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The Newtonian approach in meteorological tide waves forecasting: preliminary observations in the East Ligurian harbours

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Abstract
Sea level oscillations are the superposition of many contributions, the main ones being astronomic and meteorological low-frequency tides. In the Ligurian Sea meteo-tide components, being most ample than astronomic fluctuations, drive water exchange in harbours. The present note shows the first results on the port of Genoa concerning a coherency study between atmospheric variation and corresponding sea level adjustment (meteorological tide). The Newtonian forecasting method of meteorological tides is based on measurements of time elapsing between barometric sea level unbalance (Δg) and its meteorological tide compensation (inverse barometer component). Meteorological tide component is independent of the Earth-Moon-Sun gravitational relationships, and parameters related to the shifted water mass are too many to describe the phenomenon analytically (basin topography, barometric strength position and time, chemical water quality, off-shore sea circulation, etc.). Hence meteorological tide cannot be accurately foreseen by atmospheric pressure measurements only. A gravimeter can detect the geodetic imbalance starting time and a tide-gauge can detect the Newtonian compensation (tide wave) coming time. The difference between these two times is the meteorological tide delay. An opportune statistic of this delay provides an experimental law typical for each harbour to forecast the meteo-tide compensation wave delay. This paper describes the methodological procedure adopted and the first evidences of the phenomenon in Genoa harbour.

Key words *meteorological tide waves – Newtonian sea level compensation – tide forecasting – environmental harbours quality*

1. The phenomenon

Astronomical tide is a regular and periodic sea level up-down motion that depends on the Earth-Moon-Sun gravitational relationship. Such a phenomenon can be easily described by a Fourier analysis, both in its elementary (fundamental) components band and in the com-

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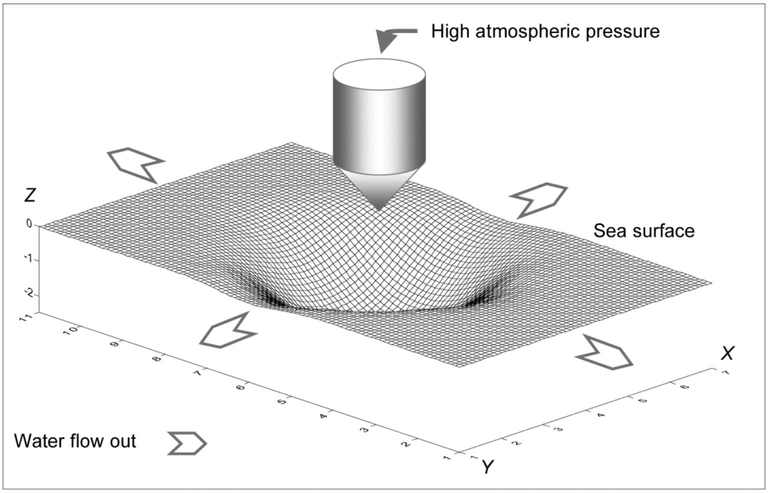
Table I. Main astronomic tide components, periods and radian frequencies.

Harmonic	Period (h)	Radian frequency (rad/s)
O_1	25.819.341	6.7597744 E-5
Π_1	24.132.140	7.2323884 E-5
P_1	24.065.890	7.2522945 E-5
S_1	24.000.000	7.2722052 E-5
K_1	23.934.469	7.2921158 E-5
J_1	23.096.474	7.5560361 E-5
$2N_2$	12.905.374	1.3524049 E-4
η_2	12.871.757	1.3559370 E-4
N_2	12.658.348	1.3787969 E-4
ν_2	12.626.004	1.3823290 E-4
M_2	12.420.601	1.4051890 E-4
L_2	12.191.620	1.4315810 E-4
T_2	12.016.449	1.4524500 E-4
S_2	12.000.000	1.4544410 E-4
R_2	11.983595	1.4564320 E-4
K_2	11.967.234	1.4584231 E-4
M_4	6.210.300	2.8103780 E-4
MS_4	61.033.392	2.8596300 E-4

posed harmonics resulting from interference among the fundamental waves themselves. The harmonic sinusoidal tide components have specific amplitude depending on the site of observation, and they are characterized by typical and recurrent frequencies (see table I).

The Rete Mareografica Nazionale (RMN), managed by the Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici (APAT) - Servizio Mareografico, provides a coverage of the Italian coasts that effectively monitors sea level fluctuations. The harmonic analysis of these data underlines both the presence of the fundamental tide components and the composed ones (also named over-tides) that cover an important role in the sea level fluctuations of shallow water (M_4 e MS_4; see table I).

Together with these contributions, there are some sea level fluctuations due to a pressure variation of thermic origin (*e.g.,* alternation night-day) and, above all, aperiodic low-frequency sea level fluctuations (due to meteorological pressure variations) representing the background level on which astronomic components overlap. These last fluctuations depend in a variable way on the transit of atmospheric fronts or, in general, on the



Scale units
X km E2; *Y* km E2; *Z* km E-4

Fig. 1. Picture of the geodetic phenomenon of sea level deformation due to atmosphere weight.

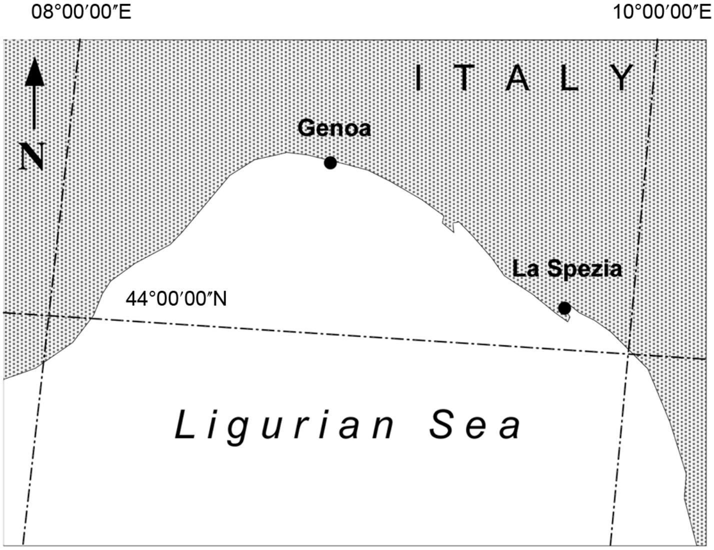


Fig. 2a. Geographical localization of Genoa and La Spezia harbours.

atmosphere meteorological dynamics over the considered sea basin (Cattaneo, 1979; Soldani *et al.*, 2004), and hence cannot be predicted by harmonic analysis. When a high-pressure area moves on a free water surface, it originates an additional weight on it. The isostatic reaction of free water surface is a concave adjustment with respect to the starting surface to compensate, in the local atmosphere-water column, the increase in atmosphere weight with a water out-flow (low meteorological tide; see fig. 1). On the contrary, when a perturbed front produces a drop in atmosphere weight, the isostatic compensation adjustment will be realized in a bump produced by a flow of incoming tide (high meteorological tide). The time between the pressure unbalance and its Newtonian compensation is called «tide inertness».

In many European harbours, the amplitudes of maxima meteorological tide waves (briefly named meteo-tides) are sensitively greater than astronomical tide waves (astro-tides). This phenomenon is typical in the Gulfs of La Spezia and Genoa (fig. 2a), where the merchant and military harbour structures are subject, under not exceptional meteorological conditions, to low-frequency meteo-tide flows showing an amplitude even four times greater than normal astro-tide amplitudes. Therefore, the importance of forecasting the meteo-tide flows is remarkable for safety reasons, environmental protection, and management of nautical traffic in waterways, harbours and in coastal navigation. As for the environmental question in harbours such as La Spezia and Genoa, the meteo-tides drive the greatest flow-reflow impulses of the harbour waters, having a primary role, *i.e.* in pollutant dispersion and water oxygenation balance. The knowledge of such phenomenon, besides defining the capacity of the harbours to resist environmental impact, is therefore able to plan human activities in the harbour waters. If, for instance, a harbour must be submitted to the dredging of the waterways or to any other heavy interaction activities with shallow water, the statistical knowledge of the seasonal period of maximum water exchange and the ability to forecast the exchange times will be decisive in minimization of environmental impact, because they can provide some indications on the best time for works execution. Currently, flow times and amplitudes of meteo-tides, unlike the astro-

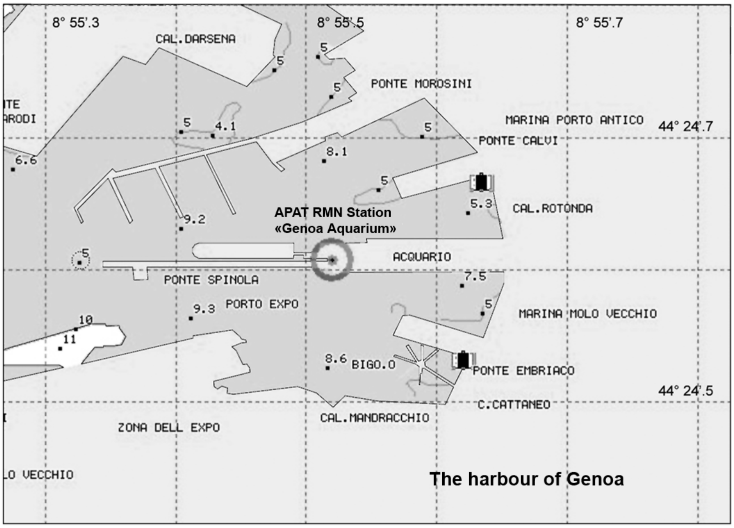


Fig. 2b. The internal part of Genoa harbour with localization of APAT-RMN station (graphic base from MapSend BlueNav Europe v. 1.00d – modified).

tides, are not easily predictable because the correlation between atmospheric pressure variation and consequent sea surface adjustment (meteo-tide) is generic both in temporal phase-displacement and amplitude, and the stochastic nature of the atmospheric dynamics so it does not provide an effective parameter in environmental harbour management (and nautical traffic).

The purposes of this work are to develop a quantitative method to forecast the flow times and amplitude of meteo-tides (based on the joined use of barometers, tide-gauges, gravimeters and clocks), describe the experimental test to obtain a preliminary law of meteo-tide parameters studying the meteo-tides as adjustment of the geodetic surface (free sea surface), and present the first results on the classification of astronomic (high) and meteorological (low) frequency bands in the fluctuations of sea level measured by the meteo-mareographic APAT station placed in Genoa harbour (fig. 2b).

2. The methodological approach

Meteo-tides flows can be considered adjustments of free sea surface resulting from local atmospheric weight variations. When the sea level is in isostatic equilibrium with atmosphere weight, tide fluctuations concern only astronomic components. When an atmospheric weight variation occurs, the sea surface reacts by a low-frequency fluctuation reaching to a new equilibrium state.

Such adjustment is characterized by a delay time due to the different dynamic responses of atmosphere compared with sea water. This delay cannot be evaluated with a theoretical law on the basis of barometric measurements. Meteo-tide flow and reflow times, in fact, feel the effects of many local factors: the most important being coast and bottom morphology and, secondly, the currents, the wind and sea water density.

On the contrary, if a gravimetric anomaly signal is detectable, the force producing meteo-tide time of start, related to atmospheric conditions change, will be technically measurable before the sea surface adjustment related to barometric variations (Faggioni *et al.*, 2004). An atmospheric weight increase induces a Newtonian adjustment in the sea surface. When the cause (high pressure) generating such adjustment stops, the sea surface is in geopotential imbalanced conditions and produces a gravimetric anomaly inducing a Newtonian tide flow to compensate this imbalance (returning to the sea surface geometry preceding the increase of pressure), as a barotropic propagating wave.

Then, using a gravimeter near the meteo-mareographic station provides an essential preliminary datum, since such instrument (if sensitive to the phenomenon) is able to measure the Newtonian signal of geodetic imbalance when it occurs. If a tide-gauge is joined to the gravimeter, the sea level measurement and the meteo-tide wave arrival time can be achieved. The difference between gravimetric maximum time and meteo-tide wave arrival time (that is the delay between the Newtonian generating cause and the geodetic reaction) is the meteo-tide time of flow (or outflow). A reasoned statistic of these measurements is able to provide the law of meteo-tide delay based on the entity of the Newtonian generating push. Such law, characteristic of every harbour, will become the gravimetric measure predictors of meteo-tide delay time.

3. Instrumentation

The observation of meteo-tides Newtonian phenomenon is carried out by multi-instrumental stations composed of mareographic, meteorological and gravimetric instrumentation and called Newtonian Meteo-mareographic Stations (NMS).

The data processed in this work come from a meteo-mareographic APAT RMN station in Genoa harbour (Genoa Aquarium Station) (latitude harbour ϕ=44°24′31″N; longitude λ==08°55′33″E; see fig. 3).

The main component of this station is the ID5793/a mechanical tide-gauge. It measures sea level vertical motion by a craft suspended by means of an anti-torsion steel cable. The tide-gauge is referred to the zero level IGM (Istituto Geografico Militare) Genoa 1942. The analogical measure is plotted by a nib connected to a drum with useful recording height of 250 mm and rotation speed of 2 mm/h. The signal amplitude is also turned into anelectric signal by means of a transducer; a converter A/D gives in output the sampled signal digital form. Such device has a precision of ±0.5 cm and vertical run sensitivity of 0.5 cm. In a short time, a NMS, with an ultrasound hydrometer tide-gauge with sensitivity of 0.1 cm, maximum systematic error of 0.1 cm and sampling rate variable from 1 to 0.05 Hz, will also be installed in La Spezia harbour.

Fig. 3. The meteo-mareographic station (belonging to APAT RMN) in Genoa harbour.

The barometer for atmospheric pressure data acquisition is constituted by a silicon capacitive transducer to guarantee high measure repeatability and stability for long period. This instrument has a measurement field of 500-1100 hPa with repeatability of ±0.03 hPa, resolution of 0.01 hPa, non linearity of ±0.05 hPa and it has a serial interface of RS232 or TTL or RS485 or RS422 for the connection, through ASCII protocol, to standard acquisition unity.

As regards the gravity acceleration measure, the starting experiment will be achieved through a series of absolute measurements every six hours by decreasing the sampling interval up to 15 min in correspondence to the high temporal pressure variation periods start and end. Such type of sampling yields information of absolute gravity in low atmospheric pressure gradient periods and in high gradient ones. The absolute gravity measurements can be related to geodetic imbalance of the sea surface and to the consequent vertical water mass rearrangements. The scheduled instrument for such type of measure is the FG5 absolute gravimeter of the Micro-*g* Solutions, Inc. The FG5 uses the free-fall method. Its technological solution guarantees an accuracy of 2 μGal, a *g* measure precision of μGal·(Hz)$^{-1/2}$ at a quiet site and 10-30°C of operating temperature range.

Then, the measures of the three instruments constituting the NMS are referred to a clock that provides the independent common reference to the three signals (sea level, atmospheric pressure and gravity acceleration). The clock in the RMN meteo-mareographic stations is referred to GMT (Greenwich Meridian Time).

4. Preliminary analysis of mareographic and barometric data

We consider now sea level and atmospheric pressure measured between 12/02/2001 and 04/11/2001 from the APAT meteo-mareographic station in Genoa harbour to disclose qualitative correlations between the two phenomena; both signals were acquired every hour.

Sea level Power Spectral Density (also named Energy Spectrum; see fig. 4) shows astronomic tide components (see table I). The most significant components have periods nearly equal of 24 and 12 h and a remarkable low-frequency contribution, independent from astronomical phenomena. This low-frequency mareographic component is related to the atmospheric pressure pattern (Crepon, 1965; Mosetti, 1969; Garrett and Toulany, 1982; Garrett and Majaess, 1984; El-Gindy and Eid, 1990; Le Traon and Gauzelin, 1997).

In particular, at low frequencies, the atmospheric pressure energy spectrum (see fig. 5)

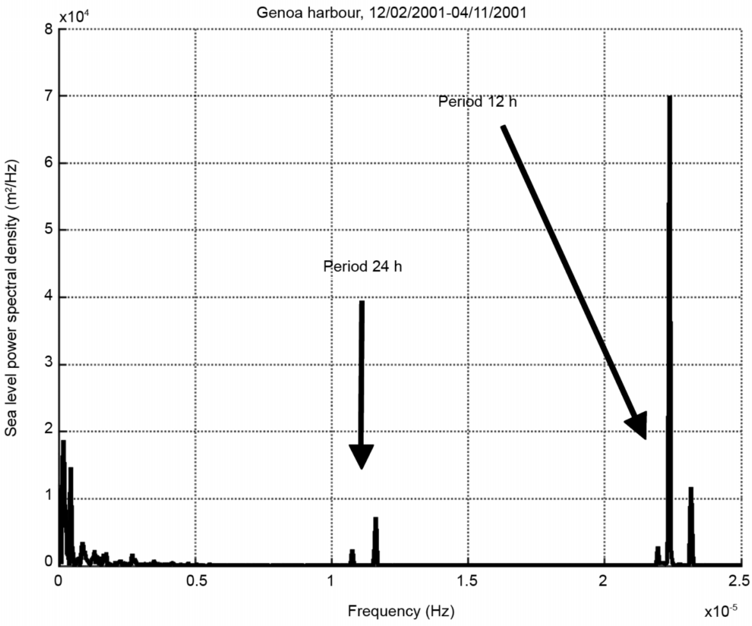


Fig. 4. Power Spectral Density of sea level measured by APAT station in Genoa harbour between 12/02/2001 and 04/11/2001.

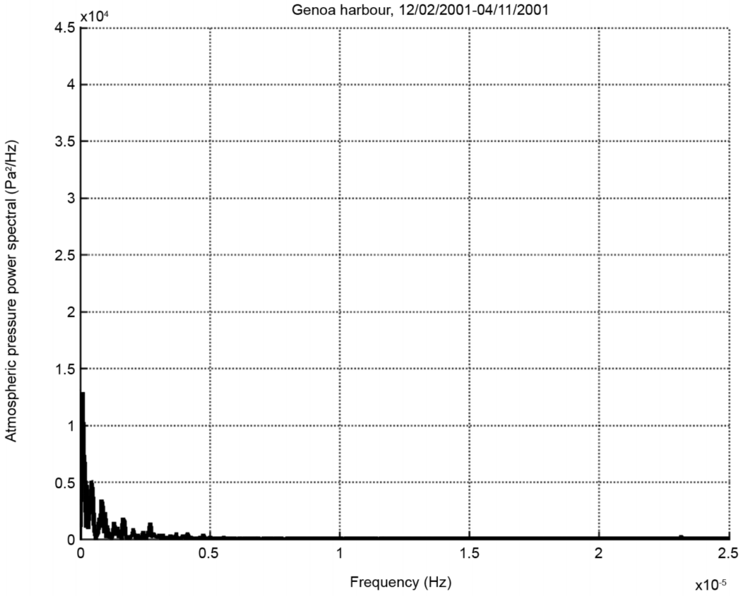


Fig. 5. Power Spectral Density of atmospheric pressure measured by APAT station in Genoa harbour between 12/02/2001 and 04/11/2001.

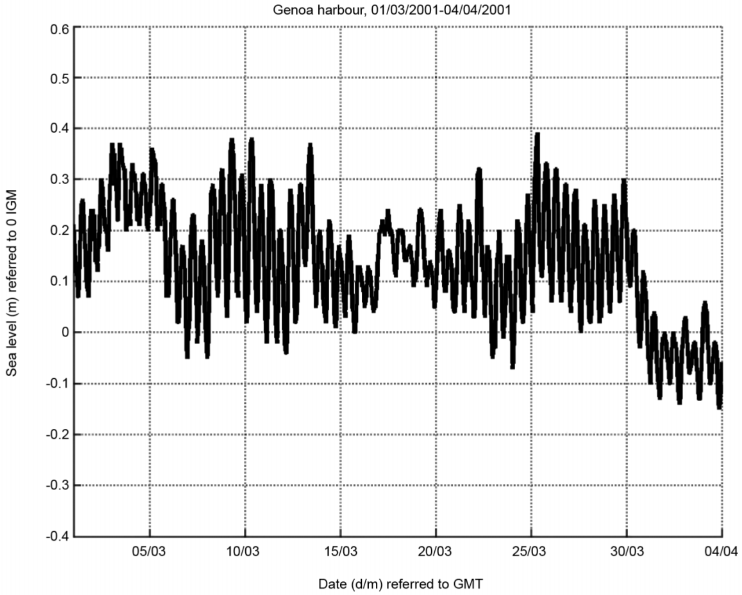


Fig. 6a. Sea level measured by APAT station in Genoa harbour between 01/03/2001 and 04/04/2001.

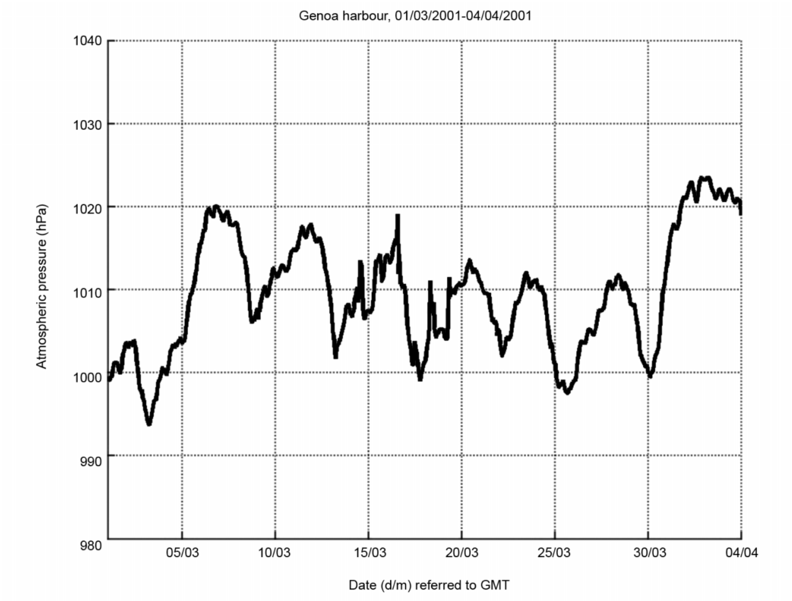


Fig. 6b. Atmospheric pressure measured by APAT station in Genoa harbour between 01/03/2001 and 04/04/2001.

looks similar to the sea level energy spectrum. At high frequencies (astronomic tide components band), on the other hand, atmospheric pressure spectrum components are nott significant. Then, it is obvious that atmospheric pressure variations drive sea level low-frequency fluctuations (Stocchino and Scotto, 1970). Now we are studying an appropriate low-pass filter able to exclude astronomic harmonics from mareographic signal and to keep only components depending on atmospheric pressure.

We now consider sea level and atmospheric pressure measured between 01/03/2001 and 04/04/2001 (see fig. 6a,b). A first qualitative comparison of these two plots shows that atmospheric pressure maxima (minima) occur shortly before sea level minima (maxima): an increase (decrease) in atmospheric pressure comes before a sea level decrease (increase).

In particular, we study the time interval between 05/03/2001 and 10/03/2001: in this period there is an entire cycle of rise-drop pressure (see fig. 7) and the consequent cycle of drop-rise sea level (see fig. 8). To evaluate the relative delay between the two signals, they are first interpolated and smoothed by a polynomial; the outcomes (with maxima and minima) are shown in figs. 7 and 8.

Geometrical comparison between low-frequency components of the two signals (see fig. 9) shows that a time $\Delta T \approx 13$ h elapses between atmospheric pressure maximum time and corresponding sea level minimum (meteo-mareogaphic reflow) time; such delay is also between atmospheric pressure minimum time and sea level maximum (meteo-mareographic flow). Moreover, we note that a sea level rise of $|\Delta H| \approx 0.27$ m corresponds to an atmospheric pressure decrease of $|\Delta P| \approx 12$ hPa.

We can now calculate the Transfer Factor J_{PH} for Genoa harbour, with regard to the period between 05/03/2001 and 10/03/2001

$$J_{PH} = |\Delta P| / |\Delta H| \approx 12/0.27 \approx 44.44 \text{ (hPa/m)}.$$

This means that an atmospheric pressure increase of 44.44 hPa would induce a sea level decrease of 1 m. This value of J_{PH} provides an interesting starting point for the Genoa harbour;

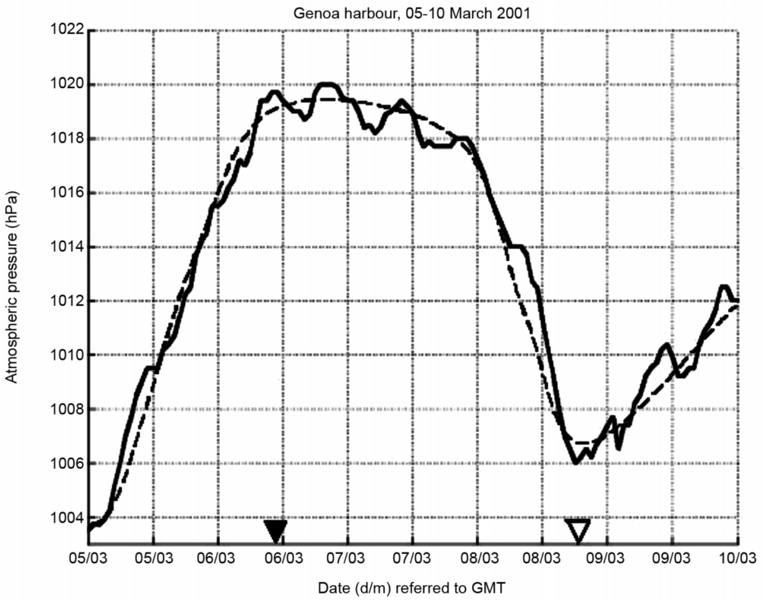


Fig. 7. Atmospheric pressure measured by APAT station in Genoa harbour between 05/03/2001 and 10/03/2001 (bold line) and its low-frequency component (dashed line). Black triangle shows the time of the pressure maximum, while white triangle shows the time of its minimum.

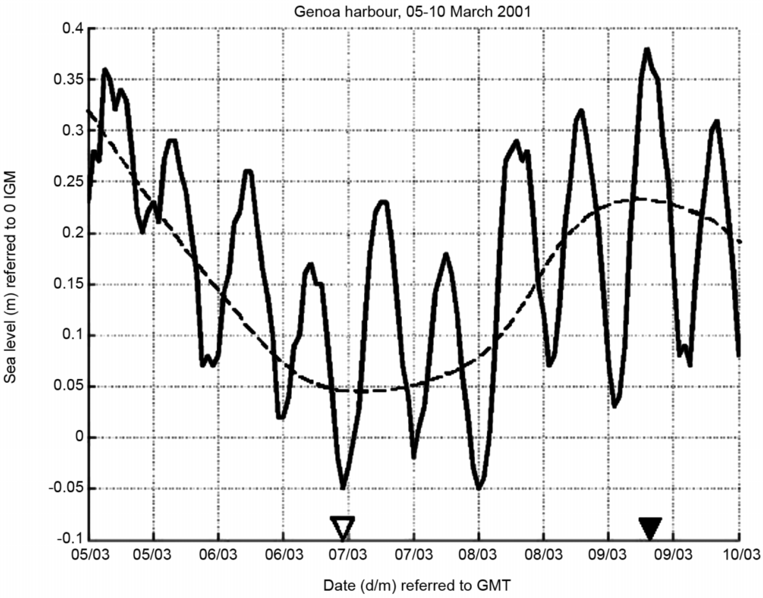


Fig. 8. Sea level measured in Genoa harbour by APAT station between 05/03/2001 and 10/03/2001 (bold line) and its low-frequency component (dashed line). Black triangle shows the time of the sea level maximum, while white triangle shows the time of its minimum.

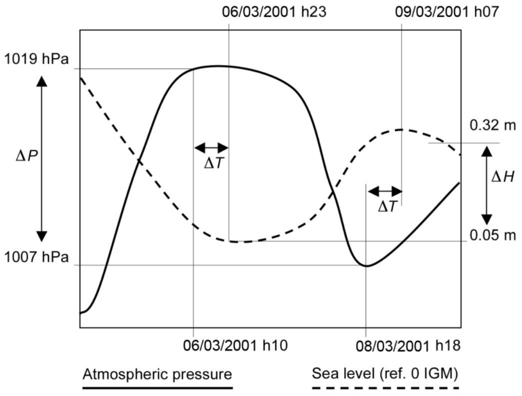


Fig. 9. Low-frequency components of pressure (bold line) and sea level (dashed line). *X* axis represents the time, *Y* axis on the left represents the pressure, and *Y* axis on the right represents the sea level.

moreover, it is in agreement with preliminary measurements performed in Tuscan and Ligurian harbours.

5. Conclusions

To detect possible relationships (in phase and amplitude) between atmospheric pressure and sea level (the starting point for a tide forecasting analysis), the two signals acquired by the APAT meteo-mareographic station near Genoa Aquarium have been compared.

The analysis of mareographic and barometric temporal series measured between 12/02/2001 and 04/11/2001 allowed us to separate the frequency components into two bands: a high-frequency band having astronomic origin and a residual low-frequency band having Newtonian origin. The low-frequency components of two energy spectra are related to each other.

In particular, the observation of atmospheric pressure and corresponding sea level measured in the time period between 05/03/2001 and 10/03/2001 allowed us to relate the low-frequency component of the two signals. A variation in atmospheric pressure and consequent opposite variation of the sea level are shifted of nearly 13 h. This delay represents the inertia of water mass responding to the Newtonian pulse generated by a variation of the atmospheric pressure.

Finally, a comparison of the two signals amplitude variations during this pressure event (05/03/2001-10/03/2001) allows us to evaluate the Transfer Factor J_{PH} for Genoa harbour: $J_{PH} = 44.44$ (hPa/m). The meteo-mareographic Newtonian Transfer Factor J_{PH}, once statistically defined over many pressure events in Genoa and La Spezia harbours, will be the starting point to evaluate the target of the gravimetric measures induced by atmospheric pressure variations (if harbour basin volume and water density will be known), that is the water mass moving during the Newtonian low-frequency oscillations of sea level in harbours of the Ligurian coast.

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