Water Surface Altimetry from GNSS Reflected Signals: System Description and Results

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Abstract: The use of Global Navigation Satellite System (GNSS) signals reflected off the ocean's surface as a way to derive geophysical parameters, such as altimetry, was first proposed in 1993. Since then, the number of GNSS satellites transmitting signals of opportunity for reflectometry has vastly increased, and are now capable of providing spatial and temporal resolutions which will allow studying ocean related processes in a way that was not possible before.

Deimos, Engenharia is currently developing a GNSS Reflectometry (GNSS-R) system called SARGO – System to Acquire Reflected GNSS Signals for Oceanography, which will allow obtaining water surfaces altimetry from a ground-based instrument. The SARGO system includes the hardware (instrument), software, which includes a mission planning tool, an orchestrator system, data processors (with three processing levels, according to the European Space Agency's (ESA) specifications for Earth Observation Missions) and an analysis and control tool.

This paper presents and compares results obtained in two different field tests, where two different signals were observed: Galileo E1 and E5a. The field tests were carried out at Padrão dos Descobrimentos and the Marina of Parque das Nações, in Lisbon.

The results demonstrate the feasibility of GNSS-R, with accuracies in the order of 1.5 m for E1 signal and of 0.20 m for E5a signal after 1 s averaging, and a small constant bias relative to the ground truth. These results show the promising features of the new GNSS signals, and can further be improved by using AltBOC modulation. It is expected to obtain improved results by using longer acquisitions and averaging times.

1. Introduction

The Global Positioning System (GPS) and, more recently, the Global Navigation Satellite System (GNSS) were originally developed for navigation and positioning purposes. However, new applications have been developed which use the GNSS signal for different purposes, due to its particular properties. Some of those applications even take advantage of what would, otherwise, be considered an error source, as a source of opportunity to study properties of the Earth's surface or atmosphere. GNSS Reflectometry (GNSS-R) is an example of a technique that uses a typical GNSS error source, the multipath, as a way to infer geophysical parameters of the Earth's surface.

GNSS-R was first proposed by Martin-Neira (1993) as a low cost and effective way to improve and densify remote observations of the ocean surface for altimetry purposes. If a GNSS receiver could be able to receive both the signal travelling directly to an upward looking antenna and the reflected signal bouncing off the earth's surface onto a downward looking antenna, it would be possible to estimate the difference in delay between both signals and use that measure to obtain geometry and altimetric measurements of the water surface.

When compared to other techniques, such as dedicated remote sensing satellites, GNSS-R has the additional advantages of being potentially able to offer higher spatial and temporal resolutions at significant lower costs than these dedicated instruments. Jin et al. (2014) demonstrate that a GNSS receiver aboard a Low Earth Orbit (LEO) Satellite is capable of collecting reflected measurements of the almost the entire surface of the earth in one day.

However, due to the fact that it is very hard to carry out GNSS-R observations using phase information, since the surface roughness causes a loss in phase coherence, the accuracy of the observations is currently significantly lower than other techniques, and many studies are focusing in ways to improve results.

Deimos, Engenharia is currently project leader of E-GEM, an FP7 project which aims to help understand geophysical processes, not only of the ocean surface, but also for biomass and ice fields. Deimos, Engenharia is responsible for developing a GNSS-R ground system, which includes hardware, processing software, data analysis and dissemination. This system is called SARGO (System to Acquire Reflected GNSS signals for Oceanography).

The current article shall present the main results obtained with SARGO, as well as its current status and expected future evolution of the system. For this purpose, two different field tests shall be presented, one carried out at Padrão dos Descobrimentos, in Lisbon, using Galileo E1 signal and the other taken at the marina of Parque das Nações, which used the new Galileo E5a signal.

The noise figures for the different signals shall be presented, as well as the difference between the observed results and tide data generated from harmonic analysis models generated by the Faculty of Sciences of the University of Lisbon (FCUL), where the method of tide agreement was applied using values published by the Hydrographical Institute (IH), and the meteorological super-elevation was also taken into account, which shall be considered the ground truth.

2. General Concepts

GNSS-R works as bi-static radar, in which the transmitter and the receiver are separated by a significant distance, comparable to the expected distance to the target (Jin et al., 2014). The GNSS signal transmitted by the satellite can either travel directly to the receiver or be reflected off the Earth's surface.

A typical GNSS receiver tracks signals by correlating the incoming signal with a local replica, which results in an autocorrelation function (or waveform) such as the ones depicted in Figure 1. This also applies to the reflected signal, although the waveform for the reflected signal has a longer code delay due to the longer path it travels until it reaches the receiver. For this reason, the direct and reflected waveforms are one of the main observables of GNSS-R. Other observables are presented by Jin et al. (2014).

The error sources that affect GNSS-R observables are the same that affect typical GNSS measurements. However, due to the fact that we work with delay differences, most of these errors will cancel out, except for antenna related error, which affect the two antennas differently, multipath and a residual tropospheric delay originated by the reflected signal crossing a part of the troposphere twice. This statement is only applicable to ground-based receivers, since for spaceborne receivers the reflected signal also crosses part of the ionosphere twice.

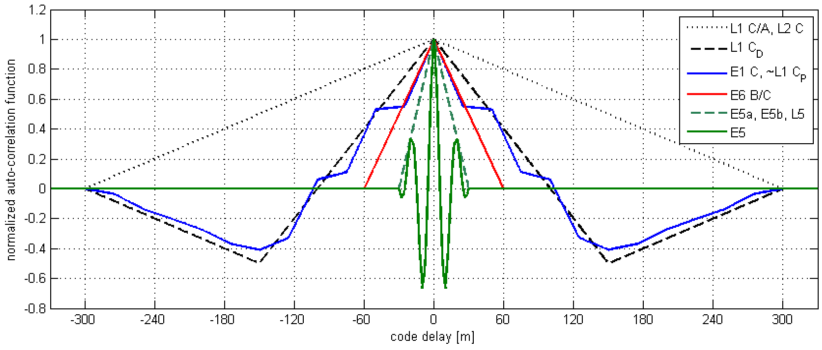


Figure 1 – Auto-correlation function or waveform for different Galileo modulations

Figure 2 demonstrates the geometry involved in a GNSS-R reflection for a ground-based instrument. The knowledge of the GNSS-R instrument position and the delay between the reflected and direct signals allows us to derive the altimetry of the specular point of reflection (the point which minimizes the distance travelled by the reflected signal).

After estimating the delay, $\boldsymbol{\rho}$ for each signal, their delay differences are given by:

$$\Delta\rho = \rho_{reflected} - \rho_{direct} \tag{1}$$

According to Jin et al. (2014), for a ground-based instrument, the curvature of the Earth can be ignored and the delay difference depends on the position of the specular point, which can be expressed as:

$$\Delta\rho = 2h\sin(\theta) \tag{2}$$

Consequently, Equation 2 allows us to determine $\boldsymbol{h}$**,** which is the height between the receiver and the reflecting surface based on the value of the satellite elevation when the reflection was originated, $\boldsymbol{\theta}$.

In order to obtain the final surface altimetry in a reference frame comparable with the tide model (which is the chart datum) one must make the proper conversions, based on Figure 2.

If we look at the diagram from Figure 2, where $\boldsymbol{h_{ell}^{rx}}$ is the ellipsoidal height of the receiver, $\boldsymbol{h_{sea}^{rx}}$ is the height difference between the receiver and the sea surface (derived from Equation 2), $\boldsymbol{h_{ell}^{geoid}}$is the geoid undulation (commonly described as $\boldsymbol{N}$and $\boldsymbol{h_{cd}^{geoid}}$is the difference between the geoid and the Chart Datum, which is equal to 2.08 m for the Lisbon and Tagus Estuary region (Antunes, 2012), the sea surface height referenced to the chart datum is then obtained by applying Equation 3.

$$h_{cd}^{sea} = h_{ell}^{rx} - h_{sea}^{rx} - h_{ell}^{geoid} + h_{cd}^{geoid} \tag{3}$$

3. Deimos GNSS-R System

3.1GNSS-R Instrument

The SARGO instrument is composed of several sub-components:

- A right-hand circular polarized (RHCP) antenna responsible for receiving direct GNSS signals (Figure 4)
- A left-hand circular polarized (LHCP) antenna responsible for receiving reflected GNSS signals (Figure 4)
- A multi-channel Radio Frequency (RF) Front-End (FE) capable of receiving, down-converting and digitizing GNSS signals (Figure 3)
- A commercial GNSS receiver (RX) which provides the navigation solution for the GNSS instrument
- An RF switch (RFS) responsible for swapping the RF signals fed to each RF channel for calibration purposes

- A Baseband Receiver (BRX) in charge of the digital signal processing, including acquisition and tracking of the direct signal and generation of the correlation waveforms for the direct and reflected signals. The BRX is also responsible of the RF switch control.

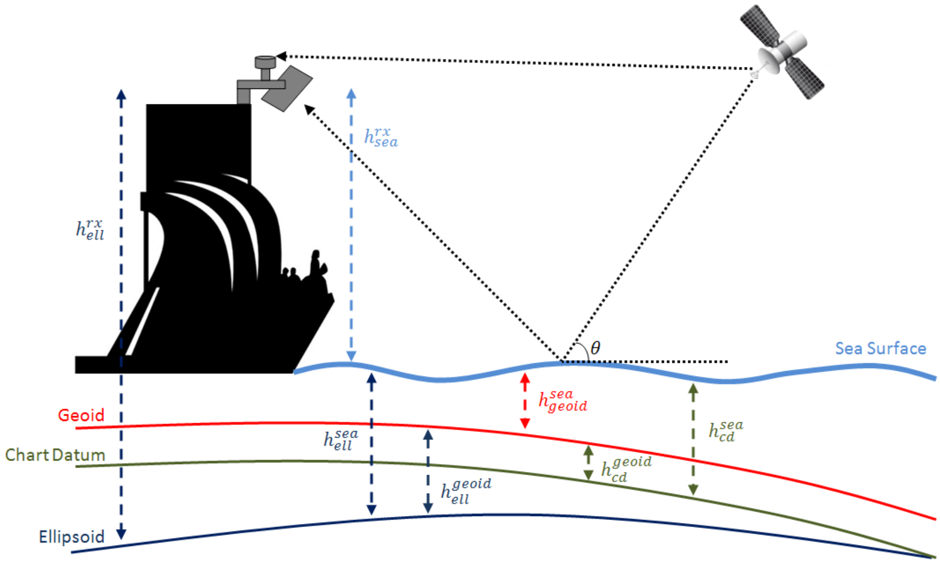


Figure 2 – GNSS-R Geometry, Reference surfaces and their relationship

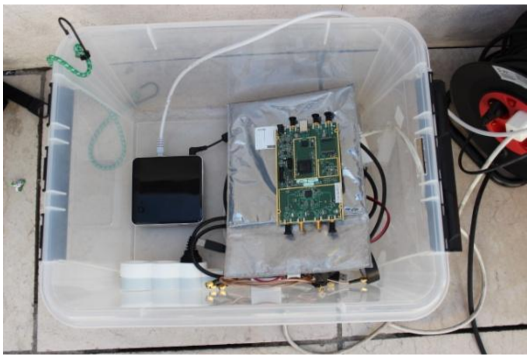


Figure3 – The processing unit and RF FE of the SARGO Instrument

Figure4– Upward and Downward looking antennas of the SARGO system

The main observables generated by the GNSS instrument are the direct and reflected correlation functions, as well as information on their acquisition time. The data generated at this stage is stored in binary products that are used as an interface between the instrument and the processors.

3.2 Data Processors

The processors for the SARGO system include the Geometry Analysis Tool (GAT-MP), the SARGO Orchestrator System (SOS) and the SARGO Data Processors.

The GAT-MP is the mission planning tool, which generates the planned acquisition schedule based on the geometric prediction of the ground coverage footprints for the SARGO instrument, obtained from an analysis of the valid specular points available in the area to be observed by the receiver.

The SARGO Orchestrator uses the acquisition schedule to control the data acquisition by the SARGO Instrument and the data processing done by the SARGO processors.

The SARGO processors have been designed according to ESA's Earth Observation missions specifications, i.e., and are divided into three levels according to what they are responsible for: Level 0 for conversion of the binary products to NetCDF format, Level 1 for calibration, time conversion and calculation of positions of specular points and Level 2 for derivation of geophysical parameters relevant to the mission or project.

3.3 Data Analysis and Control

The SARGO Analysis and Control System (SACS) is being developed to test new algorithms, validate existing algorithms and generate data plots for a visual assessment of results. It consists of a Graphical User Interface (GUI) (Figure 5) where several parameters can be defined based on the desired output.

SACS uses information from the instrument's raw binary products to estimate noise and assess the presence of errors, the data from L1 processor to compute the altimetry and compare with ground truth data and the data from the L2 processor for visualization and validation purposes.

The processing workflow implemented in SACS consists of:

1. Peak estimation of the waveforms,
2. Filtering (Signal-to-Noise Ratio filtering, outlier removal, running averages, etc.),
3. Noise, Delay or Altimetry estimation,
4. Data visualization (plots for SNR, noise, altimetry, etc.).

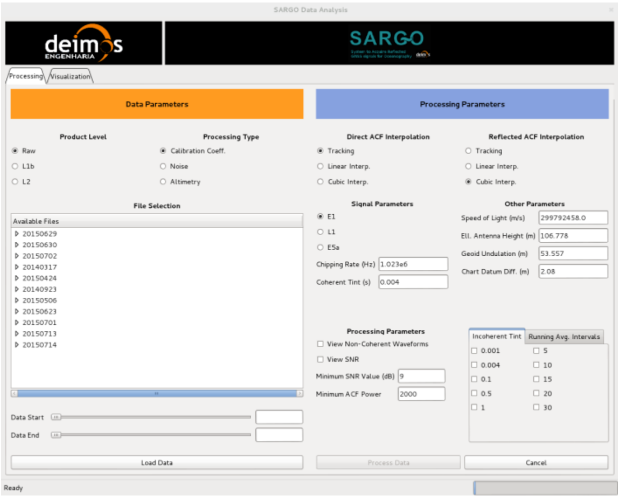


Figure 5 – SARGO Analysis and Control System main window

4. Field Tests

Currently the main SARGO field tests are being carried out at Padrão dos Descobrimentos (Lisboa) (Figure 6), with some specific field tests taking place at the Marina of Parque das Nações (Lisboa) (Figure 7). The main results presented here were obtained on the 23rd of June of 2015 at the Marina (named FT-009), where observations using the Galileo E5a band were made, and is composed of three acquisitions. These results will be compared with results obtained at Padrão dos Descobrimentos on the 17th of March of 2014 (named FT-004), where Galileo E1 signal was captured, composed of ten acquisitions.

Although, ideally, the different signals should be compared in the same observational conditions (location and instrument), at the time of writing of this paper there were no concurrent measurements with both signals. It is expected that with new field tests these measurements are carried out and compared. However, we don't expect a significant difference in the results.

Figure 6 – Padrão dos Descobrimentos, in Lisbon

Figure 7– Parque das Nações marina setup

5. Test Results

An example of the observed waveforms for FT-004 and FT-009 can be seen in Figures 8 and 9, respectively, with the respective interpolation used for peak estimation purposes.It must be noted that in Figure 8 the two waveforms are farther apart than in Figure 9, which is a result of the higher height difference between the receiver and the surface.

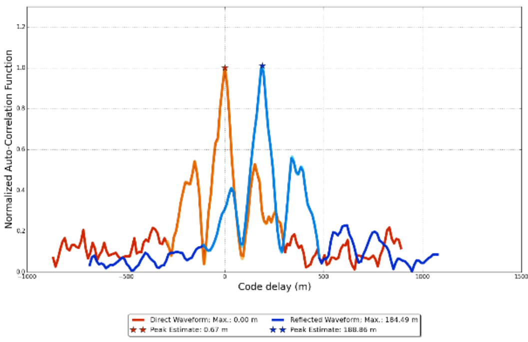


Figure 8 – Direct and reflected waveforms for E1 signal (BOC modulation)

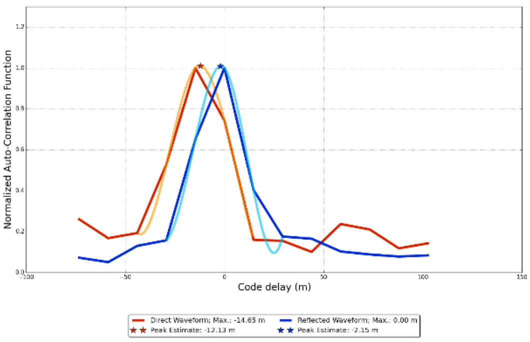


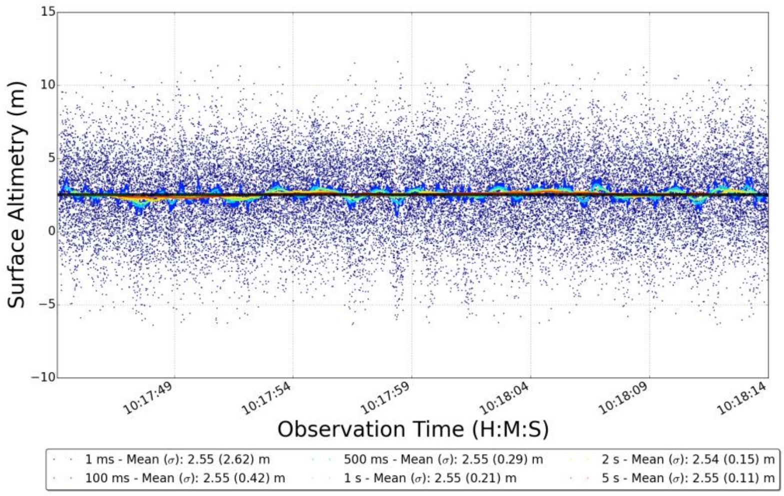
Figure 9 – Direct and reflected waveforms for E5a signal

Due to the increased chipping rate of the E5a signal, there are far less correlators defining the waveform. However, the base of the waveform crest is also ten times thinner than for E1. From Figures 8 and 9 one can easily comprehend how the delay differences are determined.

The altimetry for two acquisitions with E5a signal can be seen in Figure 10, where filtering was applied and outliers were removed, with the truth data represented by the black line.

In both plots it can be seen that the difference to the theoretical water level is very low. Besides depicting the overall water level, a closer look at the behavior of the averaged data reveals slight variations in the water level, which can occur for two reasons: multipath or small surface waves. In order to confirm this statement, further measurement sources would be necessary (such as a pressure transducer), which would be capable of detecting higher frequency variations such as the ones mentioned above.

Based on results presented by Castro et al. (2014) and Mendes et al. (2015) using Galileo E1 signal, the results obtained with E5a signal are significantly better (approximately five to six times better when no averaging is considered), which is expected due to the aforementioned properties of the E5a signal. Table 1 presents a summary of the results, where the standard deviations for non-averaged and 1 s averaged data are shown. Using E5a signal it is possible to achieve accuracies in the order of 20 cm after averaging for 1 s. Furthermore, the difference relative to the ground truth is also significantly smaller than using E1 signal, and the cause of this must also be assessed with new observations.



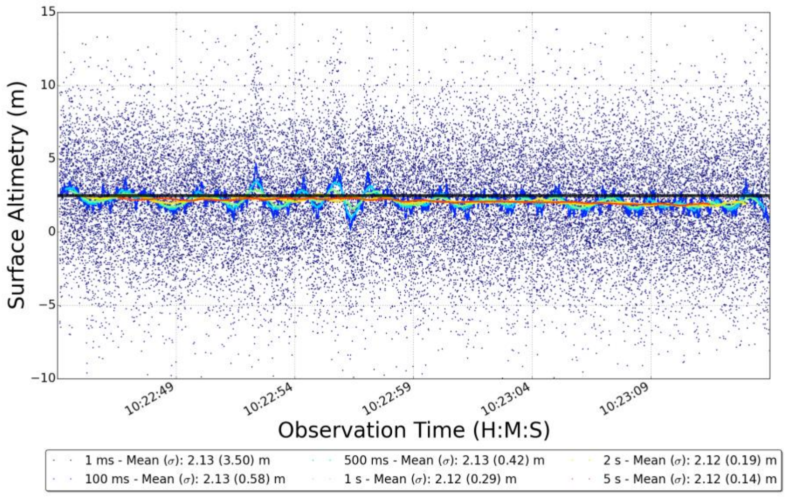


Figure 10 – Delay differences for two FT-009 acquisitions (Marina) with multiple averaging intervals applied

Table 1 – Comparison between observations obtained at different field tests with different signals. For FT-009 two acquisitions are presented.

Field Test	$\sigma_{\Delta\rho}$ (m)	$\sigma_{\Delta\rho}$ (m) 1 s Avg.	σ_{height} (m)	σ_{height} (m) 1 s Avg.	Mean Bias (m)
FT-004 (E1)	11.86	1.42	11.74	1.14	-1.94
FT-009 (E5a)	2.35	0.19	2.62	0.21	-0.36
	2.99	0.25	3.50	0.29	-0.77

6. Conclusions and Future Work

In the current paper the first altimetry results for Galileo E5a signal using the SARGO instrument were presented. The higher chipping rate of the E5a signal (ten times the E1 chipping rate) results in an increased accuracy of approximately five to six times better than the results already obtained with E1 signal.

Although the results obtained from E1 observations are in agreement with other studies, which are summarized by Jin et al. (2014), and present an accuracy between 1 m and 2 m in the best cases, the E5a observations resulted better code-based altimetry results, which proves the added improvement of this signal.

The presented results show that the newly available GNSS signals are capable of achieving a good accuracy for code based altimetry which enables the usage of GNSS-R as a technique to estimate the sea surface altimetry. If the full E5 signal is also used (instead of the E5a), it is expected that the accuracy of the results improve up to four times. This could be essential to overcome the accuracy problems of GNSS-R systems by not being able to use phase altimetry.

It is not certain that the observed bias is due to errors in the GNSS-R observations or due to the fact that the ground truth is based on a general model, not reflecting the actual conditions of the water level, which should be confirmed by installing other *in situ* equipment. If the bias is still present, one should improve the waveform modeling technique or determine calibration parameters based on the roughness conditions of the surface.

It is still not possible to detect and interpret the slight features present in the data. However, it is expected that the SARGO instrument is permanently installed on top of the VTS tower in Lisbon, allowing longer acquisitions. Moreover, the installation of a video camera and meteorological equipment should aid in understanding the surface state at the moment of acquisition.

Furthermore, it is expected that a pressure transducer will be installed near the field test site, which will yield the new true water level and be capable of sensing the slight variations in the water level, improving the analysis of the results.

New interesting applications for SARGO may also arise, which have already been proven to work, such as Significant Wave Height detection or sea surface winds.

Although still in early stages of development, the GNSS-R technique should be able to complement the available instruments for measuring the sea surface height, and aid in the management of sea level rise related risks, particularly in coastal regions, where satellite altimeters have problems in retrieving data. With measurements referenced to WGS84 ellipsoid, GNSS-R can also provide important data for calibration of other instruments, such as tide gauges or satellite altimeters.

Acknowledgements

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