The GNSS-R Eddy Experiment I: Altimetry from Low Altitude Aircraft

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Abstract

We report results from the Eddy Experiment, where a synchronous GPS receiver pair was flown on an aircraft to collect sampled L1 signals and their reflections from the sea surface to investigate the altimetric accuracy of GNSS-R. During the experiment, surface wind speed (U10) was of the order of 10 m/s, and significant wave heights of up to 2 m, as discussed further in a companion paper. After software tracking of the two signals through despreading of the GPS codes, a parametric waveform model containing the description of the sea surface conditions has been used to fit the waveforms (retracking) and estimate the temporal lapse between the direct GPS signals and their reflections. The estimated lapses have then been used to estimate the sea surface height (SSH) along the aircraft track using a differential geometric model. As expected, the precision of GNSS-R ranges was of 3 m after 1 second integration. More importantly, the accuracy of the GNSS-R altimetric solution with respect to Jason-1 SSH and in situ GPS buoy measurements was of 10 cm, which was the target with the used experimental setup. This new result confirms the potential of GNSS-R for mesoscale altimetric monitoring of the ocean, and provides an important milestone on the road to a space mission.

Keywords: GNSS-R, GPS-R, altimetry, mesoscale, PARIS, waveform, retracking, bistatic.

1. Introduction

Several Global Navigation Satellite System (GNSS) constellations and augmentation systems are presently operational or under development, such as the pioneering US Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS) and the European EGNOS. In the next few years, the European Satellite Navigation System (Galileo) will be deployed, and GPS will be upgraded with more frequencies and civilian codes. By the time Galileo becomes operational in 2008, more than 50 GNSS satellites will be emitting very precise L-band spread spectrum signals, and will remain in operation for at least a few decades. Although originally meant for (military) localization, these signals will no doubt be used within GCOS/GOOS* in many ways (e.g., atmospheric sounding). We focus here on the budding field known as GNSS Reflections, which aims at providing tools for remote sensing of the ocean surface (especially sea surface height and roughness) and the atmosphere over the oceans.

This paper reports a new development of the GNSS-R altimetric concept (PARIS). The PARIS concept (Passive Reflectometry Interferometric System [12]) addresses the exploitation of reflected Global Navigation Satellite Systems signals for altimetry over the oceans. Ocean altimetry, the measurement of Sea Surface Height (SSH), is indeed one of the main applications of the GNSS-R passive radar concept. GNSS-R can give automatically integrated measurements in the GNSS reference system. In addition, this technique can provide the unprecedented spatio-temporal samplings needed for mesoscale monitoring of ocean circulation. It is at mesoscale where phenomena such as eddies play a fundamental role in the transport of energy and momentum, yet current systems are unable to probe them.

* Global Climate Observing System/Global Ocean Observing System.
Many GNSS-R altimetry and scatterometry experiments have been carried out to date, and the list continues to grow thanks to dedicated efforts in Europe and the US. GNSS-R experimental data has now been gathered from Earth fixed receivers (14, 22 among others), aircraft (12, 13, 11, 18 among others), stratospheric balloons (6, 4 among others), and from space platforms (10 among others). This experimental work is converging to a unified understanding of the GNSS-R error budget, but so far these experiments have focused on waveform modeling and short term ranging precision. None to date have attempted to retrieve a mesoscale altimetric profile as provided by monostatic radar altimeters such as Jason-1.

In the four main sections of this paper we report PARIS altimetric processing results using data from the 09-27-2002 Eddy Experiment, carried out in the frame of the European Space Agency “PARIS Gamma” contract. The first section addresses the issue of tracking the direct and reflected GPS signals, which consist in appropriately placing the delay and Doppler gating windows and in despread- ing the GPS signals by means of correlation with clean replicas. Tracking produces incoherently averaged waveforms (typically with a cadence of 1 second). The extraction of the information needed for the altimetric algorithm from the waveforms is described in the second section. This is the re-tracking step, and it yields to the so-called measured temporal lapse (or lapse, for short) between the direct and reflected signal. In the third section, the altimetric algorithm (producing the Sea Surface Height estimates) is described and, finally, results are presented in the fourth section.

2. Data collection and pre-processing

2.1. Data set

The GNSS-R data set was gathered during an airborne campaign carried out by Starlab in September 2002. The GPS/INS (Inertial Navigation System) equipped aircraft overflew the Mediterranean Sea, off the coast of Catalonia (Spain), northwards from the city of Barcelona for about 150 km (Figure 1). This area was chosen because it is crossed by a ground track of the Jason-1 altimeter (track number 187). The aircraft overflew this track during the Jason-1 overpass, for precise comparison. In addi-

1 The buoy campaign was carried out by the Institut d’Estudis Espacials de Catalunya (IEEC).

2 STARLIGHT, also described in [2].
mimicking a higher gain antenna (a belief supported by tests with shorter integration times).

3. Retracking the waveforms

Once a correlation waveform is obtained for both the direct and reflected signals, the lapses can be estimated. We emphasize that this is not as trivial as considering the maximum sample of each waveform or the waveform centroid, for instance, as the bistatic reflection process deforms severely the signals and, in general, such distortions will displace the waveform maximum or centroid location. Moreover, the sampling rate of 20.456 MHz, while much higher than the Nyquist rate for the C/A code, is equivalent to an inter-sample spacing of 49 ns—about 15 light-meters. This coarseness in the lapse estimation is not sufficient to reach the final altimetric precision target. The main challenge for GNSS-R using the GPS Coarse Acquisition (C/A) code is to provide sub-decimetric altimetry using a 300 m equivalent pulse length, something that can only be achieved by intense averaging with due care of systematic effects. For reference, pulse lengths in monostatic altimeters such as Jason-1 are almost three orders of magnitude shorter.

For these reasons, the temporal position of each waveform (the delay parameter) is estimated via a Least Mean Squares model fitting procedure. This is the so-called retracking process, an otherwise well-known concept in the monostatic altimetric community. The implementation of accurate waveform models (for direct and reflected signals) is fundamental to retracking. Conceptually, a retracking waveform model allows for the transformation of the reflected waveform to an equivalent direct one (or vice-versa), and a coherent and meaningful comparison of direct and reflected waveforms for the lapse estimation.

3.1. Waveform model

The natural model for retracking of the direct signal waveforms is the mean autocorrelation of the GPS C/A code in presence of additive Gaussian noise, which accounts mainly for the receiver noise. As far as the reflected signal is concerned, the model is not so straightforward. In fact, the reflection process induces modifications on the GNSS signals which depend on sea surface conditions (directional roughness), receiver-emitter-surface kinematics and geometry, and antenna pattern. Among all these quan-
Figure 2: Simplified block diagram of the GNSS-R tracking concept.

tities, the least known ones are those related to the sea surface conditions. In principle, these quantities should be considered as free parameters in the model for the reflected signal waveform and estimated during the retracking process along with the delay parameter of the waveform.

On the basis of the two most quoted models in the literature for bistatic sea-surface scattering ([14] and [21]), we have developed an upgraded waveform model for the reflected signal. This new model, as the two aforementioned, is based on the Geometric Optics approximation of the Kirchhoff theory—that is to say, with a tangent plane, high frequency and large elevation assumption, which is reasonable for the quasi-specular sea-surface scattering at L-band ([17]). The main characteristics of this model are the following:

- a fully bistatic geometry (as in [21], but not in [14]),
- the description of the sea surface through the L-band Directional Mean Square Slope\(^\dagger\) (DMSS\(_L\)) (as in [21]), and
- the use of a fourth parameter, the significant wave height (SWH), to describe the sea surface (as in [14], but not in [21]).

We have checked that the impact of SWH mismodeling in our case is negligible, since the GPS C/A code equivalent pulse width is about 300 meters. Nonetheless, we emphasize that all potential sources of systematic effects must be considered. We foresee a higher and non-negligible impact of SWH if the GPS P-code (the Precision code) or similar codes in Galileo are used, since they are an order of magnitude shorter.

3.2. Inversion scheme

The retracking process has been performed through a Least Mean Squares fit of the waveforms with the models described. Because of the speckle noise affecting the reflected signal waveforms, the fit has not been performed on each complex waveform obtained from the 10 ms correlations. Rather, these waveforms have first been incoherently averaged: the average of the magnitude of a hundred 10 ms waveforms has then been used to perform the inversion—i.e., 1 second incoherently averaged real waveforms have been generated for retracking. In this way, reflected/direct temporal lapses have been produced at 1 Hz rate.

In both cases, the fit of the waveform has been performed over three parameters: the time delay, a scaling factor and the out-of-the-peak correlation mean amplitude.

The geophysical parameters that enter in the model of the reflected signal waveform have not been jointly estimated here. These parameters have been set to some reasonable \textit{a priori} value obtained from other sources of information (Jason-1 for wind speed, ECMWF for wind direction) or from theory (for the sea slope PDF isotropy coefficient). For con-

\(^\dagger\)See [8] for a discussion on the role of wavelength in the definition of DMSS.
convenience, we describe the sea surface state using a wind speed parameter, wind direction and the sea slope PDF isotropy coefficient. Using a spectrum model, these parameters can be univocally related to DMSS$_L$ with the assumption of a mature, wind-driven sea (the sea spectrum in [5] has been used in this case). We emphasize that DMSS$_L$ is the actual parameter set needed in the reflection model under the Geometric Optics approximation.

Concerning the reflected signal waveform, retracking has been performed using only the leading edge and a small part of the trailing edge, since the trailing edge is more sensitive to errors in the input parameters (including geophysical parameters and antenna pattern).

4. The altimetric algorithm

The output of the retracking process is the time series of measured lapses. The next step is finally SSH estimation. In order to solve for this quantity, we have used a differential algorithm: the classical PARIS equation (see [12]) has not been directly used. Instead, a model for the lapse over a reference surface near the local geoid has been built, and the difference of this reference lapse and the measured one has been modeled as a function of the height over the reference surface. We call this the differential PARIS equation (Equation [1]). We note that the aircraft INS has been used to take into account the direct-reflected antenna baseline motion and that we have also included both dry and wet tropospheric delays in the model by using exponential models for them with different scale heights and surface values derived from surface pressure measurements and surface tropospheric delays obtained from ground GPS and SSM/I*).

The differential PARIS equation writes

\[
\Delta_{DM} = \Delta_D - \Delta_M = 2 \delta h \sin(\epsilon) + b, \quad (1)
\]

where

- \(\Delta_D\) is the measured lapse, in meters, as estimated from the data,
- \(\Delta_M\) is the modeled lapse, in meters, based on an ellipsoidal model of the Earth, GPS constellation precise ephemeris, aircraft GPS/INS precise kinematic processing, and a tropospheric model,

\*Special Sensor Microwave Imager, a passive microwave radiometer flown aboard United States Defense Meteorological Satellite Program.

\(\delta h\) is the normal offset between the sea surface and the (model) ellipsoid surface,

\(\epsilon\) is the GPS satellite elevation angle at the specular point of reflection, over the ellipsoid, and

\(b\) is the hardware system bias.

The precision obtained after 1-second of incoherent averaging in the estimation of \(\Delta_{DM}\) using this approach is displayed in Table 1. For each PRN number, the root mean squared error of the 1-second lapse is shown (in meters). It is roughly of 3 m. This noise level is as expected from the C/A code bistatic ranging in our experimental setup (antenna gain, altitude, etc.) and consistent with earlier experiments.

5. Results

The algorithm outlined in the previous section has been used with data from the three better behaved GPS satellites. The other two visible satellites appeared to be severely affected by aircraft-induced multipath (probably due to the landing gear and wing surfaces). A SSH profile has been retrieved for each satellite and the average value of the three profiles is shown in Figure 3 along with the Jason-1 SSH, Mean Sea Level (MSL) and one SSH value obtained with the control buoy. This solution has been obtained setting a model wind speed of 10 m/s (values provided by Jason-1 along the track vary between 9 and 13 m/s), wind direction of 0 degrees North (values provided by ECMWF vary between 30 and -20 deg North), and sea slope PDF isotropy coefficient equal to 0.65 (the theoretical value for a mature, wind-driven sea according to [5]). It is important to underline that the use of constant values for the geophysical parameters along the whole track (more than 120 km) induces non-linear errors on the final altimetric estimation. Nonetheless, the bias of the final solution with respect to the SSH (the error mean) is 1.9 cm while the root mean error is 10.5 cm.
6. Conclusion

The Eddy Experiment has validated the use of PARIS as a tool for airborne sea surface height measurements, providing both the precision and accuracy predicted by earlier experimental and theoretical work. We have observed that the use of a waveform model for the reflected signal, based on geophysical parameters describing the sea surface conditions, is essential for the accuracy of the altimetric solution—a fact which may explain earlier results in which no geophysical retracking was performed (e.g., [15]). The accuracy achieved by our algorithm is of the order of 1 decimeter, but we expect that further analysis and refinements, such as the inclusion of DMSS\textsubscript{L} parameters in the inversion procedure, will improve these numbers.

Our sensitivity analysis has also shown that the altitude of this flight was not optimal for GNSS-R altimetry and made the experiment more prone to aircraft multipath problems. A higher altitude flight would lead to a smaller angular span of the reflecting area on the sea surface, thus reducing the impact of geophysical parameters, antenna pattern and aircraft multipath on the retracking process of the leading edge, making the overall altimetric solution more robust. Higher altitudes are also needed to better understand the space-borne scenario.

We would like to emphasize that GNSS-R signals can be profitably used also for scatterometric measurements (i.e., speculometry, from the Latin word for mirror, “speculo”, see [16]). In a parallel paper ([8]), the inversion of GNSS-R Delay-Doppler Maps for sea-surface DMSS\textsubscript{L} estimation is presented for the same data set. The next step is to merge the altimetric and speculometric processing in an attempt to provide an autonomous GNSS-R complete description of the sea—topography and surface conditions.

We believe the Eddy Experiment is an important

| PRN | Complete track | Beginning of the track |
|-----|----------------|------------------------|
| 8   | 3.5 m          | 2.7 m                  |
| 24  | 3.4 m          | 2.8 m                  |
| 27  | 2.9 m          | 2.7 m                  |

Table 1: Precision in the estimation of the time lapses (root mean squared error of the lapses, in meters).

Figure 3: Final altimetric result. The red line represents the average altimetric result of the three GPS satellite analyzed filtered over a 20 km—i.e., 400 seconds, the aircraft speed being about 50 m/s. The black line represents the Jason-1 SSH, while the green dashed line represents the MSL. The blue diamond is the SSH measurement obtained from the reference buoy.
milestone on the road to a space mission. We underline that the obtained precision and accuracy are in line with earlier experiments and theoretical error budgets (see, e.g., [10]). We note that the same error budgets have been used to investigate and confirm the strong impact of space-borne GNSS-R altimetric mission data on mesoscale ocean circulation models ([18] [19]). Further analysis of existing datasets (which could be organized in a coordinated database for the benefit of the community) and future experiments at higher altitudes will continue to refine our understanding of the potential of this technique.

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

References

[1] M. Caparrini. Using reflected GNSS signals to estimate surface features over wide ocean areas. Technical Report EWP 2003, ESA report, December 1998.

[2] M. Caparrini, L. Ruffini, and G.Ruffini. Gns-r altimetry with gps ll data from the bridge 2 campaign. In Proceedings of the 2003 Workshop on Oceanography with GNSS-R. Starlab, July 2003.

[3] E. Cardellach, J.M. Aparicio, A. Rius, J.S., and J. Torrobella. Application of the PARIS concept to transoceanic aircraft remote sensing. Technical report, 2001. PARIS Alpha WP5200 - ESA Contract 14285/85/NL/PB.

[4] E. Cardellach, G. Ruffini, D. Pino, A. Rius, A. Komjathy, and J. Garrison. Mediterranean balloon experiment: GPS reflection for wind speed retrieval from the stratosphere. To appear in Remote Sensing of Environment, 2003.

[5] T. Elfouhaily, B. Chapron, K. Katsaros, and D. Vandemark. A unified directional spectrum for long and short wind-driven waves. Journal of Geophysical Research, 102(15):781–796, 1997.

[6] J.L. Garrison, G. Ruffini, A. Rius, E. Cardellach, D. Masters, M. Armats, and V.U. Za-vorotny. Preliminary results from the GPSR mediterranean balloon experiment (GPSR-MEBEX). In Proceedings of ERIM 2000, Charleston, South Carolina, USA, May 2000.

[7] L. Garrison, S. Katzberg, and M. Hill. Effect of sea roughness on bistatically scattered range coded signals from the GPS. Geophysical Research Letters, 25:2257–2260, 1998.

[8] O. Germain, G. Ruffini, F. Soulau, M. Caparrini, B. Chapron, and P. Silvestrin. The GNSS-R Eddy Experiment II: L-band and optical speculometry for directional sea-roughness retrieval from low altitude aircraft. In Proceedings of the 2003 Workshop on Oceanography with GNSS-R. Starlab, July 2003.

[9] A. Komjathy. GPS surface reflection using aircraft data: analysis and results. In Proceedings of the GPS surface reflection workshop. Goddard Space Flight Center, July 1998.

[10] S. Lowe, J.L. LaBrecque, C. Zuffada, L.J. Romans, L. Young, and G.A. Hajj. First space-borne observation of an earth-reflected gps signal. Radio Science, 37(1):1–28, 2002.

[11] S. Lowe, C. Zuffada, Y . Chao, P. Kroger, J.L LaBreque, and L.E. Young. 5-cm precision aircraft ocean altimetry using GPS reflections. Geophysical Research Letters, 29(4359–4362, 2002.

[12] M. Martin-Neira. A PAssive Reflectometry and Interferometry System (PARIS): application to ocean altimetry. ESA Journal, 17:331–355, 1993.
PARIS concept: An experimental demonstration of sea surface altimetry using GPS reflected signals. *IEEE Transactions on Geoscience and Remote Sensing*, 39:142–150, 2001.

[14] G. Picardi, R. Seu, S. G. Sorge, and M. Martin-Neira. Bistatic model of ocean scattering. *IEEE Trans. Antennas and Propagation*, 46(10):1531–1541, 1998.

[15] A. Rius, J.M. Aparicio, E. Cardellach, M. Martin-Neira, and B. Chapron. Sea surface state measured using GPS reflected signals. *Geophysical Research Letters*, 29(23):2122, 2002.

[16] G. Ruffini, M. Caparrini, O. Germain, F. Soulat, and J. Lutsko. Remote sensing of the ocean by bistatic radar observations: a review. Technical report, PARIS Beta WP1000 - ESA ESTEC Contract No. 15083/01/NL/MM, 2001. Available online at http://starlab.es.

[17] F. Soulat. Sea surface remote-sensing with GNSS and sunlight reflections. *Doctoral Thesis*, Universitat Politècnica de Catalunya/Starlab, 2003.

[18] P.Y. Le Traon, G. Dibarboure, G. Ruffini, and E. Cardellach. Mesoscale ocean altimetry requirements and impact of GPS-R measurements for ocean mesoscale circulation mapping. In *Proceedings of the 2003 Workshop on Oceanography with GNSS-R*. Starlab Barcelona, July 2003.

[19] P.Y. Le Traon, G. Dibarboure, G. Ruffini, O. Germain, A. Thompson, and C. Mathew. GNSS-R measurements for ocean mesoscale circulation mapping - an update. In *Proceedings of the 2003 Workshop on Oceanography with GNSS-R*. Starlab Barcelona, July 2003.

[20] R.N. Treuhaft, S.T. Lowe, C. Zuffada, and Y. Chao. 2-cm gps altimetry over crater lake. *Geophysical Research Letters*, 22(23):4343–4346, December 2001.

[21] V. Zavorotny and A. Voronovich. Scattering of GPS signals from the ocean with wind remote sensing application. *IEEE Trans. Geoscience and Remote Sensing*, 38(2):951–964, 2000.