Quality Assessment and Signal Detection from GPS Time Series

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Introduction

The use of geodetic data is really helpful for the establishment and the maintenance of a vertical reference system. In particular the use of GPS has allowed in the last decade to densify the geodetic network suitable for the maintenance of such reference system. It is well known that the height coordinates, estimated by GPS is less accurate than horizontal ones. Besides now we have many stations with a very long data time series which make feasible to perform a critical analysis of the coordinates (Blewitt and Lavallée, 2000) helpful for the detection of signals, such as, the height displacements of the stations as in the case analysed in the present work. To perform a critical analysis we have taken into account four stations among the permanent GPS stations which are currently managed by ASI and whose data are routinely processed in the framework of EUREF/IGS service: Matera, Cagliari, Noto and Medicina (Fig. 1). For these stations data times series 5 years long are available at least. For the critical analysis of the data it has been adopted an approach for the detection of displacements which takes into account eventual harmonic signatures, together with jumps affecting the time series. The occurrence of height displacements could be due to several causes: mismodeling in the data analysis software (such as periodical effects from atmosphere, hydrological and/or oceanic loading) vertical movements induced by human activities (i.e. not detected exploitation of water or mineral oil from subsoil that could produce subsidence phenomena), or possible geophysical or geological phenomena (i.e. soft sediment deformation in the alluvial basin, tectonic deformations, post-glacial rebound etc.). In the present work we have focused our attention on the displacements due to regional or local tectonic motions which generally are not taken into account in the global models such as the ITRF. Another of the goals of this work is to understand after how long time height displacements can be detected from data. Anyway a continuous monitoring of the time series of the coordinates is a starting point to maintain a height reference system. So in the first part we will describe how we perform data analysis of the GPS network. In the second we will apply a critical analysis to the time series of some GPS permanent stations. Finally we will propose an interpretations of the estimated vertical movements.

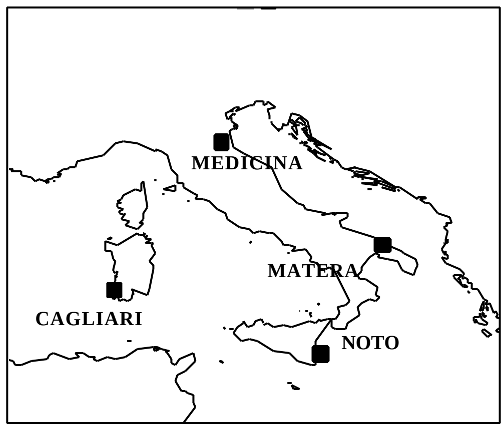

Figure1 Analysed network

1. Data analysis

The coordinate time series of the analysed stations (Matera, Cagliari, Noto and Medicina) started since October 1995, until December 2000.
They are based on network daily estimations. Each daily coordinates solution has been obtained following three main steps:
- Data pre-processing;
- Orbit determination;
- parameters estimation.

In the first step, operations of data screening have been performed, such as outliers editing and cycle-slip detection and fixing, receiver clocks synchronisation using pseudorange and application of IGS function for satellite azimuth/elevation dependency of the antenna phase center. Within orbit determination, a bayesian least square fit of IGS orbit values has been carried out, in order to estimate initial state vectors and model parameters at a reference epoch. These parameters have been kept fixed within the estimation process of the other parameters.

During last phase, a “quasi” free-network approach has been applied for estimating the following parameters:

- double difference phase ambiguities;
- total zenith delay every two hours;
- station coordinates.

The modified Hopfield model has been used for modelling the atmospheric propagation of the GPS signal, adopting the simple function: 1/cosz (z = satellite elevation angle) for mapping the atmospheric delay along the real signal path along slant directions. Ocean loading displacements at each site, according to IERS Conventions (MCCarthy, 1996), have been applied for all the stations analysed for the entire processed period, considering that neglecting this effect could cause significant height displacement in an area as the Mediterranean basin (Pacione et. al 2000). Due to the “quasi” free-network approach, the daily solutions have to be aligned with the terrestrial reference frame with *a posteriori* constraint application. Currently, we are realising the ITRF97 fixing the orbits and the position and velocity of Wettzell station. It is interesting to note that producing “quasi-free” network daily solutions, the results are free from any constraint due to the terrestrial frame, hence, the coordinate time series are not influenced by any change related to terrestrial frame variation. This approach is useful to avoid the presence of jumps in the time series, due to the differences in the coordinates of the stations used for the realisation of the terrestrial frame in each solution. In spite of this, often jumps occur in GPS coordinates time series. Usually, these jumps are due to antenna changes (e.g. different models with different antenna reference point for the application of antenna phase center corrections and antenna height) or changes in the antenna configuration system (e.g. discontinuities in the presence of the dome). The big jump on Matera time series of our solution for example (see Fig. 2) is due to such a kind of problem: on July 1996 the old ROUGUE was replaced by a TURBOROGUE.

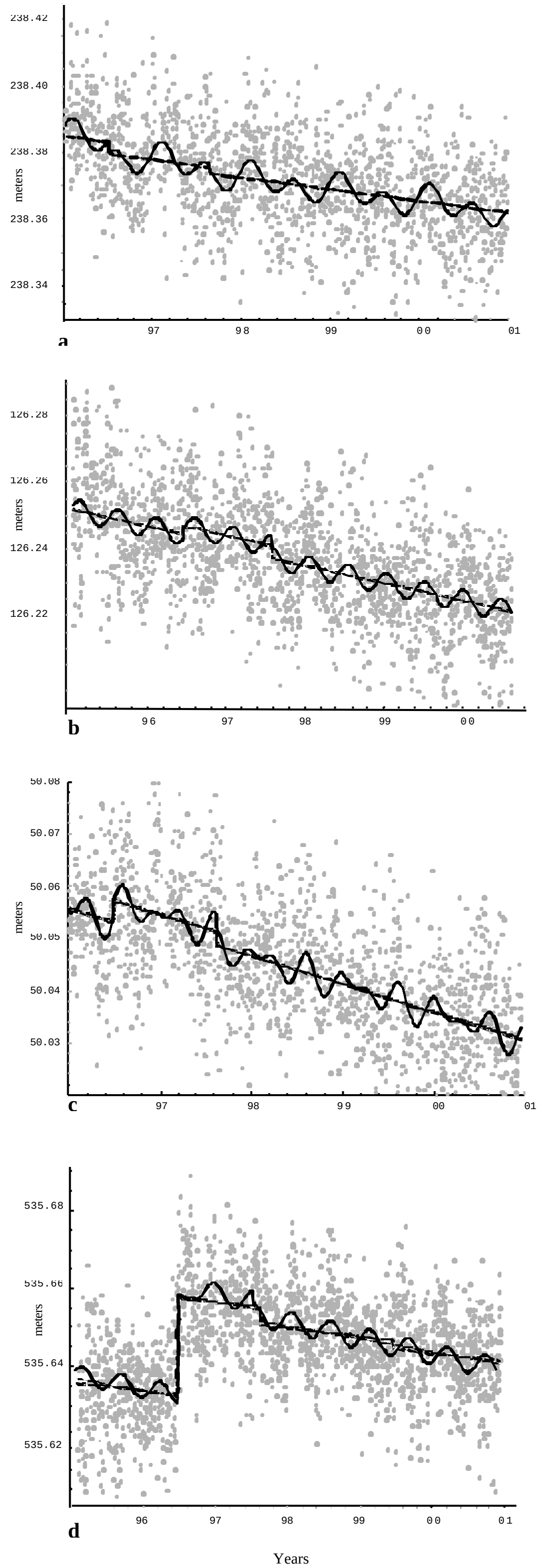

Figure 2 Estimated velocities. Dot lines represent the velocities estimated together with the harmonics, dash lines the velocities obtained without the harmonics. a) Cagliari b) Medicina; c) Noto ; d) Matera

Jumps could be also due to changes within the processing scheme. The more relevant variation, introduced along the period we have looked at, is related to the different values used for the corrections to the observations, depending on the satellite azimuth/elevation. Jumps are present for these four stations in the horizontal components (mainly North component) in correspondence with the epochs of these variations (June 30, 1996 – August 16, 1997); as it is correct to be expected, the jump value is comparable with the differences between the azimuth/elevation corrections and it is relevant in the North component because the experiments to obtain the correction values for the different kinds of antenna, are performed with a fixed azimuth angle. These discontinuities could not affect the height component because it is not involved in the equations for the implementation of the corrections. Anyway to take in account these eventual effects we have estimated the values of jumps in the epochs of such variations have been estimated.

2. Critical Analysis of Time Series

In figure 2 the time series of the heights of the stations under investigation are shown. The analysis of the time series has been performed according the following steps:

- rejection of the outliers
- harmonics analysis of the series
- fitting of the data for velocities estimation with harmonics
- extraction of signals from heights.

2.1 - Rejection of the outliers

The rejection of the data has been done estimating the slope and eventual jumps and perform the rejection according the 3-sigma rule in an iterative way till no more data rejection occurs. The average percentage of the rejected data was less then 5 %.

2.2 - Detection of harmonics signals

Next step has been the detection of harmonics signals in the time series. The data were unevenly spaced, but considering that the percentage of unevenly spaced is less then 10 % a Discrete Fourier Transform (DFT) has been adopted for a preliminary detection of the harmonics. Among the estimated harmonics we selected just these whose energy were 3 times higher than the mean energy of the periodogram, under the verified assumption that the power spectra is ruled by the Poisson statistic distribution (sigma=mean). The selected harmonics have been used as initial value to obtain a better estimation of these signals performing a non-linear fit of the time series with amplitude phase and frequency of a trigonometric function as parameters to estimate. The Lienhardt-Marquardt approach as been applied as in MATHEMATICA Package (Wolfram 1999).

2.3 - Height velocities estimation

The vertical velocities of Matera, Medicina, Noto and Cagliari stations have been obtained with a least square fit of the time series. The parameters adopted in the fitting function for each station are: the jumps (at each epoch when the azimuth/elevation correction model or processing strategy is changed or replacement of the antennas occurred), the linear slope (velocity) and the previous estimated harmonic functions (Tab.1). Moreover in order to investigate how the presence of harmonic signals could change the evaluation of the height velocities we perform the same least square fit without taking into account the harmonic functions. In figure 2 the results of the fits are summarised.
In Table 1 are reported the values of estimated velocities achieved taking into account the harmonics with more than 1 mm of amplitudes. These results shown that the estimated vertical velocities are not strictly influenced by the presence of the harmonic signals in the time series. All the values estimated with and without the harmonic signals are in agreement at least at 1-sigma level except for Matera. The discrepancy in Matera results could be ascribed to the big jump present in the time series. The presence of such a jump could be the cause of the estimation of some harmonics with no reasonable physical meaning. These harmonics have a direct influence on the value of the estimated velocities.

2.4 - Analysis of harmonics signals

In a first approximation we focus our attention on signals present in more time series such as the harmonic with a 120 days period (clearly visible in Noto, Medicina and Cagliari time series) or the strongest semi-annual signature present in all the series. The presence of some of this signals and their stationary behaviour in time - in particular the semi-annual signature present in each station and the annual signature present in Cagliari time series have been confirmed by further independent analysis (Rutigliano et al. 2001). A reliable hypothesis is that this signal could be due to unmodelled trophosperic effects or loading effects induced by air pressure, the ocean and surficial water table ocean loading corrections (Zerbini et al 2001). In our analysis the Hopifield modified model with the simple 1/cos (z) mapping function has been applied instead of the currently standard Niell mapping function. But for our time series the elevation cut off was of 15°; this means that the differences between the two tropospheric models are negligible and so this could be not able alone to explain such signature. Some spurious effects could be partly ascribed to the presence of jumps in the time series such as in Matera time series.

2.5 Remarks about vertical velocities estimation

In figure 3 are summarised some plots concerning the estimated values of the velocities. The fit has been performed with and without the harmonic functions, considering as first step a time series length of one year and appending for the next ones 50 more days of data. The goal of such approach was to understand how long time is needed to have reliable and stable values of the velocities. After 2÷3 years the estimate of the velocity seems to converge to the final (more reliable) value - confirming the Blewitt rule (Blewitt rule 2000)- but not for Matera. The huge jump, which affects the data, seems to delay the convergence of the estimate. This last evidence outlines the need to be aware of unknown jumps in the time series. The introduction of the harmonics in the fits seems to improve the quickness of the convergence only for Cagliari.
Finally in the critical analysis we have introduced the following parameter whose values are listed in the last column of Table 1:

$$h = \frac{3 * s_{fit}}{v_h} \qquad (2)$$

where s_{fit} is the root mean square of the fit and v_h is the estimated velocity. This parameter is a sort of "fingerprint" which defines the time the signal needs to emerge from the noise threshold. The chosen threshold is simply 3 times the scatter of the fit. This assumption is reasonable if the distribution of the residuals is Gaussian. In fact the chi-square test applied to residuals of all the stations have fully confirmed the assumption (all above 0.9). Essentially such fingerprint can be considered also

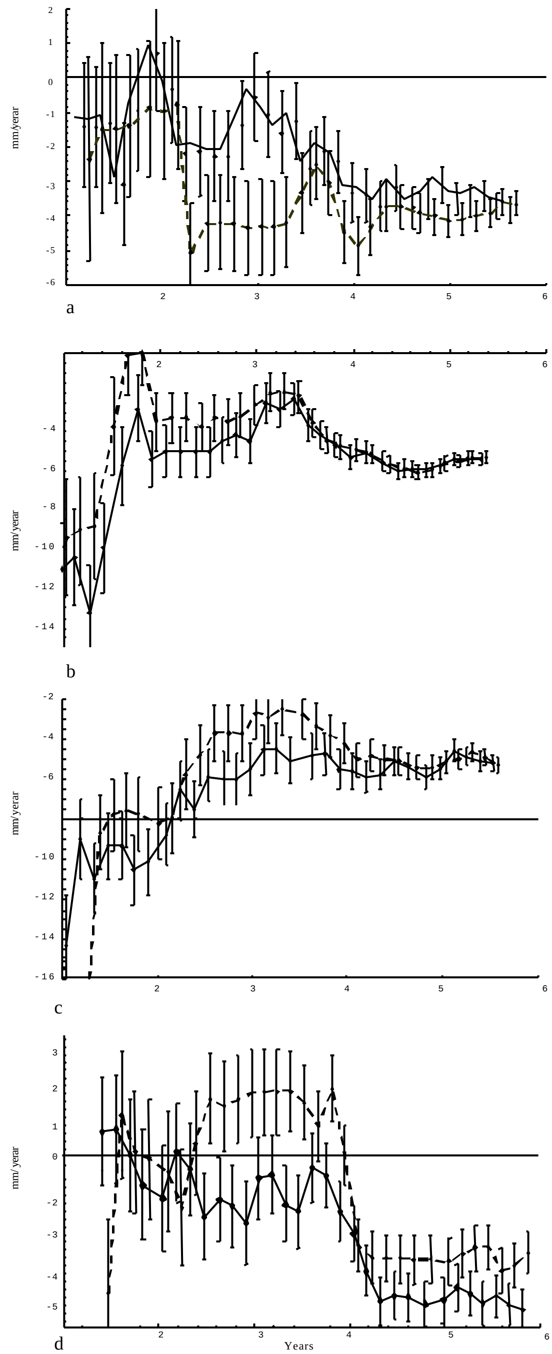

Figure 3 Estimated values of the velocities. The fit has been performed considering as first step a time series length of one year and appending for the next ones 50 more days of data. Dash lines are velocities obtained with the harmonics, solid lines show the velocities obtained without the harmonics a) Cagliari; b) Medicina; c) Noto; d) Matera

as an index of reliability of the evaluated signal. So, for example, the velocity of Medicina can be considered reliable because the time series (6 yrs) is longer than the fingerprint (5 yr.). On the other hand when the index is too high (such as for Matera) it means there couldn't be any signal (no displacement).

3. Conclusions

In order to establish a useful vertical reference system a critical point is the choice of the network sites. Of course the best choice is to place the markers in stable areas, i.e. areas not affected by not negligible and unknown motions due to tectonic, or other geophysical phenomena that could cause changes of the heights in time. Often the best choice is not available, so it's absolutely necessary to have good models of the ongoing geophysical phenomena in order to deprive the geodetic results from these effects. On the other hand just the use of such networks can be helpful for the assessment of such "disturbances". So the displacement in height could be due to several parameters, according to (Carminati & Di Donato 1999 and van Dam et al. 2001):

$$V_{tot} = V_t + V_{sl} + V_c + V_{pgr} + V_{hl} + V_a \qquad (3)$$

where V_t = tectonic signal; V_{sl} and V_c are due in turn to load sediment and by sediment compaction (Sclater and Christie, 1980) , V_{pgr} is due to post-glacial rebound, V_{hl} is the effect of water loading effects (van Dam et al. 2001) and finally V_a is due to human activities (i.e. not detected exploitation of water or mineral oil from subsoil). So to obtain a realistic model for the vertical motions in an area is useful to compare the results obtained from geodetic time series data with the independent information coming from models based on independent geological and geophysical data. Moreover using the space geodetic velocity data to monitor the evolution in time of altimetric network is important to take into account that some causes of errors in the vertical rate determination could be partially removed using different space geodesy techniques and comparing the results among them (Devoti et al 1998). These different causes height displacement are, of course, strictly "site dependent" and so they could be more or less important in different situations. In the following some examples of these effects are reported considering the estimated velocities from GPS data analysis of some station of the Italian GPS network. In particular we analysed the results from Medicina, Cagliari, Matera and Noto and some possible explanation of the estimated velocity. Medicina station is of particular interest. While for the other stations the only significant term in equation (3) is the first one for Medicina it seems all the terms give a not negligible contribution to the vertical motion. The lowering of the station, more than 5 mm/yr (Tab.1) in fact is due to several causes. First of all the pillar where is placed the GPS antenna is tilting for ground local motion with an average impact of 1 mm/yr on the vertical (Ambrico et al. 2000). According to Carminati e Di Donato (1999), the area of Medicina is affected by a detectable subsidence due to natural factors as well as to

Station	Estimated harmonics (Period in days)	Amplitudes (mm)	V_1 (mm/yr) Slope estimated without harmonics	RMS of the residuals (mm)	V_2 (mm/yr) Slope estimated with harmonics	RMS of the residuals (mm)	Index ν (yr)
Matera	220 188 134 100	1.6 3.3 1.3 1.7	-2.4 ± 0.5	10.0	-3.3 ± 0.5	10.5	≥ 15
Noto	251 219 182 120	1.8 1.6 3.3 1.6	-5.26 ± 0.40	12.8	-5.22 ± 0.40	13.2	≥ 7
Medicina	182 122 88	2.0 2.1 1.5	-5.33 ± 0.27	9.2	-5.44 ± 0.28	9.5	≥ 5
Cagliari	360 180 121	2.2 3.7 1.8	-3.64 ± 0.35	12.0	-3.61 ± 0.36	12.5	≥ 10.5

Table 1 For each station the values of the estimated harmonic (amplitude and period), the values of the velocities with and without the harmonic functions the correspond values of the RMS of the residuals and the value of the Index ν are reported.

human activity (i.e. extraction of oil and water) that are playing a not negligible role in Po Plane subsidence.
Moreover this area, according to the geological settings, in the Apennines foredeep has been recognised as a highly subsiding basin with rates in the last 5 Ma record of more than 1.6 mm/yr (Doglioni, 1994). Cagliari shows a subsidence rate (-3.64 ± 0.35 mm/yr) that has no geophysical evidence so the value could be the effect of tectonic activity.
For Noto station the observed subsidence, -5.26 ± 0.40 mm/yr, could has a tectonic explanation considering the active rifting in the Sicily Channel. On the other hand Matera seems to show a slight subsidence rate, but the high calculated value of the "fingerprint" as defined in (2)) shows that no signal could be still detected.

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