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The Use of Radar Tide Gauges to Measure Variations in Sea Level along the French Coast

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ABSTRACT

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In the last few years, radar technology has been given strong consideration for sea level monitoring. France has been a pioneer in the use of radar technology for its tide gauge network, and the first results of an 8-year-long experience are presented. The performance of the radar sensors has been assessed using the Van de Casteele test, which has been revealed to be an efficient method for detecting the main deficiencies of the installations and evaluate the data quality. The experience so far shows that radar tide gauges present interesting advantages with regard to ease of operation and that their accuracy is consistent with GLOSS 1-cm requirements, provided the installation is correctly performed.

ADDITIONAL INDEX WORDS: *Radar, tide gauges, Van de Casteele test.*

INTRODUCTION

The monitoring of sea level has become a very relevant issue at a local, regional, and global level, with various challenges to be met. On a local scale, the purposes of sea level monitoring can vary from supporting harbor activities and safer navigation to the realization of data for topography and bathymetry and, in more general terms, coastal management (*e.g.*, Wöppelmann, Zerbini, and Marcos, 2006). Sea level data are also needed for measuring and predicting storm surges and validating circulation models as well as calibrating satellite radar altimeters (*e.g.,* Cazenave and Nerem, 2004; Nerem and Mitchum, 2001). On a global scale, sea level studies are crucial to understanding the changes in the Earth's climate and their implications for populations living near the current mean sea level (*e.g.,* Church *et al.*, 2001). In addition to this, the scientific community has been urged to develop a global tsunami warning system in the Indian Ocean, with France playing a key role (IOC, 2005; Merrifield *et al.*, 2005). The capacity for setting up this and other multihazard warning systems is closely related to the development of new sensors that allow the retrieval of accurate and precise data at a higher rate. In this context, the radar technique has rapidly gained ground as a low-cost, reliable technology. As recently stated in the IOC (2004), a number of countries (*e.g.,* the U.K., the United States, South Africa, Spain) either plan to or have already started to upgrade their tide gauge stations with radar sensors. Therefore, it is essential that experience be shared as rapidly as possible. In this regard, previous papers (Barjenbruch *et al.*, 2002; Kranz, Zenz, and Barjenbruch, 2001; Martín Míguez, Perez Gomez, and Alvarez Fanjul, 2005; Woodworth and Smith, 2003) have reported experiences testing radar tide gauges manufactured by different companies and comparing them with other types of gauges. In their turn, the French authorities have pioneered the use of the radar technology for their coastal network Réseau d'Observation du Niveau de la Mer (RONIM), the first radar tide gauge having been installed in 1998. In this paper we report on the experience acquired in France after 8 years of operating radar tide gauges. The purpose of the present contribution is to provide a comprehensive view that includes both the operational aspects of radar gauges and the quality of their data.

THE RONIM TIDE GAUGE NETWORK

In the early 1990s, the Hydrographic and Oceanographic Service of the Navy (SHOM) initiated the modernization of its tide gauge network (Dupuy and Batany, 1992). This initiative led to the RONIM project. Its main component is a network of sea level observation stations located in the main harbors along the European French coast and also in the French overseas territories and departments. Nowadays the network comprises 22 mainland stations (Figure 1) and 4 overseas stations, namely Nouméa (New Caledonia), Fort-de-

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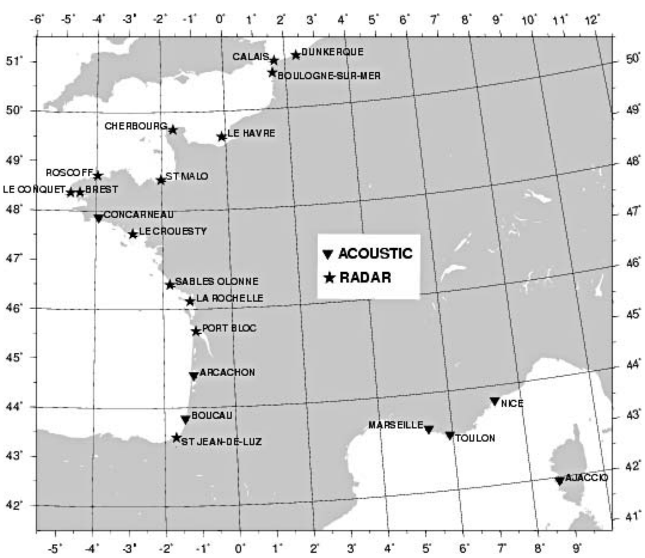

Figure 1. Location of the RONIM operational tide gauge stations in mainland France. Triangles correspond to stations equipped with radar sensors, and stars correspond to stations equipped with acoustic sensors.

France (Martinique), Pointe-à-Pitre (Guadeloupe), and Iles du Salut (French Guyana). Two additional stations are planned overseas in the Indian Ocean at La Réunion and at Mayotte.

The RONIM project aims at meeting the national and international needs related to sea level monitoring. This involves the acquisition of high quality sea level data that must then be made available to end users. Ensuring the quality of the sea level data is not an easy task: The performance of the tide gauges has to be guaranteed under wide tidal ranges and harsh weather conditions, which is the case for most of the stations located on the northern coast of France. The station characteristics may vary depending upon the site, but all of them are conceived to fulfill the requirements specified by French standards (SHOM, 2005), which are compatible with the Global Sea Level Observing System (GLOSS) program (IOC, 1997, 2002, 2006). They feature the following common characteristics:

- Sampling interval < 1h, typically 10 min
- Integration period = 2 or 4 min
- Level accuracy better that 1 cm
- Timing accuracy better than 10 s
- Measurements of sea level referenced to a local reference attached to the land. The geodetic connection between the gauge zero and the local reference is to be controlled to a precision of 1 mm every 5 y.

Each station is equipped with a data acquisition unit. This unit receives the signal recorded by the sensor and performs its averaging during the integration period. The data are recorded at 10-min intervals to internal storage mass. In addition to this, the data are recovered weekly by the data operations center in Brest. The operators in the data center visually inspect the time series and make an inventory of the more evident faults (spikes) for further correction. The data unit also acts as an alarm system when there is a memory overflow, lack of power supply, surpassing of a sea level threshold, etc.

As far as data availability is concerned, there are two main destinations for the data collected in the RONIM network in the scientific community. The first destination is the French SONEL project (details in www.sonel.org), which gives access to hourly quality-controlled sea level height values with a time delay of about 2 months, and to raw 10-min sea level data with a time delay of 1 wk. Secondly, SHOM participates in international projects such as GLOSS (both real-time and delayed mode) and more recently European Sea Level Service (ESEAS) and operational real-time activities including North West Shelf Operational Oceanographic System (NOOS) and Sea Levels along the European Atlantic Coastline (SLEAC). It also provides averaged data (monthly and annual means) to the Permanent Service for Mean Sea Level (PSMSL) (WOODWORTH and PLAYER, 2003).

At present, the RONIM tide gauges use two types of sensors: acoustic and radar. Figure 1 shows the distribution of each type of gauge on mainland France, whereas overseas stations are equipped with radar gauges. The oldest stations use MORS acoustic sensors that, in short, measure the travel time of acoustic pulses reflected vertically from the air–sea interface. Acoustic tide gauges have been used in many places for the sea level observation (IOC, 2002). Their disadvantages are currently well known and have been discussed in several studies (HUNTER, 2003; IOC, 2004), their main problem being their high sensitivity to the temperature gradient between the transducer and the sea surface. These problems are less relevant, yet by no means negligible, in the Mediterranean stations (GONELLA and SIMON, 2002), where the tidal range is much smaller than on the Atlantic coast. Keeping up with technological innovations has led SHOM to gradually replace these acoustic tide gauges by radar tide gauges, beginning with the Atlantic harbors. The first radar sensor was installed in Le Havre in October 1998, and currently the majority of the tide gauge stations are radar (18 out of the 26). Hereafter we will focus on this type of sensor, which is likely to be used for the upgrading of many tide gauge networks in the near future (IOC, 2005).

Radar sensors emit microwave pulses that are reflected by the air–sea interface and then detected and processed, either measuring the phase shift between the reflected and the emitted wave (frequency modulated continuous wave [FMCW] radar) or the transit time of the signal (pulse radar) (see BRUMBI, 2003 and references herein).

The RONIM stations are equipped either with the BM 70A or the BM 100A radar sensors, manufactured by KROHNE. The former is a FMCW radar equipped with a horn antenna (noncontact measuring [KROHNE, 2000]) while the latter is a type of pulse radar that uses a special stainless steel wave guide cable dipped into the water (KROHNE, 2004). The main lobe of the radar signal is guided down the cable thus better discerning the sea–air interface.

Following the preliminary experiences and the manufacturer's advice, the radar gauges have been installed within sheltering structures. On the one hand, this allows the sheltering of the sensors when the environmental conditions are harsh (which can be the case, especially on the north Atlantic coast). On the other hand, it ensures that the sea surface is as calm as possible, which in turn enables the signal to be reflected properly and thus to return to the receiver in optimal conditions. As we shall see, several types of structures have been tested (tubes of different materials and dimensions, stilling wells), depending upon the model of the radar sensor, but also on the existence of a previous structure that could be reused.

THE VAN DE CASTEELE TEST

As a result of SHOM's commitment to ensure the quality of the data, the stations are visited on a regular basis (ideally annually) to check the performance of the tide gauges. These onsite tests are essential because laboratory tests do not take into account the effect of the environmental conditions on the equipment. Furthermore, they avoid the always delicate operation of removing the gauge from its installation while controlling the stability of the tide gauge datum before and after the laboratory checks. A Van de Casteele test was implemented in those visits, adding to the levelling and maintenance operations. This test was conceived by the head engineer Charles de Van de Casteele (1903–1977) in 1962. Originally devised to evaluate the performance of the mechanical float tide gauges, GLOSS recommended its application to control all types of tide gauge stations (IOC, 1985), but to our knowledge its use has not been extended to the modern technologies.

The Van de Casteele test consists of taking readings of a manual probe against the tide gauge readings over a full tidal cycle. The results are then used to produce a plot representing the sea level in the Y axis and the differences in the X axis. The manual probe is used as the reference instrument, thus implicitly assuming that this provides more accurate measurements than the instrument we are testing. The probe used in the tests was an OTT optical probe whose accuracy varied between 4 mm (3-m range) and 8 mm (12-m range) according to the previous laboratory tests (LE ROY, 2006). Obviously, the results also depend to a great extent on the ability of the operator of the manual probe, thus human errors cannot be totally excluded.

Should both the probe and the tide gauge provide perfect measurements, the differences would remain constant and equal to 0, that is to say, we would expect a straight vertical line in the Van de Casteele plot. This is generally not the case, and the shape of the Van de Casteele diagram allows us to identify the problems associated with each tide gauge regardless of its origin: offset in the tide gauge datum, instrumental faults, inadequacy of the installation, etc. (IOC, 1985; LENNON, 1968).

RESULTS

Between 2002 and 2005 several Van de Casteele tests were carried out on a number of stations equipped with radar sensors. Most of the tests were undertaken during spring tides, during a full tidal cycle, measurements being taken every 5 or 10 min. The integration period for the radar gauge was reduced to 10 s to ensure a better correspondence with the manual probe measurements. The results of a selection of those onsite tests (Table 1) is now presented. These tests have permitted us to evaluate the quality of the data provided by the radar sensors as well as to optimize the design of the tide gauge stations to best suit the new sensors.

Table 1. *Main characteristics of each of the Van de Casteele tests mentioned in the text.*

Radar Tide-Gauge Site	Type of Installation	Tidal Range (m)	RMS (radar-probe) (cm)	Other Comments
La Rochelle	PVC tube	5	1.8	Metallic rings
Saint-Malo	Stainless steel tube	12	1.1	Large tidal range
Brest	Stilling well	7	0.6	Datum offset
Roscoff	Stilling well	8	2.3	Waves of 30 cm

The results of the tests are analyzed by interpreting the shape of the curve resulting from the Van de Casteele diagram, that is to say, by plotting the sea level height measured by the probe (P, Y-axis) against the differences between the probe and the radar readings ($P - R$, X-axis). We also calculate the root mean square (RMS) of the time series of $P - R$ as a way to evaluate the error of the radar measurements. Because during the test the integration period for the radar gauge is shorter than during its normal operation (10 s instead of 2 or 4 min, hence, fewer measurements are taken into account for each averaged value), we expect the RMS to be an upper error level.

Radar Installed within a PVC Tube

La Rochelle station was one of the first to be equipped with a radar sensor, a KROHNE BM 70A radar. The sensor was installed inside a protective structure, a PVC tube of 30 cm diameter fixed to the pier (Figure 2). The results of the Van de Casteele test undertaken during the maintenance visit to the La Rochelle station are presented in Figure 3. A nonrandom pattern clearly appeared with maximum positive differences taking place when the sea level was approximately at 1, 2, 3, 4, 5, and 6 m, and minimum differences in between those levels. The levels of maximum differences between the probe gauge and radar gauge readings were found to coincide with the position of the supporting rings that fix the PVC tube against the pier. The PVC material does not interfere with the radar signal and in principal has no effect upon the signal. However, the metallic rings may act as a reflecting surface that interferes with the signal reflected by the sea surface. When the sea level is in between two rings, the transducer manages to discern clearly both signals, and only processes the most intense one, thus yielding a value closer to the correct one.

The results of the Van de Casteele test can also be used to evaluate the quality of the data and in particular to assess if they comply with 1-cm accuracy, which is one of the requirements of the tide gauges to be included in the GLOSS (IOC 1997, 2002). With this purpose we first suppose that the errors due to the probe (E_P) and the errors due to the radar sensor (E_R) follow a random distribution. Under this assump-

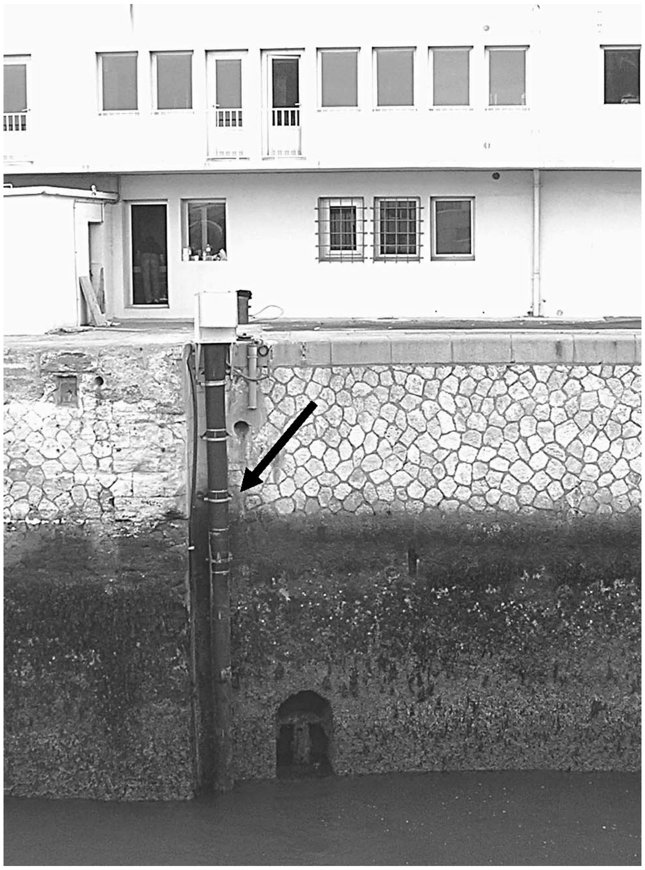

Figure 2. BM 70A radar sensor installed inside a PVC tube of 30 cm diameter, and fixed to the pier with metallic rings (black arrow).

tion, the root mean square of the time series of the differences between the two instruments (RMS_{P-R}) can be expressed as follows:

$$\mathrm{RMS}_{P-R} = \sqrt{E_P^2 + E_R^2}. \tag{1}$$

In this case, the RMS_{P-R} error is 1.8 cm. Taking into account that the probe error E_P claimed by the manufacturer under normal temperature and pressure conditions is 0.5 cm, we obtain E_r:

$$E_R = \sqrt{(\mathrm{RMS}_{P-R})^2 - E_P^2} = \sqrt{1.8^2 - 0.5^2} = 1.7\ \mathrm{cm}. \tag{2}$$

Equation (2) provides an estimation of the error of the radar level measurements (WOODWORTH and SMITH, 2003).

Even if the results are largely satisfactory for many of the tide gauge applications (*e.g.,* harbor operations), the estimated radar error is larger than the desired 1-cm level and the long-term sea level trends may be affected by this. To further investigate the effect of the rings, an additional 20-d experiment of comparison between the radar gauge and a pressure gauge was carried out, confirming what had previously been found with the Van de Casteele test.

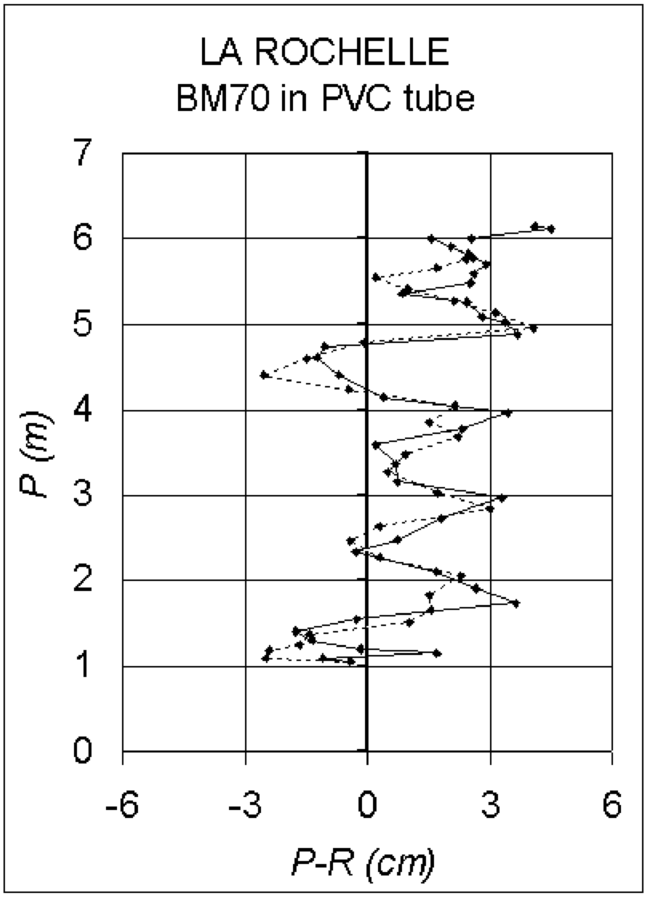

Figure 3. Results of the Van de Casteele test undertaken in La Rochelle tide gauge station. Sea level heights measured with the probe (*P,* in meters) are plotted against the differences between the probe readings and the radar readings ($P - R$, in centimeters). The dashed line corresponds to falling tide and the continuous line to rising tide.

Radar Installed within a Stainless Steel Tube

Following the problems observed in the previous case, a new type of station was conceived. This new type of station was tested at a site featuring a particularly large tidal range: Saint-Malo (12 m). The radar gauge BM 70A was installed inside a stainless steel tube, with a diameter of 9 cm. Next to it, there is a PVC tube of the same dimensions, which is used for the manual probe readings (Figure 4). In principle, the stainless steel tube does not interfere with the microwave signals; however, it increases significantly the total cost of the station.

As we see in Figure 5, this time the $P - R$ values are randomly distributed along the tidal range, which confirms that the tube has no effect upon the signal. It shows, however, that the difference $P - R$ increases slightly as we approached the low tide. This is probably due to a reduction of the amplitude of the signal as the air gap increased because of the large tidal range. Despite this, the overall results were very satisfactory given the extreme tidal range. The obtained

Figure 4. BM 70A radar sensor installed inside a stainless steel tube of 9 cm diameter. The adjoining PVC tube is used to make the probe readings.

RMS is 1.1 cm, which would yield an error $E_R = 1.0$ cm (Equation 2) for the BM 70A in this type of installation.

Radar Installed within a Stilling Well

The sea level observatory located at Brest is the oldest one in the French network (WÖPPELMANN, POUVREAU, and SIMON, 2006). Several types of tide gauges have been operating there over the years, the latest one a BM 100A radar sensor equipped with a wave guide cable. In this case, the BM 100A was installed inside a stilling well of 1-m^2 section, taking advantage of the previous infrastructure. Above the stilling well, a shelter contains the instrumentation composed of the radar transducer, the data logger, and a modem for data transmission.

The Van de Casteele diagram is presented in Figure 6. The RMS_{P-R} resulting from the experiment is 0.6 cm. Applying Equation (2) would yield $E_R = 0.3$ cm, thus largely fulfilling the GLOSS requirements of 1-cm accuracy. Nevertheless, the diagram highlights the error in the tide gauge data (otherwise, the mean of the differences between the probe and the radar sensor, $P - R$, should be centered on zero) and the slight inclination of the curve, showing that at low tides the differences, $P - R$, became more positive. Both problems were corrected by recalibrating the sensor.

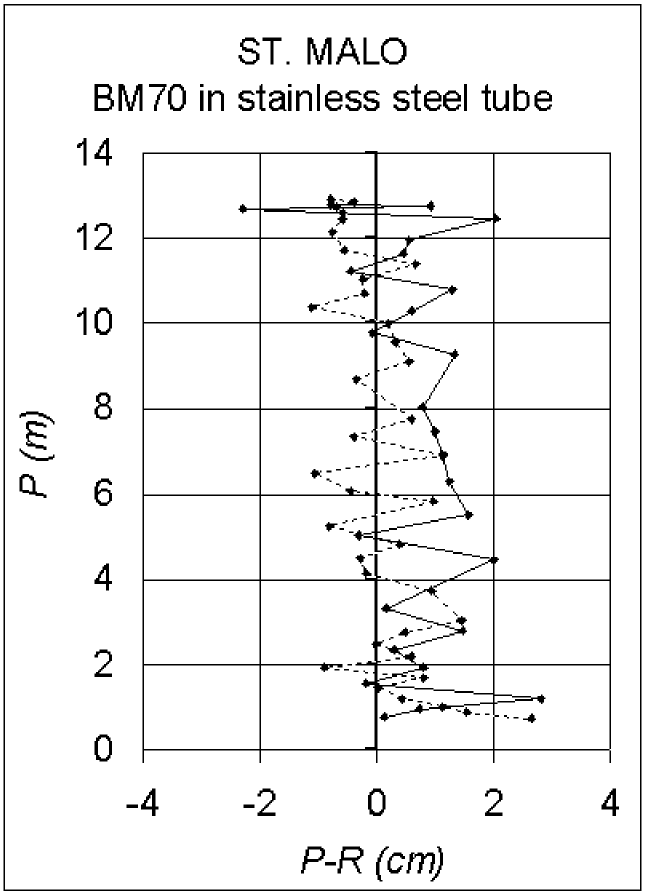

Figure 5. Results of the Van de Casteele test undertaken in Saint Malo tide gauge station. Sea level heights measured with the probe (*P,* in meters) are plotted against the differences between the probe readings and the radar readings ($P - R$, in centimeters). The dashed line corresponds to falling tide and the continuous line to rising tide.

We can also notice that the $P - R$ values for a given sea level may differ between the rising tide and the falling tide. This feature usually appears when testing mechanical gauges (IOC, 1985) and is related to hysteresis, but this effect is expected to be irrelevant in the case of radar. Occasional inaccuracies when taking the manual readings (human errors, lack of synchronization between the measurements, and others) are the most likely reason for those differences. For Figure 6, in particular, the largest $P - R$ differences are found between 4 and 7 m, coinciding with a change of probe.

Another Van de Casteele test was carried out at the Roscoff station, with results presented in Figure 7. The installation consists on a BM 100A radar sensor mounted within a stilling well, similar to Brest, but in this case the differences between the probe and the radar readings are far greater (RMS = 2.3 cm). This would lead us to think that the BM 100A sensor is not performing adequately and clearly not complying with the GLOSS requirements. The line in the diagram, however,

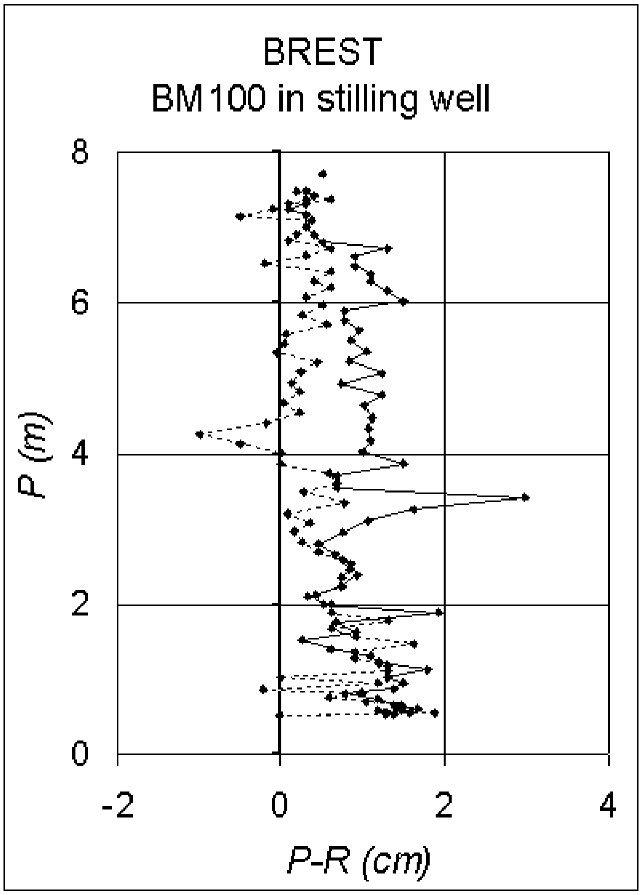

Figure 6. Results of the Van de Casteele test undertaken in Brest tide gauge station. Sea level heights measured with the probe (*P,* in meters) are plotted against the differences between the probe readings and the radar readings ($P - R$, in centimeters).

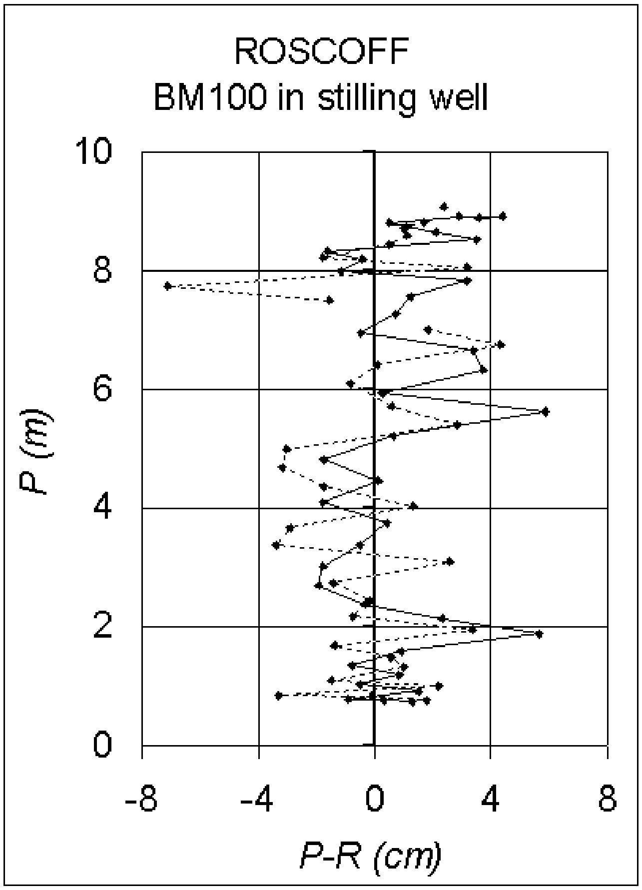

Figure 7. Results of the Van de Casteele test undertaken in Roscoff tide gauge station. Sea level heights measured with the probe (*P,* in meters) are plotted against the differences between the probe readings and the radar readings ($P - R$, in centimeters). The dashed line corresponds to falling tide and the continuous line to rising tide.

is remarkably straight and centered. In this case, the relatively high errors encountered cannot be assigned only to the radar sensor, but also to the probe readings. In fact, during the test, waves of approximately 30 cm height were observed, unlike the test at Brest, where calm conditions prevailed (Table 1). This may have prevented the operator from taking accurate readings with the manual probe, particularly in the case of stilling wells where the damping effect is less effective than within a tube. This fact sets a certain limit for the applications of the Van de Casteele test because the assumption that the reference system (the manual probe) is more reliable than the tested one (the radar) turns out to be unrealistic under certain conditions.

DISCUSSION AND CONCLUSIONS

The coastal acoustic tide gauge stations in France have been progressively replaced by radar equipment since 1998. Whenever there is a change of instrument, the reliability and the accuracy of the new equipment must be assessed. In fact, the GLOSS recommendations state that an overlapping period of at least 1 year should be ensured (IOC, 1994) to provide enough data to make a comparison between the old and the new technology. Nevertheless, the "perfect" sea level gauge does not (yet) exist, and whenever we compare two instruments, there will always be some uncertainty regarding which is the most reliable one. On the other hand, even if this is clearly the ideal situation, carrying out this type of long-term experiment is not always feasible because they require an important investment, be it financial or human. At present, only Brest is running both types of gauges, radar (KROHNE BM 100A) and acoustic (MORS), since February 2004. Our experience with the Van de Casteele test, on the contrary, has shown that this test is a very cost-effective option to evaluate the performance of the tide gauges and in particular of the new radar equipment in the French RONIM network. First of all, the Van de Casteele test provides us with an estimation of the quality of the sea level data as long as we can ensure the correct performance of the probe used as a reference, that is to say, provided the sea conditions are calm so that the manual readings can be made correctly. The results of the test have permitted us to verify that the radar tide gauges meet the 1-cm accuracy required by GLOSS (IOC, 1997, 2002, 2006).

Besides, the periodic visits to the tide gauge stations and the regular performance of the test (ideally once a year) have also permitted us to check that the sensors show no drift and thus have required no recalibration so far. Nevertheless, more data to be gathered for further assessment of this issue. Finally, the results of the test have allowed us to detect some problems related to the lack of adequacy between the radar sensors and the sheltering structures, and hence improve the design of the stations. In this regard it must be said that, unlike other types of tide gauges, radar sensors do not need to be installed within sheltering structures. On the one hand, radar sensors have proven robust enough to endure harsh weather, showing little sensitivity to external conditions. Moreover, the stilling well is no longer indispensable to reducing the spurious effect of waves in the tidal signal; because of the radar high sampling frequency, this effect can be eliminated by filtering the data (the so-called software damping used in Barjenbruch *et al.*, 2002). Finally, the open-air stations are less expensive, both to install and to maintain, because they demand fewer cleaning operations.

Having said all this, in the French network, the mounting of inside tubes or stilling wells is still undertaken, often taking advantage of a previous structure. This presents some other advantages. First of all, it reduces the risk of vandalism and it avoids the arrival of objects to the tide gauge that could cause false echoes. Moreover, the use of a manual probe to perform the onsite dipping tests (*e.g.,* the Van de Casteele test, or measuring the data offset) requires calm sea conditions, and this can be more easily accomplished when operating inside a stilling well or a tube.

The operation of radar sensors has shown that in addition to the classical stilling well problems (Lennon, 1993), there is a risk of interaction of the protective structure with the radar signal. These inconveniences were first successfully avoided by employing stainless steel tubes, but their high price was a drawback. Currently, the SHOM has opted to purchase the new KROHNE OPTIFLEX radar model, which sends the signal along a wave guide cable, thus reducing the probabilities of the signal being affected by the tube.

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☐ RESUMEN ☐

La tecnología radar ha ganado terreno en el campo de la medición del nivel del mar. Francia ha sido pionera en el uso de dicha tecnología en su red de mareógrafos y a continuación se presentan los primeros resultados de esa experiencia. Se ha empleado el test de Van de Casteele para evaluar el funcionamiento de los mareógrafos radar. Dicho método ha permitido mejorar el diseño de las estaciones y evaluar la calidad de los datos de una forma eficaz y económica. La experiencia muestra que los mareógrafos radar presentan ventajas interesantes con respecto a su operación y que proporcionan datos que cumplen los criterios de calidad exigidos por GLOSS (Global Sea Level Observing System), siempre y cuando la instalación se adecue al tipo de sensor.

☐ RÉSUMÉ ☐

La technologie radar gagne du terrain dans le domaine de la mesure du niveau de la mer. La France a été pionnière dans l'application de cette technologie à son réseau de marégraphes. Les premiers résultats sur les huit ans d'experience acquise maintenant sont présentés. Les performances des marégraphes radar sont évaluées à l'aide du test de Van de Casteele qui se révèle une méthode efficace et relativement économique pour détecter les principaux défauts des installations et apprécier la qualité des observations. L'expérience acquise à ce jour montre des atouts opérationnels intéressants, de même qu'une précision centimétrique dans la mesure de hauteur d'eau en accord avec les spécifications du programme mondial GLOSS (Global Sea Level Observing System), à condition que leur installation soit appropriée.