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Continuous gravity and tilt observations in an active geodynamic area of southern Italy: the Calabrian Arc system

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ABSTRACT Calabria (southern Italy) is a site of considerable seismic activity related to the ongoing evolution of the Calabrian Arc system, where a complex lithospheric structure is present. For over a century the Calabrian region has been going through a period of relative seismic quietness, yet its seismic hazard is at the highest levels in the Mediterranean basin due to several catastrophic earthquakes present in the historical records. In order to strengthen the geophysical monitoring of this region, a gravity and tilt recording station was set up in the premises of the University of Calabria. The recorded signals should allow to estimate a tidal anomaly, possibly correlated with the difference between some local feature of the lithosphere or geodynamic activity and the corresponding characteristics of the model used to calculate the reference gravity tide. We report here on the results obtained by the analysis of more than two years of continuous gravity and tilt observations at a site in the northern part of the region. The tidal analysis of the gravity records, covering the time interval May 2011 - September 2013, has provided amplitudes, amplification factors and phases of the main lunar and solar gravity tidal waves. A reliable model of the gravity tide is necessary for accurate processing of discrete absolute and relative gravimetric measurements and to detect in the gravity signals possible components correlated to major seismic activity. The Ocean Tide Load (OTL) effect was accounted for in the determination of the tidal field spectral parameters. The most widespread DDW99/NH Earth's model, adopted here as reference, fits the obtained results well enough. The tidal residual vectors do not highlight any significant anomaly ascribable to the complex structure of the lithosphere beneath the region. The analysis of the tilt records points out a manifest influence of the fluctuations of the air temperature on ground slope, at annual and diurnal periods. The spectral analysis highlights the presence, on both E-W and N-S components, of a significant S_1 solar wave. Values of the thermal admittance, at diurnal period, have been estimated for both tilt components. A weak energy at the frequency of 1.932 cycles/day, at the limit of statistical significance, is also observed, identifiable as the main semidiurnal lunar wave M_2 of the crustal tide. The amplitude and the amplification factors of such a wave are consistent with the values expected by the DDW99/NH model. Beyond everything, the obtained results of the analyses of gravity and tilt records have provided models for the gravity tide and tidal field in the Calabrian region. Moreover, it turns out that the response of the complex lithospheric structure in the Calabrian Arc system to the tidal stress field does not produce any significant anomaly related to the adopted model. Moreover, the absolute measurements of the gravity acceleration, carried out in 1994 and 2013, yielded coinciding values, implying that during the time interval of 20 years not any significant vertical movement and/or mass redistribution in the underground occurred in the area, despite its intense geodynamic activity.

Key words: gravity, tidal model, Calabrian Arc.

1. Introduction

Remarkable mass displacements of different origin and nature are currently active in the geological domain known as Calabrian - Peloritani Arc and in the adjacent Tyrrhenian and Ionian seas (Fig. 1).

Geological, geodetic and archeological evidence exists that the Ionian coasts are interested by intense subsidence phenomena (e.g., Marino *et al.*, 2010; Stanley and Bernasconi, 2012; Minelli *et al.*, 2013). However, over geological time, the whole Calabrian region has been rapidly rising relatively to the sea level. The region can be subdivided into several blocks that move upwards with different mean velocities, estimated in some areas to be up to about 2 mm/y in the last 700,000 years (e.g., Sorriso-Valvo, 1993; Westaway, 1993; Antonioli *et al.*, 2006). GPS observations (D'Agostino *et al.*, 2011 and reference therein) show an E-ward motion of the Calabria with respect to the Nubia plate with a horizontal velocity of about 5 mm/y. Data of the same type confirm the anomalous kinematic behaviour of the eastern coastal belt of the region. In fact, in the framework of a project of cooperation between Calabria University and Lamont Doherty Earth Observatory (D'Agostino *et al.*, 2011), nine GPS continuous recording stations were installed in 2006 along the transect Cetraro - Crotone (CETR - KROT), which crosses the north of Calabria in WNW - ESE direction (Fig. 1). After the first three years of observations, the mean velocity vector of the easternmost GPS station KROT exhibited an eastward horizontal component of about 5 mm/y with respect to the mean calculated over the whole linear array. Minelli *et al.* (2013) attribute this anomalous behaviour, also associated to widespread geological instabilities along the eastern coast of the north of Calabria, to the gravitational gliding of the uppermost crustal layers made easier by the existence of salt intercalation. Finally, as shown by the intermediate and deep local seismicity the subduction under the Tyrrhenian Sea is still active and should be taken into account, whatever its stage of development (e.g., Piana Agostinetti *et al.*, 2009, and reference therein; Monna *et al.*, 2013).

In consideration of the mass movements described above, a gravity and tilt recording station was installed in Cosenza (Fig. 1) in order to contribute to the geophysical monitoring of this seismic region. The gravity and tilt records refers to the period from May 2011 to September 2013 (870 days) and overlap with a recent seismic sequence occurred in the region (Totaro *et al.*, 2013).

The scope of this article is to provide a local model for the gravity tide, to inspect whether tidal anomalies are associated with some characteristic of the lithospheric structure beneath the Calabrian Arc system and to detect signals correlated with the intense, local geodynamic activity.

Fig. 1 - Map of the Calabria region and adjacent geological domains (modified after Orecchio *et al*., 2011). Circles: epicentres of earthquakes with $M_L \geq 3.4$ in the time interval 1986 01 01 - 2014 02 21 and depth ≥ 50 km (after ISIDe Working Group, 2010); radius increases with depth up to the maximum of 644.4 km. Reversed triangles: GPS stations. Squares: cities.

2. Gravity variations with time

The detection and the interpretation of changes in the underground mass distribution, indirectly observable by geodetic and gravity measurements, can contribute to a better comprehension of geodynamical and seismogenic phenomena. Unlike repeated gravity and classic geodetic surveys on networks, which account for the gravity changes and deformations at selected points and at discrete time intervals, continuous recordings make possible the measurement of time variations of the crustal deformation and of the gravity field at a single point. Gravity changes develop on a wide temporal scale, ranging from a few seconds to years, with amplitudes ranging from few hundredths of $\mathrm{nm/s^2}$ up to 10^2 $\mathrm{nm/s^2}$ (Fig. 2). The recorded gravity changes originate from the superposition of the contributions from different sources acting at the same time. Therefore, the separation of the inputs from different sources in the interpretation of these data proves to be a tricky task. Furthermore, apparent gravity changes originate from instrumental causes.

The main source of the non stationary component of the gravity is the tidal field resulting from the gravitational interaction between the Earth and the other bodies of the Solar system. At the Earth's surface the tidal field is modulated by the deformation response of the planet to the tidal stress. The amplitudes of the components of the tidal spectrum are amplified by

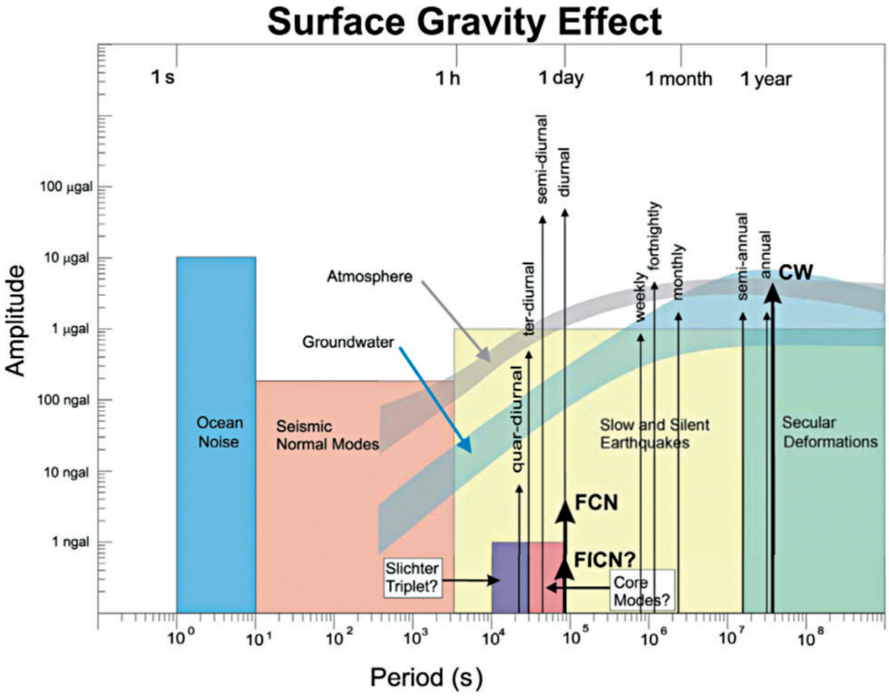

Fig. 2 - Spectrum of gravity contributions (after Crossley and Hinderer, 2008).

a factor δ (>1)[1] and their phases are shifted. Amplification and shifting are functions of the Earth's rheology and of the frequencies of the tidal waves. Several models describing the Earth's deformation response have been proposed (Molodensky, 1961; Wahr, 1981; Dehant, 1987; Zschau and Wang, 1987; Dehant *et al.*, 1999; Metivier and Conrad, 2008; Latychev *et al.*, 2009), the most widely exploited being the DDW99 (Dehant *et al.*, 1999), adopted in the present study. Additional sources of gravity changes are the gravitational and load effects caused by the dynamics of the oceans and atmosphere. The loading periodic effects due to ocean tides [Ocean Tide Load (OTL)] are computed as a function of the ocean tide model (Longman, 1962, 1963; Farrel, 1972). Refined models of the ocean tides, based among others on data from satellite altimetry, have been proposed after the historical one developed by Schwiderski (1980). The OTL contributions to the gravity of the most effective tidal waves are routinely provided by the Onsala Space Observatory (www.oso.chalmers.se/~loading/). An accuracy assessment of different OTL models is given by Baker and Bos (2003) and by Zahram *et al.* (2006). We refer here to the EOT11a model (Savcenko and Bosch, 2012). The model is based on the harmonic analysis of multi-mission altimetry (TOPEX, Jason-1, ERS1, ERS2, ENVISAT, GFO) which implies a 13-year time basis. The ocean tides are represented on a 0.125 degree grid and the contribution of the Mediterranean Sea is accounted for. An OTL effect of about 1-2% of the gravity tide has been estimated for the Italian peninsula, mainly due (~ 70%) to the tides of

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[1] According to the recommendations of the Working Group on Theoretical Tidal Model (SSG of the Earth Tide Commission, Sec. V, of the IAG), the δ factor is defined as Earth's transfer function between the body tide observed at a station and the amplitude of the vertical component of the gradient of the tidal potential (Dehant, 1991).

the north Atlantic Ocean (Chiaruttini, 1976). For the time being, the most recent OTL models provide comparable results in the Calabrian region.

The availability of a reliable model of the gravity tide, resulting from the combined effects of the tidal field and OTL, is the main requirement to extract signals from the gravity records which can be associated to other geodynamic sources. The knowledge of the gravity tide is also useful for an accurate processing of discrete absolute and relative measurements. Moreover, the measurement of the tidal field permits to assess the adequacy of the adopted model of the Earth's response to the regional structure of the lithosphere. Besides solid Earth and ocean tides, changes of the atmospheric pressure also contribute to the gravity changes. Such an effect, if not accounted for, prevents the accurate detection of small amplitude gravity signals (e.g., Hinderer and Crossley, 2004). Gravity is statistically correlated in inverse relation with the local atmospheric pressure variations. A global average baric admittance of -3.3 $nm/s^2/hPa$ was estimated (e.g., Warburton and Goodkind, 1977; Merriam, 1992). This value accounts for about 90% of the total atmospheric effect. However, a realistic description of the dependence of gravity on the distribution of pressure and temperature of the atmosphere is very complex. This issue has been addressed by several authors (e.g., Richter *et al.*, 1995; Kroner and Jentzsch, 1998; Neumeyer *et al.*, 1998; Van Dam and Francis, 1998; Crossley *et al.*, 2002; Riccardi *et al.*, 2007). A survey of the main results is reported by Albano and Corrado (2013). The time variations of the Length Of Day (LOD) and of the Earth's rotation axis [Polar Motion (PM)] also contribute to gravity change. Their contributions are computable on the basis of LOD and PM data provided by the International Earth Rotation Service (IERS) and must be taken into account for a right estimate of the instrumental drift and long period components of the tidal field. An exhaustive review describing the basic theory and techniques for the use of gravimetry at the Earth's surface is presented by Crossley *et al.* (2013).

The Earth's surface undergoes a wide range of thermal variations both in space and time. The diurnal rotation and the orbital motion of the Earth are sources of fluctuations of the temperature at the surface with main daily and annual periods. Moreover, random fluctuations are superimposed to these fundamental frequencies. Owing to the travel of thermal waves through the surface rocks, such changes of temperature will induce stresses, strains and tilts that can mask other geophysical effects.

3. Data acquisition and analysis

The gravity station at Cosenza (Φ = 39.359005° N; λ = 16.226858° E; h = 221 m asl; $g = 9.8010671 \pm 10^{-7}$ m/s^2) is situated in a basement room, at the Department of Physics of the University, Campus of Arcavacata di Rende, near Cosenza (Fig. 1). The local value of the gravity was measured in 1994 by the Istituto di Metrologia "Gustavo Colonnetti" of the Italian National Research Council (Cerutti and De Maria, 1994). The absolute station has been reoccupied in October 2013 by the Istituto Nazionale di Ricerca Metrologica; the value of $g = 9.80106699 \pm 9 \cdot 10^{-8}$ m/s^2 results (Biolcati *et al.*, 2013), consistent, within the error limit, with the value measured in 1994. The gravity sensor is a LaCoste & Romberg, mod. G gravimeter, equipped with Maximum Voltage Retroaction (MVR) feed-back (Van Ruymbeke, 1991) and with electronic levels to monitor the vertical positioning of the instrument. The gravimeter is installed on top of a concrete pillar, isolated from the floor, and is enclosed in a box of expanded polystyrene as a further environmental protection. A dual-axis bubble-type resistive tiltmeter [Applied Geomechanics Inc. (AGI), mod.712 - Scale factor: 0.05 μrad/mV, i.e., 10.3 mas/mV], equipped with a thermometric sensor (0.1 °C/mV) and a barometer (0.1 hPa/mV), are installed close to gravimeter on the same pillar, to supplement the gravity station. The AGI, mod. 712, tiltmeter hosts two bubble levels, temperature sensor and their electronics in a hermetically sealed stainless steel casing. The scale factor of the tiltmeter supplied by the manufacturer is pertinent to the temperature of 24° C. As indicated by the manufacturer, two corrective terms for different operating temperatures must be accounted for (Applied Geomechanis Incorporated, 1995). Data are sampled and logged at the frequency of 0.2 Hz under the control of a clock periodically synchronized, via Internet, to an atomic clock. Changes in time of the calibration factor of the gravimeter can occur as a consequence of perturbations of different origin (e.g., Bonvalot *et al.*, 1998; Riccardi *et al.*, 2002). Such changes, imputable to artificial or natural events (e.g., power interruptions or seismic events), alter both the amplitude and the phase of the long term components of the gravity signals and the results of the tidal analyses. The complete understanding of the physical processes responsible for the changes in sensitivity is still far from being achieved. In order to monitor the metre calibration factor, several calibration sessions have been carried out from time to time at different sites of Italy (Medicina, Napoli and Arcavacata) following the procedures described by Riccardi *et al.* (2002). As an example, the results of calibrations carried out at Medicina station, nearby Bologna, are shown in Fig. 3.

Two sessions of on-site calibration measurements have been carried out at the station of Cosenza (Fig. 4). The results are consistent, within the error limits, with the average value of the global set of calibrations carried out at the station of Napoli, and with that obtained at the station of Medicina, both also represented in Fig. 4. The global set of 20 calibration sessions has provided randomly scattered results without any significant trend versus time. In fact the slope of the regression line turns out to be -0.01 ± 0.03 (r = - 0.08).

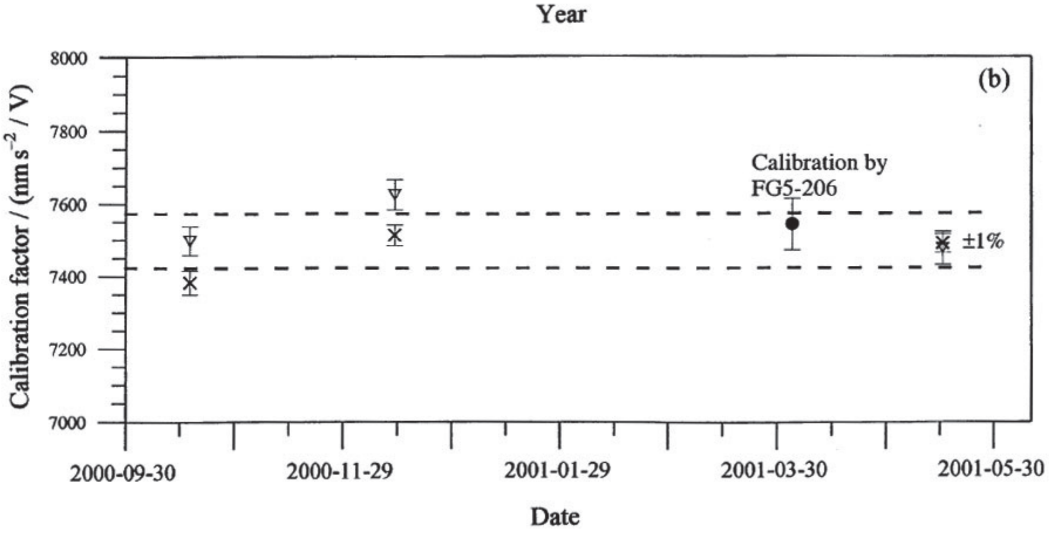

Fig. 3 - Calibration factors obtained at Medicina station (after Riccardi *et al.*, 2002).

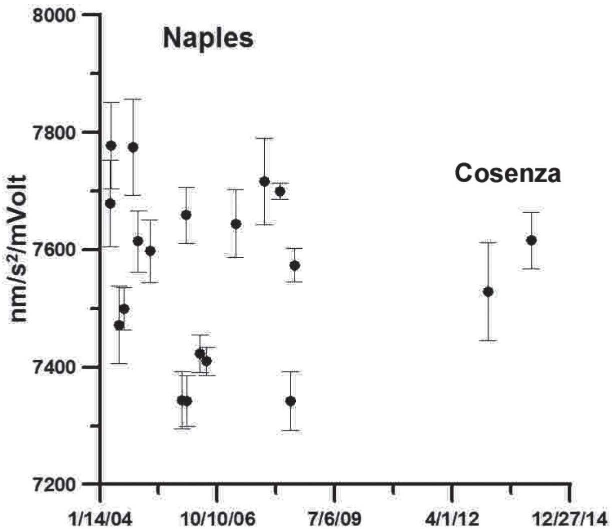

Fig. 4 - Calibration factors measured at the stations of Napoli and Cosenza.

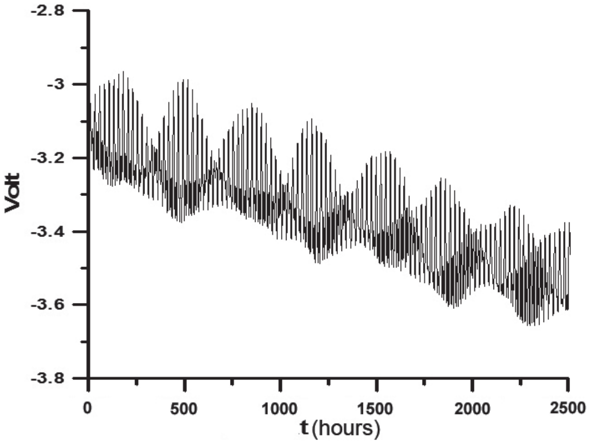

Fig. 5 - Sample of gravity record.

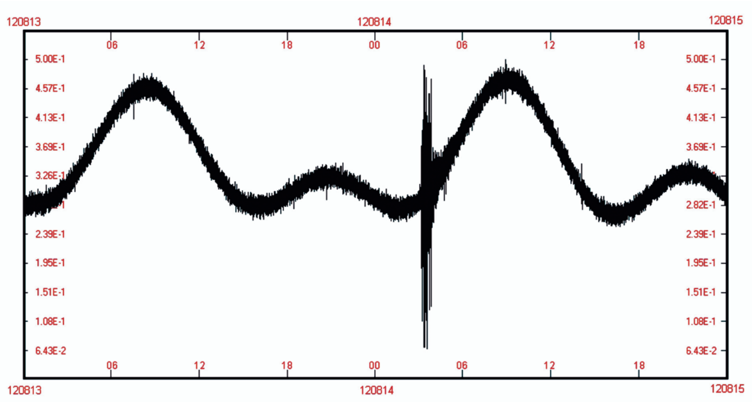

Fig. 6 - Okhotsk Sea earthquake on August 14, 2012 ($M_W = 7.7$) recorded at the Cosenza gravimeter.

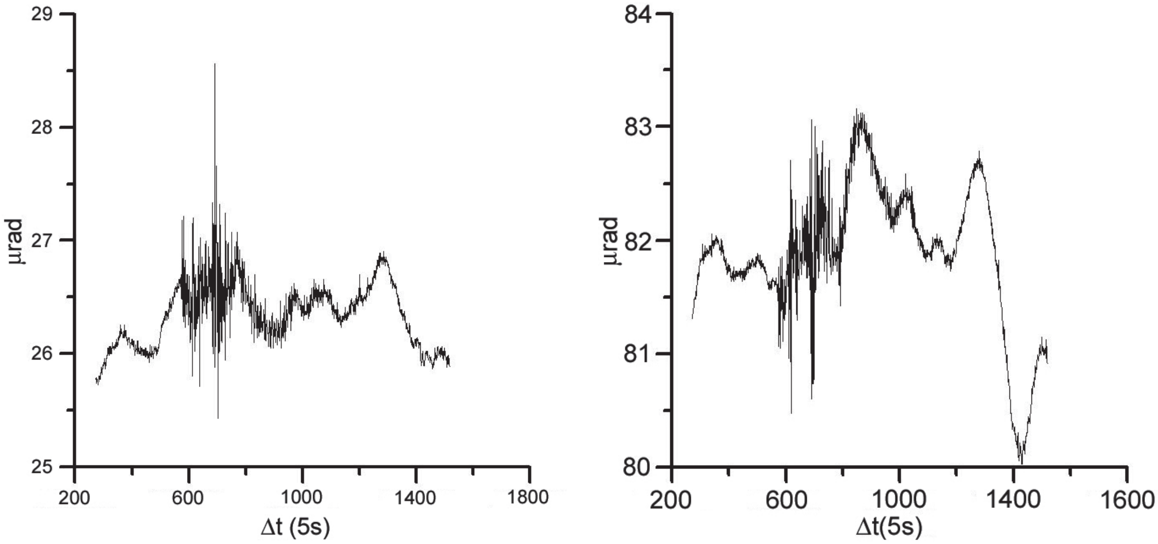

Fig. 7 - N-S and E-W components of Okhotsk Sea earthquake on August 14, 2012 ($M_W = 7.7$) recorded at the Cosenza tiltmeter.

A software developed at the Observatoire Royal de Belgique (Van Camp and Vauterin, 2005) has been employed for the pre-processing (i.e., destepping, despiking, degapping) of the records and for further analyses. A sample of the gravity record is shown in Fig. 5.

Many seismic events of variable magnitude and source coordinates have been recorded, most of them by the tiltmeters too. A particular of the gravity record shows the Okhotsk Sea earthquake ($M_W = 7.7$, depth 600 km) occurred on August 14, 2012 (Fig. 6). The same event has been recorded on both the components of the tilt (Fig. 7).

Such strong earthquakes, and those originating in the Mediterranean area, can contribute to the noise affecting the gravity and tilt records.

3.1. Analysis of gravity records

Apparent gravity changes originate from the tilt $\theta(t)$ of the vertical axis of the gravimeter, caused by small ground deformations, monitored by the tiltmeter sensors. Therefore, a correction $\delta g(\text{nm/s}^2) = g[1-\cos\theta] \sim 5\cdot10^{-3}\ \theta^2(\mu\text{rad})$ has been applied to the recorded data, based on the values of $\theta(t)$ provided by the tiltmeter. The original data, sampled at 5 s, have been decimated to 1 hour after the application of a low-pass filter (cut off frequency: 12 cycles/day) to avoid aliasing effects. The ETERNA software [ver. 3.3; Wenzel (1996b)] was used to compute amplitudes, phases and amplification factors δ of the spectral components of the gravity tide. The HW95 (Hartmann and Wenzel, 1995), the most recent and widespread catalogue among several others describing the tidal field (Wenzel, 1996a), was adopted to process the gravity record by ETERNA. It consists of 12,935 tidal waves, containing 19,300 adjusted coefficients computed using the JPL DE200 numerical ephemeris of the Solar system bodies. An error (rms) of 0.0015 nm/s^2 on the tidal field was estimated at intermediate latitudes. The obtained values of amplitude, amplification factor δ and phase shift of the main tidal waves are given in Table 1.

Table 1 - Parameters of the main tidal waves at Cosenza station.

Wave	Frequency (cpd)	Amplitude (nm/s^2)	δ ± err	Phase ± err (°)	Origin
O_1	0.926195	356.0 ± 0.6	1.1690 ± 0.0020	0.10 ± 0.10	Lunar declinational diurnal
P_1	0.993539	163.7 ± 0.6	1.1550 ± 0.0040	0.50 ± 0.20	Principal solar diurnal
K_1	1.007757	491.1 ± 0.4	1.1470 ± 0.0010	0.50 ± 0.10	Lunisolar declinational diurnal
N_2	1.892568	102.4 ± 0.4	1.1910 ± 0.0050	1.30 ± 0.20	Lunar elliptic semidiurnal
M_2	1.933260	536.9 ± 0.3	1.1952 ± 0.0008	0.97 ± 0.04	Principal lunar semidiurnal
S_2	2.000236	250.7 ± 0.4	1.2000 ± 0.0020	0.30 ± 0.10	Principal solar semidiurnal

The noise values estimated by ETERNA are 0.9 nm/s^2 in the diurnal band and 0.6 nm/s^2 in the semi-diurnal band. An assessment of the estimation of the noise in the tidal analysis is given by Ducarme *et al.* (2006). In the time window covered by the observations the atmospheric pressure has shown minimum and maximum values of 959.3 and 1005.3 hPa respectively. The atmospheric tide also contributes to the gravity tidal spectrum. The spectral analysis of the atmospheric pressure, carried out in the diurnal frequency band, following the method proposed by Chapman and Miller (Malin and Chapman, 1970), has provided amplitudes and phases of the luni-solar atmospheric tide at the Cosenza station (Table 2).

Table 2 - Solar and lunar daily variations of the atmospheric pressure at the Cosenza station.

SOLAR TERMS			LUNAR TERMS	
n	Amplitude (hPa)	Phase (°)	Amplitude (hPa)	Phase (°)
1	0.38 ± 0.02	55.6	0.020 ± 0.030	217.6
2	0.46 ± 0.01	186.6	0.030 ± 0.070	85.8
3	0.05 ± 0.05	67.4	0.010 ± 0.010	207.5
4	0.02 ± 0.05	307.5	0.003 ± 0.005	259.4

A baric admittance of (-2.9 ± 0.2) nm/s^2/hPa has been estimated by ETERNA, based on a weak correlation (r = -0.5) between the air pressure and the S_2 tidal component. This value is close to the value of the global average baric admittance (-3.3 nm/s^2/hPa) estimated by Merriam (1992). Therefore, the contributions to the gravity tide of the main S_1 and S_2 solar terms of the atmospheric tide result of 1.1 and 1.3 nm/s^2 respectively. A contribution of about 133 nm/s^2 to the gravity changes results from the maximum air pressure difference observed in the time interval analysed. The whole of the tidal spectral components obtained by the analysis represents, for the time being, a synthetic model of the gravity tide in the Calabrian area. In order to obtain the parameters of the tidal field, the contribution of the OTL to the gravity tide must be taken into account. Several models provided by the Onsala Space Observatory have been considered here. It emerges that, at the station of Cosenza, the different contribution of the examined OTL models falls within the error limits of the results. Thus to compute the OTL effect, the recent EOT11a model (Savcenko and Bosch, 2012) has been chosen. The tidal analysis, carried out after the OTL effect was removed from the gravity records, yielded the "corrected" tidal parameters (A_c, δ_c, α_c) shown in Table 3, restricted to the only waves significantly influenced by the OTL.

Table 3 - Corrected tidal parameters and expected amplification factor of the main components of the tidal field at Cosenza station.

Wave	Amplitude A_c (nm/s^2)	δ_c	Phase α_c (°)	δ (DDW99/NH)
O_1	357.4 ± 0.6	1.1730 ± 0.0020	0.100 ± 0.10	1.15424
P_1	163.6 ± 0.6	1.1550 ± 0.0040	0.400 ± 0.20	1.14915
K_1	490.6 ± 0.4	1.1460 ± 0.0010	0.300 ± 0.10	1.13489
N_2	100.7 ± 0.4	1.1710 ± 0.0050	-0.300 ± 0.20	1.16172
M_2	530.6 ± 0.4	1.1813 ± 0.0009	0.220 ± 0.04	1.16172
S_2	247.6 ± 0.4	1.1850 ± 0.0020	-0.100 ± 0.10	1.16172

To describe the Earth's response to the tidal field two models have been proposed by Dehant *et al.* (1999): the elastic/hydrostatic model (DDW99/H) and the inelastic/non hydrostatic model (DDW99/NH). As the estimated relative error of the calibration is of the order of 10^{-3} it does not allow us to distinguish between the DDW99 elastic and inelastic models whose gravimetric factors differ of 0.0014. Taking into account the geodynamic features of the southern Tyrrhenian basin, the DDW99/NH non-hydrostatic version of the model has been adopted as reference. In Table 3 the values of the amplification factor expected from the chosen model are also given. The ratio δ_{M2}/δ_{O1} between the observed amplification factors pertinent to the main M_2 and O_1 waves results 1.007 ± 0.002, consistent with the value 1.006 expected by the model. The slope of the regression line correlating the theoretic tide predicted by the DDW99/NH model, and the corresponding one obtained through the computed tidal parameters, results 1.0143 ± 0.0002 ($r = 0.99$) with a standard deviation $\sigma = \pm 11$ nm/s^2. The deviation X between the observed amplitudes and phases of tidal waves and the corresponding values expected by using the model can be attributed to lateral lithospheric heterogeneities and/or incomplete removal of the OTL effect. We have computed the corrected tidal residual vectors $\mathbf{X}(X, \chi) = \mathbf{B}(B,\beta) - \mathbf{L}(L, \lambda)$ of the main tidal waves. For each wave, $\mathbf{R}(R, 0)$ represents the Earth model tidal vector, $\mathbf{L}(L, \lambda)$ represents the indirect effect (OTL) computed for a given ocean tide model and $\mathbf{B}(B,\beta) = \mathbf{Ac}(Ac,\alpha c) - \mathbf{R}(R, 0)$ represents the vector difference between observed and Earth model spectral component (Melchior and Francis, 1986). **B** is dependent on the contribution of the OTL (Jentzsch, 1997). The Xcos χ component of the corrected residual vector **X**, which is in phase with the body tide, would be sensitive to the anomalous regional Earth's response to the tidal stress (lateral heterogeneity), although calibration errors could also affect this component (Baker and Bos, 2003). The Xsin χ component reflects instrumental noise and/or effects not considered in the model. It is significant when higher than 2 nm/s^2 (Melchior, 1995). Some parameters of the tidal residuals and corrected residual vectors are given in Table 4. As the angle between the **B** and **X** vectors are small (~ 20°) the uncertainty on X is practically the same as on B.

Table 4 - Residual vectors for the main tidal waves at Cosenza.

Wave	B (nm/s^2)	X (nm/s^2)	Xcos χ (nm/s^2)	Xsin χ (nm/s^2)
M_2	17.5 ± 0.3	8.7 ± 0.3	0.4 ± 0.01	8.7 ± 0.30
S_2	8.1 ± 0.4	4.8 ± 0.4	-1.9 ± 0.20	4.4 ± 0.30
K_1	6.4 ± 0.6	5.5 ± 0.6	3.1 ± 0.30	4.5 ± 0.50
O_1	4.5 ± 0.6	5.7 ± 0.6	5.6 ± 0.60	-0.2 ± 0.02
N_2	3.4 ± 0.4	1.6 ± 0.4	0.6 ± 0.20	1.4 ± 0.30
K_2	1.8 ± 0.4	0.9 ± 0.4	0.0 ± 0.03	0.9 ± 0.40

The long term trend of the measured gravity has been obtained by removing from the recorded signal the gravity tide and the contributions from atmospheric pressure, LOD variations and PM. A least square polynomial interpolation has been employed to model the observed trend. An average rate of (54.5 ± 0.02) nm/s^2/day is observed. Residuals, distributed as shown in Fig. 8 (left), arise from this analysis. The spectral content of the residuals is also plotted in the Fig. 8 (right); a weak residual energy still results in the diurnal and semidiurnal frequency bands.

The random component of the residuals could be imputable to several sources of noise (e.g., earthquakes, microseismic activity, storms); the weak residual energy in the diurnal and semidiurnal frequency bands could rise mainly from a not complete removal of the OTL contribution at the station.

3.2. Analysis of tilt records

As in the gravity records processing, environmental temperature and tilt data, sampled each 5 s, were decimated to 1 hour after the application of a low-pass filter (cut off frequency:

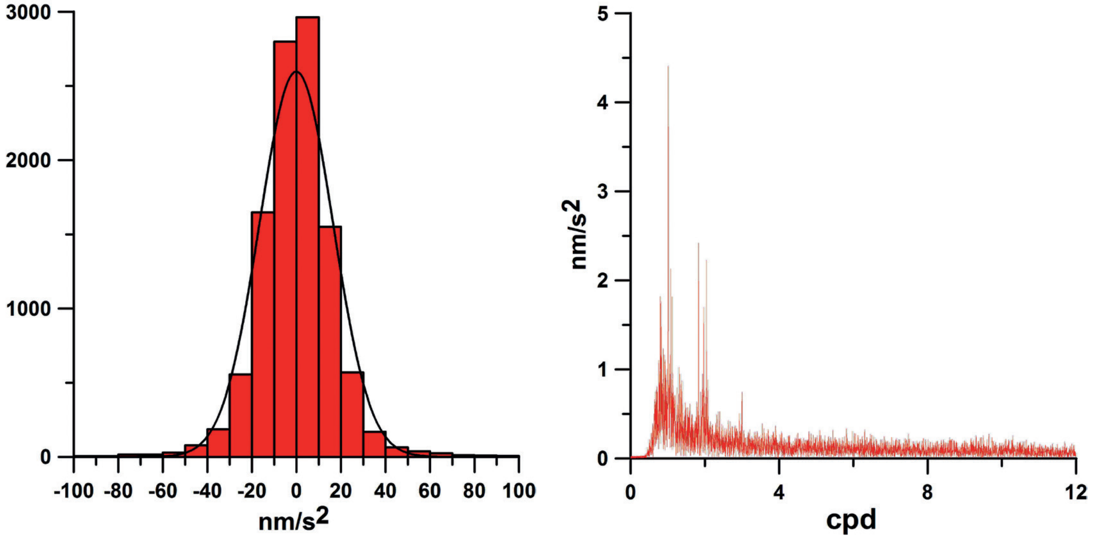

Fig. 8 - Frequency distribution (left) and spectrum (right) of the gravity residuals.

12 cycles/day) to avoid aliasing effects. The recorded temperature values are reported in Fig. 9, having an average value of 20.3 °C. The average trend, obtained through a least-square polynomial fitting, evidences a seasonal behaviour, having average range 12.6 °C. A diurnal solar wave S_1, having amplitude 0.24 ± 0.05 °C, results from the analysis of the temperature data carried out following the algorithm proposed by Chapman and Miller (Malin and Chapman, 1970). Random fluctuations, of average amplitude 1.3 °C, are superimposed on the seasonal trend.

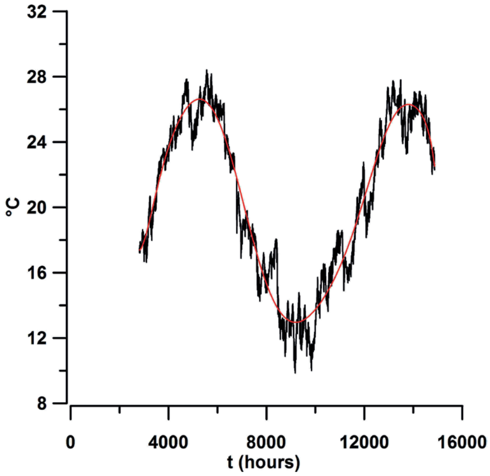

Fig. 9 - Hourly values of the temperature (first value: April 28, 2011, 08:00:00 GMT) with average trend.

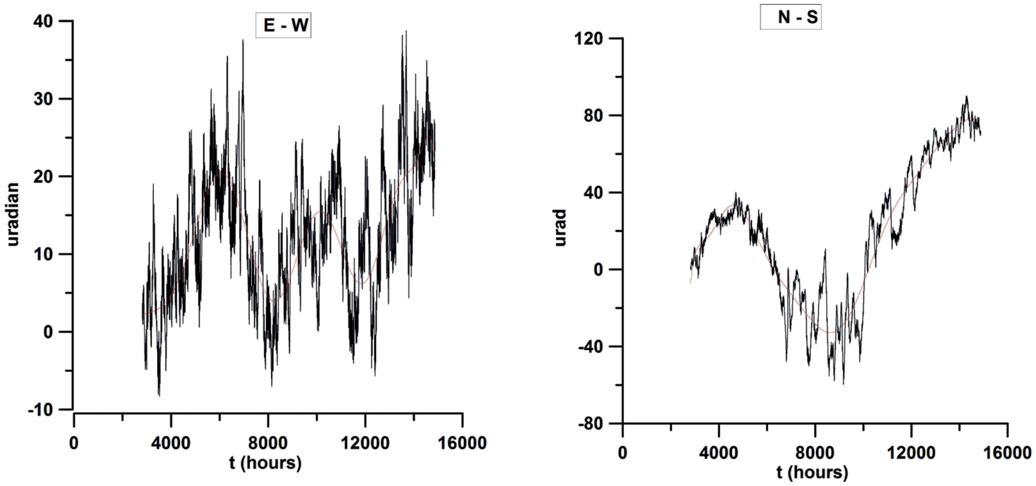

Fig. 10 - N-S and E-W components (start April 28, 2011, 08:00:00 GMT) of the ground tilt versus time, with average trends.

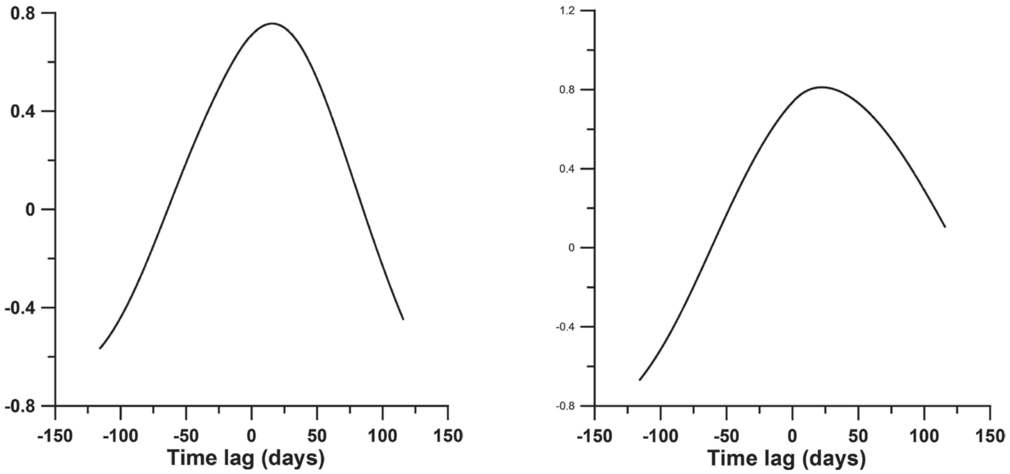

Fig. 11 - Seasonal cross correlation functions T - NS and T - EW.

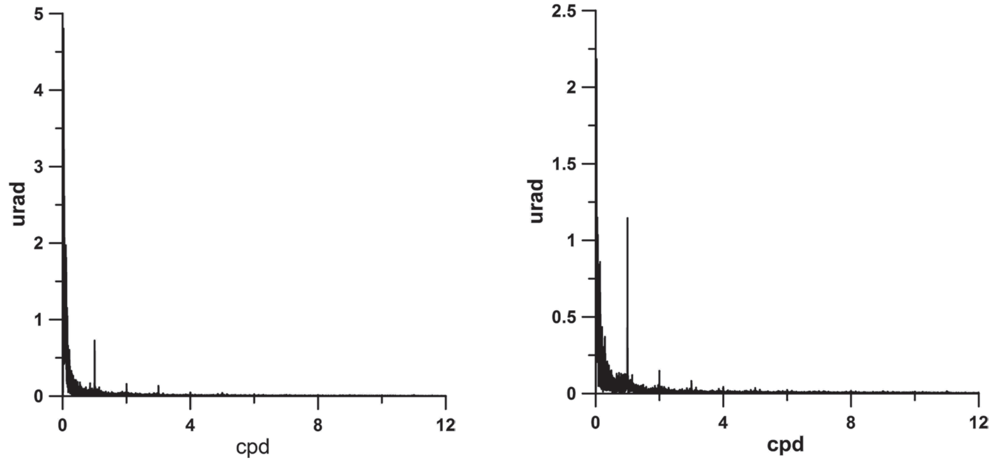

Fig. 12 - Spectral content of the detrended N-S (left) and E-W (right) components of the tilt signal.

In Fig. 10 the recorded values of the N-S and E-W components of the ground tilt are represented. Both components of the ground tilt show a clear seasonal trend, which appears to be correlated with that of the air temperature.

The seasonal trends of T and N-S tilt show a correlation value of 0.8 (Fig. 11 left). A phase shift of nearly 20 days is observed between the thermal and N-S tilt trends. A fair correlation ($r = 0.7$) also exists between the seasonal T and E-W trends (Fig. 11 right), showing almost the same phase shift as that observed between T and N-S.

As a traveling wave of temperature through the Earth's surface rocks causes strains, the observed correlation is imputable to a thermoelastic effect (Berger, 1975). The spectral contents of the detrended N-S and E-W signals are shown in the Fig. 12. A significant amount of energy is observable in the band of diurnal frequencies. A weak energy is also present in the band of the semi-diurnal frequencies.

The spectral analysis, via ETERNA, carried out in the band of the tidal frequencies, evidences the presence in both E-W and N-S components of a significant S_1 solar wave of amplitudes of about 1 μrad (E-W) and of 1.5 μrad (N-S). Thermal admittances of 5.28 ± 0.03 (E-W) and 1.94 ± 0.05 (N-S) μrad/°C result from ETERNA analysis. These values are pertinent to the diurnal S_1 solar wave. The spectra of both the E-W and N-S components of the ground tilt also contain a weak energy at the frequency of 1.932 cycles/day corresponding to the frequency of the main semidiurnal lunar tidal wave M_2 of the crustal tide. The resulting amplitudes and the amplification factors δ pertinent to the M_2 wave of both tilt components, are reported in Table 5,

Table 5 - Amplitude and amplification factor of the M_2 wave of both tilt components.

	ampl. (mas)	δ
E - W	9 ± 2 [8.4]	0.7 [0.69]
N - S	5 ± 2 [5.4]	0.7 [0.69]

where in brackets the values predicted by the DDW99/NH model are reported. The OTL contribution at the station can be neglected resulting of the order of magnitude of 10^{-3} μrad for the main tidal waves.

4. Discussion and conclusion

The tidal analysis of the gravity records over more than 2 years (April 2011 - September 2013) yielded amplitudes and phases of the main waves of the gravity tide in the Calabrian region. The gravity contribution at the Cosenza station of the OTL has been removed from the recorded gravity changes to compute amplitudes, amplification factors δ and phase shifts of the main waves of the tidal field. Moreover, the value of the baric admittance has been estimated, resulting in fair agreement with the global average value reported in literature. The values obtained for the gravimetric factor δ are in good agreement (~ 1.5 %) with the theoretical ones. The predicted values from DDW99/NH model fairly well fit the tidal field in the region. The tidal residual vectors have been also computed. The meaning of such residuals is debated. In the past some authors (e.g., Melchior and Francis, 1986; Yanshin *et al.*, 1986; Robinson, 1989, 1991, 1993; Melchior and Ducarme, 1991) have suggested the existence of correlation between local deviations of some lithospheric parameter from the model assumed as reference, here the DDW99/NH model, and the inphase component of the $\mathbf{X}$ corrected residuals (mainly of M_2). Statistical analyses carried out by Shukowsky and Mantovani (1999) have shown a significant correlation between the tidal residuals of the M_2 wave and the effective elastic thickness of the lithosphere. Objections to these hypotheses originate from the results obtained by other researchers (e.g., Rydelek *et al.*,1991; Fernandez *et al.*, 1992, 2008; Arnoso *et al.*, 2001) leading to the conclusion that the corrected residual vectors $\mathbf{X}$ chiefly depends on the instrumental noise and the inadequacy of the adopted OTL models. We report here beforehand, in comparison, the values of the tidal residual vectors resulting from the analysis of 5 years of gravity records obtained at the station of Napoli (Campania region, southern Italy, Fig. 1). Campania, located on the eastern margin of the middle-southern Tyrrhenian basin of the Mediterranean Sea, is a site characterized by intense explosive volcanism and seismic activity. The results shown in Table 6 indicate that both components of **X** vectors are basically negligible at that station; this indicates that no significant tidal anomaly is affecting that area despite the presence of active volcanoes and seismic sources (Albano and Corrado, 2013).

Table 6 - Residual vectors for the main tidal waves at Naples (after Albano and Corrado, 2013).

Wave	B	X	X cos χ	X sin χ
	(nm/s^2)	(nm/s^2)	(nm/s^2)	(nm/s^2)
M_2	8.7 ± 0.2	1.3	-1.3	0.0
S_2	3.1 ± 0.2	3.8	-3.3	-1.9
K_1	0.8 ± 0.4	2.2	-1.9	1.2
O_1	2.8 ± 0.3	1.8	0.2	1.8
P_1	1.0 ± 0.5	0.6	-0.2	0.5

A different situation is observed in the Calabrian Arc, a major tectonic structure of southern Italy, characterized by a significant heterogeneity of the lithosphere. We focus here our attention on the main tidal waves M_2 and O_1 (Table 4). The residual Xcos χ component of the M_2 wave turns out negligible while, on the contrary, the Xsin χ is not negligible. This result would exclude any correlation with lateral heterogeneity of the lithosphere beneath the Calabrian region and is probably imputable to inadequacy of the OTL model. The opposite can be observed in the O_1 residual which has a significant Xcos χ component and a negligible Xsin χ component, although the magnitudes of the effects of lateral heterogeneities should be similar for both O_1 and M_2 tidal waves (Baker and Bos, 2003). The afore mentioned results are consistent with the conclusion of the researchers who promote the idea that the uncertainties of the tidal observations mask some possible relationships between lateral heterogeneities of the lithosphere and their very small effects on the tidal field (e.g., Fernandez *et al.*, 2008). Therefore, for the time being, the empirical correlations found by other authors, although statistically significant, do not allow a reliable geological interpretation.

Seasonal trends are observable in both component of the ground tilt well correlated with the air temperature. The observed correlation is mainly attributable to the effect of the stress/strain resulting from the propagation of thermal waves through the ground, even though additional seasonal effects from different sources (e.g., rainfall) cannot be neglected. The spectral contents of the detrended N-S and E-W tiltmeter signals exhibit a significant amount of energy in the band of diurnal frequencies. A weak energy is also present in the band of the semi-diurnal frequencies. The spectral analysis marks the presence of a significant S_1 solar wave in both E-W and N-S components. The spectra of the E-W and N-S components also contain a weak energy at the frequency of 1.932 cycles/day of the M_2 tidal wave. A similar result (Albano, 2009) has been observed in the tilt signals recorded in the Neapolitan area (southern Italy). The amplitude and the amplification factors of such tidal component, though at the limit of the statistical significance, are consistent with the values expected by the DDW99/NH model. Such a result seems to confirm the validity of the adopted model to describe the crustal tide in the region despite the local complex structure of the lithosphere. In the end, the obtained results of the analyses of gravity and tilt records have provided, for the first time, models of the gravity tide and tidal field in the Calabrian region.

The availability of models of the gravity tide is fundamental for accurate processing of discrete absolute and relative gravimetric measurements and to detect in the gravity signals components associated to major seismic and aseismic slip strain episodes.

It turns out that the response of the complex lithospheric structure of the Calabrian Arc system to the tidal field does not evince any significant anomaly related to the adopted model. Moreover, the absolute measurements of the gravity acceleration, carried out in 1994 and 2013, yielded coinciding values, implying that during the time interval of 20 years not any significant vertical movement and/or mass redistribution in the underground occurred in the area despite its intense geodynamic activity.

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REFERENCES

Albano A.; 2009: *Individuazione, analisi e interpretazione di segnali tiltmetrici e gravimetrici indotti da processi geodinamici*. Doctorate Thesis, University ‘Federico II’, Napoli, Italy, 91 pp.

Albano A. and Corrado G.; 2013: *Five years of continuous gravity observations in the Neapolitan Volcanic area*. Boll. Geof. Teor. Appl., **54**, 1-21.

Antonioli A., Ferranti L., Lambeck K., Kershaw S., Verrubbi V. and Dai Pra G.; 2006: *Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and northeastern Sicily (southern Italy, central Mediterranean Sea)*. Tectonophys., **422**, 23-40.

Applied Geomechanis Incorporated; 1995: *Tiltmeter temperature coefficients: source, definition and use to improve accuracy*. Report n. B-95-1005, Rev. C., San Francisco, CA, USA, 18 pp.

Arnoso J., Fernandez J. and Vieira R.; 2001: *Interpretation of tidal gravity anomalies in Lanzarote, Canary Islands*. J. Geodyn., **31**, 341-354.

Baker T.F. and Bos M.S.; 2003: *Validating Earth and ocean models using tidal gravity measurements*. Geophys. J. Int., **152**, 468-485.

Berger J.; 1975: *A note on Thermoelastic Strains and Tilts*. J. Geophys. Res., **80**, 274-277.

Biolcati E., Origlia O., Germak A., Mazzoleni F. and Vitiello F.; 2013: *Absolute measurements of the free-fall acceleration in Arcavacata (CS), Italy*. Ist. Naz. Ric. Metrologica, INRiM, Torino, Italy, Technical Report RT-29/2013, 20 pp.

Bonvalot S., Diament M. and Gabalda G.; 1998: *Continuous gravity recording with Scintrex CG-3M meters: a promising tool for monitoring active zones*. Geophys. J. Int., **135**, 470-498.

Cerutti G. and De Maria P.; 1994: *Misure assolute dell’accelerazione di gravità a Cosenza, Ischia, Ercolano*. Ist. Metrologico G. Colonnetti, IMGC-CNR, Torino, Italy, Rapporto Tecnico Interno, R385, 12 pp.

Chiaruttini C.; 1976: *Tidal loading on the Italian Peninsula*. Geophys. J. R. Astron. Soc., **46**, 773-793.

Crossley D.J. and Hinderer J.; 2008: *The contribution of GGP superconducting gravimeters to GGOS*. IAG Symposia, Observing our Changing Earth, **133**, 841-852.

Crossley D.J., Hinderer J. and Rosat S.; 2002: *Using atmosphere-gravity correlation to derive a time-dependent admittance*. Bull. Inf. Marées Terrestres, **136**, 10809-10820.

Crossley D.J., Hinderer J. and Riccardi U.; 2013: *The measurement of surface gravity*. Rep. Prog. Phys., **76**, 046101, doi:10.1088/0034-4885/76/4/046101.

D’Agostino N., D’Anastasio E., Gervasi A., Guerra I., Nedimovic M.R., Seeber L. and Steckler M.; 2011: *Forearc extension and slow rollback of the Calabrian Arc from GPS measurements*. Geophys. Res. Lett., **38**, L17304, doi:10.1029/2011GL048270.

Dehant V.; 1987: *Tidal parameters for an inelastic Earth*. Phys. Earth Planet. Int., **49**, 97-116.

Dehant V.; 1991: *Report of the Working Group on Theoretical Tidal Model*. In: Kakkuri J. (ed), Proc. 11th Int. Symp. Earth Tides, Helsinki, Finland, Schweitzerbartsche Verlagsbuchhandlung, Stuttgart, Germany, pp. 533-548.

Dehant V., Defraigne P. and Wahr J.M.; 1999: *Tides for a convective Earth*. J. Geophys. Res., **104**, B1.

Ducarme B., Vandercoilden L. and Venedikov A.P.; 2006: *Estimation of the precision by the tidal analysis programs ETERNA and VAV*. Bull. Inf. Marées Terrestres, **141**, 11189-11200.

Farrel W.E.; 1972: *Deformation of the Earth by surface load*. Rev. Geophys. Space Phys., **10**, 761- 797.

Fernandez J., Vieira R., Diez J.L. and Toro C.; 1992*: Investigation on crustal thickness, heat flow and gravity tide relationship in Lanzarote Island*. Phys. Earth Planet. Int., **74**, 199-208.

Fernandez J., Fernandez M., Miguelsanz L. and Camacho A.; 2008: *On the interpretation of gravity tide residuals in the Iberian Peninsula*. J. Geodyn., **45**, 18-31.

Hartmann T. and Wenzel H.G.; 1995: *The HW95 Tidal Potential Catalogue*. Geophys. Res. Lett., **22**, 3353-3556.

Hinderer J. and Crossley D.; 2004: *Scientific achievements from the first phase (1997-2003) of the Global Geodynamics Project using a worldwide network of superconducting gravimeters*. J. Geodyn., **38**, 237-262.

ISIDe Working Group; 2010: *Italian seismological instrumental and parametric database*. INGV, Roma, Italy,

Jentzsch G.; 1997: *Earth tides and ocean tidal loading*. In: Wilhelm H., Zurn W. and Wenzel H.G. (eds), Tidal Phenomena, Lecture Notes Earth Sci., **66,** pp. 145-171.

Kroner C. and Jentzsch G.; 1998: *Comparison of air pressure reducing methods and discussion of other influences on gravity*. In: Proc. 13th Earth Tide Symp., Royal Observatory of Belgium, Brussels, Belgium, pp. 423-430.

Latychev K., Mitrovica J.X., Ishii Chan N.H. and Davis J.L.; 2009: *Body tides on a 3-D elastic earth: toward a tidal tomography*. Earth Planet. Sci. Lett., **277**, 86-90.

Longman I.M.; 1962: *Green's functions for determining the deformation of the Earth under surface mass loads: 1. Theory*. J. Geophys. Res., **67**, 845-850.

Longman I.M.; 1963: *Green's functions for determining the deformation of the Earth under surface mass loads: 2. Computation and numerical results*. J. Geophys. Res., **68**, 485-496.

Malin S.R.C. and Chapman S.; 1970: *The Determination of lunar daily geophysical variations by the Chapman-Miller method*. Geophys. J. R. Astron. Soc., **15**,15-35.

Marino D., Bartoli D.G., Corrado M., Liperoti D. and Murphy D.; 2010: *Prospezioni archeologiche subacquee a Crotone. Prima campagna 2009 tra le località Porto Vecchio e Tonnara*. FOLD&R Italia, **192**, 1-22.

Melchior P.; 1995: *A continuing discussion about the correlation of tidal gravity anomalies and heat flow densities*. Phys. Earth Planet. Int., **88**, 223-256.

Melchior P. and Francis O.; 1986: *Comparison of recent ocean tide models using ground-based tidal gravity measurements*. Mar. Geod., **19**, 291-330.

Melchior P. and Ducarme B.;1991: *Tidal gravity anomalies and tectonic*. In: Kakkuri J. (ed), Proc. 11th Int. Symp. Earth Tides, Helsinki, Finland, Schweitzerbartsche Verlagsbuchhandlung, Stuttgart, Germany, pp. 445-454.

Merriam J.B.; 1992: *Atmospheric pressure and gravity*. Geophys. J. Int., **109**, 488-500.

Metivier L. and Conrad C.P.; 2008: *Body tides of a convecting, laterally heterogeneous, and spherical Earth*. J. Geophys. Res., **113**, B11405.

Minelli L., Billi A., Faccenna C., Gervasi A., Guerra I., Orecchio B. and Speranza G.; 2013: *Discovery of a gliding salt-detached megaslide, Calabria*. Geophys. Res. Let., **40**, 4220-4224.

Molodensky M.S.; 1961: *The theory of nutation and the diurnal Earth tides*. Comm. Obs. R. Belgium, **288**, 25-26.

Monna S., Sgroi T. and Dahm T.; 2013: *New insights on volcanic and tectonic structures of the southern Tyrrhenian (Italy) from marine and land seismic data*. Geochem. Geophys. Geosyst., **14**, 3703-3719, doi:10.1002/ggge.20227.

Neumeyer J., Barthelmes F. and Wolf D.; 1998: *Atmospheric pressure correction for gravity data using different methods*. In: Proc. 13th Earth Tide Symp., Brussels, Belgium, pp. 431-438.

Orecchio B., Presti D., Totaro C., Guerra I. and Neri G.; 2011: *Imaging the velocity structure of the Calabrian Arc region (Southern Italy) through the integration of different seismological data*. Boll. Geof. Teor. Appl., **52**, 625-638.

Piana Agostinetti N., Steckler M.S. and Lucente F.P.; 2009: *Imaging the subducted slab under the Calabrian Arc, Italy, from receiver function analysis*. Lithosphere, **1**, 1-8, doi:10.1130/L49.1.

Riccardi U., Berrino G. and Corrado G.; 2002: *Changes in the instrumental sensitivity for some feedback equipping LaCoste & Romberg gravity meters*. Metrol., **39**, 509-515.

Riccardi U., Hinderer J. and Boy J.P.; 2007: *On the efficiency of barometric array to improve the reduction of atmospheric effects on gravity data*. Phys. Earth Planet. Int., **16**, 224-242.

Richter B., Wenzel H.G., Zurn W. and Klopping F.; 1995: *From Chandler wobble to free oscillations: comparison of cryogenic and other instruments in a wide period range*. Phys. Earth Planet. Int., **91**, 131-148.

Robinson E.S.; 1989: *Tidal gravity, heat flow and the upper crust*. Phys. Earth Planet. Int., **56**, 181-185.

Robinson E.S.; 1991: *Correlation on tidal gravity and heat flow in eastern North America*. Phys. Earth Planet. Int., **67**, 231-236.

Robinson E.S.; 1993: *On tidal gravity, heat flow and lateral heterogeneities*. Phys. Earth Planet. Int., **76**, 343-346.

Rydelek P.A., Zurn W. and Hinderer J.; 1991: *On tidal gravity, heat flow and lateral heterogeneities*. Phys. Earth Planet. Int., **68**, 215-229.

Savcenko R. and Bosch W.; 2012: *EOT11a - Empirical ocean tide model from multi-mission satellite altimetry*. Deutsches Geodätisches Forschungsinstitut (DGFI), München, Germany, Report n. 89, 49 pp.

Schwiderski E.W.; 1980: *On charting global ocean tides*. Rev. Geophys. Space Phys., **18**, 243-268.

Shukowsky W. and Mantovani M.S.M.; 1999: *Spatial variability of tidal gravity anomalies and its correlation with the effective elastic thickness of the lithosphere*. Phys. Earth Planet. Int., **114**, 81-90.

Sorriso-Valvo M.; 1993: *The geomorphology of Calabria, a sketch*. Geogr. Fis. Din. Quat., **16**, 75-80.

Stanley J. and Bernasconi M.P.; 2012: *Buried and submerged Greek archaeological coastal structures and artifacts as gauges to measure Late Holocene seafloor subsidence off Calabria, Italy*. Geoarchaeolog., **27**, 189-205, doi:10.1002/gea.21405.

Totaro C., Presti D., Billi A., Gervasi A., Orecchio B., Guerra I. and Neri G.; 2013: *The ongoing seismic sequence at the Pollino Mountains, Italy*. Seismol. Res. Lett., **84**, 955-962, doi: 10.1785/0220120194.

Van Camp M. and Vauterin P.; 2005: *Tsoft: graphical and interactive software for the analysis of time series and Earth tides*. Comput. Geosci., **31**, 631-640.

Van Dam T. and Francis O.; 1998: *Two years of continuous gravity measurements of tidal and non-tidal variations of gravity in Boulder, Colorado*. Geophys. Res. Lett., **25**, 393-396.

Van Ruymbeke M.; 1991: *New feedback electronics for LaCoste & Romberg gravimeters*. Cah. Centre Eur. Geodyn. Seismol., **4**, 333-337.

Wahr J.M.; 1981: *Body tides on an elliptical, rotating, elastic and oceanless Earth*. Geophys. J. R. Astron. Soc., **64**, 677-703.

Warburton R.J. and Goodkind J.M.; 1977: *The influence of barometric-pressure variations on gravity*. Geophys. J. R. Astron. Soc., **48**, 281-292.

Wenzel H.G.; 1996a: *Accuracy assessment for tidal potential catalogues*. Bull. Inf. Marées Terrestres, **124**, 9394-9416.

Wenzel H.G.; 1996b: *The nanoGal software: Earth tide data processing package ETERNA 3.30*. Bull. Inf. Marées Terrestres, **124**, 9425-9438.

Westaway R.; 1993: *Quatemary uplift of Southem Italy*. J. Geophys. Res. **98**, B12, 21741-21772.

Yanshin A.L., Melchior P., Keilis-Borok V.L., De Becker M., Ducarme B. and Sadovsky A.M.; 1986: *Global distribution of tidal anomalies and an attempt of its geotectonic interpretation*. In: Vieira R. (ed), Proc. 10th Int. Symp. Earth Tides, Madrid, Spain, pp. 731-755.

Zahram K.H., Jentzsch G. and Seeber G.; 2006: *Accuracy assessment of ocean tide loading computations for precise geodetic observations*. J. Geodyn., **42**, 159-174.

Zschau J. and Wang R.; 1987: *Imperfect elasticity in the Earth's mantle. Implications for Earth tides and long period deformations*. In: Proc. 9th Int. Symp. Earth Tides, New York, NY, USA, pp. 605-629.

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