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Full Length Research Paper

Spectral analysis of tide waves in the Strait of Gibraltar

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In the Strait of Gibraltar, tide waves have been investigated through the spectral analysis of tide records. These traces have been recorded from the third quarter of the year 1997 to the third quarter of the year 2004 by the stations located at the Strait of Gibraltar: Huelva, Ceuta and Malaga. All the data refer to the Tide Gauge Zero (TGZ). These data have been sampled with a ratio of one sample per hour (1 SPH). Spectral analysis has been applied to these data to obtain the tidal components as well as the spectral amplitudes of the harmonic components present in each tide record. The principal harmonic components of this digital record correspond to the tide waves. They are easily identified in the amplitude spectrum because they always appear with larger amplitudes than the other harmonic components. Thus, the tide waves are identified visually in the amplitude spectrum and their period is read directly from this spectrum. Spectral analysis has also been used to investigate the behaviour of these principal harmonic components (or tide waves), showing that the spectral amplitudes of the tide waves are not always constant. The spectral amplitudes of the tide waves M_2, S_2 and N_2 have a temporal variation with a period of 1.28 years.

Key words: FFT, tide waves, Strait of Gibraltar.

INTRODUCTION

The Strait of Gibraltar is the narrow, shallow connection that constitutes the only water communication between the Atlantic Ocean and the Mediterranean Sea. It has a minimum width of about 14 km and a sea-bottom depth of about 300 m. This exchange is crucial for the Mediterranean Sea to compensate the negative hydrological balance caused by the fact that it loses more water through evaporation than it gains through runoff and precipitation (Loget and Van Den Driessche, 2006). The circulation of water in the Strait of Gibraltar is characterised by a surface inflow of Atlantic water with low salinity and a deep outflow of dense Mediterranean water with high salinity (Lacombe and Richez, 1982). This exchange is known as inverse estuarine circulation. Echebarria et al. (2002) consider the Armi and Farmer's (1988) model, in which the circulation process is described as a simple one-dimensional two-layer system flowing in opposite directions, to be a good first approximation. This is possible because the interface between the Atlantic and Mediterranean waters is in fact spread over several tens of metres (Izquierdo et al., 2001).

Over 1900 species of marine flora and fauna live in the Natural Park of the Algeciras-Tarifa Coast, which lies along the Strait of Gibraltar (Periañez, 2004). For this reason, the tides in the Strait of Gibraltar also have an ecological importance as biological mixing mechanisms. Transport fluctuations at longer tidal periods, particularly during the spring tides, can reverse the flows of the estuarine circulation. Important mixing can accompany the large-amplitude internal motions (Wesson and Gregg, 1994). Other works show the role of hydrodynamics as a forcing agent for the plankton community structure and associated water chemistry in the Strait of Gibraltar (Garcia-Lafuente et al., 2000; 2002; Gómez et al., 2001; Reul et al., 2002).

The tidal exchange is due to a strong correlation over the tidal period between the depth of the interface and the strength of the inflowing currents (Bryden et al., 1994). For the M_2 tide at the sill, the amplitude of the interface depth is 51 m and the amplitude of the tida currents is

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1.2 m s^{-1}. Furthermore, the inflow and the interface depth have similar phases. As a consequence, the upper layer is deep on the inflowing tide so that a large slug of Atlantic water crosses the sill into the Mediterranean. On the outflowing tide the interface is shallow, so a large slug of Mediterranean water crosses the sill into the Atlantic. Similar processes occur for the tides: S_2, O_1, and K_1; though the amplitudes are smaller. In this way, tidal oscillations lead to a time-averaged exchange of water masses across the Gibraltar sill.

Another study (Candela, 1991) considers the Mediterranean as a long zonal channel closed at both straits, indicating that the principal tidal signal observed in its interior is astronomically forced. However, the tidal wave coming from the Atlantic, although strongly reflected at the entrance to the strait (at approximately 94%), has about a 10% integrated contribution to the observed tide within the sea. In the Strait of Gibraltar, most of the tidal flow (approximately 92%) is barotropic, but a clear baroclinic tide is also discernible from observations. The correlation between tidal currents and depth variations of the interface (separating Atlantic and Mediterranean waters) at Gibraltar's main sill represents up to 1/3 of the mean transport in each layer.

Tidal components are also studied in the Strait of Gibraltar (Tejedor et al., 1999). It was observed that a phase difference of around 90 degrees between tidal velocity and elevation is detected in much of the Strait of Gibraltar. This suggests a small mean tidal energy flux through this strait, as well as the general direction for the M_2 and S_2 net tidal energy fluxes to the west. This is consistent with an observed south-western tidal phase propagation and remains qualitatively unchanged when varying the strait's geometry as well as boundary and astronomical forcing. The tidal cycle and its amplitude appear as an *a priori* forcing factor causing periodic mixing events on the Gibraltar Strait sill (Macias et al., 2006), which can supply nutrient-enriched deep waters to the surface Atlantic layer flowing towards the Mediterranean Sea. These mixing phenomena have both important biological (Echevarria et al., 2002) and biogeochemical (Gómez et al., 2001) implications at the regional and even basin levels. The effect of the semidiurnal tide is to increment the mean transport by about 30% both for the inflow and the outflow. The contribution of the semidiurnal tidal component (M_2) to the transport is relevant over Camarinal Sill (Sannino et al., 2004), whereas it is negligible at the eastern end of the strait.

Due to the importance of the tide and the tidal components, the goal of this study is to analyse the tidal components in the Strait of Gibraltar from the year 1997/1998 to the year 2003/2004. The Fast Fourier Transform (FFT) will be used to reveal the behaviour of the tide components or tide waves for semidiurnal (moon: M_2, MU_2 and N_2; solar: S_2 and K_2) and diurnal components (moon: K_1 and O_1, solar: P_1).

MATERIALS AND METHODS

Data acquisition and study area

The sea surface topography data determined from tide gauges are usually used for sea level studies. The global long-term records of the mean sea-level rise exhibit considerable scatter from about 1 mm to 3 mm/yr (Douglas, 1991). In this study, we use the sea level data supplied by the tide gauge network of the Instituto Español de Oceanografía (IEO, the Spanish Institute of Oceanography) and Puertos del Estado (PE, the Spanish Harbour Authority), which data are available from: http://indamar.ieo.es/ and http://www.puertos.es/, respectively. Both institutions are responsible for oceanographic survey in Spain. All data refer to the Tide Gauge Zero (TGZ). These data have been sampled with a ratio of one sample per hour (1 SPH), from the year 1997 to the year 2004.

The locations of the Gibraltar Strait considered in this study are (Figure 1): Huelva (latitude: 37º 08'N, longitude: 6º 49.9'W), Ceuta (latitude: 35º 54.1'N, longitude: 5º 19.8'W) and Malaga (latitude: 36º 42.8'N, longitude: 4º 24.8'W). Each annual record has been divided into five records (with 4096 samples each) taken throughout that year, obtaining from each record the amplitude and period of the tidal waves present. To analyze each station, periods of time for which data sets are complete have been used, so for Ceuta and Malaga, the series is from 1997-3 (the third quarter of the year 1997) to 2003-4 (the fourth quarter of the year 2003); and the Huelva series is from 1998-2 (the second quarter of the year 1998) to 2004-3 (the third quarter of the year 2003). This approach has been used for the Huelva station because there was no available data outside this range. A sample of these records is shown in Figure 2 for the stations considered. Thus, it has been possible to find the media and standard deviation for the period and the amplitude of the tide waves, for each year considered in this study.

METHODOLOGY

The tidal analysis based on the FFT assumes a simple principle: for a linear system whose forcing can be broken down into a sum of harmonic terms of known frequency (or period), the response can be also represented by a sum of harmonics with the same frequencies (or periods), but with different amplitudes and phases from the forcing (Forrestrer, 1983; Pugh, 1996; Hernandez-Escobedo et al, 2011). Basically, the tide waves are the result of such a system, due to their astronomical cycles imposed by the motions of the Earth, Sun, and Moon. However, this system is not truly linear. In making tidal predictions for it, the sums, differences and harmonics of forcing frequencies are considered to incorporate approximately nonlinear effects. It has been found experimentally for periodic signals that Fourier analysis lends itself to accurate and efficient identification algorithms (Rodenas and Garello, 1997).

Assuming the above basic principle, the tide records were subjected to spectral analysis based on the FFT, by means of a simple BASIC program for PC, performed following the instructions and codes published by Brigham (1988), which can be obtained from the internet address http://airy.ual.es/www/programs.htm. This computer program allows the application of the spectral analysis in order to identify the principal harmonic components of each tide record considered. Thus, the Fourier spectrum H(f) of the register (or tide record) denoted by h(t) was obtained by the formula (Brigham, 1988).

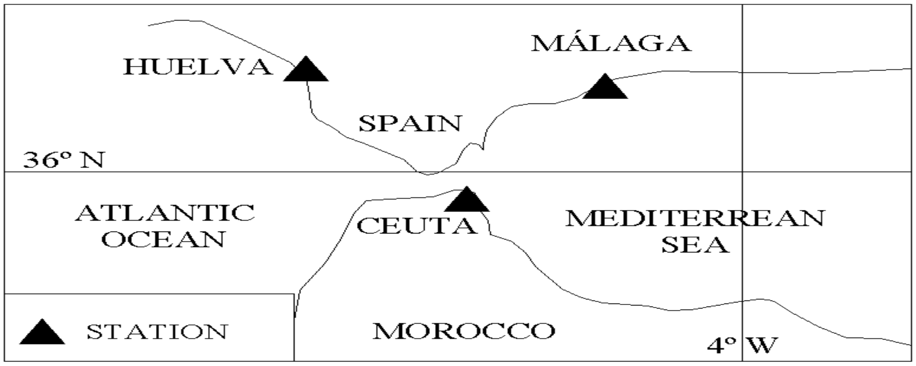

Figure 1. Geographical position of the stations used in this study.

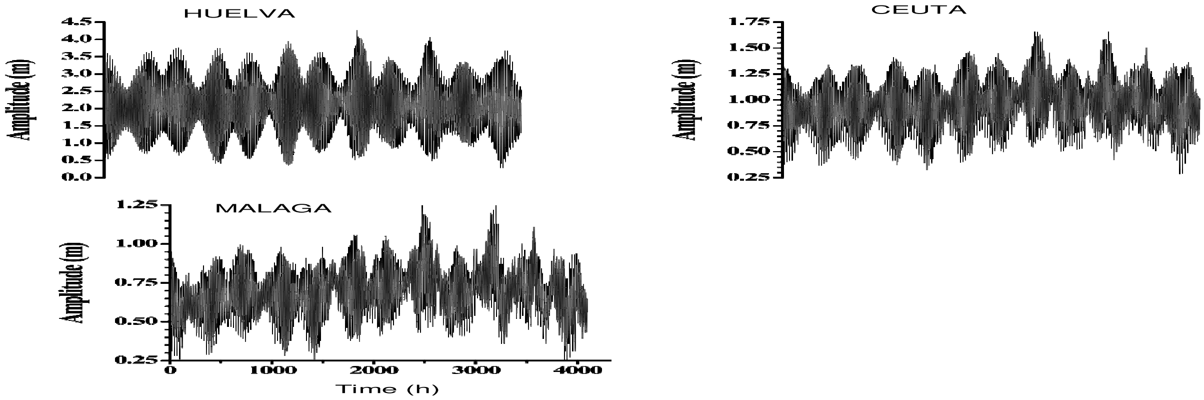

Figure 2. A sample of the records used for each station shown in Figure 1 (recorded in the year 2003).

$$H(f) = \int_{-\infty}^{\infty} h(t)e^{-j2\pi ft}dt$$

where f is frequency, t is time and j is the imaginary unit (j = $\sqrt{-1}$). In general, H(f) is a complex quantity called Fourier transform of h(t). H(f) can also be expressed as

$$H(f) = R(f) + jI(f) = |H(f)|e^{j\Phi(f)}$$

where R(f) is the real part of H(f) and I(f) is the imaginary part. The amplitude spectrum of h(t) is denoted by $|H(f)|$ and the phase spectrum is denoted by $\Phi(f)$. These are defined as

$$|H(f)| = \sqrt{R^2(f) + I^2(f)} \qquad \Phi(f) = \tan^{-1}\left(\frac{I(f)}{R(f)}\right)$$

When the amplitude spectrum of h(t) is studied, it is possible to identify the principal harmonic components of the digital record because they always appear with larger amplitudes (Bath, 1982). Frequencies corresponding to principal harmonic components are the frequencies of the tide waves present in the register. These waves are identified visually and their period T (T = 1/f) can be read directly from the amplitude spectrum. Thus, these harmonic components are easily identified in the amplitude spectrum. Obviously, spectral analysis can be used to identify and quantify any harmonic component in a digital register. For this reason, spectral analysis is considered today a standard tool of analysis in many scientific fields. This powerful technique has been applied recently by Corchete and Pacino (2007) in another field of science such as Geodesy, with successful results.

RESULTS

By application of the above described methodology, the results shown in Tables 1, 2 and 3 have been obtained for the stations Huelva, Ceuta and Malaga, respectively. These tables show the spectral amplitudes of the diurnal and semidiurnal tide waves found by means of spectral analysis. The five records into which each annual record has been divided are labelled with numbers from 1 to 5, as is shown in the above mentioned tables. Figure 3

Table 1. Spectral amplitudes of the diurnal and semidiurnal tide waves for Huelva station.

	Semidiurnal					**Diurnal**		
Origin	**Lunar**	**Solar**	**Lunar**		**Solar**	**Lunar**	**Lunar**	**Solar**
Tide wave	**M_2**	**S_2**	**N_2**	**MU_2**	**K2**	**K_1**	**O_1**	**P_1**
Period (h)	12.48780	12.04706	12.64198	12.80000	11.90698	23.81395	25.60000	24.38095
1998 – 2	0.78239	0.33239	0.47802	0.11978	0.17766	0.06951	0.03409	0.02497
1998 – 3	0.75556	0.35394	0.21878	0.15837	0.16311	0.07645	0.03111	0.03858
1998 – 4	0.72726	0.47399	0.03647	0.18533	0.15364	0.03835	0.04174	0.00680
1998 – 5	0.77877	0.19280	0.33675	0.12780	0.20021	0.04332	0.04961	0.03698
1999 -1	0.74809	0.34701	0.25401	0.14843	0.13943	0.05993	0.05999	0.03312
1999 – 2	0.79485	0.19077	0.42952	0.11597	0.27058	0.07657	0.04150	0.02321
1999 – 3	0.81008	0.14085	0.43842	0.10819	0.21466	0.08271	0.03676	0.02840
1999 – 4	0.73903	0.45129	0.33927	0.12684	0.18605	0.04145	0.05085	0.01455
1999 – 5	0.75775	0.38245	0.21720	0.15231	0.10117	0.07034	0.04983	0.01968
2000 -1	0.71386	0.43751	0.10014	0.17379	0.05141	0.06377	0.04596	0.02197
2000 – 2	0.73942	0.34666	0.04908	0.19148	0.22225	0.07706	0.04295	0.02655
2000 – 3	0.76057	0.26323	0.43116	0.12193	0.14702	0.08730	0.03964	0.03168
2000 – 4	0.80538	0.29347	0.43216	0.12003	0.30080	0.02650	0.05269	0.01473
2000 – 5	0.71630	0.41377	0.18313	0.15155	0.03406	0.06711	0.03999	0.01777
2001 -1	0.72929	0.23892	0.39687	0.08931	0.18672	0.07083	0.05046	0.02375
2001 – 2	0.71419	0.27421	0.18747	0.12751	0.32815	0.08385	0.04133	0.01842
2001 – 3	0.71200	0.39447	0.05896	0.17879	0.03055	0.08475	0.05210	0.03914
2001 – 4	0.75950	0.32667	0.36375	0.13762	0.29739	0.03960	0.04881	0.01365
2001 – 5	0.71503	0.23219	0.12049	0.15557	0.17163	0.04958	0.04049	0.04020
2002 -1	0.77551	0.17043	0.40910	0.09772	0.20935	0.06661	0.04251	0.02208
2002 – 2	0.76957	0.31306	0.45095	0.11102	0.21035	0.08041	0.04370	0.02770
2002 – 3	0.73572	0.28982	0.26702	0.13891	0.17729	0.08468	0.03823	0.03674
2002 – 4	0.66338	0.51162	0.06836	0.20054	0.20000	0.05321	0.05253	0.00727
2002 – 5	0.73113	0.25147	0.33506	0.15871	0.15402	0.06114	0.05114	0.03730
2003 -1	0.71054	0.36458	0.17983	0.15402	0.10142	0.05600	0.06381	0.03465
2003 – 2	0.77039	0.21488	0.40518	0.11548	0.27681	0.09106	0.04682	0.03576
2003 – 3	0.77864	0.14471	0.40634	0.10612	0.19221	0.09688	0.04128	0.02879
2003 – 4	0.71527	0.43889	0.36507	0.11551	0.23556	0.04810	0.06103	0.01600
2003 – 5	0.71576	0.38282	0.46096	0.14512	0.07399	0.07551	0.05338	0.01633
2004 -1	0.69582	0.41762	0.12184	0.15878	0.09644	0.07226	0.05201	0.02810
2004 - 2	0.71613	0.37667	0.01100	0.18605	0.21515	0.08526	0.05030	0.02702
2004 - 3	0.72334	0.31570	0.39670	0.11809	0.10323	0.09192	0.05068	0.03230

shows the spectral amplitudes of the diurnal and semidiurnal tide waves, obtained through spectral analysis, from the records shown in Figure 2, as an example of the performed analysis. Figures 4 and 5 are a zoom view of the spectral amplitudes of the semidiurnal and diurnal tide waves, respectively, obtained for Ceuta station. Tables 4, 5 and 6 show the media and standard deviation of the amplitudes listed in Tables 1, 2 and 3, respectively, for each year considered in this study. Each media and standard deviation has been computed from the five values of the spectral amplitudes obtained for each tide wave in a year, for each station considered are listed in Tables 1, 2 and 3.

The spectral amplitudes obtained in this study show a time-variable behaviour that can be investigated by spectral analysis. Figure 6a shows the spectral amplitude of the S_2 wave for Ceuta station. It should be noted that an oscillatory behaviour of the spectral amplitude is clearly shown in this Figure. It suggests the existence of a wave that modulates the amplitude of the S_2 wave, as it is confirmed by the spectral analysis of the data shown in Figure 6a, from which the spectral amplitudes shown in Figure 6b are obtained. This behaviour also appears in other tide waves obtained for the stations considered in

Table 2. Spectral amplitudes of the diurnal and semidiurnal tide waves for Ceuta station.

	Semidiurnal					**Diurnal**		
Origin	**Lunar**	**Solar**	**Lunar**		**Solar**	**Lunar**	**Lunar**	**Solar**
Tide wave	**M_2**	**S_2**	**N_2**	**MU_2**	**K2**	**K_1**	**O_1**	**P_1**
Period (h)	12.48780	12.04706	12.64198	12.80000	11.90698	23.81395	25.60000	24.38095
1997 – 3	0.19825	0.11616	0.02396	0.04803	0.01610	0.03439	0.01610	0.01310
1997 – 4	0.21053	0.07801	0.10810	0.03186	0.08235	0.02864	0.01732	0.01042
1997 – 5	0.20922	0.07696	0.03002	0.04970	0.04916	0.03657	0.00492	0.01371
1998 -1	0.22980	0.06192	0.12363	0.03268	0.06715	0.02916	0.01160	0.01393
1998 – 2	0.21549	0.09633	0.13512	0.03375	0.04701	0.03223	0.01203	0.00648
1998 – 3	0.21282	0.09674	0.06922	0.04680	0.04995	0.03495	0.01898	0.01702
1998 – 4	0.20093	0.13360	0.01209	0.05478	0.04304	0.02735	0.01108	0.00720
1998 – 5	0.21856	0.05326	0.09659	0.03296	0.05723	0.03441	0.01053	0.01182
1999 -1	0.21719	0.10346	0.07065	0.03779	0.03771	0.03208	0.01328	0.01824
1999 – 2	0.23134	0.04955	0.11986	0.03497	0.08079	0.03159	0.01974	0.01406
1999 – 3	0.23089	0.04245	0.12642	0.02858	0.06463	0.04059	0.01151	0.00733
1999 – 4	0.20846	0.13401	0.09644	0.03621	0.05531	0.02860	0.01137	0.00211
1999 – 5	0.21483	0.10746	0.14478	0.04305	0.02300	0.03550	0.01640	0.01252
2000 -1	0.20885	0.12626	0.02650	0.05189	0.02158	0.03803	0.01951	0.01739
2000 – 2	0.21351	0.09449	0.01180	0.05369	0.06593	0.03231	0.01839	0.01019
2000 – 3	0.21631	0.08258	0.11962	0.03259	0.04253	0.04332	0.01803	0.01632
2000 – 4	0.23135	0.08943	0.12364	0.03680	0.08610	0.02639	0.01740	0.00684
2000 – 5	0.20620	0.11601	0.04642	0.04592	0.01157	0.03583	0.01028	0.02229
2001 -1	0.20885	0.12626	0.02650	0.05189	0.02158	0.03803	0.01951	0.01739
2001 – 2	0.20850	0.12845	0.07129	0.04012	0.02865	0.02926	0.01692	0.01426
2001 – 3	0.20498	0.11690	0.01648	0.05018	0.01337	0.03583	0.02239	0.01787
2001 – 4	0.21277	0.09555	0.09768	0.03930	0.08867	0.03234	0.02325	0.00862
2001 – 5	0.20730	0.06742	0.03611	0.04119	0.04351	0.04868	0.02199	0.01633
2002 -1	0.22326	0.05188	0.12025	0.02856	0.06128	0.04056	0.00883	0.01619
2002 – 2	0.22342	0.09135	0.12973	0.03206	0.05502	0.03912	0.01896	0.00367
2002 – 3	0.20885	0.08410	0.07972	0.04392	0.05404	0.03873	0.02053	0.01629
2002 – 4	0.19364	0.14891	0.01293	0.04379	0.05000	0.03256	0.01693	0.00255
2002 – 5	0.21600	0.06555	0.09410	0.03236	0.04954	0.04443	0.01006	0.01247
2003 -1	0.20481	0.11696	0.05149	0.03874	0.02823	0.03442	0.00730	0.01325
2003 – 2	0.22196	0.06300	0.11781	0.03572	0.08290	0.03872	0.02430	0.01143
2003 – 3	0.22554	0.04721	0.11886	0.02907	0.05679	0.04621	0.01537	0.00873
2003 – 4	0.19895	0.12887	0.09950	0.03726	0.07331	0.03592	0.01681	0.00216

this study, as can be seen in Figure 7.

DISCUSSION

In classical harmonic analysis, the tidal signal is modeled as the sum of a finite set of sinusoids at specific frequencies related to astronomical parameters (Godin, 1972). There are numerous tidal processes modulated by non-tidal perturbations, in the response of non-stationary tidal processes (Jay and Flinchem, 1999). This paper has shown that the techniques based on the FFT are powerful tools to investigate the tide components, showing that the spectral amplitudes of the tide waves in the Strait of Gibraltar are not stationary, as other authors have shown in other situations of non-stationary tidal processes. These include river tides (Godin, 1985; Jay and Flinchem, 1997), estuarine currents (Godin, 1983; Jay, 1991), internal tides (Sandstrom, 1991) and tides in ice covered basins (Godin, 1986). Classical harmonic analysis problems arise in coastal regions where the tidal response is in the form of a wave propagating onshore. In this way, in large estuaries, the seasonal change in salinity and flow may change the dynamic response. But

Table 3. Spectral amplitudes of the diurnal and semidiurnal tide waves for Malaga station.

	Semidiurnal					Diurnal		
Origin	**Lunar**	**Solar**	**Lunar**		**Solar**	**Lunar**	**Lunar**	**Solar**
Tide wave	**M_2**	**S_2**	**N_2**	**MU_2**	**K2**	**K_1**	**O_1**	**P_1**
Period (h)	12.48780	12.04706	12.64198	12.80000	11.90698	23.81395	25.60000	24.38095
1997 - 3	0.12899	0.07076	0.02110	0.02801	0.00717	0.02872	0.01243	0.01500
1997 - 4	0.14899	0.05526	0.07431	0.02250	0.05454	0.01905	0.01014	0.00430
1997 - 5	0.14570	0.03996	0.02427	0.02057	0.04423	0.03262	0.01103	0.00695
1998 -1	0.14867	0.03718	0.07598	0.01973	0.04423	0.02780	0.01023	0.01243
1998 - 2	0.14064	0.06328	0.08544	0.02119	0.03313	0.03208	0.01007	0.00854
1998 - 3	0.13050	0.06243	0.03993	0.02514	0.02542	0.02955	0.01643	0.01577
1998 - 4	0.13347	0.06622	0.06865	0.01041	0.05106	0.01956	0.01084	0.00137
1998 - 5	0.11568	0.06730	0.08805	0.04163	0.02909	0.03012	0.01578	0.01378
1999 -1	0.13477	0.06415	0.04462	0.02737	0.02636	0.02958	0.01402	0.01423
1999 - 2	0.14544	0.03601	0.07675	0.02137	0.04830	0.03071	0.01936	0.01420
1999 - 3	0.14499	0.04661	0.08312	0.02495	0.02763	0.03837	0.01117	0.00935
1999 - 4	0.13347	0.06622	0.06865	0.01041	0.05106	0.01956	0.01084	0.00137
1999 - 5	0.11474	0.07481	0.03710	0.02883	0.00285	0.03192	0.01199	0.01986
2000 -1	0.13105	0.08130	0.01905	0.03007	0.00858	0.03028	0.01891	0.01645
2000 - 2	0.13486	0.06496	0.00951	0.03452	0.04254	0.02952	0.01717	0.01376
2000 - 3	0.12009	0.07281	0.01850	0.02774	0.00522	0.03378	0.01809	0.01841
2000 - 4	0.13347	0.06622	0.06865	0.01041	0.05106	0.01956	0.01084	0.00137
2000 - 5	0.11474	0.07481	0.03710	0.02883	0.00285	0.03192	0.01199	0.01986
2001 -1	0.13639	0.06513	0.08297	0.02355	0.03079	0.03308	0.02133	0.01467
2001 - 2	0.12845	0.08526	0.04309	0.02395	0.01896	0.03060	0.01702	0.01291
2001 - 3	0.14460	0.11690	0.01648	0.05018	0.01337	0.03583	0.02239	0.01787
2001 - 4	0.13000	0.06500	0.03800	0.01000	0.04000	0.01900	0.01000	0.00100
2001 - 5	0.11000	0.07400	0.06700	0.03000	0.00100	0.03000	0.01200	0.01900
2002 -1	0.14063	0.03292	0.07545	0.02044	0.03867	0.03820	0.01124	0.01028
2002 - 2	0.14065	0.05956	0.08085	0.02114	0.03943	0.03529	0.01527	0.00334
2002 - 3	0.13416	0.05590	0.04825	0.02642	0.03276	0.03609	0.01842	0.01472
2002 - 4	0.19364	0.14891	0.01293	0.04379	0.05000	0.03256	0.01693	0.00255
2002 - 5	0.13672	0.04298	0.06296	0.02391	0.03522	0.04135	0.01428	0.01420
2003 -1	0.12838	0.06855	0.03120	0.02697	0.01933	0.03294	0.01271	0.00897
2003 - 2	0.13849	0.04245	0.07212	0.02324	0.05066	0.03618	0.02149	0.01138
2003 - 3	0.14376	0.02838	0.07269	0.02065	0.03599	0.04135	0.01379	0.01023
2003 - 4	0.19895	0.12887	0.09950	0.03726	0.07331	0.03592	0.01681	0.00216

as these changes can vary from year to year, the tidal process is not really stationary (Pawlowicz et al., 2002). This may be the cause of the phenomenon observed in this study.

Conclusions

This paper has shown that tide waves in the Strait of Gibraltar are not stationary. Such features show the existence of a temporal variation of the spectral amplitude for the waves M_2, S_2 and N_2, with a clear period of 1.28 years or 467 days for these three waves, and also a period of 0.5817 years or 212 days for the waves M_2 and S_2.

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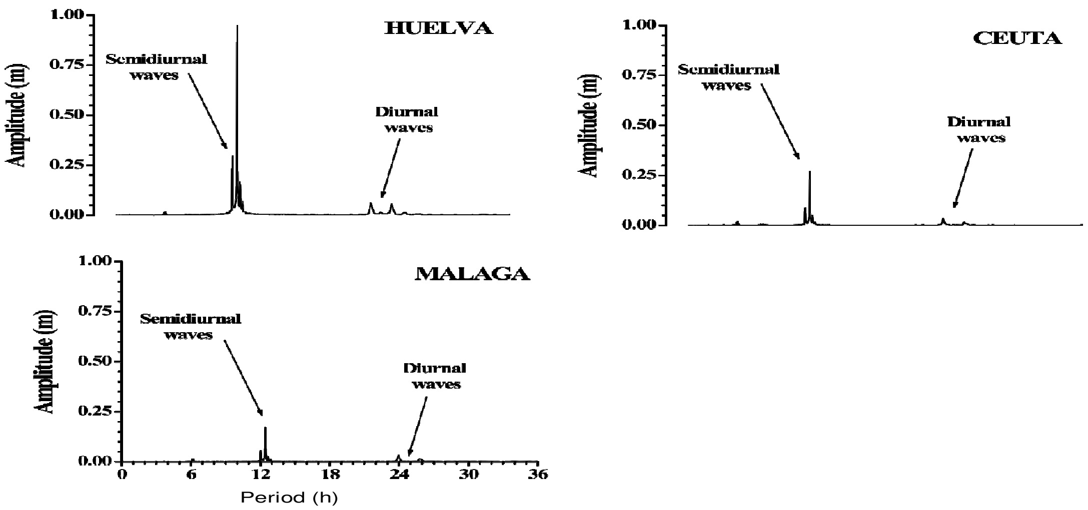

Figure 3. Amplitude spectrum computed for the records shown in Figure 2.

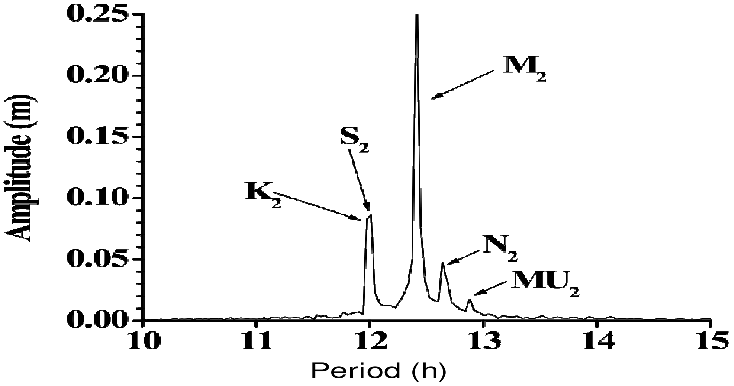

Figure 4. Semidiurnal waves obtained for Ceuta by spectral analysis.

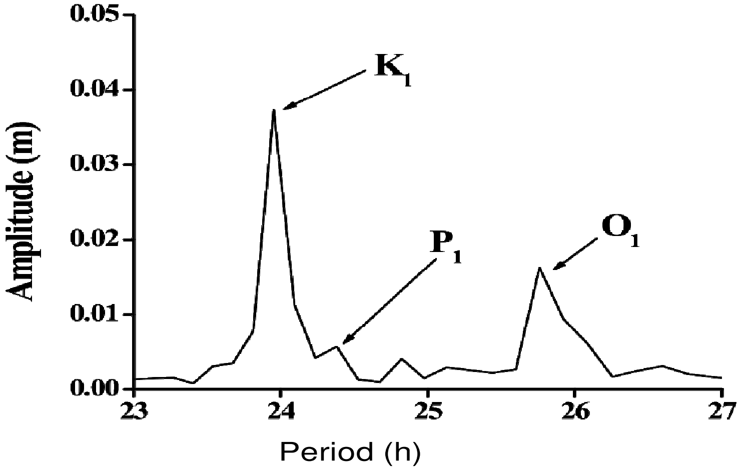

Figure 5. Diurnal waves obtained for Ceuta station by spectral analysis.

Table 4. Media and standard deviation of the amplitude listed in Table 1, computed from the five values of the spectral amplitudes obtained for each tide wave in a year, for Huelva station.

	M_2		S_2		N_2		MU_2		K_2		K_1		O_1		P_1	
Year	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**
1998	0.76996	0.02762	0.30247	0.11758	0.33568	0.08953	0.13035	0.01743	0.18238	0.05878	0.06620	0.01448	0.04779	0.00804	0.02379	0.00649
1999	0.74711	0.03374	0.35093	0.06702	0.23913	0.16292	0.15176	0.02814	0.15111	0.10112	0.06435	0.02063	0.04425	0.00480	0.02254	0.00606
2000	0.72600	0.01783	0.29329	0.06067	0.22551	0.13318	0.13776	0.02984	0.20289	0.10541	0.06572	0.01822	0.04664	0.00480	0.02703	0.01081
2001	0.73506	0.03995	0.30728	0.11308	0.30610	0.13452	0.14138	0.03643	0.19020	0.02166	0.06921	0.01177	0.04562	0.00541	0.02622	0.01106
2002	0.73812	0.02989	0.30918	0.11069	0.36348	0.09676	0.12725	0.01876	0.17600	0.07738	0.07351	0.01903	0.05327	0.00845	0.02630	0.00861
2003	0.71177	0.01165	0.37000	0.04187	0.17651	0.16214	0.15430	0.02792	0.13827	0.05443	0.08315	0.00816	0.05100	0.00073	0.02914	0.00228
2004	0.76099	0.02203	0.33828	0.09983	0.26750	0.16191	0.14782	0.02601	0.17366	0.01756	0.05691	0.01635	0.03914	0.00718	0.02683	0.01271

Table 5. Media and standard deviation of the amplitude listed in Table 2, computed from the five values of the spectral amplitudes obtained for each tide wave in a year, for Ceuta station.

	M_2		S_2		N_2		MU_2		K_2		K_1		O_1		P_1	
	Mean	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**
1997	0.20884	0.006	0.10051	0.019	0.07077	0.042	0.04217	0.006	0.04321	0.024	0.03211	0.004	0.01372	0.005	0.01303	0.001
1998	0.21552	0.009	0.08837	0.029	0.08733	0.044	0.04019	0.009	0.05288	0.009	0.03162	0.003	0.01285	0.003	0.01129	0.004
1999	0.22054	0.009	0.08738	0.035	0.11163	0.026	0.03612	0.005	0.05229	0.020	0.03367	0.004	0.01446	0.003	0.01085	0.006
2000	0.21525	0.009	0.10175	0.017	0.06560	0.047	0.04418	0.008	0.04554	0.028	0.03518	0.006	0.01672	0.003	0.01461	0.005
2001	0.20848	0.003	0.10692	0.023	0.04961	0.030	0.04454	0.005	0.03916	0.027	0.03683	0.007	0.02081	0.002	0.01489	0.003
2002	0.21303	0.011	0.08836	0.033	0.08735	0.041	0.03614	0.006	0.05398	0.004	0.03908	0.004	0.01506	0.005	0.01023	0.006
2003	0.21147	0.010	0.09320	0.032	0.10338	0.028	0.03620	0.004	0.05223	0.025	0.03902	0.004	0.01655	0.006	0.01073	0.005

Table 6. Media and standard deviation of the amplitude listed in Table 3, computed from the five values of the spectral amplitudes obtained for each tide wave in a year, for Malaga station.

	M_2		S_2		N_2		MU_2		K_2		K_1		O_1		P_1	
	Mean	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**
1997	0.140	0.007	0.065	0.015	0.048	0.026	0.0247	0.0028	0.0299	0.017	0.02792	0.0049	0.0130	0.0024	0.011	0.004
1998	0.134	0.011	0.059	0.011	0.072	0.017	0.0236	0.0102	0.037	0.010	0.0278	0.0044	0.0127	0.0028	0.010	0.005
1999	0.135	0.011	0.058	0.014	0.062	0.018	0.0226	0.0066	0.031	0.017	0.0300	0.0061	0.0135	0.0031	0.012	0.006
2000	0.127	0.008	0.072	0.006	0.031	0.021	0.0263	0.0083	0.022	0.020	0.0290	0.0049	0.0154	0.0033	0.014	0.007
2001	0.130	0.011	0.081	0.019	0.050	0.023	0.0275	0.0131	0.021	0.014	0.0297	0.0057	0.0165	0.0049	0.013	0.006
2002	0.149	0.022	0.068	0.042	0.056	0.024	0.0271	0.0086	0.039	0.006	0.0367	0.0029	0.0152	0.0024	0.009	0.005

2003	0.146	0.027	0.067	0.034	0.071	0.022	0.0271	0.0057	0.038	0.023	0.0369	0.0028	0.0172	0.0037	0.009	0.004

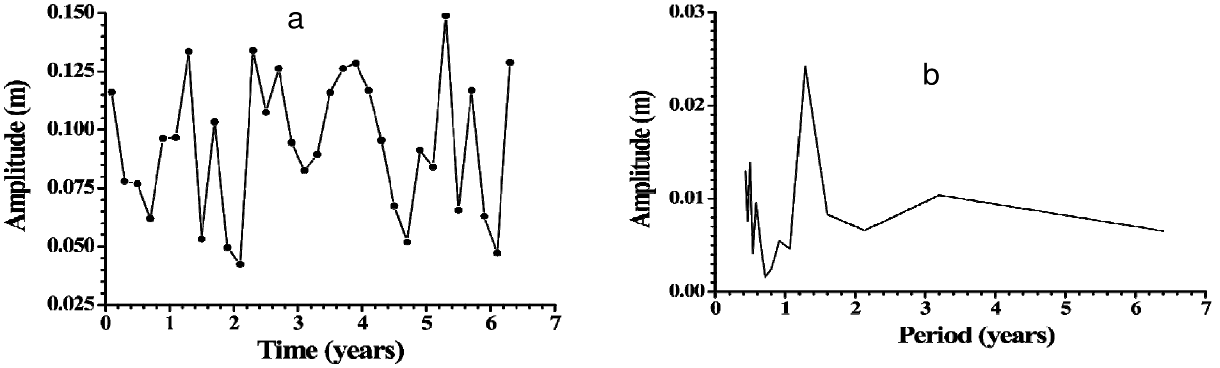

Figure 6. (a) Spectral amplitudes obtained for the S_2 wave at Ceuta station. (b) Spectral amplitudes obtained from the data shown in Figure 6a, by spectral analysis.

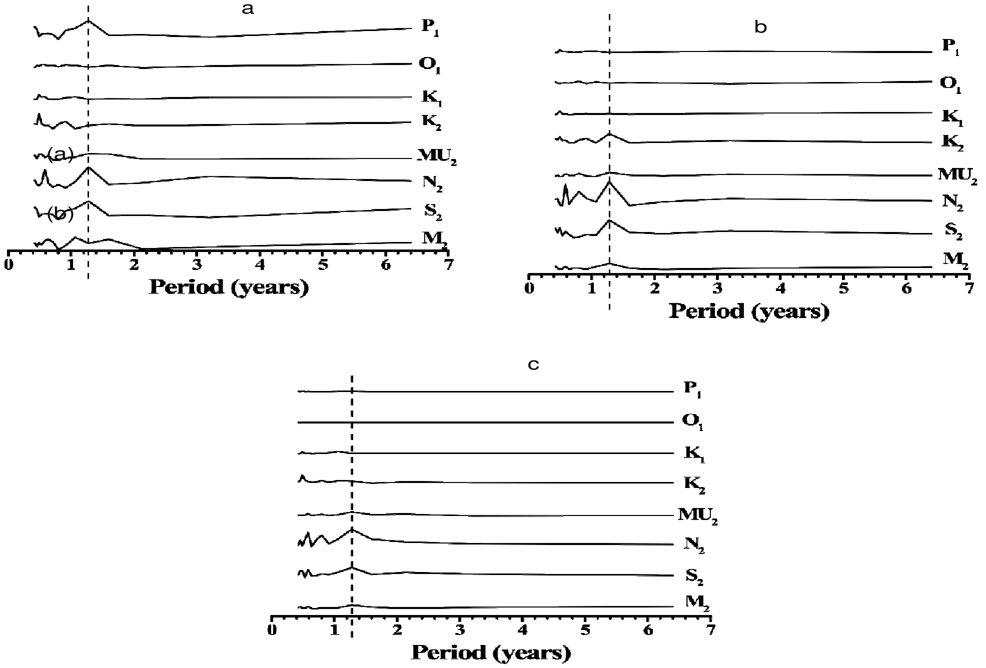

Figure 7. Spectral amplitudes obtained for each tide wave by spectral analysis of the amplitudes previously obtained for: (a) Huelva (listed in Table 1), (b) Ceuta (listed in Table 2) and (c) Malaga (listed in Table 3). The dash line shows the principal period that appears very clearly in some tide waves.

data used in this study.

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