

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 derived 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 used 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 DIA (detection, identification, and adaptation) 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, e.g., differential code biases, 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

1 Introduction

Since 15 years the International GNSS Service (IGS) processes GNSS (Global Navigation Satellite Systems) measurements on a daily basis (Dow, 2005).

Several regional 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 to detect outliers and discontinuities in time series. The program adapts a functional model containing corresponding parameters. In addition the functional model may also consider one or more linear station velocities and a set of periodic signals (periods are pre-defined 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 (suggested periods, potential discontinuities, and different velocities) by eliminating the non-significant components. Furthermore, the algorithm adds discontinuities and outliers where it is necessary to obtain the optimal representation of the original time series by the function model.

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 a functional model in the context of GPS quality control. 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 improve the performance of the program for long time series with 5000 data points in three components. This results in 15000 pseudo-observations that need to be processed per station because 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 of the algorithm 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 are described. Section 4 demonstrates the behaviour of the ATI-procedure during the iteration steps in an example of analyzing CODE¹ (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 describes examples 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., from an 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 session solutions from so-called NEQ-Files) with a consistent datum definition (represented by the coordinates and velocities of a 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.

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. Geolog-

¹ 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), the Bundesamt für Kartographie und Geodäsie (BKG, Frankfurt a. M., Germany), and the Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG/TUM, Germany). CODE is acting as a global analysis center of the IGS but also contributes as a local analysis center to EUREF.

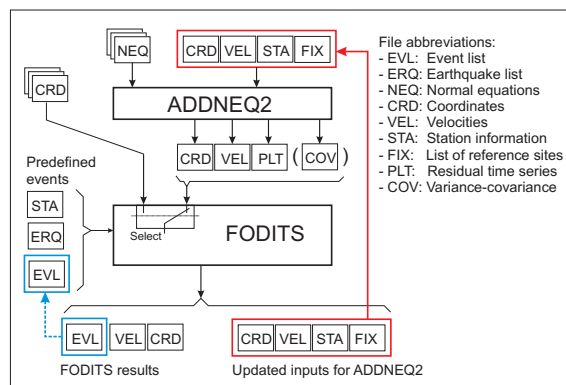


Figure 1. Embedding of FODITS in Bernese GPS Software.

ical 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. This is an important feature to make the results generated by FODITS compatible to external sources, e.g., the solution intervals given in the ITRF solutions. 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 combined 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 $\mathbf{y}_j(t_i)$ based on a number of $i = 1, \dots, n_{t,j}$ observations – epochs of the time series to be processed. 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 consists of a set of the following components:

$$\mathbf{y}(t_i) = \mathbf{c}_0 + \sum_{k=1}^{n_v} \mathbf{v}_k(t_i - t_{v,k}) \cdot \eta_{v,k}(t_i) + \sum_{k=1}^{n_d} \mathbf{d}_k \cdot \eta_{d,k}(t_i) + \sum_{k=1}^{n_s} \mathbf{s}_k \cdot \eta_{s,k}(t_i) + \sum_{k=1}^{n_p} [\mathbf{a}_k \sin(2\pi f_k t_i) + \mathbf{b}_k \cos(2\pi f_k t_i)] \cdot \eta_{p,k}(t_i) \quad (1)$$

- 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 .

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 velocities, discontinuities, outliers, and periodic functions are given by the variables n_v , n_d , n_s , 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 are processed together. Instead of station coordinates also other time series of up to three components 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 processing in FODITS is performed 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 by a result variance-covariance file (COV) and in the residual file (PLT).
2. A list of predefined events, 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 via a so-called event list (EVL file). There are three opportunities to influence the procedure: (a) The resulting functional model will contain the listed components independent from their significance, e.g., to introduce solution intervals from an external source. (b) The components can be introduced as a proposal that are verified during the processing for their significance, e.g., epochs of changing the processing models. (c) Specific components of the default functional model can be suppressed during specific intervals, e.g., to consider different environmental conditions during a specific period. These options give the user the complete control to influence the resulting functional model according even to very specific needs.

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 an alternative user-defined configuration is given.

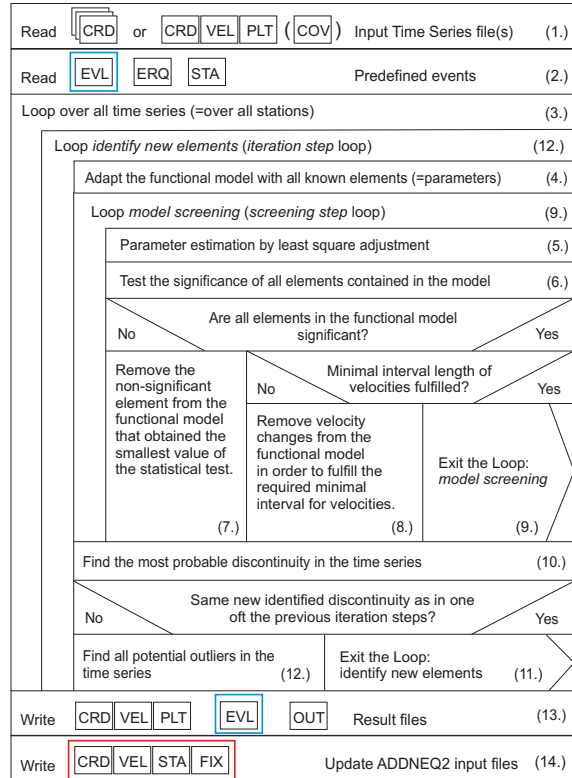


Figure 2. The Nassi-Shneiderman diagram of FODITS; the numbers refer to the steps of the algorithm in the text.

5. The parameters of the functional model are estimated by LSA using the elements of the time series as the pseudo-observations.
6. All elements – discontinuities, velocity changes, outliers, and periodic functions – of the functional model are tested for their significance.
7. All non-significant elements are gathered and sorted (from the smallest to the biggest) result of their significant tests. Only the element with the smallest significance test indicator is removed from the functional model in one step. The parameter corresponding to this element is removed from the normal equation and the system is inverted again to verify whether there are more non-significant elements in the current functional model.
To speed up the procedure, up to 10 outliers can be removed from the functional model within one step as far as no other element appears in-between with the smallest significance test value.
8. A minimal validity interval for velocities is required: from the smallest to the most significant velocity change, velocity intervals are removed from the functional model until all velocities are longer than the user-defined minimal validity interval for velocities. If one or more velocity parameters are removed from the functional model, a screening step is repeated (starting from step 5.).
9. Screening steps – steps 5. to 8. – are repeated until all elements of the functional model are significant.
10. The epoch of the biggest discrepancy between the time series and the current functional model is identified that can be fixed by a discontinuity. This "most probable discontinuity" is added to the functional model at this epoch.
11. The iteration loop is finished if the new identified discontinuity from step 10. was already found in one of the previous iteration steps. This avoids also complex infinite loop of several iteration steps where elements keep being added and removed from the functional model. At the end of the iteration loop we either continue processing the next station (step 3.) or to generate the program output and result files (step 13.).
12. Before the next iteration loop starts all potential outliers are identified and added to the functional model. We start the net iteration with step 4..
13. Result and output files are generated.
14. Input files for a follow-up ADDNEQ2 run are updated.

The core of the algorithm consists of adaptation (step 4.), test (step 6.), and identification (steps 10. and 12.) (ATI) steps. The progress of the algorithm is given in terms of screening and iteration steps: a screening step (adaptation and test steps of the ATI-procedure)

is completed with the tests of significance of step 6. while an iteration step (identification steps of the ATI-procedure) is completed with the search for the "most probable discontinuity" (step 10.).

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 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 have 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 increases significantly the speed of the program.

3.3 Tests of Significance

We verify the significance of all estimated parameters of the functional model $\mathbf{x} = \{\mathbf{d}, \mathbf{s}, \mathbf{p}\}$ 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 α .

Let us add two remarks to this significance test: First, for periodic functions we test for the significance of the amplitude. Second, a minimal 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).

Moreover, the ATI-procedure verifies for all pairs of velocities $\{\mathbf{v}_m, \mathbf{v}_n\}$ belonging to the analyzed station j , with $n = m + 1$, whether both velocities are statistically equal or not. We may assume that $\mathbf{v}_m = \mathbf{v}_n$ if the statistical test

$$T_v = \frac{|\mathbf{v}_n - \mathbf{v}_m|}{m_0 \sqrt{\mathbf{T} \mathbf{Q}_{xx}(\mathbf{v}_m; \mathbf{v}_n) \mathbf{T}^T}} < u_{1-\frac{\alpha}{2}} \quad (3)$$

holds. Again, $\mathbf{Q}_{xx}(\mathbf{v}_m; \mathbf{v}_n)$ is the cofactor matrix of velocity parameters \mathbf{v}_m and \mathbf{v}_n and \mathbf{T} is the transformation matrix of the operation.

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

$$\mathbf{v}(t_i) = \mathbf{y}(t_i) - \mathbf{A}\mathbf{x}(t_i), \quad (4)$$

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

$$t_d \text{ in a way that } g(t_d) = \max g(t_i) \quad (5)$$

with

$$g(t_i) = \left| \sum_{k=1}^i \mathbf{w}(t_k) \right|, \quad \text{where } i = 1, \dots, n_t. \quad (6)$$

The residual time series

$$\mathbf{w}(t_i) = \mathbf{v}(t_i) - \mathbf{A}_2\mathbf{x}(t_i) \quad (7)$$

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. 4) with the peculiarity of resampling the time information with $t_i = i$ for $i = 1, \dots, n_t$.

Let us add a remark to the test time series of Eq. 6: by employing the residual time series $\mathbf{w}(t_i)$ (see Eq. 7) instead of the original residual time series $\mathbf{v}(t_i)$ (see Eq. 4) 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. 4 that fulfill

$$|\mathbf{v}(t_i)| > \kappa_s m_0 \quad \text{and} \quad (8)$$

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

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.

Due to the additional elements in the follow-up iteration m_0 will be smaller than at the end of the previous iteration (at least one additional discontinuity is added to the functional model). This ensures that all potential outliers are included by the condition given in Eq. 8, which is also applied during the significance test procedure.

3.6 Velocity Handling

In long time series the linear station velocity needs to be considered. One or more time intervals of velocity parameters may be introduced into the functional model of Eq. 1. The user may define criteria to introduce the velocities in the functional model:

- no velocities,
- one velocity per station,
- 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 introduction of velocity parameters in the functional model may lead to obtain sequences of significant velocity changes separated by short time intervals, e.g., a sequence of velocity changes in the coordinate time series of stations located near seismic regions, where prominent earthquake events are followed by several afterquake events. 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 the user-defined parameter Δt_v by which a minimal interval length for separate velocity parameter is required. Resulting velocity changes are therefore removed from the functional model in a way that only reasonable long velocity intervals are estimated: the velocity parameter with a too short validity interval is connected with another (neighbouring) velocity parameter where we can detect the least non-significant significant velocity change.

3.7 Earthquake Events

Earthquake events are introduced from 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 generated significant discontinuities and/or velocity changes in the analyzed station coordinate time series or not.

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 to the epicenter of the earthquake if

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

where

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

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 while M_v is the synthetic magnitude felt by the analyzed station in function of the distance d_{erq} from the epicenter of the earthquake.

3.8 Update of ADDNEQ2 Input Files

A more consistent ADDNEQ2 reference frame solution is achieved by reporting the relative constraints on velocities in the list of used equipments (STA) and by updating 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).

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 (FIX) for which the time interval covered by their observations – from the first to the last observation – is not at least equal the minimal interval length Δt_v .

4 Examples of the ATI-procedure

Figures 3 and 4 show both the screening and iteration steps of the ATI-procedure as described in Section 3.2 when analyzing the daily CODE coordinate time series of the IGS station NTUS, Singapore (Republic of Singapore). These detailed sets of plot shall illustrate the development of the processing steps of the ATI-algorithm.

For both time series analyses a velocity change is allowed after any earthquake event, the minimal interval length for velocities Δt_v is set to 6 months, the significance level is set to $\alpha = 0.01$, the additional threshold parameters for discontinuities are set to $\kappa_d = 2.5$, $h_d = 15 \text{ mm}$, $v_d = 25 \text{ mm}$, and those for outliers are set to $\kappa_s = 3.0$, $h_s = 20 \text{ mm}$, $v_s = 30 \text{ mm}$. M_{min} is set to 5.5 magnitude.

In each plot of Figures 3 and 4 we see the functional model adapted to the time series for the three

components North, East, and Up – in each screening step. Namely, the progress of the procedure in terms of iteration and screening steps may be read on top of each subfigure.

We start with a description of the results of Figure 3, where no periodic components are considered for the functional model.

The top-left plot of Figure 3 shows the first functional model considering the user specifications: earthquakes and equipment changes. This is the starting point of the ATI-procedure – 1st iteration, 1st screening step. For station NTUS we have three pre-defined components for the functional model: (1) the earthquake event ($vE1$), a 8.6 magnitude, at epoch 28-Mar-2005 16:05:37, at a distance of 735 km between the epicenter and the station, (2) the equipment change (sra), where both receiver and antenna were replaced on 25-Jun-2007, and (3) the earthquake event ($VE2$), a 8.5 magnitude, at epoch 12-Sep-2007 11:06:10, at a distance of 689 km from station NTUS. Moreover, after each earthquake event a new velocity parameter is setup to allows a velocity change. Starting from this point the algorithm removes all non-significant elements from the functional model within three screening steps: see the first line of plots. In the 1st screening step the algorithm removes the first velocity change (see the transition of the event label from ($vE1$) to ($E1$)), in the 2nd screening step the algorithm removes the equipment change event (sra), and in the 3rd (and last) screening step no more non-significant elements need to be removed from the functional model. No further screening steps are needed. According to the ATI algorithm 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. 6). In addition, outlier candidates – visible first in the 2nd iteration step – are identified.

The first functional model of the 2nd iteration step is generated: the new identified discontinuity and outliers are set up in the functional model together with all user specifications (two earthquakes and one equipment changes). The middle-left plot of Figure 3 shows the new functional model. A sequence of three screening steps are processed in this 2nd iteration step to remove all non-significant elements from the functional model. In addition to the removal of the non-significant velocity and equipment change, the non-significant outliers are dropped out from the functional model. We observe in the middle-right plot – in the last screening step of this iteration step – that the proposed discontinuity (N) is found significant. According the the algorithm of Section 3.2, a new discontinuity (F) and new outliers are again identified, then merged to the updated functional model,

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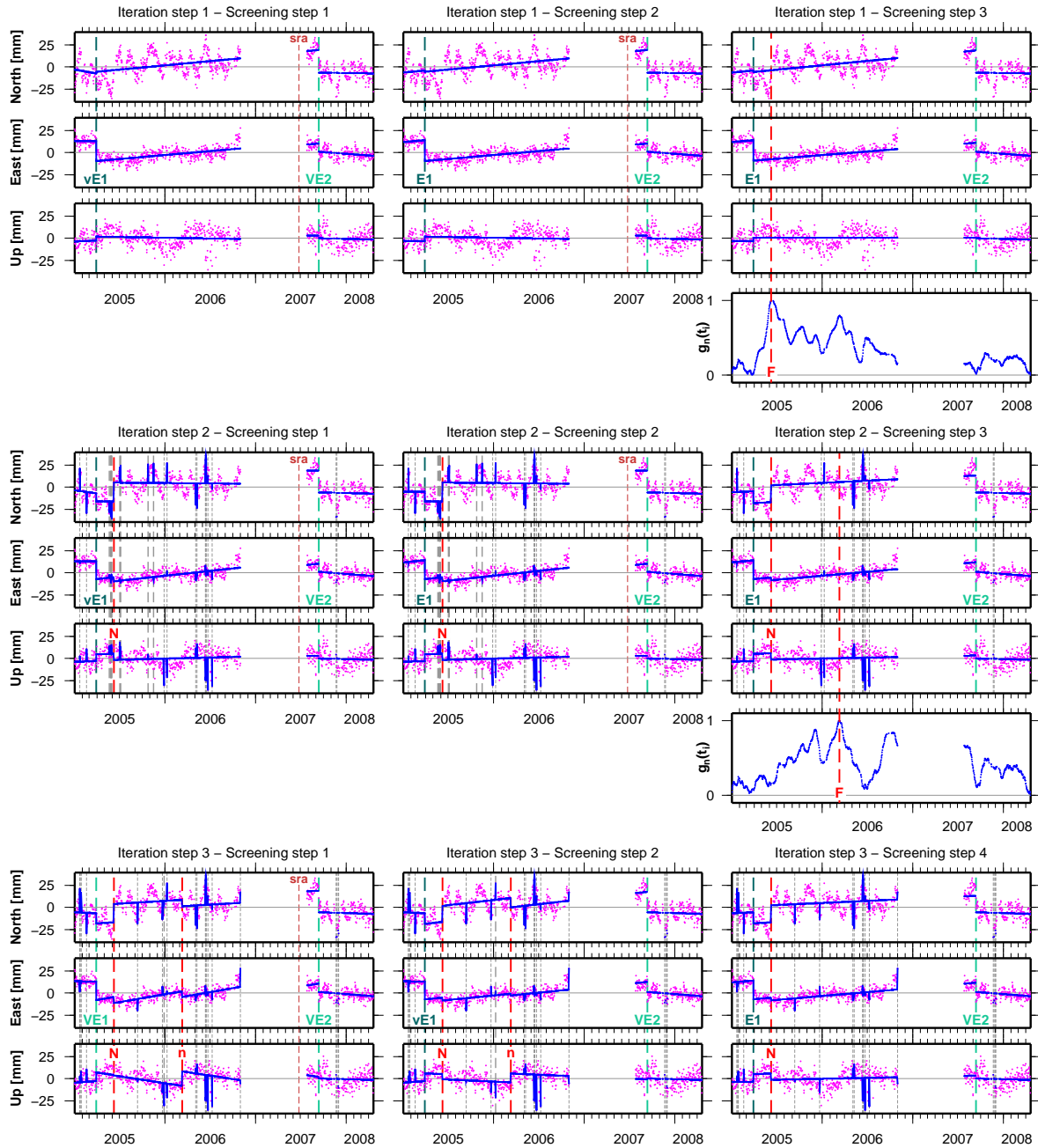
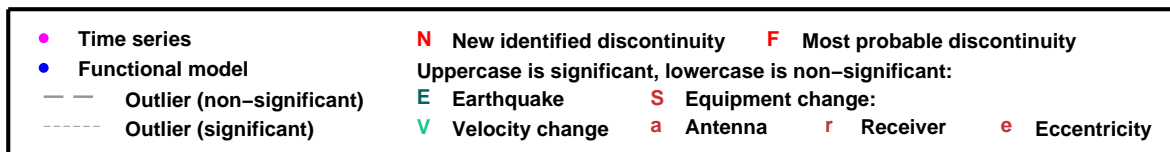


Figure 3. For each consecutive iteration and screening step of the ATI-procedure – from the top-left to the bottom-right subfigures – the time series analysis by FODITS of the IGS station NTUS, Singapore (Republic of Singapore), the residuals and the functional model are shown in their three components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



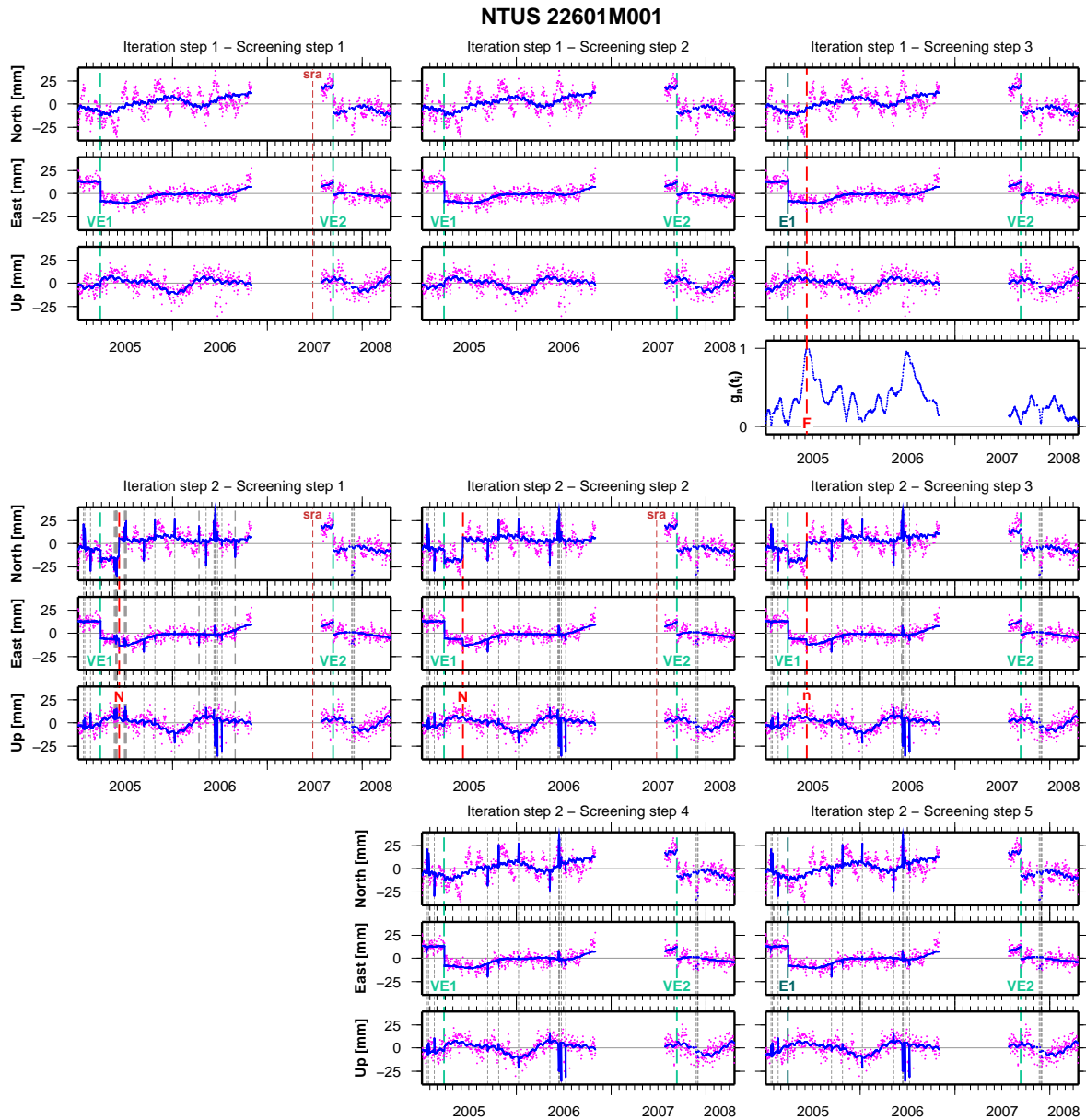
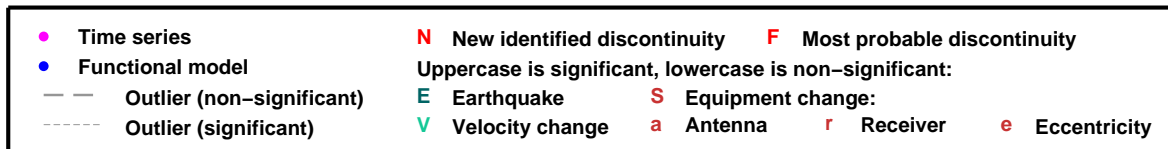


Figure 4. For each consecutive iteration and screening step of the ATI-procedure – from the top-left to the bottom-right subfigures – the time series analysis by FODITS of the IGS station NTUS, Singapore (Republic of Singapore), the residuals and the functional model are shown in their three components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



and a new iteration step starts evaluating the elements of this updated model.

The first functional model of the *3rd* iteration step is illustrated in the bottom-left plot of Figure 3. In order to see the proposed outliers for this new iteration step, compare this bottom-left plot to the middle-right one: the differences in terms of outliers are the new identified outliers. In this *3rd* iteration step a sequence of four screening steps concludes the analysis of the time series (only three of these four screening steps are plotted). The removed elements during the sequence are: in the (*1st*) an outlier and the equipment change event (*sra*), in the (*2nd*) the first velocity change (indicated by the transition in the label for the event from (*vEI*) to (*EI*)), and in the (*3rd*) the second new proposed discontinuity (*n*). Thereafter, the analysis of the coordinate time series of the station NTUS stops: the new identified discontinuity was exactly located at the same epoch of the one located after the *2nd* iteration step. The final functional model is therefore shown in the bottom-right plot.

Let us add a final remark to this first example: 8% of all proposed outliers were removed from the functional model during the last iteration. It is clear that by removing more non-significant outliers from the functional model the m_0 value increases, thus we may be sure that the algorithm found all outliers.

By looking at the time series of coordinates for the station NTUS in Figure 3 we can clearly identify periodic components that should be considered in the functional model. This is done for the second example, illustrated in Figure 4. Therefore, additional periodic function parameters – yearly, half-yearly, monthly, and half-monthly – are considered as additional components of the time series analysis. All other additional user-defined thresholds to control the ATI-procedure are the same as for the first example shown in Figure 3.

The first functional model – the start point of the ATI-procedure – is shown in the top-left plot of Figure 4. Compared to the functional model of *1st* screening step of the *1st* iteration step of the first example illustrated in Figure 3, we observe right away how, in this second example, the introduction of periodic functions lead to find the first velocity change (*VEI*) to be significant. In addition all periodic function parameters are also found significant. The only non-significant parameter is the equipment change event (*sra*). This parameter is therefore removed from the functional model in the *1st* screening step.

In the *2nd* screening step of this *1st* iteration step all elements of the functional model are found significant, see top-center plot of Figure 4. According to the ATI-algorithm, as described in Section 3.2, the first velocity change is unconditionally removed from the functional model since the time interval length

of the first velocity is shorter than the minimal interval length for velocities $\Delta t_v = 6$ months. A further screening step is therefore performed just right after this removal. In the model of the *3rd* – and last – screening step we observe two things: first, the first velocity change element is no longer component of the functional model, and second, all elements of the functional model are already significant. At this point the algorithm continues with the identification of new elements in terms of discontinuity and outliers. Two remarks may be added when comparing the two normalized test time series $g(t_i)$ at the end of the *1st* iteration step of the two examples. First, the test located in both examples the epoch 08-Jun-2005 to fix the discrepancy in terms of discontinuity between the functional model and the time series. Second, observe the impact of the additional periodic functions to the normalized test time series $g(t_i)$: the value of the peak (F) is in this second example less prominent with respect to the analogous one of the first example of Figure 3. The additionally introduced periodic components of the functional model may indeed fully compensate the discrepancy between the time series of data and the functional model.

The FODITS analysis of this second example (illustrated in Figure 4) ends up with the second screening steps' sequence. Five screening steps were necessary to remove the non-significant elements from the functional model: in the *1st* 10 outliers, in the *2nd* the equipment change event (*sra*), in the *3rd* the new proposed discontinuity (*n*), and in the *4th*, although being significant, the first velocity change (*VEI*) – due to the minimal interval length for velocities Δt_v of 6 months.

5 Examples for FODITS Processed Time Series

To demonstrate the performance of FODITS we show the results from the analysis of station coordinate time series from two different solutions: 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 of differential code biases 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 the combined weekly station coordinate time series of the local analysis center contri-

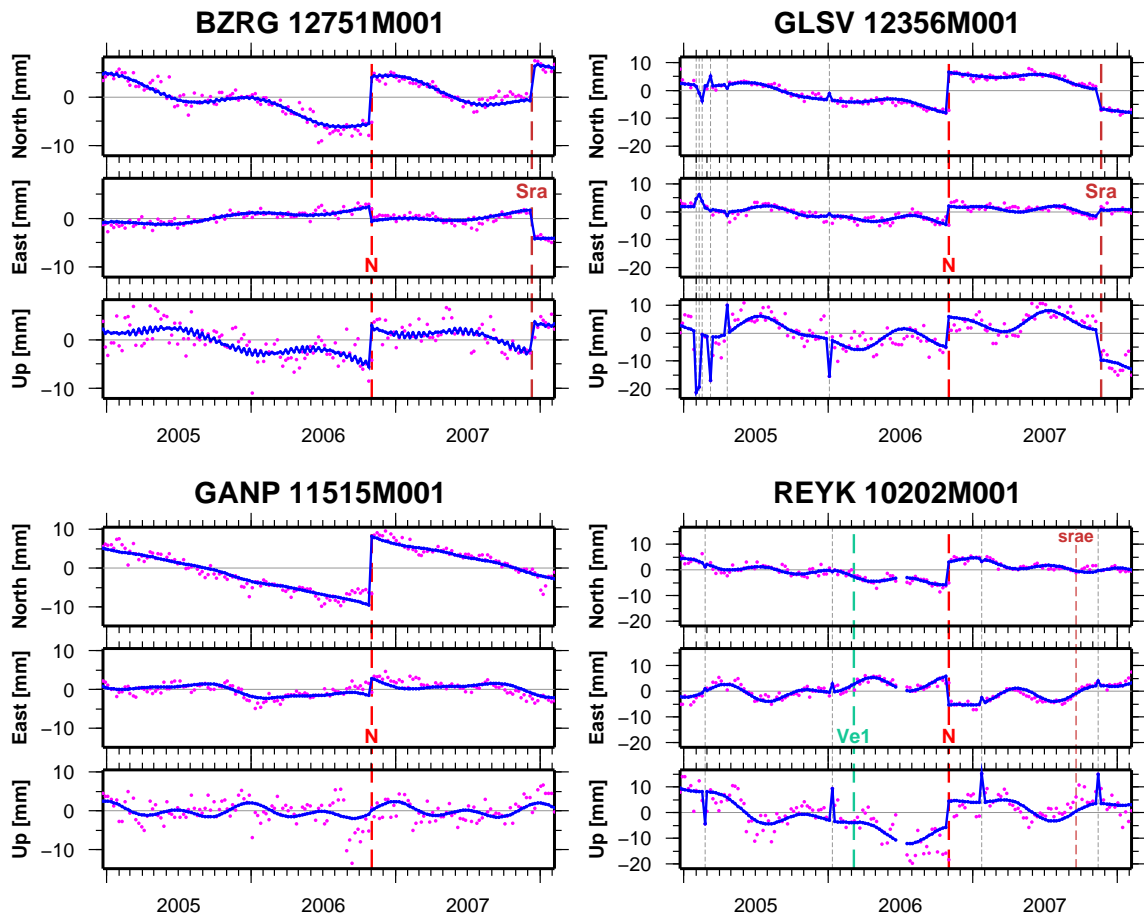
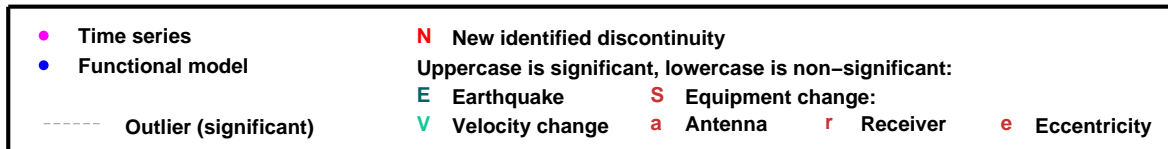


Figure 5. EUREF weekly solution time series: results of the FODITS time series analysis.



butions to the EUREF solution as it was computed at BKG (Bundesamt für Kartographie und Geodäsie, Frankfurt a. Main, Germany). Figure 5 shows four examples of stations of the EUREF permanent network (EPN): BZRG, Bozen in Italy (top-left), GLSV, Kiev in Ukraine (top-right), GANP, Ganovce in Slovakia (bottom-left), and REYK, Reykjavik in Iceland (bottom-right). Yearly, half-yearly, monthly, and half-monthly predefined periodic parameters were allowed in the functional model of the stations. Moreover, the user-defined parameters for the FODITS analysis are as follows: a velocity change was allowed after any earthquake events, the minimal interval length for velocities Δt_v was set to 6 months, the significance level was set to $\alpha = 0.01$, the additional threshold parameters for discontinuities were

set to $\kappa_d = 1.5$, $h_d = 5 \text{ mm}$, $v_d = 10 \text{ mm}$, and those for outliers were set to $\kappa_s = 1.5$, $h_s = 5 \text{ mm}$, $v_s = 5 \text{ mm}$. M_{min} was set to 4.5 magnitude. Weekly coordinate time series correspond to nothing but smoothed daily coordinate time series: this clarifies why the criteria for this analysis are more sensitive compared to the ones used for the examples of Section 4 where daily coordinate time series were processed. In all time series the ATI-procedure identified the prominent GPS week 1400 model change²

² At GPS week 1400 numerous model changes affecting both daily global and weekly EPN solutions: switch to the absolute GNSS PCV model and use of IGS05 terrestrial reference frame realization considering the absolute PCV model. In addition CODE has started to use the global mapping function (GMF), to use the a priori GPT (Global Pres-

(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 – in the time series of REYK was classified as non-significant. If we look carefully at the time series of station REYK we may 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 likely too short to recognize the equipment change as significant. An outlier for the week containing the middle epoch 14-Nov-2007 was detected instead, which might vanish after a continuation of the time series and if the ($srae$) event becomes significant. Finally, the earthquake at epoch 06-Mar-2006 14:18:56 with a magnitude of 4.5 and a distance of only 30 km from station REYK has introduced a significant velocity change into the time series.

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 analyzed 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, the minimal interval length for velocities Δt_v was set to 6 months, the significance level was set to $\alpha = 0.01$, the additional threshold parameters for discontinuities were set to $\kappa_d = 2.5$, $h_d = 15 \text{ mm}$, $v_d = 25 \text{ mm}$, and those for outliers were set to $\kappa_s = 3.0$, $h_s = 20 \text{ mm}$, $v_s = 30 \text{ mm}$. M_{min} was set to 5.5 magnitude.

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, velocity changes, and outliers in all 238 analyzed stations points out how important is the automated analysis of the time series.

Figure 6 displays four examples of the processed time series.

The top-left plot of Figure 6 shows the result of the FODITS analysis of station ALGO, Algonquin

sure Temperature) model for hydrostatic component for the troposphere (Böhm, 2006), to use an updated set of solar radiation pressure a priori model coefficients for GPS and GLONASS, and other minor model updates (see IGS-Mail 5518: GPS week 1400 model changes made at CODE).

Park (Canada). The discontinuity (N) at epoch 05-Nov-2006 was found significant: again, this discontinuity corresponds to the prominent switch from the relative to the absolute antenna phase centre modelling in GPS week 1400² in the IGS processing, which has introduced discontinuities of more than 3 cm for about 10% of the station time series, see Table 1. We further ascertain that monthly and half-monthly periodic functions were removed from the functional model.

The top-right plot of Figure 6 shows the result of the FODITS coordinate time series analysis of station BRST, Brest (Finistere, France). An equipment change at epoch 19-Apr-2007 produced a significant discontinuity: receiver (from TRIMBLE 4000SSI to LEICA GRX1200PRO), antenna (from LEIAT504 NONE to LEIAT504GG NONE), and antenna eccentricity were changed. Again, monthly and half-monthly periodic functions were removed from the functional model as non-significant components. A discontinuity due to the model changes at week 1400 cannot be evaluated here because of missing data: within the same data gap there is not only the model change but also the change of the equipment. So, the algorithm cannot distinguish, which of the two events did introduce the discontinuity.

The bottom-left plot of Figure 6 shows the result of the FODITS coordinate time series analysis of station HRAO, Krugersdorp (South Africa). Two equipment change events were tested for significance. The first, the receiver change (sr) at epoch 25-Apr-2007 (from ASHTECH Z-XII3 to ASHTECH UZ-12), was found to be non-significant. On the contrary, the second, the antenna change (Sa) at epoch 14-Feb-2008 (from ASH701945C_M NONE to ASH701945E_M NONE), was found to be significant. Again, monthly and half-monthly periodic functions were removed from the functional model. The time series contains a discontinuity at week 1400 due to the model change. Because it is smaller than the specified minimum size of a detectable discontinuity ($v_d = 25 \text{ mm}$) the event was not detected by the algorithm.

The bottom-right plot of Figure 6 shows the result of the FODITS coordinate time series analysis of station MIZU, Mizusawa (Iwate, Japan). A new, prominent discontinuity (N) was identified at epoch 04-Nov-2006: we confront ourselves again with the prominent model switch in GPS week 1400² – the discrepancy of one day with respect to 05-Nov-2006 is due to an outlier. The other element found significant in the functional model is the velocity change ($Ve8$) at epoch 16-Jun-2007 01:07:56: the reason was an earthquake of magnitude 6.6 with the epicenter at a distance of 294 km from the station.

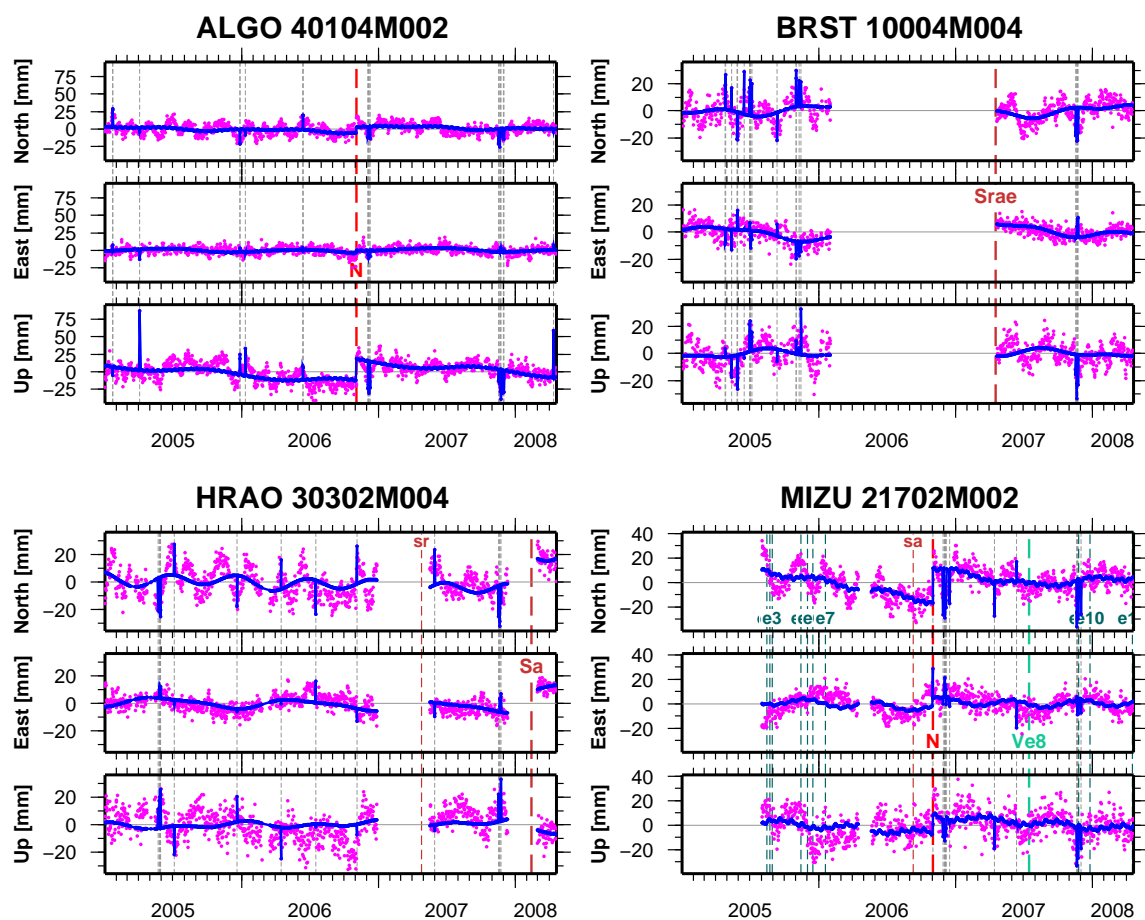


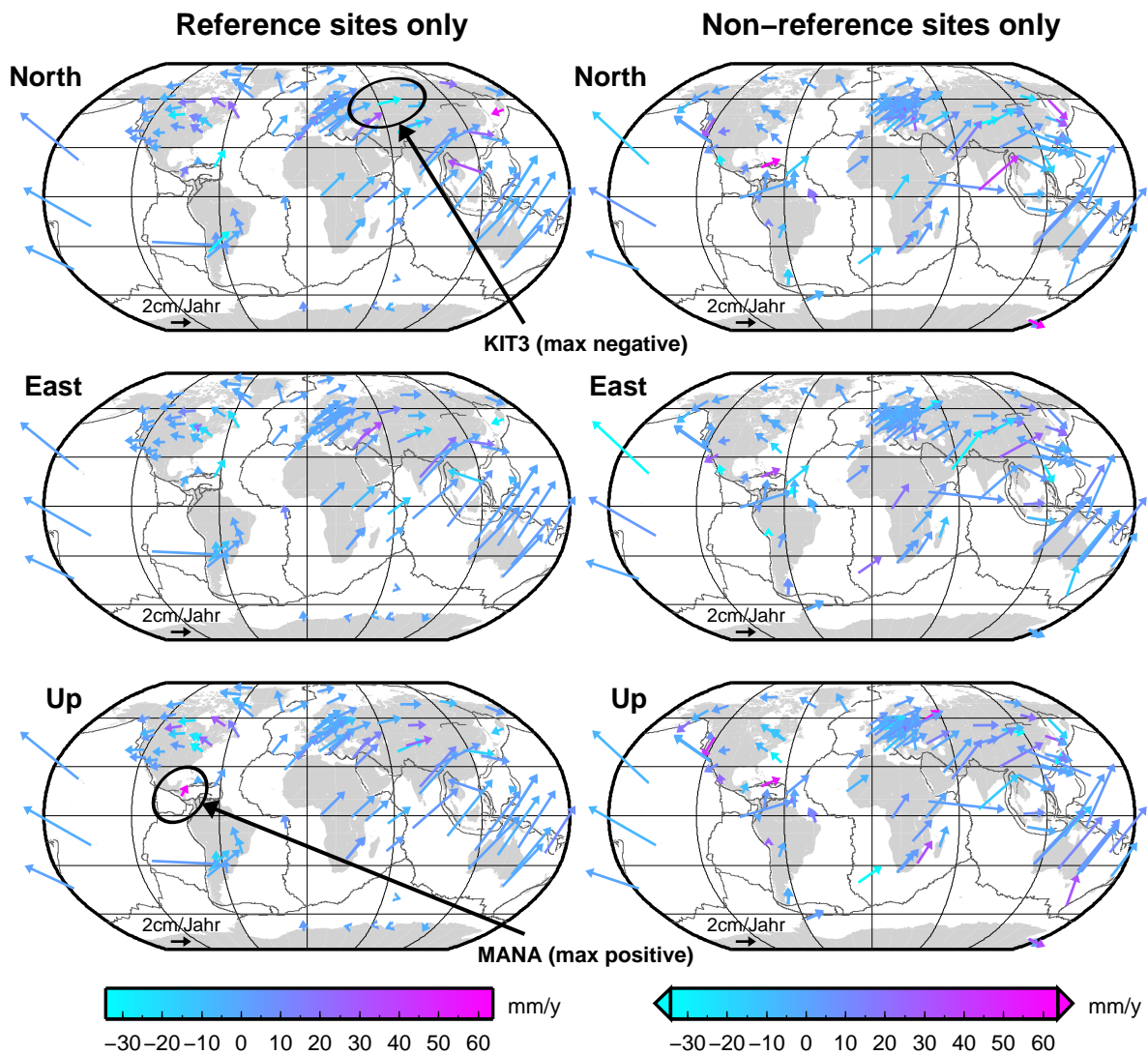
Figure 6. CODE daily solution time series.

● Time series	N New identified discontinuity
● Functional model	Uppercase is significant, lowercase is non-significant:
----- Outlier (significant)	E Earthquake S Equipment change:
	V Velocity change a Antenna r Receiver e Eccentricity

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	97
Total number of proposed discontinuities due to equipment changes	103
Number of significant discontinuities due to equipment changes	13
Total number of proposed discontinuities due earthquake events ($M > 5.5$ mag)	159
Number of significant discontinuities due to earthquake events	6
Total number of velocity changes (after earthquake events)	39
Total number of new significant discontinuities identified	78
Number of discontinuities due to model change (introduction of absolute PCV models, GPS week 1400)	34
Resulting number of new discontinuities of unknown reason	44
Total number of new significant identified outliers	3099
Number of periodic function parameters per station	238.4
Number of significant periodic function found in all stations	605
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	107
Resulting number of rejected reference sites	39

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

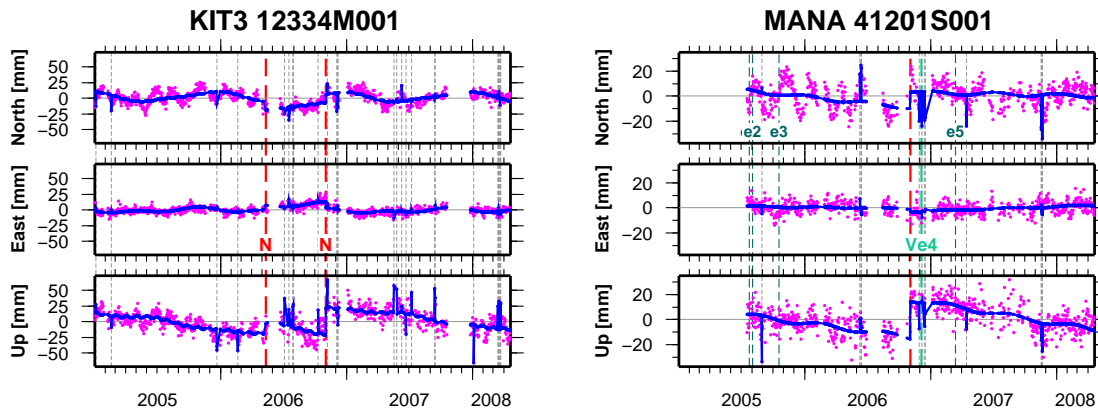


Figure 7. Result of the reassessment procedure of CODE daily solution time series (2005-2008) in terms of station velocities. (top) station velocities after reassessment: the velocity improvements are color-coded and the improvements are given for the North, East, and Up components. (bottom) time series of maxima of velocity improvements: (left) maximal negative and (right) maximal positive.

On the other hand, the earthquake events (*e1*), a 7.2 mag at a distance of 123 km, (*e2*), a 5.9 mag at a distance of 189 km, (*e3*), a 6.1 mag at a distance of 192 km, (*e4*), a 7.0 mag at a distance of 347 km, (*e5*), a 6.5 mag at a distance of 144 km, (*e6*), a 6.0 mag at a distance of 96 km, (*e7*), a 5.7 mag at a distance of 174 km, (*e9*), a 5.9 mag at a distance of 197 km, (*e10*), a 6.1 mag at a distance of 105 km, and (*e11*), a 5.8 mag at a distance of 97 km were found non-significant. At epoch 10-Sep-2006 we further observe the equipment change (*sa*), an antenna change from TPSCR3_GGD CONE to TPSCR3_GGD NONE, which was found non-significant.

After processing all station coordinate time series FODITS updated the station information file (STA) with the relative constraints on the fragmented velocity intervals, 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 7 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, indicated by the colours of the arrows. In the figure we make the distinction between reference sites (left-column) and non-reference sites (right-column) – to divide the stations into two plots to improve the visibility. In all components (North, East, and Up) of all velocity fields we cannot see any 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 -34.3 mm/y to a positive maximum of 64.1 mm/y. The analyzed coordinate time series of the maximum negative (station KIT3, Kitab, Uzbekistan) and maximum positive (MANA, Managua, Nicaragua) velocity improvements are illustrated in the bottom part of Figure 7. In both time series FODITS found a new discontinuity (*N*) at epoch of the prominent model change in GPS week 1400 is responsible for this improvement of the results.

5.3 Use of FODITS for Non-Coordinate Time Series

The algorithm to analyze time series cannot only be applied to coordinate time series as demonstrated in the previous sections for daily or weekly solutions, but also to the results from a kinematic positioning or any other time series. The easiest interface is the so-called PLT files that usually contains the residuals of the ADDNEQ2 solutions (see Figure 1 in Section 2).

Figure 8 gives an example for an alternative use of FODITS. It shows the time series of P1-P2 DCB (differential code bias) corrections for two GNSS stations. In this case only one component was analyzed. The standard deviation of the observations was considered in the analysis instead of the full covariance information of the coordinate components.

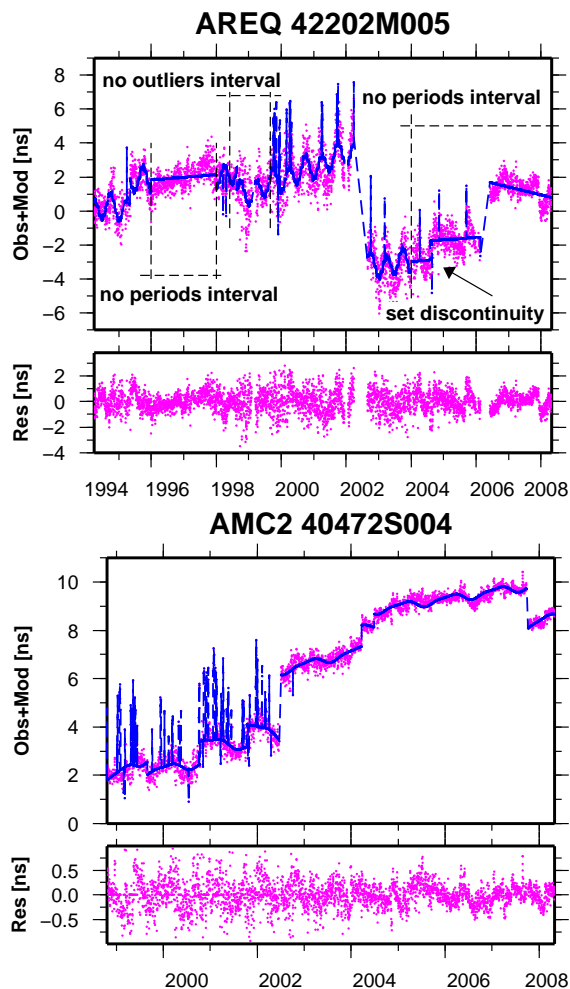


Figure 8. Re-aligned P1-P2 differential code bias (DCB) time series analyzed by FODITS. In the (top) series of both subfigures the pseudo-observations (magenta) are shown together with the functional model (blue). Pre-defined events and intervals are indicated, too. In the (bottom) series of both subfigures the series of residuals with respect to the functional model are shown.

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 options 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 components, 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 ends 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. Information 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 – to be tested for significance – or unconditionally – never tested for significance – any kind of elements 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 sub-

sequently 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. In all cases FODITS has generated proper results in a fully automated mode. The algorithm has also successfully been applied to alternative time series of parameters, e.g., P1-P2 DCB for stations and satellites.

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