International Hydrographic Review, Monaco, LXVII(1), January 1990

SEA LEVEL IN THE STRAIT OF GIBRALTAR : TIDES

by J. GARCÍA LAFUENTE (1), J.L. ALMAZÁN (2), F. CASTILLEJO (3), A. KHRIBECHE (4) and A. HAKIMI (5)

Abstract

A network of tide gauges with eight observation recording points was in operation in the Strait of Gibraltar during the years 1984 and 1985, which made it possible to draw up detailed charts of the tides showing their refined structure.

For the first order, the Strait of Gibraltar represents the nodal line of the stationary wave of the western Mediterranean, which, hypothetically, would end at the Cadiz meridian (6°17.0W). The tide is basically semi-diurnal; on average, 90% of the energy is associated with the second order and, for this, the Strait of Gibraltar tends to represent an antinode of the stationary wave, although the influence of the bottom topography and the rotation is interpreted in phase delays in the sill area (slightly progressive wave) and in increased non-linear constituents of higher orders. The radiational tide S_2 is evaluated in the area studied and it is ascertained that it shows the same characteristics as the tides having strictly gravitational constituents, which implies that it is fundamentally co-oscillating. Order 4 displays characteristics of resonant amplification due to the existence of the free oscillation mode of the western Mediterranean basin the period of which is close to 6 hours. Of order 3 it should be stressed that M_3, though small, is perfectly detectable in the area.

1. INTRODUCTION

The Strait of Gibraltar has very complex dynamics and separates two regions with distinct oceanographic characteristics. The frequency wave lengths of the tides are no exception to the rule: in the western Mediterranean basin, the tide

(1) Department of Physics, University of Malaga, Spain
(2) SECEG, Spain
(3) Spanish Institut of Oceanography, Spain
(4) SNED, Morocco
(5) LPEE, Morocco

is a stationary wave, with periods corresponding to those of the generating force of the tide, whereas in the North Atlantic it forms a well-developed amphidromic system, progressing towards the north along the side of its eastern boundary as a Kelvin wave with a phase speed (in middle latitudes) of 750 km/hour (210 m/s), the same for all the constituents as a result of its non-dispersing nature. It is, moreover, in agreement with the propagation speed of long waves, $c = (gh)^{1/2}$, when $H = 4000$ m, average depth of the North Atlantic.

In the Mediterranean, the oscillation of the tide is the sum of the independent oscillations, weak because of their small size and the co-oscillants, which, because it is dependent on the order being studied may be the dominant (semi-diurnal) type or else as weak as the independent (diurnal) type.

In the Strait of Gibraltar, which links the two regions, the tide should probably display mixed characteristics. Consequently, appreciable spatial variation exist, which make it necessary to use, for its study, a fine network of sampling in order to be able to detect them.

2. DATA

During the years 1984 and 1985, a network of tide gauges was put into operation on eight locations for collection of data (Fig. 1). Pressure sensors, installed on the seabed at depths varying between 10 and 15 m, recorded the

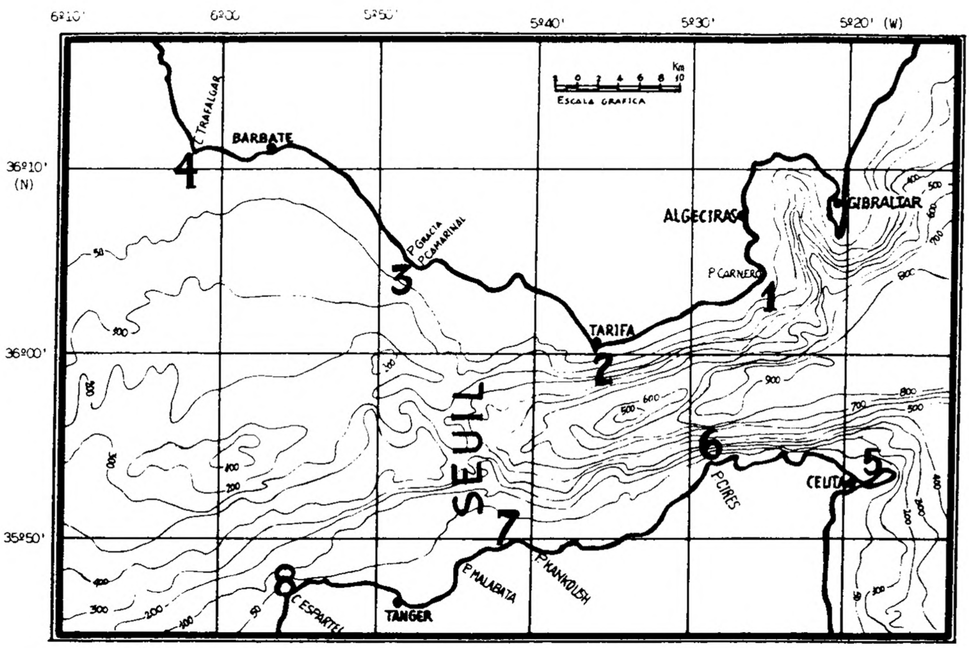

FIG. 1.— Chart of the Strait of Gibraltar area showing geographical characteristics of interest. Nos. 1 to 8 mark points where data was collected. The depths on the chart are given in metres.

total pressure, at regular 10-minute intervals. These measurements were completed with meteorological observations, atmospheric pressure, wind speed, air temperature, recorded by two meteorological stations installed at points 2 (Tarifa) and 5 (Ceuta), at regular 30-minute intervals. Tables 1.a and 1.b summarize the time series of each parameter available for this study.

Table 1.a

Length of time series available to carry out the study.
Oceanographic data

Point 1 :	Pointe Carnero (36°04.3N,5°25.7W)	25-VII-84	10-X-84
Point 2 :	Tarifa (36°00.2N,5°36.4W)	6-VI-84	8-VIII-84
Point 3 :	Pointe Gracia (36°05.4N,5°48.6W)	17-VIII-85	23-IX-85
Point 4 :	Cap Trafalgar (36°10.3N,5°17.9W)	23-VII-84	15-II-85
Point 5 :	Ceuta (35°54.3N,5°17.9W)	8-VII-84	16-I-85
Point 6 :	Pointe Cires (35°54.7N,5°28.8W)	23-XI-84	11-VI-85
Point 7 :	Pointe Kankoush (35°50.5N,5°42.0W)	22-XI-84	26-II-85
Point 8 :	Cap Espartel (35°45.9N,5°56.6W)	15-VI-85	23-IX-85

Table 1.b

Length of time series available to carry out the study.
Meteorological data.

Point 2 :	Tarifa (36°00.2N,5°36.4W)	6-VI-84	9-II-85
Point 5 :	Ceuta (35°54.3N,5°17.9W)	7-VI-84	26-IX-85

All the measurements were smoothed to eliminate high frequency noise. The smoothing techniques used are those which result from the application of certain mobile means of various consecutive weights so that the period of interruption is around one hour. The amplitudes of each constituent will subsequently be recovered by multiplying by $F^{-1}(f)$, where $F(f)$ is the response function of the smoothing of mobile means. Finally, in order to make this analysis, barometric behaviour of the sea level is assumed based upon the atmospheric pressure. This hypothesis immediately eliminates the atmospheric pressure from the tide gauges. In addition, the hypothesis $p = \rho g h$ is accepted, which converts the pressure readings into water-column heights (h, on the sensor); ρ is the density of water approached by a linear function of the water temperature T, in the form:

$$\rho(T) = \rho_o + (T - T_o)\alpha$$

where $\rho_o = 1.027$ g/cm^3,

$$T_o = 15°C, \text{ temperature of reference}$$

and the coefficient $\alpha = -1.1 \times 10^{-4}$ g/cm^3°C, calculated from density tables as a function of T, in the field of working temperatures. The deviation of $\rho(T)$ compared with ρ_o is, in any case, difficult to appreciate.

The technique of harmonic analysis employed is that of least squares adjustment of the created signal to the observed signal by a sum of cosine functions of known — astronomic — frequencies, including as great a number of these functions as the length of the recording makes it possible to separate. (G. GODIN, 1972, M.G. FOREMAN, 1977).

3. HARMONIC ANALYSIS: RESULTS

It is not possible to include, in the signal to be created, all the constituents appearing in the tide generating potential, for its adjustment by the least squares method to the original signal. Several frequencies are so close that, in cases where records are not available for sufficiently long duration, these would appear as a single contribution.

One may affirm that the contributions of constituents of frequencies f_1 and f_2 are differentiated in the recorded signal, by setting down $|f_1 - f_2| > 1/T^*$, T^* being the length of the recording. The longer the recording, the more numerous will be the constituents that can be included in the signal created.

When one of the constituents is much greater than the other, the fact of not being able to separate them is unimportant as the smaller one is disregarded. However, when they are comparable and inseparable, the result of the analysis is not correct. This problem, which is important for S_2–K_2 of the semi-diurnal type and K_1–P_1 of the diurnal type, where the lines S_2 and K_1 are more intense, is resolved by deduction, if:

$$T^* < |f_{K_2} - f_{S_2}|^{-1} = |f_{K_1} - f_{P_1}|^{-1} = 4.38 \times 10^3 \text{ hours} \simeq 182 \text{ days.}$$

This technique is based on taking as known for a given point the ratio of amplitudes (A_{K_2}/A_{S_2}) and (A_{P_1}/A_{K_1}) and the difference in the phases $(\theta_{K_2}\ \theta_{S_2})$ and $(\theta_{P_1} - \theta_{K_1})$; since there are points where $T^* > 182$ days, it is possible to calculate at these points the preceding parameters (Table 2*) and for the other points where $T^* < 182$ days, take the mean values in the quite reasonable hypothesis that such values must not change over short distances. Thus, from the only contribution detectable on short recordings and based upon the preceding

(*) The results obtained, based on yearly series, at Cadiz and Malaga, in the neighbourhood of the Strait of Gibraltar, are included. (The data for these two towns were supplied by the Spanish Institute of Oceanography).

premises, one can separate the input of each line of the pair (see G. GODIN, 1972, for example).

Table 2

Ratio of amplitudes and phase differences for $K_2 - S_2$ and $P_1 - K_1$. (In brackets, the associated errors.)

Situation	A_{K_2}/A_{S_2}	$\theta_{K_2}-\theta_{S_2}$ degrees	A_{P_1}/A_{K_1}	$\theta_{P_1}-\theta_{K_1}$ degrees
Point 4	0.281 (.012)	–5 (3)	0.24 (.13)	–9 (26)
Point 5	0.292 (.026)	–9 (5)	0.26 (.07)	–9 (16)
Point 6	0.279 (.021)	–8 (4)	0.41 (.09)	–6 (13)
Cadix	0.294 (.009)	–7 (2)	0.37 (.05)	–8 (8)
Malaga	0.295 (.033)	–2 (6)	0.35 (.08)	–5 (13)
Mean value	0.288	–7.1*	0.326	–7.4
Theoretical value	0.272		0.331	

(*) The value for Malaga is not included as it is too far removed from the others.

The ratio of the amplitudes of $K_2 - S_2$ is superior (locally and, *a fortiori*, on average) to the theoretic value (deduced from the amplitudes of the tide generating potential), as a result of the presence of the radiational tide in S_2. In the case of P_1–K_1, the mean value is close to the theoretic value and, given the dispersion of the values found, the latter has been retained.

The results obtained are shown in the Annex. Table A gives for each of the eight sampling points the amplitudes in centimetres and the phases in degrees in relation with the corresponding equilibrium component, referred to the Greenwich meridian, of all the separable constituents of the original recordings. These parameters have not been indicated for the constituents whose amplitudes do not attain the noise level (if the error in the calculation of adjustment by least squares which appears in parenthesis beside the amplitudes calculated is accepted as such), and are unimportant and there is total uncertainty as to the phase.

It should also be mentioned that Z_0, mean level, is not included in order 0 because, since there exists no accurate levelling, it becomes a meaningless constant (except as an estimation of the depth at which the instrument was immerged).

The spatial dependence is far better appreciated on the tidal charts of figures 2 to 6. The most significant constituents of each order (the amplitudes of which exceed 1 cm, accuracy level of the instrument as stated by the manufacturer) have been chosen for portrayal.

Order 1: K_1 and O_1

The most remarkable aspect to be noted in figures 2 and 3 is the rapid change of phase in moving towards the Mediterranean, and the constant increase in amplitude when moving southwards. The phase difference between the Alboran Sea (represented by Malaga) and the Atlantic Ocean (Cadiz) is 184° for O_1 and 108° for K_1. Almost all these phase variations take place in the physical dimen-

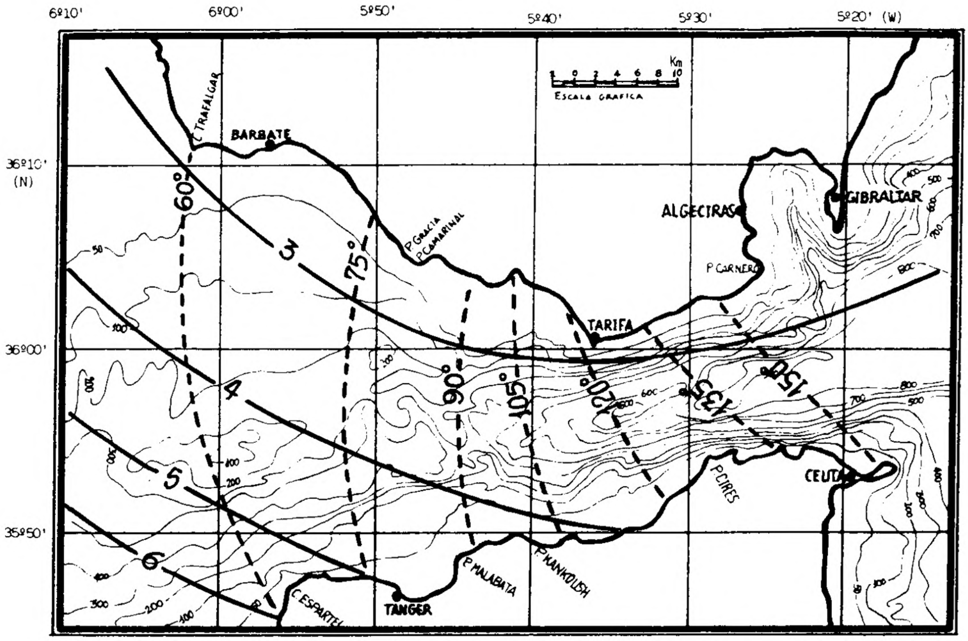

FIG. 2. — Tidal chart for K_1 constituent. Continuous lines are those of equal amplitude (in centimetres) and dashed lines are those of equal phase (in degrees).

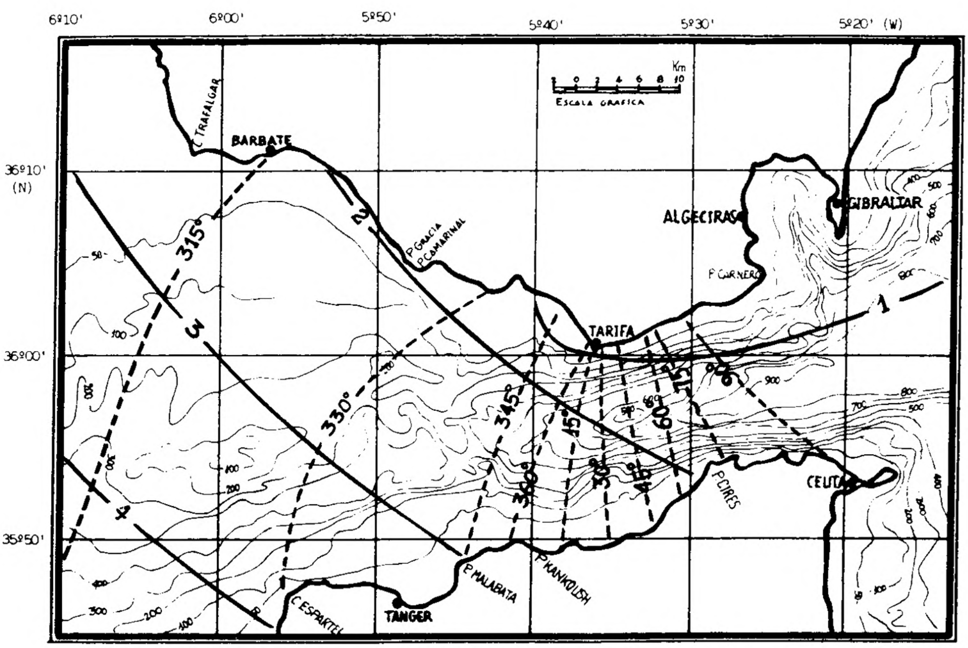

FIG. 3. — Tidal chart for O_1 constituent. (see note with figure 2).

sions of the Strait. The distribution of lines of equal amplitude and equal phase in figures 2 and 3 recalls the distribution which take place in the neighbourhood of an amphidromic point. Such a point, on these figures, would be located inland on the Spanish mainland.

Thus, generally speaking one may say that for O_1 there exists a nodal line somewhere in the Strait of Gibraltar which, locally, would degenerate in the slightly-developed amphidromic system shown in figure 3. In the case of K_1, it would not be correct to speak of a nodal line despite the analogous distribution of lines of equal amplitude, for there exists no change of phase at 180° over a relatively short distance.

This very special behaviour of the Strait of Gibraltar as regards the components of order 1 is a consequence of the comparable importance of the independent tide and the forced tide in the Mediterranean Sea for this order.

Order 2: M_2 and S_2

The tide in the Strait of Gibraltar is semi-diurnal. Its most important constituents are, in order of importance, M_2, S_2, N_2 and K_2. The effect of the first three is appreciable on any recording of a duration of over one month. Oscillation is clearly semi-diurnal (M_2), modulated by S_2 giving rise to spring tides, of $(f_{S_2} - f_{N_2})^{1}$ period and it is responsible, for example, for the fact that two consecutive spring tides are less similar than two alternate spring tides. Finally, K_2 which modulates S_2 with a period of half a year.

Figures 4 and 5, tidal charts for M_2 and S_2, show common features: a constant increase in amplitude from east to west (it is multiplied by an equal factor 2.5), which is to be hoped for if one is confronted with a stationary wave whose underside is not far to the west of the Strait of Gibraltar — which could, for all useful purposes, be considered to be the meridian of Cadiz. The increase, however, is not a linear one, a higher gradient takes place in the sill area (see Fig. 1), more than double the gradient existing to the east of the meridian of Tarifa and greater, moreover, than the values found to the west of the area in question, if judged by the results obtained at Cadiz, where the amplitudes of all the constituents already have typically «Atlantic» values.

The phase of each constituent varies in space, which contradicts the stationary wave idea, shown by the distribution of co-amplitude lines; a relative maximum appears to take place again in the area south of the sill: the distribution of co-phase lines (which indicate propagation in the direction of increasing phases) mark it as a possible area of convergence or divergence according to the moment in the tide cycle that is being considered, which makes this area the most difficult. There are no synoptic current measurements sufficiently dense to confirm this interesting result. However, a few tidal current charts drawn up by the U.S. Naval Oceanographic Office in the «Oceanographic Atlas of the North Atlantic Ocean», based on data from various sources and with a certain degree of artistic licence intended to fill in the gaps in information, report this same area as an area of convergence. But there are still other phenomena which bring out its difficult nature: navigational charts report that here there are frequent «tide rips». This is the birthplace, induced by the tide, of

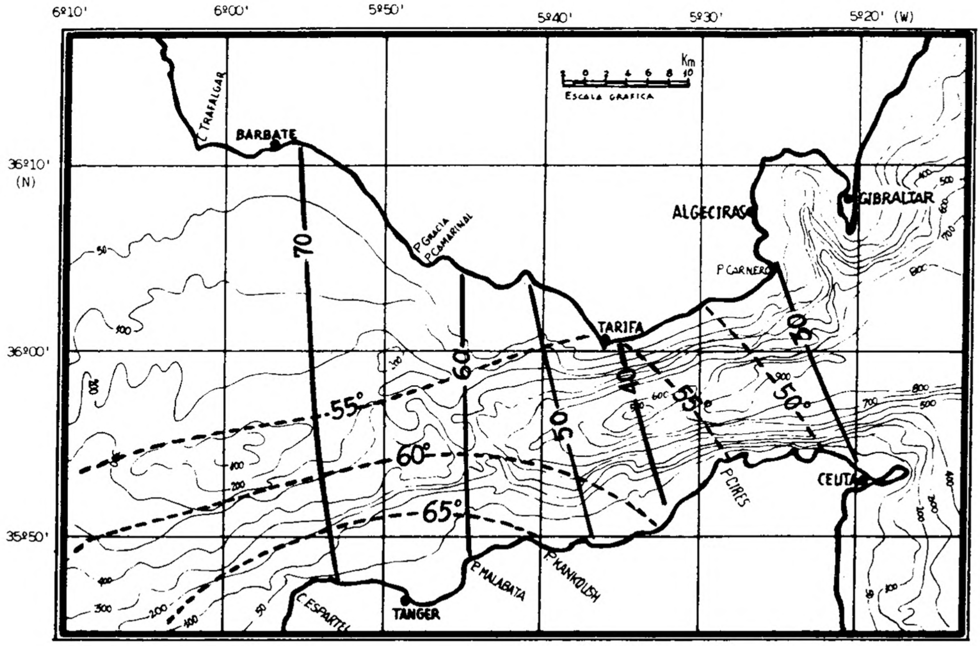

FIG. 4. — Tidal chart for M_2 constituent. (See note with figure 2).

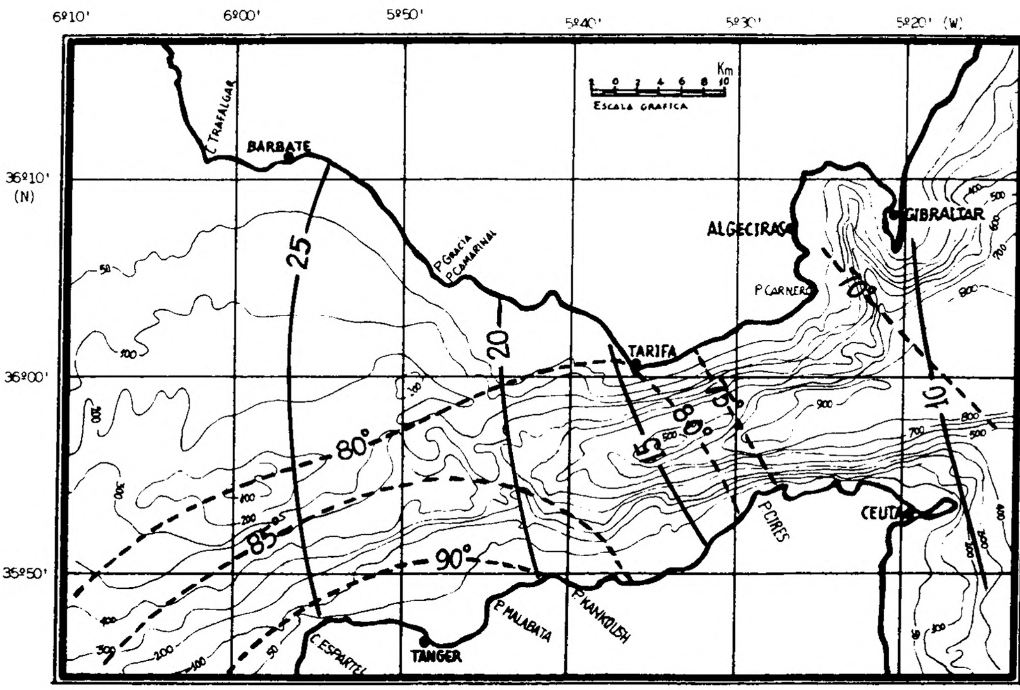

FIG. 5. — Tidal chart for S_2 constituent. (See note with figure 2).

internal waves of Brunt-Väisälä frequency (of 10-20 minute period in this area) which subsequently spread towards the Mediterranean Sea where they emerge clearly as a group (J. ZIEGENBEIN, 1969, T.H. KINDER, 1984, P.E. LA VIOLETTE, 1986). On infra-red photographs taken from a satellite one can detect an 'upwelling' zone around Cape Espartel and Malabata Point on the Moroccan coast (J.C. GASCARD and C. RICHEZ, 1984) which may be linked with the divergence of tidal cycles in this area.

There is not sufficient information to establish links of cause and effect between the phenomena in an indisputable manner. What is difficult to deny, however, is the link existing between the characteristics described on the charts in figures 4 and 5 and the bottom topography, which is no doubt responsible for phase lag and for the more rapid increase in amplitude in the sill area. The cause may be friction and, in this case, the constituents of a higher order must be of a certain importance. These constituents will be studied further on. The odd comportment of the constituents of semi-diurnal type deserves comment. Figures 6.a and 6.b show the local admittance of the sea to astronomical forces in the semi-diurnal band at the points of the area under study where K_2 has not been deduced and where one includes, in addition, Cadiz and Malaga. On these figures, and based on the spot values of the amplitude and the admittance phase, the continuous line curve has been reconstructed based on the tendency shown and also on the fact that the sea is not a good «syntoniser» for presenting narrow resonances along the admittance curve. On the contrary, it is logical to acknowledge that it must have a rather flexible dependency on frequency 'f'. W.M. MUNK and D.E. CARTWRIGHT (1966), speak of the 'credo of smoothness' with respect to what we have just said, as of a scientific «act of faith». The stretch of continuous line represents the admittance to a high degree of confidence in Figure 6.a; between the frequencies of μ_2 and N_2 two possibilities exist: based on the free mode of oscillation of period of 12/8 hours, reported by G.W. PLATZMAN (1975) in his study of the free modes of oscillation of the Atlantic Ocean and Indian Ocean together, the frequency of which falls between those of μ_2 and N_2 ('ML' line), it may be stated that the valid curve is that in non-continuous line, by analogy with the response of a simple mechanical system to a resonant or 'almost resonant' force (in our case, the forces creating the tide), a maximum of admittance existing in this frequency. The rapid change in phase would strengthen this reasoning.

However, if the criteria of flexible dependency is acknowledged, the dotted line must be chosen, which, of course, softens Z(f) more that the dashed line. Without other information, it is impossible to choose between the two possibilities and, unfortunately, there are no intense spectral lines between μ_2 and N_2 which might help in making such a choice.

Whichever alternative is envisaged, it does not affect the fact, however, that the response to S_2, both in amplitude and phase, is noticeably situated outside its 'expected' position in Figures 6.a and 6.b. The cause is the fact that S_2 is the sum of two factors: the factor due to weight and the 'radiational' factor. The latter is a phenomenon associated with meteorological changes, such as the semi-diurnal cycle of the atmospheric pressure or sea breezes, whose origin is the difference in temperature between day and night. The phenomenon is associated with solar radiation (hence its name) and it affects only the constituents of the

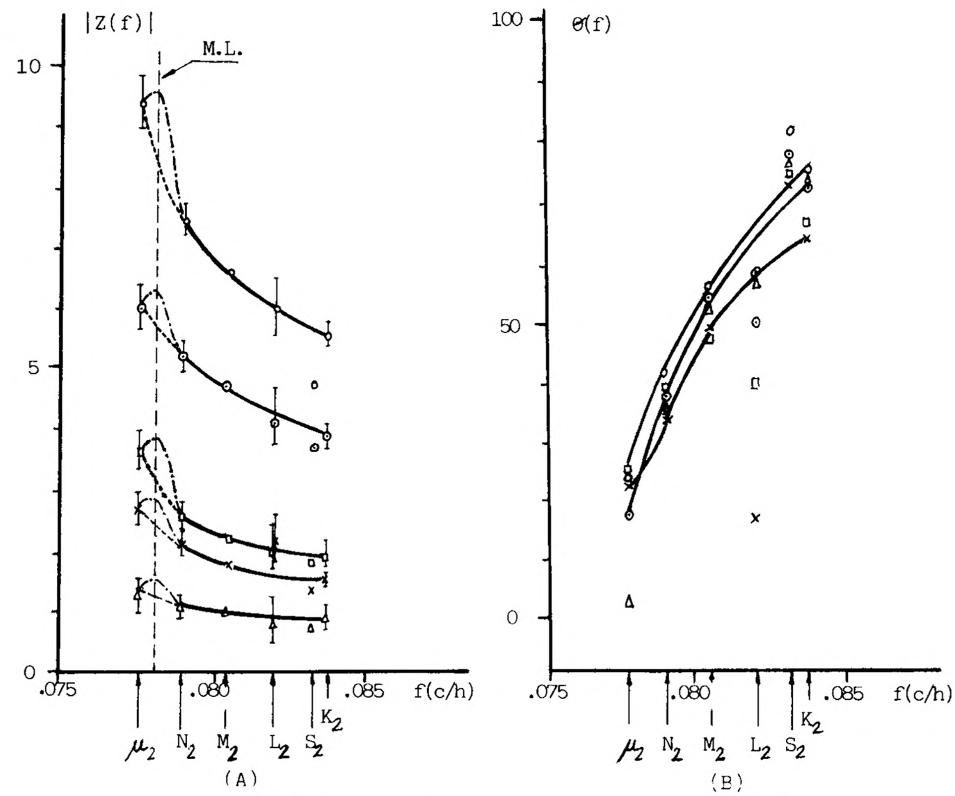

FIG. 6. — Admittance of the sea in the area studied. A. Amplitude, B. Phase.
For reasons of clarity, all curves are not shown in sketch B. The strokes, in figure A, show associated errors. For reasons already stated, error strokes have not been shown in figure B. The persistent tendency for the S_2 response to be situated outside the expected position can be seen. On both figures, the symbols indicate: (O) Cadiz, (Ø), Cap Trafalgar. (o), Pointe Cires. (x), Ceuta, (δ), Malaga.

oceanic tide of solar origin. Of the constituents studied thus far, S_2 is of solar origin and consequently subject to influence, whereas K_2 is less so; they will be the only ones which will have a 'radiational' factor. On this basis, one may separate from the S_2 constituent analysed the part due to weight the response to which must be situated on the curves in Figure 6, since one is only dealing here with gravitational constituents of the radiational part. The influence of the radiational factor K_2 (essentially — but not exclusively — lunar because in the tide generating potential the solar contribution represent 31% of the amplitude of K_2); compared to S_2, it should not be considered. The influence of S_2 would therefore be of the same order as the ratio of the solar parts of the equilibrium coefficients of the two (0.085) (B.D. ZETLER, 1971).

The result for the points where K_2 can be separated directly from S_2 is to be found in Table 3, where Cadiz and Malaga are included. Although information is lacking for five of these, there is a clear tendency of the radiational tide S_2 to follow the same spatial modulation in the area of the Strait of Gibraltar as that of the gravitational constituents, their amplitude diminishing from west to east. That means that in the Mediterranean Sea the radiational tide (like the gravitational tide) is essentially co-oscillating or forced by the Atlantic tide.

Table 3

Radiational and gravitational contributions for the S_2 constituent observed. Amplitudes are given in centimetres and phases (or phase differences) in degrees.

Situation	S_2 (GRA.+RAD.) Amp.	Phase	S_2 (GRA.) Amp.	Phase	S_2 (RAD.) Amp.	Phase	$(\theta_{rad}-\theta_{gra})$	$\frac{A_{rad}}{A_{gra}}$
Point 4	27.9	77.0	30.0	70.0	4.1	195.0	125.0	0.14
Point 5	11.2	72.0	12.5	62.0	2.5	192.0	130.0	0.20
Point 6	14.1	74.0	15.2	66.0	2.3	190.0	126.0	0.15
Cadiz	37.8	81.5	42.2	73.0	7.3	204.0	131.0	0.17
Malaga	7.4	76.0	8.1	72.0	0.9	213.0	141.0	0.13

It can be seen that, from readings of atmospheric pressure recorded, there will be obtained for the atmospheric S_2 — the only line distinguishable in the spectrum of the semi-diurnal band — either an amplitude of 0.69 mb and a phase of 292°, that is, the minimum pressure, 292–180=112° or 3.7 hours after the sun's passage (superior or inferior) over the Greenwich meridian. In other words, considering the static barometric response, there would exist an oceanic S_2 (radiational, obviously) of amplitude 0.69 cm and phase 112° (let us call it $\widetilde{S}_2$) which is far removed from the figures given in Table 3 for the radiational tide.

Other sources contribute to the radiational tide, such as sea breezes which carry water, from or towards a coast, and the changes in level by reason of water heating, to a lesser degree. However, in general, one agrees to acknowledge that the principal source is the semi-diurnal oscillation of pressure. It must then be concluded that the radiational tide is the the consequence of the atmospheric tide $\widetilde{S}_2$, in the same way that the gravitational tide $\bar{S}_2$ is a consequence of the equilibrium forces (or tide). If this conclusion is true, parallel relations between phase differences and amplitude ratios — on the basis of the same mechanism of sea response — could be verified as follows:

$$\theta_{S_{2rad}} - \theta_{\widetilde{S}_2} = \theta_{S_{2gra}} - \theta_{S_{2eq.}} = \theta_{S_{2gra}}$$

or

$$\theta_{S_{2rad}} - \theta_{S_{2gra}} = \theta_{\widetilde{S}_2} = 112^\circ$$

and

$$A_{S_{2rad}} / A_{\widetilde{S}_2} = A_{S_{2gra}} / A_{S_{2eq.}}$$

or

$$A_{S_{2rad}} / A_{S_{2gra}} = A_{\widetilde{S}_2} / A_{S_{2eq.}} = 0.1$$

The final columns of Table 3 show the phase differences and amplitude ratios calculated. These figures are the same as those reported by other authors for various areas of the Atlantic Ocean (D.E. CARTWRIGHT, 1968, B.D. ZETLER, 1971, B.D. ZETLER et al., 1975). Although they do not coincide with the preceding values, the agreement is, however, quite acceptable. The discordance can be due to sources other than the radiational tide.

Higher order constituents: M_4

These are essentially the result of non-linear interactions between the first and second order constituents, with the exception of M_3, which is the higher order constituent induced directly by the tide generating potential, directly detectable from recordings, despite its low amplitude.

The other high-order constituents are non-linear (the direct contribution upon them of the tide generating forces is totally negligible). No doubt, the most important is M_4, (Fig. 7), which possesses two atypical characteristics: the irregular appearance of lines of equal amplitude, which illustrates the strongly local nature of the original interactions, attaining a maximum in the neighbourhood of the sill, friction is therefore one of the mechanisms at the origin; next, the regular appearance of the lines of equal phase, clearly indicating propagation towards the Mediterranean Sea.

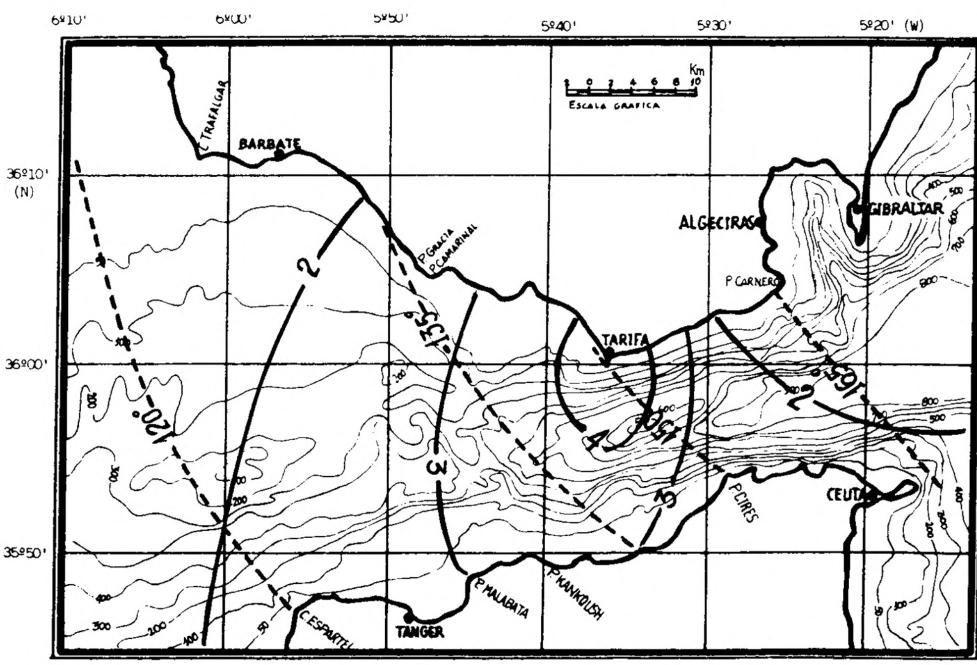

FIG. 7. — Tidal chart for M_4 constituent. (See note with Figure 2).

The comportment of the other non-linear constituents is as irregular as that of M_4, or more so. If one allows that they arise from bi-linear interactions between intense spectral lines, those arising from the pairs which may be formed with K_1, O_1, M_2, S_2, N_2 and K_2, provided the length of the recording made it possible to separate them, were calculated. Interactions of a higher order have also been studied, but the results are of little importance, with the exception, perhaps, of M_6, in some points. No doubt order 4 is the most important.

The simplest theory is that any one of them arises from an interaction between any two constituents among those quoted above with an interaction coefficient which might be represented in the following manner: if A_{MS_4} represents the (complex) amplitude of the constituent MS_4 and A_{M_2} (A_{S_2}) that of M_2 (S_2), one would find $A_{MS_4} = r\, A_{M_2} A_{S_2}$, where 'r' is the coefficient of interaction, complex to take account of possible phase lags. Its size and its phase will be given by the formulae:

$$|r| = \frac{|A_{MS_4}|}{|A_{M_2}|\,|A_{S_2}|}$$

$$\theta_r = \theta_{M_2} + \theta_{S_2} - \theta_{MS_4}$$

respectively. Table 4 shows the results obtained from each point and for the three most important quarter-day non-linear constituents. Logically, these are those where the spectral line M_6 intervenes and which have, as can be seen from the annexed table, an amplitude above the pressure level of the instrument, on several occasions, which confirms that they are well founded.

Table 4

Coefficient of interaction (amplitude and phase) between the M_2 constituent and the three most intense lines of the semi-diurnal band, M_2, S_2 and N_2. (In brackets, the calculated errors.)

Situation	MN_4 Ampl. ($\times 10^{-4}$cm)	MN_4 Phase (degrees)	M_4 Ampl. ($\times 10^{-4}$cm)	M_4 Phase (degrees)	MS_4 Ampl. ($\times 10^{-4}$cm)	MS_4 Phase (degrees)
Malaga	103 (31)	323 (18)	53 (6)	299 (10)	88 (15)	259 (12)
Point 5	41 (13)	314 (18)	28 (3)	298 (7)	50 (8)	262 (9)
Point 1	35 (11)	343 (19)	14 (2)	290 (11)	29 (7)	222 (14)
Point 6	41 (9)	337 (14)	18 (2)	303 (8)	26 (5)	266 (11)
Point 2	52 (8)	334 (9)	24 (9)	321 (4)	22 (8)	286 (11)
Point 7	28 (9)	48 (21)	12 (2)	10 (11)	11 (4)	25 (25)
Point 3	12 (4)	347 (17)	5 (1)	320 (7)	7 (2)	263 (15)
Point 8	9 (4)	30 (19)	4 (1)	11 (9)	2 (1)	238 (50)
Point 4	7 (2)	10 (18)	2 (1)	340 (13)	2 (1)	211 (45)
Cadiz	4 (1)	358 (14)	2 (1)	321 (8)	1 (1)	240 (24)

For reasons of convenience, the points have been ordered by increasing geographic longitudes (W) (including Malaga and Cadiz), which brings out the fact that, apart from a few exceptions, the coefficient diminishes as one gets further away from the Mediterranean. The preceding values, however, show such dispersion that they are not reliable if in the sill zone friction is considerable (points 2, 6, 7); it is noted that the coefficient is as great or even greater at other points further to the east (points 1 and 5) and much smaller at points to the west situated at the same distances (points 3, 4 and 8). It is also noticed that it is at Malaga that the maximum value appears. Friction does not therefore seem to be the determining factor for the values found in this case.

If, on the contrary, we allow an average coefficient of interaction for the whole area (or slightly modulated spatially so that the sill zone stands out clearly), Table 4 might be considered to be a representation of the response of the sea to the non-linear interaction of the lines in question and one should conclude that, for the points furthest east, the response is notably greater than for the points to the west. A. DEFANT (1960), calculated the natural period of oscillation of the western Mediterranean basin in 5.96 hours (0.16778c/h) in the quarter-diurnal band of frequencies, so that the great values of the constituents of this order that are found at Malaga and at points to the east of the Strait of Gibraltar might be a consequence of an amplification of resonance. However, this frequency is greater than the frequencies of all the constitutents shown in Table 4, and consequently, in principle, at each point, the greatest response should be that of MS_4, M_4 and MN_4, in that order. It is not this tendency but rather the inverse that is found, and the phase would appear to back up the latter, since it oscillates around 0^o (360^o) for the constituent MN_4, which indicates that its frequency is very close to the resonance frequency. Consequently, the natural period of oscillation of the western Mediterranean basin would be about 6.25 hours, a little greater than the period quoted by A. DEFANT.

References

CARTWRIGHT, D.E. (1968): A unified analysis of tides and surges round North and East Britain. *Phil.Trans.R.Soc.Lond.* Vol. 263, 1-55.

DEFANT, A. (1960): Physical Oceanography. Pergamon Press, New York, 2 Vol.

FOREMAN, M.G. (1977) : Manual for tidal heights analysis and predictions. *Pacific Marine Report No. 77,* Inst. of Ocean Sciences, Patricia Bay, pp. 101.

GASCARD, J.C. and C. RICHEZ (1985): Water masses and circulation in the Western Alboran Sea and in the Strait of Gibraltar *Progress in Oceanogr.* 15, pp. 157-215.

GODIN, G. (1972): The analysis of tides, University of Toronto Press, pp. 264.

KINDER, T.H. (1984): Net mass transport by internal waves near the Strait of Gibraltar *Geophys. Res. Let.* 11(10), pp. 987-990.

LA VIOLETTE, P.E., T.H. KINDER and D.W. GREEN III (1968): Measurements of internal waves in the Strait of Gibraltar using a shored-based radar, *Naval Ocean. Res. and Devel. Activity Report,* No. 118, pp. 7.

MUNK, W.M. and D.E. CARTWRIGHT (1966): Tidal spectroscopy and prediction *Phil. Trans. A.,* 259, pp. 533-581.

PLATZMAN, G.W. (1975): Normal modes of the Atlantic and Indian Oceans *J. Phys. Oceanogra.,* 5, pp. 201-221.

U.S. NAVAL OCEANOGRAPHIC OFFICE (1965): Oceanographic Atlas of the North Atlantic ocean. Section I. Tides and Currents *N.O.O. Publ.,* 700, pp. 75.

ZETLER, B.D. (1971): Radiational tides along the coasts of the United States *J. Phys. Oceanogr.*, 1, pp. 34-38.

ZETLER, B.D., W. MUNK, H. MOFJELF, W. BROWN and F. DORMER (1975): Mode tides *J. Phys. Oceanogr.*, 5(3), pp. 430-441.

ZIEGENBEIN, J. (1969): Short internal waves in the Strait of Gibraltar *Deep Sea Research*, 16, pp. 479-487.

Table A

Calculated harmonic constants. Amplitudes are in centimetres, phases in degrees and frequencies in sun cycles/hour.
(In brackets, amplitude and phase errors.)

Order	Name	Frequency	P.Carnero Amp./phase	Tarifa Amp./phase	P.Gracia Amp./phase	C.Trafalgar Amp./phase	Ceuta Amp./phase	P.Cires Amp./phase	P.Kankoush Amp./phase	C.Espartel Amp./phase
0	Ssa	.00022816	—	—	—	3.89/278 (.25/4)	2.05/51 (.22/6)	3.11/171 (.21/4)	—	—
	Msm	.00130978	—	—	—	—	2.81/129 (.21/5)	—	—	—
	Mm	.00151215	1.05/153 (.22/12)	1.16/267 (.20/10)	3.14/223 (.22.4)	2.51/252 (.24/6)	3.47/261 (.21/4)	1.37/302 (.21/9)	1.98/319 (.41/12)	1.87/187 (.32/10)
	Msf	.00282193	2.49/92 (.22/5)	1.62/160 (.21/7)	2.39/226 (.21/5)	1.10/115 (.25/13)	0.29/164 (.22/41)	1.91/40 (.20/6)	0.69/238 (.41/34)	2.38/200 (.31/7)
	Mf	.00306009	—	—	—	1.61/216 (.24/9)	0.31/219 (.20/37)	0.33/29 (.20/39)	—	—
1	α_1	.03439657	0.16/(?) (.21/)	0.09/(?) (.20/)	0.16/(?) (.21/)	0.16/(?) (.25/)	0.05/(?) (.22/)	0.18/128 (.21/86)	0.23/(?) (.40/)	0.20/(?) (.29/)
	$2Q_1$	.03570635	0.14/(?) (.22/)	0.36/292 (.21/32)	0.19/175 (.21/83)	0.08/(?) (.25/)	0.14/(?) (.21/)	0.15/(?) (.21/)	0.10/(?) (.40/)	0.18/(?) (.30/)
	σ_1	.03590872	—	—	—	—	0.28/217 (.21/38)	—	—	—
	Q_1	.03721850	0.27/227 (.21/47)	0.34/230 (.20/34)	0.70/250 (.22/19)	0.87/239 (.24/16)	0.18/119 (.21/75)	0.17/(?) (.22/)	0.93/260 (.41/25)	1.06/259 (.30/16)
	ρ_1	.03742088	—	—	—	—	0.09/(?) (.21/)	— —	— —	— —
	O_1	.03873065	0.73/181 (.22/17)	0.48/165 (.21/25)	1.84/313 (.23/8)	2.47/298 (.25/6)	1.92/94 (.22/7)	1.21/81 (.21/10)	2.90/343 (.40/8)	4.79/324 (.30/4)

Order	Name	Frequency	P.Carnero Amp./phase	Tarifa Amp./phase	P.Gracia Amp./phase	C.Trafalgar Amp./phase	Ceuta Amp./phase	P.Cires Amp./phase	P.Kankoush Amp./phase	C.Espartel Amp./phase
1	$_1$	.03895881	—	—	—	0.11/(?) (.24/)	0.12/(?) (.21/)	0.14(?) (.21/)	—	—
	β_1	.04004043	—	—	—	0.08/(?) (.25/)	0.27/59 (.22/42)	0.07/(?) (.21/)	—	—
	NO_1	.04026859	0.18/0 (.21/88)	0.45/33 (.20/25)	0.33/28 (.23/35)	0.25/359 (.25/49)	0.26/70 (.22/49)	0.16/(?) (.21/)	0.34(?) (.42/)	0.60/36 (.29/33)
	χ_1	.04047097	—	—	—	—	0.07/(?) (.21/)	—	—	—
	P_1	.04155259	0.76/138* (.21/17)	0.74/123* (.20/15)	1.24/65* (.22/11)	0.65/50 (.24/21)	1.00/127 (.21/13)	1.32/127 (.21/9)	1.52/81* (.41/15)	2.01/53* (.29/9)
	K_1	.04178075	2.30/145 (.21/5)	2.24/131 (.20/5)	3.75/75 (.22/4)	2.74/59 (.24/5)	3.83/138 (.21/3)	3.23/133 (.21/4)	4.58/88 (.40/5)	6.07/60 (.30/3)
	Φ_1	.04200891	—	—	—	0.12/(?) (.24/)	0.19/83 (.21/74)	0.23/175 (.21/63)	—	—
	Θ_1	.04309053	—	—	—	—	0.07/(?) (.22/)	—	—	—
	J_1	.04329289	0.28/196 (.22/53)	0.40/6 (.21/30)	0.28/86 (.23/49)	0.18/(?) (.24/)	0.10/(?) (.21/)	0.07/(?) (.21/)	0.34/(?) (.40/)	0.41/33 (.30/48)
	SO_1	.04460268	—	—	—	0.05/(?) (.24/)	0.25/342 (.21/47)	0.21/285 (.21/78)	—	—
	OO_1	.04483084	0.14/(?) (.22/)	0.08/(?) (.21/)	0.19/28 (.22/84)	0.05/(?) (.25/)	0.06/(?) (.21/)	0.11/(?) (.22/)	0.20/(?) (.42/)	0.15/(?) (.29/)
	$2KQ_1$	.04634299	0.08/(?) (.21/)	0.10/(?) (.21/)	0.09/(?) (.23/)	0.01/(?) (.25/)	0.03/(?) (.22/)	0.04/(?) (.22/)	0.08/(?) (.41/)	0.09/(?) (.30/)

* Deducted by inference.

Order	Name	Frequency	P.Carnero Amp./phase	Tarifa Amp./phase	P.Gracia Amp./phase	C.Trafalgar Amp./phase	Ceuta Amp./phase	P.Cires Amp./phase	P.Kankoush Amp./phase	C.Espartel Amp./phase
2	OQ_2	.07597494	—	—	—	—	0.06/(?) (.21/)	—	—	—
	ξ_2	.07617731	0.34/302 (.21/36)	0.46/23 (.20/25)	0.32/3 (.22/35)	0.62/338 (.24/23)	0.46/31 (.21/30)	0.39/348 (.22/33)	0.57/319 (.40/41)	0.20/(?) (.29/)
	$2N_2$	.07748710	—	—	—	—	0.63/16 (.22/23)	—	—	—
	μ_2	.07768947	1.55/352 (.22/8)	1.27/342 (.21/10)	2.24/340 (.22/6)	2.88/16 (.25/5)	1.32/23 (.22/9)	1.78/24 (.21/7)	1.59/348 (.40/15)	2.61/11 (.30/8)
	N_2	.07899925	6.99/35 (.22/2)	7.99/52 (.20/2)	12.35/44 (.21/1)	15.99/37 (.25/1)	6.33/34 (.21/2)	7.69/38 (.21/2)	9.37/54 (.40/3)	14.18/52 (.29/2)
	ν_2	.07920162	—	—	—	—	0.92/21 (.22/14)	—	—	—
	M_2	.08051141	31.11/47.5 (.21/.5)	41.53/57 (.20/.5)	64.90/49 (.22/.5)	76.22/53.5 (.25/.5)	29.88/47.5 (.21/.5)	36.36/46.5 (.21/.5)	51.81/69 (.40/.5)	75.83/67 (.30/.5)
	MKS_2	.08073956	—	—	—	0.30/348 (.25/54)	0.81/273 (.21/16)	1.05/8 (.21/12)	—	—
	λ_2	.08182119	—	—	—	—	0.28/351 (.21/48)	—	—	—
	L_2	.08202355	0.90/21 (.21/14)	0.82/320 (.21/15)	0.69/125 (.22/18)	1.89/49 (.24/8)	1.01/16 (.22/10)	0.95/39 (.22/13)	1.88/108 (.41/13)	1.81/80 (.29/9)
	S_2	.08333333	11.45/71 (.22/1)	14.18/85 (.20/1)	22.30/74 (.22/1)	27.94/77 (.25/.5)	11.20/72 (.21/1)	14.08/74 (.21/1)	20.05/90 (.41/2)	25.68/92 (.29/1)
	K_2	.08356149	3.31/63* (.22/4)	4.08/77* (.20/3)	6.41/66* (.22/2)	7.85/72 (.25/2)	3.29/63 (.22/4)	3.95/66 (.22/3)	5.75/82* (.41/4)	7.40/84* (.30/3)

* Deducted by inference.

Order	Name	Frequency	P.Carnero Amp./phase	Tarifa Amp./phase	P.Gracia Amp./phase	C.Trafalgar Amp./phase	Ceuta Amp./phase	P.Cires Amp./phase	P.Kankoush Amp./phase	C.Espartel Amp./phase
2	MSN_2	.08484548	—	—	—	0.07/(?) (.25/)	0.17/(?) (.21/)	0.19/157 (.21/86)	— —	— —
	η_2	.08507365	0.64/121 (.21/19)	0.29/58 (.21/54)	0.38/153 (.21/31)	0.36/115 (.24/38)	0.23/114 (.21/54)	0.36/77 (.22/36)	0.47/221 (.41/61)	1.13/164 (.29/15)
3	MO_3	.11924206	0.18/(?) (.22/)	0.89/302 (.20/14)	0.44/279 (.22/28)	0.71/245 (.24/31)	0.77/313 (.21/16)	0.43/285 (.21/29)	0.65/299 (.41/38)	0.49/307 (.30/42)
	M_3	.12076710	0.31/200 (.22/43)	0.30/242 (.21/48)	0.60/234 (.23/22)	0.55/230 (.25/28)	0.38/203 (.22/32)	0.45/220 (.21/28)	0.66/226 (41/37)	0.55/240 (.29/36)
	SO_3	.12206399	—	—	—	0.34/304 (.25/45)	0.25/47 (.22/66)	0.14/(?) (.21/)	—	—
	MK_3	.12229215	0.17/(?) (.22/)	1.10/40 (.20/11)	0.51/28 (.22/25)	0.74/347 (.25/36)	0.83/42 (.23/17)	0.60/354 (.22/33)	0.68/8 (.40/35)	0.71/46 (.29/25)
	SK_3	.12511408	0.12/(?) (.22/)	0.15/(?) (.21/)	0.33/53 (.23/37)	0.13/(?) (.24/)	0.21/87 (.21/78)	0.29/312 (.21/42)	0.09/(?) (.41/)	0.45/66 (.29/44)
4	MN_4	.15951064	0.76/100 (.21/17)	1.72/135 (.20/7)	0.93/106 (.23/16)	0.88/81 (.24/17)	0.76/128 (.21/16)	1.14/108 (.21/12)	1.38/75 (.40/18)	1.00/89 (.29/17)
	M_4	.12076710	1.32/165 (.21/10)	4.15/153 (.20/3)	2.22/138 (.23/6)	1.31/127 (.24/12)	2.50/157 (.21/6)	2.38/150 (.21/6)	3.10/128 (.40/8)	2.13/123 (.29/8)
	SN_4	.16233259	0.15/(?) (.22/)	0.61/139 (.21/22)	0.25/135 (.22/75)	0.03/(?) (.24/)	0.31/214 (.21/58)	0.35/185 (.22/39)	0.23/(?) (.41/)	0.15/(?) (.29/)
	MS_4	.16384473	1.03/256 (.21/13)	1.32/216 (.21/10)	1.05/220 (.24/14)	0.34/280 (.24/44)	1.67/218 (.22/8)	1.35/215 (.21/10)	1.10/134 (.40/23)	0.40/181 (.30/49)

Order	Name	Frequency	P.Carnero Amp./phase	Tarifa Amp./phase	P.Gracia Amp./phase	C.Trafalgar Amp./phase	Ceuta Amp./phase	P.Cires Amp./phase	P.Kankoush Amp./phase	C.Espartel Amp./phase
4	MK_4	.16407290	—	—	—	0.10/(?) (.24/)	0.75/234 (.21/18)	0.13/(?) (.22/)	—	—
	S_4	.16666666	0.17/(?) (.17/)	0.31/272 (.20/41)	0.04/(?) (.23/)	0.16/(?) (.25/)	0.16/(?) (.22/)	0.14/(?) (.22/)	0.29/(?) (.42/)	0.10/(?) (.30/)
	SK_4	.16689482	—	—	—	0.07/(?) (.25/)	0.16/(?) (.21/)	0.11/(?) (.21/)	—	—