THE PROOF OF CONCEPT FOR 3-CM ALTIMETRY USING THE PARIS INTERFEROMETRIC TECHNIQUE

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ABSTRACT

Index Terms— GNSS, GNSS Remote Sensing, GNSS-Reflections, PARIS, Altimetry

1. INTRODUCTION

Since its suggestion in 1993, the altimetric and scatterometric capabilities of the PAssive Reflectometry and Interferometry System (PARIS) [1] have been tested extensively from ground- air- and even space-based experiments [2, e.g.]. The concept is based on the use of the Global Navigation Satellite System (GNSS) signals reflected off the Earth (Ocean, Ice, Land), in a bi-static radar configuration. ESA has proposed to use the PARIS Interferometric Technique at the future PARIS In-Orbit Demonstrator Instrument (PARIS-IOD) [3]. This is a novel instrumental approach with respect to previous PARIS instruments, which obtained the observables through cross-correlating direct and reflected signals against a GPS signal model (or *replica*). The limit of such an altimetric approach was given by the availability of the GNSS codes. The new interferometric technique aligns the direct and reflected signals both in delay and Doppler and computes directly cross-correlation between the received signals (not against replicas of their codes). The principal advantage of this new technique is that in addition to public GPS signals, also encrypted signals can be used simultaneously, increasing the available signal bandwidth and power, and thus the expected precision of the altimetric measurement.

This project contributes to the PARIS-IOD concept trying to demonstrate the suitability of the interferometric technique for altimetric purposes, as well as to study and demonstrate the proposed calibration techniques for the PARIS-IOD instrument. We aim to confirm whether the interferometric technique is capable of measuring GPS signal delay differences with an associated 1 sigma error of 3 cm with 1 second

Table 1. Characteristics of the PIR Receiver.

RF Bandwidth:	programmable, 8MHz to 80 MHz, in 580 kHz steps
Sampling rate:	80 HMHz
# cplx. correlators:	320 lags
Inter-lag delay:	12.5 ns (3.75 m)
Coh. Int. Time:	1 ms

of observation time.

The first step to accomplish the objective of the activity is to build the appropriate receiver, able to perform the direct correlation between the two signals. This has been achieved by modifying the existing dedicated full-custom GNSS-reflection receiver GPS Open Loop Differential Real-Time Receiver (GOLD-RTR) [4], now called PARIS Interferometric Receiver (PIR). Although the instrument proposed for the PARIS-IOD will have beam-forming antennas, our proof-of-concept instrument will operate with real aperture antennas as we will concentrate our effort on developing the real-time digital signal processing algorithms. The details of the PIR are given in Table 1.

2. SPIRENT SIMULATOR EXPERIMENT

The experiment setup designed to determine the capabilities of the PARIS Interferometric Technique is shown in Figure 1. The GPS signals are simulated using a GPS simulator equipment. The simulated signals include all visible GPS signals for a given simulation time, instrument location and dynamics, and one reflected signal, for only one PRN, on a perfectly reflecting flat surface [5]. These signals are fed into a power splitter and divided into three paths. The first one is injected into link 1 of the PIR. This first signal is named N (Navigation). Link 1 in the PIR is used to obtain standard GPS observables (pseudo-ranges, Doppler, position, time, . . .) using an embedded commercial GPS receiver. The other two GPS signals at the output of the power splitter correspond to the
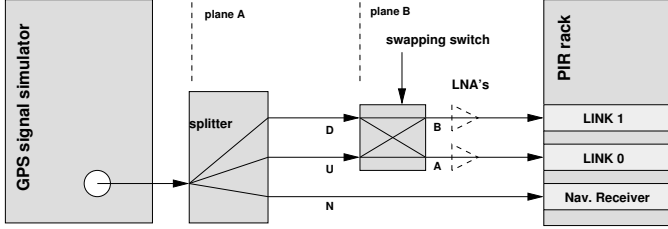
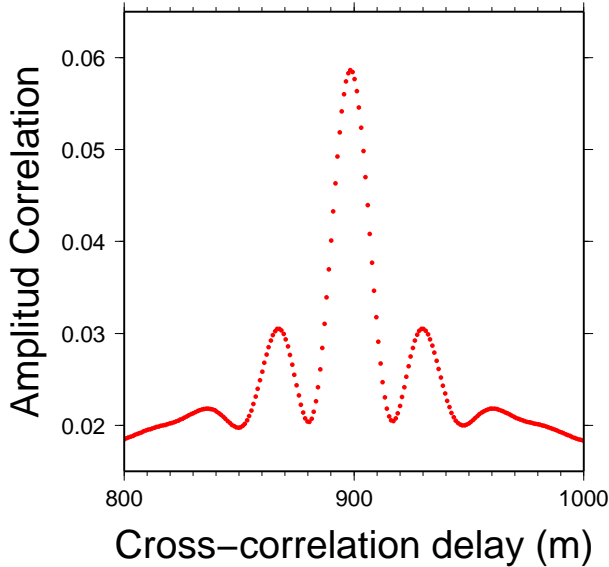**Fig. 1**. Proposed experiment set-up using a GPS simulator environment.

Fig. 2. Cross-correlation between direct and reflected signals (L1 C/A+P+M codes) generated by the SPIRENT (1:4 interpolation factor).

signals acquired by the up (U) and down (D) looking antenna arrays of PARIS-IOD. Using the switch, the U and D signals can be fed into links 0 or 1 using the swapping technique proposed in [6]. Link 0 would correspond to the front-end A and link 1 to front-end B in [6]. The PARIS interferometric technique is implemented by cross-correlating the signals of links 0 and 1. LNAs are placed between the switch and the GOLD-RTR to simulate the presence of an LNA in the real PARIS-IOD.

2.1. Group Delay Preliminary Results

General speaking, only group-delay can be measured from GPS signals scattered off the Ocean surface. Therefore, the results presented are based in group-delay measurements solely (no carrier-phase delays).

The SPIRENT simulation tests were conducted on June 22, 2010. A large sequence of *experiments* was performed, in which different combinations of the delay lines, swapping, and calibration parameters were tested. The preliminary re-

Table 2. SPIRENT results for experiment #14 after 33-samples averaging (see Figure 4). Delays in centimeter with respect to first averaged-observation. ρ_n and ρ_m for SPIRENT-nominal and PIR measured delays respectively. σ_{1sec} corresponds to the actual dispersion of the data.

T (sod)	$\rho_\mathbf{n}$ (cm)	$\rho_\mathbf{m}$ (cm)	$\sigma_\mathbf{1sec}$ (cm)	$|\rho_\mathbf{n} - \rho_\mathbf{m}|$ (cm)
300-359	0	ref	1.8	ref
360-419	1	0.8	1.8	0.2
420-479	2	1.8	2.0	0.2
480-539	5	4.6	1.8	0.4
540-599	10	9.5	2.0	0.5
600-659	20	19.5	2.0	0.5
660-719	50	49.7	2.1	0.3
720-779	100	100.0	2.1	0.0

sults presented in this paper focus on two experiments solely, and only use observations taken in *standard* mode (i.e. no calibration measurements, no swapping of the channels). Those represent 33 seconds in each minute of measurements, which are not always sequential because the instrument loops around a sequence of calibration-test modes. The simulations were based on the GNSS status corresponding to March 6 2010. The power of the direct and reflected signals were in general selected to mimic the expected signal-to-noise ratio in the Bridge Experiment, that has been estimated as 40.4 dB at the correlation peak (see Section 3 and Figure 3 for the used formula). An example of the obtained cross-correlation waveforms is presented in Figure 2. As shown in e.g. [4], the approach used so far, which usually implies the correlation of the signals with the replica of the known, C/A, code, would have resulted in a ±300 meter wide triangle. Instead, the full correlation of both signals contains other GPS codes, of wider bandwidth (P and M), which introduce narrower main and secondary peaks.

Experiment #14 consisted of a sequence of minutes of reflected data, increasing stepwise the delay of the reflected signal by re-programming of the SPIRENT simulator. Figure 3 provides more details on this experiment. The SPIRENT was programmed to introduce delay-jumps of 1 centimeter to 1 meter, in *logarithmic* steps (see 2nd column in Table 2 or details in Figure 3). The formal uncertainty of the retrieved peak-locations of 1-second averaged waveforms varies between 1.3 to 2.8 cm. The actual 1-second dispersion, as shown in Table 2, corresponds to 1.8 to 2.1 cm, all better than 3-cm. Figure 4 presents the measured delays. All the jumps introduced by the SPIRENT are detectable, even at 1-cm level. As shown in Table 2, the difference between the incremental delay measured by the PIR and the one actually programmed in the SPIRENT has a maximal value of 0.5 cm.

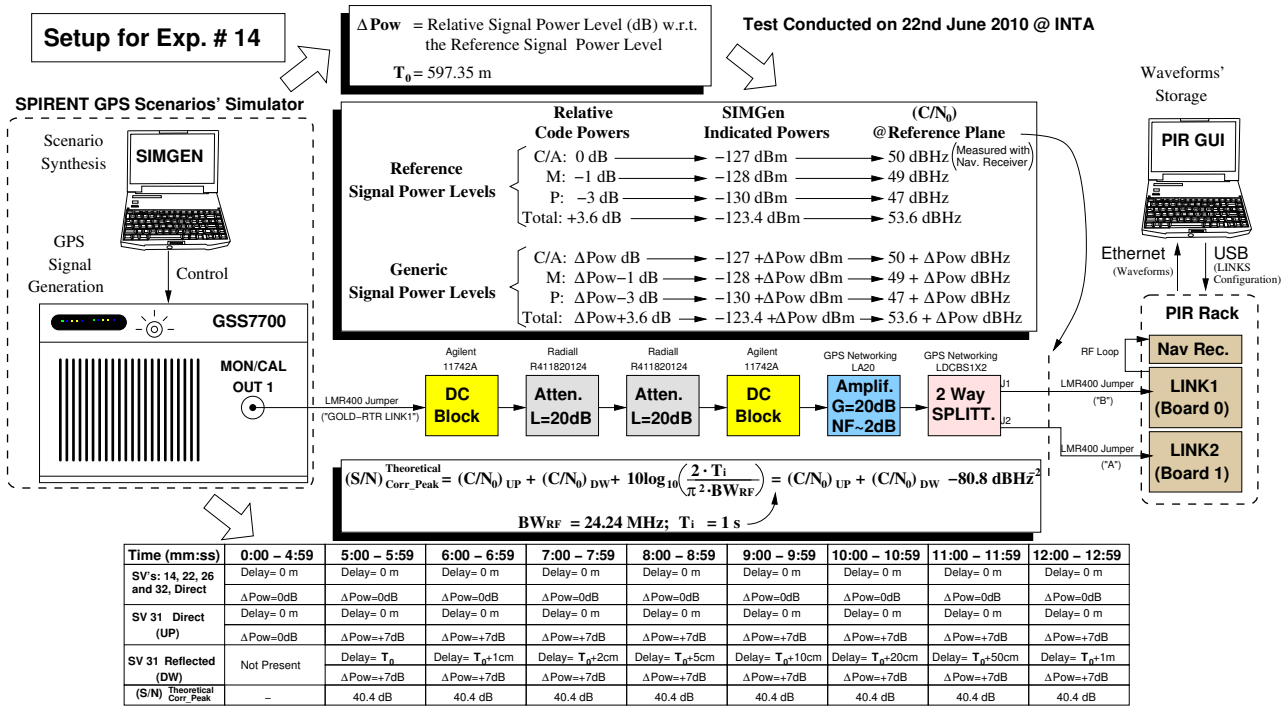Although the configured SNR should relate to the Bridge

Setup for Exp. # 14

Δ**Pow** = Relative Signal Power Level (dB) w.r.t. the Reference Signal Power Level

T_0 = 597.35 m

SPIRENT GPS Scenarios' Simulator

Scenario Synthesis — SIMGEN

GPS Signal Generation — Control — GSS7700

MON/CAL OUT 1

	Relative Code Powers	SIMGen Indicated Powers	(C/N$_0$) @Reference Plane
Reference Signal Power Levels	C/A: 0 dB →	−127 dBm →	50 dBHz (Measured with Nav. Receiver)
	M: −1 dB →	−128 dBm →	49 dBHz
	P: −3 dB →	−130 dBm →	47 dBHz
	Total: +3.6 dB →	−123.4 dBm →	53.6 dBHz
Generic Signal Power Levels	C/A: ΔPow dB →	−127 +ΔPow dBm →	50 + ΔPow dBHz
	M: ΔPow−1 dB →	−128 +ΔPow dBm →	49 + ΔPow dBHz
	P: ΔPow−3 dB →	−130 +ΔPow dBm →	47 + ΔPow dBHz
	Total: ΔPow+3.6 dB →	−123.4 +ΔPow dBm →	53.6 + ΔPow dBHz

Waveforms' Storage — PIR GUI

Ethernet (Waveforms) / USB (LINKS Configuration)

PIR Rack: Nav. Rec. / LINK1 (Board 0) / LINK2 (Board 1)

LMR400 Jumper ("GOLD–RTR LINK1") — Agilent 11742A DC Block — Radiall R411820124 Atten. L=20dB — Radiall R411820124 Atten. L=20dB — Agilent 11742A DC Block — GPS Networking LA20 Amplif. G=20dB NF~2dB — GPS Networking LDCBS1X2 2 Way SPLITT. — RF Loop — LMR400 Jumper ("B") — LMR400 Jumper ("A")

$$(S/N)^{Theoretical}_{Corr\_Peak} = (C/N_0)_{UP} + (C/N_0)_{DW} + 10\log_{10}\left(\frac{2 \cdot T_i}{\pi^2 \cdot BW_{RF}}\right) = (C/N_0)_{UP} + (C/N_0)_{DW} - 80.8 \; dBHz^2$$

$$BW_{RF} = 24.24 \text{ MHz}; \quad T_i = 1 \text{ s}$$

Time (mm:ss)	0:00 – 4:59	5:00 – 5:59	6:00 – 6:59	7:00 – 7:59	8:00 – 8:59	9:00 – 9:59	10:00 – 10:59	11:00 – 11:59	12:00 – 12:59
SV's: 14, 22, 26 and 32, Direct	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m
	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB	ΔPow=0dB
SV 31 Direct (UP)	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m	Delay= 0 m
	ΔPow=0dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB
SV 31 Reflected (DW)	Not Present	Delay= T_0	Delay= T_0+1cm	Delay= T_0+2cm	Delay= T_0+5cm	Delay= T_0+10cm	Delay= T_0+20cm	Delay= T_0+50cm	Delay= T_0+1m
		ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB	ΔPow=+7dB
(S/N) Theoretical Corr_Peak	–	40.4 dB	40.4 dB	40.4 dB	40.4 dB	40.4 dB	40.4 dB	40.4 dB	40.4 dB

Fig. 3. Summarized set-up for experiment #14.

Experiment, it is likely that some effects will degrade the performance in other scenarios (higher altitudes of the receiver, rougher sea surface conditions, instrumental, 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 40.4 dB. The resulting 1-second dispersion depends on the carrier signal-to-noise ratio as shown in Figure 5, from where we can deduce that ∼3 dB degradation with respect to the expected Bridge Experiment one (40.4 dB) might still produce 1 sigma error below 3-cm with 1 second observations. This degradation could be introduced by non-ideal conditions.

3. BRIDGE EXPERIMENT

The Bridge Experiment is planned for the second week of July 2010. The set-up for the bridge experiment is shown in Figure 6. This experiment requires independent calibration data to be provided on the sea-level height with respect to the main GNSS-R antennae; thus, a number of elements need to be surveyed accurately. The elements are (1) The ≈ 1 m diameter uplooking antenna (**U**) pointing to a fixed direction of the sky, where the selected GPS satellites will transit. The pointing direction of this antenna can be adjusted with a mechanical tilt (20 degrees respect to Zenith/Nadir), but it will not perform any tracking during the experiment. (2) An upward looking hemispherical antenna (**N**) which is used to obtain navigation observables. The position of this antenna is retrieved using a
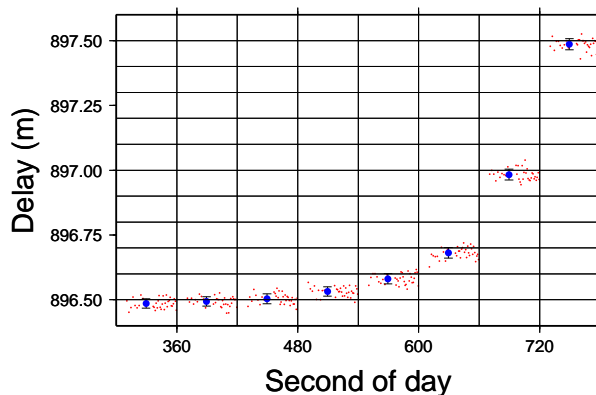
Fig. 4. Group-delays measured with the PIR during experiment #14, 33 samples per minute, at 1 second integration each (red) and the 33-samples means (blue).
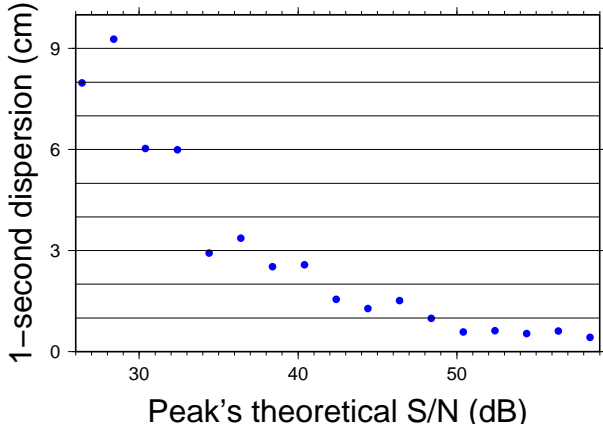
Fig. 5. 1-second dispersion of the PIR measured delays as function of the carrier signal-to-noise ratio in experiment #17 (assuming T_i=1 s, BW_{RF}=24.24 MHz). 40.4 dB is the expected SNR in the Bridge Experiment conditions.

GPS receiver. The signal of antenna **N** is also injected into the NAV inputs of the GOLD-RTR and PIR racks. (3) A $\approx$ 1 m diameter down-looking antenna **D** that points to a fixed direction towards the sea, where the GPS reflected signals will transit as well.

The PARIS interferometric antennas are antennas **U** and **D**. It is intended to perform traditional model cross-correlations (**U**, **D**) using the GOLD-RTR receiver and interferometric waveforms using the PIR. Antennas **U** and **D** are mounted at the end of the boom.

The activity of measuring the height of the Antenna Reference Point (ARP) of these three antennas (**U**, **N**, **D**) above the sea will be executed as a number of independent but interrelated tasks: (1) Local surveying and monitoring of the antenna positions (**U**, **N**, **D**) with respect to the RADAC altimeter (**WG**) and reference points (**R1**, **R2**) on the bridge. (2) RADAC WaveGuide free space radar altimeter measurements with 1 cm accuracy. (3) Connection of the bridge reference point (**R2**) to the national height datum (NAP), tide-gauge measurements from the RWS network, and optional GPS buoys measurements at nearby placement. (4) GPS buoys measurements (optional/backup).
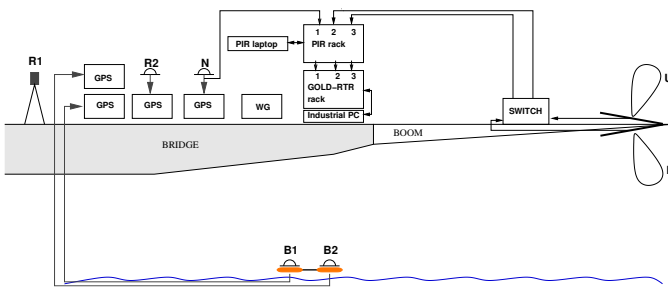

Fig. 6. Set-up for the bridge experiment.

4. CONCLUSIONS

A proof-of-concept instrument for PARIS-IOD, based on a full-custom dedicated GNSS-Reflections receiver has been developed, and the novel interferometric concept tested in several experiments using signals generated by a SPIRENT equipment. The preliminary analysis has resulted in the detection of 1-cm delay-jumps, using 33 group-delay observables of 1 second, with an associated dispersion of the order of 2-cm. A signal-to-noise degradation of the order of $\sim$3 dB with respect to the one expected for the Bridge Experiment would keep the 1-second sigma error below 3-cm.

A second experiment using real reflected signals obtained from a relatively high bridge ($\sim$15 m) over estuary waters is planned for July 2010. The aim of the activity is to confirm the PARIS Interferometric Technique concept as an altimetric system able to provide 3-cm resolution, as initially suggested by the presented preliminary results.

5. REFERENCES

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