The BfG-GNSS Monitoring Network – Delivering a Continuous Georeferencing Service for Waterway Management Tasks

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Key words: GNSS monitoring network, georeferencing of tide gauges, time series analysis, climate changes

SUMMARY

The Department M5 - Geodesy and Remote Sensing - of the Federal Institute of Hydrology (BfG) operates its own Global Navigation Satellite Systems (GNSS) monitoring network. Currently, 43 stations on the North Sea coast are equipped with a permanent GNSS receiver, an extension by 6 more stations on the Baltic Sea coast is planned this year and planning for a demand-oriented equipment of the inland gauges will start in 2022. The observations are regularly processed by the Federal Agency for Cartography and Geodesy (BKG) in an international framework. The results are up-to-date coordinates, especially heights, in both an international (global) and a national reference frame.
Continuous data from the GNSS network is the basis for modern waterway management tasks and a smart alternative to conventional terrestrial level measurements. Major task is locally comparable water level at the coast. Thus, GNSS stations are typically located at tide gauges to georeference the sensors. Also, the data of the BfG-GNSS monitoring network and their temporal analysis will provide important basic information for adaptation to climate change. In the German Adaptation Strategy to Climate Change (DAS) "Climate and Water" service, the BfG is, among other things, charged to realize the module "Land Movement". This involves the investigation of the causes of regional sea level rise (sea level variations vs. land subsidence). Furthermore, several other waterway management tasks, as well as other international services, can benefit from the continuous data provided by our network, e.g., geodetic surveys of locks or an improved georeferencing for marine navigation.
Trial and test phases of the monitoring network have been completed, so that it is officially in operation since July 30, 2020. Data transmission, processing and the annual provision of the current tide gauge bench mark heights are running, so that currently, in addition to the expansion of the network, further analyses and research regarding the development of models for geodetic time series analysis are taking place. In this contribution, the BfG-GNSS measurement network and its products are presented and first results as well as methods of time series analysis are shown, focusing on outlier tests and the detection and correction of discontinuities.

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1. Introduction

Correct water levels are an essential requirement for the execution of a number of tasks in the Federal Waterways and Shipping Administration (e.g., monitoring of new construction and maintenance), for hydrological analyses and modeling, in the field of coastal engineering (e.g., coastal protection) and for the investigation and interpretation of long-term water level changes in the context of climate research. This assumes that the height of the tide gauge zero to which the water level observations refer is reliably and currently known. Often real water level changes and vertical land movements overlap and can no longer be separated from each other. The tide gauge guideline of the Federal Waterways and Shipping Administration (WSV) takes this situation into account by requiring regular connection measurements to the levelling networks of the Land Survey. By measuring the tide gauges in a uniform national reference system, the water level data recorded at different tide gauges can be compared with each other. Such a reference frame can be realized through Global Navigation Satellite System (GNSS) stations located at or near the tide gauges. Establishing such reference frame is one of the aims of the International GNSS Service Tide Gauge Benchmark Monitoring Pilot Project TIGA. GNSS data from more than 600 stations globally distributed are being processed at the German Georesearch Center (GFZ). Since 2008, the Federal Institute of Hydrology (BfG) has started to equip important tide gauges at the North Sea coast and offshore with permanently operating Global Satellite Navigation Systems (GNSS) in order to realize tide gauges georeferencing in Germany. Figure 1 shows a few photos of permanent stations in the offshore area or in the coastal area of the North Sea. Especially for remote stations, e.g. on islands, where the connection point of the Land Survey is several kilometers away, the GNSS method offers a reliable and smart alternative to conventional terrestrial level measurements. Furthermore, the GNSS method is advantageous for stations in very unstable

Figure 1: Photos of permanent GNSS antennas at the stations Leuchturm Alte Weser, Wangerooge-Nord, Wilhelmshaven, Neuer Vorhafen operated by the Waterways and Shipping Office Weser-Jade-Nordsee and the station Knock operated by the Waterways and Shipping Office Ems-Nordsee

regions, where a level measurement every 10-15 years is not sufficient for a reliable and current height connection. Trial and test phases of the monitoring network have been completed, so it has been officially operational since July 30, 2020.
In addition, the permanent observations provide a basis for tide gauge monitoring within the framework of the German Strategy for Adaptation to Climate Change (DAS). In DAS "Climate and Water" service, the BfG is, among other things, charged to realize the module "Land Movement". In the future, for example, statements in the context of "land subsidence vs. sea level rise" will be possible after appropriate time series analyses. The focus lies here on an automated data cleaning. The time series must be removed from outliers and discontinuities, i.e. abrupt changes in the time series, as done for example in Perfetti (2006) Gazeaux (2013) or Rapinski and Kowalczyk (2016).
In this paper, the existing BfG-GNSS measurement network with its stations, the processing chain and the products will first be presented in Chapter 2. Afterwards, Chapter 3 deals with the topic of time series analysis. The problem is explained and first approaches to remove outliers and discontinuities are described and demonstrated exemplarily for one tide gauge. The paper ends with a conclusion and an outlook, about further plans and ideas.

2. BfG-GNSS Monitoring Network

Currently, the BfG has equipped 38 stations on the North Sea coast with a permanent GNSS antenna, see Figure 2, two more stations are still planned. This year, the monitoring network will be extended to the Baltic Sea coast. The WSV has already placed an order for six tide gauge stations. Furthermore, there are five permanent stations in the inland area that are used for monitoring purposes. A further expansion into the inland area is planned. From 2022, a conception phase will begin, in which a demand-oriented expansion is planned.

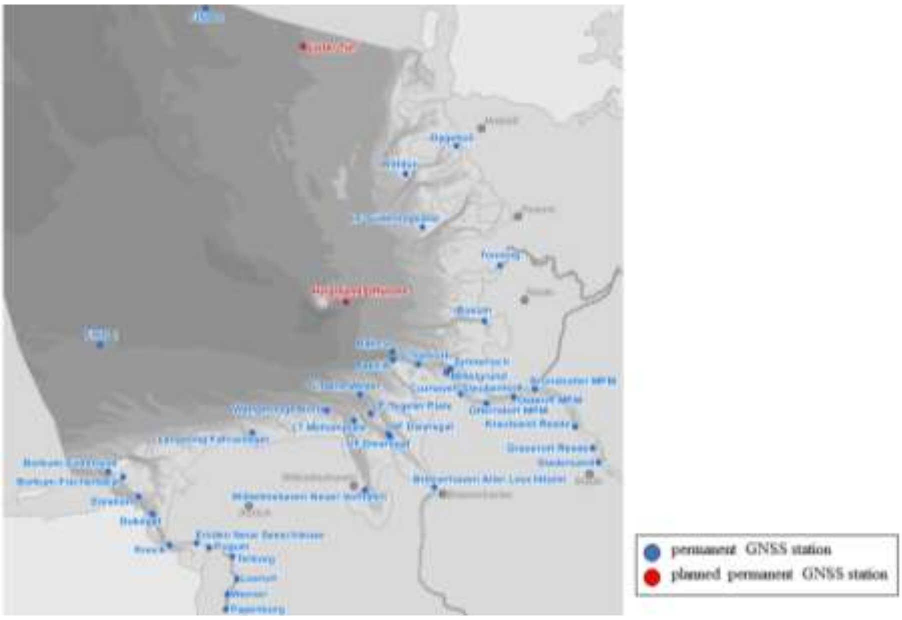

Figure 2: Overview map of existing and planned permanent GNSS stations on the North Sea coast

2.1 Processing Chain

The processing chain is summarized in Figure 3. The GNSS observation data are first stored locally on the GNSS receiver. At regular intervals, usually of several hours, the raw data are transmitted from the receiver via a VPN tunnel to the BfG, where they are combined into daily data. After a quality check, they are sent to the Federal Agency for Cartography and Geodesy (BKG), where they are regularly processed in an International Terrestrial Reference Frame (ITRF), currently the ITRF2014 (Altamimi et al. 2016) using the Bernese GNSS Software (Dach et al. 2015). Afterwards, they are transformed into a national reference frame, currently the ETRS89/DREF91.R2016 (Integrated Geodetic Spatial Reference 2016 in Germany from 01.12.2016). The results are weekly coordinates of the GNSS marker, see Figure 4, that are archived at BfG and finally processed into products that are provided to the clients.

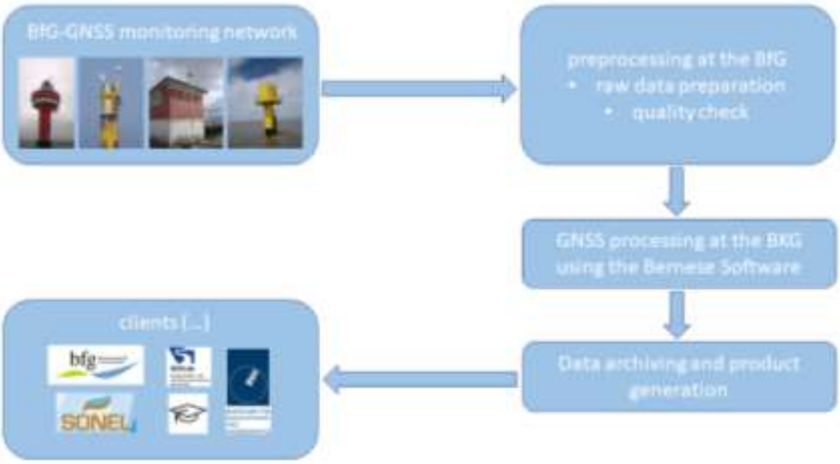

Figure 3: Processing chain of the BfG-GNSS monitoring network

2.2 Products

Continuous data from the GNSS network is the basis for modern waterway management tasks. They are used to georeference selected tide gauges that are located in remote or unstable locations. Using the permanent GNSS is the only way to ensure that the heights of the tide gauges are reliable and actually available in a homogeneous reference frame, thus, guaranteeing the required spatial and temporal comparability of water levels. Figure 5 shows the relationship to get from the GNSS marker via the height difference Δh_1 to the tide gauge bench mark heights. Via the height difference Δh_2 one further reaches the tide gauge zero. The GNSS method is a smart alternative to conventional terrestrial level measurements, which take place every 10-15 years and which are no longer possible for offshore gauges due to the discontinuation of hydrostatic levelling at the end of the 90s. After a hydrological year, the weekly solutions are averaged and current and precise fixed tide gauge bench mark heights in an international and a national reference frame are provided to the WSV, and other clients as the Federal Maritime and Hydrographic Agency (BSH) or university institutions that use the data for scientific work and research purposes. Internationally, the data of the BfG-GNSS measurement network are integrated into the Coastal Water Level Observing System (SONEL) and the Tide Gauge (TIGA) pilot study of the International GPS Service (IGS).

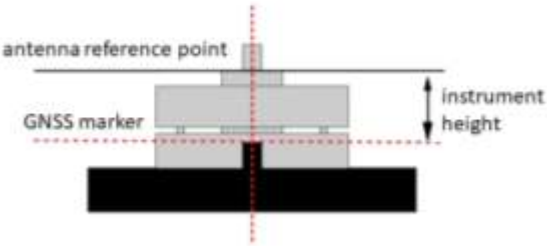

Figure 4: Geometry of the antenna mounting and the position of the GNSS antenna marker

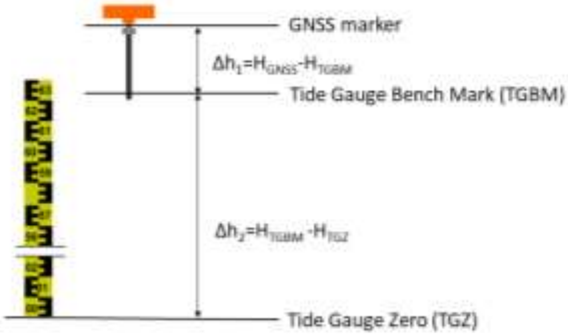

Figure 5: Height relation between GNSS marker, Tide Gauge Bench Mark and Tide Gauge Zero

In addition to gauging stations, selected buildings are also equipped with a permanent station with the aim to monitor the movement. One example is the water gate in Hessigheim at the Neckar river, see Figure 6. The geological subsurface of the construction area is characterized by instabilities. Due to groundwater flows, leaching processes of gypsum occur. This leads to ground subsidence in the order of 1mm/yr to 1cm/yr with a corresponding impact on the stability of the water gate system. These temporal changes must be observed with high accuracy and reliability. For this reason, three permanent GNSS stations were installed, two directly near the water gate and one a little further away. These are permanently integrated into the BfG-GNSS measurement network, so that they provide a consistent reference for further local density measurements in the form of GNSS campaigns, leveling, total station or unmanned aerial vehicle (UAV) measurements (Cramer et al. 2018).

Figure 6: One of the two permanent stations at the Hessigheim water gate for purposes of monitoring

Another product is the provision of real-time correction data, as is currently done at the Alte Weser lighthouse. With the help of a 2m radio, the correction data is sent in real time to the ships of the BSH. They need an accurate and reliable real-time positioning to georeference their collected geodata, e.g., to produce nautical charts. In surveying areas far from the coast, such as in the area of the Alte Weser lighthouse, the ships cannot receive the SAPOS (German satellite positioning service, Riecken and Kurtenbach 2017) correction data due to a missing internet connection, so that the correction data are received by the GNSS antenna permanently installed on the Alte Weser lighthouse by the BfG. If necessary, this is also possible from other stations of the monitoring network.

Due to the permanent observations, the data of the BfG-GNSS measurement network provide important basic information for the adaptation strategy to climate change. For this purpose, time series analyses of the GNSS marker motion behavior are necessary. The development of models for geodetic time series analysis is currently in the initial phase, so that first approaches and results are presented in the following chapter.

3. Time Series Analysis

Due to the permanent GNSS observations it is possible to monitor the movement behavior of the GNSS marker from the weekly solutions. After corresponding analysis it is possible to make statements about the trend or seasonal effects. Figure 7 shows a straightforward plot of the original weekly solutions of the GNSS marker at the FINO1 research platform with respect to the first solution for the period 12.11.2008 to 16.01.2021 divided into north, east, and height components. The solutions were transformed into the national reference system ETRS89/DREF91 with the realization 2002 until 30.11.2016 and with the realization 2016 from 01.12.2016. The permanent GNSS station is used for georeferencing water level data collected at FINO1.
The data have not been further analyzed and still contain outliers and discontinuities. These discontinuities include data gaps as well as quasi constant shifts of subsequent coordinates with respect to the previous coordinates. These jumps are caused by a hardware change, software updates, a change of the reference frame within the processing or due to other events. Especially in longer time series the number of jumps can increase and due to their cumulative effect even smaller jumps have a significant impact on the estimation of the motion. Therefore, the identification of the jumps plays an important role to understand the deformation of the earth's surface correctly (Gazeaux et al. 2013).

There are a number of possible approaches to locate the discontinuities. They can be identified by knowing the date of the event that generated the jump, for example by using the log file or by applying an automatic discontinuity detection process. Perfetti (2006) for example applies the detection identification adaptation (DIA) method, introduced by Teunnissen (2000), to GPS coordinate time series to detect offsets and outliers. A similar approach is taken in the FODITS (Find Outliers and Discontinuities In Time Series) tool of the Bernese GPS Software (Dach et al. 2015). Using an iterative DIA method, the functional model, which consists of outliers, discontinuities, one or more velocities per station and a set

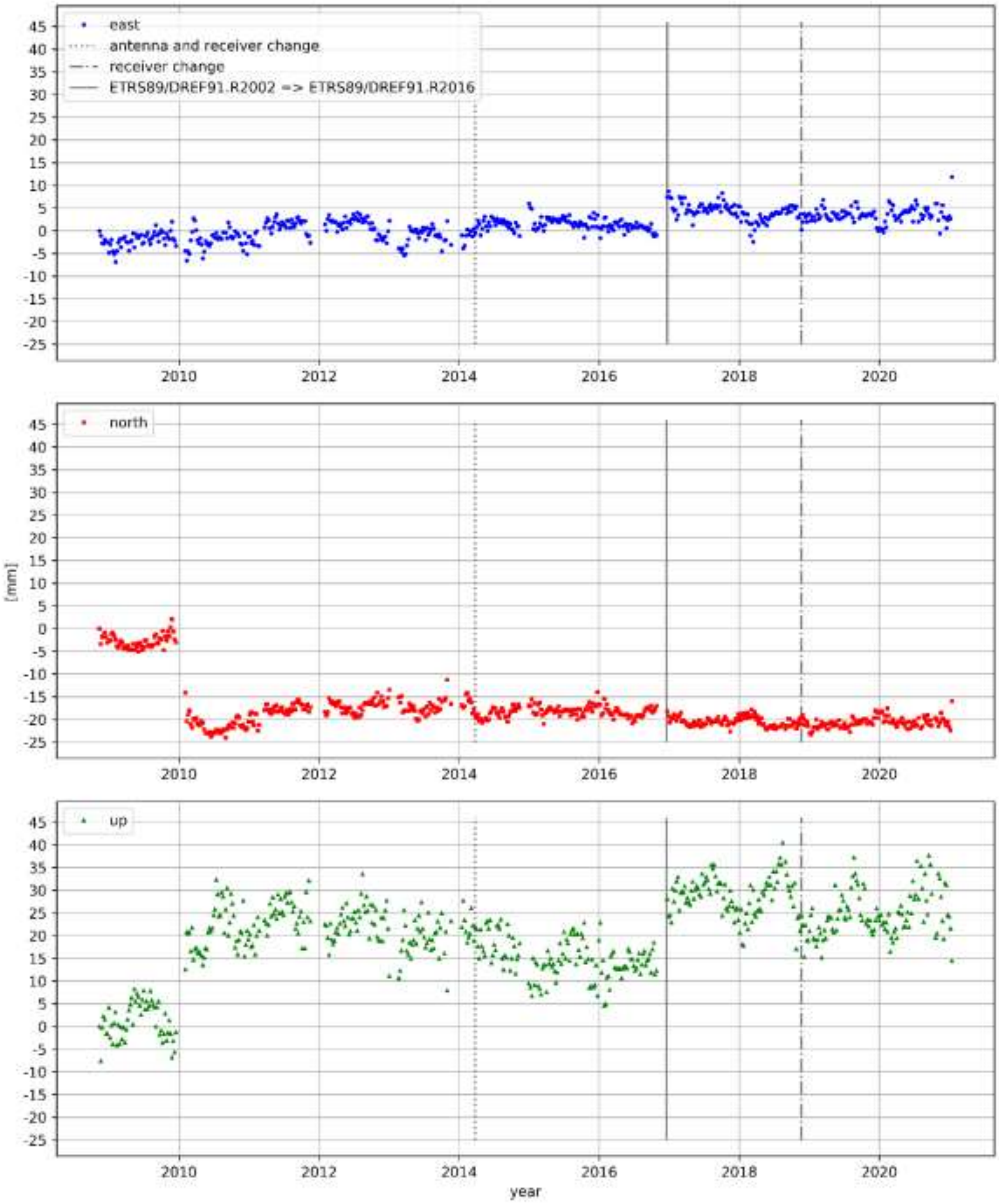

Figure 7: Original coordinate time series of the GNSS marker at the FINO1 research platform with respect to the first weekly solution for the period 12.11.2008 to 16.01.2021

of periodic functions, is fitted. Starting from an a priori model based on predefined hardware changes, other events and a global list of earthquakes, the discrepancy between the functional model and the data is reduced in each step. The known events, such as hardware changes and the change of the reference system from ETRS89/DREF91.R2002 to ETRS89/DREF91.R2016 are shown as vertical lines in Figure 7. Visually, an additional jump can be seen at the beginning of 2010 whose origin is not known a priori. To locate these discontinuitites the switching edge detector algorithm presented by Rapinksi and Kowalcyk (2016) is used in this paper. This approach is numerically relatively low-cost and does not require any further metadata, so that it is also suitable for real-time applications. However, the analysis have shown that it is advantageous to include the known events as a priori information so that a combined approach is used in this paper. In the following, the approach is described theoretically and demonstrated exemplarily for one tide gauge (FINO1).

3.1 Methodological

Before the combined approach can be used to find the discontinuities, outliers must be eliminated (Rapinksi and Kowalcyk 2018). For this purpose, the Grubbs test (Grubbs 1969) is used analogously to Rapinski and Kowalcyk (2018). The Grubbs test is a method to check for a given normally distributed sample whether the value with the largest deviation from the mean is an outlier. The test is defined for the hypothesis:

- H_0: there are no outlieres in the data set
- H_A: there is one outlier in the data set

For a given sample $x_i, i = 1 \ldots n$ of size n the test value is defined as

$$T = \frac{\max\limits_{\mathrm{i=1\ldots n}} |x_i - \bar{x}|}{s} \qquad (1)$$

with the mean $\bar{x}$ and the corresponding standard deviation s. The null hypothesis H_0 that there is no outlier in the sample is rejected if

$$T > \frac{n-1}{\sqrt{n}} \sqrt{\frac{t^2_{\frac{\alpha}{2n},n-2}}{n-2+t^2_{\frac{\alpha}{2n},n-2}}} \qquad (2)$$

where $t^2_{\frac{\alpha}{2n},n-2}$ denotes the upper critical value of the t-distribution with $n-2$ degrees of freedom and a significance level of $\alpha/2n$. The Grubbs test should be used for smaller samples up to a size of 25. In case of a large set, a moving average with a size of 25 is applied over the time series. Consequently, each data point is tested a total of 25 times. If the null hypothesis is rejected at least 10 times for a data point, that point is declared as an outlier and removed from the data set. In order to also find neighboring outliers, the test is repeated several times.

In the next step, the discontinuities are detected using the switching edge detector algorithm. Considering a single data point x_i at epoch t_i, moving averages with a size of n =50 are calculated from this data point backwards and forwards, as well as the associated variances:

$$\bar{x}_{i+} = \frac{\sum_{k=1}^{n} x_{i+k}}{n}, \qquad \bar{x}_{i-} = \frac{\sum_{k=1}^{n} x_{i-k}}{n} \tag{3}$$

$$s_{i+}^2 = \frac{\sum_{k=1}^{n}(x_{i+k}-\bar{x}_{i+})^2}{n-1}, \quad s_{i-}^2 = \frac{\sum_{k=1}^{n}(x_{i-k}-\bar{x}_{i-})^2}{n-1} \; . \tag{4}$$

The output function of the switching edge detector algorithm is defined as

$$H_i = g_{i+} \cdot \bar{x}_{i+} + g_{i-} \cdot \bar{x}_{i-} \tag{5}$$

with the switching factor

$$g_{i+} = \frac{(s_{i-}^2)^{2r}}{(s_{i+}^2)^{2r} + (s_{i-}^2)^{2r}}, \qquad g_{i-} = \frac{(s_{i+}^2)^{2r}}{(s_{i+}^2)^{2r} + (s_{i-}^2)^{2r}} \tag{6}$$

and an arbitrary exponent value r which in this case is selected with r =40. The shape of the output function is shown for the height component of the above time series in Figure 8. By means of a threshold value, which is drawn as a horizontal dashed line in Figure 8, the discontinuitites are detected as soon as the peak exceeds this value. In this case, only significant discontinuities are identified. The threshold for east and north components is set by five times the mean value of the switching factor and for the height component by 10 times the mean value. The unknown jump at the beginning of 2010 as well as the change of the reference system at the end of 2016 can be recognized by a significant peak.

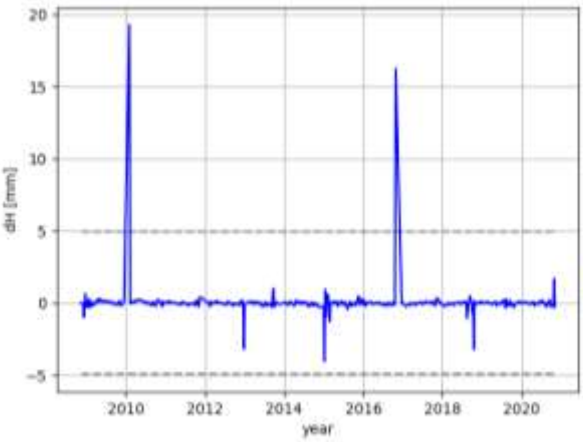

Figure 8: Shape of the output function for the height component of the coordinate time series shown in Figure 7. The horizontal dashed lines represent the thresholds from which a jump is detected.

Based on this knowledge, a matrix $\boldsymbol{C}$ is constructed, which consists of zeros and ones. It has as many rows as detected discontinuities and as many columns as epochs. In a row associated with a discontinuity, there are zeros before the event and ones after it. The known discontinuities, such as the receiver and antenna changes are still added to the matrix as additional rows.

In a final step, the magnitude of the discontinuities and a linear model are estimated in a least squares adjustment (Koch 1977) with equally weighted observations. The functional model looks like

$$\boldsymbol{x}(\boldsymbol{t}) = x_0 + v\boldsymbol{t} + \boldsymbol{C}^T\boldsymbol{s} \quad (7)$$

with the vector of data $\boldsymbol{x}$ at the epochs $\boldsymbol{t}$, the y-axis intercept x_0, the velocity v, the transposed of the matrix $\boldsymbol{C}^T$ and the magnitude of the jumps $\boldsymbol{s}$.

3.2 Results

After applying the outlier test, one observation is detected as an outlier in the east component, two outlieres are found in the north component and one in the height component. As soon as an outlier occurs in one component, the other components for this epoch are also taken out. The significance level is set to 1%. Thus, the risk for an error of the first kind, i.e., that the null hypothesis is wrongly rejected, is very low.

The finally processed coordinate time series after the outlier test and the correction of discontinuities is shown in Figure 9. The outliers are shown as red circles. In total, two epochs are removed from the time series. As already shown in Figure 8, two discontinuities are detected using the switching edge detector algorithm, one at the beginning of 2010 and one at the end of 2016. The change of antenna and receiver in March 2013 as well as the change of receiver in November 2018 are not detected. However, looking at the original time series in Figure 7, there is still no significant jump in the time series. These events are therefore included in the matrix $\boldsymbol{C}$ in (7) from a priori information, so that a total of 4 offsets are estimated in the least squares adjustment. After applying the offsets, Figure 9 shows that the time series now no longer have any significant jumps compared to Figure 7. In addition, a linear model is estimated in the least squares adjustment, which is indicated as a black line in the figure. The velocity of the east and height components is not significant, which was tested with an error probability of 5%. The velocity of the north component is significant with 0.90mm/yr.

The presented method was also applied to all of others stations time series. In summary, it turned out that the results are very good. In general, it can be said that the combined approach is very well suited to handle the GNSS coordinate time series. Since not all jumps are

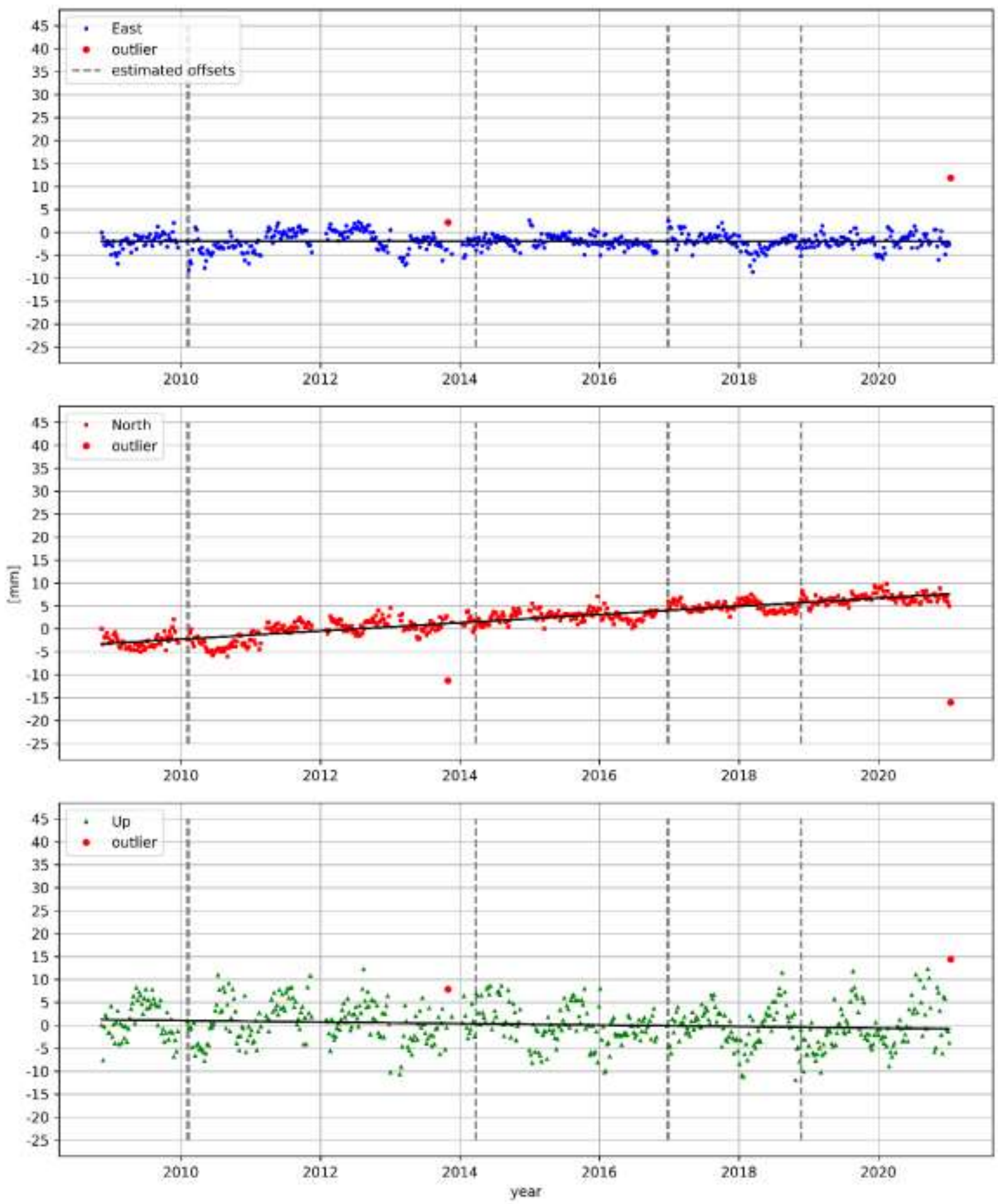

Figure 9: Processed coordinate time series of the GNSS marker at the FINO1 research platform with respect to the first weekly solution for the period 12.11.2008 to 16.01.2021 after outlier test and elimination of discontinuities.

included in the a priori information, as shown in the example from the FINO1 platform, it is helpful to additionally apply an algorithm for the automated detection of discontinuities. The origin of these jumps must then be investigated further in detail. As can be seen in Figure 9, the time series show seasonal effects in addition to the linear model. In a further step, the estimated model has to be extended accordingly.

4. Summary and Outlook

The BfG-GNSS measurement network is officially in operation since July 30, 2020 and serves as a basis for modern waterway management tasks. Currently, the network includes 38 stations on the North Sea coast and five more in inland areas. The data is weekly evaluated by the BKG in an international reference system. The results are primarily used for georeferencing the tide gauges in order to make the measured water levels comparable in time and space. The GNSS method is a smart alternative to the conventional terrestrial measurements. After the end of a hydrological year, the weekly coordinates are averaged and current and precise heights of the tide gauge bench marks are delivered to the WSV and other national and international clients as the BSH, SONEL, TIGA or universities that use the data for scientific work and research purposes. In addition to georeferencing, the permanent observations also enable a monitoring system, which is already used for selected stations and water gate constructions, or the BfG-GNSS measurement network provides the corresponding infrastructure to connect to the network with local and temporary GNSS campaigns or other measurement methods, such as total stations or UAVs. Another product is the provision of real-time correction data, as is currently done at the Alte Weser lighthouse with the help of a 2m radio antenna.

Also, the data of the BfG-GNSS monitoring network will provide important basic information for adaptation to climate change. For this purpose, a corresponding time series analysis is important. Currently, first investigations and first implementations of methods are in progress. A Grubbs outlier test has been implemented. The Grubbs test is a method to check for a given normally distributed sample whether the value with the largest deviation from the mean is an outlier. In this case, a moving average is applied to the time series, so that each data point is tested several times. After all outliers are removed, a combined approach of the switching edge detector algorithm and a priori information is used to detect discontinuities. The magnitude of the discontinuities is estimated simultaneously with the model parameters, in this case a linear model. The advantage is that it is a cost-effective computational approach that is not recursive or iterative. On most of the applied time series the approach works. However, it has been shown that further investigations are necessary with respect to seasonal effects that have so far been ignored or other effects that cannot be represented by means of a linear model. In the future, it would also be desirable to include neighborhood behavior, since so far, each station has been considered on its own.

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BIOGRAPHICAL NOTES

Christina Esch works at the BfG since April 2020. Previously, she studied geodesy and geoinformation at the University of Bonn and subsequently worked as a research assistant at the Institute for Geodesy and Geoinformation. At the BfG she is currently responsible for the scientific supervision, evaluation and further development of the BfG-GNSS measurement network for height monitoring of tide gauges and other hydraulic structures.

Thomas Artz works at the BfG since 2016. Previously, he studied geodesy at the University of Bonn and subsequently worked as a research assistant at the Institute for Geodesy and Geoinformation. At the BfG he is currently the head of the team for hydrography, which deals with the development and testing of survey systems and methods for surveying and evaluating of data

Astrid Sudau works at the BfG since 1991. Previously she studied geodesy at the University of Bonn. At the BfG she is currently working on geodetic reference systems, tide gauges and climate changes.

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