Advanced architectures for real-time Delay-Doppler Map GNSS-reflectometers: The GPS reflectometer instrument for PAU (griPAU)


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Abstract

In recent years Global Navigation Satellite System’s signals Reflectometry (GNSS-R) has stood as a potential powerful remote sensing technique to derive scientifically relevant geophysical parameters such as ocean altimetry, sea state or soil moisture. This has brought out the need of designing and implementing appropriate receivers in order to track and process this kind of signals in real-time to avoid the storage of huge volumes of raw data. This paper presents the architecture and performance of the Global Positioning System (GPS) Reflectometer Instrument for PAU (griPAU), a real-time high resolution Delay-Doppler Map reflectometer, operating at the GPS L1 frequency with the C/A codes. The griPAU instrument computes $24 \times 32$ complex points DDMs with configurable resolution ($D_f D_{\min} = 20$ Hz, $D_s D_{\min} = 0.05$ chips) and selectable coherent (minimum = 1 ms, maximum = 100 ms for correlation loss $D_q < 90\%$) and incoherent integration times (minimum of one coherent integration period and maximum not limited but typically <1 s). A high sensitivity (DDM peak relative error = 0.9% and DDM volume relative error = 0.03% @ $T_i = 1$ s) and stability ($D_q / D_t = 1$ s$^{-1}$) have been achieved by means of advanced digital design techniques.

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1. Introduction

Global Navigation Satellite Systems (GNSS) signals have been world-widely used for navigation and positioning purposes. These signals are transmitted by satellite constellations and provide global coverage. Although many systems are available or will be in the near future such as GLONASS, COMPASS, GALILEO, etc. it is the Global Positioning System (GPS) the one that has the widest acceptance, and it is fully deployed and operational.

However, this kind of signals can be used for other purposes than just positioning or navigation and specifically, they can be used as opportunity signals to remotely sense geophysical parameters after being scattered over the Earth’s surface. This technique is called GNSS Reflectometry (GNSS-R) and was first introduced for mesoscale altimetry by Martín-Neira, (1993) who proposed to process the received signal, after reflecting over the surface under observation, by correlating it with local replicas of the GPS code generated with different time delays. The result of this technique is a function called waveform that relates to the scattered power as a function of the time delay. Different approaches of this technique have been proposed for a number of remote sensing applications, especially to derive ocean altimetry and sea state (Zavorotny and Voronovich, 2000; Cardellach, 2001; Rius et al., 2002; Marchan-Hernandez et al., 2008b).

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The determination of the sea state is a key issue for Sea Surface Salinity (SSS) retrievals using L-band microwave radiometry (Font et al., 2004), and may be the limiting factor in the final achievable accuracy. In order to improve the quality of SSS retrievals, the PAU instrument was proposed in 2003 to the European Science Foundation (Camps et al., 2004a, 2009). This project consists of the development of a suite of three instruments: a digital beam-forming pseudo-correlation radiometer; a GPS reflectometer sharing the same RF front-end, IF back-end and analog-to-digital converter; and an infrared radiometer.

In the framework of the PAU project, the basic GNSS-R observable to work with has been chosen to be the whole Delay-Doppler Map (DDM), since it captures the asymmetries of the DDM tails due to the relative motion between the GPS transmitter and receiver, as well as for the relative direction of the wind speed and the instrument looking direction. The DDM tails asymmetry can be important for spaceborne receivers, as shown in Fig. 1 for two different scenarios: 12 m/s wind speed and receiver’s velocity vector parallel and perpendicular to the scattering plane. The DDM is obtained by correlating the received signal with local replicas of the pseudo-random noise (PRN) code shifted in time, and also in Doppler frequency with respect to the delay and Doppler frequency at the specular reflection point. It is a 2D function that is related to the scattered power distribution over the surface. As it takes into account all the power contributions of the complete glistening zone (i.e. surface zone that contributes to the received scattered power) it contains more information (i.e. azimuthal dependence) than just the peak value, or the time-domain waveform.

Moreover, the normalized DDM volume has been proposed as an efficient direct sea roughness descriptor that can be directly linked to the brightness temperature variations due to the sea-state effect (Marchan-Hernandez et al., 2008c; Valencia et al., 2009). To assess the theory, two field experiments have been undertaken in the Canary Islands (Marchan-Hernandez et al., 2008b; Valencia et al., 2009) with very encouraging results.

In this paper, the GPS Reflectometer Instrument for PAU (griPAU) design, implementation and performance are presented. The griPAU instrument is a real-time GPS reflectometer that computes high resolution complex DDMs coherently integrated during 1 ms, the duration of the GPS C/A code at L1 (1575.42 MHz). These basic 1 ms DDMs can be averaged coherent (amplitude and phase) or incoherently (amplitude-only).

The griPAU instrument has been developed from a previous operational version (Marchan-Hernandez et al., 2008a). This former version has been redesigned applying state-of-the-art digital design techniques so as to improve and enhance the instrument’s performance by achieving a high synchronism and making the most benefit of the available hardware resources in the Field Programmable Gate Array (FPGA). The main elements of the system that have been replaced or modified are listed in Table 1 along with the resulting system improvements.

2. Instrument description

2.1. Principle of operation

The purpose of the griPAU instrument is to compute the DDMs in real-time by correlating the received scattered signal \( s(t) \) with a local replica of the GPS C/A code \( a(t) \) for several values of the delay \( (\tau) \) and Doppler offsets \( (f_D) \):

\[
\text{DDM}(\tau, f_D) = \int_{0}^{Tc} s(t)a(t+\tau)\exp(-j2\pi(fL1+f_D)t)dt,
\]

(1)

where \( (\tau, f_D) \) are the delay and Doppler coordinates, and \( T_c \) is the coherent integration time. The noise-free received direct signal \( s(t) \) has the form:

\[
s(t) = \sum_{n=-\infty}^{\infty} \text{rect}(t-nT_s) \text{rect}(f-nf_s) \delta(t-nT_c)
\]

Fig. 1. Simulated DDM –3 dB contour plots for a LEO (\( h = 700 \) km) GNSS-R receiver in two different spaceborne scenarios for a wind speed of 12 m/s: (left) receiver’s velocity vector parallel to the scattering plane and, (right) receiver’s velocity vector perpendicular to the scattering plane.
\[
s(t) = \sqrt{2P_C/P_D(t)} \cos(2\pi(f_{t1} + f_{d})t) \\
+ \sqrt{2P_D/P_D(t)} \sin(2\pi(f_{t1} + f_{d})t),
\]
\(\text{(2)}\)

where \(D\) is the navigation message, \(P(t)\) is the precise GPS code, \(P_{CD}\) is the transmitted power of the in-phase component, \(P_P\) is the power of the quadrature component, and \(f_d\) is the Doppler shift induced by the relative motion of the transmitter and the receiver. In GPS positioning and navigation receivers the navigation message is decoded. In GNSS-R receivers this is not usually the case as it is the griPAU case, so changes in the navigation bit cause \(\pi\)-rad phase jumps that will drastically reduce the resulting SNR. Unless phase jumps are compensated for, this effect will limit the maximum coherent integration time to 20 ms at most, which is the period of the navigation bit.

As it can be seen in Eq. (2), the received signal undergoes a Doppler shift \(f_d\) as it propagates from the transmitter to the scattering surface and then to the receiver. To correctly track the reflected signal the system has to be able to detect and correct this Doppler shift. As griPAU has been designed to work mainly for ground-based applications at low heights, the Doppler shift induced in the reflected signal is the same as the induced in the direct one, and depends only on the transmitter motion. However, for airborne or spaceborne operations, the actual Doppler shifts would have to be computed from geometric considerations using the navigation solution derived by the uplooking GPS receiver:

\[
\hat{f}_D = \frac{\hat{V}_i \cdot \hat{n}_i - \hat{V}_r \cdot \hat{n}_r}{\lambda},
\]
\(\text{(3)}\)

where \(\hat{f}_D\) is the Doppler frequency shift related to the specular reflection point, \(\hat{V}_i\) is the transmitter velocity vector, \(\hat{V}_r\) is the receiver velocity vector, \(\hat{n}_i\) is the incidence direction unitary vector, \(\hat{n}_r\) is the scattering direction unitary vector, and \(\lambda\) is the electromagnetic wavelength. Considering the maximum relative radial velocity among a ground fixed point and an orbiting GPS space vehicle, the minimum range of Doppler frequencies that the receiver has to be able to compensate for is \(-5 \text{ kHz} < f_d < 5 \text{ kHz}\) (Tsui, 2000).

The implemented griPAU signal processor is embedded in a Xilinx Virtex 4 FPGA device using the VHDL hardware description language. The size of the computed DDM is limited by the available hardware resources. This implies that the Doppler shift of the received signal, as well as the time delay of its code have to be a-priori known so as to center the computing window around the DDM peak. The total number of correlators that can be implemented with the available resources not only determines the final DDM size, but also its resolution, as it will be discussed in detail in Section 2.3.

The implemented architecture has a total of three signal paths: one chain for the reflected signal and two for the direct signal to estimate the Doppler shift and time delay. A Trimble GPS receiver is used to obtain the Doppler shift of the direct signal, as well as other geometry parameters such as the elevation and azimuth of the satellite to be tracked. However, the estimated time delay from the commercial GPS is not precise enough, and it is not updated frequently enough to keep track of the reflected signal. The time delay is then estimated from the direct signal by means of a circular cross-correlation algorithm, Eq. (4), implemented in the signal processor.

\[
R_{sd,a} = IFFT(FFT(s_D) \cdot FFT^*(a)),
\]
\(\text{(4)}\)

where \(s_D\) is the direct signal down-converted to baseband and with the Doppler shift corrected. Using a circular cross-correlation based algorithm has the main advantage that it works in a continuous single acquisition state so no extra time is needed prior to starting the signal’s delay. This allows the estimator to get locked very fast and quickly recovers if it gets unlocked. Other approaches, such as the early-prompt-late correlation algorithm (Tsui, 2000) require an acquisition state prior to tracking which can last too much for the presented application. Nevertheless, these other approaches demand more hardware resources to implement the required control logic.

Once the time delay and Doppler shift of the direct signal are known, these parameters are used to center the
DDM window in the \((\tau, f_D)\) domain. Then, according to the DDM size and resolution, the \((\tau, f_D)\) coordinates are specified in samples and Hz. The coordinates of each bin are used to generate a set of signals which are local replicas of the baseband C/A code with the corresponding time delays and Doppler shifts. These signals are correlated with the down-converted reflected signal so as to obtain the resulting DDM (Marchan-Hernandez et al., 2008a).

2.2. Antenna and RF front-end

The selection of the down-looking antenna is a trade-off between directivity and beamwidth. On one hand the directivity must be high enough so as to increase the SNR, and on the other hand the beam must be wide enough so as to observe the whole glistening zone (i.e. area from where there are significant contributions of the scattered power disregarding the effect of the antenna pattern). When making the design, the extent of the glistening zone (defined as the surface area that contributes to the scattered power above 3 dB below the specular reflection point contribution) for a height of 400 m, and a moderate wind speed of 10 m/s has been estimated to have a diameter on the order of 200 m which lead to a beamwidth around 20°.

The down-looking antenna has to be left hand circularly polarized (LHCP) as it is the main polarisation of the transmitted right hand circular polarized (RHCP) signal after scattering on the surface. The antenna used in the implementation of griPAU is an array of hexagonal 7 LHCP microstrip patches. This antenna has a measured beamwidth of 22°, a main beam efficiency of 90.5% and a gain of 16.2 dB (Fig. 2).

To avoid the modulation of the measurements by the antenna radiation pattern as the GPS satellite moves, the antenna down-looking is mounted on an automatic positioning system that performs a dynamic tracking of the specular reflection point over the observation surface. This effect is observed in Fig. 3(top) where the antenna was still and the measured DDM peak for different satellite passages is represented as a function of the elevation angle. Moreover, in Fig. 3(bottom) the antenna has been pointed towards the specular reflection point when the satellite elevation was 26° and kept fixed during the capture. It is seen how the DDM peak, which is proportional to received power, decreases to half its maximum value (i.e. \(-3 \text{ dB}\)) as elevation goes down from 26° to 15° which corresponds to a movement of half the beamwidth from the antenna boresight.

Once the direct and reflected signals have been collected, they are amplified, filtered, down-converted, and sampled. The receiver used in griPAU is the one that has been developed in the frame of the PAU project (Ramos-Perez et al., 2006). This receiver has two chains with 120 dB gain, 2.2 MHz bandwidth, and the output signal is centered at an intermediate frequency of 4.309 MHz, and the sampling frequency is 5.745 MHz.

2.3. Signal processor

The griPAU instrument signal processor (Fig. 4) has been designed and implemented using the digital hardware resources of a Xilinx Virtex 4 FPGA. The design has been carried out to achieve two main objectives: (1) to take the maximum benefit of the available resources, and (2) to keep a strict control of all the timing and synchronism rules so as to implement a system as stable as possible.

A high level block diagram of the signal processor implemented for the griPAU instrument is shown in Fig. 5. The griPAU signal processor has three signal paths: two for the direct signal and one for the reflected. One of the direct signal chains is connected to the Trimble GPS receiver to obtain the signal’s Doppler frequency offset. The second direct signal chain is used by the signal processor embedded in the FPGA to estimate the signal’s delay after the RF front-end, sampling and demodulation. Once the delay and Doppler offsets are known, the DDM generator core uses the demodulated and sampled reflected signal to compute the Delay-Doppler Map. Since the FPGA clock frequency is much higher than the sampling frequency, hardware reuse techniques can be used to dramatically reduce the hardware resources needed.
or alternatively, to increase the size of the computed DDM with the same hardware resources.

The up- and down-looking signal paths to be processed are conditioned and sampled at 8 bits with a sampling frequency of 5.745 MHz. Since the IF is 4.309 MHz, band-pass sampling can be used, and the signal is centered at a digital frequency of 0.25. At this digital frequency the tones needed to I/Q demodulate the input signals can be expressed using only two bits and the digital I/Q demodulation can be performed very efficiently by using simple logical functions instead of multi-bit multipliers (Marchan-Hernandez et al., 2008a).

Once the signals have been I/Q demodulated, a digital low-pass filtering stage has been implemented to eliminate undesired high frequency components. This filter has also been designed to use the lowest possible amount of resources. To achieve that, an IIR filter topology with only power of two coefficients has been designed so that multiplications and divisions are transformed into left-shift and right-shift operations avoiding again the use of resource-consuming multipliers and dividers (Bosch-Lluis et al., 2006). At this point the main processing starts. To take advantage of hardware reuse techniques, the data acquired during a basic integration time (1 ms) is stored, so it can be read several times. The main blocks that allow this technique to be successfully dealt with, are the control unit and the data buffer (Fig. 5).

The hardware control unit is based on a finite states machine (FSM) built to replace the software control used in previous versions to have a tight control of the timing of the hardware reuse technique. One fourth of the complete DDM is computed at a time, and using the same hardware, the four DDM quadrants are serially computed during four time slots. All this process takes place in 1 ms which is the duration of the C/A code and the basic integration time. Replacing the software control unit by a FSM has improved the synchronization of the four quadrants allowing to increase the size of the DDMs significantly (from $16 \times 16$ to $24 \times 32$ bins in the Virtex4 implementation) leading to a more stable system. Fig. 6 shows two DDM captions: in the first one a synchronism problem has occurred, while in the second one, computed with the described architecture, all the DDM parts are always perfectly aligned due to the high reliability of the hardware synchronism of the control unit.

Also a new data buffer has been implemented to avoid memory swapping and minimize timing problems. This new buffer is based on a dual-port RAM memory which

![Fig. 3. (Top) Antenna pattern modulation for different satellites vs. elevation angle. (Bottom) DDM maxima is modulated by the antenna radiation pattern when the antenna is kept in a fixed position. Quick oscillations are due to multi-path in the cliff and geophysical variability of the observables.](image)

![Fig. 4. griPAU signal processor.](image)
has a depth twice the size of the I–Q data sampled in 1 ms. With this implementation, the memory is divided in two zones, so when one half is written by the writing port, the data stored in the other half is read by the reading port and processed. Each millisecond the two halves exchange their roles without any physical memory swapping and data is properly updated.

The delay estimation algorithm has been optimized leading to a reduction of the update time from 16 to 5 ms, allowing griPAU to track signals even in high dynamics scenarios. The delay estimator core is basically the one implemented in previous versions (Marchan-Hernandez et al., 2008a), using a FFT approach, Eq. (4). Due to the zero-padding needed to adapt the number of samples (5745 samples) of the data to the next power of two (8192 samples), two correlation peaks appear. The griPAU implementation has improved this core performance avoiding peak detection errors by applying a threshold to check whether the returned delay is a valid one or if it corresponds to the secondary peak of the cross-correlation. If so, the known distance between peaks (in samples) is subtracted to get the correct delay value.

Fig. 5 shows that the signal processor implements also a microprocessor. In the implementation of griPAU this microprocessor has been relegated just to interface the Trimble GPS, and to perform floating-point operations that would consume too many resources if implemented in hardware. Notice that all the timing and synchronism responsibilities have been transferred to the FSM control unit, for improved robustness in front of the uncontrolled timing of operative systems.

The last block of the griPAU signal processor is the DDM generator core which has remained essentially the same as in previous versions of the instrument (Marchan-Hernandez et al., 2008a). This block generates each of the four DDM parts at a time and is controlled by the control unit so as to implement the hardware reuse.

2.4. Clocking scheme

When designing griPAU, the stress has been put on preserving the phase coherence among all the system’s clocks to prevent undesired decorrelation effects. The clocking policy has been redefined using an oven-controlled 10 MHz stabilized reference (Fig. 7), and the FPGA-built processor has been modified to work with the 103.41 MHz clock (instead of
the original 100 MHz one) which is a direct multiple of the sampling frequency.

The final clocking scheme divides the single 10 MHz stable reference in two branches: one branch is used as the RF front-end reference for the phase-locked loops, and the other one is doubled in order to be the reference of a Direct Digital Synthesis (DDS) device that generates a very accurate 103.41 MHz clock reference for both sampling and processing in the FPGA. The accurate sampling frequency and perfect synchronism avoid artificial delay drifts caused by different chip lengths among the sampled signal and the local replica of the C/A code generated in the processing step, resulting in very high stability.

2.5. Data output

Every 1 ms, griPAU computes one complex DDM of 24 × 32 bins. Each bin is a complex number with its real and imaginary parts quantified with 32 bits, which leads to a total data output rate of 6.14 Mbps. This throughput is delivered to an external PC via an USB interface.

Using a graphical interface executed in the external PC, the user can control the instrument configuration (satellite to be tracked, capture length, etc.) and the computed data can be stored in raw format or further averaged by means of a selectable coherent/incoherent integration times.

3. Instrument performance and trade-offs

3.1. Delay estimation

Relating to the direct signal path used for delay estimation, a study has been undertaken to improve the final estimation error rate (i.e. increasing the signal’s SNR). Sample results of the three approaches tested are shown in Fig. 8. The first delay estimator uses only the in-phase signal (I). The second one uses both the in-phase and quadrature (Q) components of the direct signal to improve its robustness in front of noise, multi-path, as well as preventing signal fading due to phase rotation. This has the drawback of increasing the hardware resources (multipliers) needed if only the in-phase component is used. The third and more efficient approach works with both I/Q components and uses a wide-beam RHCP antenna instead of a single linear polarisation one to improve the robustness of the signal in front of undesired reflections and multi-path.

To validate the improvements implemented in the delay estimation algorithm, real GPS direct signal captures have been performed. Real signal has been used to test the system when all the effects, such as undesired reflections and multi-path, are present. Fig. 8 shows the delay estimation performance as a function of the algorithm implemented. The performance is nearly perfect for the last configuration. It is seen that, if the error rate is defined as the number of errors per number of measurements, it is reduced from 6.7% when only the I component of the signal is processed, down to 1.7% when both I/Q components are processed, using all the signal’s available power, and down to a nearly negligible value of 0.03% when multi-path is avoided by using a RHCP antenna.

The fast linear evolution (two complete code lengths in 1 min) of the delay is due to the inaccuracy of the sampling frequency which causes a difference between the chip lengths of the received signal and the local replica. This artificial delay evolution is overcome when the new clocking scheme is applied as the clock reference given by the DDS allows the signal processor to generate a very accurate sampling frequency. With the ultimate griPAU implementation, only the true delay evolution is observed as in Fig. 9.

3.2. Delay-doppler map size and resolution

Although using a very accurate sampling frequency and avoiding potential artificial delay drifts, the residual difference between the actual sampling frequency and the theoretical one considered at processing, still causes some measurements’ variance due to the variable DDM discrete sampling points (i.e. the delay estimation is not able to distinguish subsample variations).

This effect is deterministic, and the relationship of the final DDM amplitude variation with the resolution is monotonically decreasing, so the variance can be reduced by reducing the DDM cell size in the delay dimension. Also, if the DDMs are not to be truncated, the total DDMs size has to be increased. In the design and implementation of griPAU, the system has been rearranged in order to take advantage of all the FPGA resources, so the total DDM size has been increased from 16 × 16 points up to 24 ×
32 points allowing to compute the DDMs with a delay resolution as low as 0.5 samples (0.09 chips) (Fig. 10), so the measurements’ variance due to shifts in the DDM peak’s position in delay, in amplitude as well as in normalized
DDM volume (see Section 1), is significantly reduced. The relationship among these variances and the delay resolution has been studied.

Using a GPS synthetic signal three series of DDMs have been computed configuring the instrument with three different delay resolution values (2, 1, and 0.5 samples corresponding to, 0.36, 0.18, and 0.09 chips, respectively) while keeping the Doppler resolution constant (200 Hz) (Fig. 11). The effect of variable DDM sampling points is clearly observed, both in the normalized volume and the maximum value when a coarse resolution of 2 samples is used. These values present an evolution between two extreme values which correspond to the DDM sampled at the true maximum and at 2 samples away from it. This effect is reduced when 1 sample resolution is used and it can be nearly neglected when the DDM is computed with 0.5 samples resolution. With this fine resolution, the measurement’s variance is only due to the system’s noise. As it can be appreciated in Fig. 11, the normalized DDM volume and the maximum module present (in a stronger way when using poor resolutions) a kind of “triangular” modulation originated by the linear evolution of the time delay between the true DDM peak and its adjacent sample.

3.3. Instrument’s sensitivity and stability

When operating in the normal mode, 1 s incoherently integrated DDMs are measured. Setting the DDM resolu-

Fig. 10. Sample 24 × 32 points, 0.09 chips resolution, 1-ms DDM measured over the ocean surface from a 302 m height.

Fig. 11. DDM normalized volume vs. DDM resolution measured using a synthetic GPS signal to avoid multi-path and other error sources: (top) Δτ = 2 samples (0.36 chips), (center) Δτ = 1 sample (0.18 chips) and, (bottom) Δτ = 0.5 samples (0.09 chips).

Fig. 12. DDM 1-s incoherently integrated (top) volume (relative error = 0.03%) and, (bottom) peak module (relative error = 0.9%).
tion to 200 Hz in Doppler and 0.5 samples (0.09 chips) in delay, the measurements (Fig. 12) have a very small standard deviation (0.9% of the DDM peak value and 0.03% of the normalized DDM volume – maximum value equal to one, units [chips · Hz]). This error determines the reflectometer’s sensitivity (i.e. the minimum DDM peak or normalized DDM volume variations that can be detected or measured by the instrument).

In order to evaluate the system’s performance concerning the correlation time of the coherently integrated measurements a synthetic GPS direct signal has been used. As this signal is simply a GPS C/A code up-converted to RF, its correlation with the local replica should be constant. However, system inaccuracies and noise cause some residual decorrelation of the measured DDMs when coherent integration is performed. To evaluate this parameter (i.e. DDM decorrelation time due to the instrument), the evolution of the DDM’s maximum is studied. Results are shown in Fig. 13. For instance, if the time that the measurements decorrelate to a 90% of the maximum is considered, the instrument can perform coherent integration up to 100 ms (Fig. 13). Taking into account that at L-band the sea correlation time is estimated to be of the order of tens of milliseconds (Chapman et al., 1994), the griPAU can be used to the study of physical phenomena of the sea surface that require coherent integration or phase information. This is a significant improvement result of the large effort carried out in the system’s synchronism, sampling frequency accuracy, and improved clocking scheme.

4. Sample measurements

The griPAU instrument has already been used in two field experiments (Fig. 14): the Advanced L-Band emissivity and Reflectivity Observations of the Sea Surface 2009 (ALBATROSS 2009) over the ocean in Gran Canaria (Canary Islands, Spain) (Valencia et al., 2009) and GPS and RAdiometric Joint Observations (GRAJO) (Monerris et al., 2009) over land (Vadillo de la Guaren̳a, Zamora, Spain). Over the ocean griPAU has been used to study the derivation of sea roughness from GNSS-R measurements, and how to correct the sea state effect on the brightness temperature measurements acquired by an L-band radiometer (Valencia et al., 2009). Over land, griPAU has been used for soil moisture retrieval in conjunction with the SMIGOL reflectometer (Rodriguez-Alvarez et al., 2009) and also with the LAURA radiometer (L-band AUtomatic RAdiometer) (Camps et al., 2004b). However the raw data from this last experiment has not yet been completely processed.

In order to illustrate the griPAU instrument performance given in this paper, some relevant sample measurements related to the instrument performance are shown. The presented measurements correspond to the basic observable computed by griPAU which are 1-ms coherently integrated complex DDMs.

Fig. 15 shows a histogram of the DDM maximum module resulting from a 60 s capture of 1-ms complex DDMs (60,000 complex DDMs) taken during the ALBATROSS 2009 field experiment (Valencia et al., 2009). The main
observation scenario parameters for this capture were: a height of 382 m, an elevation angle of 26° and a WS of 2.1 m/s. As it can be seen, this histogram presents a Rice behaviour (Rice parameters: $A = 3.5 \times 10^5$ and $\sigma = 2 \times 10^5$) which is the probability density function expected for a GPS signal scattered over a sea surface when a coherent contribution from the first Fresnel reflection zone is present.

For the same capture, a detail of the phase of the DDM maximum (i.e. the phase of the coherent contribution to the scattering process) is plotted in Fig. 16. It can be noticed that this phase exhibits random $\pi$-rad phase jumps at multiples of 20 ms. These phase jumps are due to the polarity inversion of the navigation bit (Eq. (2)), showing the excellent sensitivity of the griPAU instrument, which is able to detect the navigation bit even when processing the reflected GPS signal over the ocean surface.

5. Conclusions

Emerging GNSS-R remote sensing techniques have brought out the need of implementing adequate and robust receivers. In this paper the design and implementation of the GPS Reflectometer Instrument for PAU (griPAU) is presented, as well as some relevant measurements showing its performance.

The griPAU computes high resolution complex Delay-Doppler Maps in real-time. The computed DDMs are $24 \times 32$ points with configurable resolution as well as selectable coherent (minimum = 1 ms, maximum = 100 ms for correlation loss $\Delta \rho < 10\%$) and incoherent (minimum of one coherent integration period and not limited maximum, typically <1 s) integration time. Its design has focused on achieving an extremely stable and sensitive instrument making the best use of the digital hardware resources of a FPGA, and taking exquisite care of synchronism and phase coherence. Concretely, the stability of the instrument allows to coherently integrate up to more than 100 ms (correlation loss $\Delta \rho < 10\%$) which is much longer than the ocean’s correlation time at L-band, thus enhancing the system to perform deeper studies about the ocean. Moreover, the achieved instrument’s sensitivity (DDM peak relative error = 0.9% and DDM volume relative error = 0.03% @ $T_i = 1$ s) will improve the quality of the results for geophysical parameters retrieval.

This implementation has resulted in a fully operational real-time complex DDM GNSS-R instrument that has already been used in field experiments over sea and land, with very promising results.

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