IVg - SEA LEVEL MONITORING AND FORECASTING ACTIVITIES OF PUERTOS DEL ESTADO

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A description is made of the Spanish Harbours tide gauge network (REDMAR), especially focused on the status of the Mediterranean stations. This network consists of 14 acoustic gauges with radio or modem transmission of data to the harbour office, where data is automatically sent twice a day by ftp or mail to the central station in Madrid (Clima Maritimo). This department has also developed an storm surge prediction system, called Nivmar, based in the ocean circulation HAMSOM model (which performs the prediction of the meteorological residuals), and the tide gauge data, which is used both to obtain the astronomical prediction in the harbour and to validate the system.

1. INTRODUCTION

In 1989 the old Spanish State Harbours Office (Direccion General de Puertos) decided to create a permanent sea level monitoring system which included the possibility of consulting the data in real time by the harbour users apart from generating historical series to be included in the Clima Maritimo Data Bank, linked to this Office. The design of the network was supervised and executed by the Centro de Estudios de Puertos y Costas (CEDEX, Ministry of Public Works), under the direction of the mentioned Clima Maritimo Department.

The equipment selected was the acoustic gauge of SONAR Research & Development (Ltd.), because it included real time data transmission to the harbour office and their maintenance was very easy. In 1991 13 harbours were selected to establish the REDMAR network, and the stations were tested by the Centro de Estudios de Puertos y Costas until July 1992, when the network officially began to work continuously. Since then, data is stored, quality controlled and analysed in the Clima Maritimo department of the Puertos del Estado (Spanish Harbours). The stations of the Mediterranean are: Barcelona, Valencia and Malaga. A new station is being planned for Ibiza (Balearic Islands).

A storm surge prediction system (Nivmar) has been working since 1998 for the Spanish Atlantic coast and since 1999 for the Mediterranean coast (http://www.puertos.es/Nivmar). Nivmar is based on the ocean circulation HAMSOM model and on the harmonical prediction of tides computed from data measured by REDMAR. The model is executed twice a day, forced by meteorological fields derived from the INM (Instituto Nacional de Meteorologia) operational application of the HIRLAM atmospheric model. Data from the REDMAR tide gauges are used to forecast the tidal elevations, to validate the system and to perform data assimilation, correcting systematic errors in the mean sea level due to physical processes that are not included in the ocean model. The forecast horizon is 48 hours.

The automatic data transmission from the harbours to Clima Maritimo and their inclusion in the Nivmar system is under development. At the moment, this is working for four stations: Bilbao, Villagarcia, Valencia and Barcelona.

2. REDMAR NETWORK

A map is presented in Figure 1 with the 14 stations that currently constitute the REDMAR network. Since June 1999 a pressure sensor has also been working in the island of Hierro (Canary

Islands), a point that will soon belong to the REDMAR network. A new station is also being planned for the Ibiza Island, in the Balearic Islands, in collaboration with other institutions to get a permanent GPS monitored station for altimeter calibration.

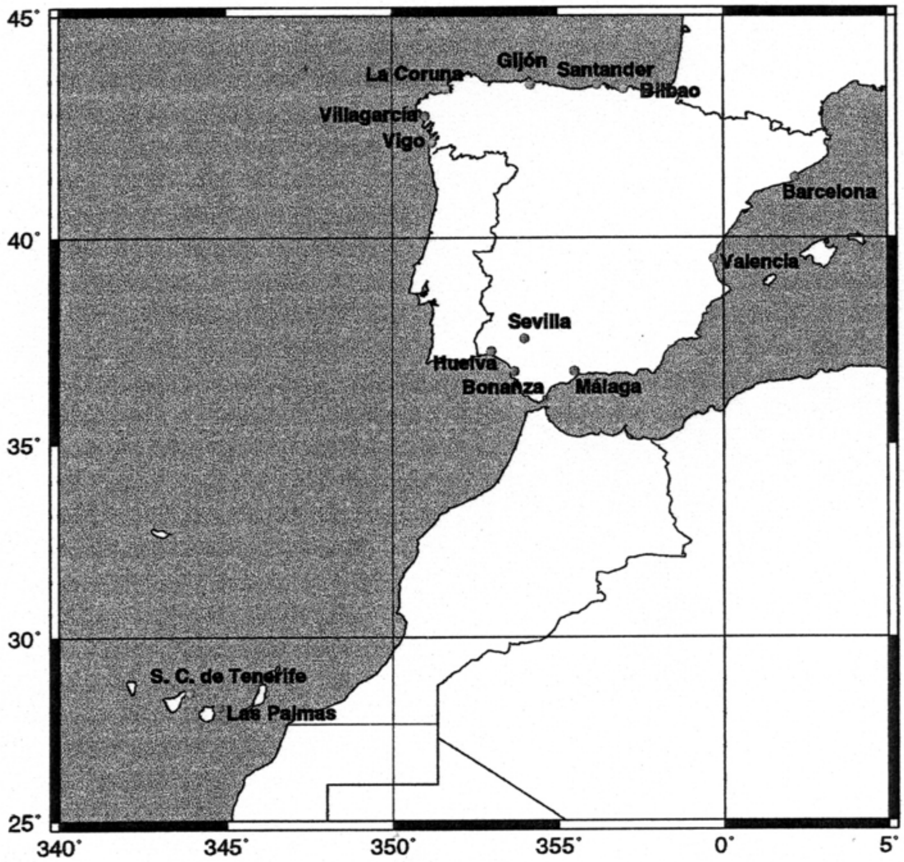

Figure 1: stations of the REDMAR tide gauges network

2.1 Description of the SONAR gauge

The selected equipment was the SONAR Research & Development acoustic tide gauge with real time radio transmission to the harbour office. The technical specifications are:

- height measurement range: 10 meters height measurement resolution: 1 cm
- height measurement accuracy: 0.05 % (better than 1 cm for instantaneous levels) time measurement resolution: 1 s
- time measurement drift lower than 1 minute per month acoustic frequency: 50 KHz
- telemetry output: RS 232 every minute
- sampling period: 1,2,3,4,5,6,10,15,20 and 30 minutes
- averaging period: number of measurements used to provide averaged tide height can be: 1,2,4,8,16,32,64.

The transducer is located above the sea surface, at a distance not less than 2 meters during high tide and not more than 9 meters during low tide (the highest tide range in Spain is about 5 meters). The transducer has to be mounted within 2 degrees of horizontal to achieve optimum results. The view of the transducer should be unobstructed within a 10-degree conical angle to avoid interfering targets. For permanent installations it is strongly recommended that the system operate down a plastic tube.

The distance to the water (air distance) is obtained from the sound velocity and the time the ultrasonic ray needs to reach the water surface and go back to the transducer again. The distance from the sensor to the reference level or zero is called the *datum;* sea level is then calculated as the difference between the datum and the obtained air distance.

As sound velocity depends on environmental conditions, especially on the temperature, it is calculated before each measurement by sending ultrasonic pulses to a fixed target located at 0.75 m from the sensor (this distance is factory set). In this way, each measurement lasts around 36 seconds: the first 10 seconds are used to determine the sound velocity by sending 128 valid echoes to the target; then another 128 valid echoes are sent to the water surface and a mean value is calculated to filter the high frequency waves.

For most of the REDMAR stations the transducer measures inside a 0.30 m diameter plastic tube, with its lower extreme at a point below the lower low water and a small hole of 3 cm. The role of the tube is of course not only to filter the waves but also to protect the ultrasonic rays path. In some places, like Santander, it was possible to install it in an existing stilling well, inside a small building.

Although the reference target is employed to take into account variations in temperature and other parameters, this is done in the first 1-meter distance of the tube, so it is still possible that strong temperature gradients along the tube affect the signal. This has happened especially in our southern harbours where the summer is very hot. Our recommendations for the harbours are the same than for other acoustic sensors: to employ white painted tubes, to avoid different ambients along the tube, to do small holes above the higher high water to facilitate ventilation and even to construct a protection from the sun. This has proven to be a very good solution. From our experience, the above-mentioned requirements of the installation are critical to get the accuracy claimed by the manufacturer. It has also been noted that the system works perfectly inside a building above a stilling well, like the stations in Santander and Malaga harbours. Even without a stilling well, as is the case for Villagarcia, the careful design of the installation to protect the tube from the sun has provided data with accuracy better than 2 cm for instantaneous measurements. The principal disadvantage of this type of acoustic sensor is that is very dependent on these conditions of the installation.

The problem of the temperature gradient is less important in the Mediterranean stations, because the tide range here is very small.

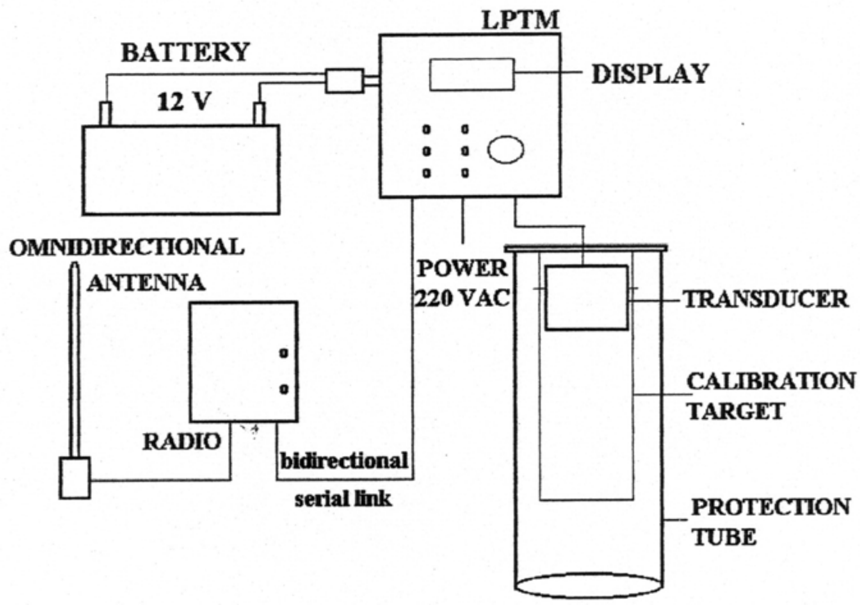

Figure 2: Elements of a normal station of the REDMAR network

2.2 Data storage and transmission

The ultrasonic transducer is connected to an intelligent unit (LPTM: Low Power Telemetry Unit), which allows to select the sampling interval (5 minutes at this moment for all the REDMAR stations), the averaging period (1 measurement), the station number and to establish the tide gauge datum, as well as to adjust the clock time, display the data and store them. It provides also the power supply (Figure 2).

The LPTM may be connected to a personal computer and transmit data by modem to the harbour and to the central station in Madrid or, as is the case for most of the stations of REDMAR, it may transmit the data by radio to the harbour office, where data are stored in a PC and transmitted by mail or ftp to the central station. The sensor has an internal cyclic memory that permits to store up to 28 days of 5-min data.

2.3 Datums and levelling status of the REDMAR stations

Most of the REDMAR stations measure sea level data with respect to the harbour-working datum, a reference provided by the harbour authorities. Besides, the Instituto Geografico National (IGN) has provided the Tide Gauge Bench Marks (TGBM) and their relation to the national levelling system for all the stations. The connection between the TGBM and the tide gauge zero is responsibility of Puertos del Estado, and is checked twice a year by the maintenance staff. The tide gauge contact point is for the SONAR gauges the ring around the centre of the transducer. This is leveled to the TGBM with a few millimeters precision, by the tide gauge maintenance responsible. Anyway, and as it is recommended by the supplier, the datum is initially adjusted to give the expected tide height as indicated on a local tide staff, or by measuring manually (e.g. an electric tape) the distance to the water surface; this allows any small anomalies between the reference measurement and the tide measurement to be assessed. Our experience is that this calibration is needed the first time the gauge is installed, and is checked twice a year, together with the levelling of the Tide Gauge Contact Point to the TGBM. However, due to the resolution of the datum value (1 cm), the reference level for this equipment is fixed at best with 1 cm accuracy.

Also the conditions to make the manual measurement or the reading of the tide staff influence very much the accuracy of the first establishment of the reference. It is very easy when the gauge is measuring in a stilling well, because here the water is quiet (for example our station in Santander), but when a tube is used, it is not possible to open it and measure inside without affecting the sensor, so we have suggested to the harbours to install a parallel calibration tube that filters the waves, in order to check the reference with more reliability.

The national datum for the Iberian Peninsula has been for the last 100 years the Alicante Mean Sea Level (NMMA) during the period 1870-1880. In 1998 the IGN redefined the levelling network and, as it has occurred in other countries in the past, the heights of the TGBM with respect to NMMA have changed up to 30 cm in the harbours of the North coast. Nowadays the IGN is beginning to establish GPS permanent stations all around the country, although only two are at this moment completely operational: Alicante and Coruna, in both cases located exactly in the place of the corresponding IGN tide gauge. Puertos del Estado and IGN are about to sign an agreement to connect the IGN GPS permanent stations close to the REDMAR tide gauges with the corresponding TGBM and to install a sufficient number of auxiliary marks in the proximity of the tide gauge, to be checked periodically (this has not been done up to now).

2.4 Data processing

The gauges measure sea levels at five-minute intervals. Once the raw data is received in Clima Maritimo a quality control procedure is initially applied to detect the most obvious errors: clear spikes, gaps, sudden change of reference-etc. So a clean 5 min-sampling series is obtained before calculating the hourly means.

The hourly means are obtained by means of a 54 points symmetrical filter (Pugh, 1987) in order to average the seiches, especially important in the Mediterranean stations.

The software developed by the University of Hawaii Sea Level Center (Caldwell, 1998), based on the harmonic analysis and prediction programmes developed by Foreman (1977), is used to obtain the harmonic constants, residuals, and mean sea levels, although an adapted version for Unix systems is being developed in the department. Also tide ranges and extremes are calculated on an annual basis and published in form of technical reports for the harbour authorities. All these data are stored in the Clima Maritimo Data Base and will be in the near future accessible for the users on the web page.

2.5 Mediterranean stations

There are three stations of the REDMAR network in the Mediterranean coast: Malaga (Alboran Sea), Valencia (in front of the Balearic Islands) and Barcelona (Cataluna). As it was mentioned another one is being planned for Ibiza (Balearic Islands).

As for the rest of the REDMAR stations, the recording interval is 5 minutes. This seems to be especially important in the Mediterranean gauges, due to the existence of sub-hourly higher frequency noise due to seiches that may occasionally reach amplitudes of nearly 0.5 meters. It is interesting for the harbour authorities to have this phenomenon registered.

In Figure 3 the daily and monthly means for the three stations are presented since the beginning of the operation in 1992. The tide range is much smaller than in the Atlantic coast, especially in Valencia, very close to the M2 amphidromic point that is located close to Alicante. In Table 1 the principal harmonic constants are shown for the three harbours. From South to North the semidiurnal constants are dominant in Malaga (semidiurnal tide, Form Factor=0.20), are less important than the diurnal ones in Valencia (mixed tide, mainly diurnal, Form Factor=2.67), and are again just a little bit higher in Barcelona (mixed tide, mainly semidiurnal, Form Factor=0.96).

	Malaga - .		Valencia		Barcelona	
	Amp (cm)	Phase (g.)	Amp (cm)	Phase (g.)	Amp (cm)	Phase (g.)
01	1.79	124.20	2.51	107.47	2.54	102.30
Kl	3.42	152.60	3.73	162.60	3.68	170.72
M2	19.06	49.43	1.79	196.22	4.71	212.87
S2	7.21	74.07	0.54	146.76	1.74	232.60

Table 1: principal harmonic constituents *derived from 1999 hourly values*

In Table 2 also the extremes for the period July 1992 to December 1998 are presented for the three stations, obtained from the hourly and 5-min data, as well as an estimation of the maximum and minimum residual value. The tide range is only included for Malaga because the tide is really small in Barcelona and Valencia. The standard deviations of the residuals in 1999 are 6.6 cm (Malaga), 7.0 cm (Valencia) and 7.0 cm (Barcelona). The hourly data standard deviations for 1999 are 18.7 cm (Malaga), 14.4 cm (Valencia) and 11.8 cm (Barcelona).

Harbour	Hourly level		5 min	level	Surge		tide range	
	Max	Min	Max	Min	Max	Min	Max	Min
Malaga	122	-8	133	-10	48	-35	84	12
Valencia	145	56	158	41	42	-35		
Barcelona	72	-25	76	-26	45	-35		

Table 2: *Extremes for the* period *July 1992-December 1998*

Malaga: (36°42'50" N, 004° 24'52" W)

The tide gauge is located beside the Instituto Espanol de Oceanografia (IEO) float gauge. They measure in the same stilling well, although in two different tubes inside it. The TGBM is SS2NGK-236, and is located in the outside of the stall, next to the door. Another stable benchmark is the NAP-548 located in the wall of the lighthouse La Farola a few hundred meters from the gauge.

The LPTM is directly connected to a PC inside the stall, which transmits automatically by modem the data to another PC in the harbour office. This second PC is connected to the local informatic network and receives data not only from the tide gauge but also from other type of sensors in buoys close to the harbour. From this PC data are sent automatically via mail or ftp to the central station (Clima Maritimo). This is cheaper than the tide gauge PC sending direct by modem the data to Madrid.

Name:	*NMMA:*	*Harbour zero:*	*IEO zero:*
SS2NGK-236	0.829	1.244	1.640
NAP-548	5.393	5.808	6.204

Table 3: altitudes (meters) *of the principal* bench marks above *the NMMA,* harbour *zero* and *TEO* zero *for Malaga station*

The IGN has recently installed a permanent GPS station at about 5 km of the tide gauges station that has not been connected yet to the TGBM.

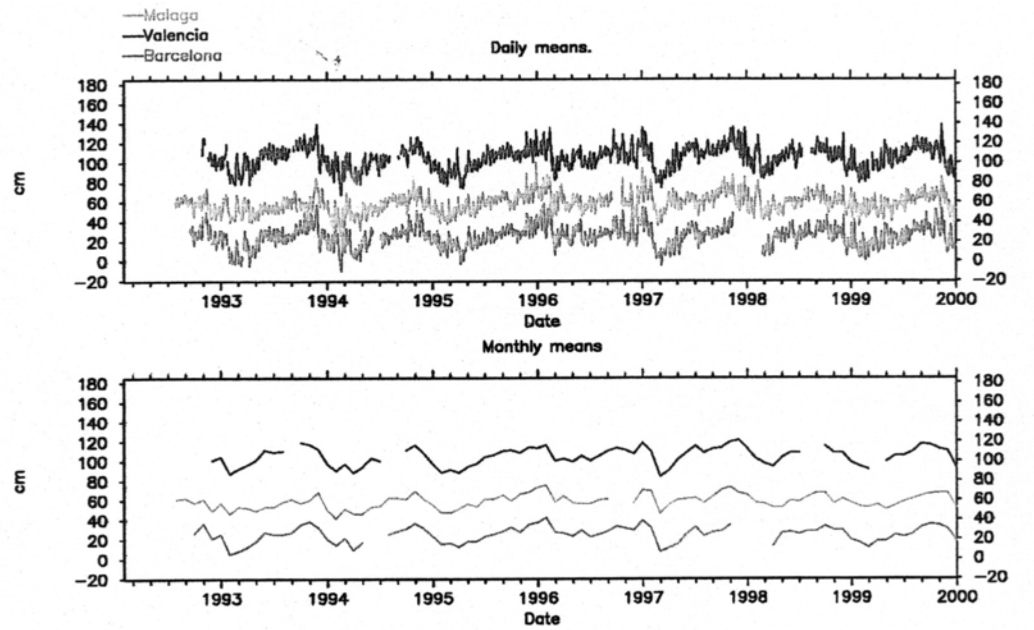

Figure 3: daily and monthly means *for the* three *Mediterranean stations since the* beginning of the operation

Valencia: (39°2T42" N.000° 19'33" W)

The tide gauge measures inside a 300 mm tube, with an outer protection for the sun and the ships. The TGBM (NGU 66) is located close to the tube on the pavement of the pier. The LPTM and the antenna are inside a nearby workroom. Another stable benchmark is the SS, located in a corner of the fish market building.

NCU- 66

Name: NMMA: T.G. Zero: 1.808 2.786
SS 1:355 2.333 B

Table 4: *altitudes* (in meters) *of the principal* benchmarks in Valencia above *the NMMA and* the Tide Gauge *Zero*

In this case, the tide gauge zero is not the harbour zero but a reference situated 1 meter below it. The IGN has established a permanent GPS station in December 1999 at about 4 km from the tide gauge, not yet connected to the TG.

Real time data are sent by radio to the harbour office and collected by a PC that, as it is connected to the local informatic network, sends the data automatically twice a day to Clima Maritimo by mail or ftp.
Barcelona: (41°21'01"N,002°09'41"E)

This gauge measures also inside a 300 mm tube and transmits the data like the Valencia station to the harbour (real time radio transmission) and to the Madrid central station (twice a day). The TGBM (NGP 791) is on the pavement in front of the South side of the stall. Another stable benchmark is NGP 792, between the CAMPSA tanks and the "Can Tunis" Institute walls.

Name: NMMA: Harbour zero: UELN:
NGP-792 4.148 4.174 3.663
NGP-791 2.412 2.438 1.927

Table 5: Altitudes in meters of the *principal* benchmarks in *Barcelona,* station

A GPS campaign (EUVN97) was made in May 1997 by the IGN. The antenna was collocated at a near TIR building inside the harbour, in such a way that the distance between the NGP 791 and the EUVN point was 580 m. The IGN also connected by high precision levelling the two points, giving the altitude of the bench mark above the UELN (Unified European Levelling Network).

3. NIVMAR SYSTEM

As mentioned in the introduction, in 1998 a storm surge prediction system was first established by the Clima Maritimo department, based on the ocean circulation HAMSOM model and on the harmonically prediction of tides derived from the REDMAR network. The HAMSOM is a three-dimensional and finite difference ocean circulation model developed by the IFM (Institute fur Meereskunde, Hamburg) and by Clima Maritimo. (Backhaus, 1983; Backhaus, 1985; Backhaus and Hainbucher, 1987; Rodriguez and Alvarez, 1991; Rodriguez et *al,* 1991; Stronach *et al, 1993;* Alvarez *et al,* 1997). It is based on the set of primitive equations (Reynolds equations) and uses hydrostatic and Boussinesq approximations. It is formulated on an Arakawa-C grid and based on a semi-implicit scheme. The model can take into account the tides, wind, atmospheric pressure, heat fluxes and baroclinic gradients inside the ocean. It has been applied to a large variety of scales and phenomena, from studies of tides in the Eastern North Atlantic to estuarine circulation in the Ria of Vigo (Galicia).

The Nivmar system consists of a set of different applications and programmes that make use of the barotropic and vertically integrated version of the HAMSOM model. The model domain covers an area extending from 20°N to 48°N in latitude and from 34°W to 30°E in longitude. The bathymetry employed, based on the DTM5 data set (GETECH, 1995), was built by using a variable grid size scheme in order to reduce the number of computational points. The region from 25ºN to 48ºN and from 20ºW to WE keeps a constant resolution of 10'x15'. The grid size in the rest of the domain is increased progressively to the boundaries.

The HAMSOM is executed twice a day using the output from the INM (Instituto Nacional de Meteorologia) application of HIRLAM (Kallen, 1996) to give the meteorological sea levels with a forecast horizon of 48 hours. The meteorological data consist of six hourly fields of winds at 10 m and pressures, with 0.5°x0.5° resolution. These are interpolated to the HAMSOM grid in an initial stage.