HARBOUR WATER MANAGEMENT FOR PORT STRUCTURES AND SEA BOTTOM DESIGN, COAST PROXIMITY NAVIGATION MANAGEMENT, WATER QUALITY CONTROL

Osvaldo Faggioni, Maurizio Soldani, Giovanna L. Piangiamore[1],
Andrea Ferrante[2],
Mauro Bencivenga, Giovanni Arena and Gabriele Nardone[3]

Tide is a sea level up-down water motion basically depending on three different phenomena: the Earth-Moon-Sun gravitational relationship, the water surface fluid reaction to atmospheric meteorological dynamic action and the Newtonian vertical adjustment of the sea surface due to atmospheric pressure variations. The first tide component (astro-tide) is periodic and well known in all points of the Earth surface; the second one is directly related to the meteorological phenomenon and then it is foreseeable; the Newtonian component, on the contrary, is not readily predictable by a general hydrostatic law, because the factor "*J*" that represents the Newtonian transfer (from the atmospheric weight to the consequent sea level) is variable in each harbour area. A statistical study and the related numerical data interpretation of the measurements performed in the Ports of Genoa, La Spezia, Marina di Carrara, Livorno, Piombino, Civitavecchia and Ravenna (belonging to the Italian Newtonian Meteotide Network) show port values of J_{ph} (from 1.4-1.6 cm/hPa to > 2 cm/hPa, on the contrary of the off-shore areas where J_{ph} is about 1 cm/hPa). This phenomenon (hydrobarometric tide wave) produces even double values of harbour sea level fluctuations amplitude in comparison to astronomic tide sea level oscillations, and is characterized by a wavelength from 8-12 h to same days and a 10-25 days/year as mean temporal occurrence in the Northern Tyrrhenian Sea. This is the most relevant ordinary risk factor for our ports activity and structures design. The present note shows a quantitative method to define the values of J_{ph} factor for ports and its use in the Harbour WaterSide Management (HWSM) based on the joined use of barometers, hydrometers and clocks, the preliminary results related to the use of the gravimeters as hydrobarometric predictor in La Spezia Port and two examples of use of J_{ph} factor in the port management: refloating of a landing ship and optimisation of a dock performance as pleasure boats mooring.

BASIC CONCEPTS

The meteorological tide

Astronomical tide is a periodical sea level up-down water motion depending on the Earth-Moon-Sun gravitational relationship and is therefore easily describable from the Fourier theory. The Fourier analysis of tide measurements underlines both the presence of the fundamental harmonic components and the composed ones. Together with these contributions, there are some non-periodic low-frequency sea level fluctuations due to atmospheric pressure variations and representing the background level on which astronomic components overlap (Crepon, 1965; Mosetti, 1969; Stocchino and Scotto, 1970; Garrett and

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[1] Istituto Nazionale di Geofisica e Vulcanologia, via Pezzino Basso 2, Fezzano, SP, 19025, Italy
[2] Consiglio Superiore dei Lavori Pubblici, via Nomentana 2, Roma, 00161, Italy
[3] Servizio Mareografico, Istituto Superiore per la Protezione e la Ricerca Ambientale, via Curtatone 3, Roma, 00185, Italy

Toulany, 1982). These last fluctuations depend, in general, from the atmospheric meteorological dynamics over the considered sea basin, and therefore they aren't predictable by harmonic analysis (Allen and Denbo, 1984; Garrett and Majaess, 1984; El-Gindy and Eid, 1990; Tsimplis and Vlahakis, 1994; Tsimplis, 1995; Le Traon and Gauzelin, 1997).

When a high pressure front moves on a free water basin, it origins an additional air weight on the water surface. The isostatic reaction of free sea surface is constituted by a concave adjustment of starting surface to compensate, in the local atmosphere-water column, the increase of atmospheric weight with an outgoing water flux (meteorological low tide, see Fig. 1); this flux can be considered as an adjustment of free sea surface resulting from local atmospheric weight variations: when sea level is in isostatic equilibrium with atmospheric weight, tide fluctuations concern only astronomic components. On the contrary, when a perturbed front produces a diminution of atmospheric weight, the isostatic compensation will be realized in a convexity produced by a flux of incoming water flux (meteorological high tide). Such sea surface adjustment is characterized by a delay time due to the different viscosity of atmosphere compared with sea water: the time elapsed among the pressure unbalance and its Newtonian compensation is called "meteorological tide inertness".

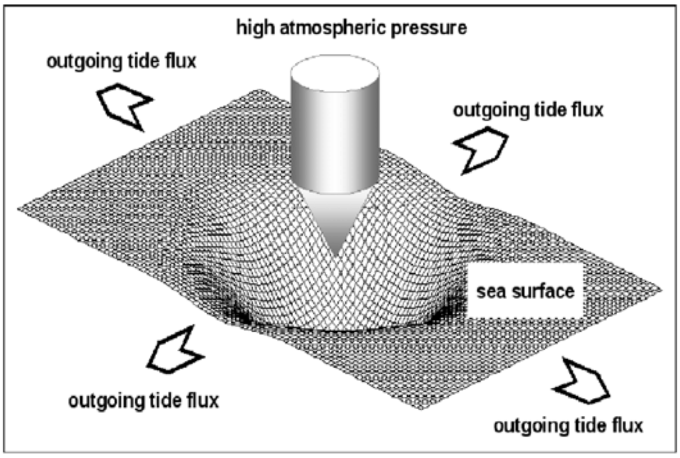

Figure 1. The meteorological low tide.

In a lot of European harbours the amplitudes of maximal meteorological tide waves (briefly named meteotides) are sensitively greater than astronomical tide waves (astrotides); this phenomenon is typical in the Northern Tyrrhenian harbours, where the merchant and military port structures are subject, under not exceptional meteorological conditions, to low-frequency meteotide flux showing an amplitude even two times greater than normal high-frequency astrotide amplitudes, a wavelength from 8-12 h to some days and a mean temporal occurrence equal to 10-25 days/year.

Therefore, the importance of forecasting meteotide flux is remarkable about safety and environmental aspects and to correctly manage ship traffics. As it regards environmental aspects in Northern Tyrrhenian harbours, meteotides rule the greatest flux-reflux impulses of the harbour waters, having a primary role e.g. in pollutants dispersion and water oxygenation balance. The knowledge of such phenomenon is therefore able to plan human activities in harbour waters. If, for instance, a port area must be submitted to the dredging of the waterways or to any other heavy interaction activities with shallow water, the knowledge of the seasonal period of maximum water exchange and the ability to forecast the exchange times will result decisive in the minimization of environmental impact, because they can provide indications on the fitter time to work execution.

However, flux times and amplitudes of meteotides, unlike the astrotides, are currently not predictable because the correlation between atmospheric pressure variation and consequent sea surface adjustment cannot be described by the general theoretical hydrostatic law. In this work we present a statistic method, based on long periods of atmospheric pressure and sea level measurements, to forecast meteotides flux times and amplitude.

Moreover, barometric measurements are indirect measurements because atmospheric effect on sea level variations depends on many local factors influence: coast and bottom morphology and, in second order, currents, wind and sea water salinity. On the contrary, the force producing starting time of meteotide, relating to atmospheric conditions change, will be directly measurable by a gravimeter (Faggioni et al., 2006), because an atmospheric weight increase induces a Newtonian adjustment in the sea surface. When the high pressure generating such adjustment stops, the sea surface is in geopotential unbalance conditions and the gravimetric anomaly is the result of the Newtonian tide flux compensation of this unbalance. A gravimeter near the meteo-mareographic station provides an essential preliminary datum, since such instrument is able to measure the Newtonian signal of geodetic unbalance. A hydrometer is joined to the gravimeter to achieve the sea level measurement and the meteotide wave arrival time; the difference between the gravimetric maximum time and the meteotide wave arrival time (that is the delay between the Newtonian cause and the geodetic reaction) is the meteotide flux (or reflux) time. A statistic of these measurements is able to provide the law of meteotide delay based on the entity of the Newtonian generating push. Such law, characteristic of every harbour, will become the gravimetric measure predictors of meteotide delay time.

Instrumentation employed

The observation of meteotides Newtonian phenomenon is carried out by measuring stations composed by mareographic, barometric and gravimetric instrumentation; such stations are located in the Italian Ports of Genoa, La Spezia, Marina di Carrara, Livorno, Piombino, Civitavecchia and Ravenna and they perform the Italian Newtonian Meteotide Network (see Fig. 2); they are composed by meteo-mareographic stations belonging to the Italian Rete Mareografica Nazionale (RMN) managed by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)-Servizio Mareografico (except the meteo-mareographic instrumentation placed in the Marina di Carrara Port, that belongs to the local Port Authority) that provides a mareographic and barometric sensor coverage of the Italian coasts to observe sea level and atmospheric pressure fluctuations, joined to PET (Portable Earth Tide) gravimeter to perform gravimetric anomaly measurements.

Figure 2. The Italian Newtonian Meteotide Network (picture from Google Earth).

METEO-MAREOGRAPHIC OBSERVATIONS AND STATISTICAL ANALYSIS

Meteo-mareographic measurements

The data processed in this section come from the meteo-mareographic RMN station located in Porto Lotti (La Spezia harbour) in the 44°05’49’’N, 09°51’26’’E position (see Fig. 3 and Fig. 4). The mareographic component is the Siap+Micros ID0810B ultrasound hydrometer: it emits ultrasonic pulses towards the sea surface and senses returning echoes; the on-board electronics performs distance calculation computing time intervals between emission and reception of pulses; sea level is referred to the IGM (Istituto Geografico Militare) Genoa 1942 zero level. The sensor to perform atmospheric pressure measurements consists of a Vaisala PTB220 barometer; its sensing element is a silicon transducer that deforms depending on the atmospheric pressure. The measures of these two instruments are referred to a clock that provides common temporal reference; the time is referred to UTC (Universal Time Coordinated). The remote receiving station performs download of data by a GSM modem link.

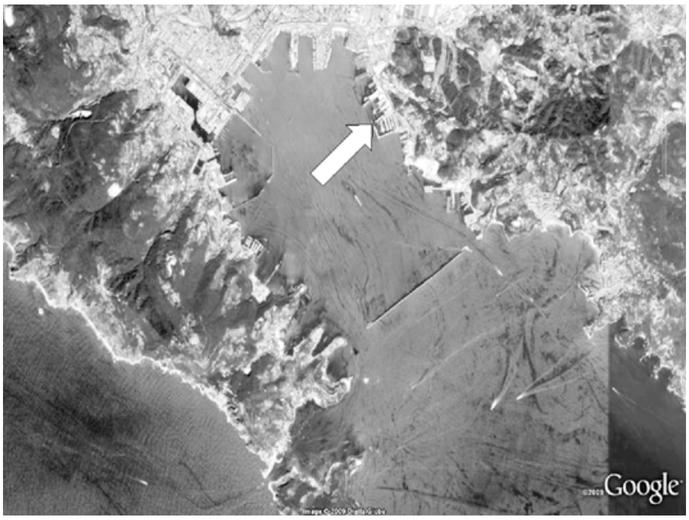

Figure 3. The position of the meteo-mareographic station in the Port of La Spezia (picture from Google Earth).

Figure 4. Instrumentation of RMN La Spezia station: ultrasound hydrometer and tide gauge (on the left), and acquisition station containing the barometer (on the right).

The J_{ph} factor

To detect statistic relationships between atmospheric pressure and sea level (starting point to perform a meteotide forecasting analysis), barometric and mareographic signals have been compared by using Low Pass components (we use a cut frequency $F_c = 10^{-5}$ Hz to separate low-frequency band having Newtonian origin from high-frequency band having astronomic origin) of measurements performed during several events occurred in last years. In particular, the hydrobarometric transfer factor J_{ph} was calculated for each studied event, according to the following formula:

$$J_{ph} = \frac{\Delta h}{\Delta p} \tag{1}$$

To explain the developed method to calculate J_{ph}, we analyze the event from 18.01.2007 to 22.01.2007 in the La Spezia harbour (see Fig. 5 and Fig. 6).

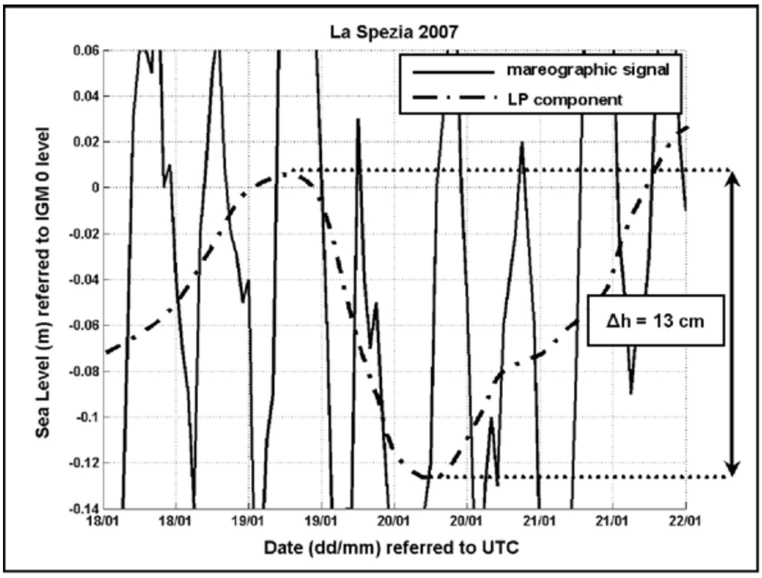

Figure 5. The mareographic signal recorded by La Spezia Newtonian Meteotide Station between 18.01.2007 and 22.01.2007 and its Low Pass component.

About this event:

$$J_{ph} = \frac{\Delta h}{\Delta p} \approx \frac{13}{6}\frac{cm}{hPa} \approx 2.2\frac{cm}{hPa} \tag{2}$$

it means that every increase of 1 hPa in atmospheric pressure was followed by a decrease in sea level of about 2.2 cm. The calculation of the factor J_{ph} was repeated for several significant events occurred during 2007 in the La Spezia harbour obtaining a J_{ph} factor value for each event. So, it was possible to calculate an estimated $\hat{J}_{ph}$ value by an extensive statistics of factor J_{ph}:

$$\hat{J}_{ph} \approx 2\frac{cm}{hPa} \tag{3}$$

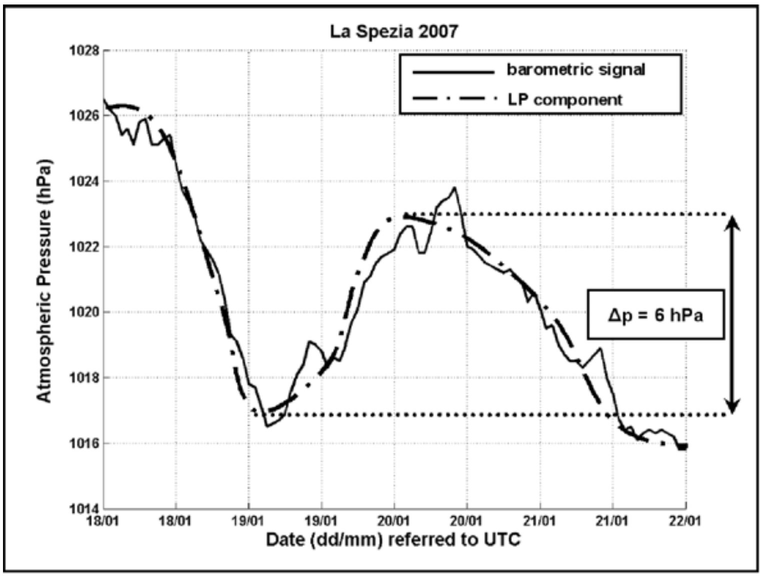

Figure 6. The barometric signal recorded by La Spezia Newtonian Meteotide Station between 18.01.2007 and 22.01.2007 and its Low Pass component.

The key role of $\hat{J}_{ph}$ is to allow the conversion of an atmospheric pressure variation into an expected sea level increase/decrease in the considered basin:

$$\Delta\tilde{h} = \hat{J}_{ph} * \Delta p \tag{4}$$

where $\Delta\tilde{h}$ is the sea level expected variation, $\hat{J}_{ph}$ is the estimated hydrobarometric transfer factor and Δp is the pressure variation.

These results indicate an opposite trend sea level variation of about 2 cm for any atmospheric pressure variation of 1 hPa in the Port of La Spezia. The described forecasting method error (difference between the expected sea level and the observed one) did not exceed 5 cm in the Port of La Spezia during 2007.

The same statistical analysis performed during last years in the other ports belonging to the Italian Newtonian Meteotide Network shows that $\hat{J}_{ph}$ ranges from 1.4-1.6 cm/hPa to > 2 cm/hPa (depending on the port), while $\hat{J}_{ph}$ is about 1 cm/hPa in the off-shore areas.

Meteotide inertness

Geometrical comparison between low-frequency components of the two signals shows that a time $\Delta t \approx 10$ h elapses between atmospheric pressure minimum time (19/01 00:00) and corresponding sea level maximum time (19/01 10:00; meteo-mareographic flux); such delay is also between atmospheric pressure maximum time (19/01 22:00) and sea level minimum time (20/01 08:00; meteo-mareographic reflux): variation of atmospheric pressure and consequent opposite variation of sea level are shifted of nearly 10 h. This delay represents, for these events, the inertness of water mass moving in reply to Newtonian pulse generated by variation of atmospheric pressure. In general, the same temporal analysis performed in the other ports belonging to the Italian Newtonian Meteotide Network shows an inertness range from 10 h and 18 h.

APPLICATIONS OF J_{ph} FACTOR: TWO EXAMPLES IN THE PORT OF LIVORNO

Refloating of a landing ship

At 18:30 UTC on 19th April 2005 a ferryboat ran aground coming out the Port of Livorno, in bad weather conditions. The ordinary unloading shares to refloat the ship (based on hydrostatic push due to the highest astronomical tide) did not produce effects, although carried out correctly (see Fig. 7).

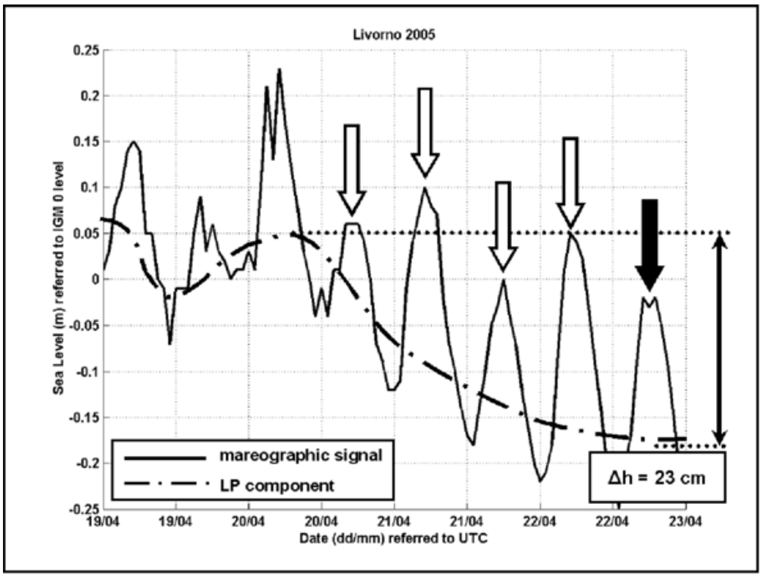

Figure 7. The mareographic signal recorded by Livorno Newtonian Meteotide Station between 19.04.2005 and 23.04.2005 and its Low Pass component.

This problem has occurred in four successive attempts corresponding to successive highest astronomical tide (white arrows in Fig. 7) and the ferryboat was refloated only the fifth attempt (astronomical tide at 18:30 on 22nd April 2005, indicated by the black arrow in Fig. 7). The studies, requested by Port Authority of Livorno to know the origin of this event, have shown an atmospheric pressure increase (about 13 hPa, see Fig. 8), the consequent sea level decrease (about 23 cm, see Fig. 7), and consequently a J_{ph} factor nearly 1.8

cm/hPa in the days following the ferryboat running aground. This quantity of water, subtracted by hydrobarometric inversion, is sufficient to explain the failures of refloating as it avoid the increase in expected astrotide water. In fact, when the phenomenon of meteotide stops its effectiveness for stabilization of atmospheric pressure on the fifth attempt, the refloating is got. In the future, the use of $\hat{J}_{ph}$ factor joined to the meteorological forecasting should provide the best instant in which to perform a refloating of a landing ship.

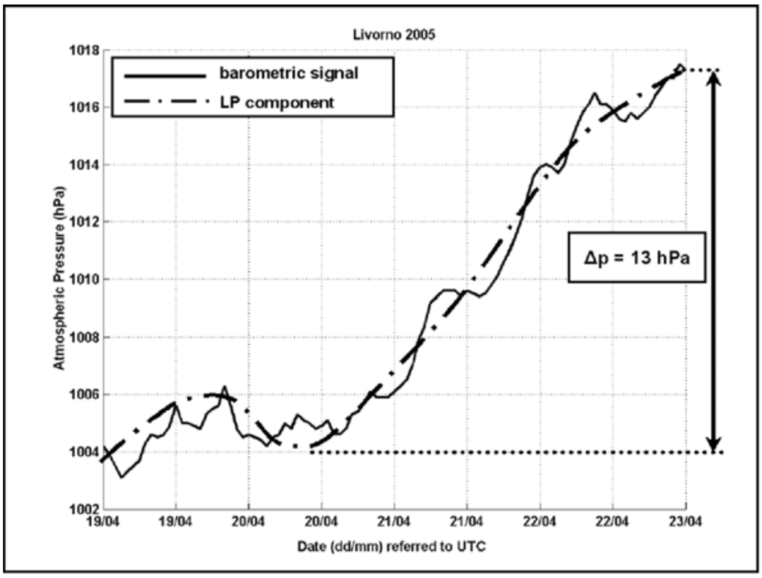

Figure 8. The barometric signal recorded by Livorno Newtonian Meteotide Station between 19.04.2005 and 23.04.2005 and its Low Pass component.

Optimization of a dock performance

Knowledge of $\hat{J}_{ph}$ is also very useful in Harbour WaterSide Management to forecast the water depth in the approaches and stationing ships knowing only the expected atmospheric pressure. The effects of the pressure variation on the water depth were applied to a dock in the Port of Livorno (see Fig. 8). Water depth goes down of nearly 50 cm consequently to an atmospheric pressure increase from 995 to 1020 hPa, and consequently J_{ph} for this event is nearly 2 cm/hPa; then, the pressure variation change the bathymetry of the basin, as displayed in Fig 8. A pressure variation could be converted, through $\hat{J}_{ph}$, into an expected sea level variation and then into a new bathymetric map. In the design phase of maritime works, it is necessary to introduce the $\hat{J}_{ph}$ factor in order to define the height of the marine protection works.

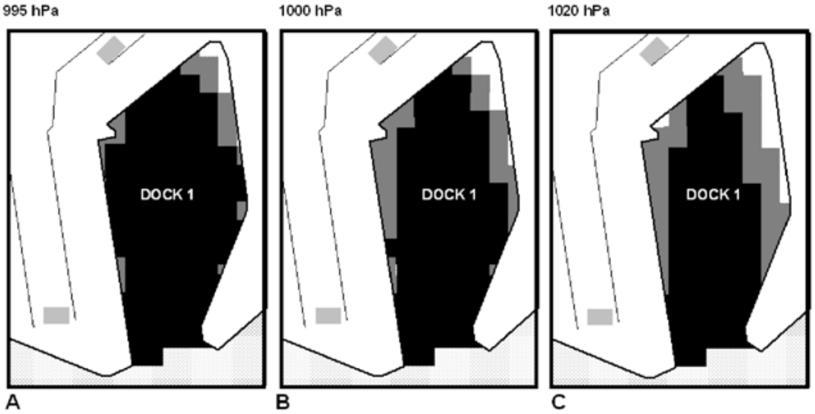

Figure 8. Bathymetric map of a dock in the Port of Livorno depending on the atmospheric pressure (995 hPa, 1000 hPa and 1020 hPa); the three colours (black, gray and white) indicate three water depth ranges (very deep, deep, not deep).

GRAVIMETRIC OBSERVATIONS AND STATISTICAL ANALYSIS

Gravimetric measurements

As it regards the gravity acceleration measure, we use the Newtonian station shown in Fig. 10.

Figure 10. The Newtonian acquisition station. The arrow indicates the gravity sensor.

The Newtonian measurement station is placed (since 2007) in the Centro di Supporto e Sperimentazione Navale (CSSN) of the Italian Navy, near the RMN station in La Spezia and more precisely in the 44°05’41”N, 09°51’56”E position; it consist of a Micro-g Lacoste PET gravimeter (its clock is referred to UTC), that measures gravimetric anomaly (by a spring elongation due to gravity acceleration variations associated to tide displacement in the Gulf of La Spezia) compared with mareographic and barometric signals. The remote receiving station performs download data by a GSM modem link.

The J_{gh} factor

The Newtonian tide forecasting is achieved coupling the gravimetric signal with the meteo-mareographic ones. We show preliminary results achieved considering Low Pass components of measurements performed by La Spezia Newtonian Meteotide Station between 18.01.2007 and 22.01.2007 (the cut frequency $F_c = 10^{-5}$ Hz separates the Newtonian low-frequency band from the astronomic high-frequency band; see Fig. 5, Fig. 6 and Fig. 11).

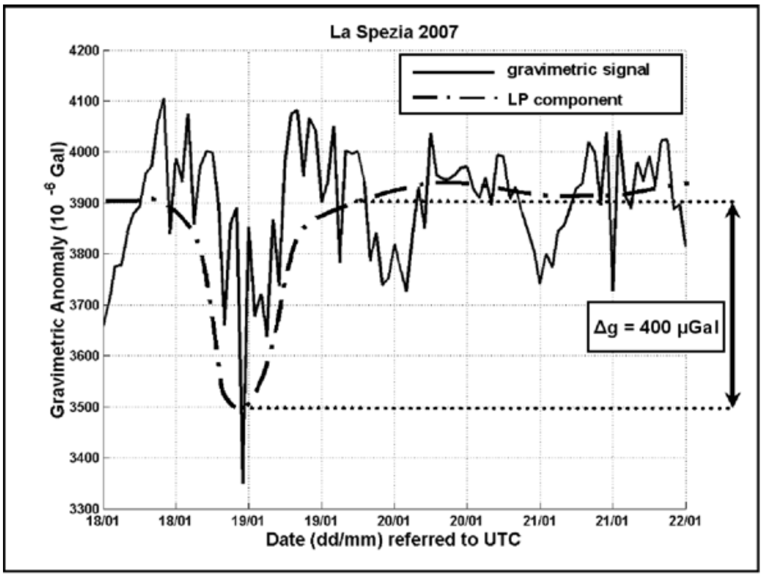

Figure 11. The gravimetric signal recorded by La Spezia Newtonian Meteotide Station between 18.01.2007 and 22.01.2007 and its Low Pass component.

The atmospheric pressure decrease ($\Delta p \approx 6$ hPa) is generated by the local atmospheric weight variations (air weight increase) and it induces a gravity variation $\Delta g \approx 400$ µgal. The Newtonian adjustment of the sea free surface is the reaction to the local mass variation of the air column. This phenomenon (the well-known “hydrobarometric tidal wave”) is an anomaly inducing a tidal flux to compensate the unbalance (return to the “start level”) and the gravimeter is able to measure the push generating the meteorological tide flux, as the result in changing weather conditions flexing the geoid.

The gravimeter provides a measure of the gravimetric anomaly, then it evaluates directly the variation of the corresponding compensation water mass: in fact, the local atmospheric weight in excess or defect is shown by the elongation of the spring (gravity variation) and it corresponds to the water mass that will move for compensation; whereas in first approximation sea water density is constant and well known, water mass can be traced back to the moved water volume and, knowing the free surface of the studied basin, to the predicted tide amplitude.

All these considerations lead to define the hydrogravimetric transfer factor J_{gh}, here calculated from the measurements performed in the Port of La Spezia in the period from 18/01/2007 to 22/01/2007 ($\Delta g \approx 400$ µgal, $\Delta h \approx 12$ cm):

$$J_{gh} = \frac{\Delta h}{\Delta g} \approx \frac{12cm}{400\mu gal} \approx 0.03\frac{cm}{\mu gal} \tag{5}$$

This means that, during this event, every increase of 1 µgal in the gravity acceleration is followed by a decrease in sea level of about 0.03 cm.

The computation of the J_{gh} factor will be repeated for several significant events in the Port of La Spezia (a J_{gh} value for each event) to get a large statistics from which calculate an estimated $\hat{J}_{gh}$ value, which will convert a gravimetric anomaly Δg into the resulting expected sea level variation $\Delta\tilde{h}$ in the studied basin:

$$\Delta\tilde{h} = \hat{J}_{gh} * \Delta g \tag{6}$$

where $\Delta\tilde{h}$ is the expected sea level variation, $\hat{J}_{gh}$ is the estimated hydrogravimetric transfer factor and Δg is the gravimetric anomaly variation.

Newtonian meteotide inertness

The gravimeter provides the meteotide arrival time forecasting, too: the gravimetric signal is generated along with the pressure variation (which is the inducing phenomenon), then a clock connected to the gravimeter provides the start time of the hydrobarometric push; furthermore, the gravimeter indicates the end of gravimetric anomaly corresponding to the reached new equilibrium (when the compensation push is completed); this instant is the same of meteotide wave arrival and a large statistic of the difference between the start and the end of the gravimetric anomalies gives a more accurate estimation of the delay between the pressure variation and the meteotide arrival (meteotide inertness).

CONCLUSIONS

The hydrobarometric transfer factor $\hat{J}_{ph}$ is the Newtonian correlation between sea level adjustment and atmospheric pressure variation in the considered port. The statistic performed is the result of several years of measurements and it confirms that hydrobarometric inversion can show higher amplitudes than kinematic phenomena due to wind or storm effects. Its application in the Harbour WaterSide Management optimizes the use of mooring facilities of ports. Furthermore, the employment of $\hat{J}_{ph}$ is very important to improve the effectiveness in safety maritime works, dock performance, and boats mooring. About port water quality, $\hat{J}_{ph}$ can explain temporary reductions of the solvent (sea water) due to an increase of atmospheric pressure, as opposed to apparent increases of the solute (pollutant factor), achieving an optimization in port water mass evaluation.

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