# **GNSS-Monitoring of Surface Displacements in Urban Environments**

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## 1 GNSS Monitoring and Inner City Challenges

## 1.1 Introduction

Subsidence processes in dense populated urban areas are of high social relevance. As there is few knowledge about the evolution and the characteristic of subsidence induced land depressions or sudden sinkhole events, a detailed and interdisciplinary focus is set on this field of research especially at regions and cities with dense population. SIMULTAN (Sinkole Instability, MULTiscale monitoring an ANalysis) aims at an interdisciplinary level to gain a deeper understanding of the complex processes, interactions and characteristics of the underground and the surface interaction in urban environments, (KERSTEN, ET AL. 2016). The aims and working packages of SIMULTAN are defined by four items:

- 1. Characterisation of the underground with high resolution methods (seismics, geoelectrics, downhole logging, seismology, direct push) and inverse techniques,
- 2. Monitoring of the surface and subsurface by combining geodetic and geological techniques (GNSS, levelling, relative and absolute gravimetry),
- 3. Interdisciplinary interaction and closed loop between field data and modelling of sinkhole evolutions with process simulation techniques, and finally
- 4. Integration of all elements into an information and hazard control platform.

This paper will focus on the second element of the SIMULTAN project and in detail on the reproducibility of derived GNSS positions and heights in inner city environments. An overview on the combination and the actual design of the geodetic and geophysical network for urban subsidence monitoring is described in KERSTEN ET AL. (2016).

## 1.2 GNSS Challenges and Obstructions in Inner Cities

Two target areas with different geological characteristics are studied in SIMULTAN and will be discussed in this paper. The first area is Hamburg Groß-Flottbek (HHX, densely populated), an area that slowly subsides due to the leach of the Othmarschen-Langenfelde salt diaper (DAHM, ET AL. 2011). From ongoing leveling campaigns annually sinking of 1-2 mm are proven. The second focus area is Bad Frankenhausen (BFH, Thuringia) where levelling surveys indicate annually sinking of 4-5 mm. In addition, sinkholes with diameters of some tens of metres are known and regularly reported as this is an ongoing process that develops along the Kyffhäuser Southern Margin Fault, (SCHMIDT, ET AL. 2013, WADAS, ET AL. 2016). Controlling factors for subsidence processes are the geological structure and specific generation processes, (WALTHAM, ET AL. 2005).

Meeting all boundary conditions for a GNSS site inside an urban monitoring network that consequently considers additional necessities to cover geophysical (absolute and relative Gravimetry) and geodetic techniques (levelling and GNSS) at identical points is right challenging.

This contribution proposes a concept of dynamic and adaptive elevation masks. Such technique can improve the repeatability of GPS network solutions at challenging GNSS sites in dense populated urban areas as noise on the observables as well as the number of necessary ambiguities is significantly reduced. We study the concept for urban GPS monitoring networks in Hamburg Groß-Flottbek and Bad Frankenhausen.

#### 1.3 Organisation of the Paper

The paper is organised as follows. The next section presents the concept of dynamic and adaptive elevations masks (dynMsk) as derived from C/N0 reference curves. The third section discusses the improvements of the proposed approach on the observation domain with respect to station specific characteristics. The fourth section discusses the impact on the position domain by comparing typical GNSS processing software packages. The fifth section closes with discussion and conclusion including practical suggestions for GNSS networks in dense populated city environments.

## 2 Dynamic and Adaptive Elevation Masks (dynMsk)

Urban environments are challenging for stable acquisition of GNSS signals due to several obstructions, diffractions, reflections, and multipath. Precedent intensive station selection that consider boundary conditions wrt. additional measurement techniques can possibly not avoid moderate numbers of obstacles at some GNSS sites. Therefore, the noise on the DD observables and the obtained satellite geometry at each individual site is affected. The observation quality, i.e. the noise on the DD OMC and the carrier-to-noise (C/N0) pattern, can be optimized and improved accordingly through dynamic and adaptive elevation mask (dynMsk) that consider the C/N0 power density ratio (LANGLEY 1997) as a quality indicator, (WIESER 2001). ZIMMERMANN ET AL. (2016) study carefully different obstruction scenarios and identified the impact on the position domain as marginal. In addition, they propose to analyse more sophisticated obstruction scenarios. Hence, we discuss this in the context of our challenging visibility properties at urban GNSS sites.

To process observed minus computed (OMC) data, to obtain intensive station analysis including skyplots, station specific parameters, to provide GPS L1 DDs and to write RINEX 3.02 files (GURTNER UND ESTEY 2013), we use our in-house implemented Ife\_GNSS\_Matlab-Toolbox Version 6.1. We implement dynMsk as a new feature for purposes of studying stochastic parameters, cleaning and preprocessing GNSS observation data.



**Figure 1:** Carrier-to-Noise power density ratio (C/N0) as signal quality indicator, (a) nominal reference curve from laboratory network and 24 hour observation set, (b) observed C/N0 at GRAV12 (Bad Frankenhausen) with the same receiver-antenna combination influenced by urban reflectors.

#### 2.1 Definition

As the C/N0 is a key parameter for describing the signal quality of GNSS observations, we propose to apply dynamic elevation masks (dynMsk) as an useful tool during the data preprocessing (cleaning and removing outliers) in cases of highly disturbed signal propagations at challenging GNSS stations, since this can improve the observation quality and reliability of geodetic estimates, (ICKING ET AL. 2016). In addition, the weighting model of the well-known Sigma- $\Delta$  approach, (BRUNNER ET AL. 1999) would be advantageous for further processing.

Our approach is contrary to a traditional hand-written obstruction mask and considers the authentic environment of the GNSS site as this is changing quickly due to vegetation, modified surroundings like, e.g., new or obsolete obstructions, buildings and infrastructure elements or comparable issues. Furthermore, applying traditional elevation masks in urban GNSS networks leads to an increased risk to erase useful geometry and observations as no azimuthal information is taken into account.

This context is summarised in Fig. 1. The expected reference curve show expectable deviations of approx. 2 dB-Hz wrt. the dotted template function in Fig. 1a, here for the case of a 24 hour data set, measured at our laboratory network under optimal conditions. In quite contrast to this, Fig. 1b indicates a large number and pronounced deviations of up to ten and more dB-Hz, already starting at mean elevations of 45°. Consequently, only some, but not all satellite tracks are affected. By applying dynMsk per satellite track at each GNSS network station and signal w.r.t the expected template function, the data is cleaned before and not during the processing. Furthermore, the appropriate information of obstacles in the antenna's field of view is considered by the corresponding elevation and azimuth. In addition, this is used implicitly to generate dynamic obstruction files for each session and individual urban GNSS site. Session lengths of four hours are considered and studied in this paper.



Figure 2: Pure elevation dependent C/N0 template functions obtained by robot based antenna calibration on a zero baseline approach for several antenna-receiver combinations, (a) Leica AR25.R3 antenna, (b) Trimble Zephyr I Geodetic.

#### 2.2 Carrier-to-Noise (C/N0) Template Functions

Taking advantage of the elevation dependence of C/N0 values in the case of undisturbed satellite signal reception (cf. Fig. 1a), the estimation of C/N0 template functions is beneficial, (BRUNNER, ET AL. 1999, WIESER 2001). These pure elevation dependent functions are obtained, using a moderate amount of satellite observations and approximate these curves by polynomial functions with low degrees (mostly 2 or 3) as this is sufficient for the most of the receiver-antenna combinations, (WIESER 2001).

The template functions used in this paper are obtained by real-time robot antenna calibrations, (WÜBBENA, ET AL. 1997, SEEBER & BÖDER 2002, KERSTEN & SCHÖN 2012). This approach provides template functions not only for the elevation but for azimuth angles which are modeled by spherical harmonics (SH) with degree 8 and order 5 as this is a common approximation to cover implicitly a broad variety of antenna characteristics. However, the pronounced majority of C/N0 template functions for GNSS antennas are elevation dependent and show almost negligible deviations in azimuth, so that low order polynomial expansions are generally justified, (KERSTEN & SCHÖN 2012).

Template functions are strongly depending on the used antenna-receiver combination (WÜBBENA ET AL. 2006, KERSTEN & SCHÖN 2012) as receiver manufactures implement different signal tracking properties. In Fig. 2 this context is summarised for two antennas, two signals and three different receivers. The depicted template functions are obtained in a zero-baseline configuration. Hence, receivers tracked the identical signals simultaneously. As the C/A code tracking is quite similar for all manufactures, the obtained C/N0 template functions are mostly close similar as indicated for the signal GPS L1 on the C/A code (GS1C), (GURTNER & ESTEY 2013). Differences between several receiver manufactures are identified on the second frequency. Different manufactures use individual and proprietary tracking algorithm and different signals. As shown in Fig. 2, this is the case for the differences between the receivers JPS Legacy, Javad TRE G3T and Leica GRX1200+GNSS. In addition, differences have to be expected by comparing the template functions between



Figure 3: Skyplot of GNSS site SL03 (DOY 280, 2015) with obstructions, (a) derived from dynMsk approach by a four hour GNSS session, (b) traditional hand-created obstruction Mask.

different geodetic receiver antennas (cf. Fig. 2a and Fig. 2b). Consequently, the correct receiver-antenna combination has to be applied carefully in those cases, where C/N0 template functions are used for a consistent GNSS data (pre-) processing and parameter estimation.

## 2.3 From Template Functions to Obstruction Masks

The processing of dynMsk is carried out per satellite arc by the following simplified steps:

- Separation of ascending and descending orbit arc (C/N0 values are not bijective wrt. elevation).
- Smoothing of measured C/N0 values with step mean of 2° in elevation as default value provides an optimal osculation for the combination of Leica AR25.R3 NONE antenna and Leica GRX1200+GNSS receivers which are used in this contribution. Implementing this value variably supports processing of several antennareceiver combinations with different characteristics.
- Separation and erasure of outliers by evaluating differences between expected and interpolated curve (polynomial interpolation with degree of 3 as default). The well-defined threshold is ±3 dB-Hz, taking into account, that C/N0 are differently obtained by manufactures, (LANGLEY 1997, WIESER 2001).
- Writing the obstruction mask (marking corresponding obstacles wrt. elevation and azimuth).
- Writing cleaned observations as RINEX 3.02/2.11 files for further processing.

During a regular campaign session of four hours, obstruction masks could be derived with very similar solution to the real environment at each urban GNSS site. Figure 3 presents the differences between the elevation mask, obtained by dynMsk approach (cf. Fig. 3a) and by a classical obstruction mask, created by hand (cf. Fig. 3b). In this case, the obtained mask by dynMsk is used for verification of the classical elevation mask. Furthermore, it is shown



Figure 4: Selected obstruction-skyplots of sites used in urban GNSS monitoring sites (selected) for characterising urban challenges, (a-c) Bad Frankenhausen (Thuringia), (d-f) Hamburg (Groß-Flottbek).

that C/N0 derived masks are physically meaningful as they take the actual environment fully into account. Challenges in GNSS elevation masks are often aligned to urban objects like, e.g., infrastructure elements, tall exposited buildings etc. as they affect the GNSS observables disadvantageously. Degradations on the carrier phase are closely related to the corresponding degradation on the C/N0 and are identified easily using the proposed approach dynMsk. Figure 4 summarises automatically derived obstruction masks for selected urban GNSS sites in Bad Frankenhausen (cf. Fig. 4a-c) and Hamburg (cf. Fig. 4d-f). Very challenging satellite geometry exist at the sites GR12, HH01 and HH05 since obstructions like, e.g., walls, trees and/or buildings of up to 30° elevation are present.

## **3** Observation Domain

## 3.1 Station Specific Parameter

Aligned to the visibility analysis (cf. Fig. 3 and Fig. 4), the multipath linear combination (HILLA & CLINE 2004) gives optimal indicators for expectable pseudo range multipath. For selected stations of the urban GNSS network in Bad Frankenhausen these parameters are depicted in Fig. 5a-c along with the corresponding C/N0 values versus the elevation



Figure 5: Improvements by applying dynMsk on selected baselines on the monitoring network in Bad Frankenhausen, (a-c) multipath linear combinations (HILLA & CLINE 2004), (d-f) erased outliers identified by bad C/N0 values (black) provides reduced noise on observations (gray) from low elevations.

(cf. Fig. 5d-f). Although disturbed observations could be erased, only small changes in the MP1 are expectable as the entire geometry of the environment at the GNSS sites can either be optimized not improved. However, by taking C/N0 template functions with dynMsk into account helps to clean the observations consistently. Hence, an optimal separation of disturbed and non-disturbed observables especially at low elevations is possible (cf. Fig. 5d-f) which will affect the quality of the carrier phase DD (cf. Fig. 6) in a positive manner.

Dilution of precision (DOP) values for the cases of w/o applying the dynMsk approach are quite similar during the processing with the Leica LGO software, (LEICA 2014). The DOP values reach higher numbers in those were too much satellites are erased since this will result in a very weak geometry. For practical use, the important break point between keeping bad observations (and good geometry) on the one hand and to reduce the outliers in the data (but loosing geometry) on the other hand should be elaborated carefully. Therefore, variable parameters like, e.g., the threshold for comparing measured and expected observations as well as the kind of correct C/N0 template function are controlling parameters and have to be chosen very deliberate.

#### 3.2 Double Differences

As shown in the previous section, it is advantageous to apply dynMsk on the raw observations as this cleans the input data for the later estimation process. This is exemplarily shown by Fig. 6. For selected baselines, the GPS L1 DD residuals with a mean deviation of approx. 1.2 cm are depicted. Outliers of more than 10 cm are identified and erased by applying the proposed dynMsk approach. At low elevations of 2°, only the outliers are removed and useful observations remain, as long as the corresponding C/N0 values provide stable reception and are not affected by entire surroundings at the GNSS site. In cases of traditional elevation masks, these useful observations would be erased consequently by fixed elevation masks.



Figure 6: GPS L1 DD OMC for selected baselines in Bad Frankenhausen w/o applying dynMsk at both sites, (a) baseline SL03-GGP1, (b) baseline SL03-GR12. Light grey dots show DD OMC obtained by dynMsk, black dots show observations, erased by the dynMsk.

#### 4 **Position Domain**

#### 4.1 Network Processing

The processing of selected baselines (GPS L1) for the monitoring network is performed using Leica LGO 8.4 as a common processor and orbits from the Center of Orbit Determination Europe (CODE). In general for our research project, the network is processed using the sophisticated scientific software package Bernese 5.2 (DACH, ET AL. 2015) and products from the European Space Agency (ESA), e.g., clock, orbits, earth rotation parameters and CODE's differential code Biases (DCBs) for GNSS processing, (KERSTEN ET AL. 2016). For reasons of comparability and due to shortage of space, only GPS processing is discussed here. Hence, we used only CODE products. The input data is cleaned as proposed in Sec. 2.1 and transferred via RINEX 3.02 for network processing.

**Table 1:** Results wrt. GPS L1 solution of selected baselines for an urban GNSS monitoringnetwork obtained w/o dynMsk with SL03 as local reference station for thecampaigns in spring (BFH-04) and in autumn (BFH-09).

Campaign	Site	dynMsk	Elevation- Mask [°]	Elliptical height [m]	Quality		
					Horizontal+ Vertical [mm]	Horizontal [mm]	Vertical [mm]
BFH-04	GGP1	yes	2	309.6647	0.7	0.4	0.6
BFH-09		yes	2	309.6637	1.2	0.6	1.0
BFH-04		no	25	309.6648	1.2	0.6	1.0
BFH-09		no	25	309.6592	1.9	0.9	1.7
BFH-04	GR11	yes	2	185.8169	0.8	0.4	0.7
BFH-09		yes	2	185.8157	1.0	0.5	0.8
BFH-04		no	25	185.8196	1.3	0.7	1.1
BFH-09		no	25	185.8164	1.7	0.8	1.5
BFH-04	GR12	yes	2	198.4831	1.3	0.7	1.1
BFH-09		yes	2	198.4810	2.3	1.3	1.9
BFH-04		no	25	198.4869	2.8	1.5	2.4
BFH-09		no	25	198.4844	3.6	1.7	3.2

 Table 2: Results wrt. GPS L1 solution of selected baselines for an urban GNSS monitoring network obtained w/o dynMsk with HHDE as local reference station for the campaigns in spring (HHX-04) and in autumn (HHX-09).

		đ	Floyation	Elliptical	Quality		
Campaign	Site	lynMsk	Mask [°]	height [m]	Horizontal+ Vertical [mm]	Horizontal [mm]	Vertical [mm]
HHX -04	HH01	yes	2	79.3036	1.2	0.6	1.1
HHX -09		yes	2	79.3039	0.8	0.4	0.7
HHX -04		no	25	79.3044	0.8	0.4	0.7
HHX -09		no	25	79.3047	0.9	0.4	0.8
HHX -04	HH05	yes	2	79.9292	2.4	1.1	2.1
HHX -09		yes	2	79.9314	1.1	0.6	0.9
HHX -04		no	25	79.9315	1.7	0.9	1.5
HHX -09		no	25	79.9323	1.5	0.5	0.9

Table 1 and 2 summarise the obtained solutions for selected baselines (length between 600-1200 m) of the network in Bad Frankenhausen and Hamburg which show moderate obstructions in comparison between w/o applying dynMsk. The local reference station SL03 provides good geometry (cf. Fig. 4b and Tab. 1). Optimal conditions are provided by the

local reference station HHDE in Hamburg (cf. Fig. 4e and Tab. 2). For both locations the spring campaign (BFH/HHX-04) and the autumn campaign (BFH/HHX-09) in 2016 are compared and each station is obtained by three sessions with four hour duration each. Quality indicators in Tab. 1-2 correspond to the standard deviation obtained during the network adjustment in LGO. For comparison reasons, the network was processed in addition with Bernese 5.2 as GPS only. Corresponding results of selected baselines for Bad Frankenhausen are summarised in Tab. 3.

Table 3: Results wrt. GPS L1 solution of selected baselines obtained w/o dynMsk withSL03 as local reference station, processed with Bernese 5.2 for the campaignsin spring (BFH-04) and in autumn (BFH-09).

	Site	dynMsk	Elevation. Mask [°]	Elliptical height [m]	<b>RMS of individual solution</b>		
Campaign					north [mm]	east [mm]	up [mm]
BFH -04	GGP1	yes	2	309.6619	1.87	2.46	2.28
BFH -09		yes	2	309.6476	0.89	0.85	3.43
BFH -04		no	25	309.6577	2.15	2.99	5.20
BFH -09		no	25	309.6509	2.32	1.04	2.04
BFH -04	GR11	yes	2	185.8218	0.79	0.96	2.14
BFH -09		yes	2	185.8216	0.57	0.71	2.13
BFH -04		no	25	185.8224	0.72	0.63	1.77
BFH -09		no	25	185.8205	2.60	1.03	2.06
BFH -04	GR12	yes	2	198.4924	0.16	0.95	1.85
BFH -09		yes	2	198.4915	0.76	1.19	1.57
BFH -04		no	25	198.4815	0.34	1.00	1.54
BFH -09		no	25	198.4884	1.26	1.40	5.65

## 4.2 Discussion of GPS L1 Network Solutions

The obtained GPS L1 solutions indicate that the concept of dynMsk is successfully applied. Due to the pre-processing of observation data, elevation masks of 2° are meaningful as the observations are aligned with the corresponding expected reception characteristic of the antenna-receiver combination and outliers are removed accordingly. Similar results were only meaningful at the selected baselines when a moderate elevation mask of at least 25° is applied. The quality (standard deviation of network adjustment) of the LGO solutions from Tab. 1 and Tab. 2 indicate, that the noise is indeed reduced as this can be noticed by the quality and reliability of the vertical and horizontal component. However, the improvements on the observation domain are not mapped by the same amount of improvement into the position domain. But either a degradation of a reliable position solution nor worse quality parameters are reported by applying dynMsk. However, in some cases (belonging on satellite geometry and session) between 10-20% of observations were erased due to out-

liers. Furthermore, Tab. 3 shows, that solutions and repeatability of the height component of each individual session solution is improved by consistency and reliability.

## 5 Conclusions

In this contribution the authors present the approach of dynamic and adaptive elevation masks. The technique reduces noise on the observations and improves therefore the repeatability of the high component at GNSS sites with challenging satellite visibility in urban environments and reduces significantly number of necessary ambiguities.

The use of dynMsk allows to model and separate the input data physically meaningful from outliers due to a consistent comparison of the expected C/N0 values wrt. the observations, obtained in the field and under moderate or sometimes challenging circumstances. Since this approach only relays on the input data and the necessary template function of the C/N0 values, it is extremely variable and practical applicable. This is important in urban environments due to possible and unexpected as well as short-time periodic changes of the entire surroundings at GNSS sites.

The threshold to separate consistently the outliers from the unaffected observations has to be determined with special care as this will affect the DOP values and satellite visibility and can cause in disadvantageous or weak satellite geometry. The right break point between keeping noisy data and erase noisy data is the most important factor to apply dynMsk not only but at least in urban GNSS monitoring networks successfully.

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