

The application of a denoising method aimed at reducing continuous gravity data

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Abstract.

This study summarizes the results obtained by using a processing method based on wavelet transform for noise-filtering of continuous gravity data. Continuous gravity recordings in volcanic area could play a fundamental role in the monitoring of active volcanoes and in the prediction of eruptive events too. This geophysical methodology is used, on active volcanoes, in order to detect mass changes linked to magma transfer processes and, thus, to recognize forerunners to paroxysmal volcanic events. Spring gravimeters are still the most utilized instruments for this type of microgravity studies. Unfortunately, spring gravity meters show a strong influence of meteorological parameters, especially in the adverse environmental conditions usually encountered at such places. As the gravity changes due to the volcanic activity are very small compared to other geophysical or instrumental effects, we need a new mathematical tool to get reliable gravity residuals susceptible to reflect the volcanic effect. The aim of the present work is to get a first evaluation about the comparison between the traditional filtering methodology and the wavelet transform. The overall results show that the performance of the wavelet-based filter seems better than the Fourier one. Moreover, the possibility of getting a multi-resolution analysis and study local features of the signal in the time domain makes the proposed methodology a valuable tool for gravity data processing.

Keywords: Gravimeter; wavelet transform; filtering; volcanic monitoring.

1. Introduction

The perturbations of the local gravity field in volcanic areas are often related to sub-surface mass/volume/density redistributions or to elevation changes in response to magmatic processes and vary significantly in both space (wavelengths ranging from hundreds of meters to tens of kilometers) and time (periods ranging from minutes to years) according to the size, depth and rate of evolution of the perturbing source. Continuous gravity recordings in volcanic areas, acquired at 1datum/min sample rate, are prized for the high frequency information they provide in order to recognize forerunners to paroxysmal volcanic events. This kind of measurements are now increasingly performed at sites very close to active craters, where there is the greatest opportunity to detect significant gravity changes due to the volcanic activity. Spring gravity meters are still the most utilized

instruments for volcano monitoring, because of their relatively low cost and small size which make them easy to transport and install. Unfortunately, this type of instruments have been shown to be severely influenced by meteorological parameters (i.e. pressure, temperature and humidity), especially when used against the adverse environmental conditions usually encountered at areas so close to the active craters. The effect due to these perturbations can have an amplitude higher by one order of magnitude than the volcanic related one. This can seriously hinder the accurate detection of geophysical signals. The presence of non-volcanic changes not only makes signal detection more difficult but also may lead to a misinterpretation of the data. Several authors have demonstrated that meteorological parameters, especially atmospheric temperature, affect continuously running spring gravimeters. In particular, El Wahabi (1997) proved that, over a yearly period, temperature changes can cause an instrumental effect up to 1 mGal (1 mGal = 10^{-5} ms⁻²). Furthermore, an admittance up to 0.2 mGal/C, over changes with period longer than 1 month, has been evidenced.² Thus, in order to obtain the volcano-related gravity signal, it is crucial to evaluate effectively the meteorological perturbations which can affect the gravity measurements at each station and to suitably remove their effect from the gravity signal. Since the transfer functions of these influences are frequency and instrument dependent, is not easy to remove their effects. Moreover, frequency-domain filters cannot be efficiently applied to remove the effect of these perturbations since the spectrum of each component of various origins has wide intervals of superposition. We thus propose a data pre-processing method for noise-filtering based on wavelet transform. This technique allows to filter out unwanted-frequency-noise while preserving localized sharp signal features. The advantage of analysing a signal with wavelets is that it enables local features of the signal to be studied with a detail matching their characteristic scale. In the temporal domain, such a property allows transient signals to be represented effectively.

2. Data presentation and analysis

The continuously gravity stations working at Etna were set up during 1998² and at present, consist of 3 gravity remote stations (SLN 1710 m a.s.l.; PDN 2820 m a.s.l.; BVD 2910 m a.s.l.) at distances from Etna's summit craters ranging between 1 and 10 Km (Fig. 1).

The gravity stations are equipped with LaCoste and Romberg (LCR) spring gravimeters, featuring analog feedback systems. The continuously recording stations were devised using innovative technologies which guarantee uninterrupted working under harsh environmental conditions. In the present study, the denoising technique is applied to about 7-month long gravity sequence acquired at PDN gravity station (Fig. 1). The continuously running station is located about 2 km NE of the summit NE crater, inside the Volcanological Observatory. Data presented and analyzed in the following were acquired through LCR PET 1081 gravimeter with a measurement range of about 5 mGal. Besides gravity, other parameters were acquired: ground tilt in two perpendicular directions, atmospheric temperature, pressure, humidity and tension from the power system feeding the station. Data were recorded at 1datum/min sample rate (each datum is the average calculated over 60 measurements) through a CR10X Campbell Scientific data-logger and transmitted through a wireless connection to Catania. Since for the sake of convenience the high frequencies components has not been considered in this study, gravity sequence was re-

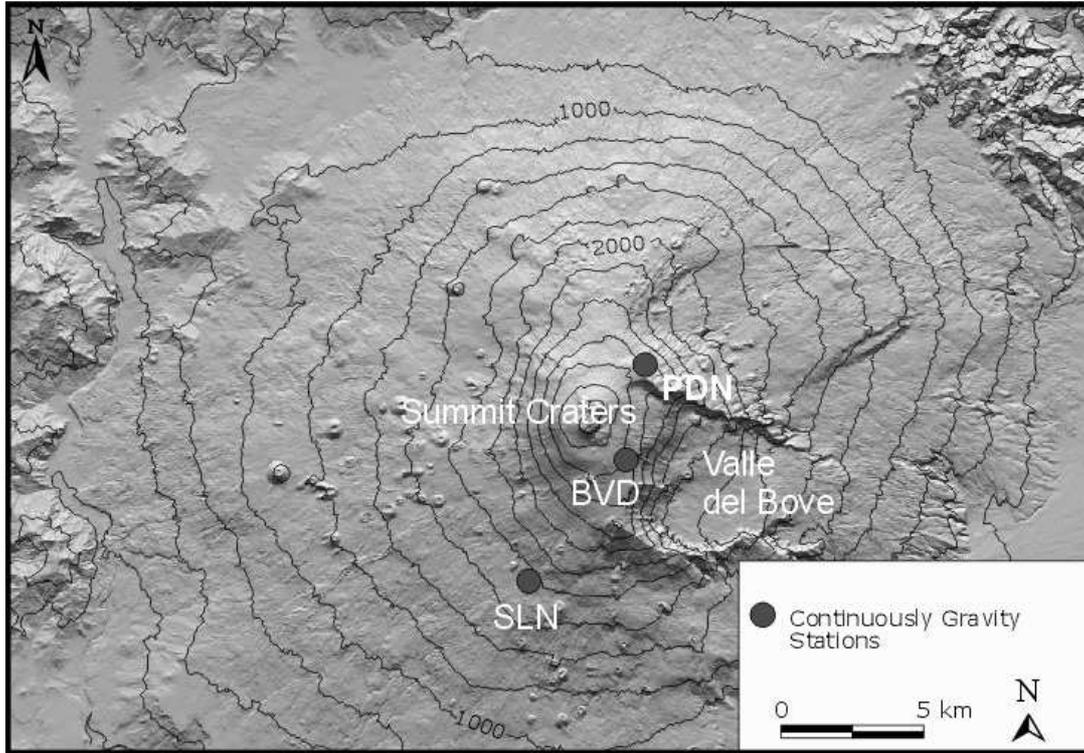


Fig. 1. Sketch map of Mt Etna showing the continuously gravity stations.

sampled to 1 hour. Previous to the filtering analysis of the sequence, spikes, gaps steps and large amplitude oscillations due to earthquakes events were corrected using T-soft, a graphical and interactive software.¹⁰ The signal from any continuous running gravity meter is affected by the tidal acceleration.⁹ The effect of Earth Tides (amplitude up to $250 \mu\text{Gal}$ ($1\mu\text{Gal} = 10^{-8} \text{ms}^{-2}$) peak-to-peak depending on latitude, elevation and stage in the tidal cycle) is modeled following the tidal potential catalogue from Tamura (1987). We computed the synthetic tide through the Eterna 3.30 data processing package,¹² using the local tidal parameters deduced from local recordings and the Wahr-Dehant-Zschau inelastic Earth model.⁵ The accuracies of the prediction model is within $\pm 1\%$, implying tidal residuals affecting the gravity signal up to $1\text{-}2 \mu\text{Gal}$ peak-to-peak over the most relevant tidal families (diurnal and semidiurnal). Continuously recording spring gravimeters are affected by aperiodic temporal variations in the display of the zero position called instrumental drift.⁹ To correct the data for the main effect of instrumental drift a best linear fit was removed from the sequence (Fig. 2).

After the pre-processing step was performed, through the optimization of an automatic one-dimensional algorithm, that enables the wavelet decomposition to be made, a multi-resolution analysis of the gravity data sequence was carried out in Matlab development environment. Different wavelet basis are obtained by varying the support width of the wavelet. In general, changes in the wavelet support affect the final frequency characteristics of the wavelet transform. Usually, the amplitudes of the coefficients change and, consequently, the scale where the signal and noise separate also changes. To optimize the choice of the wavelet basis, the maximum compactness³ or minimum entropy criterion⁷ for data compression and data analysis was applied, respectively.

In particular, this criterion was applied to the data available for this study. To find

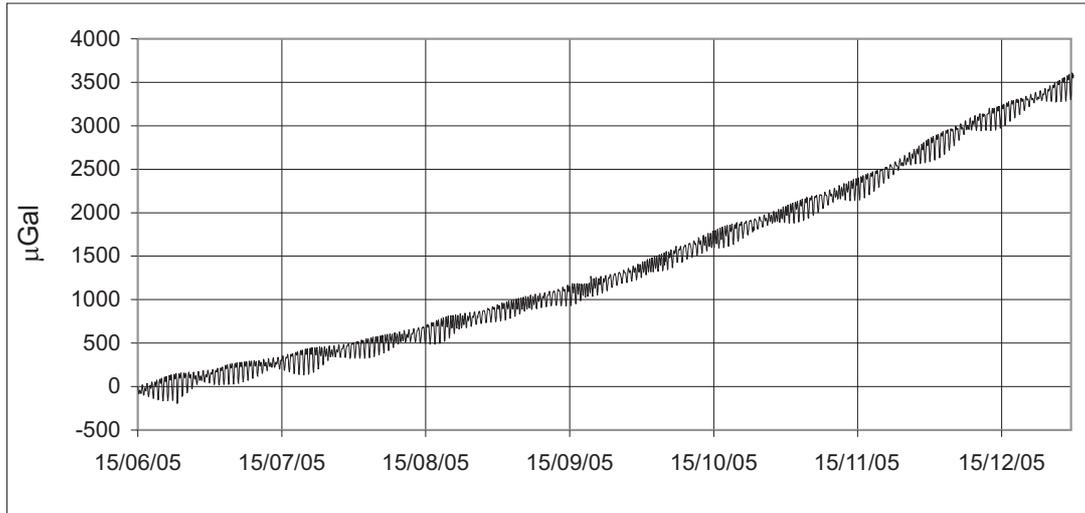


Fig. 2. Raw gravity data recorded at PDN by LCR PET-1081 gravity meter during 15 June - 31 December 2005 period. A positive trend (instrumental drift), approximately linear, is fixed around 20 $\mu\text{Gal}/\text{day}$. Long period (12-24 hours) components with amplitude up to 250 μGal peak-to-peak, due to the Earth Tide, are also shown.

Table 1. Executed test showing the averages of the entropy values for each tested wavelet basis.

Wavelet basis	Entropy
Symmlet 8	4.02
Bior 6.8	4.13
Daubechies 5	4.21
Rbio 2.8	4.22
Daubechies 7	4.27
Daubechies 9	4.37

the most appropriated support for our case the transform was repeated using different basis and Shannon's entropy of the analysed gravity sequence was then calculated. As underlined by the test carried out over 39 wavelet basis, it seems that the range of relative variability of the values calculated is more restricted only for a narrow number of wavelet basis and leads to the selection of a set of six wavelets (see table 1). The averages of the entropy values are shown in Table 1 for each tested basis of this small group. The Figure 3 shows an example of multi-resolution analysis of the continuous gravity sequence after the elimination of the tide and linear drift. It was performed using the wavelet basis Symmlet 8⁴ Fig. 3).

Since the gravity sequence consists of 4800 samples and the length of Symmlet 8 basis is 16, using the general criterion:

$$(1) \quad lev = \frac{\log \frac{lx}{lw-1}}{\log 2}$$

where: lev is the maximum allowed level decomposition; lx is the length of the signal; lw is the length of the wavelet basis. Thus, the multi-resolution analysis contains 8 scales

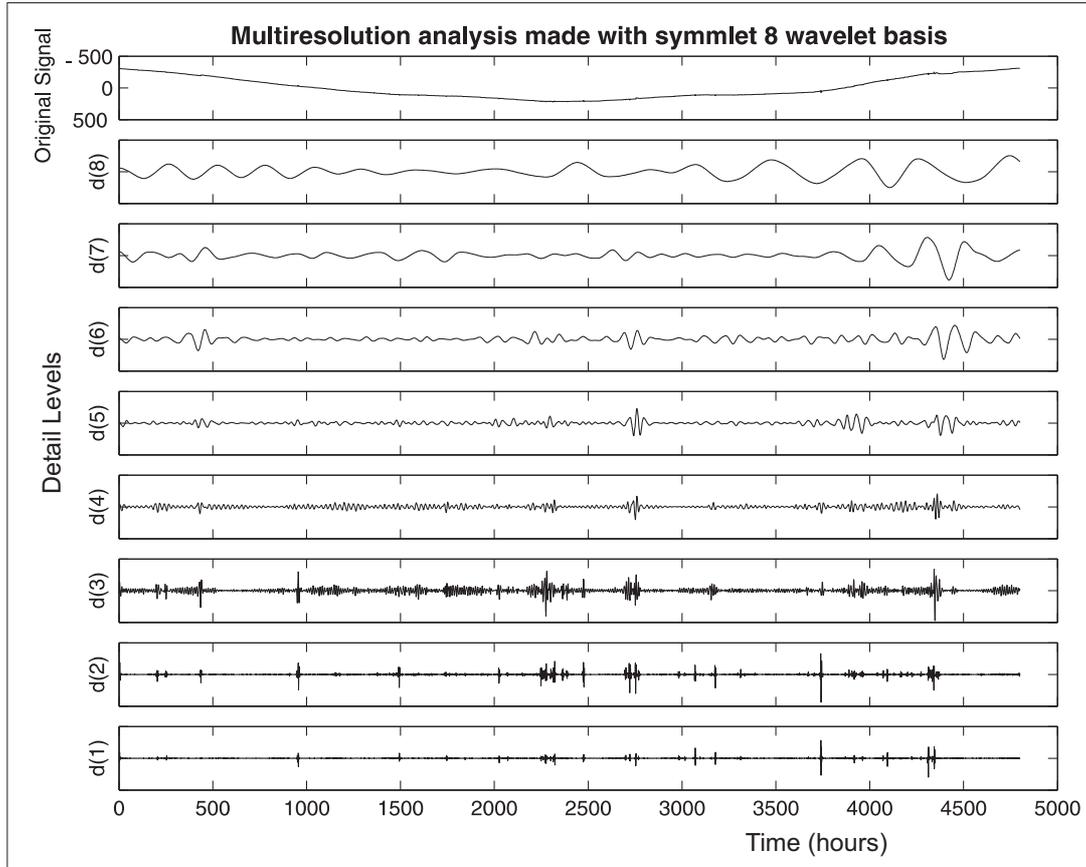


Fig. 3. Multi-resolution analysis of the gravity signal made with Sym8 wavelet basis. The input signal is displayed at the top.

each containing 4800 samples. This kind of analysis allows local features of the signal to be studied in time domain and transient signals to be represented effectively. This is an important issue to point out, since the continuous gravity signal could include some volcanic effects, which in time span from minute to years. The only way to check them is the correlation, in the time domain, with other geophysical or geochemical signals. Furthermore, the wavelet based filter furnished a good separation of the long period component from the short period one. In order to get a comparison with the classical filtering method, we tried to get the same components separation using two frequency filters type, Chebyshev and Butterworth, with different cut off frequencies and polynomial orders. The Figure 4 is an over-plot between the original signal and the two filtering methods. As clearly showed by the figure, the wavelet filter is the only one fitting perfectly the general behaviour of the curve (Fig. 4).

It seems that frequency domain filtering does not always work well because: - Depending on both cut off frequency and filter order it also can introduce edge effects and distortions of the original signal; - The frequency filters often leave some high frequency in the low pass filter, if we want to get a separation of the long period waves from the short ones; - It globally removes frequencies causing a generalized smoothing effect that substantially broadens features of interest. The long period signal obtained with the low pass filter performed by wavelet transform is more smoothed and without any significant edge effects. The same technique is then applied to the pressure, temperature and

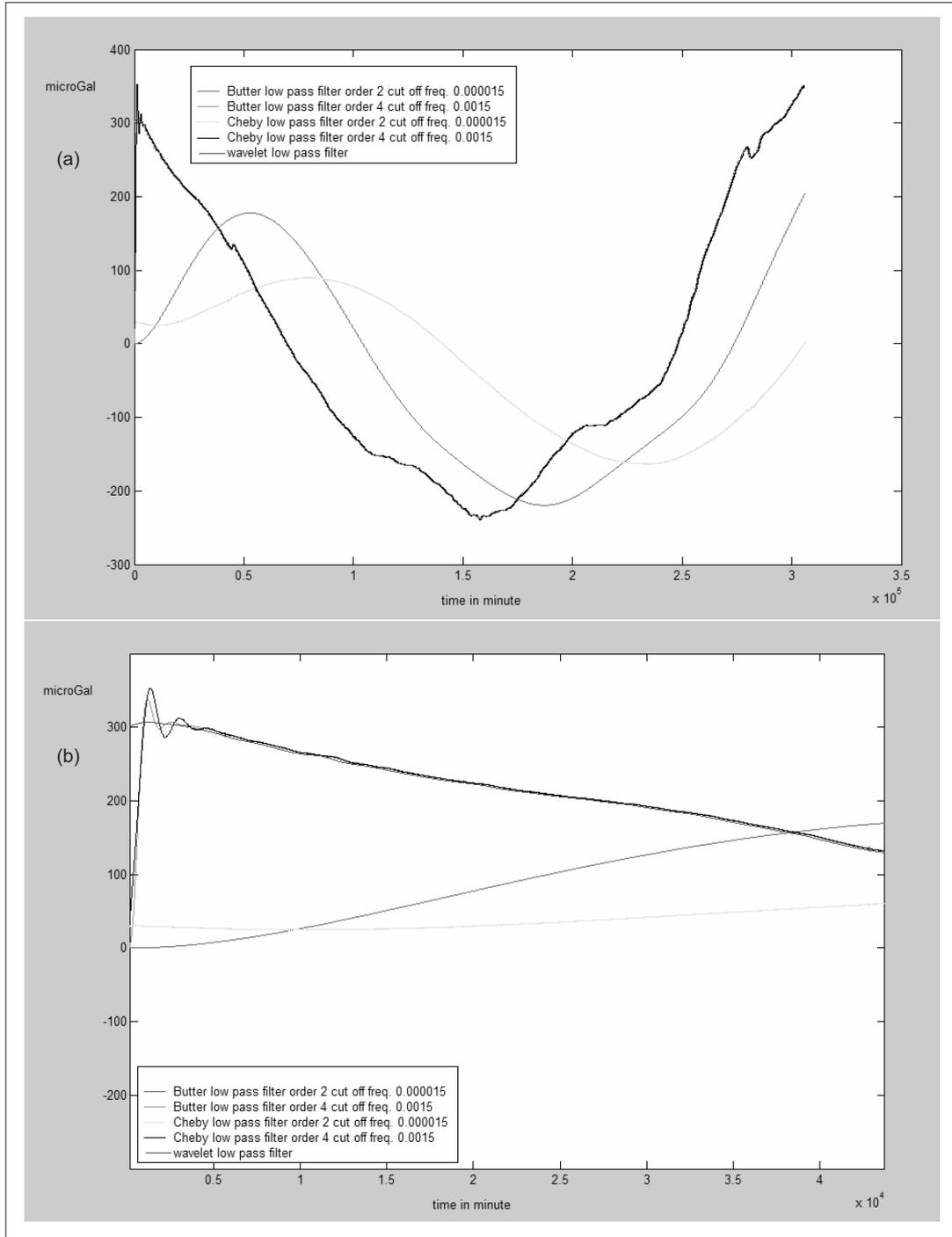


Fig. 4. Comparison between wavelet filter and two types of filters with different order and cut off frequencies: a) global view of the different filtering method; b) zoom showing the edge effects.

humidity signals, acquired at the same station, and the correlation analysis between the corresponding low frequencies component of the signals shows a strong anticorrelation with temperature (-0.7735) while the correlation with pressure and humidity are -0.5209 and -0.0896 respectively. Moreover, temperature and humidity signals show a correlation index of 0.5152 . It seems that this long period component of the gravity sequence is a part of the annual oscillation due to the mainly influence of the seasonal temperature

changes. (Fig. 5).

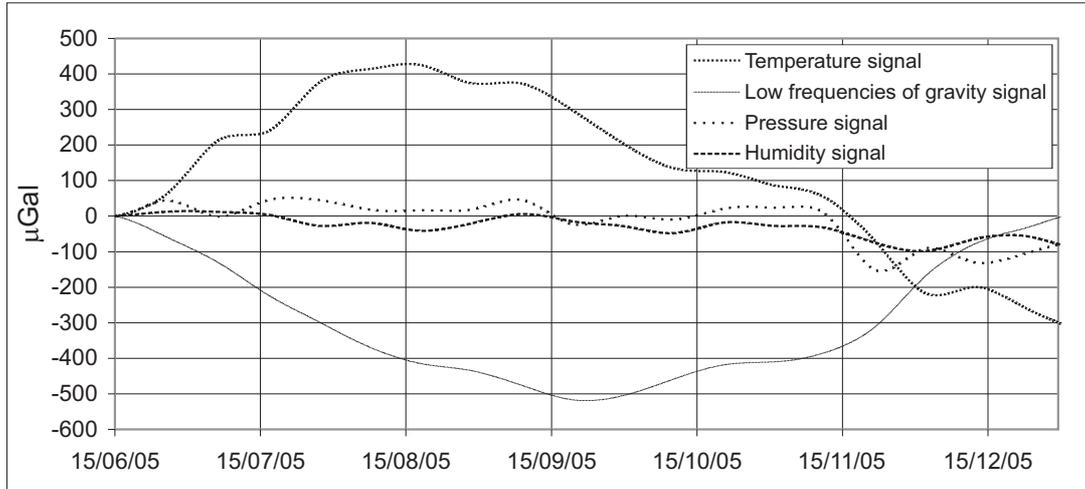


Fig. 5. Over plot between low frequency components of gravity, temperature, pressure and humidity signals. The figure shows the strong anti-correlation and the time lag between temperature and gravity signal. In order to get the same scale, the temperature and pressure signals are multiplied by an amplification factor.

The Figure 6 shows the spectra of all signals obtained with the wavelet low pass filter. It shows how the wavelet filter works well since we have only low frequencies without high frequency signal. This kind of analysis clearly shows that the spectrum of each signal contain the same main components. The main peak around 200 days is the harmonic of annual period which is not resolved properly due to the insufficient time span (Fig. 6).

It is thus more difficult to detect changes due to volcanic processes in the long period component of the signal, as this one is largely affected by the annual oscillations due to the meteorological parameters. Consequently, it is more suitable to analyze separately the low and high frequency parts of the signal. Once the meteorological effects have been removed as a difference between signal obtained with the wavelet low pass filter (Fig. 7b) and signal recorded (Fig. 7a), continuous gravity changes are within $20 \mu\text{Gal}$ peak-to-peak (a reduction of about 95% respect to original signal), thus confirming the capabilities of the proposed approach at last over periods of the order of 6-7 months. Reduced continuous gravity changes from PDN station differ from gravity changes assessed simultaneously by discrete relative observations in the same period at two sites very close to the continuous station, by no more than $10 \mu\text{Gal}$ (Fig. 7c). This value is within the error affecting discrete relative gravity measurements along the summit Etna stations typically of the order of $20 \mu\text{Gal}$.¹ That indicates that the corrected signal from PDN continuous station reflects the actual changes of the local gravity field. (Fig. 7).

3. Conclusion

A new promising technique, for continuous gravity data noise-filtering based on wavelet transform, was proposed. The aim of this preliminary work is only an overview about wavelet transform with an application on the continuous gravity data. The results obtained with wavelet decomposition seem to be better than the frequency domain filtering. The perturbations caused by the simultaneous action of different meteorological parameters (e.g. pressure, temperature and humidity) cannot be separated with frequency filters

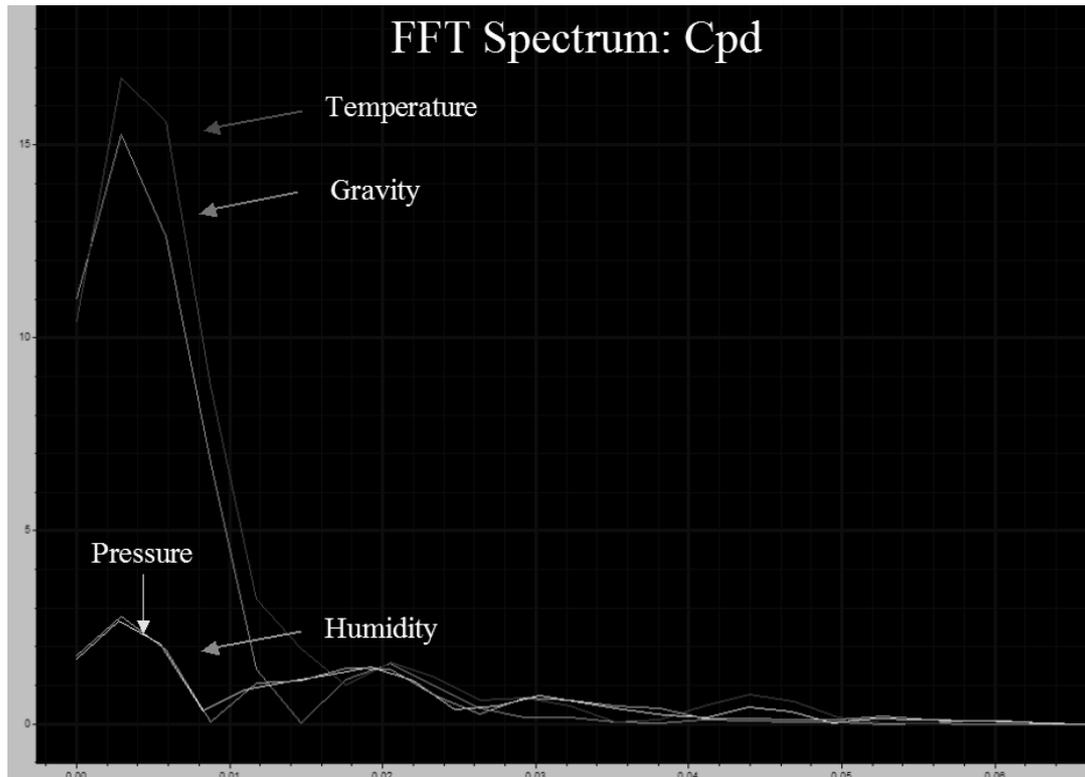


Fig. 6. Spectra (Hz vs cycles per day) of the long period components of all signals, obtained with the wavelet low pass filter. The figure shows that the filtered components contain only low frequencies.

because (i) it globally removes frequencies causing a generalized smoothing effect that substantially broadens features of interest; (ii) depending on both cut off frequency and filter order it also can introduce edge effects and distortions of the original signal and (iii) it does not allow to study local features of the signal in the time domain. The wavelet decomposition could be suitable for the construction of a non-linear multi-regression model that could enable a simultaneous correction of the main perturbing processes. Furthermore, the wavelet based filter does not require any tuning of parameters to produce results as good as the best achieved with frequency domain filters. This makes the process faster and more convenient. Finally, this paper stresses that the wavelet transform has others advantages over Fourier transform: multi-resolution decomposition and time-space localization, two important characteristics for denoising problems.

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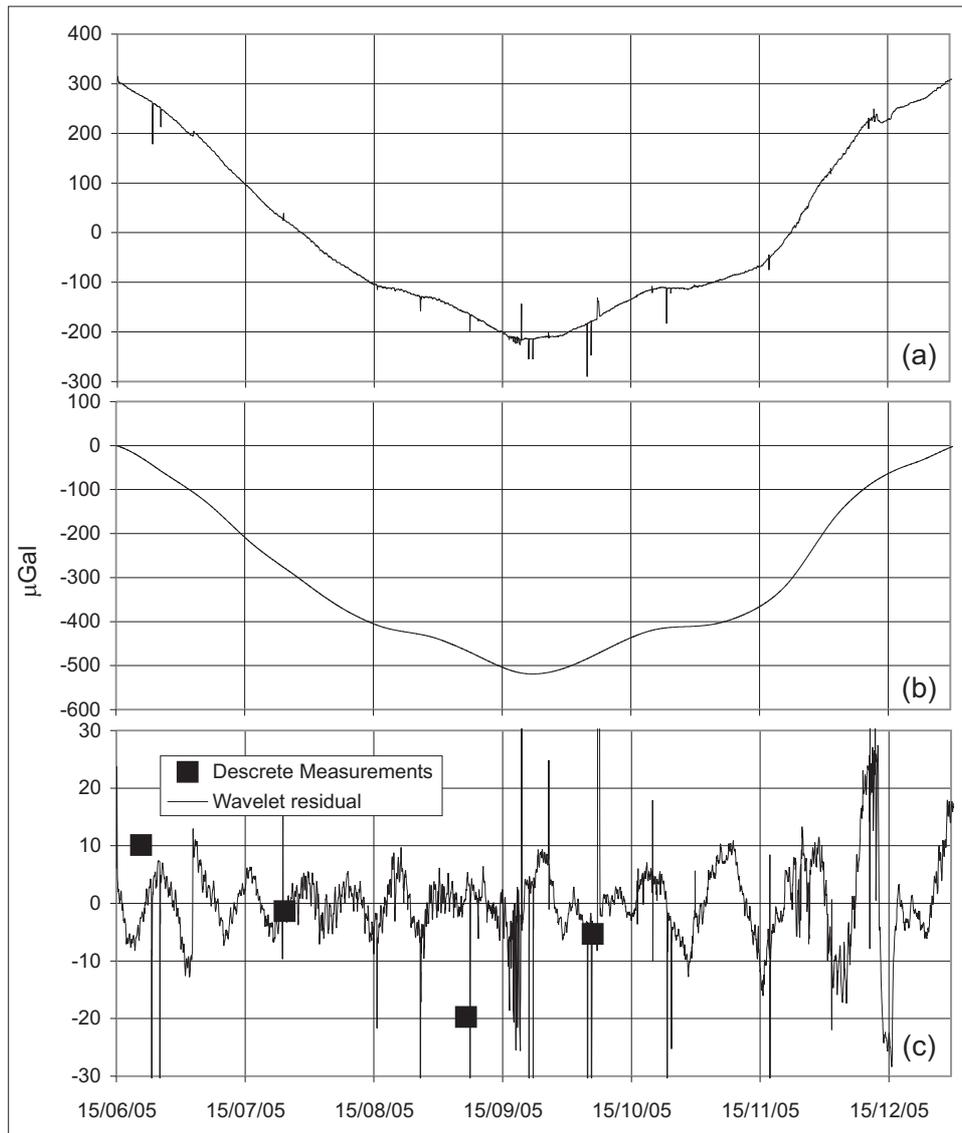


Fig. 7. Gravity sequence recorded at PDN by LCR PET - 1081 gravity meter during 15 June - 31 December period. Comparison between: (a) the original signal after removal the theoretical Earth Tide and the best linear fit (modeled as a first degree curve); (b) low frequency components of the gravity signal obtained with the wavelet low pass filter; (c) reduced gravity sequence, after removal of the best linear fit, the theoretical Earth Tide and the effect of atmospheric temperature modelled through a wavelet decomposition. Black squares in figure c are gravity changes assessed by discrete relative observations at two sites very close to the continuous station.

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