Three Years of Tide Gauge Measurements in the Pasajes Harbour

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Key words: Sea Level; Tide gauge; Data analysis; Pasajes Harbour

SUMMARY

In order to get sea level variations in the Pasajes harbour (Cantabrian Sea in the north of Spain) an automatic precision tide gauge was installed in 2007. To obtain "real" sea level variations isolated from crustal movements or local deformations, a permanent GNSS station has also been installed in a nearby building of the tide gauge.

The aim of this GNSS station is the continuous measurement of vertical crustal movements to obtain absolute sea level variations by removing these local variations from the raw tide gauge data records. Possible crustal movements with respect to the tide gauge measured sea level are being studied, as well as their possible correlation with the GNSS observations.

A high-accuracy vertical tie between the reference point of the GNSS antenna and the tide gauge bench mark is carried out yearly.

In this work the stations description, the first results obtained with three years of tide gauge measurements, the evaluation of the altimetric link campaigns, and the comparison of the levels of different measurements are presented. The statistical analysis of three years of records is presented as well.

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1. INTRODUCTION

As of February 2007, the Diputación Foral de Gipuzkoa, the University Complutense of Madrid and the company GEOLAN DONOSTI SL put into operation a Permanent GNSS Station and a tide gauge (TG) in the Pasajes harbour, in northern Spain (Figure 1) The purpose of this installation is the study of the sea level, as well as its variation. One of the goals of the GNSS station is the determination of possible vertical crustal movements in the study area as well as the linking of the TG, which is referred to a local reference frame, to the Global Geocentric Reference Frame (ITRF) by Space Geodesy techniques. These movements can be this way isolated from raw sea level records, providing absolute sea level variations through time series analysis which is the final objective (Vélez et al. 2008, Zerbini et al 1998).

Both, the TG and the GNSS station are linked accurately to three additional benchmarks (TGBM) which provide information about the local deformations. These TGBMs are linked by means of annual GNSS observations and spirit levelling, whereas the GNSS station's height is linked to the TG by simultaneous reciprocal trigonometric levelling in order to ensure a few millimetres accuracy. This way, since the TG local frame and the Global ITRF frame are linked, it is possible to get advantage of space geodesy data (Zurutuza et al 2008)

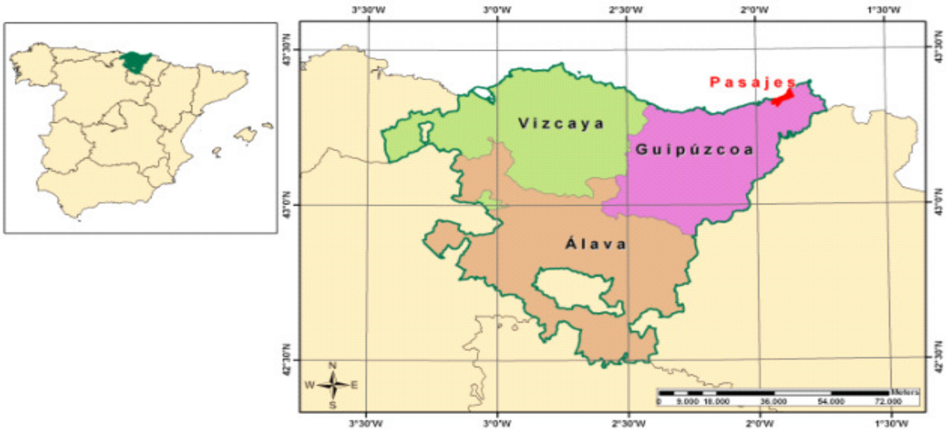

Figure 1. TG and GNSS station situation

An external meteorological sensor provides continuous pressure, humidity and temperature data. Also gravity has been measured. All these data allow for instrumental corrections and calibrations and are used later on to study possible seasonal variations in more than one isolated observable.

2. TIDE GAUGE

A Digiquartz© 8DP070-GV submersible depth sensor provides the sea-level variations since February 2007. The data are registered using a Campbell R800 Datalogger. Daily files are produced with the raw data with a 1 minute sampling interval.

3. PERMANENT GNSS STATION

3.1 GNSS Receiver

The GNSS receiver is a dual-frequency (14 GPS+12 GLONASS) Leica GRX1200GGPro which is located in the roof of the AZTI facilities (Figure 2), about 15 m away from the TG. Installed in mid 2007, the GNSS antenna is a choke-ring LEIAT504GG LEIS (also from Leica) with Dorne Margolin element. Absolutes Phase Center Variations (PCV) for this antenna are provided by IGS (IGS05_1502.ATX). The approximated coordinates (ETRS89) are: $\varphi = 43°19'18''.373$, $\lambda = -1°55'52''.059$

The daily processing of the GNSS data (only GPS observations are considered) is being performed with the AutoGNSS software (Zurutuza et al., 2007). The main processing parameters considered are (Zurutuza and Sevilla, 2007):

- Sampling interval: 30 seconds.
- Elevation mask: 10º.
- Tropospheric Model: Niell, estimated each 3 hours and piece-wise interpolated.
- Ionosphere: almost removed by using the “iono-free” frequency.
- Precise ephemeris.
- Earth tides and DD correlations are also used.
- Fixed sites: IGS stations BRUS, EBRE, VILL, YEBE.

The GNSS Station belongs to the GNSS Network of Gipuzkoa.

Figure 2. Building of AZTI and GPS Antenna

3.2 Permanent GNSS Station Control Network

The GNSS Control Network consists of 4 additional nearby stations (Figure 3) that are used to determine possible local deformations as stated in (Sevilla et al 2010, Sevilla and Romero 1991, García and Sevilla 2006). The maximum distance of the GNSS to the Control Stations is 400 m and the minimum distance is of 200 m.

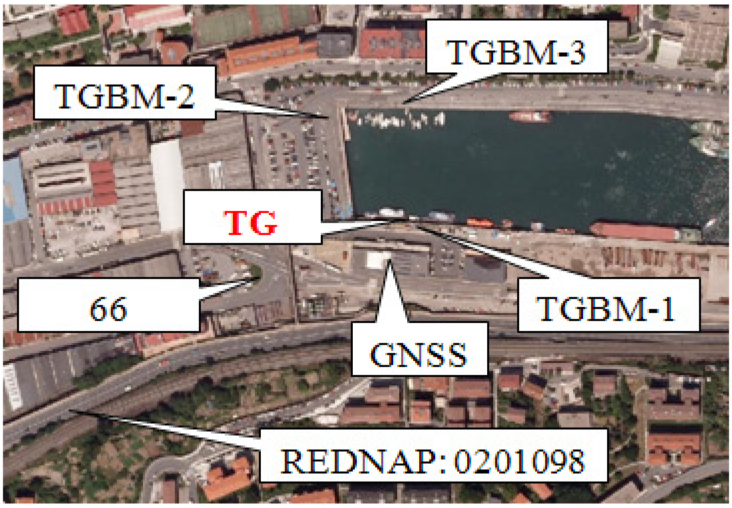

Figure 3. GNSS Station Control Network

4. LINKING OF THE GNSS NETWOKS WITH THE SEA-LEVEL AND LEVELING NETWOK IN PASAJES

The linking of the GNSS station to the height networks (REDNAP) is a major deal. Since the GNSS Station is located in the roof of a building, spirit levelling cannot be performed easily. Thus, simultaneous reciprocal trigonometric levelling is performed to get accurate height differences. This is repeated once a year. The TG is about 31 m away from the GNSS Station and the height difference is of about 14.6 m. This way, all the TGBMs are linked to he Global Reference Frame and to the REDNAP.

4.1 Levelling instrumentation

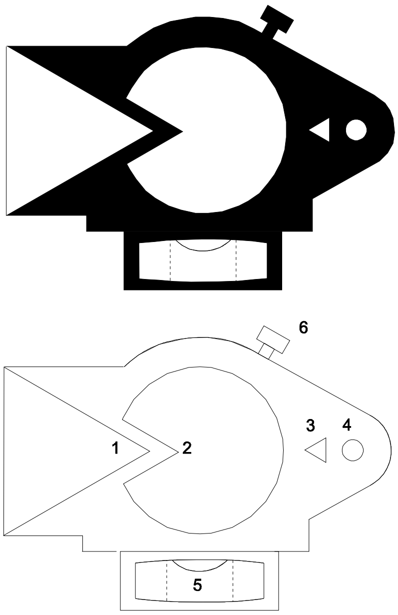

Figure 4. NITRIVAL NPT targets

The instrumentation consists of a WILD T2 theodolite with NITRIVAL NTP targeting system (Figure 4) and a PENTAX ATS-101 total station, with ranking accuracy of 2 mm + 2 ppm that includes automatic meteorological corrections for temperature and pressure. The constants were calibrated in the three pillars baseline of the Laboratory of the Faculty of Mathematical Sciences of Madrid. A SOKKIA SDL30 digital automatic level and milimetric staffs has been also used to perform the spirit levelling.

4.2 Levelling campaigns.

The levelling campaigns have been carried out during the month of July of the years 2008, 2009 and 2010. The same dates are scheduled for the coming years in order to have the same seasonal and atmospheric conditions. As stated previously, trigonometric and spirit levelling are performed to achieve the needed accuracies. Simultaneous reciprocal trigonometric levelling is the choice to link the GNSS Station's height and the TG whereas spirit levelling is used to get heights for all the TGBMs. Regarding the trigonometric levelling, the total station and the theodolite are located in eccentric places very close to the GNSS station and the TGBM-1, so that the real heights are also considered by readings to a millimetre stadia in the both-ends of the stations to be linked (as known, TGBM and the GNSS Station) with vertical angle 0º. On the other hand, spirit double levelling is performed so that the backlight and foresight are the same in order to cancel out refraction and curvature effects. This way, considering averaged heights, errors in the spirit levelling seldom exceed 1.5 millimetres (Valbuena et al, 1996).

4.3 Computations

Once concluded each campaign, and in the laboratory, all the observed differences are calculated. For the calculations of trigonometric height differences the method of independent direct calculations has been used. The points properly marked in the land with standard signals, or with solid references, are the following ones (Figure 5): tube of the tide gauge (1), TGBM-1, 2 and 3 (2), round mark (3), leveling mark201098 (4) and antenna GPS (5). In Table 1 the heights obtained for the observed reference points are presented. The reference signals were put on in the north part of the pier. The TGMB-2 is in the northwest corner to some 170 meters from the TGBM-1 and the TGBM-3 to some 170 meters of the TGBM-2. The TGBM-1 was taken as reference of the tide gauge and at this point the sea level is referred.

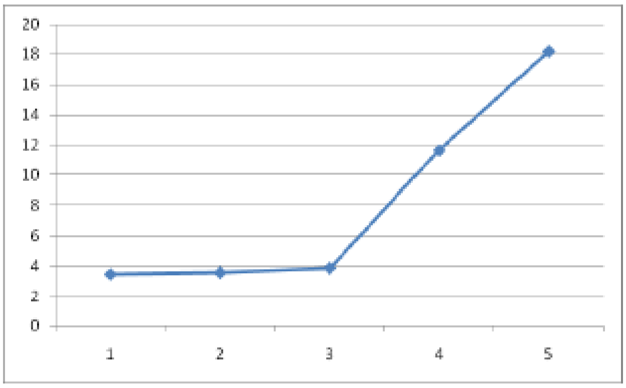

Figure 5. Profile of the spirit levelling

The measured benchmarks have the following naming:

	Naming
0	Tide Gauge
1000	TGBM-1
2000	TGBM-2
3000	TGBM-3
999	GNSS Station
66	Additional TGBM
10	REDNAP 201098

The leveling is performed by two rings. The first one, or higher ring, starts from mark 66 of the round and it ends in the leveling mark 10. Double levelling in this ring produce a closing error of 0,0001 meters. The second ring, starts from the TGBM-1, goes to the mark 66, continues in the TGBM-2 and it end in the TGBM-3. Double levelling in this ring produced a closing error of 0,0005 meters. Closing errors are also calculated individualized among 66 and 2000 of 0,0000 meters and enter 2000 and 3000 of 0,0004. These results confirm that the geometric leveling of precision is perfect. The difference between station 999 (GPS antenna) and the reference of the tide gauge TGBM-1 varies as shown in Table 1.

Table 1. Results for campaigns 2008, 2009 and 2010

POINTS	**2008**	**2009**	**2010**	**8-9**	**8-10**	**9-10**
999 minus 1000	14,6331	14,6336	14,6332	-0,468	-0,148	0,320
66 minus TGMB-1	0,2981	0,2969	0,2955	1,200	2,650	1,450
10 minus 66	7,7509	7,7511	7,7527	-0,150	-1,800	-1,650
10 minus TG (Top Reference)	8,0490	8,0480	8,0482	-1,050	0,850	-0,200
66 minus 2000			-0,6976			
2000 minus 3000			-0,0469			
TGBM-1 minus TG (Top Reference)	0,1140	0,1143	0,1146	-0,250	-0,550	-0,300
TG measuring reference minus TG (Top Reference)	6,940	6,940	6,940	0		
Measured Mean Sea Level (2008-09)	3,4786	3,4786	3,4786	0		
Heights above the Mean Sea Level						
TG (Top Reference) height	3,4614	3,4614	3,4614	0	0,000	0,000
TGBM-1 height	3,5754	3,5757	3,5760	-0,250	-0,550	-0,300
66 Height height	3,8735	3,8726	3,8714	0,950	2,100	1,150
TGBM-2 height			3,1738			
TGBM-3 height			3,1269			
NAP 201098 height	11,6244	11,6236	11,6241	0,800	0,300	-0,500
GNSSS height	18,2085	18,2092	18,2092	-0,718	-0,698	0,020
Heights above TGBM-1						
H of the TG tube	-0,1140	-0,1143	-0,1146	0,250	0,550	0,300
TGBM-1 height	0	0	0	0	0	0
66 Height height	0,2981	0,2969	0,2955	1,200	2,650	1,450
TGBM-2 height			-0,4022			
TGBM-3 height			-0,4491			
NAP 201098 height	8,0490	8,0480	8,0482	1,050	0,850	-0,200
GNSSS height	14,6331	14,6336	14,6332	-0,468	-0,148	0,320
Mean Sea Level	-3,5754	-3,5757	-3,5760	0,250	0,550	0,300
TG measuring reference	-7,0540	-7,0543	-7,0546	0,250	0,550	0,300

5. MEAN SEA LEVEL ANALYSIS

5.1 2007, 2008, 2009 and 2010 Measurements.

As stated, the TG was installed in February 2007, and started providing raw data measurements in March 28 of that year. We have considered only measurements starting from May 1st of 2007 to avoid erroneous data due to initial miss configurations in the TG software. In February 7 of 2009, the TG stopped working due to a problem in the recording PC. This is what we call the "first cycle". In this first cycle, the sampling interval was 1 minute (hourly and 5 minute data were used to compute Sea Level related constants).

The "second cycle" starts in July 10th of 2009 and, instead of a PC, a datalogger is used to register the measurements. In March 2011 the new configuration is working perfectly, so high quality raw measurements are warranted. Table 2 shows the statistics of the reviewed data.

Table 2. Statistics for all the reviewed data.

Sum	**3864,9878**					**5741**
Average	**3,5136**					
Standard Deviation	**0,1120**					
Minimum	**3,2242**	**0,3738**	**0,9780**	**6,5233**	**5,5453**	
Maximum	**4,1113**	**1,7111**				
Range	**0,8870**					
No data	**82**					

It can be seen that the mean average for all the recorded data is 3.5136 m, the standard deviation is 0.1120 m. The mean values vary from 3.2242 m (minimum) and 4.1113 m (maximum), which is a range of 0.8870 m. The reviewed raw data vary from 0.9780 m (minimum) and 6.533 m (maximum), which is a tidal range of 5.5453 m during the whole observation period. The standard deviations of the reviewed (IOC, 2000) data vary from 0.3738 m (minimum) and 1.7111 m (maximum). Figure 6 shows a graphic of daily records

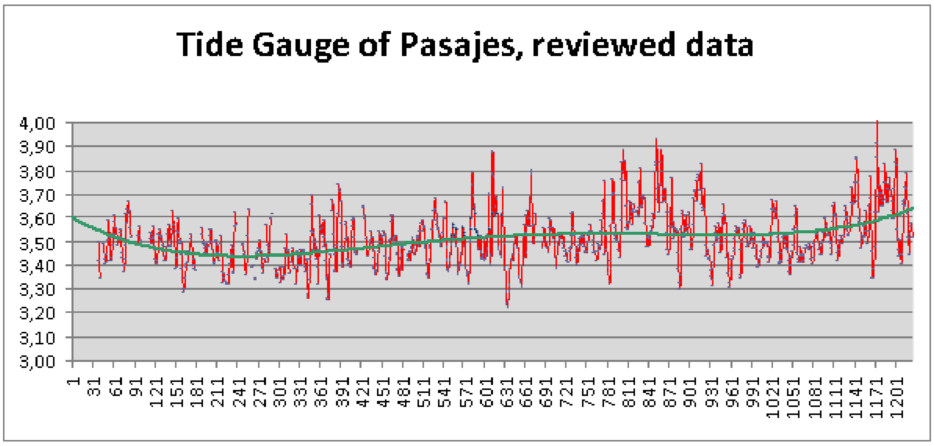

Figure 6. Pasajes TG data.

5.2. General results

Table 3 shows:

- Mean 1: Monthly average of the daily averages (28, 29, 30 or 31 days each month). The daily average is the mean of the 5 minutes registered intervals (288 per day).
- Mean 1A: Average of the accumulated daily means.
- Total average (Mean 1): average of the monthly averages (3.5114 m).
- Total average (Mean 1A): average of the accumulated monthly averages (3.5125 m).

Table 3. Monthly and total averages of daily data

Year	Month	Mean 1	Residual	Month data	Total data	Mean 1A	Residual
2007	May	3,5038	-0,0075	26	26	3,5038	-0,0087
	June	3,5110	-0,0004	24	50	3,5073	-0,0053
	July	3,4968	-0,0146	20	70	3,5043	-0,0082
	August	3,4994	-0,0120	31	101	3,5028	-0,0097
	September	3,4197	-0,0917	27	128	3,4853	-0,0273
	October	3,4489	-0,0625	31	159	3,4782	-0,0344
	November	3,4177	-0,0936	23	182	3,4705	-0,0420
	December	3,4197	-0,0916	29	211	3,4635	-0,0490
2008	January	3,4465	-0,0649	30	241	3,4614	-0,0511
	February	3,4531	-0,0583	29	270	3,4605	-0,0520
	March	3,4714	-0,0399	31	301	3,4616	-0,0509
	April	3,5114	0,0001	30	331	3,4662	-0,0464
	May	3,5107	-0,0007	27	358	3,4695	-0,0430
	June	3,4573	-0,0541	30	388	3,4686	-0,0440
	July	3,4762	-0,0351	26	414	3,4691	-0,0435
	August	3,4813	-0,0301	31	445	3,4699	-0,0426
	September	3,5232	0,0118	28	473	3,4731	-0,0395
	October	3,4859	-0,0254	31	504	3,4738	-0,0387
	November	3,5363	0,0250	30	534	3,4774	-0,0352
	December	3,4765	-0,0349	31	565	3,4773	-0,0352
2009	January	3,5179	0,0066	31	596	3,4794	-0,0331
	July	3,4999	-0,0114	22	618	3,4802	-0,0324
	August	3,4859	-0,0255	31	649	3,4804	-0,0321
	September	3,4899	-0,0214	30	679	3,4808	-0,0317
	October	3,5196	0,0083	31	710	3,4825	-0,0300
	November	3,6583	0,1470	30	740	3,4897	-0,0229
	December	3,6560	0,1446	31	771	3,4964	-0,0162
2010	January	3,5577	0,0463	31	802	3,4987	-0,0138
	February	3,6290	0,1176	28	830	3,5031	-0,0094
	March	3,5024	-0,0090	31	861	3,5031	-0,0094
	April	3,4672	-0,0442	30	891	3,5019	-0,0106
	May	3,4903	-0,0211	31	922	3,5015	-0,0110
	June	3,5247	0,0133	30	952	3,5022	-0,0103
	July	3,4706	-0,0407	31	983	3,5012	-0,0113
	August	3,4950	-0,0163	31	1014	3,5010	-0,0115
	September	3,5397	0,0284	30	1044	3,5022	-0,0104
	October	3,6182	0,1068	31	1075	3,5055	-0,0070
	November	3,6730	0,1617	30	1105	3,5100	-0,0025
	December	3,6008	0,0895	31	1136	**3,5125**	
	Total average	**3,5114**					

Table 4 shows:

- Mean 2: Monthly average of all the 5 minutes interval recorded values.
- Mean 2A: Average of all the 5 minutes interval recorded values.
- Total average (Mean 2): average of Mean 2 (3.5107 m).
- Total average (Mean 2A): average of Mean 2A (3.5127 m).

Table 4. Monthly and total averages of data every 5 minutes

Year	Month	Mean 2	Residual	Data	Total data	Mean 2A	Residual
2007	May	3,4926	-0,0181	6628	6628	3,4926	-0,0201
	June	3,4964	-0,0143	5453	18669	3,5013	-0,0114
	July	3,4994	-0,0113	8928	27597	3,5007	-0,0121
	August	3,4124	-0,0983	7347	34944	3,4821	-0,0306
	September	3,4723	-0,0384	8617	43561	3,4802	-0,0326
	October	3,4202	-0,0905	6313	49874	3,4726	-0,0402
	November	3,4202	-0,0796	6313	49874	3,4726	-0,0297
	December	3,4268	-0,0839	7711	57585	3,4665	-0,0463
2008	January	3,4388	-0,0719	7687	65272	3,4632	-0,0495
	February	3,4282	-0,0825	8013	73285	3,4594	-0,0534
	March	3,4714	-0,0392	8928	82213	3,4607	-0,0521
	April	3,5077	-0,0030	8557	90770	3,4651	-0,0476
	May	3,5033	-0,0074	7230	98000	3,4679	-0,0448
	June	3,4571	-0,0536	8622	106622	3,4671	-0,0457
	July	3,4745	-0,0362	7324	113946	3,4675	-0,0452
	August	3,4813	-0,0294	8928	122874	3,4685	-0,0442
	September	3,5215	0,0108	7953	130827	3,4717	-0,0410
	October	3,4860	-0,0247	8885	139712	3,4727	-0,0401
	November	3,5363	0,0256	8640	148352	3,4764	-0,0364
	December	3,4765	-0,0342	8928	157280	3,4764	-0,0364
2009	January	3,5184	0,0077	8774	166054	3,4786	-0,0341
	July	3,5029	-0,0078	6317	172371	3,4795	-0,0333
	August	3,4859	-0,0248	8928	181299	3,4798	-0,0329
	September	3,4899	-0,0208	8640	189939	3,4803	-0,0325
	October	3,5198	0,0091	8803	198742	3,4820	-0,0307
	November	3,6584	0,1477	8637	207379	3,4894	-0,0234
	December	3,6560	0,1453	8928	216307	3,4962	-0,0165
2010	January	3,5577	0,0470	8928	225235	3,4987	-0,0141
	February	3,6290	0,1183	8064	233299	3,5032	-0,0096
	March	3,5024	-0,0083	8928	242227	3,5031	-0,0096
	April	3,4672	-0,0435	8640	250867	3,5019	-0,0108
	May	3,4903	-0,0204	8928	259795	3,5015	-0,0112
	June	3,5247	0,0140	8640	268435	3,5023	-0,0105
	July	3,4706	-0,0400	8928	277363	3,5012	-0,0115
	August	3,4950	-0,0156	8928	286291	3,5010	-0,0117
	September	3,5397	0,0290	8640	294931	3,5022	-0,0106
	October	3,6182	0,1075	8928	303859	3,5056	-0,0071
	November	3,6730	0,1623	8640	312499	3,5102	-0,0025
	December	3,6008	0,0902	8928	321427	**3,5127**	
	Total average	**3,5107**					

Summary of the averages

Measurement type	**Average values**
Average of the raw data daily average	**3,5125**
Average of the reviewed daily average (36 days less)	**3,5136**
Monthly values average	**3,5114**
Accumulated monthly data average	**3,5125**
5 minutes interval data average	**3,5107**
5 minutes interval accumulated data average	**3,5127**

It can be pointed that the different averages considered agree within a millimeter. Therefore, the raw sea level (without any additional correction) from May 2007 to December 2010 is of **3,512** m.

Monthly averages shown an anomaly produced from November 2009 to February 2010. Residuals of those months are of 159, 156, 58 and 129 millimeters with respect to the mean value of 3.5000 m. The TG has been reviewed, as well as the meteorological data, astronomic tides, etc., in order to try to figure out which the cause of such strange behaviour could be, but no satisfying conclusion could be reached. Nevertheless, we find out in recent papers (Sveet et al 2009) that our TG is not the only one that must deal with these kinds of sea level variations and in many other areas without any explanation. This sea level anomaly is depicted in Figure 7, whereas Figure 8 shows the accumulated sea level.

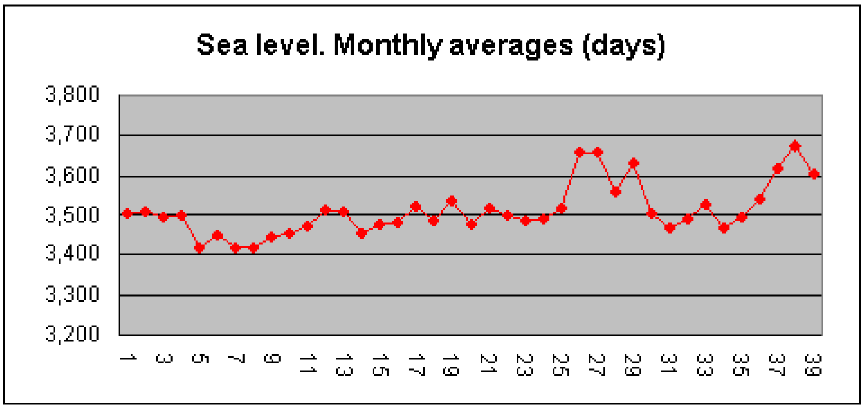

Figure 7. Monthly averages

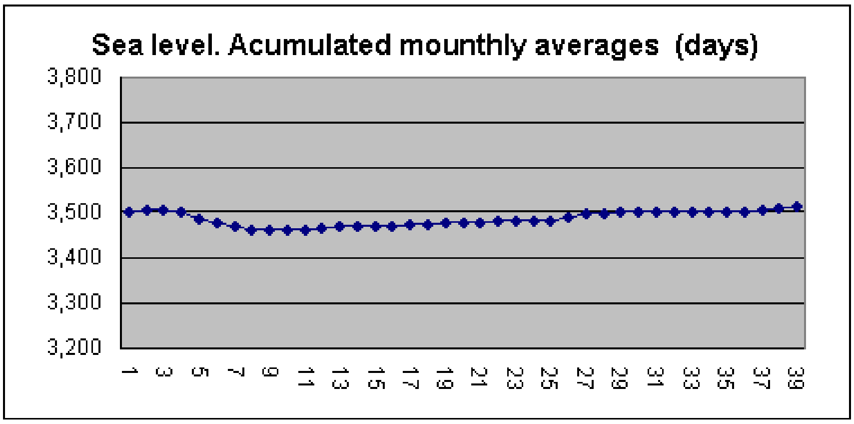

Figure 8. Accumulated average

CONCLUSIONS

This paper describes the GNSS/TG of Pasajes as well as the first results obtained after more than three years of continuous sea-level and GNSS observations. Issues like the need of accurate linking to existing networks and strange behaviors in the TG have also been dealt to eventually show the statistics of the raw and reviewed records. This results show that the GNSS/TG is fully operational and can be integrated in any sea level monitoring network to study the sea level or any other oceanographic application.

An evidence of this fact is the agreement signed by ATZ, Foral Council of Gipuzkoa and ARANZADI to warrant the continuity of the station as well as to ease the access to the registered data to any user who should be interested.

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