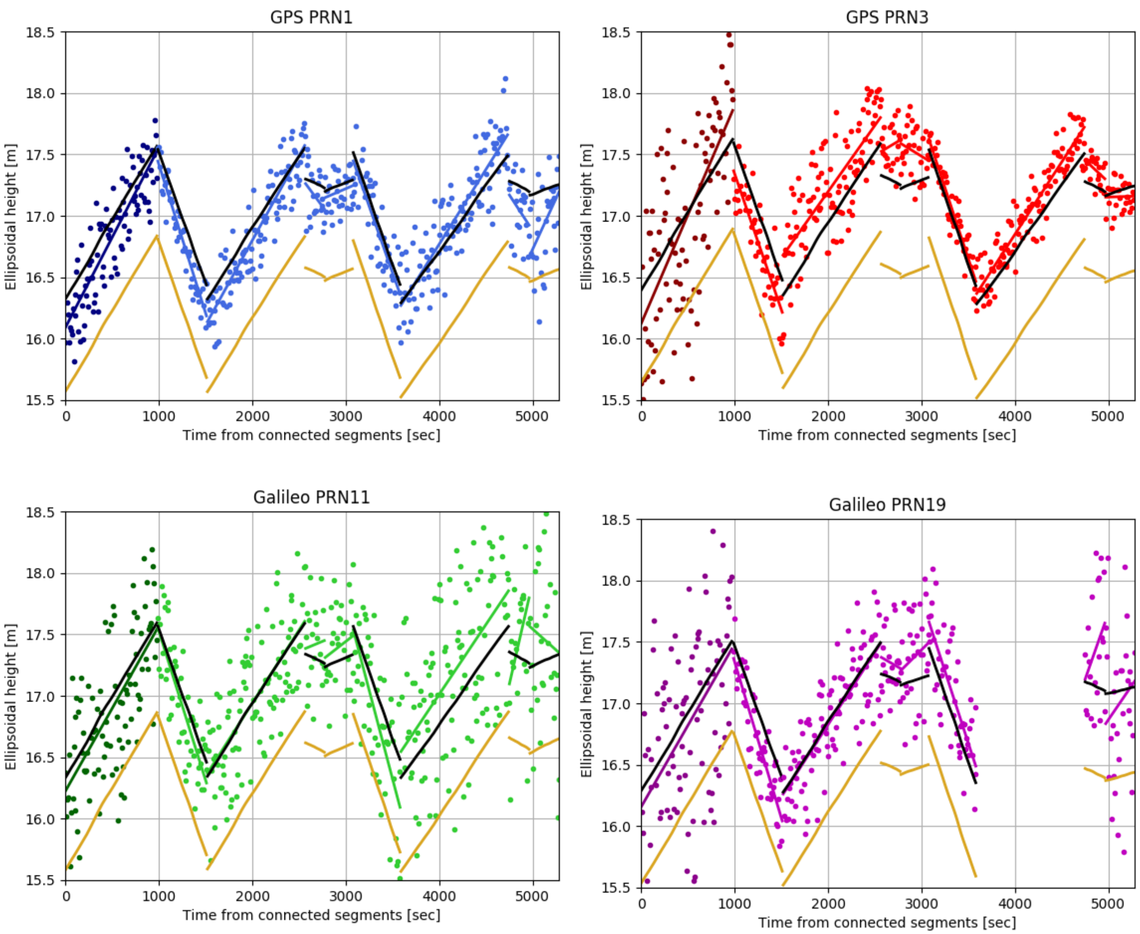

**Unbiased** overall result (black dashed)

Maximum separation between mean values of 26 cm → similar to the σ of the best case (23 cm for GPS PRN01 at L1)

Still some detailed refinement could be done (e.g. EM bias)

Clear impact of the waveform model

## Sea surface height retrieved ($SSH_{data}$)

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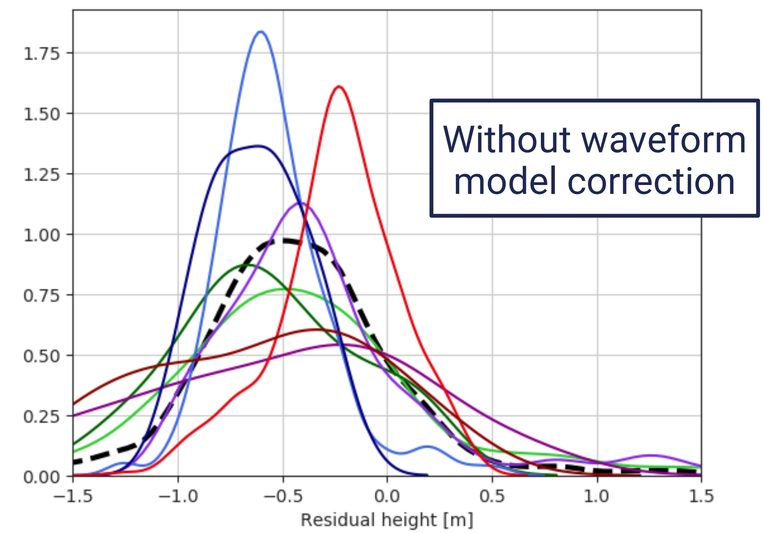


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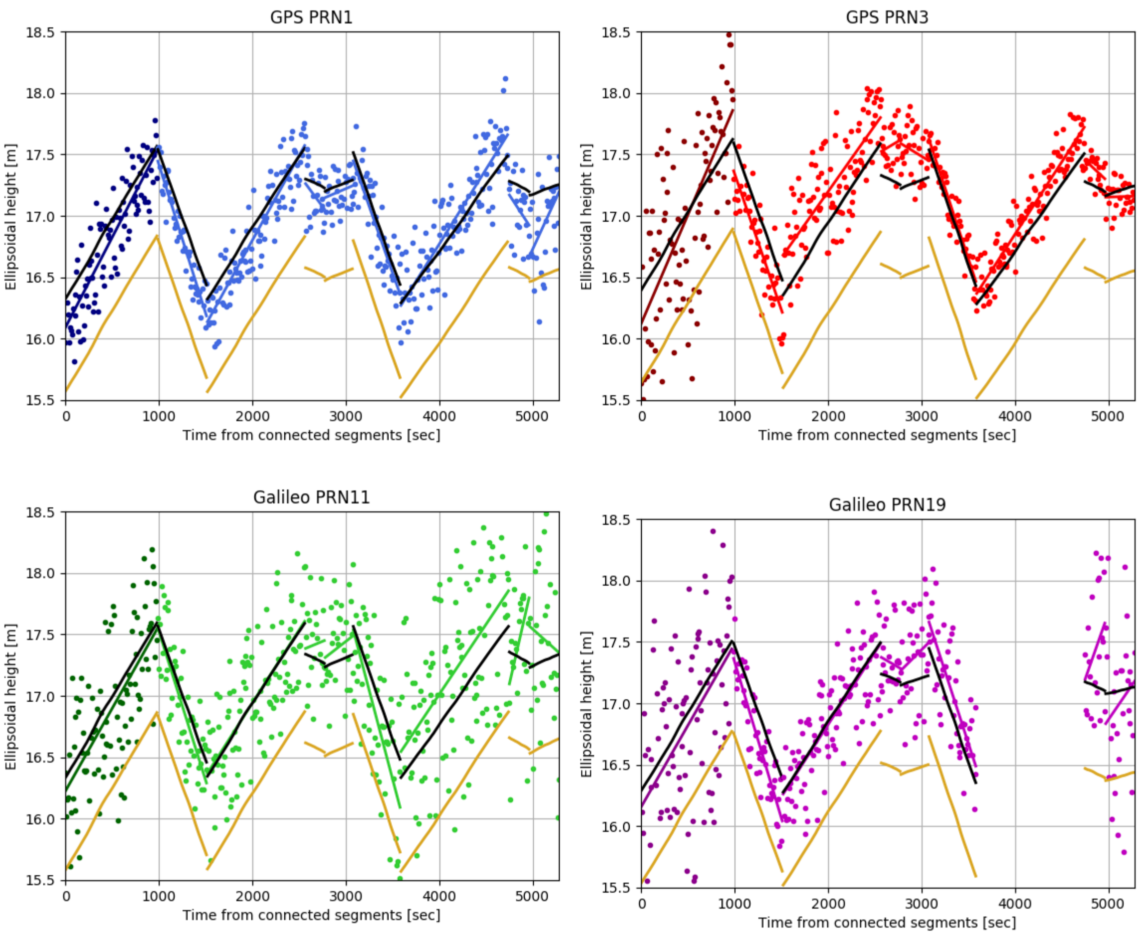


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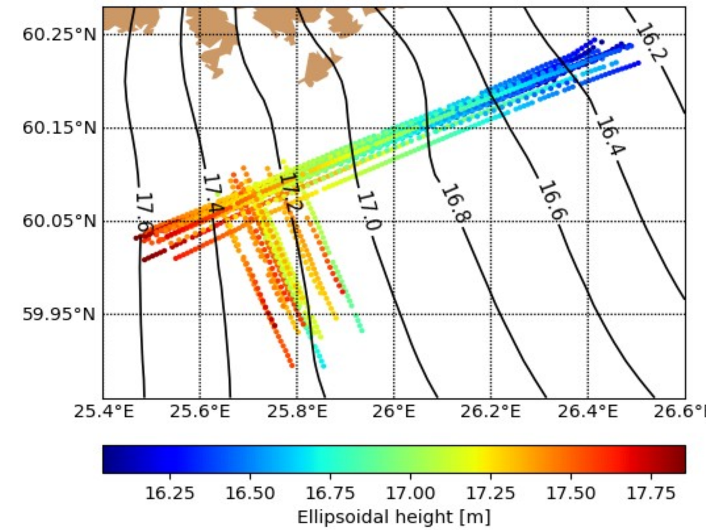
## Consistency




Linear fits of $SSH_{data}$ tracks projected over the surface

Contour lines of Finnish N2000 height system plus mean value of in-situ sea level estimation (mean sea level + measurements from buoys)

Mean square difference of crossing points of 19 cm

First dataset that permits to evaluate multiple aspects of the **accuracy** of **iGNSS-R altimetry**:

→ Comparison with reference surface information (absolute ground truth): **unbiased** overall $\boldsymbol{\sigma}_{\Delta SSH}$ of **40 cm** (ranging from **9 to 69 cm**) for **10 sec**

→ Cross-comparison between data tracks from different GNSS transmitters (GPS and Galileo), frequency bands (L1 and L5) and geometries (from 28 to 83 deg of elevation): **discrepancies** in **mean values** between **1 and 26 cm**

**Consistency** shown by the results represents a **key aspect** towards the assessment of the iGNSS-R concept for a **spaceborne** mission:

→ Spatial separation of the specular points would allow monitorization of **mesoscale features** over the ocean

In spite of applying corrections from a comprehensive waveform model, **instrumental offset** needs to be estimated and there are still some **residual** effects:

→ More effort is required to properly model all systematic effects

→ Spaceborne mission: calibration and validation measurements over specific sites would be highly recommended

# Thank you for your attention

Contents from: Fabra et al., “Is accurate synoptic altimetry achievable by means of interferometric GNSS-R?”, *Remote Sensing*, **2019**.