Towards precise synoptic altimetry by means of GNSS-R

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

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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)

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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**.
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- **PIR**
  - First **Interferometric** Receiver (L1)
  - 1 correlation channel
  - 2 front-ends
  - 512-lag complex waveform (msec rate)
  - 80 MHz (3.75 m)
  - Proof of concept of iGNSS-R altimetry from a 18-m bridge over estuary waters

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**PIRA**
- Adaptation of PIR to **aircraft** scenario (displacement of acquisition window)
- Assessment of altimetry **precision** from an altitude of 3 km

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

Height gradient **EGM96**

A single PRN acquired (high elevation)
Not **absolute** retrieval (accuracy not evaluated)

Hardware development

**Gold-RTR**

**PIR**

**PIRA**

**SPIR**

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Software PARIS Interferometric Receiver

- Raw data recorder of each front-end (320 MB/sec)
- \(\rightarrow\) **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
  \(\rightarrow\) **Digital beamforming**

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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

**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

**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)

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

\[ \Delta \rho = \rho_{\text{data}} - \rho_{\text{model}} \]

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

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

\[ \Delta \rho = 2\Delta H \sin(\text{elevation}) + K_{\text{inst}} \]

Final delay estimation is obtained after removing such instrumental offset:

\[ \overline{\rho_{\text{data}}} = \rho_{\text{data}} - K_{\text{inst}} \]

**Altimetry inversion**

Computed with respect to ellipsoid WGS84:

\[ SSH_{\text{data}} = (\rho_{\text{model}}^{\text{WGS84}} - \overline{\rho_{\text{data}}})/2\sin(\text{elevation}) \]
The results follow the height gradient and are at the same height level as the ground truth, both being above Finnish N2000.

- The evolution of $\sigma_{\text{SSH}}$ 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)

RESULTS

Unbiased overall result (black dashed)

Maximum separation between mean values of 26 cm → similar to the $\sigma$ 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

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Sea surface height retrieved (SSH$_{\text{data}}$)

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Consistency

Linear fits of SSH$_{\text{data}}$ 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 $\sigma_{\Delta SH}$ 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