Experimental Results of PARIS Measurements using X-Band Digital Satellite TV Opportunity Signals Reflected on the Sea Surface

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Outline

1. Introduction
2. Experiment
3. Instrument
4. Data Analysis
5. Conclusions
Introduction

- Support to explore scientific uses of future C-band GALILEO signals (European GNSS Evolution Program, EGEP)
- Extend the PARIS concept to other sources of opportunity and frequency ranges
  - Reduced ionospheric delay error on space-borne PARIS systems
  - Better SNR due to stronger TX power
  - Smaller antennas without reducing directivity (shorter wave-length)
  - Sensitivity to small scale waves (ocean applications)
- Build and test a versatile PARIS instrument
  - Multi-band operation (L, C, X, Ku)
  - Sub-band selection
  - Multi-bit signal quantization
  - Basic Instrumental calibration
**X-band opportunity sources**

- Plenty of sources (TV broadcast satellites)
- Plenty of commercial hardware
- Digital modulations (flat spectrum)
- Broad BW & flat spectrum (up to \( \approx 27.5 \text{MHz} \))
- Correlations waveforms significant compared to GNSS-R waveforms
Band Selection for Experimental Demonstration

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Experiment

- July 2012
- Ground-based experiment at coastal area
- Cap de Begur, West Mediterranean, $h \approx 105\text{m}$
- Pointing towards ASTRA satellite cluster (19.2E)
- Source elevation: $38.9^\circ$
- Source Azimuth: $156.8^\circ$
- Direct signal: Offset dish antenna 60cm diameter
- Reflected signal: circular horn (LNB without dish)
Experiment Location
Experiment Location

Source: Institut Cartogràfic de Catalunya
Experiment Location

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Experiment Set-up

Antennas are mounted on top of a scaffold with direct view to the sea
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## Principal Instrument Aspects

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Architecture</strong></td>
<td>L-band receiver with external coherent down-conversion LNB at C/X/Ku-band. Baseline implementation at X-band</td>
</tr>
<tr>
<td><strong>Heritage</strong></td>
<td>Design based on previous architectures</td>
</tr>
<tr>
<td><strong>COTS</strong></td>
<td>Usage intensively</td>
</tr>
<tr>
<td><strong>Multi-bit</strong></td>
<td>Quantization to handle high (positive) SNR values. Quantization to 10 bits per sample at 80 Msamples/s. Signal processor at 3 bits per sample</td>
</tr>
<tr>
<td><strong>Sub-band selection</strong></td>
<td>To choose one between many 27.5 MHz TV channels being transmitted in a 1 GHz bandwidth. Instrument channel bandwidth adjustment also possible from 4 MHz to 40 MHz.</td>
</tr>
<tr>
<td><strong>Power adjustment</strong></td>
<td>To compensate for different power levels at different TV channels</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>Calibration of instrumental errors (DC signal offset)</td>
</tr>
</tbody>
</table>
Data Analysis and Processing Steps

Data processing steps (real time)

- Real time coherent integration at 1ms
## Data Analysis and Processing Steps

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- Real time DC offset measurement at 1ms
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- Offset calibration at 1ms complex waveforms
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- Non-coherent integration of power waveforms
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#### Data processing steps (post-processing)
- Offset calibration at 1ms complex waveforms
- Non-coherent integration of power waveforms
- Altimetric delay (derivative method)
Instrumental ADC Offset Calibration

Improves waveform shape and dynamic range

Complex cross-correlation (I/IQ) (1ms)

Complex cross-correlation (Q/QI) (1ms)
Instrumental ADC Offset Calibration

Improves waveform shape and dynamic range
Instrumental ADC Offset Calibration

Improves waveform shape and dynamic range

Amplitude waveform (1ms)

Off. not corr.
Off. corr.

Amplitude [dB]

lag delay [m]
Waveforms as function of bandwidth
$\text{BW} = 4\text{MHz}$, $T_i = 10\text{s}$
Waveforms as function of bandwidth

\(BW = 8\text{MHz}, \ T_i = 10\text{s}\)
Waveforms as function of bandwidth
$BW = 12MHz$, $T_i = 10s$
Waveforms as function of bandwidth

$\text{BW} = 16\text{MHz}, \quad T_i = 10\text{s}$
Altimetric delay

- The SNR of the power waveforms $w(\tau)$ is high.
- The relative delay $\tau_{\text{spec}}$ between the direct and reflected signals is determined as the lag delay where the waveform derivative is maximum.
- A large number $M$ of power waveforms are averaged to reduce the speckle noise (exponential distribution).

$$S = \frac{1}{\sqrt{M}} \cdot \frac{w(\tau_{\text{spec}})}{d\tau_{\text{spec}}}$$

is an approximate estimate of the minimum detectable delay.
Delay estimates as a function of BW

Delay estimation bias is function of BW [1]
$S$ Parameter and precision as a function of BW

- $S < 5\text{cm}$ for $T = 10s$ and $BW > 16\text{MHz}$
- $S$ parameter improves with increasing BW
- Increasing system’s BW beyond signal’s BW does not improve $S$
- $\sigma = 10\text{cm}$ for $T = 10s$ and $BW = 20\text{MHz}$ (from measurements)
• $S < 5\,\text{cm}$ for $T = 10\,\text{s}$ and $\text{BW} > 16\,\text{MHz}$
• $S$ parameter improves with increasing BW
• Increasing system's BW beyond signal's BW does not improve $S$
• $\sigma = 10\,\text{cm}$ for $T = 10\,\text{s}$ and $\text{BW} = 20\,\text{MHz}$ (from measurements)
Waveform lag-statistics

- Statistics of the lags reveal signal origin
- Useful for analysis and interpretation of experimental data

![Estimated PDF for lag 0 [m]](image)
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Conclusions

- Plenty X-band digital TV satellite opportunity signals available
- Larger available power than with GPS (more EIRP & directive antennas)
- High SNR at 1ms coherent integrations.
- ADC offset calibration needed to maintain waveform shape and dynamic range
- Altimetric delay estimates (derivative method) improve with increasing signal bandwidth
- Bias on delay estimation depends on the used bandwidth
- Demonstrate delay precision of 10cm
- Noise statistics reveal signal origin

Acknowledgement

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Suitability of Higher Bands

**Ionosphere**
- Ionospheric delay effects are reduced with increasing frequency.
  - L-band: $\approx 200$ cm
  - C-band: $\approx 20$ cm
  - X-band: $\approx 4$ cm
- Higher bands better suited for delay measurement applications (altimetry) from space.

**Antennas**
- Antenna size can be reduced maintaining gain constant
Suitability of Higher Bands

Water & Rain at X-band

- Attenuation in the range of 0.1\,dB/km–1\,dB/km for rain intensities between 10\,mm/h-25\,mm/h
- Received Power not severely affected by moderate rain
- Altimetry still possible in areas with low to moderate rain intensities
- With generous power budget also possible with heavy rain

Figure from [2]
### GNSS-R vs Satellite TV-R

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GNSS-R L1 C/A,P,M</th>
<th>X-band (11GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP [dBW]</td>
<td>24.5</td>
<td>51</td>
</tr>
<tr>
<td>Range [km]</td>
<td>20,200</td>
<td>38,000</td>
</tr>
<tr>
<td>Directivity [dB]</td>
<td>15</td>
<td>36</td>
</tr>
<tr>
<td>Noise figure $F$ [dB]</td>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>Signal bandwidth [MHz]</td>
<td>24</td>
<td>27</td>
</tr>
</tbody>
</table>