GNSS-R for Ocean and Cryosphere Applications

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• Altimetry with Global Navigation Satellite Systems: Model correlation vs. PARIS Interferometric Technique
• Sea Ice Monitoring Experiment
• Dome-C Dry Snow Experiment
- **PARIS**: PAssive Reflectometry and Interferometry System, also called GNSS-Reflectometry
- Bi-/multi-static geometry
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- Bi-/multi-static geometry
GPS L1 signal

- **L-band** (~1.6 GHz), code division multiple access (CDMA)
- by deterministic sequences called **pseudorandom noise (PRN)** using the binary phase-shift keying (BPSK) technique (180 deg phase-shifts)

These sequences only match up, or strongly correlate, when they are exactly aligned (delay/Doppler), otherwise noise level (i.e. PRN codes are highly orthogonal to one another). A way to recognize and separate different simultaneously visible GPS satellites.

**GPS L1 Codes' Characteristics & Spectrum:**

- Coarse, Public: C/A ~2MHz,
  Tchip ~$9.8e^{-7}$ s delay ~ 293 m range

- Precise, encrypted P(Y) ~20MHz
  Tchip ~$9.8e^{-8}$ s delay ~29.3 m range

- Military, M ~24MHz
  Tchip ~$1.9e^{-7}$ s delay ~58.6 m range
• Altimetry with Global Navigation Satellite Systems: Model correlation vs. PARIS Interferometric Technique

• Sea Ice Monitoring Experiment

• Dome-C Dry Snow Experiment
How to receive the reflected signals?

- “Traditional” GNSS-R approach:

1. A replica of the signal is generated, using the well-known PRN codes and delay/Doppler information.
2. The signals are cross-correlated against the modelled orthogonal replicas.
3. In the time-domain, this brings information about the group-delay between each visible and reflected transmitter and the receiver position.
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- **PARIS Interferometric Technique:**
  1. No replica or model is used to cross-correlate with.
  2. A selected reflected signal, obtained with a high-gain narrow-beam and correctly pointed antenna is cross-correlated with the signals obtained by a similar antenna pointing toward the transmitter (without reflection).
The signals are cross-correlated against the modelled orthogonal replicas obtained with a high-gain narrow-beam and correctly pointed antenna is cross-correlated with the signals obtained by a similar antenna pointing toward the transmitter (without reflection).

(3) in the time-domain, this brings information about the group-delay between each visible and reflected transmitter and the receiver position.

Full Custom GNSS-R H/W Receiver:
GOLD-RTR
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- IEEC design/manufacture 2004-2005
- H/W signal processor, FPGA:
  - 640 complex correlators (10 channels)
  - 15 meter inter-lag space
- 70+ flights, 8+ months ground campaigns: data available for research
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public+encrypted signals contribute to the correlation,
Increased power and bandwidth: better precision?
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New PARIS Interferometric Receiver: PIR

- designed and manufactured at IEEC during 2009-2010, based on modifications of the GOLD-RTR
- cross-correlate reflected vs. direct signals using 320 complex correlators (built on FPGA),
- 12.5 ns (3.75 m) inter-lag delay,
- 1 msec coherent integration,
- sampling rate: 80 MHz,
- RF bandwidth programmable (8 to 80 MHz, 580 kHz steps)

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Increased power and bandwidth: better precision?
Theoretical shape of a PIR (interferometric) waveform, using *nominal* transmitted powers specified at IS-GPS-200:

A real PIR (interferometric) waveform, obtained in urban environment (roof/building reflections):
Test of PIR at laboratory

- Experiments conducted on **June 22, 2010**

- The SPIRENT synthesized signals included five **visible GPS signals** for a given simulation time, instrument location and dynamics, and one delayed signal, for only **one PRN, with a well controlled synthesized delay**.

We present:

- results from two SPIRENT experiments solely.

- with data taken with **standard mode** (i.e. no calibration measurements, no swapping of the channels).
## Preliminary group-delay results

<table>
<thead>
<tr>
<th>T (sod)</th>
<th>SPIRENT delay step (cm)</th>
<th>PIR measured delay step (cm)</th>
<th>1-sec sigma (cm)</th>
<th>Difference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300-359</td>
<td>ref</td>
<td>ref</td>
<td>1.8</td>
<td>ref</td>
</tr>
<tr>
<td>360-419</td>
<td>1</td>
<td>0.8</td>
<td>1.8</td>
<td>0.2</td>
</tr>
<tr>
<td>420-479</td>
<td>2</td>
<td>1.8</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>480-539</td>
<td>5</td>
<td>4.6</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>540-599</td>
<td>10</td>
<td>9.5</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>600-659</td>
<td>20</td>
<td>19.5</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>660-719</td>
<td>50</td>
<td>49.7</td>
<td>2.1</td>
<td>0.3</td>
</tr>
<tr>
<td>720-779</td>
<td>100</td>
<td>100</td>
<td>2.1</td>
<td>0</td>
</tr>
</tbody>
</table>

### Second of day

![Graph showing delay vs. time]
Experiment #17

The configured SNR should relate to the Bridge Experiment, but it is likely that some effects will degrade the performance in other scenarios: higher altitudes of the receiver, rougher sea surface conditions, instrumental, multipath, etc.

In order to inspect the effect of the signal-to-noise degradation into the altimetric performance, Experiment #17 gradually swept a range of 32 dB in the signal-to-noise ratio, around the nominal Bridge Experiment value 40.4 dB (15dB antennas' gain considered; final antennas were 9dB gain → 28.4 dB SNR).

The resulting measured delay dispersion depends on the signal-to-noise ratio at the correlation peak (for $T_i=1$s and $BW_{RF}=24$ MHz) as:
Bridge Experiment

- Zeeland Brug, The Netherlands, **July 7-8 2010**
- Bridge altitude over water: ~18 meter
- Estuary waters with tide signal (2.5 m total oscillation)
- Equipment:
  - PIR + “traditional” GNSS-R receiver (for comparison)
  - 2 high-gain narrow-beam antennas, pointing up/down at fixed directions (20 deg incidence)
  - Geodetic antenna, pointing zenith
- Complemented with a radar altimeter (RADAC wave guide working at 10 GHz) and L-band radiometer.
<table>
<thead>
<tr>
<th>Antenna Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>9.1 dB</td>
</tr>
<tr>
<td>Directivity</td>
<td>15 dB</td>
</tr>
<tr>
<td>Beam width (-3 dB)</td>
<td>32 deg</td>
</tr>
<tr>
<td>Back-front ratio</td>
<td>&lt; -35 dB</td>
</tr>
<tr>
<td>S11 (within L1)</td>
<td>&lt; -20 dB</td>
</tr>
<tr>
<td>Size (diam. hexagonal plane)</td>
<td>80 cm</td>
</tr>
<tr>
<td>Weight (approx.)</td>
<td>1.8 kg</td>
</tr>
</tbody>
</table>
We are interested in GROUP DELAY altimetry (THIS IS NOT CARRIER PHASE ALTIMETRY).

Group delay presents 1-second $\sigma \sim 7\text{cm}$.

Group delays present “contamination” by other GPS satellites. This “combined”-delay has been modelled by weighting each satellite contribution according to its location within the antenna gain pattern (simple model).

July 7 July 8:
The PIR measured altitude is presented on top, integrating the data up to one minute (34 1-sec samples + 10 swapped 1-sec samples). $\text{1-sec } \sigma_H \sim 7\text{cm}/(2 \sin(e)) \rightarrow 3.5 \text{ to } 4.3 \text{ cm.}$

On the bottom, the RADAC Wave Guide measurement of the altitude, 10 minutes averaged solution.

July 7 July 8:
Double differences (DD):

\[(\text{PIR} - \text{Radar})_{\text{day2}} - (\text{PIR} - \text{Radar})_{\text{day1}}\]

For “good” interval, peak-to-peak of ~20 cm → ~3.3 cm (DD dispersion), which represents ~6.4 cm 1-second altitude dispersion.
Summary altimetry:

- ESA PARIS-IoD aims to use interferometric GNSS-R altimetry rather than code-modulation based altimetry
- IEEC developed a PARIS Interferometric Receiver (PIR)
- A SPIRENT/lab and Bridge/real experiments have been conducted
- SPIRENT test conclusions: group delay obtained with a-few cm precision (1 second dispersion); 1-cm delay jumps detected.
- Bridge experiment conclusions:
  - In spite of non optimal conditions w.r.t. space-based measurements (strong multipath environment; antenna at fixed pointing direction; all satellites have the same differential delay & Doppler signatures) **GROUP DELAY ALTIMETRY PERFORM AT 4 TO 6 CM LEVEL IN 1-SEC OBSERVATION.**
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Sea Ice experiment

Location: Godhavn (west coast in Greenland)


Altitude = 700 meter

Low elevation range due to coastline profile: 5 to 15 deg
Sea Ice experiment

Satellites' position

GOLD-RTR

D - RHCP
R - LHCP
R - RHCP

Direct

Ground

Reflected

Ocean / Sea-ice

Strong multipath
Phase altimetry with cm precision

Potential determination of sea ice free-board level, linked to **thickness** (stage of development)

Agreement with AOTIM-5 and between polarizations
Sea-ice characterization

Polarimetric ratio between co- and cross-polar components relates to permittivity:

- The Fresnel coefficients of sea-ice depend on its dielectric properties (brine, temperature).
- At the observation geometry, 5-20 deg elevation, both co- and cross-polar components are of the same order of magnitude. Its ratio is therefore sensitive to variations in dielectric properties.
Sea-ice characterization

Ice parameters (sea-ice concentration, form, and thickness) from DMI's “egg-charts” interpolated to PRN02 specular point location:

GPS parameters for same PRN02: polarimetric ratio; slope of the trailing edge (roughness); and 1-sec RMS dispersion of the phase observables:
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Dome-C, Antarctica
Shorter campaign due to stability (Macelloni et al. 2005) of the dry snow: 10\textsuperscript{th} to 21\textsuperscript{st} January 2010
Clean visibility, large range of elevations (5 to 65 deg) and absence of near-multipath
Validation area for remote sensing: availability of ancillary data
45 m vertical distance: overlap of direct and reflected signal for several lags
Not a single ”surface”: reflected signal as a contribution from different layers
Only GNSS-R snow model available in the literature was Wiehl et al. [2003]: volumetric scattering, which does not explain the “beating” of the waveform.

New simple model, multi-layer single reflection:
Amplitude modelling:
- only cross-pola component of the reflection considered
- only co-polar component for transmission
Need for a model

Complex waveform generated:
- Incident signal at surface with $A=1$
- Direct signal set to lag 22 (RHCP to LHCP leakage with $A=0.1$)
- Frequency of direct signal as a reference
Spectral components depend on the waveform lag:

→ to conduct FFTs of the time series of each lag within the waveform
Summary cryosphere:

SEA ICE

- Phase altimetry with cm precision at two polarizations
  → Potential determination of the ice **thickness** (related to freeboard level)

- Polarimetric and RMS measurements matches with ice percentage
  → **Permittivity** and **roughness** can be used for sea ice classification

DRY SNOW

- A model with multiple layers has been tested

- Lag by lag FFT series separates interferometric information from other effects

- Preliminary results show good agreement

- Proper inversion could determine **dominant layers** of the dry snow profile at L-band