Good practice guide for high accuracy global navigation satellite system based distance metrology

Imprint

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Executive summary

This guidance document has been written to meet the need for a basic document for laboratories undertaking the use of GNSS based distance meters (GBDM) with accuracies in the millimetre regime using geodetic grade GNSS equipment for antennae, receivers, and software analysis. The focus of this document is the identification, quantification and recommendations on minimisation of experimental uncertainty sources for the GBDM in surveying practice in this uncertainty regime. The algorithmic data analysis is not within the scope of this document. Conclusions are mainly based on the results of respective experimental studies performed by the joint research project (JRP) "SIB60 metrology for long distance surveying" as part of the European metrology research programme (EMRP) between July 2013 and June 2016, but takes into account state of the art of respective literature.

1 Introduction

The purpose of this technical guideline is to improve harmonisation and to suggest good practices on the use of GBDM measurements. The guideline is based on the experiments performed by the joint research project “SIB60 metrology for long distance surveying” as part of the European metrology research programme (EMRP) between July 2013 and June 2016.

It is structured in three main chapters: chapter 3 is dealing with preparatory measures on the hardware, including calibration needs of the electromagnetic properties of the antennae and an optimized station set up. Chapter 4 focuses on the actual measurement situation, with a focus on the tropospheric correction strategy. In chapter 5, an exemplary quantitative assessment of uncertainties and their propagation in typical GBDM analysis is given although a full uncertainty budget according to the “Guide to the Expression of Uncertainty (GUM)” cannot be provided for fundamental reasons.

2 Scope and field of application

This guideline refers to distance measurements of several hundred metres up to a few kilometres performed with geodetic grade GNSS equipment for antennae, receivers, and software analysis with targeted uncertainties between several tenths of millimetres up to millimetres.

The guideline provides recommendations for optimized strategies for set-up and analysis procedures, taking into account the leading uncertainty sources at this uncertainty level. These are the characterization of the electromagnetic antenna properties, near-field and multipath effects and environmental corrections.

The guideline does not cover proper general handling of the equipment or particularities of different analysis strategies or standard software packages.

An exemplary treatment of uncertainty propagation is included. However, the quantitative applicability of this example depends strongly on the actual measurement situation on site. This study does not allow conclusions on the general performance of specific software packages.

3 Preparation

In high-precision GNSS applications, usually a relative position estimation using carrier-phase measurements is performed. By forming double-differences of the observables, the majority of systematic errors, e.g. satellite orbit and clock errors, atmospheric delays or receiver clock errors, can be completely eliminated or at least minimized. One of the remaining accuracy limiting factors is station dependent errors, e.g. multipath or antenna errors. They cannot be eliminated or prevented by processing strategies, since they depend on the antenna surrounding, the antenna set-up and the antenna. In order to reduce the influences of these error sources, the station set-up has to be optimized. This optimization includes the usage of individually calibrated antennas and an identical station set-up of the antenna stations included in the position and distance estimation process.

3.1 Antenna calibration

In a coordinate estimation process, the observations are assumed to refer to one fixed point, the so called antenna reference point (ARP). In reality, the position of the reference point for the carrier-phase observations depends on the direction of the incoming signal (azimuth α, elevation β). The overall impact can be described by two components: (1) the phase centre offset (PCO), denoting the position of the mean phase centre in relation to the antenna reference point, and (2) the phase centre variations (PCV), denoting the direction-dependent variations of the mean phase centre.

In recent years, two procedures were proven to be the most effective approaches to calibrate GNSS antennas: absolute robot calibration and a calibration in an anechoic chamber (Wübbena et al, 2000 and Zeimetz and Kuhlmann, 2008). Since antennas of the same type show similar phase centre characteristics, type specific calibrations (type mean), e.g. provided by the IGS (ftp://igscb.jpl.nasa.gov/igscb/station/general/igs08.atx), can be used to reduce the influences described above. Nevertheless, an optimum elimination of the influences can only be achieved by using individually calibrated antennas. The differences between individually calibrations and type mean calibrations can reach several millimetres. Especially for the PCO values, this is critical, since deviations in this parameter will lead to systematic errors in the estimated coordinates. Thus, for GNSS applications with very high accuracy requirements at the millimetre or sub-millimetre level, it is strongly recommended to use individually calibrated antennas with determined PCO and PCV values, representing the antenna specific phase centre corrections.

3.2 Station set-up

In addition to antenna specific errors, GNSS multipath is a further site dependent error which has to be taken into account. In general, multipath can be separated into far-field and near-field multipath. Far-field effects arise from reflecting surfaces in the environment of the antenna and lead to one or more signals arriving at the antenna by indirect paths (Hofmann-Wellenhof et al., 2008). The interference of the direct and indirect signals leads to short periodic errors in the observation and position domain, which can be averaged out by sufficiently long observation times (Seeber, 2003). Furthermore, far-field multipath can be reduced by a special antenna design, e.g. antennas with ground plates or choke rings. Nevertheless, it is recommended to carefully select the observation site. Reflecting surfaces in the environment of the antenna, especially vertical surfaces leading reflections from above the antenna horizon should be avoided and a preferably free horizon should be targeted.

In contrast, near-field multipath results from the closest vicinity of the antenna, often described as the first 50 cm around the antenna. On one hand, near-field effects can lead to long-periodic errors, which result in a non-zero mean distributed and un-modelled bias in the estimated parameters. On the other hand, the antenna near-field can change the overall electromagnetic properties of the antenna (Dilssner, 2008). Hence, individual antenna calibrations, as described in section 3.1, are actually only valid if the near-field situation has also been reproduced during the calibration procedure (Wübbena, 2006). Nevertheless, size and weight limitations usually preclude this kind of near-field calibration.

Since near-field effects arise from the closest vicinity of the antenna, for applications in which distance determination with highest accuracy is required, it is recommended to create a preferably identical near-field situation at all antenna sites. This implies the usage of the same antenna types at all stations. Since the antenna calibration patterns described in section 3.1 are direction dependent, the antennas have to be oriented to the north to utilize the full potential of the antenna corrections. Furthermore, the type and material of the antenna mounting, like e.g., tribrach, tripod, pillar, etc., as well as the orientation of the respective parts, should be identical. It is well known that the routing of the antenna cable can have a direct impact on the phase centre characteristic of the antenna. Thus, also the cable routing should be identical and the antenna cables should be fixed to the antenna mount (tripod or pillar) to prevent influences on the antenna phase characteristics by loose cable parts. By creating a similar near-field situation at the antenna sites, also the near-field effects can be denoted as being similar. This enables a minimization of the effect during the coordinate estimation process by the double-differencing approach.

In a field study, Zimmermann *et al.* (2016) show that, if all of these recommendations have been followed and under excellent GNSS conditions, it is possible to reach accuracies lower than 0.5 mm for both, the distance and height components of baselines up to lengths of 1 km.

The antenna near-field is commonly described as an area of about 50 cm around the antenna. Hence, one attempt to reduce influences from this area is to use antenna spacers to increase the distance between the antenna mounting and the antenna itself. This approach has three disadvantages:
(1) If the antenna spacer exceeds lengths of 40 cm to 50 cm, the whole set-up becomes unstable. Especially for heavy antennas, e.g., choke-ring antennas, this is critical. Thus, in case of very long spacers, additional effort is necessary to stabilize the set-up.
(2) The exact straightness of the antenna spacers has to be ensured, since a bending of the spacer can lead to a systematic error in the estimated baseline lengths, which is proportional to the spacer length. Moreover, the centre of the bottom thread and the screw on top of the spacer has to coincide precisely, e.g. below the required sub mm accuracy level. Deviations between these two points will also lead to systematic errors of the same magnitude. As a consequence, the accuracy requirements during the manufacturing of the antenna spacers are extremely high.
(3) To reach a very high accuracy level, the antenna spacers have to be levelled and centred accurately over the reference point of the antenna monument station. Since this is the most crucial step during the whole measurement process, a lot of effort and precise measurement equipment is required.
Due to these disadvantages, it is not recommended to use antenna spacers to reduce the influence of the antenna near-field. Moreover, in case of an identical antenna set-up at all stations, this is not necessary. Similar near-field effects will be minimized by the double-differencing approach during

the coordinate estimation process. Hence, only if the application or the antenna site requires the usage of additional spacers between the antenna and the antenna mount, spacers should be used.

3.3 Schematic description of the set-up

The same practice at all sites and all antennas should be followed, so that the conditions are as equal as possible.

Minimization of antenna specific errors →

- antennas should be calibrated individually
- antennas have to be oriented to the north

Minimization of near-field multipath during double-differencing process by creating identical near-field situation →

- type, material and orientation of antenna mounting should be identical
- cable routing should be identical and cables should be fixed to monumentation
- the same antenna types should be used
- if application or monumentation requires the usage of antenna spacers, very careful leveling and centering over reference point

Minimization of far-field multipath by station selection, antenna design and averaging →

- observation duration should be at least 2 hours
- high-grade antennas should be used (e.g. ground plate, choke ring)
- reflective surfaces should be avoided, preferably free horizon

3.4 Annotation regarding single-difference processing of common clock data

Santerre and Beutler proposed already in 1993 the connection of receivers to joint common physical clock in a GNSS based distance measurement in order to perform the analysis of single-difference level instead of the standard double difference approach. Fibre-moderated frequency transfer technology has meanwhile been established in time and frequency metrology. In the course of the research project, common clock configurations were set up for different lengths in order to study experimentally the impact of multipath and short periodic tropospheric refraction without analytical ambiguities induced by double-differencing.

The use of single-differences in a common-clock configuration, however, proved not to be a suitable approach in the investigations during JRP. The assumptions underlying the Santerre's and Beutler's predictions regarding the stability of the time and frequency signal distribution could not be fulfilled in the investigated, state-of-the-art installations. Thus, common-clock experiments unfortunately proved of little benefit for the investigation of second order uncertainty contributions for determining static distances. Leute *et al.* (2016) concluded that they will hardly ever be fulfilled in an installation that comprises distributed equipment and is used in practical surveying tasks.

On the other hand, Schön *et al.* (2016a) were able to show that, for a kinematic analysis, i.e. for estimating high rate coordinate time series, the situation can be significantly improved if a common clock is connected to different GNSS receivers in a network or on a baseline. Consequently, between-station single-differences would be sufficient to solve for the baseline coordinates. In such a case, the positioning geometry would be significantly improved which is reflected by a reduction of the standard deviation of kinematic heights by about a factor 3.

4 Measurement strategy

4.1 Recommendation on the actual measurement

Several recommendations should be taken into account when performing GBDM measurements:

- The time taken to perform the measurements, as referred in section 3.3.
- Valid meteorological conditions, in the temperature ranges stated by the manufacturer

Since mismodelling the tropospheric delay can influence critically the attainable accuracy on GPS distance metrology, it is of major importance to evaluate the tropospheric influence on the measurements. Consequently, it is proposed to use single or double differences that will eliminate almost all physical refraction effects (in short baselines with small height differences), rather than to estimating a tropospheric zenith wet delay parameter. The impact depends on the geometric settings and analysis strategy:

- if the stations are close (few meters to hundreds of meters) and at the same height (e.g. at geodetic EDM calibration bases), forming observation differences will readily eliminate the tropospheric impact.

- if height differences between the stations exist or the station separation is large, asymmetries are generated which cannot be eliminated by forming differences. Then a tropospheric delay parameter has to be estimated. This estimation weakens the geometry of the adjustment problem and introduces correlations between the height and the tropospheric delay.

In relative positioning, the impact of tropospheric refractivity fluctuations on the length is largely reduced when observation differences are used, e.g. double differences. The variance-covariance matrix of the parameters (e.g. coordinates) estimated by least squares, describes their variability. The variances and covariances increase when the observation correlations induced by atmospheric fluctuations are taken into account. The horizontal components are almost not affected.

In baselines shorter than 200 m, the role of ionosphere modelling can be assumed negligible. The tropospheric gradients describing the local variability of the wet component of the troposphere do not have realistic meaning on short distances.

There are 3 different scenarios that can be considered to link two stations (P1 and P2) connected with a short baseline to a global network. In the first scenario, P2 linked to P1 and P1 linked, by a long baseline, to the reference station (REF) from the global network. In the second scenario, P1 and P2 linked to the same REF by long baselines. In the third scenario, P1 and P2 linked to different REFs. It was evidenced that the influence of troposphere on coordinate determination in global networks containing short baselines can be compensated by combining L1 and L3/L3T solutions in the normal equations or by determining a height correction term (first scenario). This scenario currently appears as the best case scenario because it leads to reasonable results that agree with terrestrial local tie measurements. For the second scenario, according to Krawinkel *et al.* (2014), a height correction is applicable but it results in a noisier solution with a strong dependency on the chosen reference station. The third scenario with two different reference stations is not recommended because an appropriate correction is not applicable. As correction factor is site dependent, remaining constant, it can be calibrated.

4.2 Data format

The receiver internal algorithms are proprietary, so it is difficult to assess the influence on the "raw observations" that the respective geodesy is using. Studying software receivers could help to some extend to identify in laborious experiments the impact of different firmware versions of GPS receivers. Consequently, data in the Receiver Independent Exchange Format RINEX is considered as raw data. However, experience shows that also the convertor from raw data to RINEX may impact the data. Finally from a physical point, short delay multipath (< 0.1 µs or 30 m) is the most critical since it is very hard to separate it from the direct signal. The analysis of the - hopefully soon available and stable/final - Galileo signals with new modulation schemes may help to push this part.

4.3 Data processing

In GNSS analysis different data processing schemes are possible. They include

- The observables used. These can either be the original carrier frequencies, like e.g., GPS L1, L2, L5, linear combinations of the latter, like e.g., the ionosphere-free linear combination, or observation differences, like e.g., double-differences.

- The observation weighting (identical weighting or various elevation-dependent weightings)

- The estimation of additional parameters especially tropospheric zenith delays

A variety of combinations is possible yielding differences in the estimated coordinates of up to a few centimetres.

Recommendations:

For short baselines (few meters to up to 1-2 km) we recommend to

1. Use the most precise L1 carrier phase observations:

The noise in the observation is minimized as well as that of the estimated coordinates.

2. Form double-differences:

Double-differences combine four GNSS carrier phase observations into one new observable. This is a very strong analysis concept that reduces largely systematic effects that are similar at both stations and at both satellites as well as along the signal propagation path. Subsequently, as long as the similarity is preserved by identical equipment, dedicated site selection, and similar atmospheric conditions (e.g. only small height differences), most of the systematic effects can be largely reduced or even eliminated.

3. Do not estimate tropospheric zenith path delay parameters:

Due to the large correlation between height and troposphere parameters (and receiver clocks), the impact of non-modelled systematic effects will be increased by estimating tropospheric zenith path delays since the adjustment model is changed. This deteriorates the coordinate solution, especially the height by up to some millimetres, Krawinkel *et al*. 2014. In addition, for small height differences between the baseline endpoints, no physical tropospheric delay persists in the double-differences and thus such a parameter should not be set up.

In Beutler et al. (1989) and Santerre (1991) the correlations between the geodetic parameters height, troposphere (and clock) are explained. Rules of thumb are given how remaining systematic effects affect the estimated coordinates. Applications to small networks are presented in Rothacher (2000), while the impact with large height differences is discussed in Schön (2007). Examples for violations of the similarity hypothesis between the endpoints of GPS baselines are discussed in Schön (2010). Brockmann et al. (2010) discusses the impact of different processing strategies on co-located stations in the Swiss AGNES network, where ground truth information from local ties is available, measured by terrestrial instruments. In addition, Schön et al. (2016) proposed an easy-to-use post-processing strategy to remove discrepancies between local ties and GPS-derived heights when tropospheric effects are mis-modeled.

5 Assessment of uncertainties of GPS-distances

5.1 Introduction

The various external input parameters into the analysis of a GPS based distance measurement prevent a stringent uncertainty analysis of a distance measurement performed by GPS. Therefore, GPS measurements are basically not traceable in the metrological sense. The user has little information neither on the uncertainties of the provided satellite orbit data, nor in the propagation of these uncertainties when using standard software packages.

Propagation of the signal through the ionosphere and troposphere, effect of multipath, antenna phase center variation and other sources of error are not controllable and are mostly unknown during the data processing. Although one can estimate the magnitude of these variables in the analysis, uncertainties of these estimations are mostly unknown, and especially their propagation in the final results. As a consequence, analyses of the same data with different software with their recommended set of parameters will produce different results and uncertainties.

One way to assess the uncertainty of the GPS-distances on a given site for the specific local situation and equipment used is a direct comparison of GPS-based distance measurements compared to reference distances measured with a calibrated instrument with the scale traceable to the SI definition of the meter. The sensitivity of the GPS-based distance measurement to the local surrounding (multipath effects) infers that the results of such comparisons should not be applied to other measurement configurations without further considerations.

In the course of the JRP, the Monte Carlo Method (MCM) was used for an assessment of the sensitivity of GPS coordinate differences and distances on small changes in antenna calibration table, troposphere correction difference and multipath. Although the MCM can be improved by developing the models of uncertainty sources, the accuracy of the method is limited by the number of the MCM iteration rounds. In each interaction a new full set of GPS observation data are generated which must be processed by the GPS software. This is not applicable in practice for routine uncertainty estimation.

In daily practice, the surveyor can get a realistic uncertainty estimate using empirical data and a traceable reference distance on site. The assessment of the combined uncertainty of GPS measurements based on reference measurements are summarised in the next section.

5.2 Approximation of the combined uncertainty

The combined uncertainty of the GPS lengths can be computed based on the standard deviation of the GPS length, the EDM reference measurement and its uncertainty:

$$u(l_{GPS}) \approx \sqrt{\left(\Delta l_{GPS-EDM}\right)^2 + u\left(l_{EDM}\right)^2 + u\left(l_{Bern}\right)^2}$$

where

$\Delta l_{GPS-EDM}$	deviation of the GPS from the EDM distance as an estimate of the magnitude of systematic effects like multipath, obstruction and so on, acquired under similar environmental and local conditions as the actual measurement
$u(l_{EDM})$	standard uncertainty of the EDM measurement, and
$u(l_{Bern})$	standard deviation of the GPS length.

The standard deviations of the GPS lengths are derived from the standard deviations of the coordinates reported in final results of the GPS processing. It includes only part of the uncertainty sources. The other part can be estimated by the difference between the GPS and the reference (EDM/tachymeter) lengths and by the uncertainties of the reference measurements themselves. The GPS lengths were corrected by the so called residual offsets estimated earlier for the baselines.

As an example, estimated uncertainties of daily GPS solutions at a baseline are shown in Figure 1. The uncertainties vary between 0.1 and 0.9 mm independent of the baseline length. The difference to the reference distance is the most dominating factor of the combined uncertainty. The standard deviations for the GPS lengths are in all cases below 0.05 mm and the uncertainties of the reference distances below 0.1 mm for lengths shorter than 100 m and below 0.2 mm for the longest baselines (< 200 m).

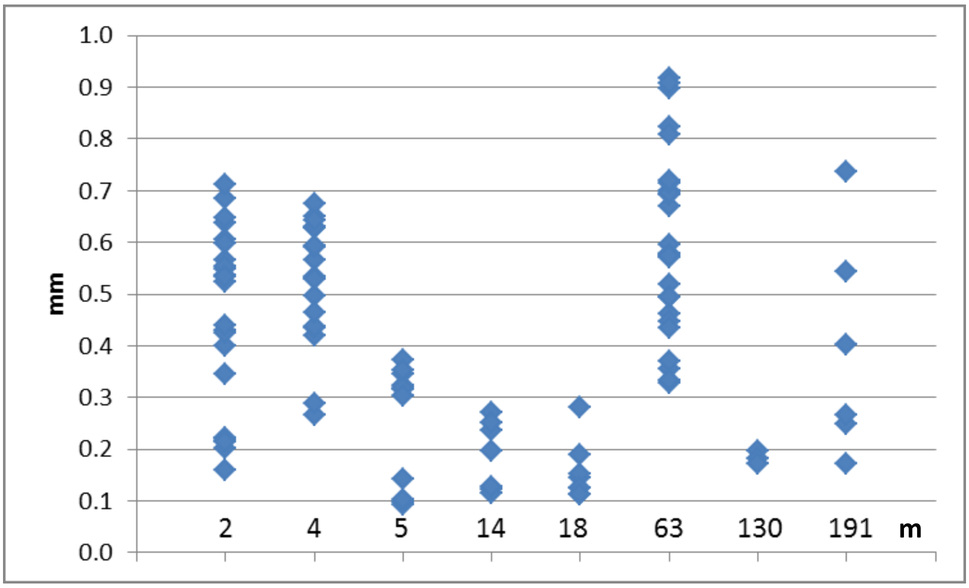

Figure 1 The uncertainties of each daily GPS solution by baseline. The baselines are shown from the shortest (2 m) to longest (191 m) from left to right, respectively.

The expanded uncertainty corresponding to a confidence interval of 95 % can be derived by multiplying the combined uncertainty by a coverage factor *k* = 2.

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