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Time series analysis of daily solutions of IGFN permanent GPS stations

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ABSTRACT This paper presents the results of the time series analysis for 1997, 1998 and 1999 for the permanent GPS stations of Medicina, Genoa, Noto, Turin, Cagliari, Perugia and Venice, belonging to the Italian GPS Fiducial Network of the ASI. The BPE module of the Bernese software v.4.2 was used to process data to obtain time series of daily solutions. The model used for the least-square interpolation of the series allowed us to consider both the secular trend (uniform motion) and periodic variations (period of one year), as well as possible jumps in the series. The DIA (Detection Identification Adaptation) procedure was used to remove blunders. The statistical analysis also included an estimate of the internal reliability of the time series.

1. Introduction

The presence, in Italy, of permanent GPS stations of the Italian GPS Fiducial Network (IGFN) of the ASI has the potential of enabling a systematic study of geodynamic phenomena on a national scale.

This paper deals with a time series analysis of daily solutions of the stations of Medicina, Genoa, Noto, Turin, Cagliari, Perugia and Venice with respect to the station of Matera, in order to verify if, and with what reliability, it is possible to constrain relative movements of these stations with respect to Matera (Fig. 1). The phases of the study were: processing of the GPS data, transformation of the results to the ITRF2000, calculation of the series for the north, east and up components (in the local reference system of each station), formulation of a model to interpolate them, estimation of its parameters and statistical analysis of the results.

2. GPS data processing

The 1997, 1998 and 1999 data for the permanent GPS stations were supplied by the GeoDAF centre of the ASI, while the data for the precise ephemerides (in sp3 format) were obtained via FTP from the IGS. They were processed with the BPE module of the Bernese software v.4.2; the calculation was carried out via the standard procedure outlined in the software manual (Hugentobler *et al.*, 2001). A preliminary iono-free solution was calculated to check for the quality of the data. The ambiguities were estimated with the QIF method, and the station coordinates and their variance-covariance (VC) matrix were calculated. The baselines used in the calculation corresponded to the maximum number of data (according to the OBSMAX scheme). An elevation cut-off angle of 10° was adopted for the data processing. The Datum was fixed on the basis of the Matera station coordinates: for each daily solution, the Matera coordinates were determined by updating the ITRF values at the time of the solution (ITRF94 for the period 01/01/1997-28/02/1998, ITRF96 for the period 01/03/1998-31/07/1999 and ITRF97 for the period 01/08/1999-31/12/1999), on the basis of the velocity field provided.

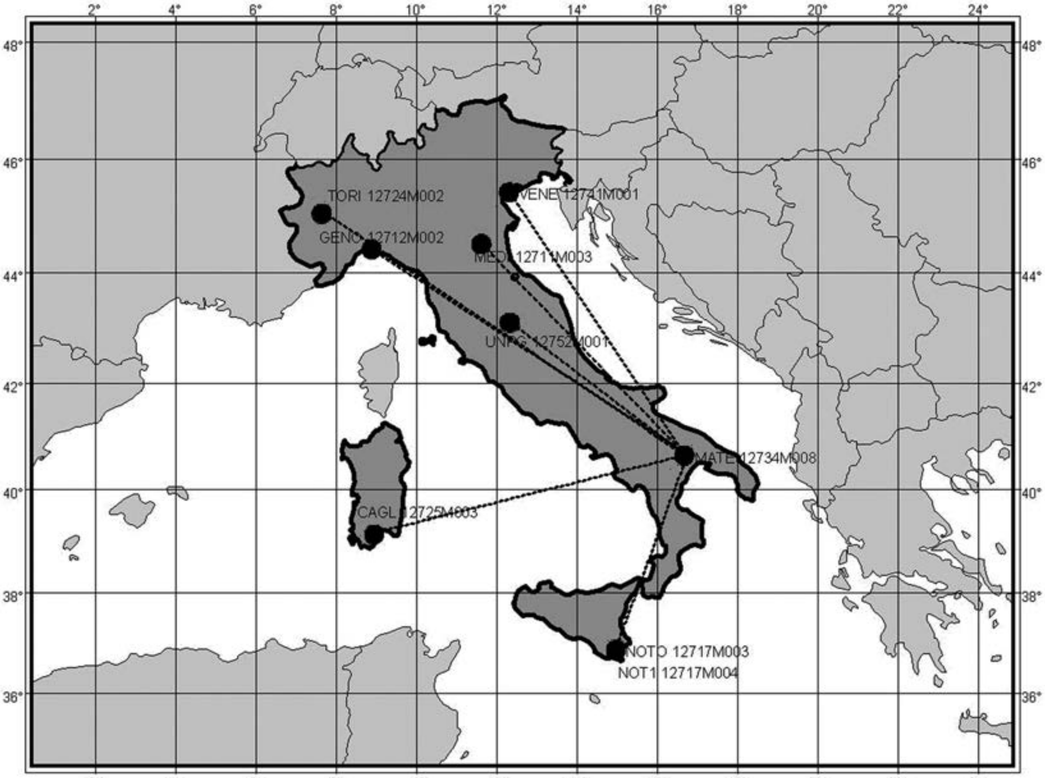


Fig. 1 - Baselines for the study of the possible movements of permanent GPS stations with respect to the station of Matera (MATE 12717M003).

3. Time series computation

The station coordinates and VC matrices obtained from the BPE processing were expressed in the ITRF2000 following the guidelines in the IERS Technical Notes 32 (Boucher and Altamimi, 2001; McCarthy and Petit, 2003). The estimated coordinates were used to form the baselines (i) of all the stations with respect to Matera, for each daily solution (j) $[\Delta x_i(t_j), \Delta y_i(t_j), \Delta z_i(t_j)]^t$. For value $[\Delta x_i(t_0), \Delta y_i(t_0), \Delta z_i(t_0)]^t$, the reference for the baselines at epoch 1997.0, we used the value deduced from the ITRF2000 (file ITRF2000_GPS.ssc):

$$\begin{aligned}\Delta x_i(t_0) &= x_{i_{ITRF\,2000}} - x_{MATE_{ITRF\,2000}}\\ \Delta y_i(t_0) &= y_{i_{ITRF\,2000}} - y_{MATE_{ITRF\,2000}}\\ \Delta z_i(t_0) &= z_{i_{ITRF\,2000}} - z_{MATE_{ITRF\,2000}}\end{aligned} \tag{1}$$

The time series of the variations were produced for each baseline:

$$\begin{aligned} \delta x(t_i) &= \Delta x_i(t_i) - \Delta x_i(t_0) \\ \delta y(t_i) &= \Delta y_i(t_i) - \Delta y_i(t_0) \\ \delta z(t_i) &= \Delta z_i(t_i) - \Delta z_i(t_0) \end{aligned} \qquad (2)$$

The values were subsequently transformed into $[n_i(t_j), e_i(t_j), u_i(t_j)]^t$ within the local reference system of each station. Similarly, the VC matrices of the coordinates obtained with the daily solutions (Q_{i_x}, the subscript x indicates that the matrix is expressed in the ITRS) were also expressed in the local system ($Q_{i_{neu}}$). In this phase, we hypothesized that the VC matrix of the vectors $[\Delta x_i(t_0), \Delta y_i(t_0), \Delta z_i(t_0)]^t$ is $\underset{3x3}{Q_{\Delta x_i}(t_0)} = 0 \,\forall i$.

4. Behaviour and interpolation model of the time series

The behaviour of the series is reported in Fig. 2: a secular trend (linear trend in first approximation) is overlapped by a periodic trend and there are jumps in the series. The secular trend can be approximated to uniform motion for all three components; the periodic trend, or at least the most obvious one, has a roughly one-year period (Kleijer, 2002). The jumps in the series are due to changes of the GPS instrumentation (antenna, receiver) or to updating of the GPS receiver's firmware. Therefore, the model chosen to interpolate the series is a kinematic model overlapped by a periodic model (period of one year), plus a model to account for jumps in the series:

$$\begin{cases} {}_i(t_j) = n_i(t_0) + v_{ni}(t_0)(t_j - t_0) + a_{ni} sen(\omega t_j + \varphi_{ni}) + \sum\limits_{k, t \le t_i} s^k_{ni}(t) \\ {}_i(t_j) = e_i(t_0) + v_{ei}(t_0)(t_j - t_0) + a_{ei} sen(\omega t_j + \varphi_{ei}) + \sum\limits_{k, t \le t_i} s^k_{ei}(t) \\ {}_i(t_j) = u_i(t_0) + v_{ui}(t_0)(t_j - t_0) + a_{ui} sen(\omega t_j + \varphi_{ui}) + \sum\limits_{k, t \le t_i} s^k_{ui}(t) \end{cases} \qquad (3)$$

The linearized model is $Ax + e = y$ and the parameters of the model are

$$x = (\ldots\ (n_i(t_0), v_{ni}, a_{ni}, \varphi_{ni}, \ldots, s^k_{ni}, \ldots)\ (e_i(t_0), v_{ei}, a_{ei}, \varphi_{ei}, \ldots, s^k_{ei}, \ldots)\ (u_i(t_0), v_{ui}, a_{ui}, \varphi_{ui}, \ldots, s^k_{ui}, \ldots)\ \ldots)^t$$

subdivided by station and according to the north, east and up components. $n_i(t_0)$, $e_i(t_0)$, $u_i(t_0)$, are the values of the model at epoch $t_0 = 1997.0$, v_{ni}, v_{ei}, v_{ui} are the velocities of uniform motion of the model a_{ni}, a_{ei}, a_{ui}, are the amplitudes of the periodic model φ_{ni}, φ_{ei}, φ_{ui}, are its phases and s^k_{ni}, s^k_{ei}, s^k_{ui} are the possible jumps in the series (for the i-th station). The corresponding Gauss-Markov model (GMM) is:

$$\begin{cases} E(y) = Ax \\ D(y) = Q_y \end{cases} \qquad (4)$$

where $y = (\dots\ n_i(t_j)\ e_i(t_j)\ u_i(t_j)\ \dots)^t$ is the vector of the observations, consisting of the time series and

$$Q_y = \begin{pmatrix} \dots & \dots & \dots & \dots & \dots \\ \dots & Q_{i_{neu}}(t_j) & 0 & 0 & \dots \\ \dots & 0 & Q_{i+1_{neu}}(t_j) & 0 & \dots \\ \dots & 0 & 0 & Q_{i+2_{neu}}(t_j) & \dots \\ \dots & \dots & \dots & \dots & \dots \end{pmatrix} \tag{5}$$

is the VC matrix. The parameters of the model are estimated by the least-squares.

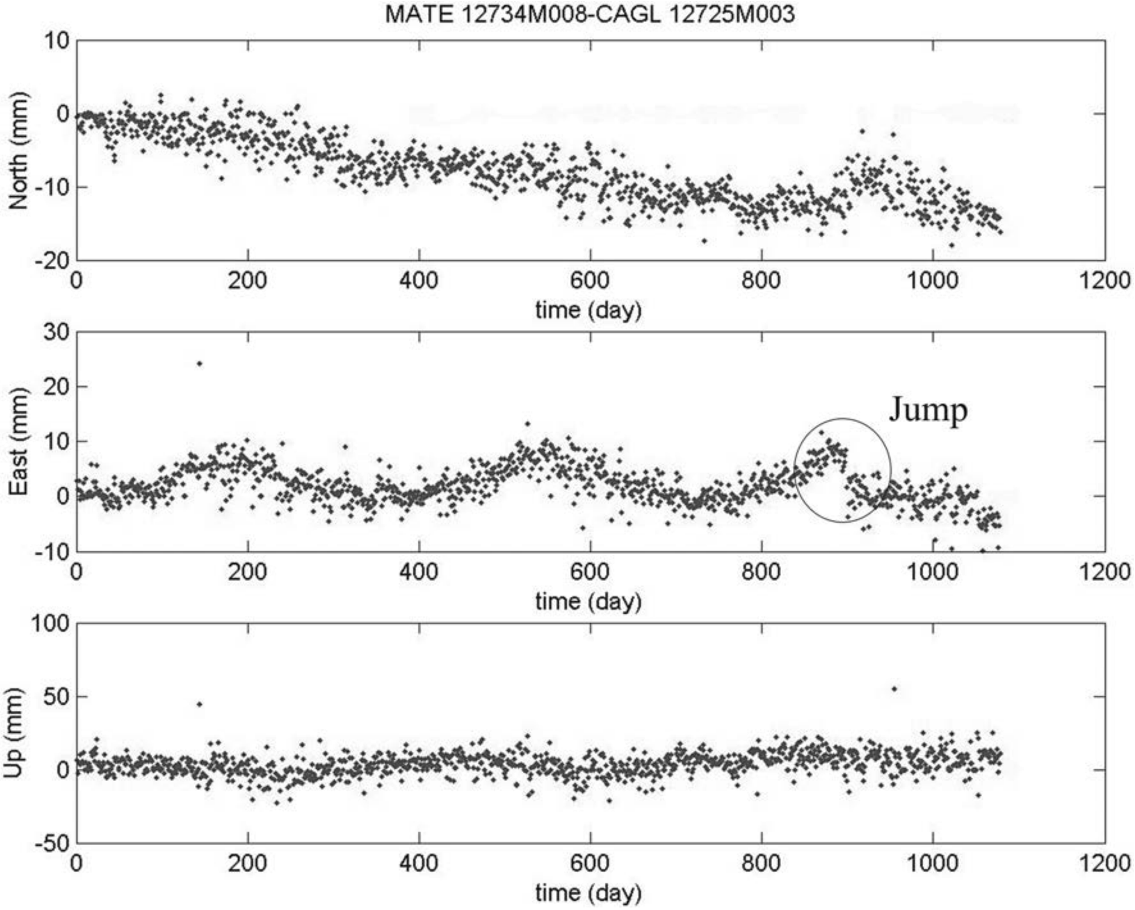


Fig. 2 - Behaviour of the time series, example of the CAGL1275M003 station.

5. Statistical analysis of the results

The statistical analysis consisted of two phases: in the first, blunders present in the series were removed; in the second, the internal reliability of the series was estimated in terms of the MDB (Minimal Detectable Bias; Baarda, 1968; Teunissen, 1998, 2000), the smallest error recordable in an observation.

5.1. Statistical tests for the removal of blunders

The DIA procedure (Detection Identification Adaptation; Teunissen, 1998, 2000) was used in the first phase of the statistical analysis. In the Detection phase, the Overall Model Test (OMT, or global test) is used to assess the validity of the null hypothesis [Eq. (4)]. Possible errors in the GMM are identified in the Identification phase and are removed in the Adaptation phase. In general, errors could be related to the hypothesized interpolation model (if it fails to adequately explain the behaviour of the series) or to blunders in the data. In the present study, we only considered the second hypothesis, with the awareness that the model chosen to interpolate the series provides only a first approximation interpretation.
The null hypothesis (H_0) formulated on the basis of model (4) is:

$$H_0 : y \sim N(Ax, Q_y) \tag{6}$$

If the OMT rejects the null hypothesis, an alternative hypothesis (H_A) can be formulated:

$$H_0 : y \sim N\left[(A\ C_y)\begin{bmatrix} x \\ \nabla \end{bmatrix}, Q_y\right] \tag{7}$$

to which the GMM corresponds:

$$\begin{cases} E(y) = Ax + C_y\nabla \\ D(y) = Q_y \end{cases} \tag{8}$$

The vector $C_y\nabla$ represents the model of the error in the GMM [Eq. (4)]. After specifying the matrix and vector, a test can be performed to evaluate the effective presence of such error (Identification). We considered two types of blunders in the series. The first type corresponds to an error affecting only one component of the series of a station; the vector $C_y\nabla$ is constructed by setting ∇ equal to the scalar $\nabla_{c,i}(t_j)$, i.e. the magnitude (unknown) of the error in the series of station i at time t_j, allowing $c = n, e, u$ to vary so as to perform the test on all three components of the series for that station. The corresponding matrix C_y is reduced to vector:

$$C_{y_{c,i}}C(t_j) = c_{y_{c,i}}(t_j) = (0\ .\ .\ 1\ .\ .\ 0)^t \tag{9}$$

By varying element *1* in vector $c_{y_{c,i}}(t_j)$, all the observables of vector y (hence all the series of all the stations) are tested one at a time. The second type of test corresponds to an error contemporaneously affecting all three components of a time series solution of a given station. To construct the model of error $C_y\nabla$, we set $\nabla = \nabla_i(t_j) = [\nabla_{ni}(t_j)\ \nabla_{ei}(t_j)\ \nabla_{ui}(t_j)]^t$, and the matrix becomes:

$$C_{yi}(t_j) = \begin{bmatrix} 0 \dots 1 & 0 & 0 \dots 0 \\ 0 \dots 0 & 1 & 0 \dots 0 \\ 0 \dots 0 & 0 & 1 \dots 0 \end{bmatrix}^t \tag{10}$$

As in the previous case, by varying the (3x3) identity matrix [shown in the Eq. (10)], from a north, east, up system of one solution to another, all the observations of vector y are tested in groups of three. The first test is one-dimensional in that it searches for an error that affects only one observable: in the present context, an observable is a component (north, east or up) of a daily solution of one of the stations. The second test is three-dimensional in that it is believed that the error affects all three components of a daily solution of a station.

5.1.1. Execution of the statistical tests

The OMT for the Detection phase consists in computing the statistic

$$s_0^2 = \frac{\hat{e}^1 Q_y^{-1} \hat{e}}{m-n} \tag{11}$$

where $\hat{e}$ is the vector of the least-squares residuals. The statistic $T_{m\text{-}n} = s_0^2\ (m\text{-}n)$ is distributed according to a central χ^2 with $m\text{-}n$ degrees of freedom $T_{m\text{-}n} \sim \chi^2_{m\text{-}n}$. When the level of significance α of the test is fixed [e.g. with the B-method (Baarda, 1968; Teunissen, 2000), in this case the OMT and the tests for blunders have the same non-centrality parameter and the same power] and its corresponding critical value k_α is defined, the null hypothesis is rejected if $T_{m\text{-}n} > k_\alpha = \chi^2_{\alpha,m\text{-}n}$. This means that there is at least one blunder among the observables. If this occurs, statistics are constructed for the one-dimensional test (station i, time t_j, component $c = n,e,u$)

$$T^1_{c,i,j} = \frac{\left(c^1_{y_{c,i,j}} Q_y^{-1} \hat{e}\right)^2}{c^1_{y_{c,i,j}} Q_y^{-1} Q_e Q_y^{-1} c_{y_{c,i,j}}} \tag{12}$$

and for the three-dimensional test (station i, time t_j)

$$T^3_{i,j} = \hat{e}^1 Q_y^{-1} C_{y,i,j} (C^{-1}_{y,i,j} Q_y^{-1} Q_e Q_y^{-1} C_{y,i,j})^{-1} C^{-1}_{y,i,j} Q_y^{-1} \hat{e} \tag{13}$$

for the localization of the blunders (Identification). Q_e indicates the VC matrix of the residuals. Statistic (12) is distributed according to a χ^2_1; when the level of significance α_0 of the test is fixed and the critical value $k_{\alpha_0,1}$ is defined, the null hypothesis is rejected if $T^1_{c,i,j} > k_{\alpha_0,1}$. Statistic (13) is distributed according to a χ^2_3; when the level of significance α_0 of the test is fixed and the critical value $k_{\alpha_0,3}$ is defined, the null hypothesis is rejected if $T^3_{i,j} > k_{\alpha_0,3}$. The observations that cause the tests to fail are then removed from the series (Adaptation).

5.2. Internal reliability of the series: Minimal Detectable Bias

Internal reliability is a measurement of the amount of errors in the measurements that cannot be detected by the statistical tests. The value of the smallest blunder in a measurement (or group of measurements) that can be detected by a test is called the Minimal Detectable Bias (MDB). In this study, the value of MDB was estimated only in the one-dimensional test for the components north, east and up of the series, with the formula (Teunissen, 2000):

$$\left|\nabla^{1}_{c,i,j}\right| = \sqrt{\frac{\lambda_o}{c^{1}_{y_{c,i,j}} Q_y^{-1} Q_e Q_y^{-1} c_{y_{c,i,j}}}} \tag{14}$$

where λ_0 is the non-centrality parameter of the distribution χ^2_1 (for the chosen level of significance α_0 and the power of the test γ).

6. Results

The results are considered as preliminary. Fig. 3 refers to the series for the Noto station; it also reports the respective interpolation models.

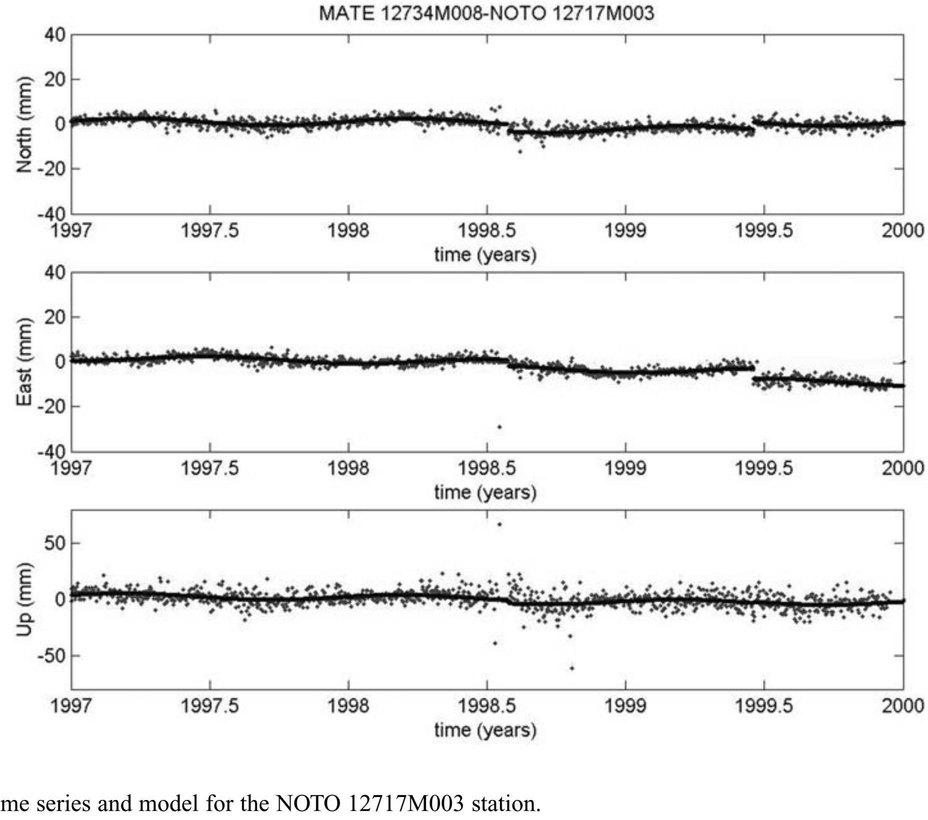


Fig. 3 - Time series and model for the NOTO 12717M003 station.

6.1. Parameters of the model

The values of the estimated parameters of the model are reported in the Tables 1 to 4.

Table 1 - Estimated values of the model at epoch 1997.0.

Station	$n(t_0)$ (mm)	$e(t_0)$ (mm)	$u(t_0)$ (mm)
MEDI 12711M003	-4.0±0.1	0.8±0.1	-6.3±0.7
GENO 12712M002	0.9±1.0	0.2±0.7	2.6±6.0
NOTO 12717M003	1.0±0.1	1.8±0.1	3.2±0.8
TORI 12724M002	-4.4±0.2	3.3±0.2	-7.8±1.3
CAGL 12725M003	-0.8±0.1	2.3±0.1	-0.2±0.7
UNPG 12752M001	-5.3±0.5	0.4±0.4	130.6±2.8
VENE 12741M001	-2.9±0.1	-1.7±0.1	-29.3±0.9

Table 2 - Estimated velocities of the stations with respect to the Matera station.

Stazione	v_n (mm/year)	v_e (mm/year)	v_u (mm/year)
MEDI 12711M003	-2.0±0.1	2.4±0.1	0.0±0.5
GENO 12712M002	-5.2±0.5	1.7±0.4	-3.8±3.0
NOTO 12717M003	-0.1±0.1	-1.3±0.1	-1.2±0.8
TORI 12724M002	-7.4±0.2	0.6±0.2	5.1±1.2
CAGL 12725M003	-5.2±0.1	0.4±0.1	2.5±0.5
UNPG 12752M001	-3.3±0.3	-0.7±0.2	-2.9±1.9
VENE 12741M001	-2.1±0.1	-0.6±0.1	-8.5±0.8

Table 3 - Estimated amplitudes of the periodic model.

Station	an (mm)	ae (mm)	au (mm)
MEDI 12711M003	2.4±0.1	2.8±0.1	1.0±0.5
GENO 12712M002	2.1±0.1	1.4±0.1	6.0±1.1
NOTO 12717M003	1.5±0.1	1.3±0.1	2.4±0.6
TORI 12724M002	0.8±0.1	2.3±0.1	4.6±0.6
CAGL 12725M003	0.8±0.1	2.9±0.1	3.6±0.5
UNPG 12752M001	0.9±0.1	1.0±0.1	0.0±0.8
VENE 12741M001	2.9±0.1	3.5±0.1	3.1±0.6

Table 4 - Estimated phases of the periodic model (expressed in days).

Stazione	φ_n (days)	φ_e (days)	φ_u (days)
MEDI 12711M003	153±2	299±2	46±28
GENO 12712M002	100±5	293±3	41±7
NOTO 12717M003	10±3	269±4	16±12
TORI 12724M002	105±9	305±3	65±8
CAGL 12725M003	290±6	274±2	19±8
UNPG 12752M001	133±10	297±6	225±9
VENE 12741M001	99±2	259±1	69±10

The periodical signal (with one-year period) was introduced in the model to enable a rough interpretation of the periodicity present in the time series. Therefore, at the present level of investigation, it is difficult to detect significant correlation among the signals of the stations by analysing the estimated parameters of the periodical model. Only the component φ_e seems to indicate some coherence.

6.2. Comparison of the estimated velocities with the ITRF2000 velocities

The estimated velocities were compared with those obtained from the ITRF2000 (file ITRF2000_GPS.ssc). Tables 5 and 6 report the velocities relative to the Matera station calculated on the basis of the ITRF2000 values and the differences from the values obtained in the time series analysis.

Table 5 - Velocities relative to MATE 12734M008, deduced from published values for the ITRF2000 (ITRF2000_GPS.ssc).

Station	v_n (mm/year)	v_e (mm/year)	v_u (mm/year)
MEDI 12711M003	-3.6	0.8	-2.7
GENO 12712M002	-4.4	-0.2	-1.1
NOTO 12717M003	-0.6	-1.9	1.1
TORI 12724M002	-7.3	-1.7	3.6
CAGL 12725M003	-5.7	-0.5	3.6
UNPG 12752M001	-1.7	0.2	44.5
VENE 12741M001	-4.4	-1.8	7.4

Table 6 - Differences between the velocities estimated in the present study and the ITRF2000 velocities.

Station	v_n (mm/year)	v_e (mm/year)	v_u (mm/year)
MEDI 12711M003	-1.6	-1.6	-2.7
GENO 12712M002	0.8	-1.9	2.7
NOTO 12717M003	-0.5	-0.6	2.3
TORI 12724M002	0.1	-2.3	-1.5
CAGL 12725M003	-0.5	-0.9	1.1
UNPG 12752M001	1.6	0.9	47.4
VENE 12741M001	-2.3	-1.2	15.9

The absolute values of the differences in n and e shown in Table 6 are less than 3 mm/year; high differences in u are present for the Perugia and Venice stations. In the case of the Perugia station, a remarkable value for the ITRF2000 velocity appears along the up component. Processing of the data for the years after 1999 will allow us to improve the quality and the reliability of these results. Table 6 shows that some differences between the estimated values of the velocities and those from ITRF2000 significantly exceed the standard deviation. Nevertheless, more investigations are necessary to state the significance of such differences because, as known (Mao *et al.*, 1999; Barzaghi *et al.*, 2002, 2003; Caporali, 2002, 2003a, 2003b), the least-square standard deviation estimations could be underestimated by a factor of 4, if only white noise is assumed to be present in the series.

6.3. Estimate of the jumps in the series

The values of the jumps are reported in Table 7. Jumps were usually due to changes in instrumentation (antenna, receiver, firmware) at one of the stations. When the instrumentation was changed at the Matera station, the jump was present in all the time series.

Table 7 - Estimated values of the jumps in the time series. The first column reports the station whose series presents the jump. When the jump is due to a change in instrumentation at the MATE 12734M008 station, the initials MATE appear in the first column (A = change of antenna, R = change of receiver).

Station	jd	year	jumpN (mm)	jumpE (mm)	jumpU (mm)	Reason
VENE	274	1997	-5.5±0.2	0.8±0.2	39.5±1.4	A/R
TORI	194	1998	-5.5±0.3	3.8±0.2	-89.2±1.5	A
NOTO	211	1998	-3.2±0.2	-2.7±0.2	-3.1±1.4	A/R
UNPG	327	1998	0.1±0.3	-0.5±0.2	-15.3±1.9	-
TORI	13	1999	6.1±0.2	-6.2±0.2	86.8±1.3	-
MEDI-MATE	169	1999	1.6±0.2	-5.0±0.2	-0.6±1.3	A/R
GENO-MATE	169	1999	2.7±0.5	-5.7±0.4	4.4±3.0	A/R
NOTO-MATE	169	1999	3.1±0.2	-4.4±0.2	0.7±1.4	A/R
TORI-MATE	169	1999	3.8±0.3	-4.1±0.3	-2.3±1.8	A/R
CAGL-MATE	169	1999	3.5±0.2	-4.6±0.2	3.5±1.3	A/R
UNPG-MATE	169	1999	2.8±0.3	-4.1±0.2	4.3±1.5	A/R
VENE-MATE	169	1999	2.3±0.3	-4.1±0.2	14.6±1.8	A/R
VENE	237	1999	-0.2±0.3	-0.2±0.2	-50.0±2.1	-

The reasons for the jumps indicated in Table 7 are, in most cases, in agreement with the information present in the logbooks of the permanent stations.

6.4. Results of the statistical analysis

The level of significance (α_0=0.0001) and the power of the tests (γ=0.80) correspond to extremely conservative tests with regard to the elimination of observations: in this preliminary time series analysis, we tried to reject the smallest number of data. The results of the statistical

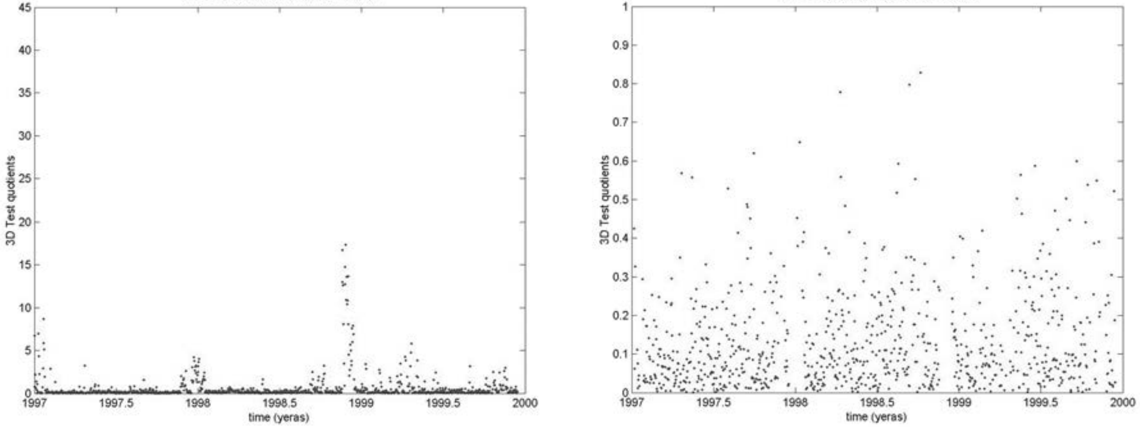
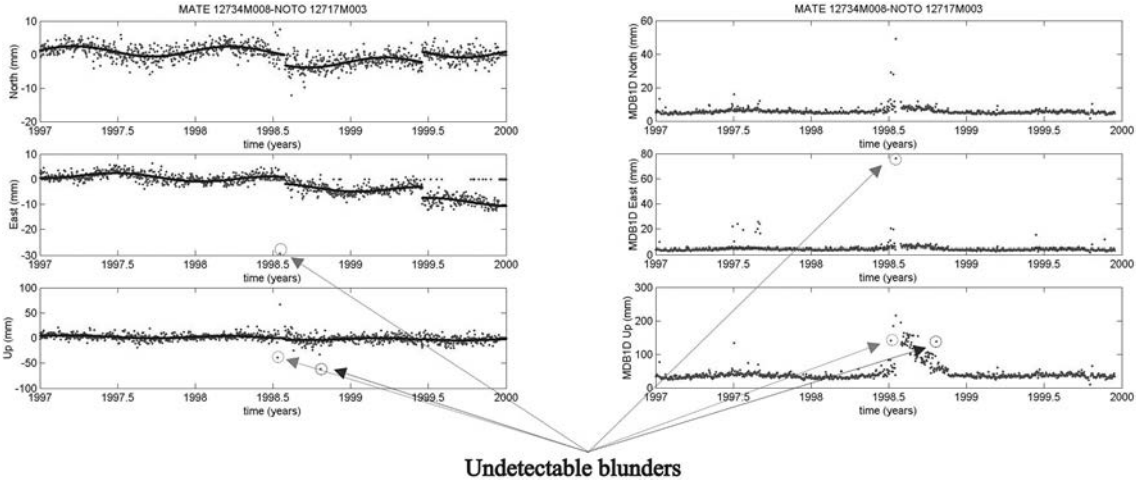


Fig. 4 - Test quotient values before (left) and after (right) removal of blunders from the series of the MEDI 12711M003 station (three-dimensional test).

analysis also include the values of the test quotients, i.e. the ratios of the statistics $T^1_{c,i,j}$ and $T^3_{i,j}$ and their respective critical values $k_{\alpha_0,1}$ e $k_{\alpha_0,3}$. Fig. 4 reports the values for the three-dimensional test quotients calculated for the Medicina station (before and after removal of the solutions affected by blunders in the series). For this station there are periods with high test quotient values, indicating that the blunders are concentrated in those time spans.

The MDB values appear to indicate the possibility of performing less conservative tests. Some solutions, apparently affected by blunders, were not rejected by the tests, as reported for the Noto station in Fig. 5. In this case, the low internal reliability of the measurements (high MDB values) can perhaps be attributed to rather imprecise solutions.



Undetectable blunders

Fig. 5 - Internal reliability for the series of the NOTO 12717M003 station. Some solutions seem to be affected by blunders but were not rejected by the tests (left). These solutions are associated with high MDB values (right).

6.5. Residuals of the time series

We have not yet made a detailed analysis of the residuals. However, Fig. 6 seems to indicate the presence of other signals in the series, presumably periodic and with frequencies different from the annual one.

7. Conclusions

The present research was aimed at designing and testing a procedure for time series analysis of daily solutions of permanent GPS stations. The results show that a possible motion of the stations can be interpreted, in first approximation, by a kinematic model combined with a periodic model with a one-year period. The correct calculation of the parameters of these models required the addition of a third model to account for jumps in the series. After adding the values of jumps to the unknowns, it was possible to determine the parameters of the models and to establish the magnitude of the jumps in the series, even without a priori information about them.

The statistical analysis revealed that a mismodelled phenomenon may be present in the residuals, therefore it is necessary to make an improvement in the interpolation model. Processing of the data for the years after 1999 will allow us to improve the reliability of the model and its parameters. The values obtained for $n_i(t_0)$, $e_i(t_0)$, $u_i(t_0)$ (t_0=1997.0) and for the velocities (v_{ni}, v_{ei}, v_{ui}) are highly dependent on the availability and quality of the data.

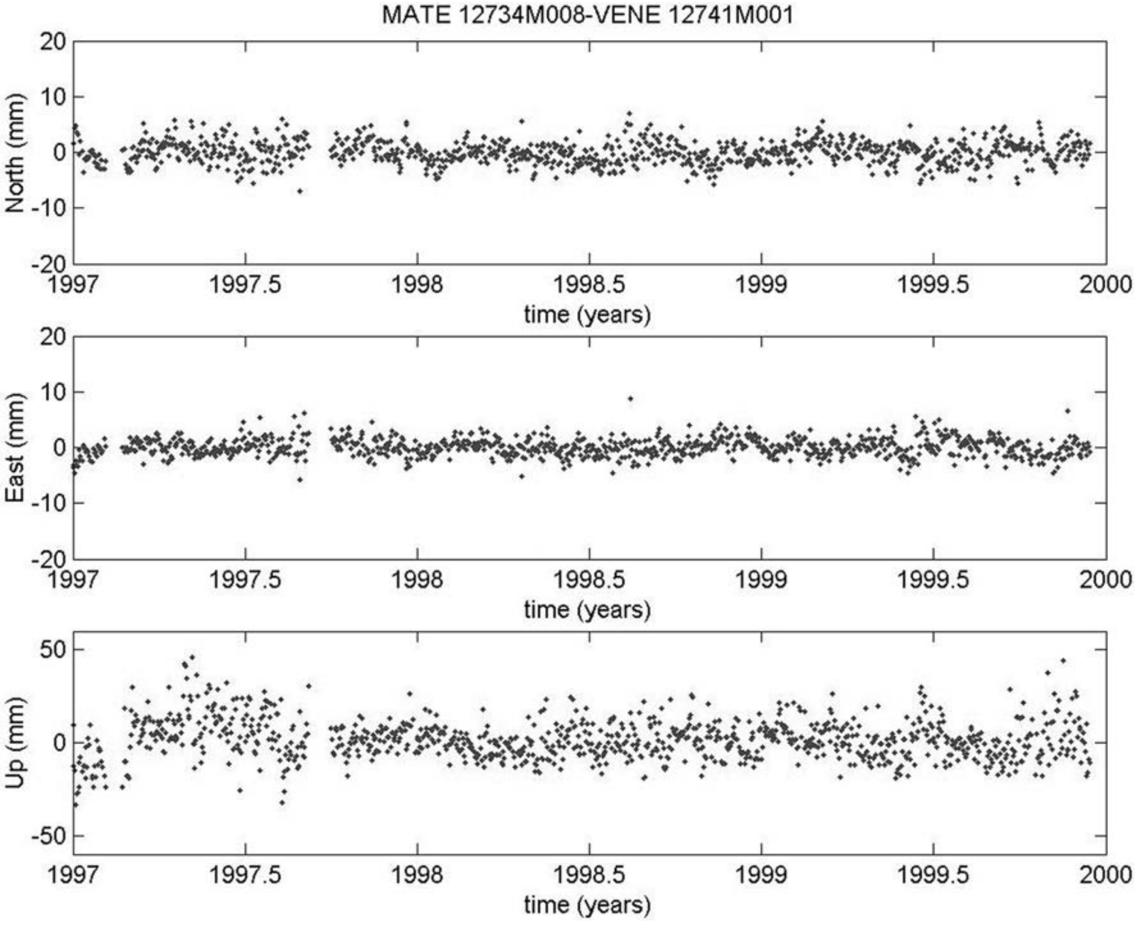


Fig. 6 - Values of the residuals for the series of the VENE 12741M001 station.

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Data:
ftp:// igs.ifag.de, http://geodaf.mt.asi.it,
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