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ORIGINAL PAPER

AUTOMATIC DETECTION OF DISCONTINUITIES IN THE STATION POSITION TIME SERIES OF THE REPROCESSED GLOBAL GNSS NETWORK USING BERNESE GNSS SOFTWARE

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ABSTRACT

For over 25 years, the International GNSS Service (IGS) has been processing observational data from the Global Navigation Satellite Systems (GNSSs). Hence, long time series of station coordinates are available, however, they are burdened with discontinuities, station velocity changes, and gross errors. Discontinuities and periodic variations are caused by equipment changes at stations, earthquakes, geophysical processes, data problems, as well as local environmental changes. As a result, many approaches have been identified that identify and remove discontinuities in the GNSS coordinate time series. One of them is the program Finding Outliers and Discontinuities In Time Series (FODITS) implemented in the Bernese GNSS Software environment (Dach et al., 2015), developed by the Astronomical Institute, University of Bern. The program is designed for the automatic analysis of time series, in which the functional model is adapted to the time series of coordinates depending on the adopted parameters. This study presents the analysis of long-term GNSS coordinate time series reprocessed in the framework of the realization of the International Terrestrial Reference Frame 2014 (ITRF2014) using the FODITS program. The results show that the optimum confidence level for the autonomous detection of station discontinuities in FODITS is 99 % and 98 %, for 7-day and 3-day GNSS solutions, respectively, when compared to the manual discontinuity detection from ITRF2014. However, the manual analysis unsupported by statistical tests as conducted in ITRF2014 may contain errors over which further elaboration is indispensable. On the other hand, routine interpretation of GNSS coordinate time series in a fully autonomous manner, although much faster, is not free from drawbacks, in particular in detecting appropriate epochs of discontinuities and changes in station velocities.

1. INTRODUCTION

For 25 years the International GNSS Service (IGS) has been processing data from the GNSSs (Global Navigation Satellite System) observations. Thanks to this, a long time series of station coordinates are available. The GNSS station time series consists of a systematic part (trend, constant, seasonal fluctuations) and a random part (noise, outliers and discontinuities, which are caused by station equipment changes, earthquakes, other geophysical processes, data problems or unknown origin). Part of the systematic signal is relatively easy to interpret. For example, to identify a seasonal signals, which are mainly caused by changes in the mass redistribution in the earth system, resulting from changes in atmospheric pressure loading, non-tidal ocean fluctuations or land hydrology (Dow et al., 2009), but also due to systematic errors, such as draconitic periods of satellite techniques (Ray et al., 2008) just enter the annual or semi-annual signals. While the identification of the random part is still a big problem of analyzing. With the development of data analysis, the time series of the GNSS station coordinates achieve more and more precision (Santamaria-Gomez et al., 2011). But the discontinuities that occur in almost all long time series of coordinates derived from GNSS observations (Williams, 2003), including processed ones (Steigenberger et al., 2009) have not been fully eliminated. Correct time series analysis is crucial for obtaining high accuracy solutions, among other things to ensure that the International Terrestrial Reference Frame (ITRF) reaches an accuracy of 0.1 mm/year for designated station velocity vectors to meet future scientific requirements (Altamimi et al., 2011).

GNSS coordinate discontinuities, changes in station velocity and outliers are caused by both hardware components, such as exchanges of receivers and antennas at GNSS stations, as well as geophysical phenomena, such as earthquakes and deformations of the earth's crust caused by changes in atmospheric and oceanic pressure loading, redistribution of masses in earth's crust including post-glacial rebound, and

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changes in land hydrology, problems with data or of unknown origin (Ostini, 2012; Bruni et al., 2014). If discontinuities occurring in GNSS observation time series are not properly identified and removed, they can distort reliable modelling of long-term trends and non-linear deviations that may have arisen as a result of phenomena related to geophysics and climate change (van Malderen et. al., 2017). Undetected discontinuities negatively affect forecasted models and results in describing geophysical phenomena (Vitti, 2012). What's more, the parameters observed give direct evidence of many global processes that affect human society such as earthquakes, volcanism, floods, changes in sea level, mass balances of polar glaciers or redistribution of groundwater, so their proper analysis is particularly important.

There are many approaches to identify and remove discontinuities in time series, which can be divided into two groups: manual and automatic or semi-automatic. Manual methods give better results, but they are time-consuming and objective. However, automatic tools give slightly worse results but are much faster which becomes important in the case of elongation existing time series of station coordinates (Gazeaux et al., 2013). Analysts or algorithms can identify discontinuities thanks to information about equipment change at stations and earthquake lists. But discontinuities and outliers in the GNSS coordinate time series also occur for other reasons. According to the SOPAC archive (the Scripps Orbit and Permanent Array Center[1]), discontinuities caused by either equipment changes or seismic activity they constitute about 2/3 of all discontinuities. However, the remaining discontinuities are caused by unknown reasons and they must be detected by post-processing or possibly pre-processing approach (Gazeaux et al., 2013).

Many scientific studies document the researchers' interest in this topic, and thus newer and more recent approaches to analyzing time series of data are emerging. An example of this is the DOGEx experiment (King and Williams, 2010), in which a simulated coordinate series was developed to contain realistic signal elements such as noise, outliers and discontinuities. 25 solutions (some were variants of the same time series analysis strategy) made with the help of techniques and tools such as FODITS (Ostini et al., 2009), TSOFT (van Camp and Vauterin, 2005), CATS (Williams, 2008) and iGPS were verified (Tian, 2011). The experiment selected the best methods of data analysis, of which the first two belong to the group of manual solutions, while the third approach was generated using an automatic tool - FODITS. Due to the results obtained in the DOGEX experiment, I decided to use the FODITS tool to detect discontinuities in the time series of GNSS stations positions.

Automatic methods for analyzing the time series of GNSS station positions are becoming especially important in view of the increasing number of stations. Therefore, newer and newer methods of time series analysis are being developed. An example may include such automatic time series analysis algorithms as STARS (Rodionov, 2004), MIDAS (Blewitt et al., 2016) and Hector (Bos et al., 2013). The procedure of detecting discontinuities with STARS is based on the Sequential *t* test Analysis of Regime Shifts (Rodionov, 2004). Median Interannual Difference Adjusted for Skewness (MIDAS) is a customized version of Theil-Sen (uses a robust TheilSen based median trend estimator; Theil, 1950; Sen, 1968) that incorporates the qualities needed for accurate GPS station velocity estimation, such as insensitivity to seasonal variation. The Hector algorithm is used by the Working Group 10 "GNSS Data and Product" of the Project "European Plate Observing System - Implementation Phase (EPOS-IP)" to assist in detecting discontinuities in time series. The Hector Software (Bos et al., 2013) uses Maximum Likelihood Estimation (MLE). In addition, as part of the research, which uses data from the global navigation satellite system (GNSS) it is essential to have time series, which are devoid of discontinuities. An example of such activities is the Working Group 3 ("Use of GNSS tropospheric products for climate monitoring") of COST ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC). For the homogenization of GNSS data, they used many algorithms for detecting the offsets (van Malderen et al., 2020).

Due to the increasing number of permanent stations GNSS around the world (over 18,000) and their constant extension, it was decided to explore an automated analysis tool that could replace the long, subjective and time-consuming interpretation of data in the future. For this purpose, the FODITS tool was used, which is implemented in the Bernese GNSS Software environment (Dach et al., 2015), developed by the Astronomical Institute, University of Bern. It allows identifying events that caused changes in station time series. This study aimed to determine the optimal confidence level of automated analysis so that the results obtained are consistent to the extent possible with manual discontinuity detection used in the development of the latest implementation of the international ground reference frame ITRF2014 (Altamini et al., 2016). Additionally, the obtained results were confronted with the results obtained from the JPL (Jet Propulsion Laboratory, California Institute of Technology) tool, which also belongs to the group of methods of automatic time series analysis.

Automated methods are tested by testing them against synthetic time series. The author of the FODITS tool performed analyzes with sample time series. The authors of the DOGEx experiment also began testing various approaches to finding discontinuities from synthetic time series. Simulated series of GPS coordinates for 50 "places" were

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[1] http://sopac.ucsd.edu/

developed to include realistic GPS signal elements such as noise, shifts and data gaps. Then, analysts sent solutions with the most accurate possible discontinuity search (King and Williams, 2010). Due to the fact that the FODITS tool has already undergone analysis on synthetic time series in this study, I decided not to perform such research. If anyone wants to see the results achieved by the FODITS tool, please refer to the doctoral dissertation of the program author (Ostini, 2012), as well as to the article by King and Williams (2010).

2. METHODOLOGY DESCRIPTION

2.1. ANALYSIS OF TIME SERIES IN FODITS

FODITS (Finding Outliers and Discontinuities In Time Series) is one of the Bernese GNSS Software (Dach et al., 2015) programs released in version 5.2. The program enables the automatic analysis of the coordinate time series, including automatic detection of discontinuities, velocity changes, periodic events, and outliers, as well as the identification of epochs of all events. FODITS can be used, not only for the analysis of GNSS station coordinates but also for all data represented in the form of n-dimensional time series. The FODITS algorithm adapts the user-specified functional model, step by step, to the best approximate of the time series of GNSS station coordinates.

The time series of the GNSS coordinate products that are used to perform the analysis can be represented by three components: north, east and altitude. There are many possibilities for representing the time series of station positions. Equation 1 shows how they are implemented in the FODITS tool. For more information on time series representations, particularly of earthquake-affected stations, see Bevis and Brown (2014).

$$
\begin{aligned}
f(t_i) = {} & d_0(t_0) + v_0(t_i - t_0) + \sum_{k=1}^{n_d} d_k \eta_{d,k}(t_i) + \sum_{k=1}^{n_s} s_k\, \eta_{s,k}(t_i) + \sum_{k=1}^{n_v} v_k(t_i - t_k)\eta_{v,k}(t_i) \; + \\
& + \textstyle\sum_{k=1}^{n_p} \left[\mathrm{p}_{a,k} \cos\left(\omega_k(t_i - t_0)\right) + \mathrm{p}_{b,k} \sin\left(\omega_k(t_i - t_0)\right)\right] \eta_{\mathrm{p},k}(t_i)
\end{aligned}
\tag{1}
$$

where:

$i = 1, \dots N$ is the index of epoch t_i of the series of N elements,

d_0, v_0 are the initial coordinate and velocity values,

$\eta_{d,k}(t_i)$, $\eta_{s,k}(t_i)$, $\eta_{v,k}(t_i)$, $\eta_{\mathrm{p},k}(t_i)$ are functions returning either 0 or 1 to indicate the validity of the related component (d_k is the list of η_d discontinuities, s_k is the list of η_s outliers, $v_k(t_i - t_k)$ is the list of η_v velocity changes), and

$\mathrm{p}_{a,k}$, $\mathrm{p}_{b,k}$ are the in–phase and out–of–phase components for the η_{p} periodic functions.

The functional model of the tool assumes the analysis of the time series of positions of different stations independently. Therefore, it is possible to analyze the time series station-by-station. The functional model (eq. 1) only applies to the position of one station. FODITS does not take into account the time series data points in the analysis. Such a procedure was introduced to simplify and reduce the time of analyzes (Ostini, 2012; Fernandes and Bos, 2016). Moreover, no temporal correlation is assumed between the time series data points. Only the space correlations (in North, East, and Up) are taken into account between components of the time series.

Elements a priori introduced to the analysis in FODITS

A priori elements can be introduced into the time series analysis procedure in FODITS. This viable information about events that affected investigated stations allows for more reliable analysis, as well as for precise identification of the reasons for the discontinuities in the time series. The above-mentioned information constitutes changes of the equipment at stations, epochs, magnitudes, depths, and locations of earthquakes, periodic functions, as well as user-defined elements.

The list of pre-defined elements used in the analysis contains a list of equipment changes at the stations, which is based on station logs, and a list of earthquakes. In the case of IGS stations, access to the current and historical information on equipment used can be obtained through the website: http://www.igs.org/network. Based on log files, a station information file can be developed using the Bernese Software. One can also download IGS.STA and EUREF.STA[2] files that are updated regularly using the current information from the Solution Independent Exchange Format (SINEX) files: igs.snx and euref.snx files. The list of earthquakes introduced in FODITS comes from the United States Geological Survey (USGS[3]) database together with information on the epoch, location, depth, and magnitude of the earthquake occurrence.

Moreover, during the analysis process, additional parameters can be entered in the program, such as:

1. Parameters related to earthquakes
2. Maximum number of iteration steps and screening steps,

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[2] http://www.aiub.unibe.ch/download/BSWUSER52/STA

[3] http://neic.usgs.gov/neis/epic/epic%20global.html

3. Maximum number of outliers per iteration and an overall threshold for outlies detection,
4. The minimum length of the interval for velocity changes
5. Criteria for new periodic functions
6. The minimum displacement for individual components
7. Significance test

For the purposes of this analysis, the values of the parameters listed above have been set at the optimum level as proposed by the Author of the program (Ostini, 2012). [1] The parameter associated with earthquakes that can be defined in the program is the minimum time interval between discontinuities introduced in connection with such events. This parameter has been introduced, because often after earthquakes are aftershocks (Yagi et al., 2001). The author of the program recommends using the optimal value of 60 days. [2] The maximum number of iteration steps was 20, while the filtration steps 50. [3] The maximum number of outliers per iteration was 200, while the overall threshold for outliers was 100. [4] The approach that excludes the reliable estimation of station velocity from derived from 2.5 years of continuous GNSS observations (Blewitt and Lavallé, 2002) becomes outdated due to the extend time series of GNSS stations, as shown by Klos et. al. (2018). However, in the case of station time series analysis in the ITRF2014 and JTRF2014 solutions, such an approach was used. Accordingly, also in this analysis the minimum interval for velocity changes has been set to 2.5 years. [5] It is very common to observe periodic signals in the station position time series, which are the manifestation of not only geophysical phenomena, but also technique systematic errors. In addition to the annual and semi-annual signals, it also stands out a tropical year (365.2421 days), a draconitic year (~351 days) or Chandler periods. Bogusz and Klos (2016) wrote about the impact of individual periods on the time series of station positions. However, based on the studies by Altamimi et al. (ITRF2014, 2016) and by Abbondanza et al. (JTRF2014, 2017), seasonal signals (annual - 365.25 and semi-annual - 182.625 days) were introduced for the new periodic functions. [6] The minimum values of displacements for individual components have not been fixed at a specific level because the equipment used in the past and currently at stations is different. All GNSS receivers have their own noise, which are functions of random frequencies and amplitudes affecting the accuracy of position determination. Thus, the criteria used to eliminate the effect of the minimum coordinate noise level have not been authoritatively applied to avoid using the same setting for stations with different noise levels. What is more, the noise in processed GNSS observations is not necessarily constant over time (Langbein, 2008). [7] To compensate for the lack of minimum displacement values of individual components, the criteria for minimum outliers were introduced. The threshold for outliers was set at 5σ, because the CODE solutions have already been pre- filtered at the observation level and should, therefore, be free from gross errors. However, the filtering did not include the coordinate (parameter) analysis. The high threshold enforces the functional model to be adapted to large discontinuities (e.g. in the case of significant earthquakes) without removing a substantial number of solutions in the post-earthquake period because such periods could erroneously be identified as outliers. The question of finding the optimal criterion for removing outliers is very important as it may affect further analysis. One possibility is to use a multiple of the standard deviation (usually 3 or 5). Such a possibility is defined in the FODITS tool. Alternatively, you can also use the median of the absolute deviation (see Klos et al., 2015) or inter-quartile range rule (IQR, as applied in Bos et al., 2013).

Statistical test for the threshold of relative improvement

The coefficient, which was subject to change in the conducted analyzes, was the value of the statistical test for the threshold of relative improvement, which in FODITS was implemented in the form of (Ostini et al., 2009):

$$T_t = \left(\frac{v_n^T P v_n}{v_p^T P v_p} - 1\right) * \frac{n_{obs}}{n_{obs,a}} \tag{2}$$

with $v_n^T P v_n$ being the new weighted sum of squared residuals (i.e., after a new element has been added to the functional model in the least-squares adjustment) and $v_p^T P v_p$ being the previous weighted sum of squared residuals (i.e., before adding the element) with n_{obs} denoting the number of observations in corresponding solutions.

It should be mentioned that significance tests for periodic functions test for the significance of the amplitude. A minimum size of a detectable discontinuity and outlier is specified in relation to the noise level of the time series and as an absolute threshold for the horizontal and vertical components. Such a method gives 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 no sense anymore due to general GNSS experience; Ostini et al., 2009).

Without an external control, the algorithm would add more and more elements to the functional model, provided that the degree of freedom would be positive (based on the least-squares adjustment). The user can terminate the analysis at a reasonable time, when the functional model describes the time series in an acceptable manner, by adjusting the threshold for the significance levels. Enabling the user's external control over the algorithm it is aimed at adapting the analysis to the nature of the conducted research.

In order to find the most appropriate set of threshold parameters, the introduced values were

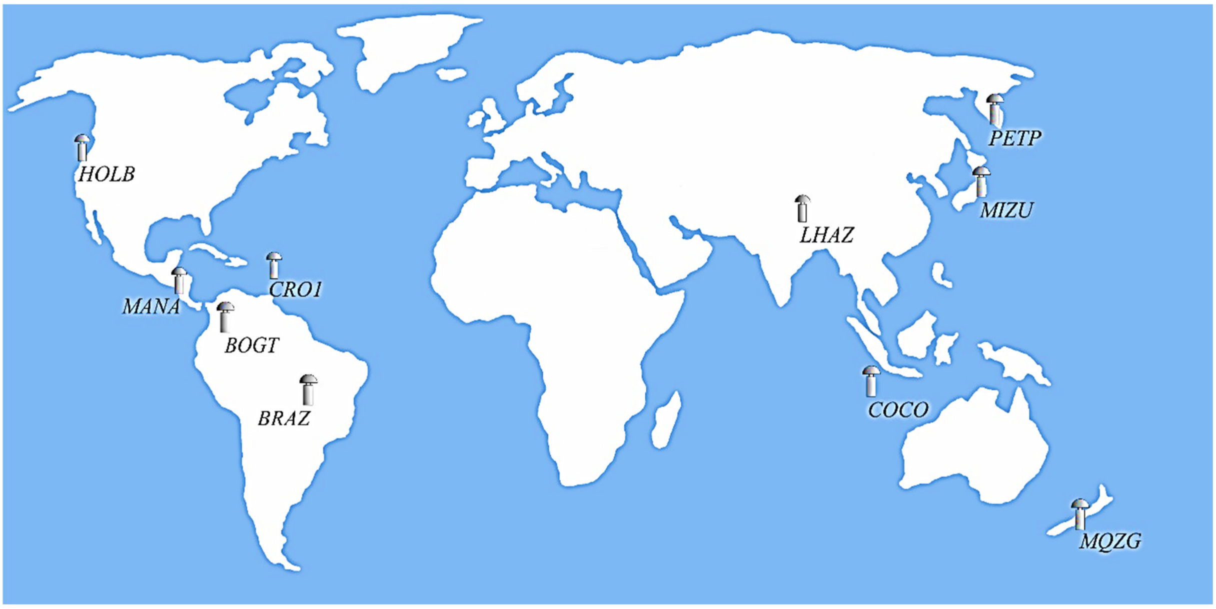


Fig. 1 The distribution of GNSS stations used in the study of the automatic discontinuity detection in coordinate time series.

initially selected to match the values of the tests carried out by the Author of FODITS. Threshold levels used in Ostini (2012) are 0.005, 0.01, 0.1 and 0.5, which correspond to the significance level of 99.5 %, 99 %, 90 %, and 50 %. In addition, calculations were made for intermediate values, i.e., 0.015, 0.02, 0.03, and 0.05, corresponding to 98.5 %, 98 %, 97 %, and 95 % significance levels. On the basis of the discontinuity values, the corresponding elements in the functional model were marked as significant from the statistical point of view at various levels of significance or statistically insignificant. This allowed further analyses to check for what value the functional model would describe the time series satisfactorily. Subsequent and final analyses were performed for significance levels between 0.01 - 0.05.

2.2. DATA CHARACTERISTICS

The 3-days and 7-days solution output products from the second CODE processing campaign (The Center for Orbit Determination in Europe) were used to conduct the analysis. The global GNSS network was reprocessed using the latest standards recommended by the IGS and described in CODE Analysis Strategy Summary. 3-day solutions (CO2) are based on the normal equations of three consecutive one-day solutions, having regard continuity conditions at the borders of the middle day of three-day observations. 7-day products are created on the basis of the statement of seven 3-day solutions (Thaller et al., 2012). The 3-day and 7-day solutions included a total number of 406 GNSS stations with estimated station coordinates, however, for some stations, the time series was very short. In the case of 3-day solutions, the data covered the period from January 5th, 1994 to June 7th, 2015, including 7,824 epochs in total. In the case of 7-day solutions, the period of data consisted of 1095 epochs, that is from January 5th, 1994 to December 31st, 2014. In CODE solutions, GPS orbits are available throughout the life of the data tested, while GLONASS orbits are added only after January 2002 (Steigenberger et. al., 2014).

To the realization of ITRF2014 7714 daily solutions have been used as inputs, resulting from the second reprocessed campaign (CODE Repro2; Rebischung et al., 2016). The data covered the time period 1994.0–2015.1. For the implementation of JTRF2014, daily solutions were used as input data, as in the case of ITRF2014, but before further analysis daily solutions have been averaged to weekly solutions (Abbondanza et al., 2017).

However, according to research Lutz et al. (2014) orbits related to the middle day of three-day arcs provide better solutions then daily solutions, as they are usually associated with much smaller errors at the orbit boundaries, as well as better estimates of Earth's rotation parameters. At the ends of the time frame, orbital errors reach 6 cm for GPS and 10 cm for GLONASS for 1-day solutions, while for 3-day solutions for both systems are about 3 cm (Steigenberger et al., 2014).

2.3. SELECTION OF STATION FOR ANALYSIS

Stations with long and continuous data and located in various places on Earth (Fig. 1) were selected for the analysis, especially in areas where there were significant displacements of the earth's surface with anthropogenic and natural origin. The basic condition for selection was to include GNSS stations from the second CODE processing campaign and from ITRF2014. In addition, it was important that the stations selected for analysis had a large number of

Table 1 Characteristics of the stations with the number of discontinuities in ITRF2014 and their main causes.

DOMES	Code	Location	Number of discontinuities	Main reasons for discontinuit
41901M001	BOGT	Bogota, Columbia	8	Equipment changes
41606M001	BRAZ	Brasília, Brazil	7	Equipment changes
50127M001	COCO	Cocos Islands	5	Earthquakes
43201M001	CRO1	Virgin Islands	8	Equipment changes
40130M001	HOLB	Holberg, Canada	9	Equipment changes
21613M002	LHAZ	Lhasa, China	6	Equipment changes /Earthquake
41201S001	MANA	Managua, Nicaragua	5	Earthquakes
21702M002	MIZU	Mizusawa, Japan	11	Earthquakes
50214M001	MQZG	Christchurch, New Zeland	7	Earthquakes
12355M002	PETP	Petropavlovsk-Kamchatsky, Russia	6	Unknown

discontinuities or outliers. This was caused by the approach in which the given analysis parameter best adapted to the station whose time series were extreme and therefore burdened with many discontinuities.

Station characteristics along with the number of discontinuities and their main causes are presented in Table 1. Selected locations were classified according to the causes of discontinuities to examine whether the nature of the event had an impact on the identification and introduction of discontinuities in time series. For of the ten selected stations had discontinuities due to equipment changes (BOGT, BRAZ, CRO1 and HOLB), another four were affected by strong earthquakes (COCO, MANA, MIZU and MQZG), while the reasons for the discontinuities of the last two stations are unknown (PETP) or mixed (equipment changes at the station and earthquakes) - LHAZ.

2.4. TIME SERIES ANALYSIS IN ITRF2014 AND JPL

The latest realization of the International Earth Reference System (ITRS) published in January 2016, ITRF2014, brought together all available observations from four space-geodetic techniques until the end of 2014. The latest version of ITRF is a significant improvement with respect to the previous realizations because it is precisely simulating the real trajectory of stations in post-seismic periods, including non-linear deformations, which leads to better design and correct determination of station velocities (Altamimi et al., 2016). Currently, researchers are also using other methods to simulate the actual trajectory of GNSS stations affected by earthquakes, see Klos et al. (2019).

The analysis of the GNSS time series in ITRF2014 was implemented at the first stage of data analysis. This allowed to identify linear and non-linear station displacements and movements. The time series have been examined visually in ITRF without used of pre-defined statistical tests on the significance of the discontinuities detected. To the time series, iteratively fitted a model composed of a step function, a constant velocity, annual and semi-annual signals and, when a station was affected by a major earthquake, also the functions describing the post-seismic deformation were introduced. The expansion of the functional model had been iterated until a satisfactory effect was obtained (Altamimi et al., 2017). External databases with information about equipment changes obtained from station logs collected from various sources were used in ITRF (Rebischung et al., 2016). Additionally, they built a catalogue of predicted coseismic offsets. For each earthquake registered in the Global Centroid Moment Tensor Project during the period 1980–2015, they calculated the coseismic ground deformation at all the ITRF2014. Every earthquake with magnitude larger than 4, and all computed coseismic displacements larger than 1 mm were flagged as possible causes of discontinuities (Altamini et al., 2016). In ITRF2014, parametric models were fitted to the input time series for stations subjected to large earthquakes, in order to take the PSD into account. Four models were used: (Log)arithmic, (Exp)onential, Log + Exp, and Exp + Exp. The PSD models were adjusted to the stations where the PSD was assessed as visually significant. The PSD models have been fitted separately in each east, north and up component, simultaneously with piece-wise linear functions, annual and semi-annual signals.

The second solution belonging to the group of automated methods tested in the DOGEx was the Jet Propulsion Laboratory (JPL) experiment (Gazeaux et. al., 2013). The results used in this study come from the development of the JTRF2014 system (Abbondanza et. al., 2016). The procedure of the JPL time series analysis in the first step consists in removing the average offset values from the reference coordinates, trends and annual and semi-annual seasonal signals by means of Tseri analysis, made using the program in the Quasi-Observation Combination Analysis (QOCA) package (Dong et. al., 1998; for more information, please visit: http://qoca.jpl.nasa.gov).

3. RESULTS OF THE ANALYSIS

3.1. ANALYSIS RESULTS FOR 3-DAY SOLUTIONS

Figure 2 represents the number of discontinuities that were considered significant for individual relative improvement thresholds obtained from tests

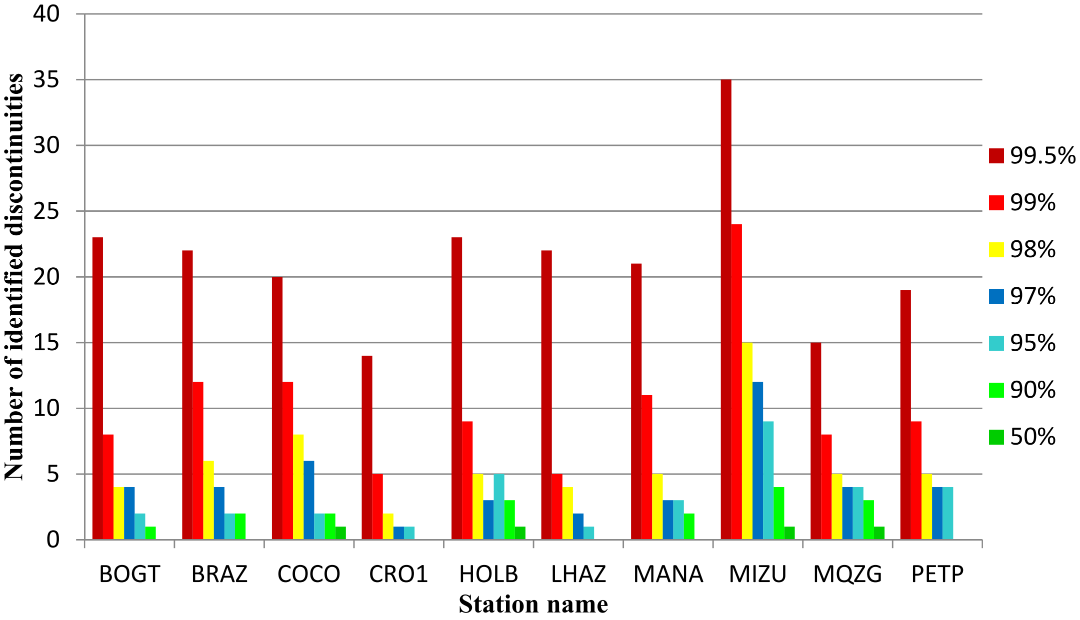


Fig. 2 The number of discontinuities detected by FODITS depending on the applied significance level for 3-day solutions.

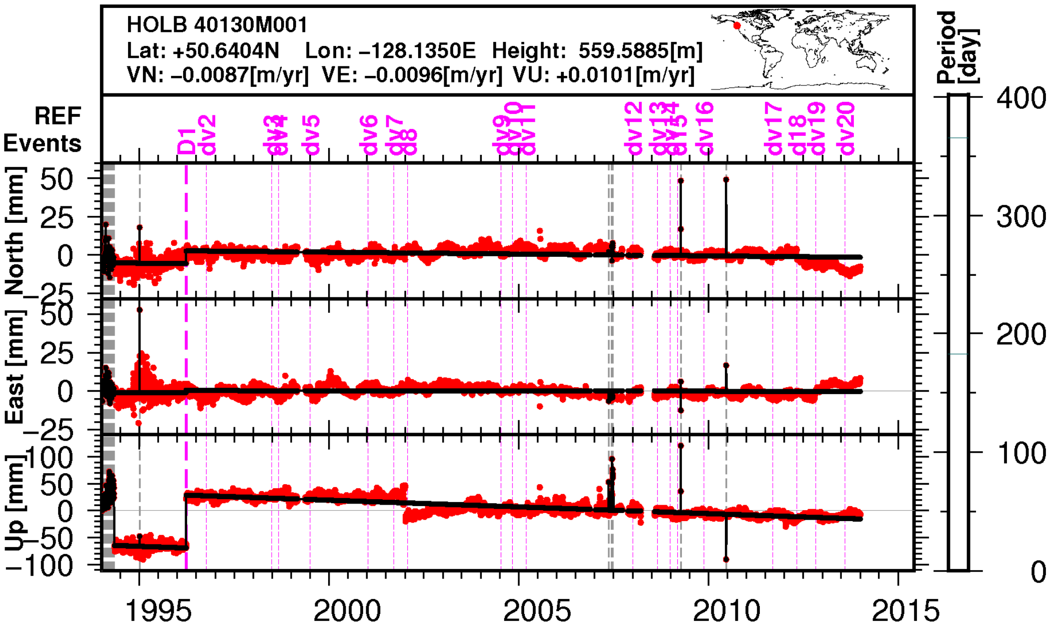


Fig. 3 Time series of HOLB station (Holberg, Canada) for the significance level of 50 % for 3-day solutions. The station positions are marked in red, the functional model is in black, significant discontinuities and velocity changes are marked by thick magenta lines.

performed in FODITS. The higher the level of significance, the larger number of discontinuities was included in the final analysis. When the level of significance for discontinuities was set at 0.1 or 0.5 (corresponding to 90 % and 50 %), the algorithm detected only the events that caused the largest changes in the coordinates or velocities of a station.

The solution based on a low significance level leads to the omission of discontinuities causing smaller displacements, but in the case of our analyses, the functional model does not acceptably describe the time series (Fig. 3). As can be seen in Figure 3, the functional model does not represent satisfactorily the time series of the HOLB coordinates. The algorithm did not consider, among others, the leap of the height component at the beginning of 2002 and the change in the trend of stations the northern and eastern components in mid-2012. Performing analyses with larger values of the significance level shows that, with a larger range of searches, the time series are better

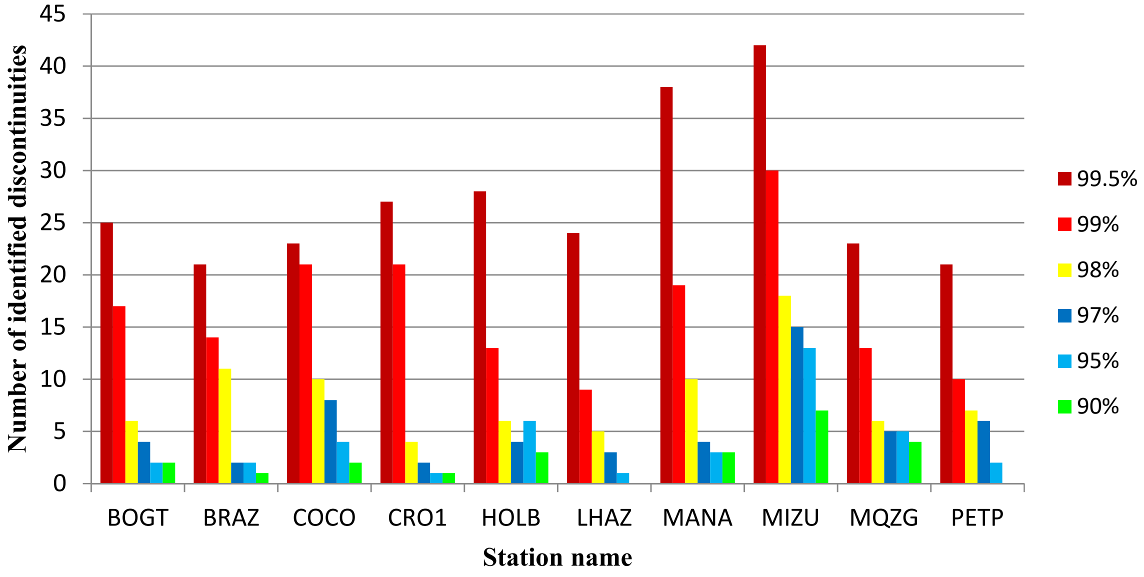


Fig. 4 The number of discontinuities detected by FODITS depending on the applied significance level for 7-day solutions.

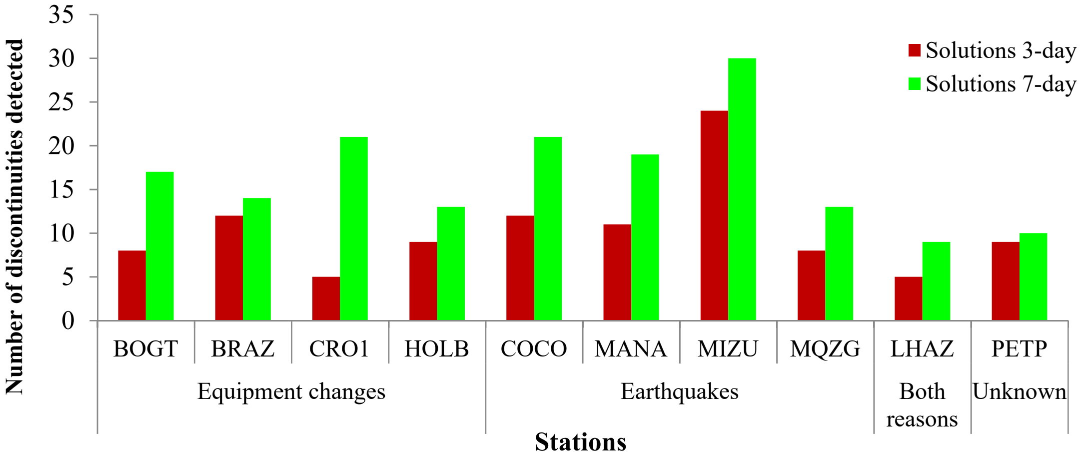


Fig. 5 Comparison of detected discontinuities for the materiality level of 99 % for 3-day and 7-day products.

represented by the functional model. Using a low significance level leads to the description of time series using linear functions. In both IGS products (3- day and 7-day solutions), there are outliers in the same epoch for most stations. It is possible that the CODE solutions of April 8, 2009, are incorrect (Fig. 3). Unfortunately, the reason for this anomaly is unknown.

3.2. ANALYSIS RESULTS FOR 7-DAY SOLUTIONS

Performing analyses for 7-day products aimed at comparing solutions and confronting the choice of parameters in relation to the type of data subject to analysis. For this purpose, 6 tests were performed using FODITS. The other program parameters were not changed in order to consistently and objectively compare the results. Figure 4 represents the results of tests performed in terms of the number of reported discontinuities by the program's algorithm. As one can see, these values do not correspond to the number of detected discontinuities for 3-day solutions. The total number of detected discontinuities for individual discontinuities in relation to the analysis of 3-day solutions is much higher, which implies that different parameters should be introduced for 3-day and 7-day solution. For MIZU in total 42 discontinuities were detected at the significance level of 99.5 % in 7-day solutions, whereas 35 discontinuities were detected for the same significance level in 3-day solutions. For CRO1, 27 and 14 discontinuities were detected in 7- day and 3-day solutions, respectively.

The number of detected discontinuities in the FODITS program are not consistent between the individual significance levels because the algorithm implemented in FODITS calculates the displacement values based on the fit of the functional model and the level of observational noise, which is different in 3-day and 7-day solutions (Fig. 5). The discrepancy between the GNSS time series analysis results for IGS products is due to their properties. The 7-day products are subject to a lower measuring noise because such a result was obtained by combining seven 3-day solutions, where individual estimated coordinates were stacked at the normal equation level and had to be averaged. This implies that the noise is 2.65 times lower in 7-day than in 3- day solutions, provided that no other systematic errors occur. Seven-day solutions seem to be a better input product for time series analysis from the noise perspective, but averaging data in some cases may not only reduce the measurement noise but also it may highlight gross errors. On the other hand, the high-frequency station motions, i.e., with the periods shorter than 7-days, cannot be recovered from 7-day solutions.

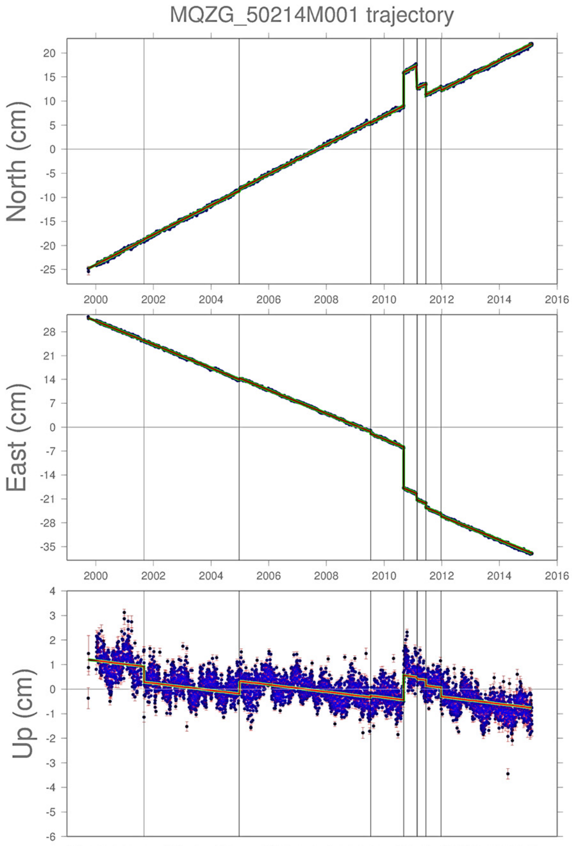
3.3. ANALYSIS OF THE TIME SERIES FROM ITRF2014

In order to select the best relative improvement threshold parameter for both 3-day and 7-day solutions, it was necessary to compare the results of the analysis with the manual solution available on the market, i.e. with the time series from ITRF2014. However, earlier it was necessary to analyze the introduced discontinuities for the time series of GNSS stations in the ITRF2014 solution. On the website http://itrf.ign.fr/ you can find graphs of time series and information about the characteristics of identified discontinuities in ITRF2014, along with the date and size of displacements for individual stations.

BOGT is a station where frequent discontinuities occur due to equipment changes. In the case of BOGT, the period in which data was not collected by the station caused by two receiver exchanges took place on August, 1st 1997 and on September, 28th 2000. The time series for this station also shows the relevance of the equipment replacements and its calibration in terms of the noise characteristics. The initial data logging period has a large measurement noise, which after mid-2002 decreased. Comparing the values of the displacements of individual components along the north - dN, east - dE and height - dU, it can be noticed that the smallest displacement value is denoted as discontinuity number 5 at displacements of 3.6 mm, 1.3 mm and 1.9 mm, respectively. The period between discontinuities 4 and 5 is short and lasts only 119 days. For this station, also the discontinuity number 7 is characterized by small displacement values, respectively -3.6 mm, -4.9 mm and 1.8 mm for the components dN, dE and dU.

The MQZG and MIZU stations were exposed to numerous earthquakes that had an impact on the stations' positions. For all components of the MIZU station, the post-seismic deformation modelling was applied in ITRF2014. The MIZU station in the ITRF2014 solution has the largest number of discontinuities from all the stations tested in this study. It can be seen that some of them occur at intervals of several or several dozen days. The interval between discontinuities 4 and 5 is 34 days (the first discontinuity is the antenna replacement at the station, the second is the earthquake), discontinuities 6 and 7 are to each other within 40 days (both caused by earthquakes), and between 8 and 9 (earthquakes) is just 3 days. The 8 and 9 discontinuities are so close to each other that they have been included together because it is impossible to determine a new position based on the observations of two days. Also, not specified station velocity have been defined, as it is not recommended to estimate the speed based on such short periods. Introducing discontinuities caused by earthquakes even at short intervals may be correct (in case they can be explained). However, it is important to note that earthquakes are often characterized by secondary shocks associated with viscoelastic relaxation lasting 6 months or more (Ergintav et al., 2009).

The MQZG station, like the MIZU station, had discontinuities mainly due to earthquakes. In this case,



Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

Fig. 6 Time series of the northern, eastern and altitude components of the MQZG station (Christchurch, New Zealand) in ITRF2014 implementation.

Table 2 Summary of the number of discontinuities using FODITS tool, as well as ITRF2014 and JTRF2014 solutions. TP stands for discontinuities that were reported by ITRF2014 and FODITS, while FN defines discontinuities detected by FODITS but not by ITRF.

Station name	**Defined levels of significance**																**ITRF2014**	**JTRF2014**
	3-day solutions								**7-day solutions**									
	99 %		**98.5 %**		**98 %**		**97 %**		**99 %**		**98.5 %**		**98 %**		**97 %**			
	TP	**FN**	**TP**	**FN**	**TP**	**FN**	**TP**	**FN**	**TP**	**FN**	**TP**	**FN**	**TP**	**FN**	**TP**	**FN**		
BOGT	**3**	**5**	2	3	**2**	**2**	2	2	2	15	**2**	**5**	**2**	**4**	2	2	8	8
BRAZ	**5**	**7**	4	2	**5**	**1**	2	2	4	10	**5**	**6**	**3**	**8**	1	1	7	4
COCO	**4**	**8**	4	5	**4**	**4**	4	2	4	7	**4**	**9**	**4**	**6**	4	4	5	7
CRO1	**4**	**1**	3	1	**1**	**1**	1	0	1	19	**4**	**1**	**3**	**1**	1	1	8	4
HOLB	**2**	**7**	2	5	**3**	**2**	3	0	4	9	**4**	**3**	**4**	**2**	3	1	9	6
LHAZ	**2**	**3**	2	2	**2**	**2**	2	0	3	6	**2**	**3**	**2**	**3**	2	1	6	2
MANA	**1**	**10**	2	5	**0**	**5**	0	3	2	17	**2**	**9**	**1**	**9**	1	3	5	7
MIZU	**3**	**21**	3	15	**2**	**13**	2	10	4	26	**3**	**16**	**3**	**15**	2	13	11	4
MQZG	**6**	**2**	4	0	**4**	**1**	3	1	5	8	**5**	**6**	**4**	**2**	4	1	7	5
PETP	**0**	**9**	1	8	**0**	**5**	0	4	0	10	**0**	**9**	**0**	**7**	0	6	6	3

the discontinuities were also introduced at short intervals (~3 months). Figure 6 shows the time series of the MQZG station before considering the effect of discontinuities. As can be seen, the up component has a non-linear trajectory after 4 discontinuity, while the north and east components are linear. The PSD models could be fitted separately in each east, north and up component. So it could be considered whether it should be applied in this case. As it was done for the north component of the MANA station (Managua, Nicaragua).

3.4. SELECTION OF THE OPTIMAL PARAMETERS OF STATISTICAL TEST FOR THE THRESHOLD OF RELATIVE IMPROVEMENT

To determine the optimal value of the relative improvement threshold test, a scheme had to be defined. In order to verify the correctness of the detected offsets in time series, 4 cases can be used: "True Positives" (TP, defines an offset that was originally simulated and also detected by a solution), "False Positives" (FP, defines an offset that was not simulated but which has however been reported by the solution), "False Negatives" (FN, defines an offset that wasn't simulated but which has not been detected) and "True Negatives" (FN, defines an offset that was not simulated and has not been detected; Venema et al., 2012). For this purpose, a method similar to that used in the DOGEx experiment was used (Gazeaux et al., 2013), where three cases were used: TP, FP and FP. Among the detected discontinuities, only those identified within a difference of ± 10 days to those detected as part of the ITRF2014 implementation were described as "True Positive" (TP). Other discontinuities were classified as "False Negative" (FN). I did not use the "False Positive" (FP) case because it describes a offset that was not simulated but was reported by the solution. The elimination of this case was dictated by the fact that in this case the actual shift epochs for individual components are undefined, as the data from GNSS stations are analyzed and not artificially simulated data series.

The time series to which the test results refer are the time series developed in the preparation of ITRF2014 and JTRF2014. The number of discontinuities detected in ITRF2014 and JTRF2014 solutions, as well as for different significance levels in FODITS are summarized in Table 2. As can be seen, no solution has a significantly higher or much lower percentage of reported discontinuities identified as TP to shift marked as FN in the case of analyzes for both IGS products. By comparing the number of discontinuities reported by FODITS with the ITRF2014 solution, the most optimal statistical test value for the relative improvement threshold can be selected. For 3-day products, the best value of the relative improvement threshold ranges from Ut = 0.01 to Ut = 0.020 (corresponding to 99 % and 98 % confidence levels), and for 7-day solutions between Ut = 0.015 to Ut = 0.02 (corresponding to 98.5 % and 98%). For only two stations, the severity levels presented did not adequately describe the time series of GNSS positions. These are the MIZU and COCO stations (see Table 2). According to ITRF2014, the COCO station was not exposed to such a large number of events; only 5 discontinuities were detected when the JTRF2014 solution already reports 7 discontinuities. Both ITRF and JTRF have been using daily solutions, so the reason for such a different number of reported discontinuities is unknown. For a 3-day solution, FODITS for COCO stations reports 8 discontinuities for value of the relative improvement threshold of 0.02. This may suggest that the number of discontinuities reported by the ITRF2014 solution is too small. However, in the case of MIZU stations, the situation is the opposite. The ITRF2014 solution reports 11 discontinuities, the JTRF2014 solution reports 4 discontinuities, while FODITS - 15 (for value of the relative improvement threshold of 0.02). In the case of MIZU stations, such a large difference between the individual solutions may result from the fact that it is a station that is exposed to frequent earthquakes. However, in the case of COCO stations, they may be

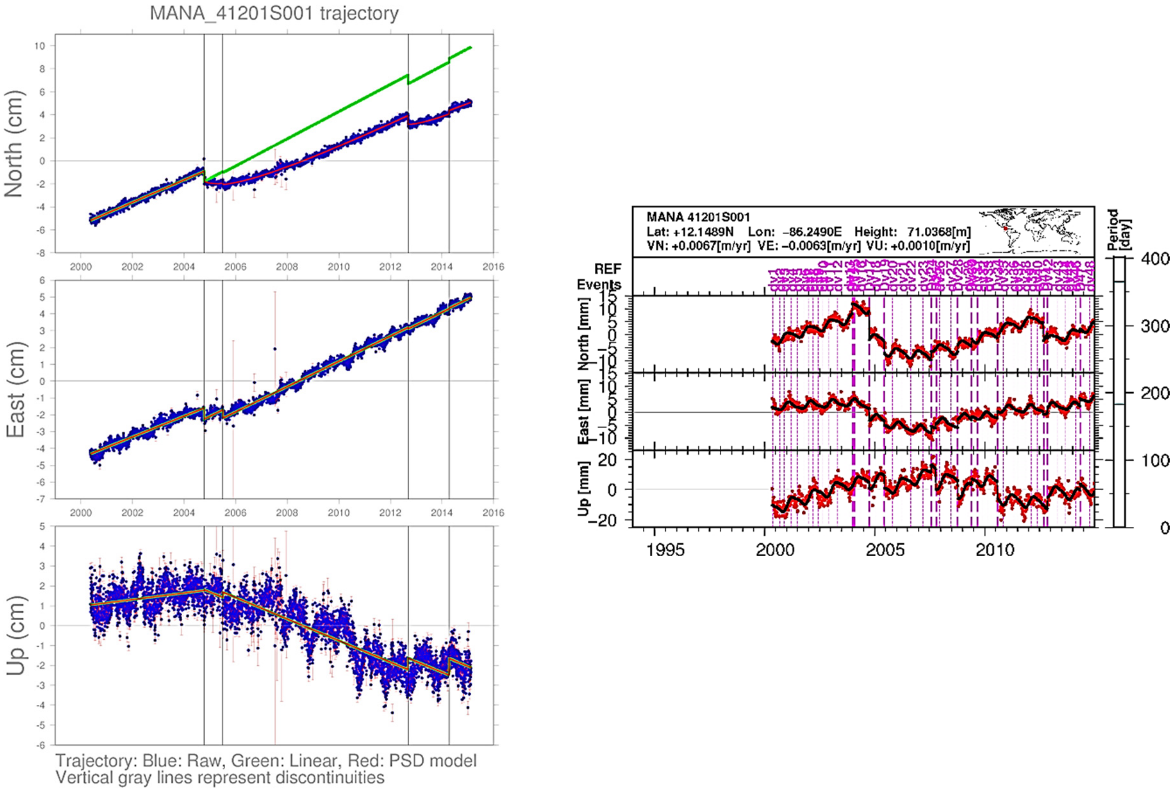


Fig. 7 Time series of the northern, eastern and altitude components of the MANA station in ITRF2014 implementation (left) and FODITS (right) for the significance level of 98.5 % for 7-day solutions.

affected by an error that has not yet been determined and described such as multipath errors or other (Bogusz et al. 2015; Bogusz et al. 2016). For these two stations, the optimal value of the statistical test level is higher and amounts to Ut = 0.4 for both the 3-day and 7-day solutions.

The number of reported discontinuities is different for all three solutions. This may be caused by different approaches in individual methods of time series analysis, but also by different input data. Even though both ITRF2014 and JTRF2014 used IGS daily solutions, for JTRF daily solutions were averaged to weekly solutions prior to analysis. In most cases, FODITS detected a greater number of discontinuities than the ITRF and JTRF for both the 3-day and 7-day solutions. This may suggest that FODITS may be a good tool for initial time series analysis that should be checked later.

Figure 7 represents the MANA time series in the ITRF2014 and FODIT solution. As can be seen, the number of discontinuities detected varies considerably. The ITRF solution detected 5 discontinuities caused by earthquakes. The FODITS for the 7-day solution for the significance level of 98.5 % detected 11 discontinuities while the JTRF reported 7 discontinuities. In case of the northern component, ITRF solution uses the PSD model, which very well represents the real trajectory of this component. Such a large difference between the number of detected discontinuities may suggest that further analysis of the time series of GNSS stations are necessary.

The FODITS program is mainly aimed at finding epochs for discontinuities and changes in station velocities and outliers. It does not conduct a network solution taking into account the full variance-covariance matrix with a full no-net-rotation constraint as used for the ITRF realization. To obtain real displacement values, the final solution should be calculated by using the full system of normal equations with the proper datum definition (see, e.g., Zajdel et al., 2019). The solution obtained from FODITS would serve to provide metadata to detect epochs in which discontinuities occurred, so that normal equation inversion could generate individual values of coordinates and station velocities between discontinuities. The final discontinuity values from a network solution that takes into account the full variance-covariance matrix should, therefore, come from the inversion of the full normal equation system with proper network constraints removing all datum defects.

4. SUMMARY AND CONCLUSIONS

This paper analyzes the discontinuities in the position time series determined using the program FODITS of the Bernese GNSS Software and compares the obtained results with ITRF2014 and JPL solutions. The number of detected discontinuities and velocity changes strongly depends on the significance level employed in the analysis. The proper analysis of the coordinate time series is crucial for reliable estimation of station velocities. Excessive segmentation and misidentification of discontinuities, especially for the final fragments of the GNSS station coordinate time series, is still a serious problem in the realization of reliable global geodetic reference frames. Undetected discontinuities have a negative impact on the forecasted models and results describing geophysical phenomena (Vitti, 2012). If the discontinuities occurring in the GNSS observation time series are not properly identified and removed, they may distort reliable modelling of long-term trends and non-linear motions that may have arisen as a result of phenomena related to geophysical and environmental changes. What is more, the observed changes in the time series of geodetic parameters give direct evidence of many global processes that affect human society such as earthquakes, volcanism, floods, sea-level changes, mass deviations of polar glaciers or redistribution of groundwater, therefore their careful analysis is particularly important.

Therefore, the optimum threshold significance of the automatic analysis in the FODITS program were identified, so as to be able to optimally conduct the analysis of the GNSS station coordinate time series for 3-day and 7-day solutions. In addition, the reported discontinuities in ITRF2014 were verified to check the correctness of the epochs of detected discontinuities and to evaluate the manual detection that is not based on statistical tests. The study shows that for the 3-day GNSS solutions, the optimal value of the relative improvement threshold fluctuates from Ut = 0.01 to Ut = 0.02, which corresponds to significant levels of 99 % and 98 %, whereas for 7-day solutions resulting from the combination of 3-day orbital GNSS arcs, the optimal value is within Ut = 0.015 to 0.020.

The FODITS program is mainly aimed at finding epochs for discontinuities, changes in station velocities and outliers. It does not conduct a network solution taking into account the full variance-covariance matrix with a full no-net-rotation constraint as used for the ITRF realization. To obtain real displacement values, the final solution should be calculated by using the full system of normal equations with the proper datum definition (see, e.g., Zajdel et al., 2019). The solution obtained from FODITS would serve to provide metadata to detect epochs in which discontinuities occurred, so that normal equation inversion could generate individual values of coordinates and station velocities between discontinuities. The final discontinuity values from a network solution that takes into account the full variance-covariance matrix should, therefore, come from the inversion ofthe full normal equation system with proper network constraints removing all datum defects.

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