Harbor Resonance induced by pressure-forced surface waves

César Vidal¹, Rául Medina¹, Sebastiá Monserrat² and Francisco L. Martín¹

Abstract.

Using field data and numerical computation the relationship between a specific atmospheric perturbation and the long wave oscillation called “Rissaga” in the Ciutadella harbor, situated in the island of Menorca (Spain) in the Mediterranean sea, has been demonstrated. The transfer of momentum from the atmosphere to the ocean occurs when the atmospheric pressure oscillations travels at a speed similar to that of the generated long wave. That long wave is trapped in the shelf between Mallorca and Menorca Islands, generating a complex stationary system that has its energy peak at a frequency of 24 minutes. The Ciutadella cove, with a resonant period of 11 minutes is excited by the first harmonic of that outer wave, generating the Rissaga event.

Introduction.

Extremely strong seiche oscillations are regularly observed in specific sea areas around the world, in particular, see figure 1, in Nagasaki Bay, Japan (Honda et al., 1908; Hibiya and Kajiura, 1982), Longkou Harbor, China (Wang et al., 1987) near Sicily and in Trieste Bay, Italy (Defant, 1961; Wilson, 1972), in the Adriatic Sea (Hodžić, 1979) and the Aegean Sea (Papadopoulos, 1993), etc. These oscillations have the same temporal and spatial scales as ordinary tsunami waves and affect coasts in a similar destructive way, but they are related to meteorological rather than to seismic forcing. Nomitsu (1935) and Defant (1961) used the term ‘meteorological tsunamis’ for these type of waves.

Ciutadella Harbor (Menorca Island, Spain) see figure 2, is one of the places where such meteorological tsunamis are quite common. They are known by the local name of ‘rissaga’ (Ramis and Jansà, 1983; Monserrat et al. 1991). The first written reference of a Rissaga is from the 15th century and since then many dramatic events have occurred. The largest measured Rissaga happened in 1984, when oscillations of more than 3 m flooded the harbor and the town and sunk 35 vessels. Similar oscillations also occur in some other harbors and inlets of the Balearic Islands and
the Mediterranean coast of the Iberian Peninsula, although they are typically not as strong as in Ciutadella.

A lack of reliable observation data is the main factor limiting the understanding of the generation mechanism of *rissaga* waves (as well as large amplitude seiches in other regions of the world’s ocean). For this reason, in 1988, the University of the Balearic Islands began field experiments to obtain simultaneous records of long sea surface waves and atmospheric fluctuations in the Ciutadella region. A few spectacular cases of strong oscillations recorded in these experiments were analyzed by Monserrat et al. (1991) and Garcies et al. (1996). Precise
measurements of the peak period of these extreme oscillations (10.6 minutes) showed that they were exactly the same as the period of usual background oscillations. Relatively high-frequency spectral peaks with periods of 1.5 to 3.5 minutes were probably associated with the higher eigenmodes, and a peak with a period of 24 minutes was possibly caused by resonant oscillation over the self between Mallorca and Menorca Islands. These studies also corroborated the atmospheric origin of the Rissagas showing the correlation between pressure disturbances and seiches. Based on these results the proposed mechanism for the generation of Rissagas was suggested to be atmospherically generated offshore surface waves, which could act as an intermediate mechanism and force the harbor, by resonance. This hypothesis remains to be confirmed or discarded.

In 1997, an extensive experiment, LAST’97 was performed to improve the data base. Simultaneous records of atmospheric pressure and bottom pressure were recorded in the Ciutadella inlet, in near self and in Mallorca Island (some 50 Km South West of Ciutadella). Those data were analyzed by Monserrat et al. (1998), who obtained the transfer function between the atmospheric disturbance and the oscillations in the sea.

The objective of this work is to demonstrate that the external forcing of the Ciutadella Cove is generated by the coupling between the atmospheric disturbance and the generated long wave, as suggested by Rabinovich and Monserrat (1998). This coupling is only possible when the atmospheric disturbance travels at a speed similar to the phase speed of the long waves, controlled by the water depth in the shelf between Mallorca and Menorca Islands. The generated long waves are trapped in the shelf between the islands becoming standing waves with 24 s of peak frequency. The Ciutadella Cove, whose natural resonant period is 10.5 s, is near the first super harmonic of this external wave. Other nearby coves such as that of Platja Gran, with 5.5 minutes of natural period also show high amplifications due to the second super harmonic of the forcing waves.

First, a brief description of the LAST97 experiment is presented. Second, the numerical models used to propagate the long waves are outlined. Third, results are presented showing the mechanism of Rissaga formation. Finally, some conclusions are presented.

LAST’97 field experiments.

An extensive field experiment was developed in Ciutadella in the summer of 1997 to provide simultaneous measurements of long ocean waves on the Menorca shelf and at nearby inlets. Four sea level recorders (pressure gages) were deployed on the shelf in front of the Ciutadella Cove. Another two were located inside the Ciutadella harbor and a last one was installed in the neighboring cove of Platja Gran, see figure 3. Also, data from the permanent tidal recorder (property of the Spanish Institute of Oceanography) installed in Palma Bay (Mallorca Island) was used. In addition, three microbarographs, installed on land around Ciutadella, measured atmospheric pressure in the area. In Table 1, a summary of the instruments’ location and technical characteristics is provided. All tidal gauges were programmed to take
an average of 30 data for 30 s every minute. Barometer gauges were programmed to take 1 data every 30 s.

All the instruments’ clocks were synchronized at the moment of deployment. After deployment and before unloading the data, all pressure tidal gages were submerged simultaneously to obtain a common signal to synchronize the clocks. The microbarographs’ clocks were synchronized with the official local time.

The arrangement of instruments allowed the separation of amplitude, phase speed and direction of water waves and the amplitude, speed and direction of atmospheric perturbations.

![Figure 3. LAST’97 instrumentation deployment.](image)

Instruments were deployed from June 1997 to September 1997. Available data is shown in figure 4. Also in this figure, the most relevant recorded Rissaga events are indicated at the bottom of the graph with a vertical line topped with a dot. The length of the line indicates the maximum long wave height recorded by the M-2 instrument, located at the bottom of the Ciutadella harbor. The size of the dot indicates the event duration. It can be seen that two Rissaga events in July surpassed 1 m vertical oscillations.

For example, figure 5 shows the simultaneous record of the Rissaga on July 24, taken by several instruments. It can be seen that in this Rissaga a maximum vertical oscillation of 170 cm was measured at sensor M-2. It can also be seen that the vertical oscillation diminishes outside the port, with 0.6 cm in the MW4 instrument and 0.5 m in Palma Bay. Finally, the record of the microbarograph MB3 shows the kind of atmospheric perturbation that generates the Rissaga. Inside the port the oscillation clearly shows the fundamental resonant period of 11.6 minutes in Ciutadella Cove. Outside the port, the oscillation is more complex, with main oscillation periods around 6, 12 and 24 minutes.
Table 1. Instrument characteristics

<table>
<thead>
<tr>
<th>Instr.</th>
<th>Sensor type</th>
<th>Range, Accur., Resol. (m and mb)</th>
<th>Location Position and depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endeco M-0</td>
<td>Strain gauge</td>
<td>15 / 0.0150 / 0.00370</td>
<td>Ciutadella harbor N 39º 59.958' E 3º 49.868' / 1.6</td>
</tr>
<tr>
<td>M-1</td>
<td>Strain gauge</td>
<td>40 / 0.0021 / 0.00081</td>
<td>Plaça Gran N E / 4</td>
</tr>
<tr>
<td>M-2</td>
<td>Strain gauge</td>
<td>40 / 0.0021 / 0.00081</td>
<td>Ciutadella harbor N 40º 0.0106' E 3º 50.107' / 1.7</td>
</tr>
<tr>
<td>MW-1</td>
<td>Digiquartz</td>
<td>50 / 0.0025 / 0.00075</td>
<td>Outer platform N 39º 59.116' E 3º 48.560' / 36.6</td>
</tr>
<tr>
<td>MW-2</td>
<td>Digiquartz</td>
<td>50 / 0.0025 / 0.00075</td>
<td>Outer platform N 39º 59.417' E 3º 49.071' / 28.2</td>
</tr>
<tr>
<td>MW-3</td>
<td>Digiquartz</td>
<td>50 / 0.0025 / 0.00075</td>
<td>Outer platform N 39º 59.647' E 3º 49.368' / 19.5</td>
</tr>
<tr>
<td>MW-4</td>
<td>Digiquartz</td>
<td>50 / 0.0025 / 0.00075</td>
<td>Outer platform N 39º 58.917' E 3º 49.017' / 34.5</td>
</tr>
<tr>
<td>HID</td>
<td>Buoy</td>
<td>19 / -------- / 0.00100</td>
<td>Palma de Mayorca Bay</td>
</tr>
<tr>
<td>MB2</td>
<td>Microbarograph</td>
<td>40 mb / ----/ 0.01 mb</td>
<td>Ca’n Joan Segi N 39º 59.994’ E 3º 49.850’ / ---</td>
</tr>
<tr>
<td>MB3</td>
<td>Microbarograph</td>
<td>40 mb / ----/ 0.01 mb</td>
<td>Ca’n Aiet N 39º 58.892’ E 3º 51.498’ / ---</td>
</tr>
<tr>
<td>MB4</td>
<td>Microbarograph</td>
<td>40 mb / ----/ 0.01 mb</td>
<td>Cala Blanca N 39º 58.068’ E 3º 50.072’ / ---</td>
</tr>
</tbody>
</table>

Figure 4. LAST’97 available data.
Figure 6. Simultaneous records of different instruments during a Rissaga event.

If the energy of the atmospheric perturbation (MB4) and the sea level oscillation in Ciutadella (M-0) are compared, figure 7, it can be seen that a relation exists. But this is not a clear relationship. Although there is an increase of wave
oscillation when the atmospheric perturbation energy increases, sometimes (case 2) the efficiency of the energy transfer from the atmosphere to the sea is low and in other cases (case 1), the efficiency is very high. Analyzing the directional properties of the atmospheric perturbation, it can be observed that when the atmospheric perturbation travels as a non-dispersive wave in the SW – NW direction and at a phase speed around 25 m/s, the energy transfer from the atmosphere to the ocean is optimized (case 1).

![Figure 7](image)

**Figure 7.** Comparison of the energy of the water oscillation (M-0) and the atmospheric oscillation (MB4).

If the wave spectra in calm situations and in Rissaga events in different points are compared, figure 8, it is possible to separate the part of the forcing that is time-dependent (depends on the event) from the part of the forcing that depends on the geometry (instrument position). Figure 8a shows the comparison of spectral shapes recorded by the instrument M-0, installed in the middle of the Ciutadella harbor. It can be seen that, when the Rissaga event occurs, the energy increases in all frequencies. Among these frequencies, the 24.4-minute peak represents the main resonant period of the oscillation in the platform between Mallorca and Menorca Islands. This period represents the forcing of the Ciutadella Cove and other neighboring coves such as Platja Gran. The 10.5-minute period is the resonant period of the Ciutadella Cove, that is very near the first super-harmonic of the external forcing. Figure 8b shows the same curves for the neighboring cove of Platja Gran as recorded by the M-1 instrument. In this case, the spectral peaks are at 24.4 minutes and 5.5 minutes, this second being the resonant period of this smaller cove. In this case, this 5.5 period is near the second super-harmonic of the external forcing wave.
Figure 8c shows the measured spectra in M-2, located in the closed end of the Ciutadella Cove, see figure 3. At this point, the amplification of the resonant period is greater than in instrument M-0, located in the middle of the harbor. Also at this point, the 2ₚ harmonic period of 4.3 minutes is amplified but not in M-1 located in the node of this mode. Finally, figure 8.d shows the spectra outside the Ciutadella Cove, instrument MW3. It can be seen that in the outer platform, only the main forcing period of 24.4 minutes is present and amplified. The straight line shows a $\omega^{-2}$ fit.

![Figure 8](image)

**Figure 8.** Comparison of spectral shape of Rissaga (black line) and non-Rissaga events (grey line), at different points.

In summary, data obtained shows that the forcing for the Ciutadella Cove is a long wave with a period of 24.4 minutes. The Ciutadella Cove and the neighboring
The cove of Platja Gran oscillates with resonant periods that are respectively near the first and 2nd harmonic of the outer wave of 24.4 minutes.

The oscillation of 24.4 minutes is always present in the outer platform between Mallorca and Menorca Islands, suggesting that it is a resonant mode of the shelf between the islands. Also data shows that the amplification of this external forcing is highly correlated with some typical atmospheric perturbations. The maximum amplification occurs when the atmospheric perturbation travels from SW to NE at a speed of about 25 m/s. This speed is approximately the phase speed of a long wave traveling over the platform between the islands. This suggests that the transfer of momentum from the atmosphere to the ocean occurs only when there is a match between those propagation velocities. These two suggestions can be demonstrated using numerical modeling and this is the objective of the next section.

**Figure 9.** Outer and inner numerical regions.
Numerical modeling of the long wave propagation.

The objective of the numerical modeling is to demonstrate that a measured “Rissaga-forcing” atmospheric perturbation, traveling SW to NW over the shelves of Mallorca and Menorca, creates the measured standing wave of 24.4 minutes of period that forces the oscillation of Ciutadella Cove.

To achieve this objective, a finite difference, 3D long wave numerical model has been modified to allow an atmospheric pressure term into the momentum equation. Two different grids have been used, figure 9, first for the shelf propagation and second, for propagation into the Coves of Ciutadella and Platja Gran. The small grid model has been fed with the results obtained with the outer model grid.

The outer numerical model is a classical 3D long wave model which integrates the equations of mass and momentum and diffusion over a finite differences grid:

Mass conservation:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]

Momentum conservation:

\[ \frac{\partial u}{\partial t} + u \cdot \frac{\partial u}{\partial x} + v \cdot \frac{\partial u}{\partial y} + w \cdot \frac{\partial u}{\partial z} = f \cdot v - \frac{1}{\rho_0} \cdot \frac{\partial P_a}{\partial x} - g \cdot \frac{\partial \eta}{\partial x} - \frac{g}{\rho_0} \cdot (\eta - z) \cdot \frac{\partial \rho_o}{\partial x} \]

\[ - \frac{g}{\rho_0} \cdot \frac{\partial }{\partial x} \int_{-z}^{0} \rho' dz + \frac{\partial }{\partial x} \left[ 2 \cdot \epsilon_h \cdot \frac{\partial u}{\partial x} \right] + \frac{\partial }{\partial y} \left[ \epsilon_h \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial }{\partial z} \left[ \epsilon_z \cdot \frac{\partial u}{\partial z} \right] \]

\[ \frac{\partial v}{\partial t} + u \cdot \frac{\partial v}{\partial x} + v \cdot \frac{\partial v}{\partial y} + w \cdot \frac{\partial v}{\partial z} = -f \cdot u - \frac{1}{\rho_0} \cdot \frac{\partial P_a}{\partial y} - g \cdot \frac{\partial \eta}{\partial y} - \frac{g}{\rho_0} \cdot (\eta - z) \cdot \frac{\partial \rho_o}{\partial y} \]

\[ - \frac{g}{\rho_0} \cdot \frac{\partial }{\partial y} \int_{-z}^{0} \rho' dz + \frac{\partial }{\partial x} \left[ \epsilon_h \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \frac{\partial }{\partial y} \left[ 2 \cdot \epsilon_h \cdot \frac{\partial v}{\partial y} \right] + \frac{\partial }{\partial z} \left[ \epsilon_z \cdot \frac{\partial v}{\partial z} \right] \]

Diffusion equations for temperature, T and salinity, S (here both are denoted as C):

\[ \frac{\partial C}{\partial t} + u \cdot \frac{\partial C}{\partial x} + v \cdot \frac{\partial C}{\partial y} + w \cdot \frac{\partial C}{\partial z} = \frac{\partial }{\partial x} \left( \epsilon_h \cdot \frac{\partial C}{\partial x} \right) + \frac{\partial }{\partial y} \left( \epsilon_h \cdot \frac{\partial C}{\partial y} \right) + \frac{\partial }{\partial z} \left( \epsilon_h \cdot \frac{\partial C}{\partial z} \right) \]

where, x, y, z form the right-handed Cartesian coordinate system, u, v and w are the velocity components, \( \eta \) is the free surface, f is the Coriolis term, \( P_a \) is the atmospheric pressure, \( \epsilon_h, \epsilon_z \) are, respectively, the horizontal (Smagorinsky, 1963)
and vertical (Jim and Kronenburg, 1993) eddy viscosity coefficients and $\rho = \rho_0 + \rho'$ is the water density, with $\rho_0$ being the reference viscosity. Density is obtained from the values of T and S using the UNESCO equation of state, as adapted by Mellor (1991). The use of this 3D propagation model allows us to take into account the influence of a thermocline into the propagation velocity of waves.

**Model results.**

The measured atmospheric time series pressure, figure 10, was introduced and propagated into the model at the measured propagation speed, starting at the SW end of the grid. The model was run throughout the duration of the pressure time series of about 12 hours. During this time, a trapped standing wave pattern built up on the shelf between the Mallorca and Menorca Islands, figure 11.

**Figure 10.** Atmospheric pressure time series propagated in the numerical model.

**Figure 11.** Trapped standing wave after 8 hours of model run (real time).
Figure 12. Comparison of the measured and computed spectra of the free surface at three points. a) Outside the Ciutadella cove, b) Measured free surface (pressure), c) Landward end of the Ciutadella cove and d) Landward end of the neighboring cove of Platja Gran.

The spectral characteristics of the numerically-generated long wave are compared with the measured spectra in figure 12. Figure 12a shows the measured
and computed spectral shapes obtained outside the Ciutadella cove, in the outer shelf, in approximately 30 m water depth. The measured bottom pressure oscillation at this point is also shown in figure 12b. It can be seen that outside the cove the oscillation is very weak, peaking at .041 cpm (24 minutes), both in the numerical and in the measured spectra. Other smaller peaks, appearing both in higher and lower frequencies, have poorer match due to the limitations of the grid (for lower frequencies) and the definition of the boundaries.

Figure 8c shows the spectra of the oscillations inside the port, in its upper end, where the oscillations are maximal. In this case, the peak corresponds to the resonant period of the port, 10.5 minutes, excited by the first harmonic of the main 24-minute outer wave. The matching between the measured and the computed spectral density is excellent. Also the second harmonic of about 5 minutes shows an almost perfect match.

Finally, figure 8d, shows the spectra of the oscillations inside the neighboring cove of Platja Gran, in its upper end, where the oscillations are maximal. In this case, the peak corresponds to the resonant period of this smaller cove, 5.1 minutes, excited by the second harmonic of the main 24-minute outer wave. Again, the matching between the measured and computed spectra is very good.

Conclusions

This study demonstrates that the external forcing of the Ciutadella Cove is generated by the coupling between the atmospheric disturbance and the generated long wave, as suggested by Rabinovich and Monserrat (1998). This coupling is only possible when the atmospheric disturbance travels at a speed close to the phase speed of the long waves, controlled by the water depth in the shelf between Mallorca and Menorca Islands. The generated long waves are trapped in the shelf between the islands becoming standing waves with 24 s of fundamental frequency. The Ciutadella Cove whose natural resonant period of 10.5 s is near the first super harmonic of this external wave. Other nearby coves such as that of Platja Gran, with 5.5 minutes of natural period also show high amplifications due to the second super harmonic of the forcing waves.

Acknowledgements.

This work has been funded by the Spanish CYCYT by the project CYTMAR MAR95-1863. Also the help with the computations of the Phd. student Marta Marcos is acknowledged.

References.


