

# FODITS: A New Tool of the Bernese GPS Software

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**Abstract.** Nowadays long continuous time series of products obtained by GNSS (Global Navigation Satellite Systems) measurements are available. Due to reprocessing efforts these time series have achieved a very high consistency level. In this context the analysis, reassessment, and the interpretation of these time series become more and more important.

In particular station coordinate time series from GNSS observations may be affected by discontinuities, e.g., because of equipment changes, earthquakes, other geophysical processes, data problems, and environmental effects.

In the Bernese GPS Software the program ADDNEQ2 is responsible to combine individual (e.g., daily or weekly) solutions over a long time interval of even ten years and more. Regarding the fact that today usually between 100 and 200 (or even more) stations are included in a continuous processing schema over years, an automated analysis of the time series is very appreciated.

FODITS (find outliers and discontinuities in time series) has been developed as a new tool of the Bernese GPS Software. A functional model including outliers, discontinuities, one or more linear velocities per station, and a set of periodic functions is adapted by the program to the time series of the data according to the significance of the components. The used algorithm is based on the ATI (adaptation, test, and identification) method—developed for preprocessing of GNSS data—and is optimized for the analysis of long time series of coordinates. Nevertheless, it is also possible to analyse other time series using FODITS. In this paper we present examples of analysed time series of station coordinates and differential code biases.

**Key words.** Time series analysis, automated processing

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## 1 Introduction

Since 15 years the International GNSS Service (IGS) processes GNSS (Global Navigation Satellite Systems) measurements on a daily basis. Several re-

gional and national services are in place for a long time (e.g., the European Permanent Network, EPN, (Bruyninx, 2004)). The interpretation of the available time series of station coordinates and other parameters requires an automated processing of these data. Recently FODITS (find outliers and discontinuities in time series) has been developed as a new component of the Bernese GPS Software (Dach *et al.*, 2007).

As the acronym implies the purpose of the program FODITS is intended to detect outliers and discontinuities in time series. The program adapts a functional model containing parameters for outlier and discontinuity handling. In addition the functional model may also consider one or more linear station velocities and a set of periodic signals (pre-selected by the user). Epochs of potential discontinuities may be introduced by the user from a list of earthquakes or from a list of equipment changes. The program reduces the components of the functional model from the user specified maximum set of components by eliminating the non-significant ones. Furthermore the algorithm adds discontinuities and outliers where it is necessary to represent the original time series by the function model in an optimal way.

The adaptation of the functional model is the core functionality of FODITS. It is performed iteratively. Such iterative approach, the so-called detection, identification, and adaptation (DIA) procedure, was presented in Teunissen (1998) for validating the assumptions underlying the functional model. Perfetti (2006) used a DIA-procedure to analyze the time series of the Italian GPS fiducial network. In FODITS the original DIA-algorithm has been modified and optimized to increase the performance of the program for long time series with 5000 data points in three components. Namely, FODITS processes the two horizontal and the vertical components of a station coordinate at the same time. The algorithm used within FODITS can be described as adaptation, test, and identification (ATI). A detailed description is given in Section 3.2.

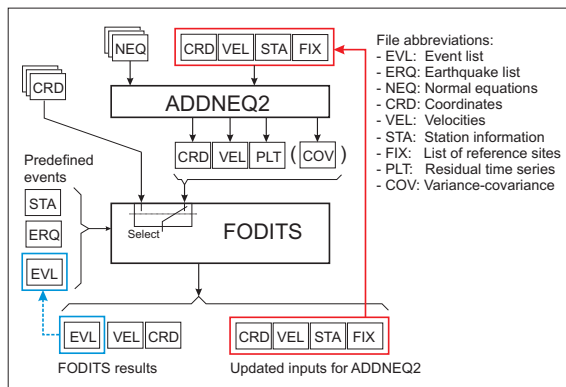
We start in Section 2 to describe how FODITS is embedded into the processing flow of the Bernese GPS Software. In Section 3 the algorithms used within FODITS to identify the outliers and discontinuities are given. Section 4 shows the behaviour of the ATI-procedure during its first iteration steps while

analyzing CODE (Center for Orbit Determination in Europe) coordinate time series. The paper gives examples for processed weekly coordinate time series for some of the stations in the EPN in Section 5.1. Section 5.2 illustrates an example of the reassessment of CODE global daily station coordinate time series. The analysis of the P1-P2 DCB (Differential Code Biases) is presented as an example for the processing of non-coordinate one-dimensional time series in Section 5.3. A summary is given in Section 6.

## 2 Description of FODITS and its Embedding in the Bernese GPS Software

Time series of coordinates may be represented as a set of coordinate files resulting from the processing of individual sessions (e.g., hourly, daily, or even weekly processing scheme). Introducing the coordinates directly we have to presume a consistent definition of the geodetic datum. Alternatively, series of coordinates may be generated by ADDNEQ2 (combining the normal equations of the individual solutions from so-called NEQ-Files) with a consistent datum definition (represented by the coordinates and velocities as well as a selection list of the reference frame sites). In that case the coordinates of the individual solution may be reconstructed from the resulting station coordinates and velocities (CRD/VEL) in conjunction with the residuals of the individual contributing normal equation files with respect to the combined solution (PLT). In both cases the variance-covariance information of the individual coordinate solutions may be considered.

Figure 1 illustrates the embedding of FODITS in the Bernese GPS Software.



**Figure 1.** Embedding of FODITS in Bernese GPS Software.

Events of potential discontinuities that shall be tested by FODITS for their significance are given

with the information on the used equipment for each station (STA) and a list of earthquakes (ERQ) extracted from an external database, e.g., U.S. Geological Survey Earthquake Hazards Program (U.S.G.S., 2008). It is also possible to enforce the program to set a discontinuity at dedicated epochs and to setup a certain set of periodic functions in any case—even if they are not significant. These predefined events are introduced by a so-called event list file (EVL). Apart from the program output, FODITS provides the list of outliers and discontinuities in a station information file that can directly be introduced into ADDNEQ2 to generate the updated (final) time series of station coordinates. In addition the list of reference frame sites is adapted according to the detected discontinuities.

## 3 Functionality of FODITS

FODITS allows the analysis of time series up to three components. GNSS station coordinate time series are in fact analysed and modelled in their local components (North, East, and Up). The space variance-covariance information of coordinates (exported from ADDNEQ2 through PLT and COV files, see Figure 1) flows into the least squares adjustment (LSA) if they are available. The temporal variance-covariance information is not taken into account in FODITS.

### 3.1 The Functional Model

For each station  $j = 1, \dots, n_q$  we define the functional model  $\mathbf{y}_j(t_i)$  consisting of a number of  $i = 1, \dots, n_{t,j}$  epochs. The functional model is independently derived for each station. For that reason and to improve the readability of the formulas we do not use the station index  $j$ .

The functional model may consist of a set or a subset of the following components:

- station coordinates  $\mathbf{c}_0$  at an epoch  $t_0$ ,
- one or more station velocities  $\mathbf{v}_k(t_i - t_0) \cdot \eta_{v,k}(t_i)$ ,
- a number of discontinuities  $\mathbf{d}_k \cdot \eta_{d,k}(t_i)$ ,
- a list of outliers  $\mathbf{s}_k \cdot \eta_{s,k}(t_i)$ , and
- a set of periodic functions  $\mathbf{p}_k$  with the predefined frequency  $f_k$  and the parameters  $\mathbf{a}_k$  and  $\mathbf{b}_k$ :

$$\mathbf{y}(t_i) = \mathbf{c}_0 + \quad (1)$$

$$\sum_{k=1}^{n_v} \mathbf{v}_k(t_i - t_{v,k}) \cdot \eta_{v,k}(t_i) +$$

$$\sum_{k=1}^{n_d} \mathbf{d}_k \cdot \eta_{d,k}(t_i) + \sum_{k=1}^{n_s} \mathbf{s}_k \cdot \eta_{s,k}(t_i) +$$

$$\sum_{k=1}^{n_p} [\mathbf{a}_k \sin(2\pi f_k t_i) + \mathbf{b}_k \cos(2\pi f_k t_i)] \cdot \eta_{p,k}(t_i).$$

The functions  $\eta_{v,k}(t_i)$ ,  $\eta_{d,k}(t_i)$ ,  $\eta_{s,k}(t_i)$  and  $\eta_{p,k}(t_i)$  are either 0 or 1 to indicate the validity of the corresponding component for the epoch  $t_i$ . The total number of discontinuity, outlier, velocity intervals, and periodic functions are defined by the variables  $n_d$ ,  $n_s$ ,  $n_v$ , and  $n_p$  respectively.

The elements of the coordinate time series are used as pseudo-observations to estimate the parameters of the functional model. All three components of a coordinate time series may be processed together. Instead of station coordinates also other time series can be introduced to compute functional models.

### 3.2 The ATI-procedure

The Nassi-Shneiderman diagram (norm DIN-66261) of FODITS is shown in Figure 2. The time series pro-

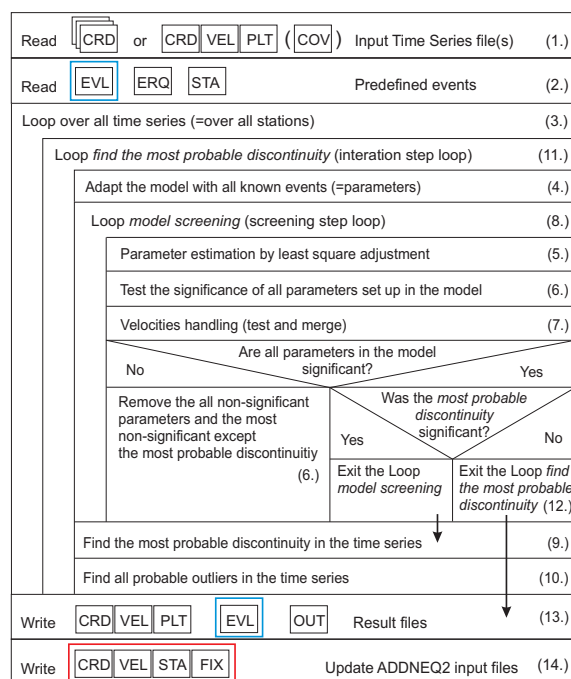


Figure 2. The Nassi-Shneiderman diagram of FODITS.

cessing in FODITS may be divided by the following steps:

1. The coordinate time series are read either from a list of coordinate files (CRD) or are reconstructed from the residuals (PLT) in conjunction with the resulting coordinate and velocities (CRD/VEL) from the combination of normal equations in the ADDNEQ2 program. The variance-covariance information of the coordinate time series may be provided in a result variance-covariance file (COV) and in the residual file (PLT).

2. A list of predefined events like, e.g., equipment changes (from the station information file, STA) and earthquakes (ERQ), is generated from the input files. All these events will be tested in step 6 whether they cause significant discontinuities or not. Components of the functional model can be introduced by the user (EVL file). There are three opportunities to influence the procedure: The resulting functional model will contain these components independent from their significance. The components can be introduced as a proposal that are verified during the processing for their significance. Specific components of the default functional model can be suppressed during specific intervals.
3. FODITS analyzes one station at a time and considers each station independent from the others.
4. A first functional model is defined. It contains parameters for all predefined events for this station taken from step 2. In addition, the parameters for the user-defined periodic functions are set up. Moreover, a new velocity parameter is set up after each earthquake event unless alternative user-defined configuration (no velocities, only one velocity, or a new velocity parameter after each discontinuity parameter) is given.
5. The parameters of the functional model are estimated by LSA using the elements of the time series as the pseudo-observations.
6. All parameters of the functional model are tested for significance. All non-significant parameters are removed from the functional model step-by-step.
7. Velocity changes are tested for significance. Non-significant velocity changes due to earthquakes are removed from the functional model if user-defined.
8. All possible velocity changes are reconsidered. The steps 5., 6., and 7. are repeated until no more non-significant parameters are included in the functional model.
9. The epoch of the most probable discrepancy between the time series and the functional model is identified that can be fixed by a discontinuity. A new discontinuity is added to the functional model at this epoch.
10. Probable outliers are identified and also added to the functional model.
11. The full functional model with all components described in step 4. together with the new identified discontinuity and outliers is setup. The procedure is repeated from step 5.
12. The iterative procedure terminates if the last identified *most probable discontinuity* is removed from the functional model in step 6. because it is not significant anymore.

13. Result and output files are generated.
14. Input files for ADDNEQ2 are updated.

In summary the algorithm consists of adaptation (step 4.), test (step 6.), and identification (steps 9. and 10.) (ATI) steps. The progress of the algorithm can be given in terms of screening and iteration steps: a screening step (adaptation and test steps of the ATI-procedure) is completed with the handling of velocities (step 7.) while an iteration (identification step of the ATI-procedure) is completed with the search for probable outliers (step 10.) (see Figure 2).

There is an important advantage in setting up the full functional model and removing the non-significant elements. The most computer time consuming part is the setup of the components of the functional model from the pseudo-observations, the elements of the time series, e.g., coordinates. So it is preferable if only components need to be removed and no parameters for a new component of the functional model has to be added within one iteration step: the removal can be done on normal equation level whereas adding new parameters requires a reprocessing of the complete time series. This significantly increases the speed of the program.

### 3.3 Tests of Significance

We verify the significance of all estimated parameters  $\mathbf{x} = \{\mathbf{d}, \mathbf{s}, \mathbf{p}\}$  by the following statistical test:

$$T_x = \frac{|\mathbf{x}|}{m_0 \sqrt{\mathbf{T} \mathbf{Q}_{xx}(\mathbf{x}, \mathbf{x}) \mathbf{T}^T}} < u_{1-\frac{\alpha}{2}}, \quad (2)$$

where  $m_0$  is the unit weight of the LSA,  $\mathbf{Q}_{xx}(\mathbf{x}, \mathbf{x})$  is the cofactor matrix of the parameter  $\mathbf{x}$ , and  $\mathbf{T}$  is the transformation matrix of the operation. Moreover, we have the critical value  $u_{1-\frac{\alpha}{2}}$  of the normal distribution for a user-defined significance level  $\alpha$ .

Let's add two remarks to the significance tests: First, for periodic functions we test for the significance of the amplitude. Second, a minimum size of a detectable discontinuity ( $|\mathbf{x}| > \kappa_d \cdot m_0$ ) and outlier ( $|\mathbf{x}| > \kappa_s \cdot m_0$ ) is specified in relation to the noise level of the time series and as an absolute threshold for the horizontal ( $|\mathbf{x}_h| > h_d, |\mathbf{x}_h| > h_s$ ) and vertical ( $|\mathbf{x}_v| > v_d, |\mathbf{x}_v| > v_s$ ) components. In this way, the computation time can be significantly reduced, and the user has a better control of the algorithm (e.g., events with a size below 1 mm might be detected as significant in the time series of very good stations, what makes from the general experience of the GNSS processing no sense anymore).

### 3.4 Searching for New Discontinuities

The removal of the most probable discrepancy (in terms of discontinuity) between the functional model

and the time series requires the identification of the epoch of such potential discontinuity. In FODITS, the identification of this epoch is based on the analysis of the time series residuals with respect to the recent functional model

$$\mathbf{v}(t_i) = \mathbf{y}(t_i) - \mathbf{A}\mathbf{x}(t_i), \quad (3)$$

where  $\mathbf{A}$  is the design matrix of the updated functional model.

Because the original statistical test for the identification step in the DIA-procedure as proposed in (Teunissen, 1998) is very computer time consuming, we have implemented a simplified algorithm to detect the epoch of the most probable discontinuity discrepancy at

$$t_d \text{ in a way that } g(t_d) = \max g(t_i) \quad (4)$$

with

$$g(t_i) = \left| \sum_{k=1}^i \mathbf{w}(t_k) \right|, \quad \text{where } i = 1, \dots, n_t. \quad (5)$$

The residual time series

$$\mathbf{w}(t_i) = \mathbf{v}(t_i) - \mathbf{A}_2 \mathbf{x}(t_i) \quad (6)$$

is obtained by fitting a first degree polynomial function (described by the design matrix  $\mathbf{A}_2$ ) to the original residual time series  $\mathbf{v}(t_i)$  (see Eq. 3) with the peculiarity of resampling the time information with  $t_i = i$  for  $i = 1, \dots, n_t$ .

Let's add a remark to the test time series of Eq. 5: by employing the residual time series  $\mathbf{w}(t_i)$  (see Eq. 6) instead of the original residual time series  $\mathbf{v}(t_i)$  (see Eq. 3) we make the identification step robust with respect to the data gaps in the time series (not unusual for time series derived from GNSS data).

### 3.5 Searching for Additional Outliers

All residuals of Eq. 3 that fulfill

$$|\mathbf{v}(t_i)| > \kappa_s m_0 \quad \text{and} \quad (7)$$

$$|\mathbf{v}_h(t_i)| > h_s \quad \text{or} \quad |\mathbf{v}_v(t_i)| > v_s$$

are identified as outliers. Outliers will be added to the functional model and tested for significance in the next iteration step of the ATI-procedure.

### 3.6 Velocity Handling

In long time series the station velocity needs to be considered. One or more time intervals of velocity parameters may be considered in the functional model (see Section 3.1). The (user-defined) criteria to introduce the velocities in the functional model are:

- no velocities,
- one velocity,
- velocity change after earthquakes, and
- velocity change after discontinuities.

In case of a significant discontinuity at a predefined epoch due to equipment changes no velocity change is permitted. On the other hand a velocity change is allowed after any predefined epoch due to an earthquake.

The ATI-procedure (see Figure 2) verifies for all pairs of velocities  $\{\mathbf{v}_m, \mathbf{v}_n\}$  belonging to the analyzed station  $j$ , with  $n > m$  and no more than one earthquake event between  $m$  and  $n$ , whether the velocities are statistically equal or not. We may assume that  $\mathbf{v}_m = \mathbf{v}_n$  if the statistical test

$$T_v = \frac{|\mathbf{v}_n - \mathbf{v}_m|}{m_0 \sqrt{\mathbf{T} \mathbf{Q}_{xx}(\mathbf{v}_m; \mathbf{v}_n) \mathbf{T}^T}} < u_{1-\frac{\alpha}{2}} \quad (8)$$

holds.  $\mathbf{Q}_{xx}(\mathbf{v}_m; \mathbf{v}_n)$  is the cofactor matrix of velocity parameters  $\mathbf{v}_m$  and  $\mathbf{v}_n$  and  $\mathbf{T}$  is the transformation matrix of the operation. If significantly equal the two original velocities and all velocities between them are then represented by the same velocity parameter in the next screening step of the ATI-procedure.

### 3.7 Earthquake Events

Earthquake events, especially registered along the tectonic plate boundaries, are nowadays monitored all over the world down to a magnitude of 4.0. By means of an external earthquake information database, e.g., U.S. Geological Survey Earthquake Hazards Program (U.S.G.S., 2008), we test whether these seismic events produced discontinuities and/or velocity changes in the analyzed station coordinate time series.

Therefore, we set up a discontinuity parameter and allow a velocity change at epoch of the (registered) earthquake event of magnitude  $M_{erq}$  and of distance  $d_{erq}$  from the analyzed station if

$$M_v \geq M_{erq} \quad \text{and} \quad M_{erq} \geq M_{min}, \quad (9)$$

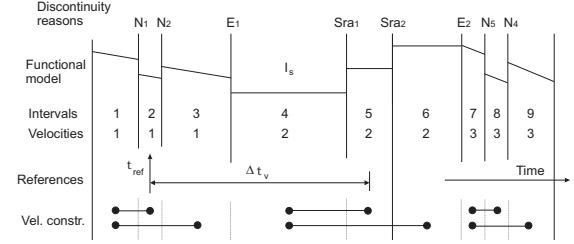
where

$$M_v = -11.3475 + 3.2358 \cdot \log_{10} d_{erq} \quad (10)$$

is a rule of thumb derived from world-wide felt earthquakes of different magnitudes, at different distances, and on different bedrocks—information taken again from the U.S. Geological Survey Earthquake Hazards Program (U.S.G.S., 2008).  $M_{min}$  is user-defined.

### 3.8 Update of ADDNEQ2 input files

A more consistent ADDNEQ2 reference frame solution is achieved by updating the list of used equipment (STA), the list of reference sites (FIX), and the a priori coordinates and velocities (CRD/VEL) files with the analyses result of the time series collected by FODITS (see Figures 1 and 2).



**Figure 3.** Hypothetical scenario of velocity changes. The vertical lines represent the delimitation of the velocity intervals. The reasons of the delimitations are indicated on top of them: ( $N_n$ ) are new identified significant discontinuities, ( $E_n$ ) earthquakes, and ( $Sra_n$ ) indicates equipment changes ( $r$  denotes a receiver and  $a$  an antenna). The velocity parameters are enumerated. The reference epoch  $t_{ref}$  and the a minimum interval length  $\Delta t_v$  are user-defined parameters. Set up relative constraints on velocity intervals are indicated with a connection line.  $I_s$  is the selected velocity interval which represents the reference site (if any).

By allowing velocity changes (see Section 3.6) during the ATI-procedure we may end up with the time series fragmented in time intervals delimited by new or predefined events. Figure 3 illustrates an hypothetical scenario of velocity changes allowed after earthquakes ( $E_n$ ) and new discontinuities ( $N_n$ ).

Velocity intervals belonging to the same velocity parameter—after all iteration and screening steps—are continuous (e.g., velocity intervals 1, 2, and 3 of Figure 3). Updated ADDNEQ2 input files will then contain the subdivision of the time series in velocity intervals and, if any, the relative velocity constraints set up on them. As Figure 3 illustrates, the relative velocity constraints are set up on pairs of velocity intervals belonging to the same velocity parameter.

From the experience of the GNSS analysis we know that a reliable station velocity cannot be derived from a too short interval of data. For that reason we introduce two user-defined parameters, a minimum interval length  $\Delta t_v$  and the reference epoch  $t_{ref}$ , to select the main—long enough—velocity interval of stations (see Figure 3). The procedure of selection of this main velocity interval can be resumed in:

1. Selection of the velocity parameter as close as the reference epoch  $t_{ref}$  for which  $\Delta t_v$  covers the biggest time interval.

2. Select the main velocity interval belonging to the selected velocity parameter selected in step 1. as close as the reference epoch  $t_{ref}$ .

For long time series of coordinates a datum definition for station velocities is advisable. This implies to have only well observed reference sites within the time interval covered by the time series and, as a consequence of that, to reject poorly observed reference sites from the list of reference stations (FIX). FODITS rejects those reference stations from the list for which the time interval of the selected velocity parameter—the one including the main velocity interval—does not cover at least the minimum interval length  $\Delta t_v$ .

#### 4 Examples of the ATI-procedure

Figures 4 and 5 show both the first four iteration steps of the ATI-procedure (see Section 3.2) while analyzing the daily CODE<sup>1</sup> coordinate time series of the IGS station NTUS, Singapore (Republic of Singapore).

For both time series analyses a velocity change was allowed only after significant discontinuities due to predefined earthquake events (see Sections 3.6 and 3.7), the significance level was set to  $\alpha = 0.01$  (see Section 3.3), the additional threshold parameters for discontinuities were set to  $\kappa_d = 0$ ,  $h_d = 5 \text{ mm}$ ,  $v_d = 10 \text{ mm}$  (see Section 3.4), and those for outliers were set to  $\kappa_s = 3.0$ ,  $h_s = 20 \text{ mm}$ ,  $v_s = 30 \text{ mm}$  (see Section 3.5).  $M_{min}$  was set to 5.5 magnitudes. We point out that the additional threshold parameters for discontinuities— $\kappa_d$ ,  $h_d$ , and  $v_d$ —were set on purpose to low values for the ATI-procedure to progress for at least four iteration steps.

We start describing the results of Figure 4. With the solely aim to better illustrate the behaviour of the ATI-procedure we did not add on purpose any periodic functions for the analysis. This allows us to better visualize the velocity changes and to better perceive the behaviour of the normalized test time series  $g(t_i)$ .

The (top-left) subfigure (of Figure 4) shows the screened functional model after the *1st* iteration step of the ATI-procedure. According to the legend (below Figure 4) we observe that at both epochs of the two earthquake events—(*E1*), a 8.6 magnitude, at epoch 28-Mar-2005 16:05:37, at a distance of 735 km); and (*VE2*), a 8.5 magnitude, at epoch 12-Sep-2007 11:06:10, at a distance of 689 km—a discontinuity was

found significant. These two discontinuities due to earthquake events are also clearly verifiable by eye in the residual time series. After the first earthquake (*E1*), according to the legend, no velocity change was detected. As consequence the velocity parameter after (*E1*) was removed from the functional model during the screening procedure. On the contrary, after the second earthquake event (*VE2*), a significant velocity change was found. In this case the velocity parameter after the epoch of (*VE2*) was therefore kept in the functional model. From near the end of 2006 until after mid 2007 we notice a lack of data. Just before the end of such long interval (of about 9 months), on 25-Jun-2007, we observe the equipment change (*Sra*): both receiver and antenna were replaced. According to the legend, the discontinuity parameter set for this equipment change was removed from the functional model after have been found non-significant. After this three-steps screening procedure the most probable discrepancy in terms of discontinuity (*F*) is identified by locating the maximal value in the normalized test time series  $g(t_i)$  (see Eq. 5).

After the *2nd* iteration step (top-right subfigure) we immediately observe that the (in the previous (*1st*) iteration step and labeled with (*F*)) proposed new discontinuity, was now found significant (*N*). As consequence of that, the ATI-procedure carries on by searching for for a new *most probable discontinuity*. Compared to the situation after the *1st* iteration step, we now have (after this *2nd* iteration step) a significant discontinuity for the equipment change (*Sra*). This discontinuity is particularly visible in the north-component of the functional model. Some of the proposed outliers after the *1st* iteration step were found significant at the end of this *2nd* iteration step (see the thin dashed vertical lines without label in all subfigures).

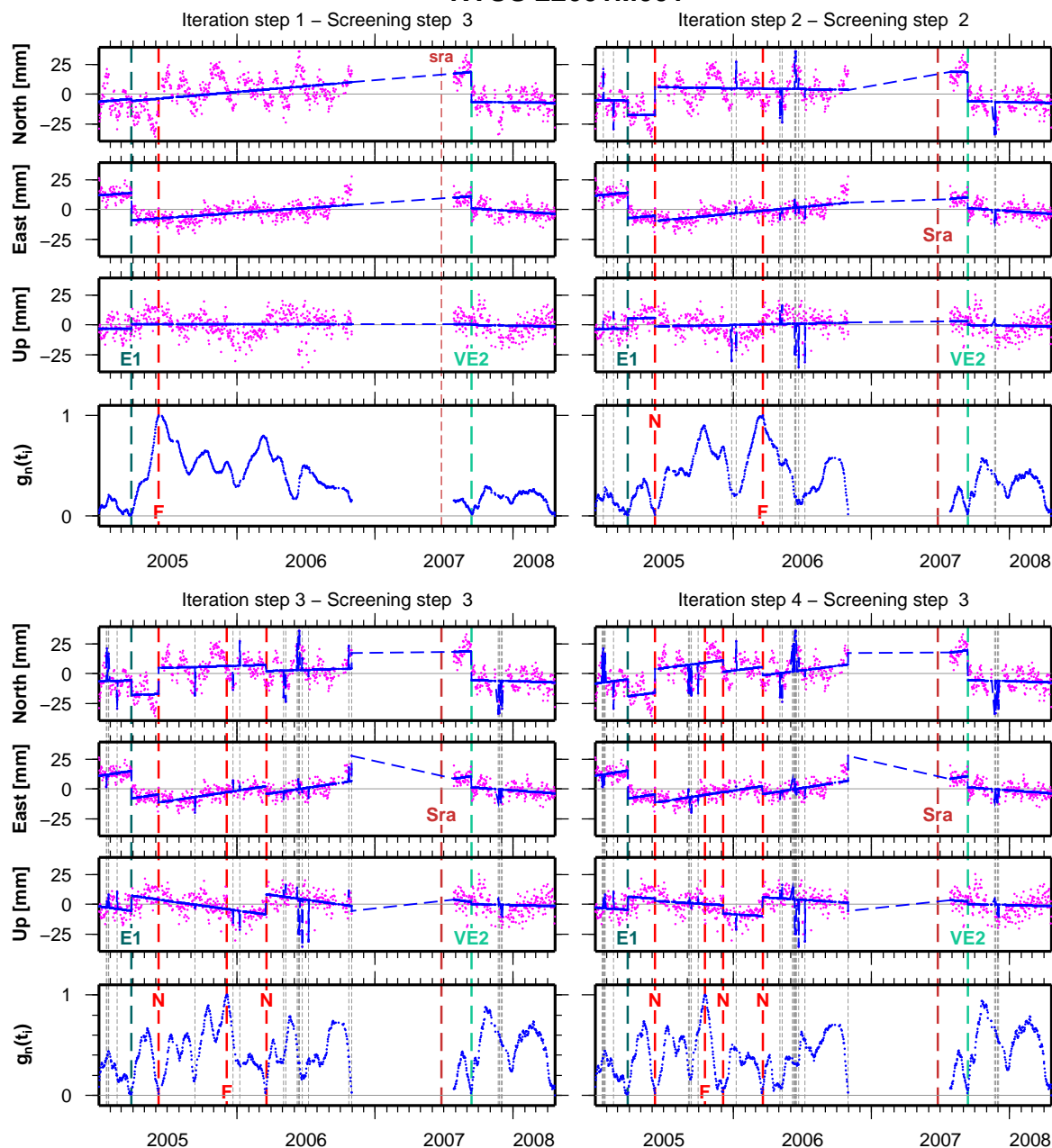
After the next two iteration steps—the *3rd* and *4th*—we only observe how the ATI-procedure proposes a new discontinuity to compensate the discrepancy between the functional model and the time series, and how this proposed discontinuity is then accepted as significant in the successive iteration step. The significance of the equipment change (*Sra*) as well as the two earthquake events (*E1*) and (*VE2*) does not change anymore.

The number of significant outliers increments after each iteration step. This is easily explained: since the residuals as well as the RMS (Root Mean Square) become smaller and smaller after each iteration step, more and more residuals fulfill the criteria and are proposed as outliers.

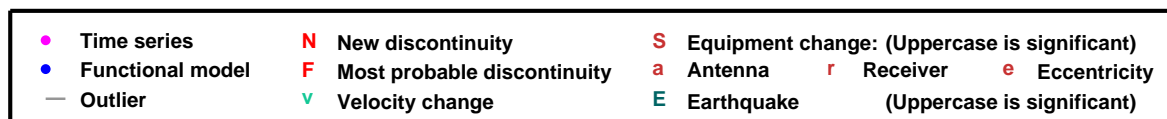
The configurations and the additional thresholds used for the analysis shown in Figure 5 are the same as the ones used for the analysis of Figure 4 except

<sup>1</sup> Center for Orbit Determination in Europe (CODE), a consortium consisting of the Astronomical Institute University of Bern (AIUB, Switzerland), the Federal Office of Topography (swisstopo, Wabern, Switzerland), and the Bundesamt für Kartographie und Geodäsie (BKG, Frankfurt a. M., Germany).

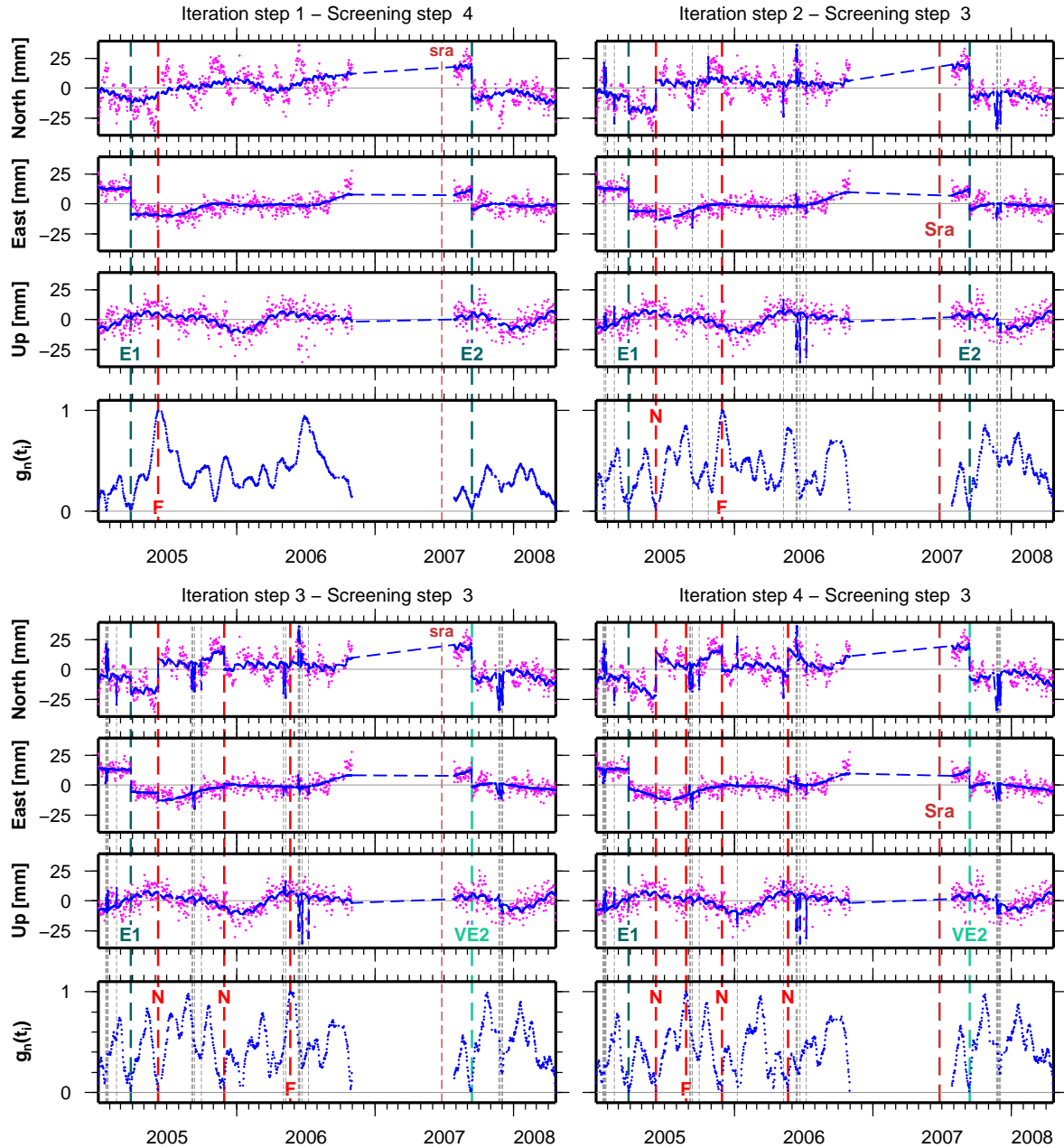
## NTUS 22601M001



**Figure 4.** Iteration steps 1 (top-left), 2 (top-right), 3 (bottom-left), and 4 (bottom-right) of the ATI-procedure for the time series analysis by FODITS of the IGS station NTUS, Singapore (Republic of Singapore). The CODE daily time series covers a time interval from 01-Jan-2005 to 20-Apr-2008. For each iteration step the residuals and the functional model are shown for the three components North, East, and Up. The normalized test time series for the identification of the most probable discontinuity ( $g_n(t_i)$ ) are shown.



## NTUS 22601M001



**Figure 5.** Iteration steps 1 (top-left), 2 (top-right), 3 (bottom-left), and 4 (bottom-right) of the ATI-procedure for the time series analysis by FODITS of the IGS station NTUS, Singapore (Republic of Singapore). The CODE daily time series covers a time interval from from 2005-01-01 to 2008-04-20. For each iteration step the residuals and the functional model are shown for the three components North, East, and Up. The normalized test time series for the identification of the most probable discontinuity ( $g_n(t_i)$ ) are shown.

that we ordinarily added periodic parameters (yearly, half-yearly, monthly, and half-monthly).

The (top-left) subfigure of Figure 5 illustrates (again) the screened functional model after the *1st* iteration step of the ATI-procedure. Let us compare it with the screened functional model after the

*1st* iteration step of Figure 4. Right away we notice the presence of significant periodic parameters. In fact all added periodic parameters—yearly, half-yearly, monthly, and half-monthly—were found significant. As a consequence of that, this time more difficult to be observed by eye and rather understand-



able by means of the legend, no significant velocity change was found after the second earthquake event (*E2*). Again compared to the 1st iteration step of Figure 4 we further notice a light different behaviour of the normalized test time series  $g(t_i)$ . Nevertheless, the most probable discontinuity (*F*) was identified exactly at the same epoch as without additional periodic functions. An incumbent remark: especially in the north-component we observe one or more signals of period of about three/four months that were clearly not absorbed by the functional model since these periods were not added to it.

The next three iteration steps of the ATI-procedure are shown in sequence in the (top-right), (bottom-left), and (bottom-right) subfigures of Figure 5. As opposed to the 1st iteration step, we end up after the 2nd iteration step with a significant discontinuity due to equipment change (*Sra*). From a reasonable point of view the ATI-procedure should have been stopped after this 2nd or even already after the 1st iteration step, because in the next two iteration steps—the 3rd and the 4th—the ATI-procedure introduces only new discontinuities to compensate the signals not absorbed by the functional model. The introduction of these new discontinuities led to alternatively change the significance of the equipment change—(*sra*) to (*Sra*) and vice versa—and to even review the significance of the velocity change after the second earthquake event (*E2*)!

Let us now add some final remarks to both sequences of four iteration steps. We saw that the ATI-procedure keeps adapting the functional model to the residual time series as long as the new identified discontinuity parameters was found significant (see Section 3.2). Practically, in absence of limiting criteria, the ATI-procedure could keep adding new discontinuity and new outlier parameters to the functional model as long as the degree of freedom of our inversion problem does not become negative. It is therefore task of the user to know and define the right additional criteria to control the ATI-procedure before a meaningless adaptation of the model to the time series begins.

## 5 Examples for FODITS Processed Time Series

Two station coordinate time series are analyzed by FODITS: the weekly EUREF-combined (see Section 5.1) and the CODE global daily solution (see Section 5.2) where the analysis results were used to update the input files for a new, more consistent, ADDNEQ2 solution with reassessed time series. Not only coordinate time series may be analyzed by FODITS: an example of this versatility of FODITS

with a non-coordinate, one-dimensional time series is presented in Section 5.3.

### 5.1 Time Series of Weekly EUREF-Combined Station Coordinates

The ATI-procedure—the core algorithm of FODITS—is applied to weekly station coordinate time series. Coordinate time series extracted from the combined solutions computed at BKG (Bundesamt für Kartographie und Geodäsie, Frankfurt a. Main, Germany) from the local analysis center contributions were processed by FODITS. Figure 6 shows four examples of stations of the EUREF permanent network (EPN): BZRG, Bozen (Italy) (top-left), GLSV, Kiev (Ukraine) (top-right), GANP, Ganovce (Slovakia) (bottom-left) and REYK, Reykjavik (Iceland) (bottom-right). Yearly, half-yearly, monthly, and half-monthly predefined periodic parameters were added in the functional model of the stations. For all analyses a velocity change was allowed only after significant discontinuities due to predefined earthquake events (see Section 3.6), the significance level was set to  $\alpha = 1.0$  so that the progress of the ATI-procedure was controlled only by the additional threshold parameters: for discontinuities they were set to  $\kappa_d = 1.5$ ,  $h_d = 5 \text{ mm}$ ,  $v_d = 10 \text{ mm}$  (see Section 3.4) and for outliers they were set to  $\kappa_s = 1.5$ ,  $h_s = 5 \text{ mm}$ ,  $v_s = 10 \text{ mm}$  (see Section 3.5).  $M_{min}$  was set to 4.5 magnitudes. In all time series the ATI-procedure identified the prominent GPS week 1400 model change <sup>2</sup> (the only indicated with (*N*) for all stations). Significant discontinuities due to antenna and receiver changes (*Sra*) were found for both stations BZRG and GLSV. Whereas the equipment change (*srae*, antenna, receiver, and antenna eccentricity from 0.0555 m to 0.0630 m in the height) in the time series of REYK was classified as non-significant. If we look carefully at the time series of station REYK we may do observe a change in the noise level after the epoch of (*srae*) in the up component: the time interval from (*srae*) to the last epoch of the analyzed time series was eventually too short to recognize the equipment change as significant. An outlier for the week containing the middle epoch 14-Nov-2007 was detected instead.

<sup>2</sup> At GPS week 1400 significant model changes affect for both daily global and weekly EPN solutions: switch to the absolute GNSS PCV model and use of IGS05 terrestrial reference frame realization conform to the absolute PCV model. In addition CODE has started to use the global mapping function (GMF), to use the a priori GPT (Global Pressure Temperature) model for hydrostatic component for the troposphere Boehm (2006), to use an updated set of solar radiation pressure a priori model coefficients for GPS and GLONASS (see Dach *et al.* (2007)), and other minor model updates.

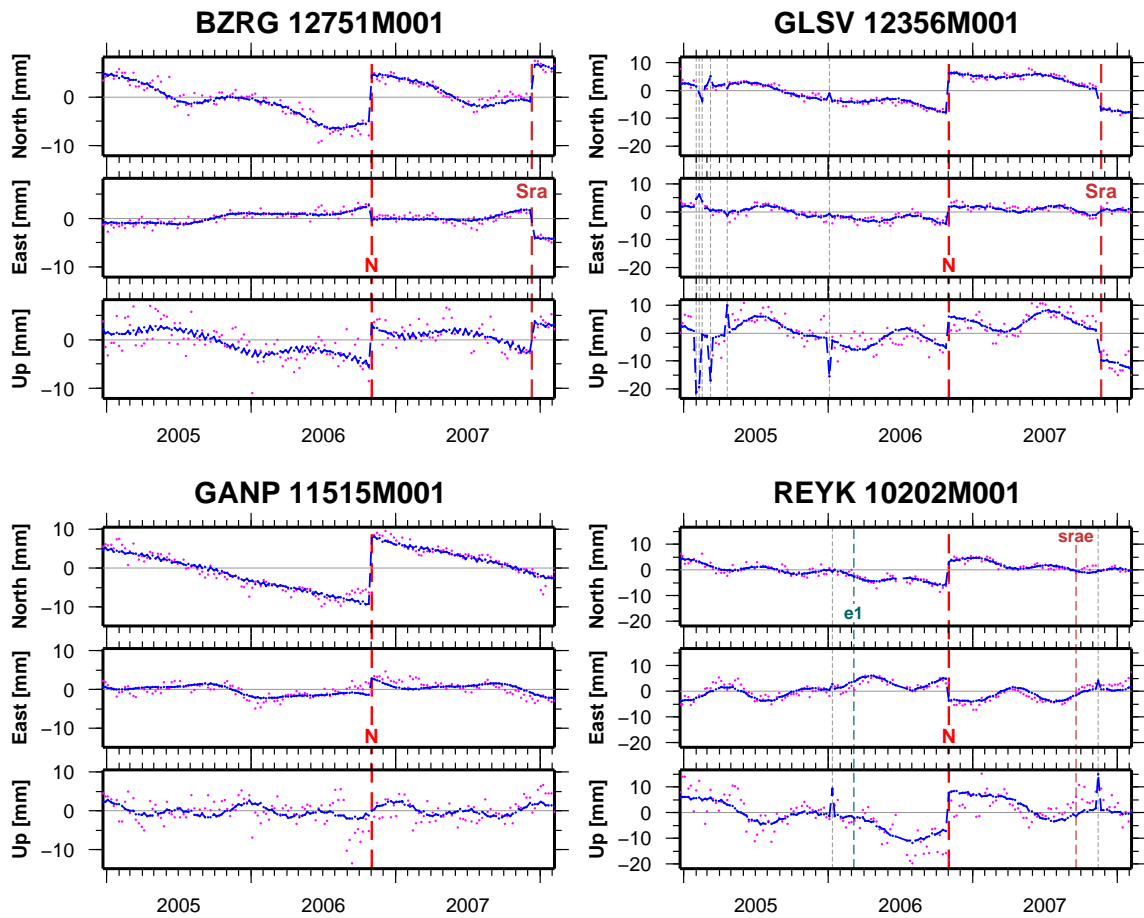


Figure 6. EUREF weekly solution time series.

● Time series	<b>N</b> New discontinuity	<b>S</b> Equipment change: (Uppercase is significant)
● Functional model	<b>F</b> Most probable discontinuity	<b>a</b> Antenna <b>r</b> Receiver <b>e</b> Eccentricity
— Outlier	<b>v</b> Velocity change	<b>E</b> Earthquake (Uppercase is significant)

At epoch 2006-Mar-06 14:18:56 a discontinuity parameter due to an earthquake of magnitude 4.5 with epicentre of 30 km from station REYK (*e1*) was found to be non-significant. Since velocity changes are allowed only after significant discontinuities due to predefined earthquake events, no velocity changes were allowed after that earthquake—which also was not necessary if we compare into the time series and functional models in Figure 6.

## 5.2 Reassessment of Daily CODE Station Coordinate Time Series

The realization of a more consistent reference frame is achieved by reassessing the coordinate time series (see Section 3.8). Daily station coordinates of CODE's IGS final solution (2005-2008) are ana-

lyzed by FODITS in this example in order to realize a more consistent reference frame by the program ADDNEQ2.

The user-defined parameters for the FODITS analysis are as follows: a velocity change was allowed after any earthquake events (see Section 3.6), the significance level was set to  $\alpha = 0.01$ , the additional threshold parameters for discontinuities were set to  $\kappa_d = 3.0$ ,  $h_d = 10 \text{ mm}$ ,  $v_d = 30 \text{ mm}$  (see Section 3.4), and those for outliers were set to  $\kappa_s = 4.0$ ,  $h_s = 10 \text{ mm}$ ,  $v_s = 30 \text{ mm}$  (see Section 3.5).  $M_{min}$  was set to 6.0 magnitudes. Furthermore, the minimum interval length for velocities was set to  $\Delta t_v = 2.5 \text{ years}$  while the reference epoch  $t_{ref}$  was set to (01-Jan-2000 00:00:00) according to the IGS05 realization of the reference frame.

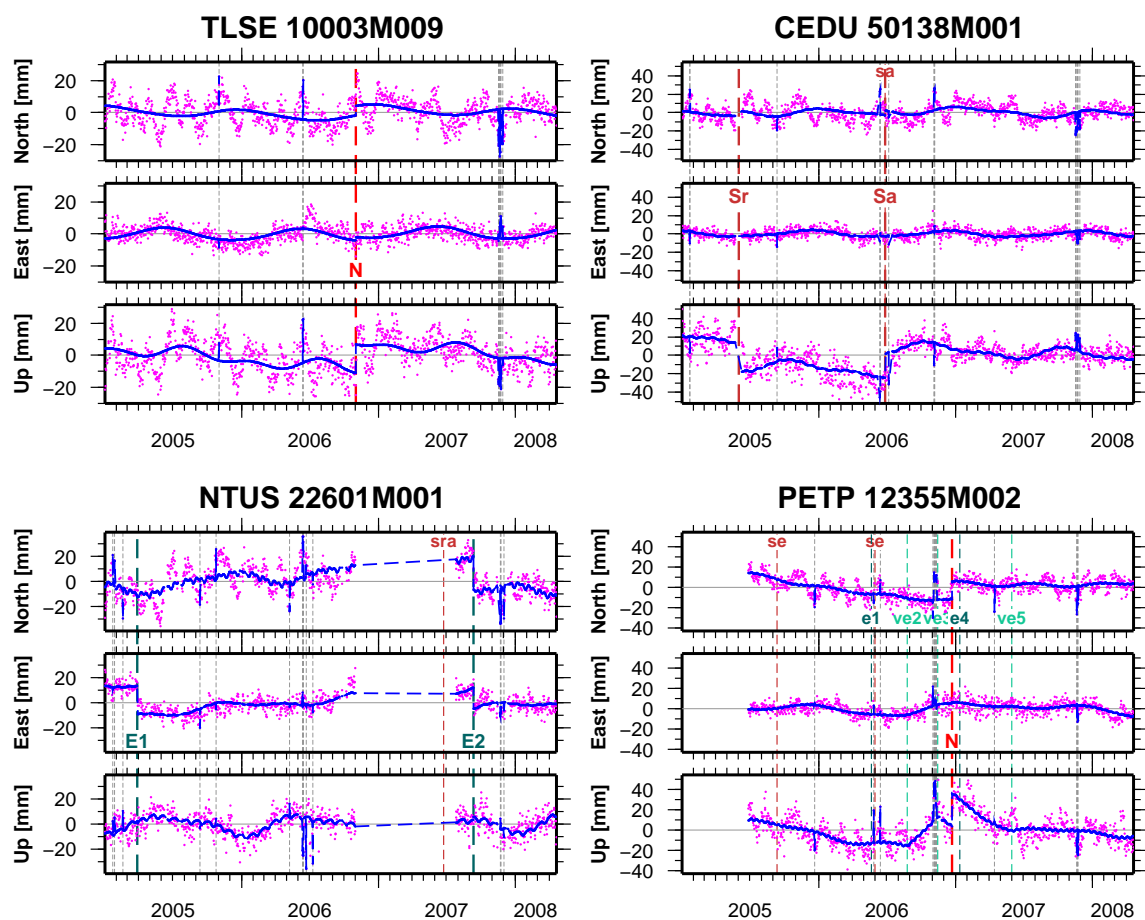


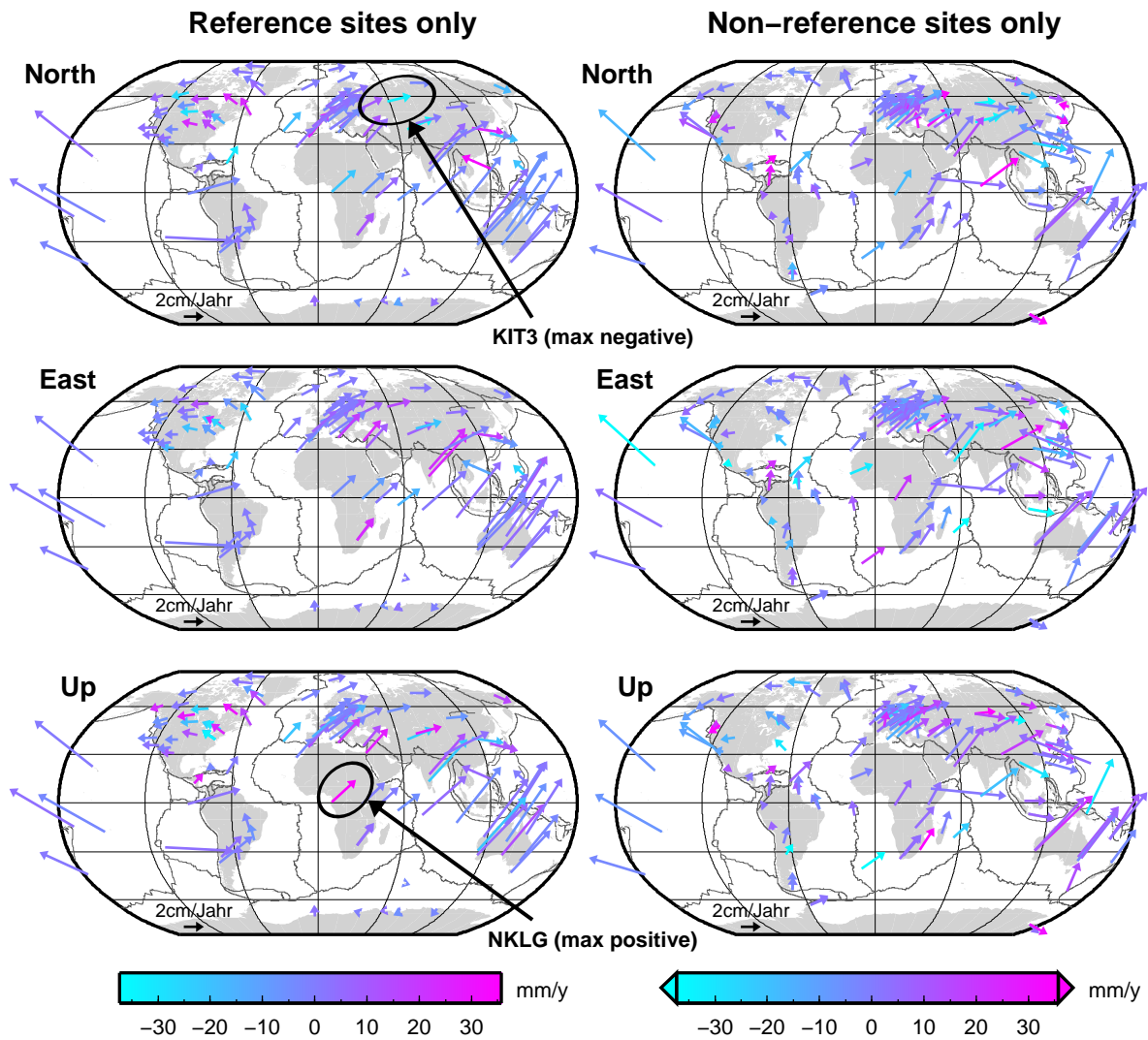
Figure 7. CODE daily solution time series.

● Time series	<b>N</b> New discontinuity	<b>S</b> Equipment change: (Uppercase is significant)
● Functional model	<b>F</b> Most probable discontinuity	<b>a</b> Antenna <b>r</b> Receiver <b>e</b> Eccentricity
— Outlier	<b>v</b> Velocity change	<b>E</b> Earthquake (Uppercase is significant)

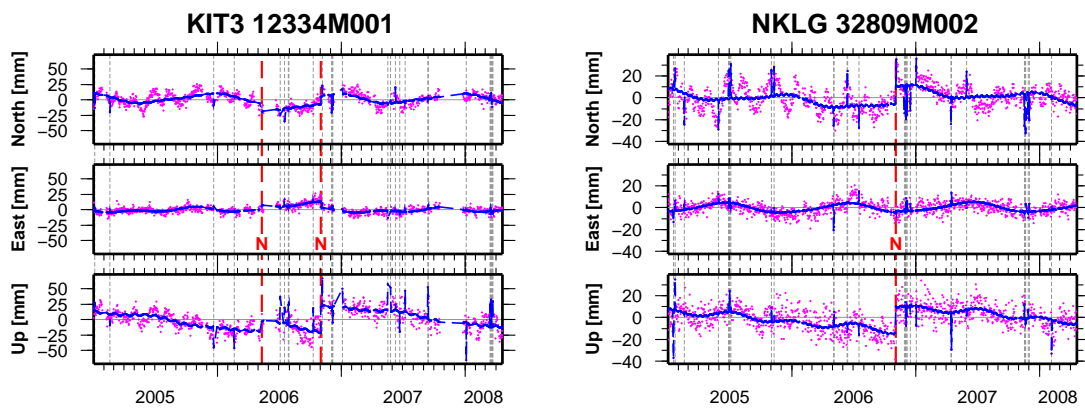
Table 1. Summary of the FODITS analysis of daily station coordinates of CODE's IGS final solution (2005-2008).

Number of analyzed stations	238
Total number of all significant discontinuities detected	224
Total number of proposed discontinuities due to equipment changes	103
Number of significant discontinuities due to equipment changes	21
Total number of proposed discontinuities due earthquake events ( $M > 6.0$ mag)	87
Number of significant discontinuities due to earthquake events	9
Total number of new significant discontinuities identified	197
- Number of discontinuities due to model change (1) (introduction of absolute PCV models, GPS week 1400)	81
Resulting number of new discontinuities of unknown reason	116
Total number of new significant identified outliers	3139
Total number of velocity changes	32
Total number of relative constraints on velocity parameters	397
Number of reference sites contributing to datum definition before the FODITS analysis	146
Number of reference sites contributing to datum definition after the FODITS analysis	104
Resulting number of rejected reference sites	42

## Station velocities of stacked CODE daily solutions (2005–2008) after reassessment procedure with color-coded velocity improvements



### FODITS analyses of maxima improvements of reference sites



**Figure 8.** Result of the reassessment procedure of CODE daily solution time series (2005-2008) in terms of station velocities. (top) station velocities after reassessment: the velocity improvements are color-coded and the improvements are given for the North, East, and Up components. (bottom) time series of maxima of velocity improvements: (left) maximal negative and (right) maximal positive.

Additional periodic parameters—yearly, half-yearly, monthly, and half-monthly—were considered in this FODITS analysis.

Table 1 reports the summary of the results of the FODITS analysis. The number of detected discontinuities and outliers in all 238 analyzed stations points out how important is the automated analysis of the time series.

Figure 7 illustrates the four results of the FODITS analysis.

The (top-left) subfigure shows the result of the FODITS analysis of station TLSE, Toulouse (France). The discontinuity ( $N$ ) at epoch 06-Nov-2006 was found significant. This discontinuity, again, corresponds to the prominent switch from the relative to the absolute antenna phase centre modelling in GPS week 1400 in the IGS processing. Table 1 reports the impact of this model change on the results of the FODITS analysis.

The (top-right) subfigure of Figure 7 shows the result of the FODITS coordinate time series analysis of station CEDU, Ceduna (Australia). Two of the three equipment changes produced significant discontinuities: the first one was a receiver change (from a AOA ICS-4000Z ACT (GPS+GLONASS) to an ASHTECH UZ-12 (GPS-only)) at epoch 11-May-2005 04:00:00, while the second one was practically due to the removal and montage of the same antenna—in fact the antenna AOAD/M.T AUST was first substituted by the antenna LEIAT504 AUST on 27-Jun-2006, then, the latter was again re-substituted by the original antenna AOAD/M.T AUST about twenty days later. Since the two last equipment changes were chronologically close to each other, FODITS rightly identified only one of them—the first one—as significant.

The (bottom-left) subfigure of Figure 7 shows the result of the FODITS coordinate time series analysis of station NTUS, Singapore (Republic of Singapore). This result corresponds to the result of the ATI-procedure of Figure 5 after 1st iteration step with the exception that more outliers were identified, this due to the slight different criteria for outliers: the horizontal additional threshold  $h_s = 10\text{ mm}$  for this analysis was smaller compared to the  $h_s = 20\text{ mm}$  of the analysis presented in Section 4. We remind that the two discontinuities correspond to the two earthquakes 8.6 magnitude at epoch 28-Mar-2005 16:05:37 at a distance of 735 km ( $E1$ ) and 8.5 magnitude at epoch 12-Sep-2007 11:06:10 at a distance of 689 km ( $E2$ ). No significant velocity change was found after any of these two earthquakes.

The (bottom-right) subfigure of Figure 7 shows the result of the FODITS coordinate time series analysis of station PETP, Petropavlovsk-Kamchatka (Kamchatka Region, Russian Federation). None of

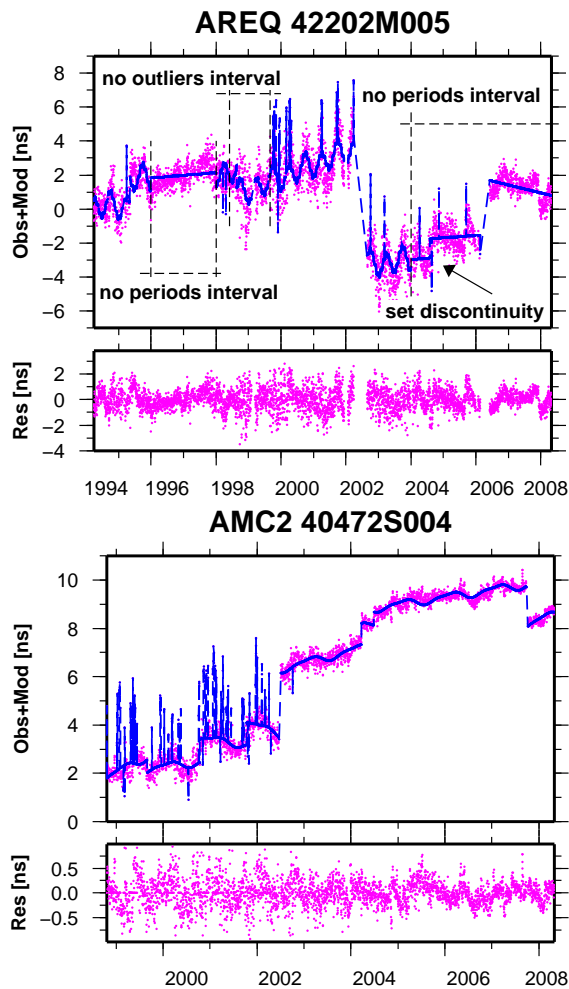
the two equipment changes (labeled with ( $se$ ), where, according to the legend,  $e$  stays for antenna eccentricity) and five earthquake events—the first ( $e1$ ) a 6.2 magnitude at epoch 22-Jun-2006 13:04:49 at a distance of 134 km, the second ( $ve2$ ) a 6.5 magnitude at epoch 28-Aug-2006 21:30:13 at a distance of 225 km, the third ( $ve3$ ) a 8.3 magnitude at epoch 15-Nov-2006 11:08:29 at a distance of 815 km, the fourth ( $e4$ ) a 8.1 magnitude at epoch 13-Jan-2007 04:13:56 at a distance of 813 km, and the fifth ( $ve5$ ) a 6.4 magnitude at epoch 30-May-2007 20:13:17 at a distance of 136 km—apparently generated significant discontinuities in the coordinate time series. Namely, FODITS rather inserted a new discontinuity ( $N$ ) between earthquake events ( $ve3$ ) and ( $e4$ ). The real behaviour of the station PETP between the epochs of the first ( $e1$ ) and the last ( $ve5$ ) earthquake events remains unknown. Nevertheless, the discontinuity ( $N$ ) introduced by FODITS solves our issue to reassess the time series.

After have analyzed all station coordinate time series FODITS used the collected analysis results to updated the list of used equipment (STA) (with the relative constraints on the fragmented velocity intervals (see Section 3.8)), the list of reference sites (FIX), and the a priori coordinates and velocities files (CRD/VEL) for the successive and (in this example) final more consistent reference frame realization computed by ADDNEQ2 (see Section 3.8).

Figure 8 reports the result in terms of station velocities and velocity improvements with respect to the first coordinate set solution performed by ADDNEQ2 before the reassessment procedure. In the figure we make the distinction between reference sites (left-column) and non-reference sites (right-column). In all components (North, East, and Up) of all velocity fields we hardly see regional correlations of velocity improvements. We rather see prominent velocity improvements at single stations that are not regionally correlated to each other instead. For reference sites the velocity improvements varies from a negative maximum of  $-37.4\text{ mm/y}$  to a positive maximum of  $35.3\text{ mm/y}$ . The analyzed coordinate time series of the maximum negative (station KIT3, Kitab, Uzbekistan) and maximum positive (NKLK, Libreville, Gabon) velocity improvements are illustrated in the bottom part of Figure 8. In both time series FODITS found a new discontinuity ( $N$ ) at epoch of the prominent model change in GPS week 1400 (see Table 1).

### 5.3 Use of FODITS for Other Applications

The algorithm to analyze time series cannot only be applied to daily or weekly coordinate time series, but also to the results from a kinematic positioning or any other time series. The easiest interface is the so-



**Figure 9.** Re-aligned P1-P2 differential code bias (DCB) time series analyzed by FODITS. In the (top) series of both subfigures the pseudo-observations (magenta) are shown together with the functional model (blue). Predefined events and intervals are indicated, too. In the (bottom) series of both subfigures the series of residuals with respect to the functional model are shown.

called PLT files that usually contains the residuals of the ADDNEQ2 solutions. Figure 9 gives an example.

It shows the time series of P1-P2 DCB (differential code bias) corrections for two GNSS stations for 15 years. In this case only one component was analyzed. The standard deviation of the observations were considered in the analysis.

By the EVL file the user has the opportunity to set up discontinuities, outliers, and periodic components either conditionally (tested for significance) or unconditionally (fixed) at given epochs. By the EVL file these three components of the functional model can also be removed unconditionally from the functional model during specific intervals. This is why we may introduce signals of same period with both different or the same phases. These detailed control op-

tions may be very useful to influence the results from FODITS in a special way (e.g., to keep the discontinuity for the model change at the GPS week 1400 at this epoch, even if there are not data during this interval because the station was inactive). Of course this opens a wide field for special experiments. In the case of processing the DCB time series these options were used to suppress the outlier detection for intervals with a higher noise level or to define intervals without periodic functions, e.g., because the thermic environment for the receiver seems to be different than in other intervals.

## 6 Summary

FODITS, a new component of the Bernese GPS Software, allows the analysis of time series up to three components per series. The spatial variance-covariance information is considered as far as it is available. The program is mainly used in combination with ADDNEQ2, the program for the combination of the normal equation to generate time series.

Basically, the core of FODITS consists in a functional model with discontinuity, outlier, periodic parameters, and one or more linear station velocities. The corresponding parameters are set up in the functional model in order to adapt the model to the time series. The epochs for outliers and discontinuities information may either be predefined or automatically identified. The identification of these model components may be seen as a rejection/reduction of discrepancies between the time series of the data and the functional model. The algorithm starts with the biggest and end with the smallest discrepancy. The adaptation, test, and identification procedure (ATI-procedure) works iteratively until no further new identified discrepancies are found to be significant. The significance level is user-defined. The time series are analyzed independently from one another.

Peculiar input/output interfaces have been designed for station coordinate time series reassessment purposes. Such time series are read by FODITS directly from ADDNEQ2 outputs result, or, from a series of coordinate files. Informations of equipment changes and earthquakes can be considered by FODITS, too, so that discontinuity parameters at their epochs can be set up and be tested for significance. By means of a user-defined events list file (EVL) one has the opportunity to set up conditionally or unconditionally any kind of parameters of the functional model, or, define intervals of time where no parameters should be set up in the model. The collection of the FODITS analysis results allows it finally to update the a priori information for a subsequently ADDNEQ2 solution which takes into account found peculiar events in the time series.

The functionality of FODITS has been verified with different types of examples: coordinate time series from a daily or weekly processing or even a multi-year time series of P1-P2 DCB. In all cases FODITS has generated proper results in a highly automated mode.

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