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Assessment of accuracy and operational properties of different tide gauge sensors

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ABSTRACT

In December 2002 a pilot station of tide gauges was established by Puertos del Estado (Partner 6) at the port of Vilagarcía de Arousa (NW Spain). The aim was to compare the accuracy and the operational properties of the different technologies to support the future decisions concerning the improving of the sea level observing system (Work Package 4, Task 4.1, ESEAS-RI project). This report summarises the most important results obtained during the study.

REPORT STRUCTURE

1. INTRODUCTION

Sea level is a crucial environmental variable for understanding processes related with Global Climate Change. As recently stated in the Galway Declaration (EurOCEAN2004,[18]), one of the challenges of the EU is “responding to the implications of global climate change and its impacts on marine and coastal environments and communities”. Sea level monitoring requires of a network of tide gauges, adequately located and managed, and this is one of the aims addressed at the ESEAS-RI (European Sea Level Service Research&Infrastructure) project [7]. The European network of tide gauges currently consists of more than 150 tide gauges. It is obvious that the better the data provided by the tide gauges are, the better those applications will be accomplished. In this respect, the upgrading of the tide gauges sites will improve the research utility provided by the ESEAS network.

This report intends to shed light on the advantages and disadvantages of the different technologies available for measuring the sea level. It is the first time that so many systems are tested simultaneously over such a long period. Radar sensors, in particular, are of especial interest for they are a relatively new technology.

The examination of the performance and adequacy of the equipment can be approached from different perspectives which, for our purposes, we will divide in two. The first perspective is that of the quality of the data. The quality of the data, considered in a broad sense, includes their accuracy, lack of spikes and gaps, stability of the measurements, etc. Nevertheless, when purchasing an equipment, there is also an operational perspective that must be considered. The robustness (lack of malfunctions), for example, can be crucial, for obtaining long time series. Installation and maintenance requirements are also relevant aspects, for they may bring about extra expenses. Security is also a very important issue, for the equipment can be exposed to vandalism and some of the tide gauges can be more easily protected and less visible than others.

GLOSS (Global Sea Level Observing System) requirements for a GLOSS-quality tide gauge are the main reference. These requirements are described in the Implementation plan for GLOSS [9] and the IOC (Intergovenrmental Oceanographic Comission) manuals [10], and in brief, they imply that the equipment must measure to centimetre accuracy in all weather conditions for the temporal averaging indicated (typically hourly).

The report is structured as follows. After the introduction, in section 2 we make a thorough description of the sensors included in the experiment focusing on their operational properties. In section 3 we describe the pilot station and relate the main incidences that took place during the experiment. Section 4 contains the results of the comparison performed on the time series provided by the tide gauges. Finally, in section 5 we draw some general conclusions and propose some recommendations for the upgrading of the tide gauges network.

2. DESCRIPTION OF THE TIDE GAUGES: TYPES AND OPERATIONAL PROPERTIES

Table 1 summarises the main characteristics of the equipment that took part of the experiment and the total amount of data that they have delivered. Some of the tide gauges were loaned from public institutions (NOAA, POL) or private companies (ENRAF, SIDMAR). Puertos del Estado (PE) provided 3 of the sensors.

Type of Sensor	Sensor	Beginning of data	Months of operation(1)	Provider
Acoustic	Aquatrak (AQU)	1 Mar 2003	10	NOAA(2)
Acoustic	Sonar (SRD)	Permanent gauge	15	PE
Hydrostatic Pressure	Seabird (SBE)	2 Mar 2003	11	SIDMAR
Bubbler Pressure	POL (POL)	11 Dec 2003	7	POL(3)
FMCW Radar	Radac (RAD)	7 Mar 2003	14	ENRAF
FMCW Radar	Miros (MIR)	1 Mar 2003	15	MIROS
Pulse Radar	Geonica (GEO)	24 Mar 2003	14	PE
Pulse Radar	Seba (SEB)	2 Mar 2003	10	PE

Table 1 Tide gauges that have been considered in the experiment.

(1) up to June 2004
(2) United States National Oceanic and Atmospheric Administration
(3) Proudman Oceanographic Laboratory

As we can see in Table 1, the sensors involved in the experiment basically belong to three main types: acoustic, pressure and radar. In short, the first type of sensors measure the travel time of acoustic pulses reflected vertically from the air/sea interface. Pressure sensors use the changes in the pressure exerted by the water column as the tide progresses. Finally, radar sensors detect microwave pulses that are reflected by the air/sea interface, either by measuring the transit time of the signal (pulse radar) or the phase shift between the reflected and the emitted wave (optical phase ranging [12]). These different ways of measuring involve changes in the operational features, which will be explained in detail in the present section. By operational features we refer to all those aspects that might be of interest when working with one tide gauge. For example, the infrastructure requirements differ greatly. Pressure systems require the hiring of divers for its installation, whereas acoustic systems must be installed within a protective tube. Radar systems can be more easily installed by fixing them to a supportive structure.

These are the aspects that we shall consider:

1. Components of a station

We can distinguish three types of components:
- Measuring components (Sensor, transducer...)
- Protective/support components (Tube, stilling well, mast...)
- Storing/controlling components (Self-contained datalogger, PC...)

2. Measuring

We will provide a detailed explanation on the technique used by each sensor to determine sea level: type of signals employed and how the transducer makes their conversion into level measurements. Sensors of different type and even of different brands perform the measurement in a different way and the total amount of data that are integrated along each sampling period can be very different. This will be examined and described in detail as these differences could help to interpret part of the results of the comparison in section 4.

3. Data Storage

Data can be stored at different rates in the corresponding storing unit. When possible, the systems were configured with the highest rate available. In fact, the storing rate is the actual sampling rate for the person who receives the time series.
Regarding the storing component, it is important to bear in mind the way the system makes the assignment of the date and time. Aquatrak, Miros, Radac and POL bubbler sensor pour their data directly to the PC, so the time associated with the data depends on the correctness of the PC time. This should be possible to be controlled easily but it was not done during this experiment. In other cases, it is the datalogger which assigns the time (SEBA, GEONICA). Finally in the case of the SRD acoustic gauge or the Seabird the time and date is assigned by an internal EPROM inside the sensor.

4. Data Reduction

Some of the systems perform the processing of the raw data in order to deliver an average value over the final sampling period. This processing can involve getting rid of the out of range values, averaging, in a more or less sophisticated way, which in general is not known in detail by the user. The length of the sampling period can be selected by the user thus we set it to the minimum available in each case (from 5 min to 1 s). When the instrument allowed the recording of the data with a high storing rate (1 Hz), we had to make a basic quality control and the averaging to obtain the final time series. The sampling strategy for the first comparisons was designed to fit the SRD data from the reference REDMAR station, that is to say, we achieved time series with a 5-min interval. As we shall see, the different strategy of measurement followed by the equipment originates differences in the number of samples that are actually averaged to provide the final value each 5 min. Besides, some of the tide gauges also require taking into account some other variables (atmospheric pressure, water density) to calculate the final sea level value.

5. Maintenance requirements

All equipment require some maintenance operations to be carried out such as cleaning the protective tubes, checking the clock, controlling the stability of the sensor, draining the compressor (for the bubbler pressure)... A summary table is provided (Table 2).

6. Reliability (claimed by the manufacturer)

Resolution: the smallest change in water level that can be detected by the sensor.
Accuracy: ratio of the error to the full-scale output or the ratio of the error to the output, as specified, expressed in percentage (how close the scaled sensor output is to the actual water level). Both magnitudes are reported in Table 3.In general the resolution and accuracy improve as the range of the sensor decreases.

AQUATRAK (AQU)

The US National Oceanic and Atmospheric Administration (NOAA) provided this acoustic sensor.

Components

- Measuring components: Transducer Aquatrak s/n 1717-3944 within a calibration tube s/n1289
- Protective components: PVC tube (80 mm diameter).
- Controlling/Storing components: Controller Mod. 4100 s/n 110398/PC

Measuring

The Aquatrak sensor sends an acoustic pulse down a 13-mm diameter PVC calibration tube towards the water surface. The elapsed time from transmission until the reflection of the pulse from the water surface returns to the transducer is used as a measure of the distance to the water surface. Since the velocity of the acoustic pulses depends greatly on the air temperature, a calibration tube is needed in order to correct changes in their speed. In the calibration tube there is a discontinuity at a known distance, which causes a decrease in acoustic impedance as the pulse passes it, resulting in another reflection, used as reference for calculating the speed of sound [8].
The calibration tube is located within a protective well, painted white to minimise the significance of temperature gradients, which can be really relevant in places with large tidal ranges. No thermistors were placed in the tube despite this is usually done in the NOAA network.

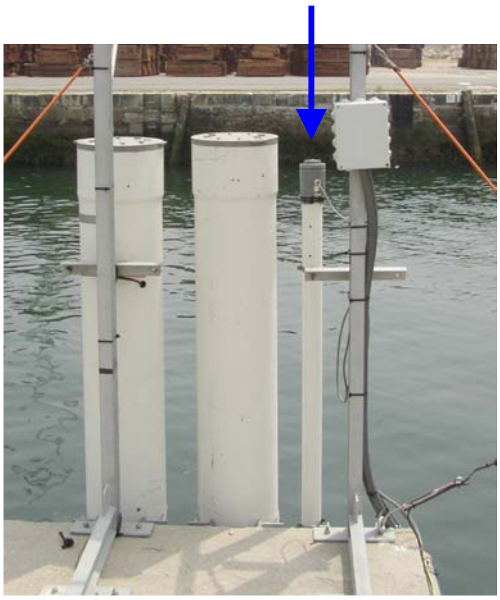


Figure 1 Aquatrak tide gauge installed within its protective well (signalled by an arrow)

Data Storage

The gauge has no recording unit; data are stored in a PC. The data are captured and recorded at a rate of 1cps using a software developed by SIDMAR (the company that performs the maintenance of the station) in LabView.

Data Reduction
We eliminated the out of range values and obtained the arithmetic mean over a 5-min period (300 samples/averaged value). Data were stored in a PC.

GEONICA (GEO)

Pulse radar sensor purchased by Puertos del Estado.

Components

- Measuring components: Transducer VEGAPULS 42
- No protective component. Mast
- Controlling/Storing components: Geonica System METODATA/HYDRODATA-1256C with modem GSM and GPS/Datalogger s/n MU-9012.0011

Measuring

The antenna of the radar sensor emits short GHz radar signal as short pulses. The radar impulses reflected by the air-water interface are received by the antenna as radar echoes. The running period of the radar impulses from emission to reception is proportional to the distance and hence to the level. The radar impulses are emitted as packages with a pulse duration of 1ns and pulse intervals of 278 ns, which corresponds to a pulse package frequency of 3.6 MHz. The processing of this signal is accomplished through a special time transformation procedure which spreads out the more than 3.6 million echo images per second in a slow-motion picture, then freezes and processes them. Eventually 43 echoes per second are generated out of the 3.6 million images [5].

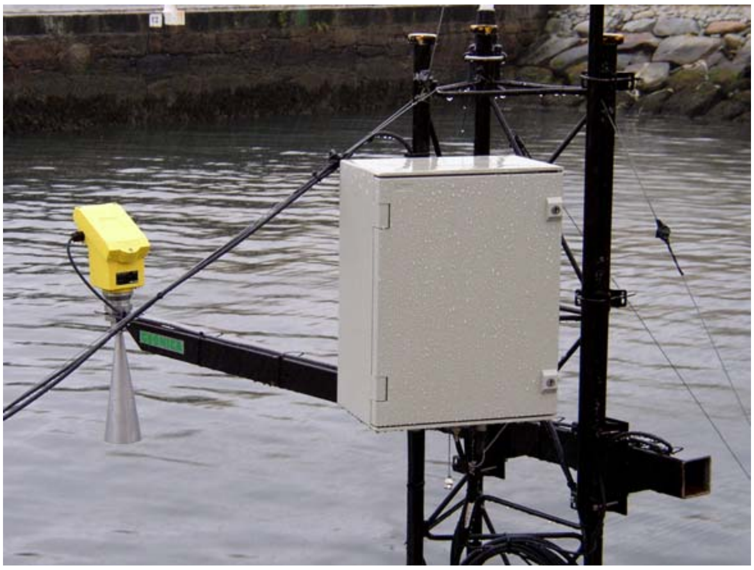


Figure 2 Horn-antenna and box containing the datalogger for the GEONICA system

Data Storage:
Data are stored in a datalogger each 5 min at the end of the integrating period. The GEONICA datalogger manages the strategy of measurement and acquisition and storing of data. The user can modify the storing interval. Besides, data are transferred via modem GSM and allows the communication with a PC where data are also recorded in an Microsoft Access database. It is the only tide gauge in the pilot station that permits the control of the assignation of time via GPS.

Data Reduction:
Arithmetic mean performed by the GEONICA software. This software also calculates the maximum, minimum and standard deviation of the high-frequency data (in principle values per s) integrated along the 5-min period.

MIROS (MIR)

FMCW radar sensor supplied by the manufacturer for the experiment. The frequency of operation ranges between 9.4 and 9.8 GHz.

Components
- Measuring components: Sensor (Miros Range Finder) SM-094/20W s/n P010049
- No protective component. Mast
- Controlling/Storing components: Software MirLog06/PC

Measuring:

MIROS sensor uses the FMCW (continuous wave swept frequency modulation) method which makes use of the optical phase ranging [12]. In principle, this method is more accurate than the pulse one even though it can have some other drawbacks. The frequency of the emitted continuous radio wave undergoes a triangular modulation, and this brings about a phase shift Δf between the emitted wave and the received wave. That shift is proportional to the running time and therefore to the distance. By mixing, a differential frequency is generated in the low-frequency range. This differential frequency can be converted into distance by being split into their component parts, which are then examined for frequency content using calculation-intensive Fourier transformations (FFT). The FFT calculations consists of finding the peak value, setting the detection level, finding the range cell corresponding the shortest range with amplitude above the detection and determine the range by interpolating between adjacent range channels and by adding a fixed internal range offset. The effect of multi-path, fading and multiple time around echoes is eliminated by means of a range-tracking window. The centre of the window is determined by low-pass filtering of the measured range values. As long as the measured range falls within the tracking window the value is used as an output. If the value is outside the window, the range will be set equal to the last accepted value. Furthermore, fixed unwanted echoes may be suppressed by subtraction of an averaged background echo vector before the range estimation algorithm is applied to the FFT output [13].

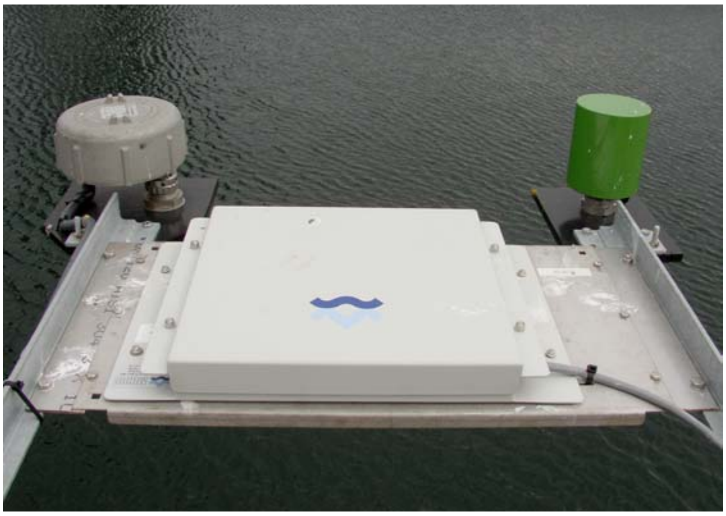


Figure 3 Miros model with a planar antenna, installed between two horn-antenna radar sensors.

Data Storage:
The digital output rate can be 2 or 4 Hz (for the SM-094/20W model). This sampling rate is high enough to allow the monitoring of waves. Besides, the software package provided by the manufacturer enables the

output of files resampled to provide data each exact second, and with several averaging periods (1, 5 min..) which are stored in a PC.

Data Reduction:

We did not perform any processing because the Miros equipment performed the arithmetic mean of the 2Hz data and provided the averaged value each 5 min.

POL (POL)

Pneumatic bubbler pressure sensor provided by the POL.

Components

- Measuring components: Differential Pressure Transducer Paroscientific Digiquartz 230G-119
- No protective component
- Controlling/Storing components: Datalogger Dataring (developed by POL)/PC.

Measuring:

In a pneumatic bubbler system air is passed at a metered rate through a small controlled tube to a pressure point submerged well below the lowest expected tidal level. The pressure point normally takes the form of a short vertical cylinder with a closed top face and open at the bottom. A small hole is drilled about half way down its length and metered air is entered through a connection on the top surface. As air from the tube enters the pressure point it becomes compressed and pushes the water down inside the chamber until the level of the bleed hole is reached when the air bubbles out through the hole and back to the surface. Provided that the air flow rate is low and the air supply tube is not unduly long the pressure of air in the system now equals that of the pressure due to the depth of the water above the bleed hole plus atmospheric pressure. A pressure recording instrument connected into this supply tube will now record the changes in water level as changing pressures. In this case, the pressure-recording instrument is a Parascientific Digiquartz, a differential pressure transducer. The precision quartz crystal resonator has a frequency of oscillation that varies with pressure-induced stress. The barometer mechanism employs bellows as the pressure-to-load generators [19].

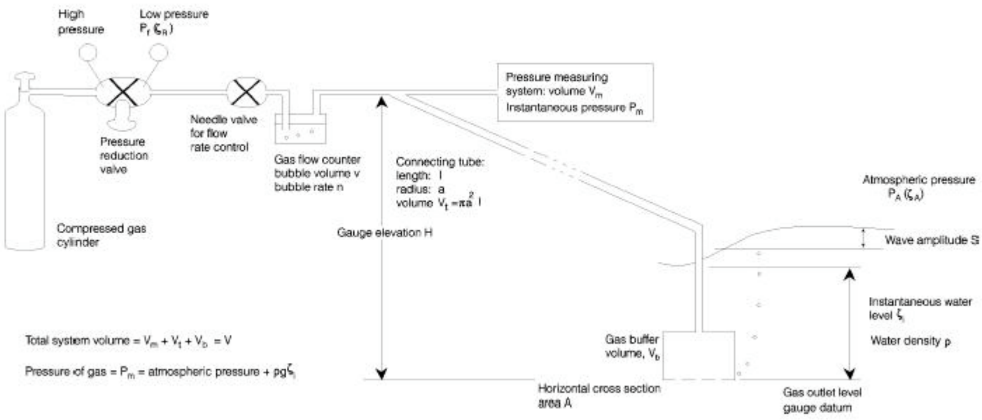


Figure 4 Schematic of a Bubbler Pressure Gauge System (Figure taken from [10]) and detail of the measuring point.

Data Storing:

The frequency capture, processing and data storage is performed by a datalogger DATARING developed by POL. Data are continuously integrated and averaged over a 10s period. At the end of each 10 s interval, the average value was stored in the PC.

Data Reduction:

We eliminated the out of range values and obtained the arithmetic mean over a 5-min period (30 samples/averaged value).

RADAC (RAD)

FMCW radar sensor supplied by the manufacturer for the experiment. The frequency of operation ranges between 9 and 11 GHz. It is not a last-generation tide gauge.

Components

- Measuring components: ENRAF-SmartRadar adapted for open waters UEAZ873YZAF08/0300-NL s/n 873-02-041
- No protective component. Mast
- Controlling/Storing components: ENRAF conditioning and controlling unit/PC

Measuring:

This sensor uses the Synthesised Pulse Radar measuring system (SPR). During a small timeframe (a pulse), a radar frequency sweep is emitted towards the product level. Coming back in a split second from the product level, at the antenna there will be a frequency difference between the sent and received signal, which is the basic parameter for distance calculation. This frequency difference is digitised for further digital signal processing where computer power is decisive for the overall gauge performance. SPR gives the accurate product level immediately using one single frequency sweep. SPR digitises the measurement signal and then full digital signal processing does the rest. The measurement signal is decomposed into its original frequency differences. Using the parameters in the radar gauge, the complete measuring range can be divided into zones where different selection criteria are used to find the product level [17].

Figure 5 Horn antenna of the RADAC tide gauge.

Data Storing:

The gauge has no recording unit; data are stored in a PC with a 1 s sampling interval. As in the case of AQUATRAK, the data were captured and the time was assigned with a software specially developed by SIDMAR for the experiment.

Data Reduction:

We eliminated the out of range values and obtained the arithmetic mean over a 5-min period (300 samples/averaged value).

SEABIRD (SBE)

Pressure sensor supplied by the company who performs the maintenance of the Pilot Station. The equipment also measures the water temperature.

Components

- Measuring components: SBE 26 s/n 2616957-0199 with a Paroscientific Digiquartz transducer (Model 245AT)
- Protective component: PVC tube (300 mm diameter).
- Controlling/Storing components: Datalogger self-contained

Measuring:

The SBE 26 contains a Paroscientific Digiquartz pressure sensor with a temperature-compensated quartz element. Tide measurements are obtained by continuously counting the pressure frequency with a 40 bit ripple counter. Each time the SBE 26 wakes up the ripple counters are latched into registers and then reset. A continuously powered real-time clock sets the wake-up time with an accuracy of 5 ppm and a resolution of 2 milliseconds. The pressure sensor output is continuously integrated to average out wave action. It makes 4 measurements per s. The user-programmable tide integration time can be set from 1 min to 500 h, on 1-min intervals. High-accuracy temperature information is recorded with each tide measurement [13]. The sensor also allows the monitoring of waves.

Figure 6 The installation of a SBE tide gauge requires the hiring of divers. In the pilot station, the sensor was placed inside a protective PVC tube.

Data Storage:

The SBE was configured so that it integrated the pressure sensor output over a 5-min interval, calculating and storing an average pressure for that time period. Averaged values are recorded each 5 min and the date and time corresponds to the beginning of the sampling period.

Data Reduction:

We used the 5-min data provided by the instrument and then we converted them into sea level measurements taking into account the density of the seawater and the atmospheric pressure. Unlike the case of POL, where the system performed all the calculations needed for the estimation of the sea level, in this case it was us who had to make that correction. The density was calculated according to the International Sea State Equation, using the temperature data provided by the sensor and assuming a constant value = 35 psu for the salinity. Atmospheric pressure was obtained from a nearby meteorological station managed by MeteoGalicia [21].

SEBA (SEB)

Pulse radar sensor purchased by Puertos del Estado.

Components

- Measuring components: Transducer SEBAPLUS s/n 122764
- No protective component. Mast

- Controlling/Storing components: Datalogger s/n MDSIII Nº1607

Figure 7 Horn antenna of the SEBA tide gauge.

Measuring:
The antenna of the radar sensor emits short 24 GHz radar signal as short microwave pulses. Then the sensor rests for a short time. During this time the response signals of the water is received and transmitted to the integrated evaluation system [20].

Data Storage:
Data are stored in a datalogger each 1 min.

Data Reduction:
We obtained the arithmetic mean to obtain one average value each 5 min (i.e. 5 samples/averaged value).

Sonar (SRD)

Acoustic sensor forming part of the Spanish tide gauge network operated by Puertos del Estado. It is a permanent station, which has been functioning since 1997 and we will use it as a reference throughout the experiment.

Components:
- Measuring components (at sea level): Transducer SRD + control unit (LPTM) and transmission unit (radio)
- Protective components: PVC tube (300 mm diameter)+ Protection well against boats.
- Controlling/Storing components (at the harbour): Reception unit (MTU) and PC.

Measuring:

The transducer emits an acoustic pulse (50 kHz) and receives the signal after this has been reflected by the sea surface. The distance to the water is calculated from the sound velocity and the time the ultrasonic ray needs to reach the water surface and travel back to the transducer.
The sampling period lasts about 37-50 s. During the first 10 s, 128 echoes are sent to a calibration point fixed at a known distance. This allows the correction of the effect of the air conditions and the calculation of the effective sound velocity. Soon after that, another 128 echoes are sent to the sea surface, which are averaged to filter out the waves and provide the final value [10]. The system operates down a protective PVC tube, with 30 cm of diameter, with aprox. 3 cm hole. This tube filters out the short-period waves.

Figure 8 SRD station in the harbour of Vilagarcía de Arousa

Data Storage:

Each 5-min at the end of the 37-50 s period.

Data Reduction:

This tide gauge is part of the Spanish tide gauge network (REDMAR), thus, the data undergo near-real time quality control (automatic detection of spikes, interpolation of short gaps and adjustment of the time of measurement).

MAINTENANCE REQUIREMENTS

In the next table we report the most important maintenance operations that were carried about during the experiment.

Maintenance	Type of tide gauge							
	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
Checking of clock	X	X	X	X	X	X	X	X
Levelling of the transducer	X	X	X	X	X	X	X	X
Controlling the power supply (batteries, IAS, automatic rechargers)	X	X	X	X	X	X	X	X
Downloading of data (from PC or datalogger)	X	X	X	X	X	X	X	X
Calibration of the sensor	X	X	X	X	X	X	X	X
Controlling the beam angle		X	X		X		X	
Cleaning of the tube[(1)]	X					X		X
Draining the compressor				X				
Cleaning of the sensor						X		
Checking of oil level and air pressure				X				

Table 2 Maintenance requirements of the tide gauges that take part of the experiment

(1) in general, these operations do not require the desinstallation of the transducer but it is necessary the hiring of divers as during its installation.

RELIABILITY

	Type of tide gauge							
	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
Accuracy (mm)	1	1	1	0.5	1	0.5	10	2.5
Accuracy (%)	0.02%	0.02%	0.02%	0.01%	0.02%	0.01%	0.2%	0.5%
Resolution (mm)	1	1	1	1	1	1	10	10

Table 3 Reliability of the tide gauges claimed by the manufacturers assuming a 5 m tidal range and a 1-min integration period for the averaged measurements.

3. DESCRIPTION OF THE EXPERIMENT

The pilot station is installed in the port of Vilagarcía de Arousa. The port of Vilagarcía is situated on the Northwest coast of Spain, in the sheltered waters of the inner Ría of Arousa (Longitude: 8º 46' W Latitude: 42º 36'). The Ria de Arousa, is a partially mixed estuary [1]. This location has several advantages: it has an adequate tidal range (mesotidal, up to 4.2 m), it is affected by varying meteorological conditions, and it has 24 h surveillance.
At this port, Puertos del Estado (Spanish Harbours Authority, PE) has operated an acoustic SRD tide gauge station since 1997, which forms part of the REDMAR (PE tide gauge network). The tide gauges that formed part of the test station were placed on a different dock, approximately half a kilometre from the REDMAR permanent station.

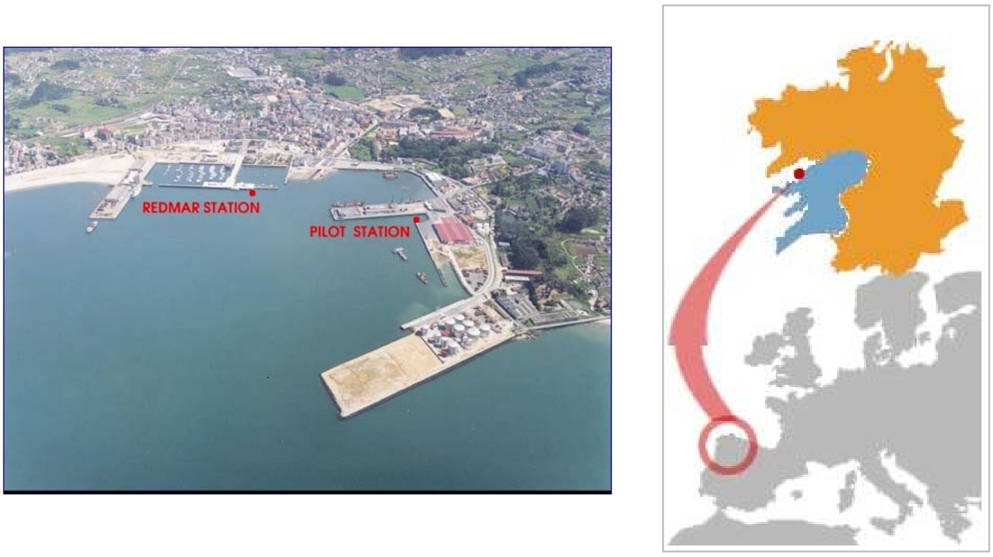


Figure 9 Location of the pilot station in the port of Vilagarcía de Arousa (left), NW of Spain (right)

As we have already seen, some of the tide gauges did not have their own datalogger, but sent the data to an external storing unit (a PC in our case). Computers and other electronic devices necessary for the operation of the tide gauge equipment: data loggers, the power supplies etc., were kept in a hut nearby the gauges (see Figure 11).

Figure 10 Location of the hut next to the pilot station.

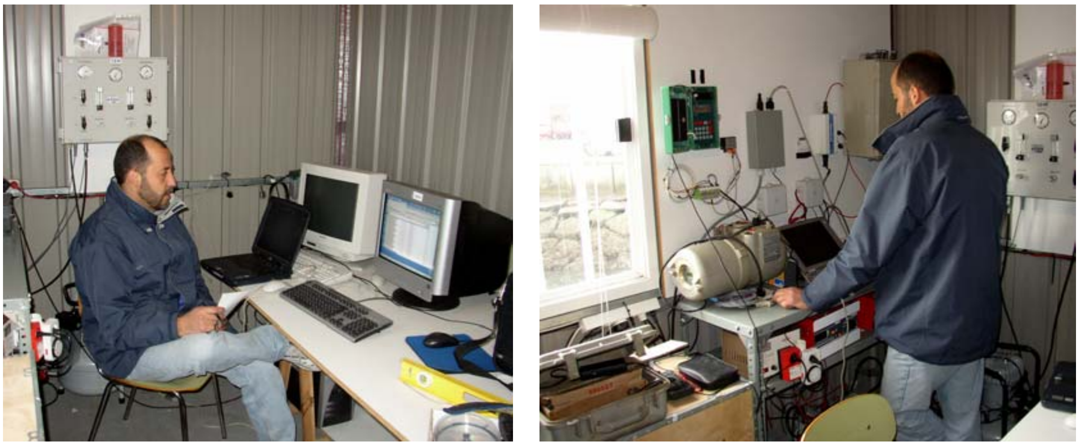


Figure 11 Interior of the hut with the computers and the rest of the electronic devices for the tide gauges.

The installation of the infrastructure needed for the tide gauges began in December 2002 yet it was not till March 2003 that first data were obtained. Between 9 and 15 December 2002, the principal support steel structures were installed, as well as the PVC tubes that contained some of the tide gauges and the hut for the auxiliary equipment. The first instruments installed were a pressure gauge (AANDERAA) and a floating tide gauge (THALIMIDES), which were placed inside the PVC tubes and two radar (SEBA and RADAC). Due to several reasons, the first two sensors had to be removed shortly after and they have not been considered in the analysis. New sensors were progressively added to the experiment. In February 2003, the MIROS radar system, AQUATRAK and SEABIRD. The last radar equipment to be incorporated in the pilot station was GEONICA in March 2003. Finally, a bubbler pressure from POL was installed in November 2003. As we can notice in Figure 12, several weeks had to pass from the installation date before the beginning of the time series. The lack of experience with the equipment made it necessary a period of trials and adjustments before valid data were obtained.

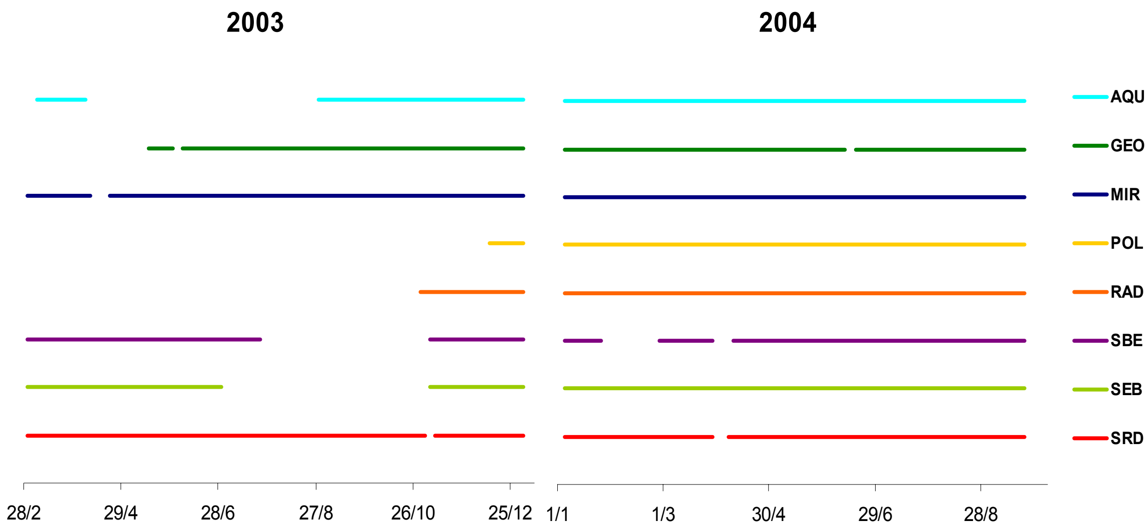


Figure 12 Periods of operation of each of the tide gauges

3.1 Major breakdowns and other incidences

In Figure 12, we can observe the gaps associated to the breakdowns and incidences experienced by the tide gauges. Next, we will relate these problems for each tide gauge trying to establish their possible reasons (sometimes related to the lack of previous experience with them).

AQU

09 April 2003 – The system breaks down for unknown reasons. The controller is sent to the US for being repaired. Eventually, the origin of the malfunction is a shortcut in the transducer due to moisture within a connector plug.
28 August 2003 – The sensor is reinstalled and a new datum is set
09 November 2003 – After a maintenance visit, the sensor is not properly fitted within the tube and this brings about a small jump in the datum.
Approximately a 6% of 1 Hz raw data is lost due to a default in the software developed to allow the communication between the transducer and the PC. Thus, it is NOT a problem of the sensor.

GEO

1-5 June 2003: lost of data due to the overwriting of the memory of the datalogger after a hard disk failure.
14-16 June 2004: the storing interval was reduced from 5 min to 1 min.

MIR

09 April 2003: Lost of data due to a hard disk failure and over writing of datalogger.
02 June 2003: Evidences of vandalism are found as if they had tried to steal it.

POL

No major breakdowns nor incidences.

RAD

28 August 2003 – The sensor was lifted 1m. The antenna was firstly installed in the same platform as the MIROS and SEBA. However, it was observed that it provided erroneous data during high tide because it was too close to the water surface.
4 November 2003- The antenna was reoriented and adjusted.
20 July 2004 – During a maintenance visit a change in the datum is observed (2.7 cm) with respect to the value of March. That difference can be due to a progressive expansion of the metal fixing structure or a loosen of the cables that supported the horn antenna.

SBE

28 August 2003: Problem during the downloading of data related with a low level of battery and subsequent lost of time series.
29 January 2004: Problem during the downloading of data and subsequent lost of time series
31 March 2004: No atmospheric pressure data, thus we cannot calculate the sea level.
24 April 2004: During the downloading of data, the date field presented wrong characters and had to be reconstructed.

SEB

The gauge begins providing out of range values and finally breaks down on July 05th. The instrument failure might be related to the presence of moisture within the system.
04 November 2003. The sensor is reinstalled.
11 December 2003. Problem with the assignation of time for unknown reasons. We detect and correct a delay of 30 min that begins when the POL system is installed and spans over a 2 month period.

SRD

4 November 2003: Loss of data due to a failure of the supply of electricity.
1 April 2004: Loss of data due to problems of communication via radio, between the LPTM and the MTU.

Thus, in short, the test tide gauges that presented less problems and allowed the recording of the most complete time series were GEO, MIR and POL (more than 95% of valid data since the beginning of the operation of the system).

3.2 LEVELLING

The levelling of the systems was undertaken by measuring the distance between the reference mark of each sensor (defined by each manufacturer) and the Tide Gauge Bench Mark or, alternatively, an auxiliary mark defined by SIDMAR, the company that performs the maintenance of the station.

Figure 13 Levelling of the Tide Gauge Bench Mark (TGBM) and zoom in the auxiliary marks.

The levelling operations were performed approximately each 4 months. These operations consisted in checking the distance between the sensors and the TGBM (datum) with a milimetric flexometer and a level TOPCOM ATG2. The error in the measurements was ± 1cm. Ideally, the datum of the sensors should have remained the same along the experiment, but some slight changes were found during the maintenance visits. Besides, the detailed study of the time series allowed us to detect a small jump of the datum level for the AQUATRAK sensor that had not been accounted for by SIDMAR. Since the installation of the sensors took place in several steps and some of the systems had to be reinstalled, these changes are not surprising, yet it is clear that the operation of a permanent station would require of a more strict of the datum. In addition to this, some of the changes reported might be a result of the inaccuracy of the levelling and not a real change. To overcome all these problems and avoid their effect when comparing the time series and evaluating the precision, we always substracted the mean value before making the regression analysis (see section 4).
Despite the difficulties, some attempt for detecting possible drifts in the datum was done. In the case of POL gauge, the equipment had its own method of controlling the datum by means of an additional pressure point located approximately at mean sea level (see [10]). For the rest of the sensors, we approached this issue by studying the evolution of the daily mean values. As we shall see in the next section, there is no clear evidence of a drift of the datum that can be due to a bad functioning of any equipment.

4. DATA QUALITY COMPARISON

In this section we have tried to explore the possibilities of the equipment to monitorize the water level in a general sense. In order to choose one equipment of the other it is important to ask ourselves which our expectations are. In principle, tide gauges are conceived to provide sea level data in order to study the signals of frequency of the order of the tide signal or lower frequencies (mean sea levels). The so-called sea level is in fact a sum of several signals that we can identify and relate to different processes: one is, obviously, the astronomical tide, whose energy concentrates mainly in the hourly-daily range. But in the subtidal range some other processes such as the changes in the atmospheric pressure or the effect of wind can also leave their trace. In addition to this, higher-frequency waves, with typical periods of several minutes can also appear (seiches, tsunamis...).

Our first aim has been to evaluate the performance of the systems when measuring sea level with an interval of several minutes to hourly values and most of the results will be interpreted on the basis of this application. However, we will also tackle the issue of determining whether the 1 Hz time series provided by some of the tide gauges are useful for studying other processes which take place in the supratidal range or, on the contrary, only when averaged can these data be considered reliable.

4.1 EVALUATING THE QUALITY OF THE DATA – (I) 5-min TIME SERIES

PROBLEMS ENCOUNTERED DURING THE PREPARATION OF THE DATA

Averaging – The sampling strategy for the first comparisons was designed to fit the SRD data from the reference REDMAR station, that is to say, we aimed to achieve time series with a 5-min interval. As stated in the previous section, the different strategy of measurement followed by the tide gauges originates differences in the number of samples that are actually averaged to provide the final value each 5 min.

Other variables needed – Pressure systems (namely POL and SBE) need the value of density to convert the pressure measurements into sea level. The place of the experiment, within a Ria, is subject to changes in salinity that imply changes in the seawater density. In addition to this, the SBE record is affected by the atmospheric pressure and it is indispensable to take it into account to correct the records. As we have already mentioned, atmospheric pressure was obtained from a nearby meteorological station managed by MeteoGalicia. Obviously, the problem in this case is that there can be gaps (as it is the case in March 2004) in the atmospheric pressure time series.

Clock – One of the variables to be evaluated is the root mean square error (RMS) between the time series. A very relevant influence of the clock shifts in the RMS results has been detected, consequently, extra care must be taken to avoid those errors. Clock shifts can be avoided by controlling the time of the measurement via GPS, but in our case only GEO system had this possibility. For the other tide gauges, the clock was adjusted during the visits of the company who performed the maintenance of the pilot station (each 4 months approximately). During the visits, differences of up to 6 min between the PC clock (where data from AQU, MIR, POL and RAD are stored) and the UTC time were detected, and they could not be easily mended for the shift appeared to be progressive. In addition to this, a 30 min shift was found in the SEBA time-series which affected a 2-month period. Luckily enough, this last time shift could be corrected. Nonetheless, as we shall see the effect of these shifts in the final results has been minimised, and as far as we know their relevance concerns only the RMS value.

VARIABLES EVALUATED AND STATISTIC COMPARISON

After achieving homogeneous, in principle simultaneous 5-min time series, we made the comparisons between each pair of sensors. With this aim, we studied the scatter-diagrams of the sea level data provided by the gauges and obtained the coefficient of determination (R^2), that indicates the amount of variability which is shared by the series. We also performed the linear regression analysis between them and calculated the slope, which indicates the differences between the tidal range registered by each gauge, and their distinct sensitivity to the changes in the sea level (change in measured distance over true distance). Finally we obtained the Root Mean Square Error, (RMS) that is to say, the mean absolute deviation between the sea level time series.

As we have just mentioned, clock shifts of the order of several minutes were detected. Clock shifts of this magnitude are not unusual and have little influence in the usefulness of the tide gauge for most of their habitual applications. However, the difference in the RMS can be very important, obviously depending on the typical tidal range (for the greater the tidal range the greater the changes in the sea level between two moments). As an example, we calculated the R^2/slope and RMS between SEB and GEO time series for the month of May, with different shifts. We can see how the first two statistical values seldom vary whereas important differences are obtained for the RMS.

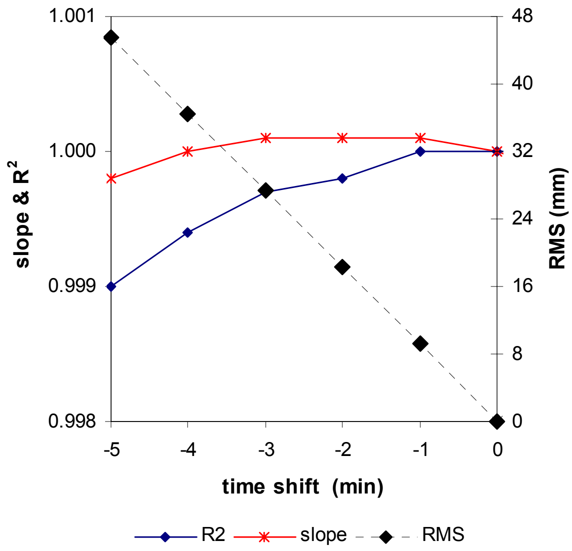


Figure 14 Changes in the R^2, slope (left axis) and RMS (right axis) between two identical time series with a time lag between them

To avoid this effect, and minimise the influence of the clock, we obtained 1-min time series via linear interpolation between the 5-min data and made the comparisons between the time series when theoretically simultaneous and when delayed from 1 to 5 min till we achieved the best result (i.e. the minimum RMS between them, which coincides with the R^2 value closer to 1.000). The optimal delay varies between sensors and along time. We divided the time series in shorter intervals of 14 days and calculated the optimal delay and the R^2, slope and RMS in each interval. The final R^2, slope and RMS presented as results are in fact an average of the values obtained along the experiment. We have checked that the results are consistent when changing the duration of the intervals. The time of simultaneous working of each pair of sensor varies from 13 months (MIR and SRD) to 4 months (POL and SBE), obviously being dependent on the periods of operation of those sensors. In Table 4 we indicate the total length of the period used for the comparisons.

Months	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
AQU	8	8	8	6	6	6	6	8
GEO	8	12	12	6	6	7	7	12
MIR	8	12	13	6	6	8	8	13
POL	6	6	6	6	6	4	6	5
RAD	6	6	6	6	7	5	6	6
SBE	6	7	8	4	5	10	7	9
SEB	6	7	8	6	6	7	9	8
SRD	8	12	13	5	6	9	8	14

Table 4 Duration of the period when the pairs of sensors were working simultaneously (in months)

RESULTS – RMS, R^2, slope

RMS	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
AQU	0	14	20	13	16	14	16	16
GEO	14	0	12	8	9	9	7	11
MIR	20	12	0	14	10	16	11	15
POL	13	8	14	0	11	7	10	11
RAD	16	9	10	11	0	14	9	14
SBE	14	9	16	7	14	0	13	14
SEB	16	7	11	10	9	13	0	13
SRD	16	11	15	11	14	14	13	0

Table 5 RMS for the records of differences between the 5-min time series obtained with the tide gauges (in mm)

As we see in Table 5 the RMS between the pairs of time series is never greater than 20 mm. Bearing in mind that the accuracy claimed for the manufacturers is sometimes no better than 10 mm, it is obvious that differences in the RMS are not very important. Following [16], RMS values below 15 mm would yield a precision value better than 1 cm, which is consistent with Global Sea Level Observing System (GLOSS) standards[10]]. Consequently, all tide gauges would meet these standards when measuring at a 5-min rate. However, there are other interesting features worth mentioning:

- In general, for each sensor, the lowest RMS corresponds to the tide gauge with the most similar technology, e.g. SEB and GEO; POL and SBE; MIR and RAD.
- Higher RMS between AQU and the rest of the sensors are probably related to the temperature gradients within the tube, which could not be accounted for because the system did not have thermistors.
- It is also remarkable that the location of SRD in a different dock does not bring about a significant increase in the RMS found with the other sensors.

R^2	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
AQU	1	0.9997	0.9995	0.9998	0.9997	0.9998	0.9997	0.9997
GEO	0.9997	1	0.9998	1	0.9999	0.9998	0.9999	0.9998
MIR	0.9995	0.9998	1	0.9998	0.9998	0.9996	0.9998	0.9997
POL	0.9997	1	0.9997	1	0.9998	0.9999	0.9998	0.9999
RAD	0.9997	0.9999	0.9998	0.9998	1	0.9996	0.9999	0.9997
SBE	0.9993	0.9998	0.9994	0.9998	0.9996	1	0.9995	0.9996
SEB	0.9997	0.9999	0.9998	0.9998	0.9999	0.9997	1	0.9997
SRD	0.9996	0.9998	0.9996	0.9999	0.9997	0.9997	0.9997	1

Table 6 R^2 between the 5-min time series obtained with the tide gauges.

Very high values for R^2 are expectable l if we take into account that the astronomical tide forces force the 98% of the oscillation. Nonetheless, it is interesting to observe again that the higher values are found when comparing tide gauges that employ the same technology.

Some more information is derived from Table 7, which expresses the distinct sensitivities of the sensors to the tidal range.

slope	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
AQU	1	1.003	1.006	0.995	0.999	0.997	1.002	1.006
GEO	0.997	1	1.001	0.996	1.000	0.996	1.001	1.002
MIR	0.994	0.999	1	0.994	0.999	0.995	0.999	1.001
POL	1.005	1.004	1.006	1	1.005	1.001	1.005	1.006
RAD	1.000	1.000	1.001	0.995	1	0.996	1.000	1.001
SBE	1.002	1.004	1.005	0.999	1.004	1	1.004	1.006
SEB	0.998	0.999	1.001	0.995	1.000	0.995	1	1.001
SRD	0.994	0.998	0.999	0.994	0.999	0.994	0.999	1

Table 7 Slope between the 5-min time series obtained with the tide gauges

If we take a look at the SRD column, we can appreciate that the slope between SRD time series and the other systems time series is always > 1. This means that SRD system seems to be recording slightly higher tidal ranges (6‰ higher than AQU, 1‰ higher than GEO, 2‰ higher than RAD...). Nonetheless those differences are only statistically significant when making the comparison with AQU, POL and SBE (up to 6‰). Considering the columns for these two pressure sensors, we can verify that they are the less sensitive systems. In this regard, there are previous studies that show the effect of salinity when estimating the effective density [14]. Thus, since POL and SBE assume a constant salinity of 35 psu, some bias might be introduced for not taking into account the likely decreases of this variable in the Ria due to the run-off.

It is also interesting to study the distribution of energy by means of the Fast Fourier Transform. The spectral analysis of the data allows us to find out whether the differences depend on the range of frequency considered.
As we have previously mentioned, achieving long records when all the tide gauges were providing data was not always easy. We have selected a 1-month period just after the installation of POL gauge. The results are presented in Figure 15.

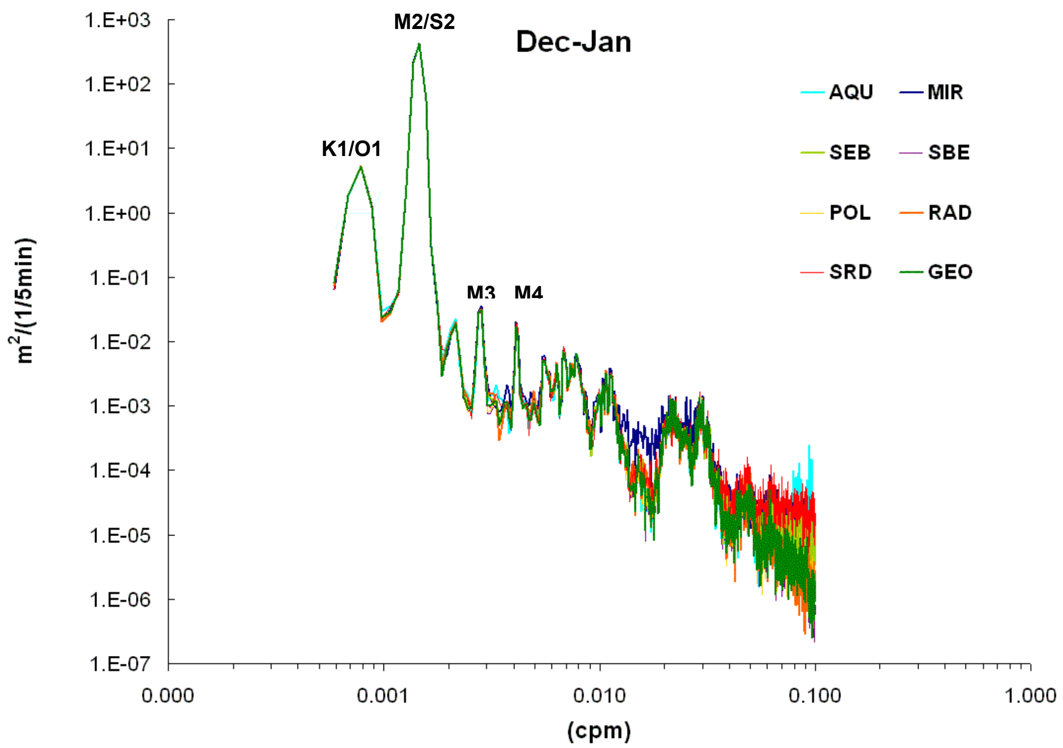


Figure 15 Power spectral density for the 5-min time series of all the tide gauges that take part in the experiment during the period December 2003-January 2004.

Beginning from the low-frequency ranges, we first distinguish the most important tidal peaks, which present similar values for all the time series. As the frequency increases, differences arise: in the range 0.01<F(cpmin)<0.03, the MIR data present more energy. After consulting with Miros technical staff, the differences were found to be due to small inaccuracies in an interpolation algorithm used internally in the sensor (personal communication). This problem has seldom any effect in the results for the tidal range, but might be of importance when considering the long wave phenomena, and the company has undertaken to solve it by upgrading the software.

In the high-frequency range (F>0.05 cpmin), even greater differences are found. However, on the one hand we have to bear in mind that the plot is using a logarithmic scale, thus, the differences concern an almost non-energetic part of the spectra and they are exaggerated. Nontheless, as explained in section 2, the measuring technique is different (e.g. pressure, time of flight, phase shift...) and the tide gauges are actually measuring physicaly different oscillations. Another possible reason is that the data reduction process performed to obtain the 5-min time series (i.e. the actual raw data evaluated and averaged) is different for each tide gauge.

4.2 EVALUATING THE QUALITY OF THE DATA (II) – Harmonic Analysis

We performed the harmonic analysis of the time series provided by each tide gauge by means of the set of procedures and programs (based on the package of the University of Hawaii) employed in Puertos del Estado for the treatment of the data of the REDMAR network. The results for the most important tidal constituents are presented in Table 8.

H (cm)	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
SA		6.3	6.5			5.7		6.3
SSA	2.5	2.5	2.9		4.7	4.4	4.5	2.6
MM	0.9	1.8	2.2	2.6	1.7	1.7	2.2	1.5
MSF	2.6	1.5	1.6	1.4	1.5	1.5	1.5	2.1
O1	6.3	6.4	6.3	6.3	6.4	6.3	6.3	6.3
K1	7.2	7.6	7.5	7.3	7.4	7.7	7.3	7.6
N2	24.0	24.1	24.0	23.3	24.1	24.3	24.2	24.2
M2	113.7	113.9	114.1	113.8	114.0	113.2	114.1	114.1
S2	40.0	39.8	39.8	40.8	40.6	39.5	40.6	40.0

G (deg)	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
SA		308.9	307.0			285.6		310.5
SSA	84.0	110.9	105.9		162.8	62.9	173.4	119.3
MM	238.3	253.1	251.1	237.1	197.3	247.1	208.6	257.8
MSF	2.6	96.5	91.7	138.2	79.0	348.7	59.2	99.4
O1	320.6	321.4	320.6	319.1	319.2	320.6	320.2	321.1
K1	65.3	64.8	63.5	61.8	62.9	61.3	62.8	66.0
N2	60.9	61.7	60.8	59.8	60.9	59.8	61.0	61.3
M2	79.6	80.4	79.5	79.4	79.9	78.0	79.9	79.8
S2	108.8	109.8	109.0	111.6	110.5	107.0	110.6	107.8
Months of data	9	13	13	6	7	15	7	13

Table 8 Main tidal constituents (amplitude H and Greenwich phase lag G) determined for all the tide gauges that took part of the experiment. The months of data used for the harmonic analysis is also indicated.

The amplitudes for the main diurnal and semidiurnal component are very similar, and the same applies for the phase lag values. The values found for the SBE gauge differ to a greater extent, likely due to the over estimation of salinity, the two-month gaps in the series and the difficulties in the timing of the datalogger clock of this equipment.
Regarding the long period tides, some of the differences are due to the difficulties for considering long enough (>12 months) simultaneous periods. This was only possible for GEO, MIR, and SRD systems. Slightly larger amplitudes are found for MIR.

More information can be extracted from the comparison between the series of residuals for the tide gauges (resAQU, resGEO, resPOL etc., hereafter). But in this case we face the problem of the different length of the time series and the clock errors. We have opted for calculating the residuals subtracting the SRD predicted time series (using 68 constituents) to the hourly values for each tide gauge. The results are shown in
Figure 16 (we present the time series once the POL system was installed). As expected, the noisiest residual time series corresponds to the SBE.

The time series of the significant wave height (Hm) calculated at the entrance of the Ria de Arousa is also plotted along with the atmospheric pressure (P).

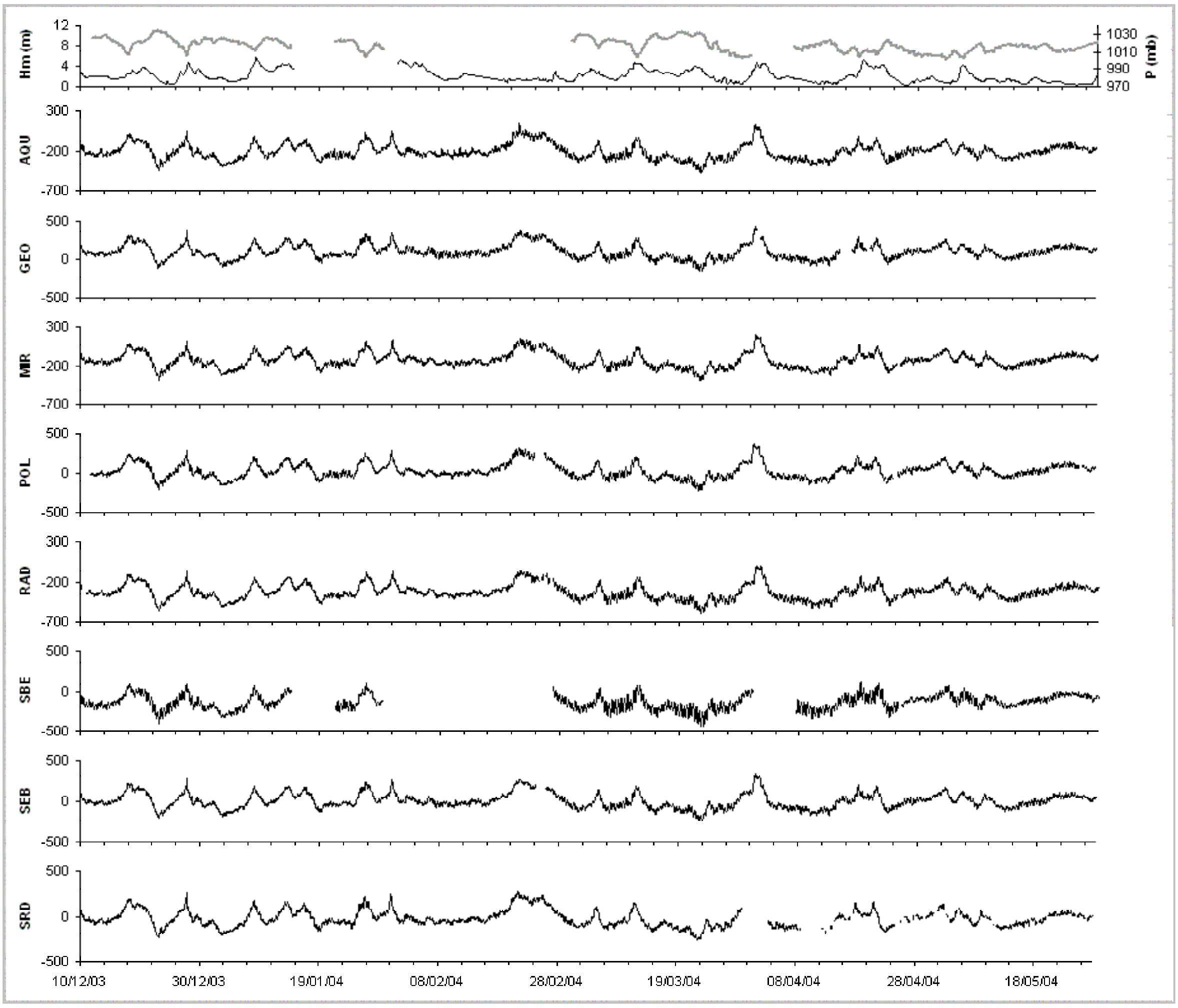


Figure 16 Time series of significant wave height (Hm), atmospheric pressure (Patm,in grey) and residuals for all the tide gauges after the installation of POL.

In principle, the time series of residuals contain the effect of non-tidal forcing such as the atmospheric pressure or the wind set-up. Should all tide gauges measure exactly the same way, their time series of residuals should also be the same. But it might happen, for example, that radar measurements were biased during high wave conditions if reflection takes place to a proportionately greater extent from wave troughs than crests (as it is warned in [16]). In order to investigate this possibility we performed a multiple regression analysis with Hm and P as independent variables and the time series of residuals as dependent variable. We obtained very similar results (in terms of coefficient of determination and partial regression coefficients) for all the tide gauges (see Table 9).

	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
Hm (m)	0.27	0.28	0.29	0.27	0.29	0.20	0.29	0.30
P (mb)	-0.66	-0.65	-0.64	-0.69	-0.63	-0.68	-0.66	-0.66
Adjusted R^2	0.48	0.48	0.46	0.52	0.45	0.47	0.48	0.49

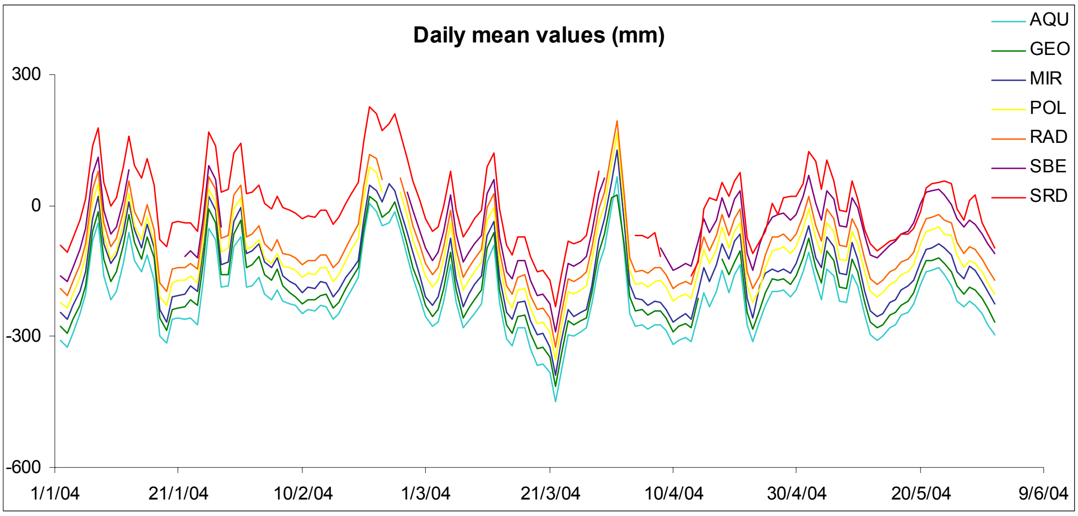
Table 9 Results of the multiple regression analysis between the residuals hourly time series for each tide gauge (dependent variable) and the significant wave height (Hm) and the atmospheric pressure (P) as independent variables. Partial regression coefficients and adjusted coefficient of determination.

We have repeated the analysis selecting stormy periods that might be potentially more prone for observing different behaviours and we centred them in the comparison between AQU, POL, MIR and RAD, so as to minimise the effect of the different assignation of time. In general, what we observe is that the residuals for resMIR and resRAD look very much the same, whereas resAQU and resPOL present greater differences, which may be a result of the effect of the temperature gradients and the slight changes in salinity. However, up to now we have not managed to find any evidence of a clear or systematic effect of the sea state on the FMCW radar residuals, at least in this range of frequencies (hourly values) and with the variables considered (P, Hm).

Daily mean values

As previously mentioned, the long-term stabiliy of the datum is a very important part of the operation of a tide gauge. In order to approach this issue, we have calculated the daily mean values for the 2004 period after the installation of the POL tide gauge. As we can see, the evolution of the daily mean values is similar for all equipment, and the trends are also comparable except for the SBE (Figure 17). We do not find any clear evidence of any drift in the datum of the tide gauges.

The anomalous positive trend in the case of SBE might be related with the lack of data in February 2004. Besides, the fact that the calculation of sea level for SBE requires more external variables to be accounted (temperature, atmospheric pressure) might introduce errors that are difficult to control.



Trend (mm/day)	AQU	GEO	MIR	POL	RAD	SBE	SEB	SRD
	-0.3	-0.3	-0.3	-0.2	-0.2	0.1	-0.3	-0.4

Figure 17 Evolution of the daily mean values in 2004 for all the tide gauges and trend (in mm/day) for the same period.

4.3 EVALUATING THE QUALITY OF THE DATA (III) – HIGH-FREQUENCY TIME SERIES

One of the particular interests of Puertos del Estado when evaluating the systems was to decide to what extent the high-frequency time series (from now on by "high-frequency time series" we will refer to time series with a sampling interval < 5 min) are useful for other purposes than measuring the tide. Long wave phenomena, for example, with typical periods of 30 s – 10 min, can be very important for the harbours operations. The study of this phenomena obviously requires a more frequent storing rate than 1 data/ 5 min. This implies that storage units must have more capacity or be downloaded more frequently. In addition to this, the greater exposure of the radar systems raised doubts about its performance under bad weather conditions. Furthermore, when studying the 5-min time series and the time series of residuals we found evidences of greater similarities between the data obtained with tide gauges that use the same technology and we wondered whether those differences were also evident in the high-frequency registers.

Our main constraint is not having a wave recorder in the harbour to compare with, thus we will attempt different approaches to these issues by 1) studying the 'raw' higher frequency data and 2) studying the dispersion of data around the average value (the time series of the standard deviation).

First of all we can plot the MIR, AQU, RAD and POL raw data along with the wind data (W, grey line). As already mentioned, these four systems permit the recording of data each 1s, 1s, 0.5 s and 10 s respectively. We have selected a 1 d winter period characterised by relatively strong winds (gusts up to 24 m s^{-1}). Constant values have been added to original series in order to obtain clearer plots and ease the visual comparison. It is obvious that data collected with the radar systems (RAD, MIR) have a higher dispersion (especially RAD) than those with the acoustic (AQU) and bubbler (POL) sensors. In principle, the radar systems should be more sensitive to the agitation processes associated to the wind since they measure directly the sea surface and they are not inside a protective structure. Logically, as the wind regime is more intense, it originates more waves which cause a greater variability of the sea level registered by these radar sensors.

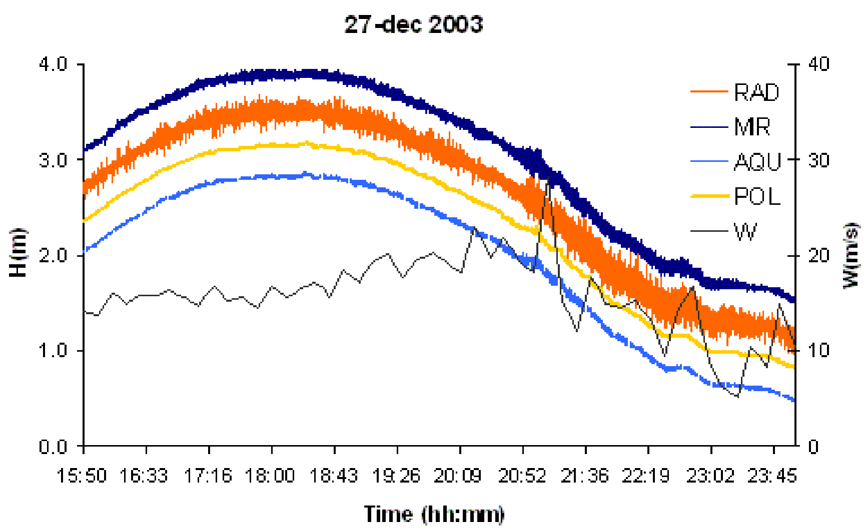


Figure 18 Evolution of the high-frequency time series of sea level (m) and wind (m/s) on 27 December 2003

If we focus on the two CWFM radar systems, MIR and RAD, it is obvious that sea level can not change that drastically in such a short period (40 cm in a few seconds according to Figure 18), not even under bad weather conditions. So, the first question we would like to answer is: are the raw data provided by the CWFM radar sensors really providing us with useful information about the sea state, or are they too noisy? Secondly we would like to find out which one of the radar sensors is providing the best data in the higher-frequency range.

The spectral analysis (Figure 19) shows that RAD signal contains more energy in the range 0.01<F<0.1 cps. As we approach the hourly range (F = 0.001 cps), the situation is the opposite, just as we saw in Figure 15.

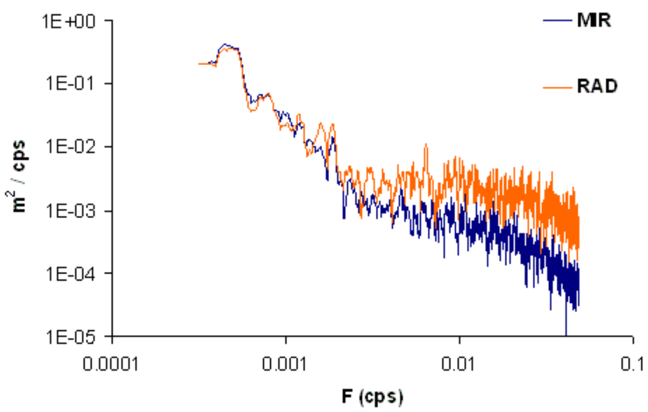


Figure 19 Comparison between the power spectral density of the raw 1s time series provided by MIR and RAD

We will try and obtain more details on the performance of the MIR and RAD sensors by comparing their high-frequency time series and using POL as a reference. Since the three systems pour their data in the same PC, we can be sure the assignation of time is exactly the same for them all. We worked with time series of one data each 10 s (following the sampling strategy of POL gauge).
Provided that part of the energy contained in the higher frequency range can be due to instrumental noise, we applied a wavelet filtering ([5]) so as to get rid of the white noise signal that otherwise would difficult the comparison. We chose a 1-week period and we compared the time series (once eliminated the white noise) simply by substracting. In Figure 20 we see the evolution of the differences along the chosen week.

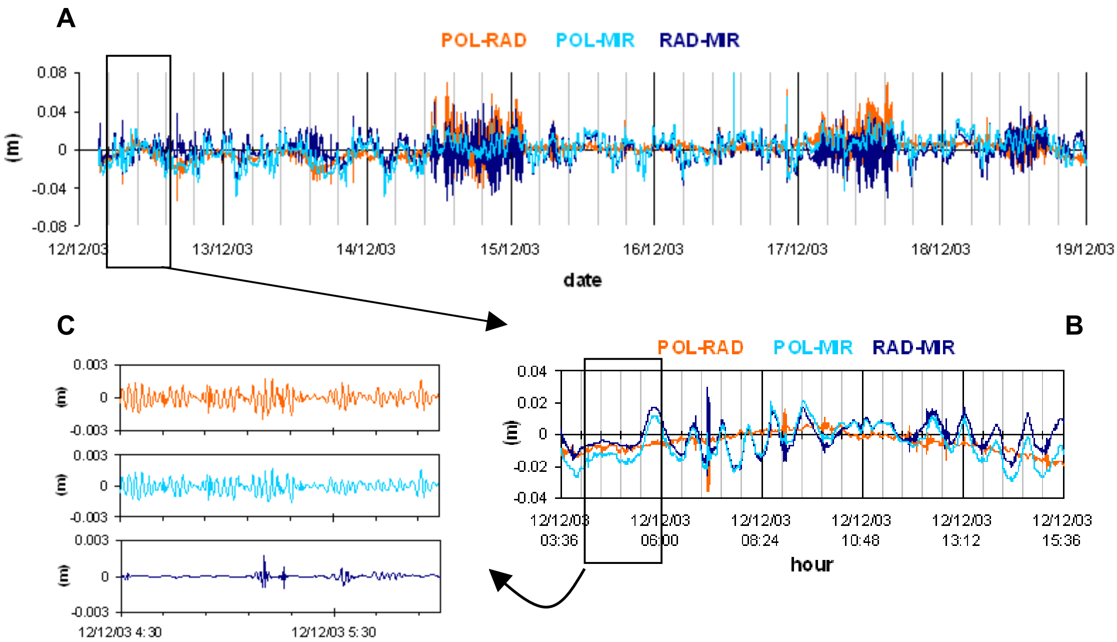


Figure 20 Evolution of the differences between the data provided by POL, RAD and MIR (averaged each 10 s) during one week (A) and during one day (B) and one hour (C). See text for details.

Focusing on Figure 20, the first feature we want to draw our attention towards is the semidiurnal oscillation that we distinguish in he POL-RAD and POL-MIR plots. That oscillation is probably due to the change of salinity (thus of density) associated to the progression of the tide, which can be more or less intense depending on the characteristics of the mixing.
The second feature is that the differences are greater when we compare RAD with the other two, especially in some periods in particular (between 14 and 15 and between 17 and 18 December). Those moments coincide with periods of more intense wind. In this case, the fact the plot POL-MIR does not show such differences suggests that there is either some instrumental problem that brings about some inaccuracy in the RAD series or that only RAD is able to see those oscillations. We will find evidences that support the first hypothesis as we will explain later when dealing with the STD.

We can now make a zoom on the 1-day period delimited by the square. The zoom allows us to distinguish new characteristics. On the one hand, the time series of RAD-MIR and POL-MIR present an oscillation with a period of several minutes that, as we saw in section 4.1, is due to a problem in the interpolation algorithm used by the MIR sensor. On the other hand, it is interesting to note that the line that corresponds to the comparison between the two CWFM radar sensors, (the dark blue line), has less short-period oscillations, in other words, it is a flatter line than the lines we obtain when the comparison is made with the POL sensor. To illustrate this we present Figure 20C. To ease the visual inspection and highlight the differences between the three plots we have got rid of the underlying oscillation due to the MIR problem with the algorithm. The figure suggests that both MIR and RAD radar sensors are registering the same type of oscillations (with typical periods that would coincide with those typical of the long-wave phenomena) whereas the pressure sensor, maybe due to the type of installation (underwater, the measuring point resembling an inverted bucket as we can see in Figure 4), does not sense them. That explains why the POL-MIR and POL-RAD plots are so similar whereas MIR-RAD is almost a flat line. This is only evidenced in particular moments and after a strong zooming, due to the episodic character of the long-wave phenomena which, besides, appears to be not too strong in Vilagarcía.

We were also interested in comparing the performance of the CWFM radar (MIR, RAD) and the pulse radar (GEO, SEB) sensors. Neither GEO nor SEB provided us with the raw data, only the averaged ones each 1min/5 min, but at least GEO system did provided the standard deviation of the data integrated along that 5 min period. With this in mind we tried a new approach: we evaluated the standard deviation (STD) of the raw data around the 5-min averaged value for the MIR, RAD, AQU and POL gauges, taking into account the 600, 300, 300 and 30 values integrated each 5 min respectively. So, for these 5 instruments and each 5 min we had one averaged sea level value and we also had the STD, which represents the dispersion of the data around that average.

The study of the STD provided us with highly relevant information regarding the performance of the tide gauges. As an example, in Figure 21 we depict the evolution of STD obtained as mentioned above for the MIR system during a 3-day period.

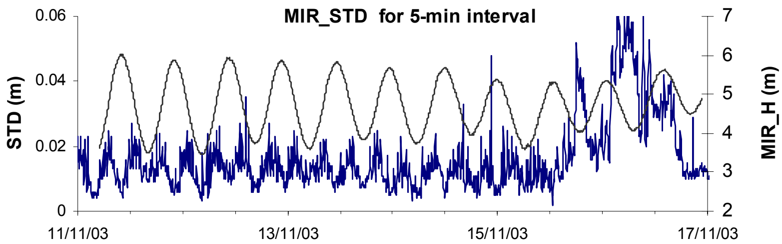


Figure 21 Evolution of the STD (blue line) and the sea level (black line) registered by the MIR sensor

In the first place, we can observe a clear quartidiurnal oscillation of the STD variation. This is due to the sea level changing more slowly during high and low water (i.e. the STD decreases), whereas during the transition between both states that change is faster (i.e. the STD increases). Apart from that, we can also see the print of other processes having an effect on the dispersion of the data (see, e.g, the outstanding high values of the STD between 15 and 17th November, which coincides with a period of strong winds). We can expect that strong wind conditions may cause higher waves and consequently, a higher dispersion of data. On the other hand, we can suspect that an incorrect measurement would imply anomalous values and thus, high STD values that would NOT reflect a real process.

To dillucidate all these aspects, we will present now the evolution of the STD during a 2-month period as registered by the 5-sensors aforementioned (Figure 22). The time series were low-pass filtered (by means of a 1-day moving average) in order to get rid of the tidal variability that difficults the visual inspection. In addition to this, we know that the meteorological processes that are typical in the area (lows and highs associated with more intense winds) have a periodicity of several days ([1]) thus, our interest was in the subtidal range.

The first aspect worth mentioning is the difference between the STD values obtained with the CWFM radar sensors (particularly the RAD) and the other three. According to Figure 22, the dispersion of the data collected by those sensors is much higher than AQU, POL and GEO.

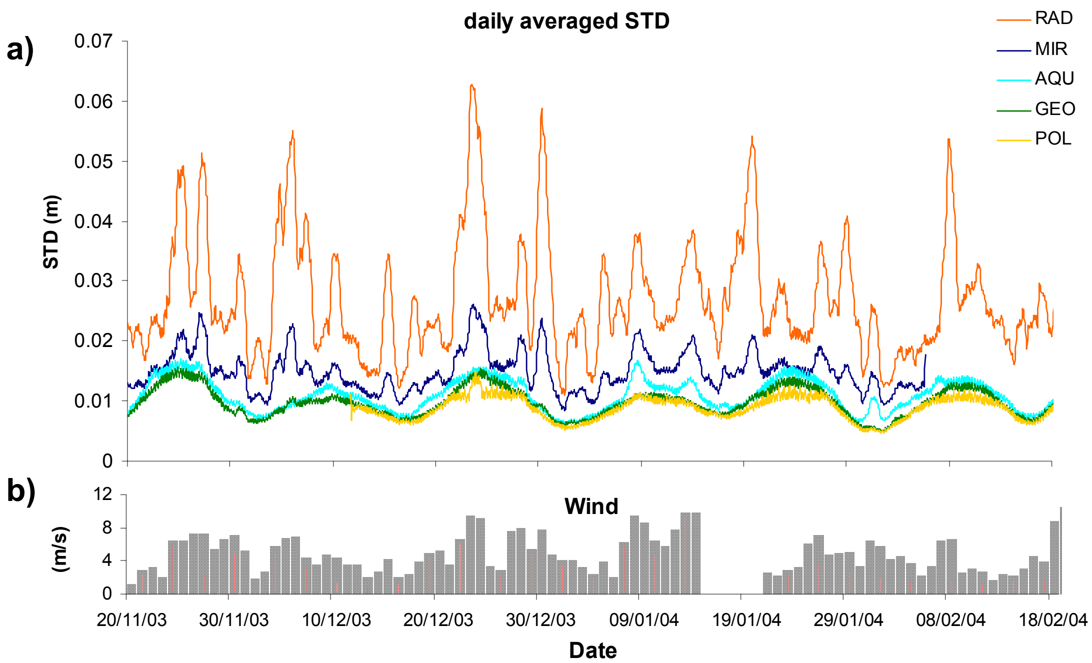


Figure 22 a) Time series of STD values calculated in each 5-min interval around the average value. b) Time series of the intensity of the wind speed is also presented (grey bars).

Regarding the shape of the line, it is clear that AQU, POL and GEO data STD feature a fortnightly oscillation, related to variation of the tidal range (and thus of the rate of sea level change) with the occurrence of spring tides and neap tides. The evolution of MIR and RAD system is more complex and it suggests that those systems area noticing the effect of the wind/waves. In order to verify this we used the meteorological data obtained in nearby station (data obtained from MeteoGalicia) and, as a first approximation, we calculated the correlation between the wind velocity and the STD values. The STD for both CWFM radar sensors (regardless the differences in the magnitude) is quite similar and yields a positive correlation of 0.76 with the time series of velocity (Table 10) whereas for the rest of the sensors is below 0.32. Logically, as the wind regime is more intense, the irregular waves are more likely. In this situation the variability and error of the measurement increase due to a modulation of the beam by inclinations of the relief of the surface roughness[4].

R	AQU	GEO	MIR	POL	RAD
Wind	0.23	0.25	0.76	0.32	0.76

Table 10 Coefficient of correlation between the wind speed and the low-passed time series of STD

The higher STD values for the RAD system can obey to two reasons. On the one hand, the RAD system which took part of the experiment corresponds to a version that is currently out of the market and is not capable of obtaining as accurate measurements as currently does. In addition to this, the height of the transducer over the sea surface is approximately 1 m higher that the other sensors, which alters the SNR (signal-to-noise) ratio. This fact should also bring about a different behaviour of the sensor in low tide when compared to high tide, and the spectral analysis of the STD series proves that. In fact, clear quartidiurnal peaks are found for all the STD time series and only for RAD, semidiurnal and diurnal peaks of the same magnitude are also present.

The lack of relationship between the wind (thus increasing oscillations and higher dispersion) and the STD in the case of AQU is due to the sensor being installed within a tube that filters the high-frequency oscillations. In the case of the POL, the oscillations are partially reduced by the shape of the measuring point. In addition to this, the integration period is 10 s, so very short-period oscillations are eliminated and do not contribute to the STD value.

From our point of view, the most striking aspect is that GEO pulse radar sensor does not respond in the same way as the CWFM radar sensors, and does not show any dependence with on the wind/wave conditions, despite being installed out of any protective structure. Previous studies show that Vegapuls transducer uses an internal filtering so as to improve the signal-to-noise ratio which leads to an underestimation of the amplitude of the signal [12] and this might help to explain the less noisy data set. This would mean that, even if the sensor was capable of providing data at a higher rate (each second, for instance), those “raw” data would be in fact too smoothed to provide information about the water level in that range of frequency. On the other hand, it is obvious that a good part of the dispersion recorded by the CWFM MIR RAD is not real (otherwise, the values should be more similar) but due to the instrumental noise. As we have already mentioned we do not have a wave recorder to verify, so we are trying a different approach by simulating a wave oscillation superimposed to a tidal oscillation to find out what the expected dispersion should be.

Let’s suppose, then, that H_tot= H_tide+H_waves

H_tide is the result of a prediction of the tidal curve using the harmonic constants as deduced from the analysis of the historic records obtained with the permanent station of Vilagarcía. H_waves corresponds to a wave sinusoidal oscillation with T= 10 s and H= 10 cm, considered habitual in a sheltered harbour as Vilagarcía. We will now calculate the dispersion of the data around the average value in each 5-min interval. Our purpose is double. In the one hand, we want to know which of the STD time series shown before resemble more to this theoretical plot. On the other hand we want to demonstrate that the GEO system indeed filters the high-frequency oscillations (even though it must “see” them since it measures directly the sea surface).

The answers to both questions can be found in the next Figures. In Figure 23 we plot the expected evolution of the STD (the dispersion) of data, given the conditions in (1), and we include the sea level (H_tot) as a reference. Focusing on the STD(H_tide) plot (green line) we can observe again the strong relationship between the STD(H_tide) and the tidal state, with values close to 0 at high and low tides. However, if we are considering the dispersion of the H_tot (blue line) we can see that the STD(H_tot) values are never lower than 0.035 m. This is due to the dispersion of data caused by the “wave” oscillation assumed by us. Should the tide gauge be taking into account those high-frequency "wave" oscillations, the STD should be more similar to the blue line than to the green line.

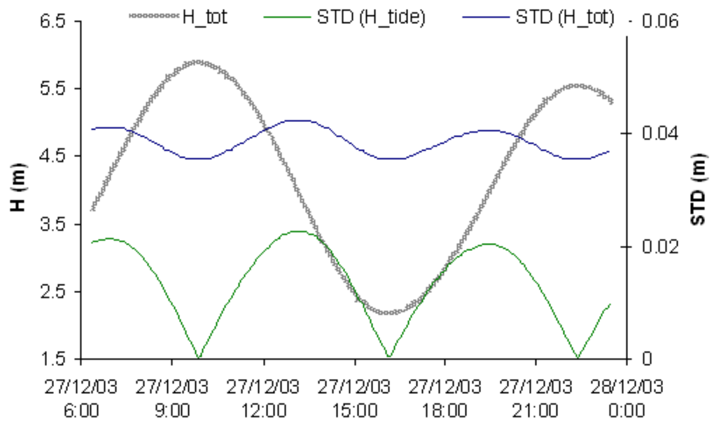


Figure 23 Theoretical evolution of the STD for a tidal curve with (green line) and without waves (blue line). The evolution of the sea level is also presented as a reference (in grey, thicker line).

In Figure 24 we depict the STD found for GEO, RAD and MIR (the difference with Figure 22 is that in this case we have not low-pass filtered the data). It seems evident that the plot corresponding to MIR is the most similar one to what we would expect to find (according to Figure 23). RAD raw data have too much noise, even though once processed to obtain an average value each 5 min the results are just as good as the others as we have shown in section 4.1. On the other hand, GEO is acting as if it did not noticed the higher frequency oscillations. Nonetheless, in some cases (as around 15th November, for example), we do find a "reaction" in GEO data. It might well be that the "reaction" may depend on the type of waves arriving at the site (their significant height, their typical period...).

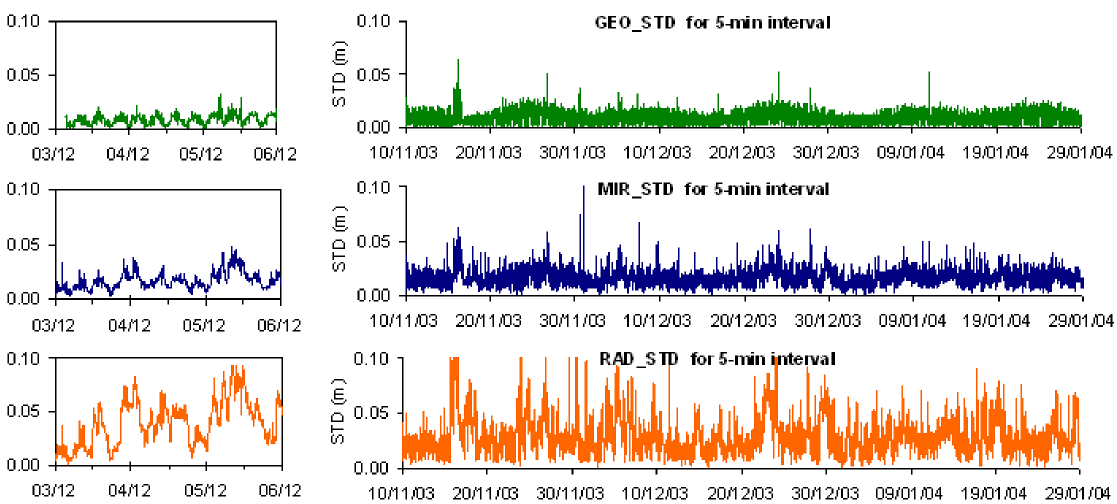


Figure 24 Evolution of the STD time series for the pulse radar sensor GEO and the CWFM radar sensor MIR and RAD

4.4 GEO PULSE RADAR OPERATING INSIDE A TUBE

At the end of the experiment we made a last trial on the GEO tide gauge and the transducer was installed and re-configured so that it measured within a tube (see the pictures). In this case our purposes were:

1- to verify whether the functioning of the sensor was correct in the new type of installation
2- to detect possible differences in the time series compared to the data obtained in the habitual non-protected type of installation.

We analysed a 3-week period between December 2004 and January 2005 and we obtained the STD. It is important to notice that after 16 June the storing interval was reduced from 5-min to 1-min, so these STD values now correspond to a 1-min interval. As a reference, we will also present the data obtained by the sensor outside the tube in October 2004, a period that we have chosen because the tidal ranges and the meteorological conditions were similar to those in the December04-January05 period.

In Figure 25 we plot the STD values for both periods. We appreciate a greater number of peaks (i.e. STD values that we may consider spurious because they are too high) while the transducer is measuring within the tube. This fact is likely due to an increase in the number of pulses that are reflected by the walls of the tube and are not correctly processed by the transducer. Nonetheless, we have verified that these peaks do not imply a worsening in the quality of the sea level time data. That is to say, an anomalous value of STD is not necessarily associated with an out-of-range sea level value.

Despite the number of peaks being greater while the transducer is measuring within the tube, in principle we would expect the tube implying a decrease in the average STD, because the tube (as in the AQU, for example) should reduce the effect of small waves. We have calculated the averaged STD for both periods, inside and outside the tube and the difference is not very important (STD=2.9 mm, and STD 2.4 mm). This, again, stresses the fact that the transducer is internally smoothing the signal in order to improve the signal to noise ratio (SNR).

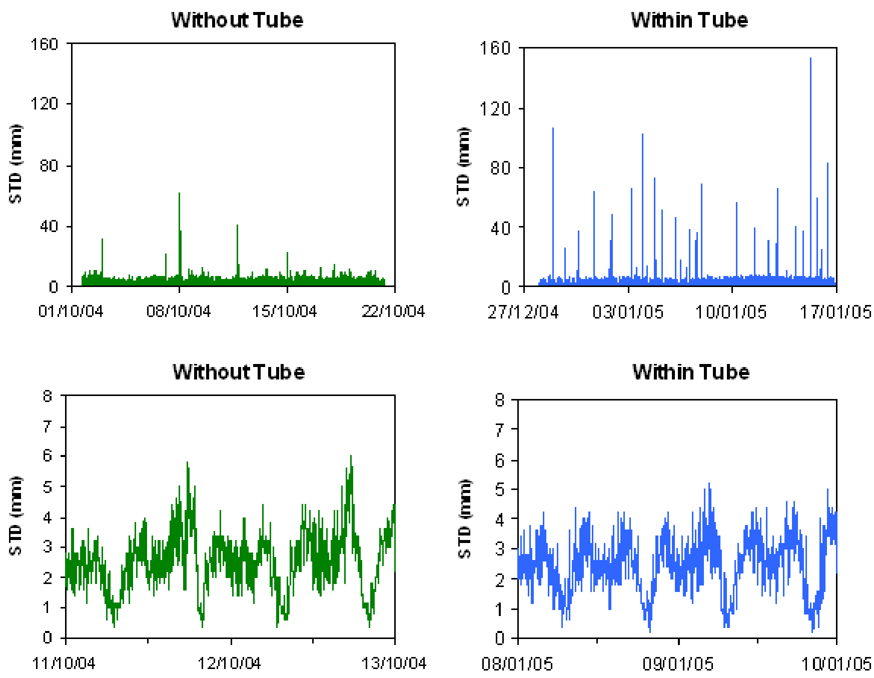


Figure 25 Comparison of the evolution of the STD value provided by the GEO sensor when installed without or within the tube.

As we have just mentioned, the performance of GEO inside the tube was correct. We compared the GEO data with the SRD data for the same following an analogous process to that described in section 4.2 and we have obtained a RMS = 11 mm.

5. CONCLUSIONS AND REMARKS

- The study of the 5-min averaged time series shows that all the tide gauges, under the environmental conditions encountered, provided data that are suitable for the study of the sea level according to GLOSS standards (IOC, 2002). Tide gauges using the same measuring technology provided more similar data sets.

- Data in the range of frequencies > 1 cpmin were not comparable. The high dispersion of the raw data in the case of RAD suggest that they were not accurate enough to allow the monitoring of the sea level short-period oscillations. However, as long as the tide gauge allows the recording of data at a 2Hz or 4Hz rate (as is the case in MIR), the specific analysis of the time series would permit obtaining wave parameters such as the significant wave height. On the other hand, pressure tide gauges are capable of recording such ancillary parameters if properly configured.

- The performance of the radar sensors, which have been operating without a stilling well, has been correct through all the experiment and they did not show any failure related to the occurrence of storms or strong winds. However, we have to bear in mind that the site of the experiment has not experienced extreme conditions. In this regard, the design of the antenna can play an important role in its resistance. SEB seemed to be the less rugg system, whereas MIR and GEO provided the most complete datasets.

✓ Some interesting features about the radar systems are:

  - PRICE: (especially the pulse) radar are relatively cheap
  - INSTALLATION and MAINTENANCE: no need for divers or stilling wells etc.
  - OTHER VARIABLES: there is no need of controlling other variables such as temperature, seawater density, atmospheric pressure etc.
  - WEATHER CONDITIONS: capable of withstand strong winds and storms
  - OTHER STUDIES [2, 3,15] : Previous studies in Germany [2, 3] and UK [15] provide additional information on the (favourable) experience with radar tide gauges. In addition to this, and within ESEAS-RI project, Partner 5 (IEO, Spain) also presented a report included in the final report of the WP4 for the 2nd year where they compared the performance of a SEBA sensor with a mechanical float working in the same well. In their report they stress the advantages of the pulse radar sensor because of its easier maintenance and the importance of an accurate calibration.

✓ The correct assignation of time is an essential part of the sea level value. A GPS control of time is strongly recommended for future tide gauge stations.

✓ Even though it is not indispensable for the radar tide gauges, their installation within a protective tube/well might be of help for the prevention of vandalism and robbery.

✓ Controlling the datum of the sensor is always a difficult issue to tackle with, especially for pressure gauges, even though POL has designed a method for overcoming those difficulties [10]. Switch systems are another alternative.

✓ Some other aspects to bear in mind are: the software provided, the power requirements, the transmission of data and, of course, the price!

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Álvarez-Salgado XA, Rosón G. Pérez FF, Pazos Y. (1993). Hydrographic variability off the Rías Baixas (NW Spain) during the upwelling season. Journal of Geophysical Research,98 (C8);14447–14455
[2] Barjenbruch U, Mai S, Ohle N, Mertinatis P, Irschik K. (2002). Monitoring of water level, waves and ice with radar gauges. HYDRO 2002. Hydrographic Surveying and Mapping.
[3] Barjenbruch U, Zenz T, Krank S. (2000). A New Technology Applicable to Water-Level Gauging. Proc. Of the XXV General Assembly of the European Geophysical Society EGS. Nice, France.
[4] Burenin PV, Pakov SV, Sizikov OK. (1998) Reducing the Measrument Error of Pulse-Radar Level Gauges for Bulk Media. Measurement Techniques, 6.
[5] Cuesta Frau D, Novák D, Pérez Cortés JC, Andreu García Gm Eck V, Sastre Mengual C, Llorca Alcón M (2000). Reducción del ruido en señales electrocardiográficas mediante la transformada Wavelt. Conferencia Anual de la Sociedad Española de Ingeniería Biomédica (CASEIB-2000). Cartagena, Spain. September 2000.
[6] Devine P. (2000). Radar level measurement – the user's guide. Vega Controls Ltd.
[7] ESEAS-RI (2002). European Sea Level Service Research Infrastructure (ESEAS-RI). Project No.: EVR1-2001-00042. Description of Work.
[8] Grønlic Ø. (2002). Electromagnetic Sensor Measures Water Level. Sea Technology pp:10-13.
[9] IOC (1997). Global Sea Level Observing System (GLOSS) Implementation plan –1997. Intergovernmental Oceanographic Commission, Technical Series, 50, 91 pp& Annexes.
[10] IOC (2002). Manual on Sea Level Measurement and Interpretation. Unesco.
[11] ITR (1999). Water Level Sensor and Datalogger
[12] Mai S, Zimmermann C. (2000) Applicability of Radar Level Gauges in Wave Monitoring. Porc. Of the 2nd Int. Conf. Port Development & Coastal Environment. Varna. Bulgaria,
[13] Miros Document 1201/TH/001, rev 01.16/10/02 (2002). Miros Mircrowave Range Finder - Technical Handbook.
[14] Pugh, DT. The physics of pneumatic tide gauges. International Hydrographic Review, v.49, pp. 71-97, 1972.
[15] UNESCO (1983). Algorithms for computation of fundamental properties of seawater, 1983. Unesco Technical Papers in Marine Science. No 44.
[16] Woodworth PL, Smith DE. (2003): A One Year Comparison of Radar and Bubbler Tide Gauges at Liverpool. International Hydrographic Review 4(3), pp 2-9.
[17] http://www.enraf.com
[18] http://www.eurocean2004.com/galway-declaration.html
[19] http://www.paroscientific.com
[20] http://www.seba.de
[21] http://www.siam-cma.org/
[22] http://www.vegacontrols.co.uk