Article

MEASURING SEA LEVEL WITH GPS-EQUIPPED BUOYS: A MULTI-INSTRUMENTS EXPERIMENT AT AIX ISLAND

By Gaël ANDRÉ[1], Belén MARTÍN MÍGUEZ[2], Valérie BALLU[3,4], Laurent TESTUT[5] and Guy WÖPPELMANN[3]

[1]Service hydrographique et océanographique de la Marine (SHOM), Brest (France)
[2]Centro Tecnológico del Mar (CETMAR), Vigo (Spain)
[3]LIENSs (Université de la Rochelle – CNRS), La Rochelle (France)
[4]IPGP (Institut de Physique du Globe de Paris) (France)
[5]LEGOS (CNES-IRD-CNRS-Université Paul Sabatier), Toulouse (France)

Abstract

Measuring sea-level in a global reference frame with sub-centimeter accuracy is a relevant challenge in the context of current global warming and associated sea-level rise. Global Navigation Satellite Systems (GNSS) can provide sea-level measurements directly referenced in an absolute geocentric frame. We present here the results of a multi-instruments experiment with three buoys equipped with Global Positioning System (GPS), a radar tide gauge and a tide pole. This experiment was carried out at Aix Island (West coast of France) on the 27-28 March 2012. The GPS buoys were evaluated against conventional tide gauge measurements through a Van de Casteele test. The Root Mean Square Error (RMSE) computed from the difference between the GPS-buoys and radar tide gauge data ranges from 1 cm to 2.2 cm, which is suitable for tidal applications and offers interesting perspectives for future sea-level variations studies.

Résumé

La mesure du niveau de la mer dans un référentiel mondial avec une précision sub-centimétrique est un défi pertinent dans le contexte actuel du réchauffement climatique et de l'élévation du niveau des mers qui en résulte. Les systèmes mondiaux de navigation par satellite (GNSS) peuvent fournir des mesures du niveau de la mer directement rapportées à un référentiel géocentrique absolu. Nous présentons ici les résultats d'une expérience multi-instruments avec trois bouées équipées d'un système de positionnement par satellite (GPS), un marégraphe à radar et une échelle de marée. Cette expérience a été effectuée à l'île d'Aix (côte ouest de la France) les 27 et 28 mars 2012. Les bouées GPS ont été évaluées par rapport aux mesures du marégraphe conventionnel au moyen d'un test de Van de Casteele. L'erreur quadratique moyenne (RMSE) calculée à partir de la différence entre les données des bouées GPS et celles du marégraphe radar est comprise entre 1 cm et 2,2 cm, ce qui convient pour les applications marégraphique et offre d'intéressantes perspectives pour les futures études des variations du niveau de la mer.

Resumen

La medición del nivel del mar en un marco de referencias globales con una precisión subcentimétrica es un desafío importante en el contexto del calentamiento mundial actual y del aumento del nivel del mar asociado al mismo. Los Sistemas Mundiales de Navegación por Satélite (GNSS) pueden proporcionar medidas del nivel del mar directamente

Resumen (Continuación)

referenciadas en una estructura geocéntrica absoluta. Presentamos aquí los resultados de un experimento multi-instrumentos con tres boyas equipadas de un Sistema de Posicionamiento Global (GPS), un mareógrafo con sistema de radar y una escala de mareas. Este experimento fue llevado a cabo en la Isla de Aix (Costa Occidental de Francia), los días 27 y 28 de Marzo del 2012. Las boyas GPS fueron evaluadas comparándolas con las medidas de los mareógrafos convencionales mediante un test Van de Casteele. El Error Cuadrático Medio (RMSE) calculado a partir de la diferencia entre los datos de las boyas GPS y los datos de mareógrafo, oscila de 1 a 2,2 cm, lo que es apropiado para las aplicaciones de mareas y ofrece perspectivas interesantes para futuros estudios de variaciones del nivel del mar.

1. Introduction

In spite of recent advances in remote sensing technologies such as satellite altimetry, sea-level measurements for tidal applications and other sea level variation studies related to climate change still rely highly on local measurements using tide gauges. There are many cases, where conventional tide gauges present limitations, regardless the type of sensor. The main limitation is that tide gauges are anchored on the ground and are subject to land movements. The ground anchorage requires on-land infrastructures and monitoring of the support stability through time. This limitation has been recognized previously and has led the Global Sea-Level Observing System (GLOSS) under the auspices of the Intergovernmental Oceanographic Commission (IOC) of UNESCO to recommend the installation of continuously operating GNSS stations at tide gauges and make their data freely available through its dedicated data assembly center (IOC, 2012). Ground stability and instrumental drift control requires regular leveling and calibration operations which can be difficult to perform in remote areas. An important advantage of using the GNSS technique is that it provides data referenced to a global geocentric reference frame, whereas tide gauges provide sea level data relative to the Earth's crust. This is one of the reasons why Löfgren et al. (2011) and Larson et al. (2013) explore the possibility of using a GNSS-based tide gauge (fixed device, not a buoy) for the long-term monitoring of sea-level. Another solution to free the sea level measurements from the land movement is to use GPS buoys, which allow the assessment of sea-level height independently from tide gauge sensor drift, onshore infrastructure and ground stability. Some papers have presented different GPS-buoy applications such as the calibration of coastal tide gauges on remote islands (Watson et al., 2008; Testut et al., 2010; Martín-Míguez et al., 2012; Fund et al., 2013), or even in offshore areas (Bouin et al., 2009; Ballu et al., 2010).

These previous works encouraged three different French teams: the Service Hydrographique et Océanographique de la Marine (SHOM), the Institut National des Sciences de l'Univers (INSU) and the Institut de Physique du Globe de Paris (IPGP), to design their own GPS buoys for different objectives. In 2012, these teams met at Aix Island on the West coast of France (***Fig. 1***) to carry out an inter-calibration experiment taking advantage of the facilities offered by the site. Aix Island has a sea level observatory with a radar tide gauge, a pressure tide gauge, a meteorological station and a permanent GPS station. In addition, local authorities are sensitive to sea level related scientific issues and their impact on coastal risk, especially after the Xynthia storm surge that severely hit this part of the coast on the 27–28 February 2010.

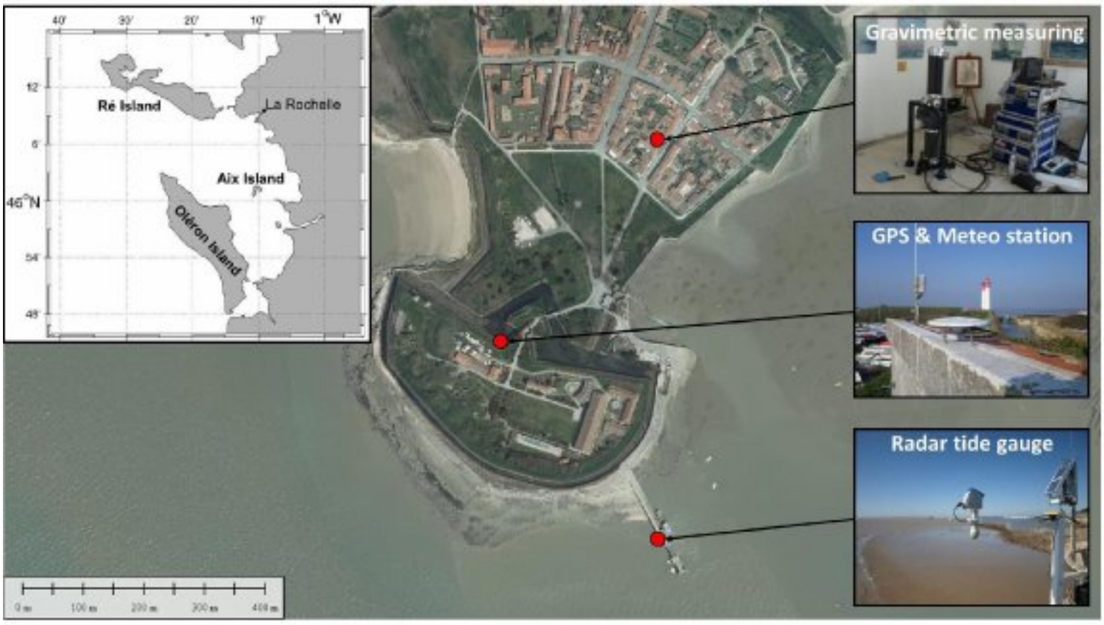

Figure 1

Aix Island sea level observatory in which the experiment was conducted. This observatory includes a radar tide gauge, a meteorological station and a GPS station.

The experiment and data processing will be described in section 2. Results will be presented and discussed in section 3 and 4 respectively. Finally, a summary and perspectives will be provided in section 5.

2. Materials and methods

2.1. The experiment

On the 27-28 March 2012, three prototypes of GPS buoys (***Fig. 2***) were deployed at Aix Island. The deployment site is a relatively sheltered 10 m depth area (***Fig. 3***), located approximately 100 m from the wharf where a tide pole, a pressure and a radar tide gauge belonging to the SHOM-RONIM network are installed. The experiment area is also located near the ILDX reference station of the GNSS Permanent Network (RGP). On March 28th, additional sea level heights were measured manually over a tidal cycle at the tide pole and with an optical probe. In addition, ancillary measurements of relative and absolute gravity, ocean currents and leveling were conducted.

The three GPS-buoys collected data from 27 March to 28 March over about 30h (***Table 1***). The IPGP buoy record was interrupted on March 27th between 13:28 and 14:44, due to a water intrusion into the receiver module. GPS data were recorded at 5 Hz for the INSU and SHOM buoys and at 1 Hz for the IPGP buoy.

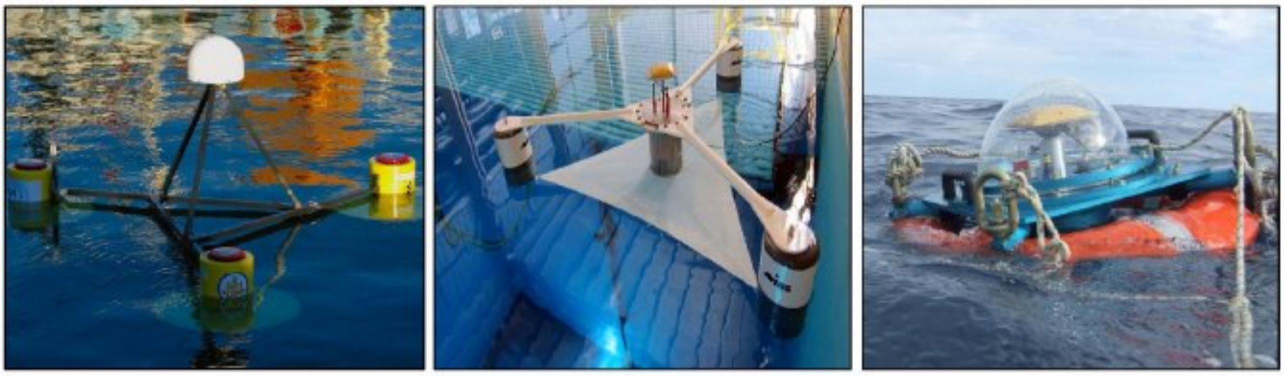

Figure 2 *The three GPS buoys. SHOM (left), INSU (center) and IPGP (right).*

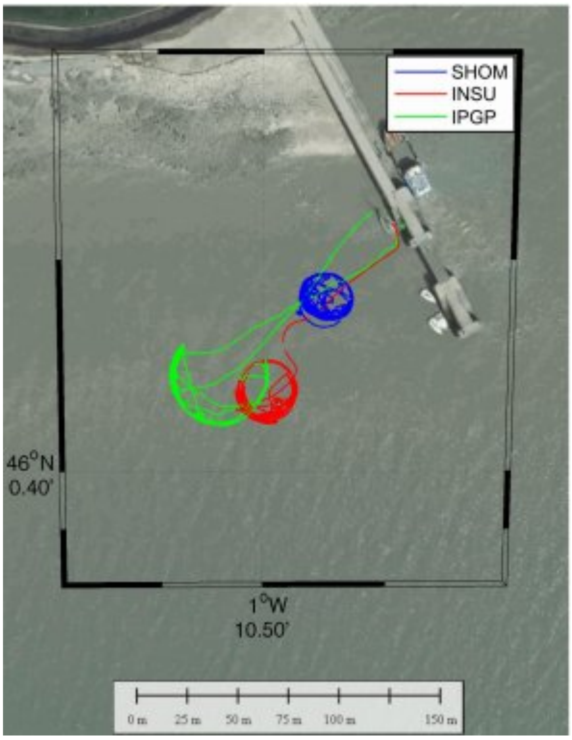

Figure 3

Experimental setting and GPS-buoys trajectories. GPS receivers of the IPGP and INSU buoys started recording while on the wharf, which explains why the towing of buoys by the boat between the wharf and the mooring position is visible. By contrast, SHOM buoy receiver was plugged in after the mooring of the buoy.

Table 1 . *Buoys measurement periods and sampling rates.*

Buoy	Begin date	Interruption	End date	Sampling rate
SHOM	03/27/2012 10:34	None	03/28/2012 16:52	5 Hz
INSU	03/27/2012 09:44	None	03/28/2012 17:12	5 Hz
IPGP	03/27/2012 08:34	03/27/2012 between 13:28 and 14:44	03/28/2012 17:17	1 Hz

2.2. GPS data processing

The GPS data were post-processed in kinematic mode with centimeter-level precision method with respect to ILDX fixed on-land reference station. The processing is performed in differential mode, with ambiguity fixing to integer values. It involves the use of a static reference station at a known location that simultaneously collects data and reduces systematic errors, common to both the kinematic and the fixed stations, such as atmospheric delays, satellites orbit, satellites clock and receiver's clock. The accuracy of the solution depends on the baseline length, since the use of a differential method assumes that both ends of the baseline have similar ionospheric and tropospheric conditions. Therefore, GPS buoy data cannot be processed accurately too far from the land using a kinematic processing method. Advances in PPP (Precise Point Positioning) methods offer an alternative which will allow future measurements to be carried out further from the shore (Fund et al., 2013).

Data processing was performed in two steps, using IGS precise orbits and a 10° elevation cut-off angle for all stations. First, data from the ILDX on-land station were processed in static mode using GAMIT/GLOBK software (Herring et al., 2010a and b) in order to compute its position in the International Terrestrial Reference Frame 2008 (ITRF08; Altamimi et al., 2011), using the Geodetic Reference System 1980 (GRS80) ellipsoid. Then, the positions of the buoys were estimated with respect to ILDX station using the differential mode kinematic processing TRACK module from the GAMIT/GLOBK suite. In our case study, the ILDX on-land reference station is located very close to the GPS-buoy deployment zone (at about 400 meters). This allows the use of TRACK on both frequencies (L1, 1.6 GHz, and L2, 1.2 Ghz) separately, giving better results for short baselines, than the use of the ionosphere-free linear combination (LC).

2.3. Buoy characteristics

The IPGP buoy was designed initially in the framework of sea-floor geodesy projects for which accurate sea surface height measurements are required. The sea surface heights are combined with bottom pressure measurements and water density data to derive the height of on-bottom geodetic points in a global reference frame (Ballu et al., 2010). This buoy consists of a cylinder housing the receiver (Topcon GB1000), electronics, ancillary sensors (temperature, pressure and 6-components accelerometer) and batteries, on top of which sits the antenna (PG-A1 with ground plane) and communication devices (X-Bee module, allowing to remotely check the receiver proper functioning at any time). The buoyancy is provided by a commercial safety ring. The buoy was designed to be shipped overseas, ready to use, and to be deployed at sea from a zodiac-type boat by one or 2 people. Its cylindrical shape and relatively heavy (30 kg) weight aims at avoiding capsizing in high seas. Together with a low antenna elevation above water (<15 cm), it is able to closely follow the motion of the water surface. A solar-rechargeable battery container may be connected to the main cylinder to extend the initial 3-days autonomy and allow longer-term deployments.

The INSU buoy was developed by the Division Technique of INSU/CNRS (Mellet, 2009) in the framework of the French Southern tide gauges network (ROSAME; Testut et al., 2006). This buoy is a design-improved version of the GPS buoy originally developed by an Australian team (Watson et al., 2003) for satellite altimetry validation. It was developed to be used in remote and/or difficult to access areas and designed so that it can be handled by only 2 people. It is the lightest of the three tested buoys (***Table 2***) with only 20 kg for a 2 m diameter and autonomy of 5 days. It is equipped with a TOPCON GB1000 receiver, and a PG-A1 Antenna with ground plane. A fabric drogue is tied up between the three ends and the center of the buoy, to improve its stability.

Table 2 . *Buoys main features and dimensions*.

Buoy	Weight	Diameter	Antenna height	Autonomy	Receiver type	Antenna type
SHOM	65 kg	2.5 m	92.7 cm	10 days	Trimble SPS852 GNSS	Leica AT504GG LEIS choke ring
INSU	20 kg	2 m	33.5 cm	5 days	TOPCON GB1000	PG-A1 with ground plane
IPGP	30 kg	0.75 m	14.9 cm	3 days	TOPCON GB1000	PG-A1 with ground plane

The SHOM buoy was developed in order to measure the sea surface ellipsoidal height accurately. This stable and robust equipment can be used for monitoring tide gauges, for recording sea level in remote or non-instrumented sites, for rapid environmental assessment, or for the validation of maritime vertical reference surfaces like VORF (Turner et al. 2010) in the UK or BATHYELLI (Pineau-Guillou, 2009) in France. The buoy weighs 65 kg for a surface of almost 2.5 m², an antenna height of about 1 m above sea water and autonomy of 10 days. This buoy is equipped with a Trimble SPS852 GNSS receiver and a Leica AT504GG LEIS choke-ring antenna used to reduce multipath signals. Its massive structure associated with a large stabilisation plate of 1 m diameter reduces high-frequency movements considerably.

3. Results

3.1. Buoys trajectories

Time-series of the horizontal positions of the three buoys were computed using TRACK software. The map of the buoys' trajectories is given in ***Figure 3***. GPS-buoys were moored at about 50 meters (SHOM) and 100 meters (IPGP and INSU) from the wharf on which the radar tide gauge is installed. Each buoy was tied to a submerged dead weight around which they could freely move at a maximum distance imposed by the rope length. As the three buoys were in position for more than one day, they were subject to the reversing tidal currents as well as to the wind, which explains the almost circular horizontal pattern. Currents are strong in this area and locally very variable due to the presence of the wharf. It can be noticed, that the IPGB buoy did not describe a full circle and that the tension on the mooring line seems more constant (***Figure 3***); this is likely due to a different position with respect to the local current pattern and suggests that hydrodynamics flow pattern could be also locally very variable.

3.2. Van de Casteele test

The Van de Casteele test is a method used to assess the performance of a tide gauge (IOC, 1985) regardless the technology employed (Martin Miguez et al., 2012). It implies taking simultaneous sea level heights both with the gauge being checked and with a reference gauge (tide pole, optical probe, etc.). Differences between both measurements are calculated (ΔHe) and plotted (X axis) against the sea level height (He) (Y axis). Assuming that the reference gauge provides high quality data, a vertical line centered at zero indicates that the checked gauge is well calibrated.

In a first step, the performance of the radar tide gauge was assessed. Despite being a well-known technology used in many tide gauge networks including France (Martin Miguez et al., 2008), radar sensors must be regularly checked to ensure a correct performance. During the experiment at Aix Island, measurements of the radar tide gauge, previously quality controlled and corrected for the presence of spikes, were compared with visual measurements at a tide pole on 28 March (***Figure 4***). Although somewhat rudimentary, visual measurements taken by experienced operators under calm sea conditions are reliable at the 1-2 centimeter-level (e.g., Testut et al., 2010). The standard deviation and the mean of the ΔHe time series are respectively 1.76 cm and 0.37 cm, which is comparable with previous results obtained during maintenance operations of the French Réseau d'Observation du NIveau de la Mer (RONIM) network (Martin Miguez et al., 2008) and is suitable for tidal applications.

In a second step, the performances of the GPS buoys were explored. After verifying the proper calibration of the radar tide gauge, we used it as a reference to assess the performance of the buoys. GPS-data were processed at 1 Hz and then smoothed and resampled at 1 minute, to be consistent with tide gauge measurements. Sea-level heights recorded with the tide-gauge initially referenced to the chart datum were tied to the ellipsoid, using leveling data between the tide gauge benchmark and the ILDX GPS station. Finally, Van de Casteele diagrams were outlined using the differences between the ellipsoid referenced radar tide gauge data and GPS buoy measurements. These diagrams are represented on ***Figure 5***. The residuals between the radar gauge and the GPS measurements (ΔHe) are in the order of a few centimeters for the three instruments. In a Van de Casteele test, the diagram displays a straight vertical line when the instrument is not biased by a systematic error such as a scale factor, compared to the reference instrument. In our case (***Figure 5***), the diagrams are not perfectly straight and vertical; however, we cannot suspect any scale factor on the GPS data and we have verified that the radar gauge is well calibrated (with respect to the tide pole, Figure 4). The non-straight vertical line, observed for the three buoys, could result from dynamic topography between the radar gauge and the buoys locations. The difference between the three buoys behavior will be further investigated in the following sections.

3.3. Results of the comparison

Figure 6 shows the radar tide gauge sea level heights (He) above the GRS80 ellipsoid, and the time series of the residuals (ΔHe) between the three GPS-buoy and the radar sea level heights. Our results show the good agreement

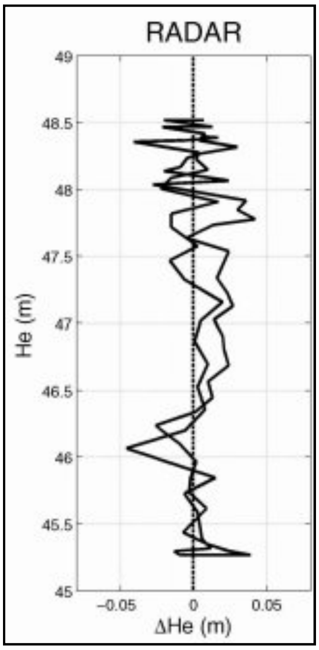

Figure 4.

Results of the Van de Casteele test for the radar tide gauge using tide pole measurements as a reference.

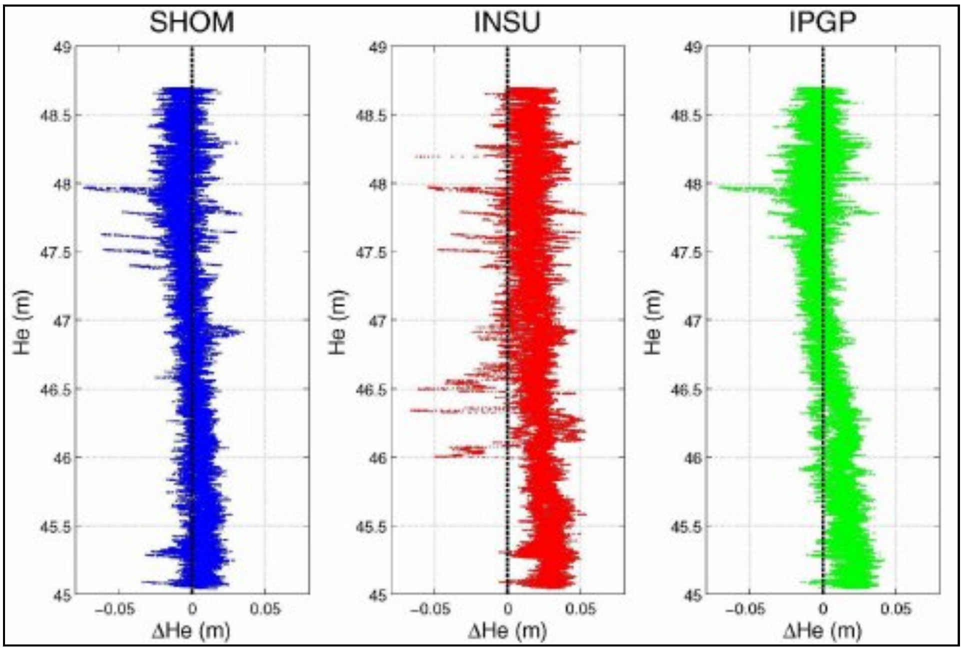

Figure 5.

Results of the Van de Casteele test for GPS buoys using the radar tide gauge as a reference. Note the non-verticality of the three diagrams, which illustrates that the residual of GPS buoys heights with respect to radar measurements are higher at low tide than at high tide. This could be due to dynamic topography (see text for explanation).

between the GPS buoys and the tide gauge data. Statistical values were computed on the residuals for the three buoys. The mean difference ranges between 0.13 cm and 1.84 cm, the standard deviation between 0.94 and 2.15 cm and the Root Mean Square Error (RMSE) between 0.95 and 2.18 cm (***see Table 3***).

The differences in the statistics for the three buoys reflect different phenomena:

1. the mean value of the residuals corresponds to the accuracy of the "absolute" referencing, which integrates any GPS processing bias, leveling errors both from the determination of the buoy antenna height elevation above water surface and the referencing of the radar tide gauge above the ellipsoid (leveling between the gauge and the ILDX reference station) and also the local difference in water height between the reference gauge (i.e. radar gauge) and the GPS buoy, due to local dynamic topography effects;

2. the standard deviation reflects the noise level in each time series, which integrates, on the one hand the real motion of the buoy, and on the other hand radar and GPS instrumental and processing random noise. As expected from their design, the SHOM buoy is the most stable: it mechanically filters the movement induced by the short scale surface waves. In contrast, the IPGP buoy is more affected by high-frequency waves;

3. the RMSE is a combination of both previous factors. It reflects in a single parameter the noise in the series (including real motion of the buoy) and the difference in the absolute referencing.

4. Discussion

This experiment was a practical case study for testing the ability of GPS buoys of various designs to accurately measure sea level. The comparison between the measurements provided by the buoys and the radar tide gauge clearly demonstrates the good performance of the buoys, with cm-level accuracy. Nevertheless, this study reveals some differences:

- the INSU buoy data shows a mean difference of about 2 cm with the radar tide gauge. This "calibration" difference may result from a real difference in water height due to dynamic topography, which cannot be discarded in the context of the Aix Island strong current environment. It may also have been induced by an excessive tension on the submarine drogue, which could have slightly bent the buoy frame upwards, thus changing the antenna height;

- the residuals between the radar measurements and the buoys seem to be correlated with the tidal cycle for the three buoys, which translates into a slope in the Van de Casteele diagrams (Figure 5). This behavior is exacerbated on the IPGP buoy data and can be seen clearly on Figure 6. Indeed, IPGP buoy gives heights similar to the radar gauge and the SHOM buoy at mid and high tide, but it measures a sea-level height 2 cm higher than the radar gauge and the SHOM buoy (closer to the INSU buoy) during the two low-tide periods. This difference in residual variations between the three buoys may reflect spatial variations of the dynamic topography and could be explained by the distance to the wharf in the high-energy hydrographic environment of the Aix Island;

- not surprisingly, the buoy design influences their behavior at sea. The widest and heaviest SHOM buoy moves very smoothly and is not perturbed by short wave-length wind waves, whereas the IPGP buoy "dances" much more at the surface, following closely the water surface movements. Due to its intermediate design (lighter but wider than the IPGP buoy), the INSU buoy has an intermediate behavior. These different behaviors may be adapted to different scientific purposes, depending on the sea-surface height variation frequency components that one may want to investigate.

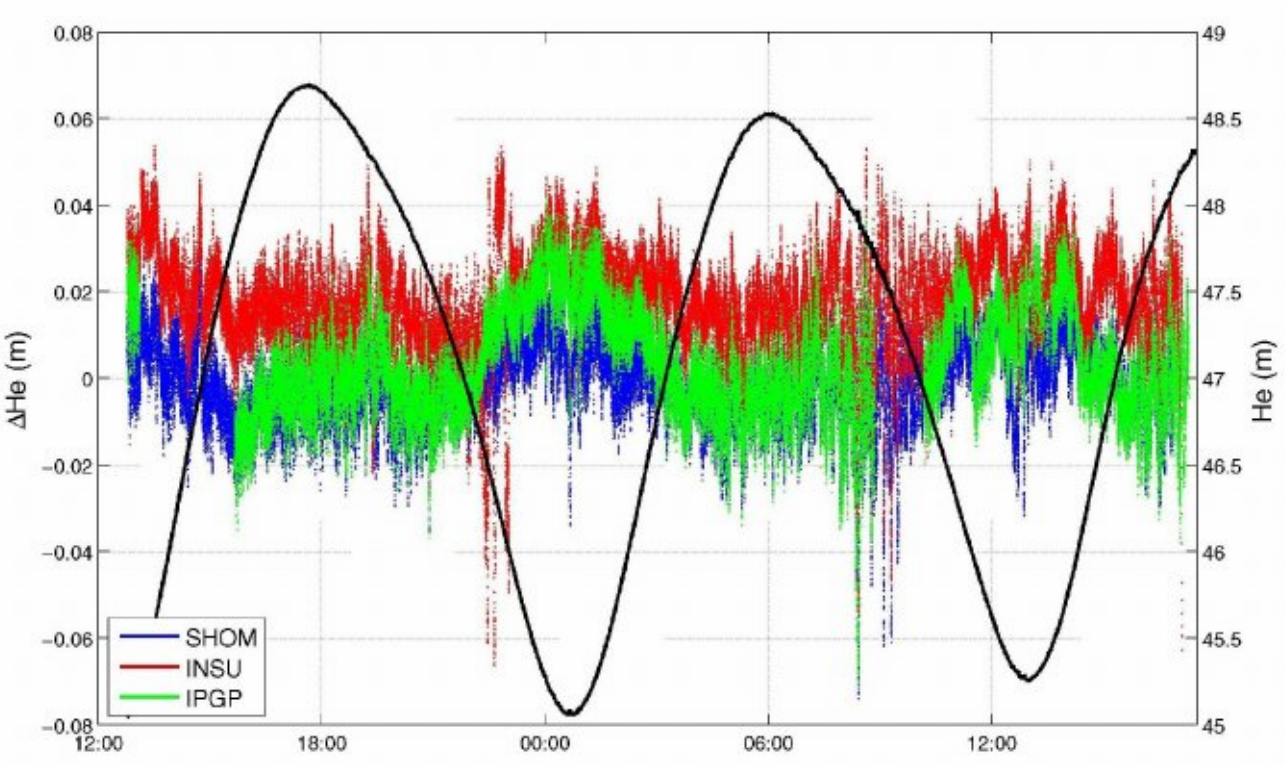

Figure 6.
Radar tide gauge sea level heights (He) above the GRS80 ellipsoid are shown in black (Y axis on the right), and residuals (ΔHe) between the three GPS-buoy height time series and radar sea level heights (He) are shown in color (Y axis on the left).

Table 3. *Statistical values obtained with the time series of residuals between GPS buoys data and radar tide gauge data.*

Buoy	Mean	Standard deviation	RMSE
SHOM	0.13 cm	0.94 cm	0.95 cm
INSU	1.84 cm	1.14 cm	2.16 cm
IPGP	0.33 cm	2.15 cm	2.18 cm

March 2012, during which three buoys equipped with GPS, were deployed in order to evaluate their performance for the measurement of sea level. These three GPS buoys are different prototypes developed by three independent institutions (SHOM, INSU and IPGP), whose study domain, scientific interest and coverage area vary. Hence the design and technical characteristics of these GPS-buoys are different (***see Table 2***). The INSU and IPGP buoys are lightweight and easily deployable (from helicopter or rigid-inflatable boat). The SHOM buoy is heavier, but its massive structure makes it more stable and robust. We have shown that the design of the buoy has a non-negligible impact on its accuracy and precision. The large offset present in the INSU GPS-buoy (18.4 mm), still under investigation, should warn us about the precautions to undertake during antenna calibration and deployment.

5. Summary and perspectives

A multi-instrument experiment was held at Aix Island (NW coast of France) on the 27-28 The comparison between the measurements provided by the GPS buoys and the radar tide gauge clearly demonstrated the good performance of the buoys. These results show that GPS buoys are able to measure the sea level height with cm-level accuracy, which is comparable to the precision of the reference radar tide gauge. This proves the overall potential of these buoys to measure accurately the sea level heights directly referenced to the ellipsoid GRS80.

Conventional tide gauge measurements are, by nature, tied to the shore, which means that they are limited to coastal areas and that their relevance to global and off-shore studies depends on the quality of the land motion monitoring. GPS-buoy measurements are a promising tool to calibrate coastal tide gauges or near-shore moorings, and tie them to an absolute geocentric reference frame, since they are independent from land movements. However, this tool still faces some practical limitations, both on the buoy technical aspects (battery endurance and rugged design to resist high-seas) and on the data processing. To meet these challenges for future ocean-wide sea-level monitoring, we are currently working on long-term autonomous GPS-buoy measurements, as for instance in the framework of the MoMAR (Monitoring of the Mid-Atlantic Ridge) sea-floor observatory (e.g. Ballu et al., 2012).

New perspectives of data processing for offshore areas are offered by the development of PPP techniques. Several studies have already used this processing method in order to determine buoy positions (Kuo et al., 2012; Fund et al., 2013). Results are still not as good as those obtained from differential processing when a reference station is available at short distance, since many common errors (troposphere, orbits) do not cancel out. However, thanks to continual improvements in PPP processing methods, the use of GPS buoys should soon no longer be restricted to coastal areas.

6. Acknowledgements

We would like to thank the staff members at DT/INSU (M. Calzas, A. Guillot), SHOM (Y-M. Tanguy, R. Legouge, Y. Dupont, G. Jan, S. Enet and J-P. Boivin), IPGP (O. Pot, B. Lecomte and T. Gabsi), and LIENSs (P. Tiphaneau, M. Gravelle and T. Guyot) who contributed to the development of the buoys and participated in the Aix Island experiment. The authors acknowledge Xavier Bertin (LIENSs) for discussion on dynamic topography around Aix Island and Sylvain Loyer (CLS) for discussion on the GPS data processing. We wish to express our gratitude to local authorities at Aix Island for their interest and logistical support. The Région Poitou-Charentes is gratefully acknowledged for the 3-month visiting grant of Dr. B. Martín Míguez. The SHOM buoy development has been supported by the French National Research Agency (CECILE project: Coastal Environmental Changes: Impact of sea LEvel rise), under grant number ANR-09-CEP-001-01. The IPGP buoy has been developed thanks to the support of CNES through the TOSCA program and the INSU buoy thanks to CNES and INSU support. The sea level data of Aix Island are the property of LIENSs, SHOM, CG17 and are available on the REFMAR website (http://refmar.shom.fr). This experiment was carried out within the framework of the SONEL project that aims at providing quality controlled sea level data which includes the performances of tide gauge technologies evaluation (www.sonel.org).

7. References

- Altamimi, Z., Collilieux, X. and Métivier, L. (2011). “ITRF2008: an improved solution of the International Terrestrial Reference Frame”, **Journal of Geodesy**, 85, 8, pp. 457-473.
- Ballu, V., Bouin, M.N., Calmant, S., Folcher, E., Bore, J.M., Ammann, J., Pot, O., Diament, M. and Pelletier, B. (2010). “Absolute seafloor vertical positioning using combined pressure gauge and kinematic

GPS data", **Journal of Geodesy**, 84, 1, pp. 65-77.

- Ballu, V., de Viron, O., Crawford, W.C., Cannat, M. and Escartin, J. (2012). "Long-term observations of seafloor pressure variations at Lucky Strike volcano, Mid-Atlantic Ridge," **AGU Fall Meeting**, San Francisco, 3-7 Dec. 2012.
- Bouin, M.N., Ballu, V., Calmant, S., Pelletier, B., Ammann, J., Bore, J.M. and Folcher, E. (2009). "Methodology of kinematic GPS experiment for local sea surface mapping, Vanuatu", **Journal of Geodesy**, 83, 21, pp. 1203-1217
- Fund, F., Perosanz, F., Testut, L. and Loyer, S. (2013). "An Integer Precise Point Positioning technique for sea surface observations using a GPS buoy", **Advances in Space Research**, 51, 8, pp. 1311-1322.
- Herring, T.A., King, R.W. and McClusky, S.C. (2010a). **GAMIT: Reference Manual. GPS Analysis at MIT**, Release 10.4, Massachusetts Institute of Technology, Cambridge.
- Herring, T. A., King, R.W. and McClusky, S.C. (2010b). **GLOBK Global Kalman Filter VLBI and GPS analysis program**, Release 10.4, Massachusetts Institute of Technology, Cambridge.
- IOC (1985). **Manual on sea-level measurement and interpretation, Volume I – Basic procedures**, Intergovernmental Oceanographic Commission, Manuals & Guides No 14.
- IOC (2012). **The Global Sea Level Observing System Implementation Plan 2012**, Intergovernmental Oceanographic Commission, Technical Series No. 100.
- Kuo, C.Y., Chiu, K.W., Chiang, K.W., Cheng, K.C., Lin, L.C., Tseng, H.Z., Chu, F.Y., Lan, W.H. and Lin, H.T. (2012). "High-frequency sea level variations observed by GPS buoys using precise point positioning technique", **Terr. Atmos. Ocean. Sci.**, 23, pp. 209-218.
- Larson, K., Löfgren, J. and Haas, R. (2013). "Coastal Sea Level Measurements Using a Single Geodetic GPS Receiver", **Advances in Space Research**, 51, 8, pp. 1301-1310.
- Löfgren J., Haas R. and Johansson J. (2011). "Monitoring coastal sea level using reflected GNSS signals", **Advances in Space Research**, 47, pp. 213-220.
- Martín Míguez, B., Le Roy, R. and Wöppelmann, G. (2008). "The use of radar tide gauges to measure the sea level along the French coast", **Journal of Coastal Research**, 24, 4C, pp. 61-68.
- Martín-Míguez, B., Testut, L. and Wöppelmann, G. (2012). "Performance of modern tide gauges: towards mm-level accuracy". **Scientia Marina**, 76, pp. 221-228.
- Mellet, M. (2009). **Conception d'une bouée GPS et étude de faisabilité d'un système GPS tracté pour mesurer le niveau de la mer**, Rapport de projet de fin d'études ENSIETA.
- Pineau-Guillou, L. (2009). "Projet BATHYELLI : Détermination du zéro hydrographique à partir de l'altimétrie spatiale et du GPS", **Navigation**, 57, pp. 226.
- Testut, L., Wöppelmann, G., Simon, B. and Téchiné, P. (2006). "The Sea Level at Port-aux-Français, Kerguelen Island, from 1950 to the present", **Ocean Dynamics**, 56, 5-6, pp. 464-472.
- Testut, L., Martín-Míguez, B., Wöppelmann, G., Tiphaneau, P., Pouvreau, N. and Karpytchev, M. (2010). "Sea level at Saint Paul Island, southern Indian Ocean, from 1874 to the present". **Journal of Geophysical Research**, 115, C12028.
- Turner, J.F., Iliffe, J.C., Ziebart, M.K., Wilson, C. and Horsburgh, K.J. (2010). "Interpolation of Tidal Levels in the Coastal Zone for the Creation of a Hydrographic Datum". **J. Atmos. Oceanic Technol.**, 27, 3, pp. 605–613.
- Watson, C., Coleman, R. and Handsworth, R. (2008). "Coastal tide gauge calibration: a case study at Macquarie Island using GPS buoy techniques", **Journal of Coastal Research**, 24, 4, pp. 1071-1079.
- Watson, C., White, N., Church, J., Burgette, R., Tregoning, P. and Coleman, R. (2003). "Absolute Calibration of TOPEX/Poseidon

8. Biography of the Authors

Gaël André works currently, as scientific expert in tidal domain, at the French Navy Hydrographic and oceanographic Service (SHOM), within the department of coastal dynamics. His Ph.D. thesis was in the field of physical oceanography. His research interests include tide and tidal current analysis and predictions, storm surges, sea level trends, and GNSS positioning techniques.
gael.andre@shom.fr

Belén Martín Míguez holds a PhD in Marine Science. As a sea level expert she has worked in several governmental and intergovernmental agencies both in Spain and France, including the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and published more than 20 papers in peer-reviewed scientific journals. She is currently working at the Marine Technological Centre (CETMAR) in Vigo, Spain.
bmartin@cetmar.org

Valérie Ballu is a researcher in geophysics and geodesy at CNRS (Centre National de la Recherche Scientifique). She works at LIENSs (Littoral Environnement and SocieteS) in University of La Rochelle. One of her main scientific interests is the development of underwater geodesy for geodynamical purposes.
Valerie.ballu@univ-lr.fr

Laurent Testut is a researcher in LEGOS Toulouse, France. He is responsible for the French Southern Ocean tide gauge network and specializes in tides and satellite altimetry.
laurent.testut@legos.obs-mip.fr

Guy Wöppelmann, Professor in Geodesy and Geophysics at the Université de la Rochelle, France. Chair of the science steering group of the IOC/UNESCO Global Sea-Level Observing System (GLOSS) since 2012, and GLOSS national contact since 2004.
guy.woppelmann@univ-lr.fr