THREE YEARS OF GRAVITY CONTINUOUS OBSERVATIONS IN THE CALABRIA ARC SYSTEM: A MODEL OF THE GRAVITY TIDE AND THE TIDAL FIELD

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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). Geophysical, geological and archeological evidence exists that the Ionian coasts are interested by intense subsidence phenomena (e.g. Marino *et al.*, 2010; Minelli *et al.*, 2013; Stanley and Bernasconi, 2012). However, over geological times, 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 vertical velocities, estimated in some areas up to about 2 mm/yr in the last 700,000 years (e.g. Sorriso-Valvo, 1993; Westaway, 1993; Antonioli *et al.*, 2006). 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. Monna *et al.*, 2013; Piana Agostinetti *et al.*, 2009, and reference therein). Although since over a century the Calabrian region is going through a period of relative seismic quietness, its seismic hazard is at the highest levels in the Mediterranean basin due to several catastrophic earthquakes present in the historical records.

In consideration of the mass movements described above, a gravity recording station was installed in Cosenza (Fig. 1) in order to contribute to the geophysical monitoring of this seismic region. The recorded signals could allow in fact to reveal tidal anomalies correlated with the difference between some local feature of the lithosphere and/or geodynamic activity and the corresponding characteristics of the models used to calculate the reference gravity tide.

Albano *et al.* (2014) present and discuss the results of the analysis of less than two years of gravity and tilt records obtained in the Calabrian Arc System. Here we present an updating of the results presented there based on the analysis of observations overlapping those already considered and extended to a time interval of more than 3 years, a duration almost doubled. With the occasion we refer on an absolute gravity measurement and on three calibrations of the recording instrument carried out in the meanwhile.

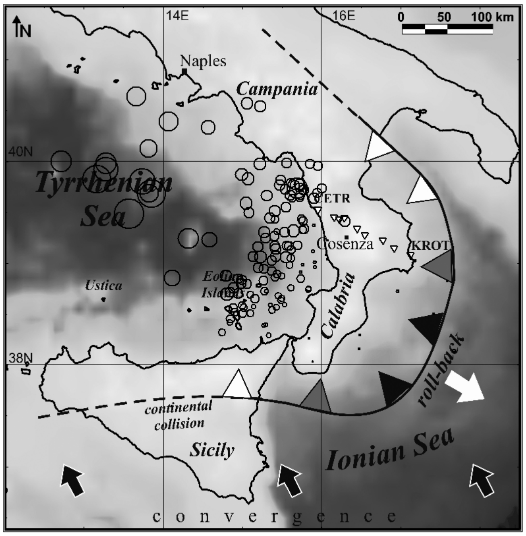

Fig. 1 – Map of the Calabria region and adjacent geological domains (after Orecchio *et al.*, 2011 modified). Circles: epicentres of earthquakes with mL ≥ 3.4 in the time interval 19860101 – 20140221 and depth ≥ 50 km (after ISIDe, Working Group (INGV, 2010), Italian Seismological Instrumental and parametric database; http://iside.rm.ingv.it); radius increases with depth up to the maximum of 644.4 km. Reversed triangles: GPS stations. Squares: cities

The records are accomplished at the station located at the Department of Physics of the University, Campus of Arcavacata, near Cosenza (ϕ = 39°.359005 N; λ = 16°.226858 E; h = 221 *m* asl; g = 9.8010671 ± 10^{-7} m/s^2). The local value of the gravity was measured in 1994 by 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 Istituto Nazionale di Ricerca Metrologica (Biolcati et al., 2013); the second value of g = 9.8010670 ± 10^{-7} m/s^2 is consistent with the preceding one within the error limits, indicating that during the corresponding time interval of 20 years occurred not any vertical movement and/or mass redistribution in the underground significant for the gravity value at the Earth's surface.

As changes in time of the calibration factor of the gravimeter can occur as a consequence of perturbations of different origins (e.g. Bonvalot *et al.*, 1998; Riccardi *et al.*, 2002), four sessions of on site calibration of the gravimeter have been carried out at the station of Cosenza. The results are shown in Fig. 2 together those of the set of 18 calibrations carried out at a station in Naples, where the same instrument had been operating for several years before to be moved to Cosenza.

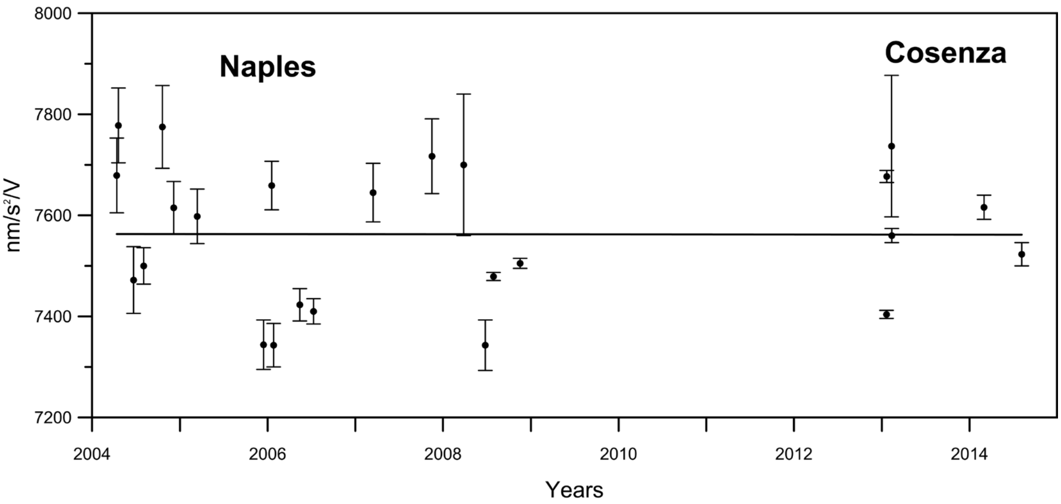

Fig. 2 – Calibration factors measured at the stations of Naples and Cosenza.

The global set of 24 calibration sessions shows randomly scattered results without any significant trend versus time. In fact the slope of the regression straight line turns out to be -0.01 ± 0.03 (r = -0.08).

To further check the long term trend of the calibration factor, the latter has been computed on temporal windows of 48 hours, with reference to the gravity tide predicted by the DDW99/NH tidal model (Dehant *et al.*, 1999). Not even the resulting values by this second method show any significant temporal trend; effectively they result randomly scattered around a straight line having the slope of $(3 \pm 0.4) \cdot 10^{-3}$ (r = 0.3) nm/s^2/mVolt/day.

The gravity data recorded 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[1] 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. The catalogue consists of 12935 tidal waves, containing 19300 adjusted coefficients computed using the JPL DE200 numerical ephemeris of the Solar System. A rms error 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 Tab. 1.

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, 1989).

Tab. 1 - Main components of the gravity tide at Cosenza station.

Wave	Amplitude (*nm/s*²)	δ	Phase (°)
O_1	357.3 ± 0.7	1.173 ± 0.002	0.23 ± 0.08
P_1	163.9 ± 0.5	1.157 ± 0.003	0.5 ± 0.2
K_1	492.3 ± 0.5	1.150 ± 0.001	0.37± 0.06
M_2	538.4 ± 0.3	1.1986 ± 0.0006	0.99 ± 0.03
S_2	250.8 ± 0.2	1.200 ± 0.001	0.41 ± 0.06

Many seismic events of variable magnitude and source coordinates have been recorded. Strong earthquakes and the most recent seismic sequence occurred in the region could contribute to the noise affecting the gravity records. The noise values estimated by ETERNA are 0.6 nm/s² in the diurnal band and 0.3 nm/s² in the semi-diurnal band. 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 Ocean Tide Load (OTL) to the gravity tide must be taken into account. Several models provided by the Onsala Space Observatory (http://www.oso.chalmers.se/~loading/) have been considered here.

It emerges that, at the station of Cosenza, the contributions of all the examined OTL models fall within the error limits of the results. Thus to compute the OTL effect, the recent EOT11a model (Savcenko and Bosch, 2008) 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, $\delta_c = A_c/A_{th}$ and α_c, where A_c and α_c are the computed amplitude and phase and A_{th} is the amplitude of the astronomical tide) shown in Tab. 2 for only the waves significantly influenced by the OTL.

Tab. 2 - Corrected tidal parameters and expected amplification factors of the main components of the tidal field at Cosenza station.

Wave	Ac (*nm/s*²)	δ ± err	Phase ± err (°)	δ (DDW99/NH)
O_1	358.7	1.177 ± 0.002	0.16± 0.08	1.15424
P_1	163.8	1.156 ± 0.003	0.4 ± 0.2	1.14915
K_1	491.9	1.149 ± 0.001	0.23 ± 0.06	1.13489
M_2	532.1	1.1847 ± 0.0006	0.25 ± 0.03	1.16172
S_2	247.7	1.185 ± 0.001	-0.004 ± 0.064	1.16172

Among several models describing 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 Tab. 2 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 lunar waves results 1.007±0.002, consistent with the value 1.006 expected by the model. The slope of the regression line correlating the values obtained using the computed tidal parameters and the corresponding values predicted by the model, results 1.002 ± 0.001 (r = 0.99), with a standard deviation $\sigma = \pm$ 14 nm/s². The deviation X between the observed amplitudes and phases of tidal waves and the corresponding values expected by the model can be attributed to lateral lithospheric heterogeneities and/or to an incomplete removal of the OTL effect (Baker and Bos 2003). We have computed the corrected tidal residual vectors **X**(X, χ) = **B**(B, β) - **L**(L, λ) of the main tidal waves. For each wave, **R**(R, 0) represents the Earth model tidal vector, **L**(L, λ) represents the indirect effect (OTL) computed for a given ocean tide model and **B**(B, β) = $\mathbf{A_c}(A_c,\alpha_c)$ – **R**(R, 0) represents the vector difference between observed and Earth model spectral component (Melchior and Francis, 1986). **B** depends 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 residual vectors are given in Tab. 3.

Tab. 3 - Residual vectors for the main tidal waves at Cosenza.

Wave	B (*nm/s²*)	X (*nm/s²*)	Xcos χ (*nm/s²*)	Xsin χ (*nm/s²*)
M_2	18.8 ± 0.3	10.1 ± 0.3	0.5 ± 0.01	10.1 ± 0.3
S_2	7.6 ± 0.4	4.4 ± 0.4	-1.5 ± 0.2	4.1 ± 0.3
K_1	7.4 ± 0.6	6.7 ± 0.6	4.7 ± 0.3	4.7 ± 0.5
O_1	5.7 ± 0.6	6.8 ± 0.6	6.8 ± 0.6	-0.5 ± 0.02
N_2	3.7 ± 0.4	2.0 ± 0.4	1.0 ± 0.2	1.8 ± 0.3
K^2	1.8 ± 0.4	1.0 ± 0.4	0.20 ± 0.03	1.0 ± 0.4

The tidal analysis of the gravity records over more than 3 years (May 2011 – July 2014) after all yielded amplitudes and phases of the main waves of the gravity tide in the Calabrian region. The whole of the obtained tidal spectral components represents, for the time being, the first synthetic model of the gravity tide in the region. The gravity contribution at the Cosenza station of the ocean tides has been removed from the recorded gravity changes to compute, via ETERNA, amplitudes, amplification factors δ and phase shifts of the main waves of the tidal field. The slope of the regression line correlating the values predicted by the DDW99/NH model and the values obtained through the computed tidal parameters, results 1.002 ± 0.001, with a standard deviation σ = 14 nm/s^2. The ratio δ_{M2}/δ_{O1} results 1.007 ± 0.002 consistent with the value 1.006 expected by the DDW99/NH model. The predicted values by DDW99/NH model fairly fit the observed 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, 1993) suggested the existence of correlation between local deviations of some lithospheric parameter from the model assumed as reference (here the DDW99/NH) and the in phase component of the X corrected residuals (mainly of M_2 wave). 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.*, 2008) leading to the conclusion that the corrected residual vectors X chiefly depends on the instrumental noise and the inadequacy of the adopted OTL models. We focus here our attention on the main lunar tidal waves M_2 and O_1 (Tab. 3). The residual Xcosχ component of the M_2 wave turns out negligible while, on the contrary, the Xsinχ 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 Xcosχ component and a negligible Xsinχ component, although the magnitudes of the effects of lateral heterogeneities should be similar for both O_1 and M_2 waves (Baker and Bos, 2003).

We recall here, for comparison, the values of the tidal residual vectors resulting from the analysis of 5 years of gravity records obtained at the station of Naples (Campania region, southern Italy). 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 of the analyses 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). 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. Beyond everything, the obtained results of the analyses of gravity 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 seems not produce any significant anomaly related to the adopted model.

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STRUCTURAL AND SEISMOLOGICAL CLUES FOR A LITHOSPHERIC SCALE TEAR FAULT SYSTEM IN CENTRAL-EASTERN SICILY (ITALY)

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Introduction. The convergence between Africa and Europa plates in the central Mediterranean is currently controlled by the NW-wards sink down of the Ionian oceanic lithosphere and its rolling-back (Faccenna *et al.*, 2004). This process, together with the SE spreading of the Calabrian Arc, implies the propagation of intraplate/interplate transfer fault zones. The latter commonly nucleates at the edges of the subduction system and can also propagate in the overriding plate resulting in scattered shear zone segments at the surface. Deformation at slab edges depends on the dynamics of the lower plate whose rolling-back account for detaching along ocean-continent transition and resulting in lithospheric scale tear faults (STEP, Subduction Transform Edge Propagator; Govers and Wortel, 2005). For decades, many researchers have been seeking for STEP at the western edge of the Ionian subduction system (e.g. offshore eastern Sicily), most of which have favored the Malta Escarpment (Argnani and Bonazzi, 2005; Govers and Wortel, 2005; Argnani, 2009) or others normal faults imaged by seismic profiling