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OCEANPAL®, A GPS-REFLECTION COASTAL INSTRUMENT TO MONITOR SEA-STATE

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ABSTRACT

Global Navigation Satellite Systems (GNSS, such as the GPS and GLONASS constellations) and their augmentation systems (WAAS, EGNOS) constitute premium sources of opportunity for passive remote sensing. By 2010, after the deployment of the European Galileo constellation, more than 50 GNSS satellites will be emitting self-calibrating, dual-frequency, rain-immune, L-band spread spectrum signals, with long-term availability and stability.

The use of GNSS reflections (GNSS-R) for sea-surface monitoring is a bistatic radar technique only requiring a receiving system. The concept has already been implemented from coastal platforms (few tens of meters above the water), effectively demonstrated from aircraft and balloons (1 km to 40 km) and successfully proved in space (LEO, orbiting at 500 km). The potential applications include sea-surface altimetry, sea-state, surface roughness, surface currents and salinity, both for scientific and operational oceanography.

In this paper, we discuss *Oceanpal®*, Starlab's GNSS-R instrument for coastal applications. *Oceanpal®* features two antennas: one RHCP, zenith-looking antenna collects the direct GPS signal while one LHCP, nadir-looking antenna recovers the reflected signal. Each antenna acquires simultaneous data bursts of some minutes which are sampled at 16 MHz and recorded. The data is then fed into the *Oceanpal®'s* processor, *Starlight*, which retrieves both the direct and reflected complex electromagnetic fields (Level 0 products).

Presently, *Oceanpal®* can deliver two products. The fist one is the antenna height over the reflecting surface. This is measured by analyzing the phase delay between the reflected and direct signal. The precision of this measurement is of the order of 1 cm after 2 minutes in calm waters (e.g., inside a harbour or a lake). In rough waters, estimation is based on code ranging, thus performance degrades to e.g., ~40 cm using the GPS C/A code, but will improve significantly with more precise GNSS codes. The second one is the significant wave height, based on an estimation of the reflected signal coherence time which is linked to sea-surface surface motion. Coherence time can be related to SWH with a precision of the order of 20 cm using a semi-empirical algorithm adapted to the coastal region of interest. These products are then stored in the data management unit which also acts as a web server to provide the information to any remote user via a web browser interface.

Introduction

Coastal management is nowadays a wide-ranging issue, with enormous social and economic impact. It implies dealing with sudden threats such as storm surge and flooding, but also with slow processes such as coastal erosion and conflicting land use issues. In fact, the coastal zone is a peculiar environment in which terrestrial, oceanic, atmospheric, and human inputs of energy and matter all converge. Storm surges and coastal flooding events have caused considerable damage and economic loss on European coasts. Such events, possibly linked to the world climate change, are expected to get worse in the near future, due to increasing sea levels and storm activity.

Coastal areas support the greatest concentration of living resources and people on the planet. These regions of the world have experienced explosive increases in population density and it is projected that by the year 2025, 75% of the world's population will live within 190 kilometres of the coast. Conflicts between commercial interests, recreational activities, infrastructure development, environment conservation, and exploitation of natural resources will become increasingly contentious, politically and legally charged, and a mismanagement of these issues may be very expensive in terms of economic and social cost.

This brief description highlights the need for coastal monitoring systems able to cope with these monitoring needs, that is characterized by a relatively low cost, low maintenance and easy deployment, in order to be available to the widest possible user community.

The Oceanpal® instrument is Starlab's answer to this need. Oceanpal® is a GNSS-R based sensor for operational coastal monitoring. It is an inexpensive, all-weather, dry and passive concept which can be deployed on multiple platforms, static (coasts, harbours, off-shore), and slowly moving (boats, floating platforms, buoys). In its present form, Oceanpal® can deliver two kinds of Level-2 products: sea-surface height and significant wave height (SWH).

Global Navigation Satellite Systems (GNSS, such as the GPS and GLONASS constellations) and their augmentation systems (WAAS, EGNOS, MSAS) constitute the best source of opportunity signals for passive remote-sensing in L-band. After the deployment of the European Galileo constellation, more than 50 GNSS satellites will be emitting multi-frequency, L-band signals, with long-term availability and stability.

The use of GNSS reflections (GNSS-R) for sea-surface monitoring is a bistatic radar technique only requiring a receiving system. The concept was initially proposed by M. Martin-Neira in 1993 [1] and has, since then, been successfully implemented in coastal receivers, in aircraft and recently in space ([2]-[10]). Potential applications of this concept include sea-surface altimetry, sea-state, surface roughness, surface currents and salinity, for both scientific and operational oceanography.

In the next section, the Oceanpal® instrument is described. Next, algorithms are presented and subsequently examples of experimental campaigns are discussed, together with results. In the last section, a set of conclusions is drawn.

Instrument architecture

Oceanpal® comprises three subsystems: a radio frequency (RF) section, an intermediate frequency section and a data processing section. The RF section features a pair of low gain L-band antennas. An RHCP zenith antenna collects the direct GNSS signals while an LHCP nadir antenna collects the sea-surface reflected GNSS signals. Data bursts of some minutes are acquired from each channel using two radio frequency receivers that down-convert the signal to

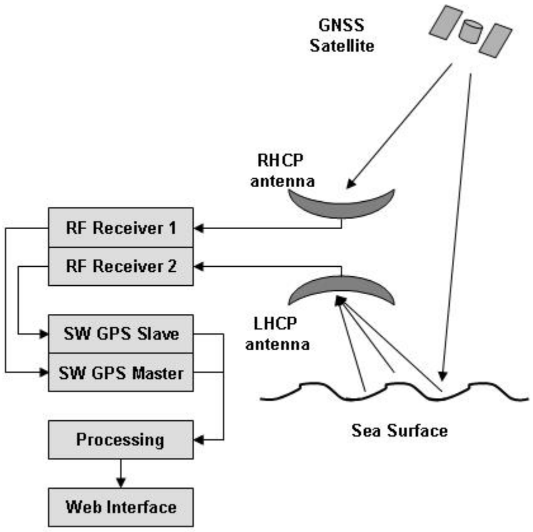


Fig. 1: Principle of the GNSS-R based sea surface monitoring.

intermediate frequency. Within the IF section, the signal is one-bit sampled and stored on a hard disk.

These direct and reflected raw data are then fed into the processing section of the instrument where a pair of software GNSS receivers detect and track the available signals in the direct channel (which works as master) and blindly despreads the reflected signals in the reflected/slave channel. The result of this processing is a set of direct and reflected electromagnetic field time series for each satellite in view, plus some ancillary information, such as the PRN numbers and GPS time references, among others. This architecture is illustrated in Figure 1.

Oceanpal® is characterised by a very low maintenance requirement, when compared to other current instruments measuring significant wave height or sea level. Oceanographic buoys which use accelerometers and magnetic compass or GPS buoy are in contact with the sea water, which implies costly infrastructure and costly and frequent maintenance operations. When talking about X-band Radars used to measure wave height, peak wave period, mean wave period, and wave direction, or HF radars capable of measuring wave spectra and currents, both of them they are by far more expensive than the proposed instrument (although the range of these instruments is different from the range of Oceanpal®).

Data processing: sea level retrieval

The latest model of Oceanpal® allows the measurement of the significant wave height (SWH) and tide. Two different algorithms are used to determine these quantities, both having as input the direct and reflected electromagnetic field time series for each satellite in view.

The gauge of the tide is based on the estimation of the altitude of the antennas above the sea surface. This value is obtained from the measurement of the delay between the direct and reflected GPS signals. Such delay can be estimated using either the code or the phase of the incoming signals. The phase based estimation provides more precise values but it is only available for very calm sea surface. In case of rougher surfaces, the code based algorithm must be used.

Phase altimetry is feasible usually inside harbours or over lakes, where the phase of the reflected signal, though very distorted, retains a sufficient amount of coherency in order to infer the altitude of the receiving antennas above the reflecting surface. In this case, the signal used for the altimetric estimation is the interferometric field $I(t)$ defined as the ratio between the reflected signal $R(t)$ and direct signal $D(t)$. The use of this interferometric field entails the elimination of the effects of the modulations of the GPS navigation message and of all errors (such as propagation noise, clocks, residual Doppler, etc.) common to both signals.

The phase $\Phi(t)$ of the interferometric field for each transmitting satellite (with an elevation $\varepsilon(t)$) can be related to the height $h(t)$ of the antennas above the sea surface through the simple relation:

$$\Phi(t) = 2k\ h(t)\sin\varepsilon_p(t) + \theta(t) \qquad (1)$$

where k is the wave number of the GPS carrier frequency and $\theta(t)$ is an additional system bias introduced by hardware unbalances. In order to solve for the height $h(t)$, the modulo-2π wrapping of the phase must be taken into account. Considering that the interferometric field as defined above can be modelled as set of unitary phasors $e^{i\tilde{\phi}(t)}$, in order to jointly estimate h and θ, one can

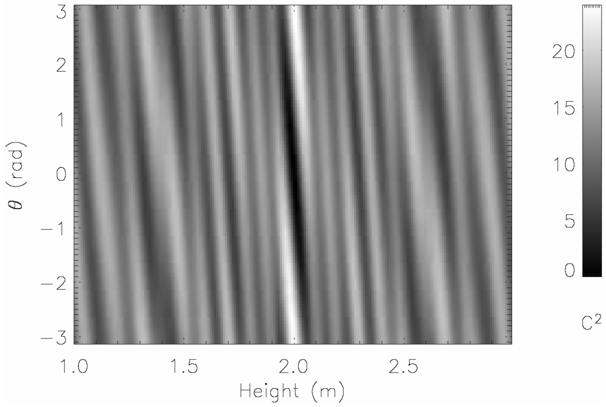


Fig. 2: Simulated cost function (Eq. 4) obtained with six satellites and a true value of *h* of 2 meters, and *Φ=0*.

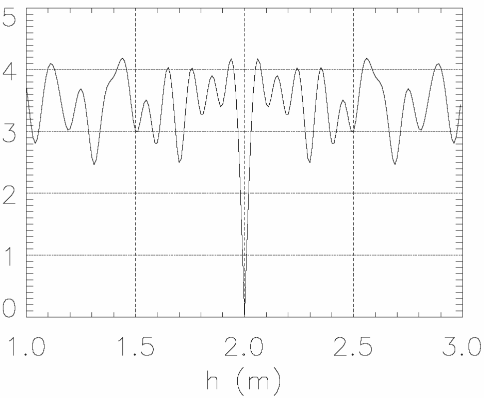


Fig. 3: Curve obtained as a cut in the simulated cost function (Fig. 2, Eq. 4) for the correct value of offset *Φ*. It is evident the deep minimum which identifies the right height estimation (*h=2* m).

minimize the following error function:

$$C(h,\theta) = \sum_{p,t} \left| e^{i\tilde{\phi}(t)} - e^{i\phi(t)} \right| \tag{2}$$

where *Φ(t)* is the phase model of eq.(1). An example of this cost function (eq. 2) obtained using simulated data is shown in Fig. 2. The ambiguity introduced by phase wrapping manifests in the presence of many local minima. Nonetheless, the existence of a very deep global minimum (see Fig. 3), ensures a precise estimation of the sought magnitudes.

When sea state conditions do not permit the unambiguous identification of such a clear global minimum, the use of phase based algorithms is precluded and code based algorithms have to be used to estimate the tide. Code altimetry, especially from low altitude sites, which is the case for coastal applications, is computationally easier than phase altimetry, since no ambiguity problem arises. The basic equation for code altimetry is the following

$$\tau(t) = 2 \cdot h \cdot \sin\varepsilon(t) + b \tag{3}$$

where τ represents the lapse between the time of arrival of the reflected and the direct signal, *h* is the height to be estimated, ε is the elevation of the satellite considered, and *b* is the system bias, which is considered unknown but constant during every estimation. Solving a linear system with many of such equations, for different satellites and along, say, one minute of time, provides the sought estimation of *h* (and *b*).

Data processing: sea state retrieval

The estimation of the SWH is based on the interferometric field as well. In this case, the coherence time of the interferometric field is used to estimate the sea state, based on the principle that a rougher surface implies a lower coherence of the field. The coherence time τ_I is defined as the width of the autocorrelation function *Γ(Δt)* of the interferometric field. Assuming that the sea surface elevation is a gaussian distribution, then for short time intervals *Δt*, the autocorrelation function can be expressed as:

$$\Gamma(\Delta t) \approx A(\sigma_z, l_z, \varepsilon, G_r) \cdot e^{-4k^2\sigma_z^2 \frac{\Delta t^2}{2\tau_z^2} \sin^2\varepsilon}, \tag{4}$$

where σ_z is the standard deviation of the sea surface elevation, l_z is the autocorrelation length sea surface, ε is the satellite elevation, G_r is the gain pattern of the receiving antenna, and τ_z is the correlation time of the surface. Under these assumptions, the coherence time of the interferometric field can be written as

$$\tau_I = \frac{\tau_z}{2k\sigma_z \sin\varepsilon} = \frac{\lambda}{\pi \sin\varepsilon} \frac{\tau_z}{SWH}, \tag{5}$$

where the SWH has been introduced as a function of σ_z.

Equation (5) states that the coherence time of the interferometric field depends from both the surface coherence time τ_z and the SWH. These two magnitudes are not independent and their value is determined by various parameters such as sea state, sea maturity, fetch, and bathymetry. The relationship between *SWH* and τ_z, especially in coastal areas, is very difficult to derive theoretically and a semi-empirical expression has been obtained trough extensive Monte-Carlo simulations of different sea states conditions. The empirical expression obtained writes:

$$SWH = SWH_0 + \frac{\alpha}{k\tau_I \sin\varepsilon - \beta}, \qquad (6)$$

where SWH_0, α and β are calibration parameters. Using this equation it is possible to derive the SWH value from the measured value of τ_I.

Experimental campaigns: sea level retrieval

Various experimental campaigns have been performed to validate the instrument. In the ESA Bridge campaign using scientific instrumentation and a different phase algorithm (see [4] for details), 1 cm altimetric precision after 2 minutes was demonstrated in a favourable environment (good satellite visibility). Such a value is in line with the normal user requirements for tide gauges.

A more operational campaign was carried out in 2004 in the port of Vilagarcia de Arosa, in north-western Spain. The site was chosen because of the presence of a reliable ground truth (various tide gauges available at the same place), for its position in the innermost part of the harbour (which is a must condition for altimetric algorithms based on signal phase) and finally, for the magnitude of tide events in that region (normally of around 3 meters). The phase altimetry algorithm described in the previous section has been applied to this set of data. The standard deviation of the error between the estimated tide and the ground truth (i.e. the measurements from a close radar tide gauge) resulted to be 3.1 cm after 2 minutes (see Fig. 4). These values are close to the usual requirements for tide gauges

Code based algorithms have been used for the data collected during a campaign in (open) rough waters near Le Conquet, in northern France using the GPS C/A code. This site offers very wide visibility in both azimuth and elevation: at least one GPS satellite is usable 87% of the time and up to six satellites can be utilizable at a time. As expected, the error of this code-based estimation is higher than in the previous case, where the phase-based algorithm was used.

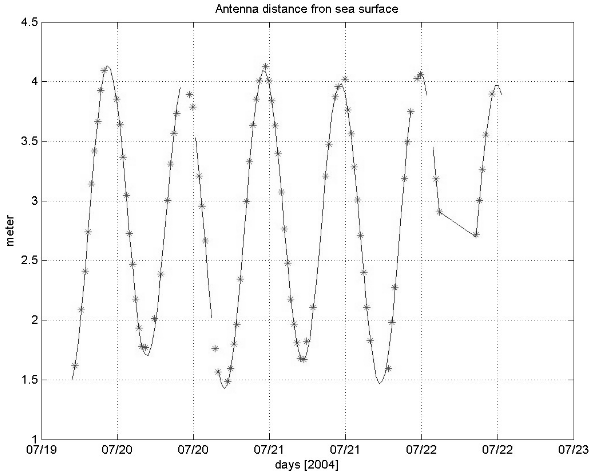


Fig. 4: Ground truth (solid line) and Oceanpal® estimated values (dots) for the Vilagarcía campaign, using phase algorithms.

The standard deviation of the error between the estimated tide and the ground truth (provided by the French Hydrographic and Oceanographic Department of the Marine Defence) was found to be 46 cm after one minute (see Fig. 5), or ~10 cm after 30 minutes. Use of P-code like signals can improve performance by about a factor of 10.

Experimental campaigns: sea state retrieval

Oceanpal® for significant wave height (SWH) retrieval has been deployed at a permanent site in the harbour of Barcelona, thanks to the collaboration of the Barcelona Port Authority Environmental Monitoring Department (APB).

The instrument is placed on the breakwater, with the antennas looking towards the open sea. The algorithm for SWH estimation previously explained in this paper is applied and, every hour, an average value of SHW is provided. In Fig. 6, the comparison between the SWH data obtained by Oceanpal® and those of two nearby buoys are shown, for a 13 days time period. The standard deviation of the error between the estimated SWH and the ground truth is 18 cm after 1 minute (see also [10]).

As an embryonic coastal operational system, these data are accessible to the APB, in real time, via the internet through a graphical user interface shown in Fig. 7.

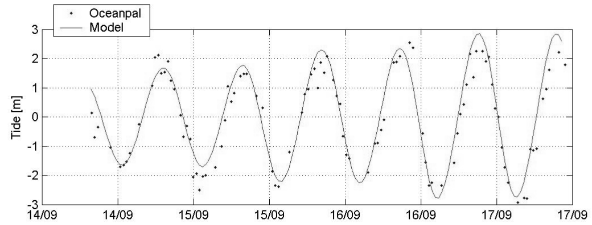


Fig. 5: Ground truth (solid line) and Oceanpal® estimated values (dots) for the Le Conquet campaign, using code algorithms.

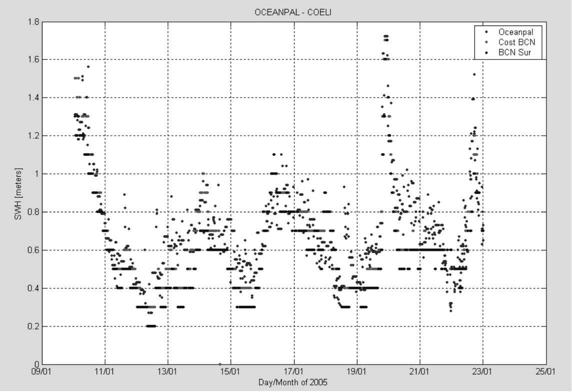
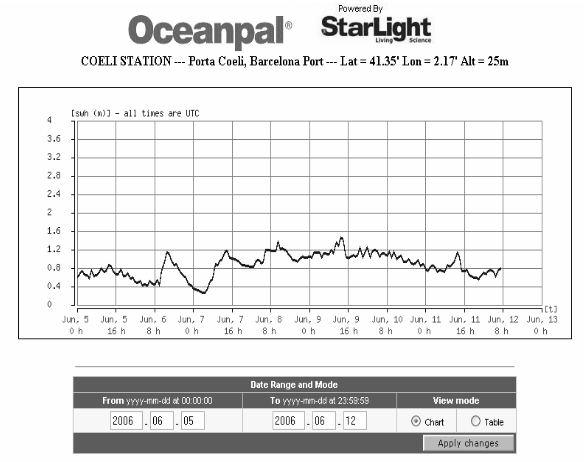


Fig. 6: Comparison of SWH estimation with Oceanpal (dots) and two nearby buoys (segments), along 13 days, at the Barcelona port.


COELI STATION --- Porta Coeli, Barcelona Port --- Lat = 41.35' Lon = 2.17' Alt = 25m

Date Range and Mode

From yyyy-mm-dd at 00:00:00: 2006 - 06 - 05

To yyyy-mm-dd at 23:59:59: 2006 - 06 - 12

View mode: ● Chart ○ Table

Fig. 7: Oceanpal® GUI. Through this interface the Barcelona Port Authority has access to the SWH measures provided by the Oceanpal® deployed in their premises.

Conclusions

Oceanpal® is a GNSS-R instrument for coastal monitoring of sea surface. Two applications have been discussed: tide measurements and significant wave height estimation. These measurements are both based on a unique GNSS-R product: the complex interferometric field, defined as the ratio of the reflected and direct GNSS signals. Two experimental campaigns have been described, which demonstrate precisions of 1-3 cm for tide estimation and 18 cm for *SWH* estimation. Finally, we emphasize the fact that these tests are just the beginning. A modernized GPS constellation and Galileo will provide more numerous and better signals for future applications in the next decade and beyond.

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All Starlab authors have contributed significantly; the Starlab authors list has been ordered randomly.

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