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Global Navigation Satellite System (GNSS) - Precipitable Water (PW) Omnibus

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Abstract

This omnibus provides detailed guidelines on the GRUAN GNSS-PW measurement program, including instrumentation, operation procedures and all aspects of data management. It also addresses specific GRUAN requirements, such as reference measurements, measurement uncertainty and managing changes.

Editor Remarks

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by GRUAN.

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This document incorporates much of the content of the following (superseded) GRUAN documents:

- GRUAN-TD-6, v.1.0 (23 May 2012): GRUAN Ground-based GNSS Site Guidelines (Shoji *et al.*, 2012) (http://www.gruan.org/gruan/editor/documents/gruan/GRUAN-TD-6_GNSS_v1.0.pdf)
- International GNSS Service (IGS) (http://www.igs.org/).

Contacting GRUAN Lead Centre

Please contact the GRUAN Lead Centre (gruan.lc@dwd.de) if you have any questions or comments in relation to this document, or in relation to GRUAN's use of GNSS-PW. If appropriate, the Lead Centre will redirect requests to the GRUAN GNSS-PW Task Team (GTT) (tt-gnss-pw@gruan.org) or GFZ (the GRUAN data processing and analysis centre (PC) for GNSS-PW).

Revision history

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Appendix

1 Introduction

1.1 Instrument Heritage

Water vapour is the primary natural GreenHouse Gas (GHG) and is central to global water and energy cycles. It acts primarily as a feedback, amplifying the effects of increases in other GHGs. Water vapour is the raw material for clouds and precipitation, and limited knowledge has compromised our ability to understand and predict the hydrological cycle, and understand its effect on radiative transfer (Peter *et al.*, 2006). Water vapour is also a source of OH in the upper troposphere and stratosphere, influencing methane, ozone and halogenated GHGs. High clouds due to water vapour in the Upper Troposphere / Lower Stratosphere (UTLS) affect the planet's shortwave albedo and its longwave greenhouse effect. Cloud particles and water molecules are involved in chemical reactions that govern stratospheric ozone concentrations. Fully quantifying the Earths radiation budget depends on an accurate assessment of the radiative properties of clouds and the water vapour continuum. Changes in water vapour in the UTLS exert a greater radiative forcing than changes elsewhere (Solomon *et al.*, 2010). For these reasons, robust reference measurements of the water vapour column, expressed as total Precipitable Water (PW), are imperative for our understanding of weather and climate.

Traditionally, there have been two atmospheric water vapour observing systems on a global scale: radio soundings, and satellite observations with passive sensors. Atmospheric humidity observations from radiosondes have been used to study water vapour variability and trends (e.g., Dai *et al.*, 2002; Wang *et al.*, 2016). Satellite observations from either infrared sounders or microwave radiometers have also been used to quantify water vapour variability and changes (e.g., Wentz, 1997; Trenberth *et al.*, 2005). Two main issues remain unsolved in these data sets: a lack of high temporal-resolution observations to resolve high-frequency (e.g., diurnal) variations; and the poor quality of radiosonde humidity data for climate change studies.

Since the early 1990s it has been demonstrated that the delay of radio signals transmitted from Global Navigation Satellite System (GNSS) satellites to ground-based GNSS receivers were directly correlated to the precipitable water above the GNSS antenna (Bevis *et al.*, 1992). Since this time, significant effort has been devoted to making PW measurements from these GNSS receiving stations. GNSS-based measurements of PW (GNSS-PW) have a number of advantages over the traditional methods of water vapour measurement. GNSS-PW instruments produce low cost, high accuracy (uncertainty $<2\,\mathrm{mm}$ PW), and continuous measurements that can operate under all weather conditions (Ware *et al.*, 2000). A number of organizations have completed the World Meteorological Organization (WMO) Rolling Review of Requirements with respect to PW. Their requirements at the time of publication are presented in Table 1. GNSS-PW fulfils and even surpasses many of the requirements. There are large discrepancies in global GNSS coverage, and increasing the density of GNSS stations in areas of low spatial resolution should be a priority. GNSS-PW measurements have been used in a number of applications, including the validation of radiosonde, satellite and reanalysis data (e.g., Yang *et al.*, 1999; Haase *et al.*, 2003; Guerova *et al.*, 2003; Hagemann *et al.*, 2003; Li *et al.*, 2003; Vey *et al.*, 2004; van Baelen *et al.*, 2005; Wang and Zhang, 2008a), improving numerical weather prediction (e.g., Kuo *et al.*, 1993; Vedel and Huang, 2004; Vedel *et al.*, 2004; Gutman *et al.*, 2004; Gendt *et al.*, 2004), studying diurnal variations of PW (e.g., Dai *et al.*, 2002; Wu *et al.*, 2003), and monitoring climate change (e.g., Gradinarsky *et al.*, 2002).

Table 1: The WMO Rolling Review of Requirements for PW. In reading the values, goal is marked blue, breakthrough green and threshold orange. Source: http://www.wmo-sat.info/oscar/variables/view/162.
The global coverage of GNSS is increasing in resolution as more stations come online.

Application Area	Uncertainty	Horizontal Resolution	Observation Cycle	Timeliness	Coverage
GNSS-PW Final:	<1 mm	Point	5 min	< 1 month	Global
Near Real Time:	<1 mm	Point	5 min	(2 to 3) h	
Climate-AOPC	1 mm	50 km	3 h	7 d	Global
	1.4 mm	100 km	4 h	14 d	
	3 mm	200 km	6 h	60 d	
Global NWP	1 mm	12 km	60 min	6 min	Global
	2 mm	50 km	6 h	30 min	
	5 mm	250 km	12 h	6 h	
High Res NWP	1 mm	0.5 km	15 min	15 min	Global
	2 mm	5 km	60 min	30 min	
	5 mm	20 km	6 h	2 h	
Nowcasting / VSRF	1 mm	5 km	15 min	5 min	Global
	2 mm	10 km	30 min	10 min	
	5 mm	50 km	60 min	30 min	

1.2 The Role of the Instrument

As detailed in GCOS-112, GRUAN's objectives are to:

- Provide long-term high quality climate records;
- Constrain and calibrate data from more spatially-comprehensive global observing systems (including satellites and current radiosonde networks);
- Fully characterize the properties of the atmospheric column.

In support of these goals, GNSS-PW measurement has been included as a priority 1 measurement of the essential climate variable water vapour. A minimum of twice daily measurements (hourly ideally) of PW are required as entrance to the GRUAN program. GNSS-PW exceeds this entrance requirement: the GNSS-PW program produces a continuous reference measurement of PW. The nature of the GNSS-PW reference measurement within GRUAN is defined in Section 3.1.

The GRUAN GNSS-PW Task Team (GTT) has the responsibility to develop, update and assist in the implementation of explicit guidance on hardware, software and data management practices to ensure GNSS-PW measurements of consistent quality are obtained at all GRUAN sites. The GTT is currently (August 2019) co-chaired by Kalev Rannat and Jonathan Jones. GTT members and their affiliation at the time of publication are listed in Table 2. For further information concerning the role of the GTT, please contact tt-gnss-pw@gruan.org.

Table 2: The GNSS-PW Task Team (March 2019),
https://www.gruan.org/network/task-teams/tt-gnss-pw/

Name	Institution
Kalev Rannat	Tallinn University of Technology, Estonia
Jonathan Jones	Met Office, UK
Junhong (June) Wang	State University of New York at Albany, USA
John Braun	UCAR, USA
Galina Dick	GeoForschungsZentrum Potsdam, Germany
Gunnar Elgered	Chalmers University, Sweden
Yoshinori Shoji	Meteorological Research Institute, Japan
Jens Wickert	GeoForschungsZentrum Potsdam, Germany
George Liu	Hong Kong Polytechnic University, Hongkong
Rosa Pacione	e-GEOS S.p.A., Italy
Ning Tong	Lantmäteriet (Swedish Mapping, Cadastre and Land Registration Authority), Sweden
Fadwa Alshawaf	GeoForschungsZentrum Potsdam, Germany

1.3 Organization and Design Concepts

GRUAN operates under the joint governance of GCOS and WMO as a WIGOS Implementation Project. A defining attribute of GRUAN is the standardization and centralization of data processing with the goal of ensuring network-wide homogeneity of the resultant data products.

1.3.1 Terminology

A GRUAN GNSS-PW Program is a GNSS-PW measurement program implemented at a site having been assessed and certified as defined in Sections 3.1 and 3.2.1.

A GRUAN GNSS-PW Product is a PW product resulting from the measurements made within a GRUAN GNSS-PW Program. A GRUAN GNSS-PW Product is always produced by the German Research Centre for Geosciences (GFZ) in-house GNSS software package, Earth Parameter and Orbit determination System (EPOS).

A GRUAN GNSS-PW Site is a location of a certified GRUAN GNSS-PW Program.

1.3.2 Responsibilities

The GTT, in consultation with the GRUAN Lead Centre and Task Team on Site Intercommunication and Reporting, is responsible for integrating best GNSS-PW measurement practices into GRUAN operations. These best practices shall be synthesized in the form of requirements and recommendations compiled in this Guide and shall be implemented in all certified GRUAN

GNSS-PW Programs.

GRUAN sites hosting a GRUAN GNSS-PW Program shall use a designated system of methods, techniques and facilities in full compliance with the requirements and recommendations detailed in this Guide. For any given GRUAN GNSS-PW Program, this system will not be changed without advanced notice to the GTT and GRUAN Lead Centre. GRUAN GNSS-PW Programs incorporate a program to validate the stability and uncertainty of the measurements, agreed with WG-GRUAN, and managed in detail by the GRUAN GTT and GRUAN Lead Centre. This assurance program includes the GRUAN Standard Operating Procedures (SOPs) described in Section 7.2.

The design of GRUAN GNSS-PW Programs shall recognise the heterogeneity of the network of sites, many of which will have primary responsibility to networks other than GRUAN. GRUAN GNSS-PW Programs shall integrate, where possible and when feasible, with other international long-term monitoring programs.

GRUAN GNSS-PW Programs shall be responsive to the latest technological and scientific progress in GNSS-PW measurement techniques and observational requirements. Non-GRUAN GNSS-PW development work can continue at a GRUAN site in collaboration with the GTT until mature and validated, at which point any improvements can be introduced into GRUAN operations with the agreement of the GTT and GRUAN Lead Centre.

WG-GRUAN, the GRUAN Lead Centre and GTT will act as the interfaces between GRUAN and the community of users of GRUAN GNSS-PW products.

1.4 Implementation of the Measurement Program

The implementation of GRUAN GNSS-PW Programs as a whole, and specific issues relevant to an individual GNSS-PW Program, shall be guided by the GTT and WG-GRUAN. These two teams will work with other relevant expertise in support of GRUAN and coordinate with the GRUAN Lead Centre.

The GRUAN Science Coordinators shall identify focused, short-term research topics that will meet the needs of the GNSS-PW program. The WG-GRUAN is also likely to identify such needs. In either case, the Science Coordinators shall assemble a team from across the wider GRUAN community to undertake the required research. The work will be conducted in coordination with the GTT and with other GCOS programs when appropriate.

The WG-GRUAN and GTT shall use this report to establish standard operational procedures (SOPs) and metadata requirements for all GRUAN GNSS-PW Programs. The GTT shall evaluate the appropriateness of uncertainty estimates, the usefulness of particular measurements and operational procedures, synthesize the available knowledge, and develop recommendations to improve GRUAN measurements and operations. The GTT, GFZ and WG-GRUAN shall confer regularly to evaluate the current status of GRUAN observations, to identify weaknesses, and to incorporate new scientific understanding into GRUAN. The expertise of these teams shall also be used to support the Lead Centre in guiding individual sites through changes in instrumentation and operating procedures without impacting long-term measurement time series.

The GRUAN Lead Centre shall identify sites where instrument operators need training and/or re-training, and organize cost-efficient training courses for the network at appropriate locations as advised by the appropriate GTT member. The aim is to encourage uniformity of instrument operation between sites.

All activities associated with the implementation of GRUAN are the responsibility of the institution/organization hosting the GRUAN site and should, as far as possible, be met through national funding. To best serve the needs of the climate monitoring and research communities, it is essential that GRUAN is cognizant of the evolving science that drives the measurements and accuracy of the GRUAN data. The GNSS-PW instrumentation deployed may differ between sites, as agreed with WG-GRUAN as part of the site assessment and certification process, but the methods of observation used with the main observing systems are expected to be uniform between all GRUAN sites.

1.5 Use in Partner Networks

As stated by the GRUAN-Guide (GCOS-171, 2013):

> "GRUAN shall not operate in isolation of existing networks and GRUAN is not intended to replace existing networks in any way. Many initial and candidate GRUAN sites already belong to existing networks. One of the essential characteristics of a successful GRUAN shall be close coordination with the user community and many of these networks are also likely to be users of GRUAN data. Similarly, complementary measurements from these other networks should be collated in a database to enable cross-comparison and to quantitatively link GRUAN measurements to similar measurements made within other networks. As a result, close coordination between the governing bodies of these networks and with the WG-GRUAN is required on a continuous basis. This close coordination can be achieved by having members of the WG-GRUAN attend steering group meetings of partner networks and by inviting co-chairs or steering group members from partner networks and projects to attend WG-GRUAN meetings."

GNSS-PW measurements can draw on the substantial experience of the GNSS community. There is a wide range of tools and methodologies that have been developed by the GNSS community that GRUAN can adopt, extend if necessary, and learn from.

1.5.1 International GNSS service (IGS)

The IGS (http://www.igs.org) began operating in 1994 and comprises an international network of over 400 continuously operating dual-frequency GNSS stations, more than a dozen regional and operational data centres, three global data centres, seven analysis centres and a number of associate or regional analysis centres. The Central Bureau for the IGS is located at the Jet Propulsion Laboratory, which maintains the Central Bureau Information System (CBIS) and ensures access to IGS products and information. The IGS is widely regarded as the highest precision GNSS community in the world. The GTT recognizes the efforts and success of the IGS and has developed GNSS-PW guidelines that closely follow their recommendations (IGS 2015, http://kb.igs.org/hc/en-us/articles/202011433). Plenty of useful information about GNSS can also be found from UNAVCO (https://www.unavco.org).

1.5.2 Other GNSS networks

SuomiNet
SuomiNet (http://www.suominet.ucar.edu) was established in 2000 and consists of 237 sites primarily based at universities in North America. The organization is a real-time national GPS network for atmospheric sensing. SuomiNet is administered by UCAR's COSMIC program.

Plate Boundary Observatory (PBO)
PBO (http://www.unavco.org/projects/major-projects/pbo/pbo.html) is a component of Earth-Scope which consists of 1100 permanent GNSS stations collecting data on a Near Real Time (NRT) basis. The goal of PBO is to study the 3D strain field across the active plate boundary between the Pacific and North American tectonic plates.

GEOnet
GEOnet (http://www.geonet.org.nz) comprises 36 continuous GNSS stations across New Zealand. GEOnet is administered and maintained by GNS Science.

Integrated German Geodetic Reference Network (GREF)
GREF (http://www.bkg.bund.de) comprises a series of 30 GNSS stations operated by the Bundesamt für Kartographie und Geodäsie, other Federal or Länder (states) institutions, or jointly.

Automated GNSS Network for Switzerland (AGNES)
AGNES (https://www.swisstopo.admin.ch/en/knowledge-facts/surveying-geodesy/permanent-networks.html) is a network of 30 GNSS stations. The network goal is to support surveying and provide coverage for the entire country.

FinnRef GNSS reference network
Finnish Geospatial Research Institute (FGI) (http://www.fgi.fi/fgi/) operates as GNSS network of 20 stations across Finland. The goal of these stations is to link to international reference frames and define a national EUREF-FIN reference system.

EUREF GNSS Permanent Network (EPN)
The EUREF (http://www.euref.eu) Permanent Network (EPN, http://epncb.oma.be) is a science-driven network of continuously operating GNSS reference stations covering the European continent. As of 16 May 2018, the EPN contains 323 permanent tracking stations with the primary purpose of maintaining the European Terrestrial Reference System (ETRF).

Use in Serving GRUAN's Key User Communities
The four key user groups of the GRUAN GNSS-PW data product are:

i) *The climate detection and attribution community.* GNSS-PW data have been used to monitor long-term PW climate changes (e.g., Gradinarsky *et al.*, 2002; Mears *et al.*, 2017; Ning *et al.*, 2016a; Wang *et al.*, 2016; Guerova *et al.*, 2016). It is also frequently used as a transfer standard to validate other climate datasets, such as radiosonde data and reanalysis products (e.g., Vey *et al.*, 2004; Wang and Zhang, 2008b, 2009; Wang *et al.*, 2013). In addition, GNSS-PW is also used to study diurnal variations of PW and diurnal asymmetry of long-term PW trends (e.g., Dai *et al.*, 2002; Wu *et al.*, 2003; Wang and Zhang, 2009; Wang *et al.*, 2016). In the context of GRUAN, the GNSS-PW data will be used as a redundant PW dataset to inter-compare with radiosonde and other ground-based and satellite remote sensing measurements, to study PW variations from diurnal to long-term time scales and to evaluate climate models to improve future climate predictions.

ii) *The satellite community.* GNSS-PW measurements have historically provided a key dataset for validating satellite-based measurements of PW and ultimately improve satellite retrievals (Mears *et al.*, 2015, 2017). The high temporal resolution of the GNSS-PW data is useful for detecting diurnal biases in satellite retrievals. GRUAN GNSS-PW Programs, with their well characterized measurement uncertainties and network-wide homogeneity, are expected to provide a database that will be essential for validation of satellite-based measurements of PW. Because the GRUAN GNSS-PW measurements are likely to serve a wide range of end-users within the satellite measurement community, WG-GRUAN and GTT members shall be assigned to liaise with key clients within the satellite community to ensure that GRUAN GNSS-PW data products are tailored, where possible, to best meet the needs of this community. The GRUAN GNSS-PW measurements should be used to remove offsets and drifts between separate satellite-based measurement series within the limitations imposed by the uncertainties on the GRUAN GNSS-PW measurements.

iii) *The Numerical Weather Prediction (NWP) community.* The GNSS-derived Zenith Tropospheric Delay (ZTD) and/or PW have been regularly assimilated into NWP models and show great promise in improving numerical weather forecasting (e.g., Kuo *et al.*, 1993; Vedel and Huang, 2004; Vedel *et al.*, 2004; Gutman *et al.*, 2004; Gendt *et al.*, 2004; Shoji, 2009; Shoji *et al.*, 2011; Guerova *et al.*, 2016). Given the limited number of GRUAN sites, it might not be cost-effective to assimilate GRUAN GNSS data in NWP models, but given the highly constrained uncertainty the GRUAN GNSS-PW data product would be very useful for the model water vapour verifications.

iv) *Nowcasting and Very Short Range Forecasting community.* GRUAN GNSS PW data can be assimilated to improve the precipitation forecasting in short ranges (cf. Guerova *et al.*, 2016, and references therein). Recently, new, enhanced, more detailed GNSS tropospheric products, such as ZTD gradients and slant delays, can be explored for nowcasting and very short range forecasting (Kawabata *et al.*, 2013; Shoji, 2013; Shoji *et al.*, 2015) (cf. Guerova *et al.*, 2016, and references therein).

Table 3: Equipment costs for a GNSS-PW site.

Equipment	Requirement	Costs (EURO)
GPS Receiver/Antenna	Geodetic quality dual frequency carrier phase observations are needed for any GRUAN site.	15,000–20,000
Surface Observations (pressure and temp.)	Pressure accurate to $<0.5\,\mathrm{hPa}$ to remove hydrostatic delay. A $0.5\,\mathrm{hPa}$ error in surface pressure involves a $\sim 0.2\,\mathrm{mm}$ error in PW.	700–1,600
Station Monumentation	GPS antenna should be installed in a manner that conforms to IGS standards.	700–13,000
Installation		5000
Communication (Internet)	Data need to be provided to analysis centre(s) in timely manner to ensure that are included in routine processing.	Variable

1.6 Finances

The cost of establishing and maintaining a GNSS-PW station will vary significantly from site to site due to differences in the local environment and the goods and services cost of the region. The values provided here are estimates as of 2019.

Equipment and installation: The figures in Table 3 are based on an installation at an existing site, with no special requirements for the antenna mounting and/or cable ducting/length. The quoted figure is based on the COST Action 716 Final Report (COST, 2016). It estimates the cost to purchase the surface instruments but does not include calibration and maintenance. The expected life of this instrumentation is approximately 10 years.

Maintenance: The figures in Table 4 are based on maintenance for a standard site as assessed in the COST Action 716 Final Report (COST 2016). In Table 4, the spares estimate is based on one complete spare per ten sites, but this figure is dependent on network redundancy and the support agreement with the vendor.

Table 4: Maintenance costs for a GNSS-PW site.

Maintenance	Average Costs (EURO)
2 Site Visits per year (1 maintenance & 1 emergency)	3000
Spares	2500
Rent Costs	Variable
Local Archiving	500–200

2 Instrumentation

2.1 Terminology

These definitions are based on the formal metrological definitions set out in JCGM (2012).

True value: This is a value consistent with the definition of a given particular quantity that would be obtained by a perfect measurement. True values are by nature indeterminate.

Measurement accuracy: Every measurement has imperfections that cause it to differ from the true value. The measurement accuracy describes the closeness of the agreement between the result of a measurement and the true value of the measurand.

Measurement uncertainty: A parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand. Measurement uncertainties may be time dependent.

Measurement precision: The closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same measurand under specified conditions. The 'specified conditions' can be, for example, repeatability conditions of measurement or reproducibility conditions of measurement.

Repeatability: The measurement precision under conditions of measurement that involves the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same measurand over a short period of time.

Reproducibility: The measurement precision under conditions of measurement of the same measurand that includes different locations, times, operators, measurement procedures and measuring systems. A specification should give the conditions changed and unchanged, to the extent practical.

Measurement error: The result of a measurement minus the true value of the measurand. Measurement error should not be confused with production error or mistake. The overall measurement error will include both random and systematic error sources.

Random measurement error: The component of measurement error that in replicate measurements varies in an unpredictable manner. For a single measurement it is the result of that measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions. The random error component of any measurement is the result of stochastic variation in quantities that influence that measurement. While random errors cannot be designed out of a system, the random error on the mean of multiple measurements is reduced since, by definition, the expected value for the random error is zero. The random error is closely linked to the measurement precision.

Systematic measurement error: The component of measurement error that in replicate measurements remains constant or varies in a predictable manner. It is the mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions minus the true value of the measurand. It results from systematic effects that do not average to zero as the number of measurements increases. However, if these systematic biases can be identified and quantified, they should be corrected for. The systematic error is closely linked to the measurement accuracy. Note that the term 'bias' refers to an estimate of a systematic measurement error.

Stability: Stability refers to the consistency of random measurement errors and systematic measurement errors with time. Undetected changes in systematic measurement errors induce artificial trends in measurement time series.

Correction lifetime: A corrected result is one where a measurement has been corrected for any systematic measurement error. This correction may depend on an independent measurement from another source and may have a finite "lifetime" in the sense that later reprocessing of the measurement may revise the estimate of the systematic measurement error, requiring a new correction.

2.2 Theoretical Basis

GNSS-PW measurements use the Total Tropospheric Delay in the zenith direction (ZTD) associated with the GNSS signal combined with surface measurement of pressure and estimated or measured water-vapour-weighted mean temperature (P_s and T_m, respectively) to estimate the overhead column PW (Figure 1).

The measured ZTD of the GNSS signal can be broken down into two components: the Zenith Hydrostatic Delay (ZHD) and the Zenith Wet Delay (ZWD). The ZHD is the delay occurring from the non-dipole component of refractivity of a number of atmospheric gases including water vapour, while the ZWD is the component of refractivity from the dipole moment of water (the only common gas in the atmosphere to contain a dipole moment). It is possible to model the ZHD (Elgered *et al.*, 1991):

$$\text{ZHD} = \frac{(2.2779 \pm 0.0024)\, p_s}{f(\lambda, H)}, \tag{2.1}$$

$$f(\lambda, H) = 1 - 0.000266 \cos(2\lambda) - 0.0028\, H, \tag{2.2}$$

where p_s is the total pressure (in hPa) at the Earth's surface, λ is latitude, and H is the surface height above the ellipsoid. Calculating the ZWD simply follows:

$$\text{ZWD} = \text{ZTD} - \text{ZHD}. \tag{2.3}$$

Relating ZWD to PW can be done using a series of equations detailed in Bevis *et al.* (1994):

$$\text{PW} = \frac{\text{ZWD}}{\Pi} \tag{2.4}$$

$$\Pi = \frac{\rho_w R_v \left(\frac{k_3}{T_m} + {k_2}'\right)}{10^6} \tag{2.5}$$

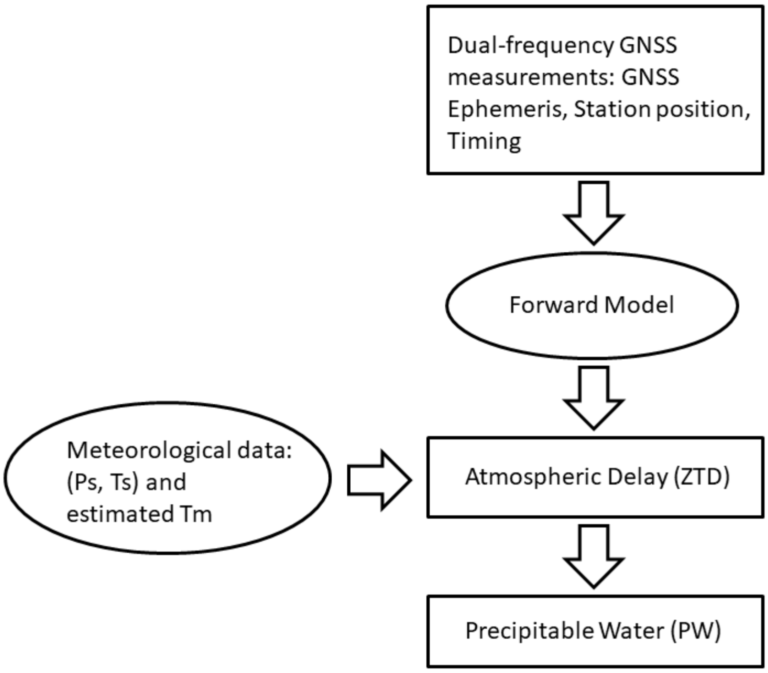

Figure 1: The schematic plot shows how PW is derived from GNSS measurements.

$$k_2{}' = k_2 - \frac{M_w}{M_D} k_1, \tag{2.6}$$

where ρ_w is the density of liquid water, R_v is the specific gas constant for water vapour, T_m is the water-vapour-weighted mean temperature of the atmosphere, M_w and M_D are the molar masses of water vapour and dry air, respectively, and k_1, k_2, and k_3 are physical constants from the widely used formula for refractivity (Smith and Weintraub, 1953; Boudouris, 1963). For more detail on the values of k see Bevis *et al.* (1994) and Table 5. T_m can be calculated from the vertical profile of water vapour pressure (p_w) and the physical temperature (T), with S the integration path:

$$\int \frac{p_w(S)}{T(S)} dS = T_m \int \frac{p_w(S)}{(T(S))^2} dS. \tag{2.7}$$

T_m can also be modeled by temperature and humidity profiles, estimated from surface temperatures or calculated from reanalysis products or NWP models (cf. Wang *et al.*, 2005). For the GRUAN GNSS-PW data product, it is recommended that T_m is calculated from temperature and humidity observations from co-located high-quality, calibrated meteorological sensors. If this is not possible, profiles from numerical weather prediction model analyses or reanalyses with temporal, horizontal and vertical interpolation to the time and location of the GNSS site, following Heise *et al.* (2009), can be used.

Table 5: Physical constants k_1, k_2, and k_3 found and justified by different authors. Table modified from Bevis *et al.* (1994).

	k_1 / K hPa^{-1}		k_2 / K hPa^{-1}		k_3 / K hPa^{-1}	
Reference	Value	Error	Value	Error	Value	Error
Smith and Weintraub (1953)	77.607	0.013	71.60	8.50	3.747	0.031
Thayer (1974)	77.604	0.014	64.79	0.08	3.776	0.004
Hasegawa and Stokesberry (1975)	77.600	0.032	69.40	0.15	3.701	0.003
Bevis *et al.* (1994)	77.600	0.050	70.40	2.20	3.739	0.012

2.3 Justification for Instrument Selection

Extensive tests to evaluate and compare the applicability of receiver-antenna pairs for GRUAN have not been completed. However, in general, nearly all geodetic grade receivers and antennas (IGSCB-RA) work well for GNSS-PW provided they meet the GRUAN requirements (Section 7.1.1) and preferably meet the desired characteristics. Notable exceptions to the GRUAN requirements are the one-band (L1 receivers), as they do not allow the elimination of ionospheric refraction and often do not have stable enough clocks. Choke-ring type antennas are recommended because of their capability to reduce multipath effects. The use of radomes is not recommended unless required operationally and then the antenna radome pair must be documented in the IGS (see Section 7.1).

2.4 Instrument Redundancy

There are two primary additional measurements which can provide redundancy to GNSS-PW instruments: radiosondes, and Microwave Radiometers (MWRs), either ground or satellite mounted.

Radiosondes provide in situ measurements with good vertical resolution. Once weekly soundings are a minimum requirement for entry into GRUAN; sites must also have aspirations to make twice to four times daily soundings. Radiosondes have been frequently used to estimate the accuracy of GNSS-PW (e.g., Tregoning *et al.*, 1998; Ohtani and Naito, 2000; Dai *et al.*, 2002; Bokoye *et al.*, 2003; Guerova *et al.*, 2003; Li *et al.*, 2003; Nakamura *et al.*, 2004; Deblonde *et al.*, 2005). However, the PW discrepancies found in these studies can result from measurement errors in the radiosondes, GNSS-PW measurements, or both. In addition, GNSS-PW measurements have been successfully used to constrain the measurement errors associated with radiosondes (e.g., Wang and Zhang, 2008b). Radiosondes provide an excellent comparison to GNSS-PW measurements though their biases must be taken into account. Finally, it is important to remember that radiosondes can cover a horizontal distance of a few $100\,\mathrm{km}$ as they ascend and therefore measure humidity along a path, which can introduce discrepancies due to heterogeneities in the atmosphere.

Satellite MWRs produce PW measurements over wide areas. These systems have difficulty measuring PW in areas with clouds, precipitation, or high winds Mears *et al.* (2015). Several studies have compared MWRs and GNSS measurements of PW (e.g., Wang *et al.*, 2007; Mears *et al.*, 2015). Both studies found correlation between GNSS-PW and MWR-PW to be better than GNSS-PW to radiosondes. Co-location of ground based MWR is an important factor as spatial separation can be an additional source of error (Wang *et al.*, 2007).

In addition to the above, two other geodetic techniques can also estimate PW: Very Long Baseline Interferometry (VLBI), and Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS) measurements. They are very similar to GNSS-PW as PW is calculated from the measured ZTD, but VLBI has high directivity and therefore is not subject to the systematic measurement errors occurring from signal multipath (see Section 4.1.2) (Ning *et al.*, 2016b). While VLBI instrumentation is fairly uncommon, where it is co-located with GNSS-PW receivers it can be a useful technique to calculate the measurement errors of GNSS-PW in a statistical fashion (see Section 4.1.1) (Ning *et al.*, 2012). DORIS is in operation since January 1990 and is composed of a network of over 60 ground transmitters homogeneously distributed around the globe (Bock *et al.*, 2014).

2.5 Instrument Co-location

The typical spatial representation of a GNSS-PW system remains an area requiring further investigation. Early studies at the GRUAN site Tateno (Japan) show that the typical spatial representation of GNSS PW data using dense Japanese GNSS networks varies by season but can be conservatively assessed as $50\,\mathrm{km}$ (GCOS-161, 2012, GRUAN ICM-4). There is a need for similar studies to be completed at other GRUAN sites to better constrain the effects of spatial separation of GNSS receivers. Limited studies also show that the vertical separation between instruments contributes most to the mean PW difference, and the instrument difference has the largest effect on the scatters of the PW differences (Shoji *et al.*, 2004). Here an ideal GNSS-PW station setup would consist of two independent sets of GNSS receiver/antenna installed at each GRUAN site. However, this is not a mandatory GRUAN requirement, merely a suggestion of an idealized situation. If a dual-station setup is installed, to take advantage of measurement system redundancy, these independent systems should not be changed simultaneously.

Where possible, GRUAN GNSS-PW instruments should be co-located with other instrumentation. To fulfil the minimum site requirements (Section 7.1.1) a GNSS receiver must be co-located with instrumentation to measure surface pressure and temperature. In addition, it is valuable to co-locate the GNSS receiver with redundant measurements of PW (e.g., MWR or radiosondes launch sites). Additionally, co-location with other geophysical systems (e.g., SLR, VLBI, DORIS, absolute or superconducting gravimeters, Earth tide gravimeters, seismometers, strain meters, and ocean tide gauges) enhances the value of the station for multi-disciplinary studies. Finally, when feasible, co-location with scientific systems that rely on accurate positioning (e.g., timing labs) is recommended.

2.6 Calibration, Validation, and Maintenance

All GRUAN GNSS-PW sites must maintain an accurate calibration for the station antenna (or antenna and radome pair, if a radome is necessary) and for all surface meteorological instrumentation relating to the GNSS-PW data product. Antenna must have its phase centre variation calibrated and available following IGS guidelines (see IGSCB-AR and IGSCB-08), and the antenna type should be of a type approved by the IGS antenna Working Group (see https://kb.igs.org/hc/en-us/categories/200150556-Antenna-Working-Group). If a radome must be used, the pair must be documented in the IGS phase centre variation file (see IGSCB-08). Zenith and azimuth-dependent calibration values must be recorded down to the horizon. If the pair is not calibrated, an absolute calibration from an independent recognized laboratory is required (see IGSCB-AR). If an uncalibrated pair is removed, please make it available to a calibration laboratory. For any assistance in the calibration of antennas and/or antenna and radome pairs, contact the GRUAN Lead Centre. The surface meteorological instruments must also be calibrated as specified in the manufactures recommendations and any supplementary GRUAN procedures.

Validation of GNSS-PW instruments within GRUAN should include well documented and traceable calibration procedures and participation in regular inter-comparisons with similar instruments (e.g., radiosondes or MWR). Most sites will probably not have identical instrumentation, with the result that instrument validation will often be site specific. A standard recommendation for the use of redundant instrumentation and remote sensing instrumentation should be developed by the Lead Centre (in consultation with the Task Teams) to aid site-specific, regularly scheduled, instrument validation.

All GRUAN GNSS-PW sites must be adequately maintained. Responsible staff shall take responsibility for GNSS-PW instruments operated at the GRUAN site. The operating agency must always have the capability to repair or improve the station and its software systems, including situations in which the original technical staff are no longer available. However, because all maintenance of an instrument can also introduce discontinuities and systematic measurement errors in measurement series, maintenance shall not be conducted more frequently than is necessary. Maintenance schedules must be developed for all instruments, and all maintenance actions shall be documented as part of the metadata of that instrument. Maintenance of supporting infrastructure at GRUAN sites is also essential, particularly in regards to maintaining those aspects of the environment that may affect measurements (e.g., controlling the growth of nearby trees or the change of any structure in the vicinity of the GNSS antenna which may lead to increased signal multi-path error).

3 Reference Measurements

3.1 Making Reference Measurements

A GRUAN reference measurement

- is traceable to an SI unit or accepted standard,
- provides a comprehensive uncertainty analysis,
- maintains all raw data,
- includes complete metadata description,
- is documented in accessible literature,
- is validated.

In order for GNSS to make reference measurements of PW, the abovementioned criteria must be met. All IGS final products are traceable to an SI unit, providing any other input parameters for deriving GNSS-PW (e.g., surface pressure and surface temperature, physical constants in conversion formulas) are being measured by instruments calibrated to an SI unit. As detailed in Section 4, all GRUAN GNSS-PW measurements will undergo a thorough uncertainty analysis providing the requirements in Section 7.1.1 are met. As detailed in Section 6, both the raw data and the metadata will be stored at the appropriate GRUAN data centre (GFZ at time of publication). The measurement methods and algorithms are documented in the scientific literature and are detailed in this document. Finally, Section 4.4 details the method by which GRUAN GNSS-PW data shall be validated.

3.2 Managing Change

3.2.1 Guiding principles

The GRUAN GNSS-PW Task Team recognizes that ground-based GNSS measurements may undergo changes from time to time due to improved understanding of the monitoring system or technology advancement in hardware and/or software. These changes (termed as 7 items hereinafter) include:

(1) GNSS instrumentation,
(2) Operating procedures,
(3) GNSS data processing algorithms,
(4) Instrument maintenance (e.g., firmware bug fix or upgrade) and operators,
(5) Location of GNSS instruments,
(6) Operating environments for GNSS instruments and other factors,
(7) Auxiliary measurements and data (p_s and T_m) used to derive PW.

They are all likely to introduce inhomogeneity into the GNSS-PW product. Some of these changes may take place instantly, while others take place gradually (e.g., the gradual growth of nearby vegetation or urbanization of the surrounding area). As a result, both stepwise and gradual changes are expected to appear in GNSS PW product.

GRUAN welcomes any necessary changes that can bring scientific, financial or operational benefits while trying to avoid any unnecessary changes. The ultimate goal is to manage the changes in such a way that inter-comparability, continuity and integrity of long-term records of GNSS-PW data are maintained across the transition.

This section describes the protocols for managing changes in GRUAN GNSS-PW product. This document is based upon the principles of the document "GCOS climate monitoring principles" (https://gcos.wmo.int/en/essential-climate-variables/gcos-monitoring-principles), and the section "Managing change" in the 'GRUAN-Guide' (GCOS-171, 2013).

Specific to GRUAN GNSS-PW product, the following principles are considered:

1) *Embracing and preparing for change*: GNSS technologies, such as new GNSS instrumentation (e.g., GNSS receiver, GNSS antenna, and auxiliary sensors such as temperature, humidity and pressure sensors), new GNSS algorithms, and new GNSS data analysis software packages, undergo rapid growth along with the development of various satellite systems. GRUAN welcomes changes and technological advantages, although the inherent disadvantages of making a change must be weighed against the advantages and benefits that are to be gained. In addition, some unplanned changes may also happen as a result of loss of GNSS instruments due to breakage/damage or premature aging.
2) *Change event notification*: In GRUAN every change must begin with a change event notification. A change event notification is issued by the proposer of the change. Proposed changes in operating procedures will likely arise from GRUAN GNSS sites, while proposed changes in data processing algorithms will most likely be initiated by the nominated central processing facility. Whatever the origin of the proposed change, the change event notification is sent to the GRUAN Lead Centre as an email. A change event begins with the start of change of any one of the aforementioned '7 items'. A change event ends with the official acceptance of the change that has been made after a careful and rigorous assessment. The change event end date is not necessarily the day when the physical change is made. For instance, when a GNSS instrument is replaced, the change event does not end on the day when a new GNSS instrument is installed but on the day when the change assessment report is officially accepted.
3) *Justification of change*: Any putative change in the GNSS-PW product must be fully justified. An assessment report must be submitted in which advantages and disadvantages of making the change must be carefully assessed. Laboratory tests of old and new items (any one of the '7 items' listed previously) should be included in the assessment report. Lead Centre, GRUAN GNSS-PW central processing facility (GFZ), a GNSS site, a GNSS instrument manufacturer, or another member of the GRUAN community can initiate a proposal for changes. Whatever the origin of the proposed change, the change event notification is sent to the GRUAN Lead Centre as an email. The Lead Centre must act as a clearing-house for all proposed changes.
The Lead Centre, in consultation with experts at the designated GNSS data central processing facility, makes an initial evaluation of the proposed change. If considered to be worth pursuing, the Lead Centre assesses the advantages, disadvantages, and potential impacts of the proposed change; in particular, which parts of the GNSS-PW system will most likely be affected. If the knowledge needed for quantitatively assessing the impact of changes already exists, it should be immediately encapsulated in the metadata associated with the change event. If additional laboratory studies are required, such laboratory

studies must be undertaken by either the Lead Centre or a task force commissioned by the Lead Centre. The information and data required to manage the change are captured in a change evaluation report that will become a key component of metadata associated with the change.

4) *Preparing for change*: A quantitative assessment of the impacts of any planned change must be undertaken before the actual implementation of such a change. The assessment must cover a sufficiently long period of time, not just covering the change period. For instance, the change of GNSS software may need an assessment period of at least 12 months in order to assess its performance under all the seasons. The impact on both the GNSS-PW product and its uncertainty needs to be assessed.
The impacts of a change to the GNSS-PW product should be quantified through laboratory studies in such a way that: (1) knowledge of the newly changed item is at least as detailed as knowledge of the old one; (2) extensive tests are conducted (e.g., processing a large number of common datasets by both new and old algorithms if a change in algorithm is proposed); and (3) the GNSS-PW products after the change are superior to those prior to change, in terms of continuity, accuracy or integrity. If continuity, accuracy and integrity cannot be improved at the same time, they should at least not be compromised. However, if a considerable improvement in one aspect (e.g., accuracy) is gained at the cost of a slight degradation of other aspects, it might be still justifiable to propose a change.
When laboratory studies are proposed, regular observation schedules must not be interrupted. In cases where laboratory studies cannot be reconciled with the results derived from in situ simultaneous observations, this must be noted as part of the metadata. A proposal of how to resolve the discrepancy should be developed. If the GNSS site decides to proceed and implement the change, any data and metadata collected as part of the change process, as well as a full report on how the change is managed and implemented, must be submitted to the Lead Centre within 3 months of the completion of the change. This information will then be archived as part of the metadata record for the GNSS-PW data series from that GNSS site.

5) *Validating impacts*: Some changes need to be validated using historical data to see whether a continuity of GNSS-PW data and their uncertainties can be maintained. Every effort must be made to ensure that the change is properly managed so that systematic measurement errors and/or drifts between the old and new GNSS-PW data are minimized. For instance, a change in a processing algorithm may require a reprocessing of historical data. However, not every change will ensure the homogeneity in PW and its uncertainty. For example, if a new GNSS instrument of much higher accuracy is installed, it will provide much higher accuracy GNSS data. The time series of GNSS-PW data uncertainties after this kind of change may not be continuous, but the improvement could be noticed as a large decrease in uncertainties. Impacts of changes must be assessed in light of the different uses of GRUAN-PW data products, with respect to:

   i) PW trend detection: Changes in GNSS-PW data uncertainties will affect the statistical significance of a derived trend in the long-term PW record.

   ii) Calibration/validation of other systems: While GNSS-PW data are used for calibration/validation of other systems, the proposed change should ideally be avoided during any planned calibration/validation campaign or known platform transition of other systems.

6) *Single changes*: Whenever a GNSS-PW system is changed, as many similarities as possible between the old and new systems should be maintained. E.g., a GNSS instrument and its location should not be changed simultaneously. Multiple simultaneous changes should be avoided so that the change impact of each component on the whole GNSS-PW system can be quantitatively assessed.
7) *Network homogeneity*: Maintaining network-wide homogeneity of GNSS-PW data is important. If change is implemented unilaterally at a single GNSS site, that change may introduce inconsistency with other stations in the network. Changes at GRUAN-PW GNSS stations should therefore be conducted in such a way that the homogeneity of the resultant GRUAN-PW product across the network is not compromised. Thus, the impact of the change on network-wide GNSS-PW data should be included in the assessment report prior to proposing such a change. Lead Centre should consult with users of the GRUAN GNSS-PW data product and other climate data bodies such as GCOS, World Climate Data and Monitoring Programme (WCDMP) and World Climate Research Programme Data Advisory Council (WDAC) to thoroughly evaluate the potential implications of network-wide implementation of the proposed change. If the proposed change is approved, the Lead Centre, in consultation with the GNSS-PW central processing facility, will develop a formal change plan for implementation across the network. The formal change plan is then communicated to all GNSS sites within the network. Any changes or deviations from the documented approvals must be considered a new change and must be reassessed by the Lead Centre.

   This does not necessarily imply, for example, that any change in instrumentation must be implemented at all sites at the same time (which may be detrimental to the management of that change), but rather that change at any one site must be conducted within the context of, and in consultation with, other sites in the network. The Lead Centre shall play a key role in ensuring such smooth transitions. However, changes are not necessarily always network-wide. In special circumstances, changes to individual site are allowed. For instance, changes of GNSS instrument operators or changes of operating environments for GNSS instruments. Documentation of these site changes in the form of metadata is essential. Sites will be audited on the completeness of their metadata submitted to GRUAN archives as part of the site assessment and certification process.

   After a change has been implemented, the Lead Centre, together with the GNSS-PW central processing facility, will formally audit the implementation of the plan and write a Change Impact Report. The report will assess the degree to which the formal change plan is implemented and it will be archived as part of the metadata record for the GNSS-PW data.
8) *Supporting reprocessing*: If a substantial impact on GNSS-PW data is observed following a change event (e.g., new GNSS data processing software; new procedures [e.g., new technique to process GNSS data of low satellite elevation]; changes in auxiliary data such as precise GNSS orbit and precise GNSS satellite clock data), reprocessing of historical GNSS data may be necessary. However, when there is a GNSS hardware change only (e.g., GNSS receiver or GNSS antenna), reprocessing of the whole record of GNSS data is not necessary. In the reprocessing, the homogenization procedures used in the previous change events can be adopted in order to produce a homogenized data record. The raw GNSS data, as well as detailed metadata collected during change events, needs to be carefully collected so that such reprocessing can be easily achieved. Because raw data

from various GRUAN GNSS sites will be processed at a centralized processing facility, changes in data processing algorithms will be implemented uniformly across the network.

9) *Data versioning*: Every reprocessing generating a new homogeneous time series of the full record of GNSS measurements must be reflected in an increment in the data version. Such data updates must also be communicated to users who have accessed earlier versions of the data or who have voluntarily registered to receive notifications of such data updates. It is also important that all older versions of any data set are always made available through the GRUAN archives.

10) *Monitoring changes*: Most changes are planned and therefore can be managed. However, some changes may be unplanned or occur sufficiently slowly so that they are not immediately identified, e.g., a slow drift of GNSS antenna monument, construction of new buildings, or trees being planted or removed at a site that may alter the field of view of the GNSS instrument.
It is imperative that all such change events be recorded in the metadata associated with the GNSS instrument (log books) and that these events be specifically identified as potential breakpoints in the time series to the central data processing facility. A comprehensive set of photographs providing a horizon-wide view of the GNSS site, taken from various reference locations around the site and approximately 4 times through the year, will provide a valuable resource for assessing changes in the environment at the site. Constant vigilance to proactively detect and correct such changes is required. This can be achieved, in part, through comparison with independent redundant measurements, models, or meteorological reanalyses.

    i) *Use of independent, redundant measurements*: Inter-comparability test of the system undergoing change with other measurement systems before and after the change can validate the robustness of the management of the change. This benefit increases further when three or more instruments measure the same PW. Ideally at least triple redundancies exist. It is recommended that two independent sets of GNSS receiver/antenna be installed at each GNSS PW station. To take advantage of measurement system redundancy, these independent systems should not be changed simultaneously.

    ii) *Instrument calibration*: When GNSS instruments are calibrated to fundamental calibration standards, changes in instrumentation can be more easily managed. One calibration method may be examining the performance of the GNSS instruments by looking at its static positioning quality. The higher quality GNSS instruments should produce stationary positioning solutions of higher accuracy and stability. Another calibration method may be examining the quality of derived GNSS-PW data by comparing with PW data from other sources, such as radiosonde.

    iii) *Use of models*: We aim to maintain a complete record of all historical GNSS-PW data. In cases where changes in the historical GNSS-PW measurement record have not been adequately managed, if physical or statistical models can faithfully reproduce the PW data the model time series can be used as a means of detecting and correcting possible systematic measurement errors between old and new measurement systems.
    Statistical models may be in the form of regression models that are fitted to measurements from the old system and then projected forward to cover the period sampled

by the new system, or could rely on measurements from surrounding GNSS sites to estimate values at the site of interest. When all changes are well managed, the use of models for this purpose should not be necessary.

iv) *Manufacturer involvement*: Efforts must be undertaken to avoid unknown changes. For example, the instrument manufacturer may make unannounced changes, and manufacturers may occasionally make announcements of GNSS receiver firmware upgrades to fix bugs. Late response to the upgrade announcement may result in GNSS data loss or interruption. The GTT and central processing centre must therefore establish close two-way links to instrument manufacturers, as well as the IGS and CIMO multi-sensor field campaigns. Specifically, GRUAN sites and the central processing centre need to establish close working relationships with GNSS instrument manufacturers so that any changes to be implemented or having been implemented are known to them. Preferably the changes should be known substantially in advance of deployment, allowing sufficient time to investigate, understand, prepare for and document the change and its likely impacts. Close two-way links to instrument manufacturers will achieve this, and inclusion of the IGS in discussions of instrument change within GTT would be advantageous. A productive point of interaction with the different vendors and manufacturers would be the periodic communication with IGS as well as the Commission for Instruments and Methods of Observation (CIMO) multi-sensor field campaigns.

3.2.2 The importance of metadata

Metadata are very important in documenting network changes. Complete metadata should include a full account of all the changes that have been made (including GNSS instruments, operational procedures and software, see Section 7) within the full cycle of process. A full and complete record of the metadata of the GNSS PW stations should be maintained, as a minimum, from the date of its certification as a GRUAN site to the present.

Metadata should include, for example, manufacturer/model/serial number of GNSS instruments (antenna, receiver, auxiliary sensors), geo-tagged and time stamped digital images of the GNSS instruments, GNSS software output files, detailed steps in GNSS instrument installation and calibration, detailed steps in the GNSS data processing, geo-tagged and time stamped digital images of the GNSS site and its surrounding region, and a detailed description of how each change in the GNSS-PW system is managed. Pictures may capture as much information as possible to prepare for future GNSS-PW product reprocessing. GNSS-PW operators should collect as much metadata as possible to prepare for any future uses. Sufficient metadata must be available to tie the new instrument via a comparable traceability chain back to the same recognized standard as the old instrument.

3.2.3 Validating managed changes using parallel observations

Overlap regimen design: When transitioning from old GNSS to new GNSS instrumentation, a length of parallel operation time of the old and new GNSS-PW systems should be not less than 12 months, considering the impact of seasonal variation on GNSS-PW. The GNSS-PW systems should run at the same configuration as usual. More than one parallel observation period may be required after the initial 12-month overlap period, depending on the validation result. It is recommended to conduct a second parallel testing two years later to gauge whether there has been any drift in the bias between the old and new systems. The number of parallel observation periods required may be site dependent, but must be at least 12 months.

Use of redundant, independent measurements: When parallel observations of old and new GNSS-PW measurement systems are not feasible, the availability of additional redundant GNSS-PW systems with similar sampling attributes (e.g., vertical resolution, temporal sampling frequency) is essential for validating a managed change. In such cases, an evaluation of the redundant system(s) with the old and new systems over an overlap period of at least 12 months must be undertaken to validate the robustness of change management.

4 Measurement Uncertainty

4.1 Evaluating Measurement Uncertainty

An extensive review of the methods to determine the uncertainty of GNSS-PW measurements was completed by (Ning *et al.*, 2016b) to support the development of a GRUAN GNSS-PW data product. This review is summarized here.

All GNSS-PW measurements are subject to a series of measurement error sources. There is the uncertainty of the estimated ZTD which primarily depends on the errors in GNSS satellite orbits. The uncertainty of ZHD depends on the uncertainty of ground pressure measurements (Ning *et al.*, 2016b). Finally, the conversion from the ZWD to PW will add uncertainties associated with T_m and the physical constants from the widely used formula for refractivity (k_1, k_2, and k_3). These uncertainties may be random or systematic. Since the expected mean value of random measurement errors is zero, the impact of such errors is reduced with increasing number of measurements. Systematic measurement errors cannot be averaged out, but can occur at a specific time, e.g., the change of an antenna, or slowly, e.g., the signal multi-path effects of slow growing of vegetation at a measurement site. All these error sources must be included in the determination of GNSS-PW measurement uncertainties.

There are two methods to determine uncertainty. If there is co-location of three or more techniques to measure PW then a statistical analysis can be completed. This statistical technique is applied using the ERA-Interim (Dee *et al.*, 2011) as a reference data set as well as radiosonde measurements where they are available.

A theoretical approach has been implemented for those sites which do not have sufficient measurement techniques for the statistical method. Ning *et al.* (2016b) found that the theoretical estimate of uncertainty is lower than, but comparable to, the statistical approach. This is most likely because of site specific sources of uncertainty that cannot be accounted for in the statistical method, such as multi-path errors (see paragraph "Uncertainties of Zenith Total Delay" in Section 4.1.2). Due to the current observational network where most stations do not have the co-location of three techniques, the theoretical technique will be implemented in the GRUAN GNSS central data processing. At sites where the statistical method can be implemented, it can also be used to assess the stability of the data quality and improve the operational theoretical method.

4.1.1 The statistical approach to measurement uncertainty

Where three or more measurement systems are co-located it is possible to measure the uncertainty of the techniques through a statistical analysis (Moses, 1986). Over long measurement periods (e.g., long enough that the mean random measurement error goes to zero) the standard deviation of the difference of two PW measurements can be defined as:

$$S_{\mathrm{A-B}} = \sqrt{\overline{\varepsilon_{\mathrm{A}}^2} + \overline{\varepsilon_{\mathrm{B}}^2}}, \tag{4.1}$$

where ${\varepsilon_{\mathrm{A}}}^2$ and ${\varepsilon_{\mathrm{B}}}^2$ are the random measurement errors of technique A and B, respectively.

For the full derivation of this relationship see Ning *et al.* (2016b). From here it is possible to calculate the random measurement error of each technique through a series of equations comparing all three measurement systems. In order to derive the total uncertainty of each technique the systematic measurement errors must also be calculated. The mean PW difference between two techniques for long time periods where the mean random measurement errors sum to zero can be defined simply as:

$$\overline{\mathrm{PW}_{\mathrm{A}(i)} - \mathrm{PW}_{\mathrm{B}(i)}} = M_{\mathrm{A}} - M_{\mathrm{B}}, \tag{4.2}$$

where M_{A} and M_{B} are the biases for techniques A and B, respectively. If the bias is known, or can be reasonably assumed for one technique, then the bias of the other techniques can be calculated and the total uncertainty of the technique can be calculated by:

$$\sigma = \sqrt{\overline{\varepsilon^2} + M^2}. \tag{4.3}$$

While this is a very thorough method to calculate the uncertainty of a PW technique, the requirements of three co-located techniques means that it cannot be widely implemented across the GRUAN GNSS-PW network.

4.1.2 The theoretical approach to measurement uncertainty

The other approach is to account for all of the theoretical uncertainties inherent in the measurement systems. In this approach the total uncertainty of GNSS-PW is calculated from the propagation of uncertainty from the input variables according to the equation (Immler *et al.*, 2010):

$$\sigma_V = \sqrt{\sum_{i=1}^{M} \left(\frac{\partial f(V_1, \ldots, V_M)}{\partial V_i} \sigma_i \right)^2}, \tag{4.4}$$

where $f(V_1, \ldots, V_M)$ is the functional relationship between the GNSS-PW and input variables, and σ_i is the one-sigma uncertainty of the corresponding variable. This approach yields:

$$\sigma_{\mathrm{PW}} = \sqrt{\left(\frac{\sigma_{\mathrm{ZTD}}}{\Pi}\right)^2 + \left(\frac{2.2767\sigma_{p_0}}{f(\lambda, H)\Pi}\right)^2 + \left(\frac{p_0 \sigma_c}{f(\lambda, H)\Pi}\right)^2 + \left(\mathrm{PW}\frac{\sigma_\Pi}{\Pi}\right)^2}, \tag{4.5}$$

$$\sigma_\Pi = 10^{-6} p_w R_w \sqrt{\left(\frac{\sigma_{k_3}}{T_m}\right)^2 + \sigma_{k_2'}^2 + \left(k_3 \frac{\sigma_{T_m}}{{T_m}^2}\right)^2}, \tag{4.6}$$

where σ_{PW}, σ_{ZTD}, σ_{p_0}, σ_c, σ_Π, σ_{T_m}, σ_{k_3}, and $\sigma_{k_2'}$ are the one-sigma uncertainties of PW, ZTD, the surface pressure (p_0), the constant in the derivation in ZHD (see Section 2.2), the conversion coefficient (Π), T_m, and the constants from widely used formula for refractivity (${k_2}'$) and k_3 (Section 2.2) respectively, and ρ_w and R_w are the density of water and the specific gas constant for water, respectively. The details of the assumptions used to arrive at this determination are provided below.

Uncertainties of Zenith Total Delay

The uncertainties inherent in the ZTD arise due to errors in the GNSS satellite orbits, the uncertainties arising from the calculation of ionospheric delay, signal multi-path and mapping functions, and antenna related errors.

Errors associated with the estimates of satellite coordinates propagate directly into GNSS estimate parameters. The orbit error can be compensated by ZTD, receiver clock and ambiguity parameters if the Precise Point Positioning (PPP) strategy is used to process the data, the final clock product from the IGS is used, and the ionospheric delay is eliminated to the first order (Douša, 2010):

$$\cos \Psi_{\mathrm{A}}^{i} \cdot \sigma_{X_{\mathrm{Rad}}^{i}} + \sin \Psi_{\mathrm{A}}^{i} \cdot \sigma_{X_{\mathrm{Tan}}^{i}} = \frac{1}{\cos z_{\mathrm{A}}^{i}} \sigma_{\mathrm{ZTD}} + \sigma_{T_{\mathrm{A}}} + \lambda_f \sigma_{N_i} \tag{4.7}$$

$$\Psi_{\mathrm{A}}^{i} = \arcsin\left(\sin z_{\mathrm{A}}^{i} \cdot \frac{R_{\mathrm{A}}}{R^{i}}\right), \tag{4.8}$$

where z_{A}^{i} is the zenith angle seen from the ground receiver A to the satellite i, R_{A} and R^{i} are the distances from the top of the receiver to the geocentre, and the geometrical distance from the satellite to the geocentre, respectively; $\sigma_{X_{\mathrm{Rad}}^{i}}$ and $\sigma_{X_{\mathrm{Tan}}^{i}}$ are the radial and the tangential (along-track + cross-track) orbit errors. σ_{ZTD} is the ZTD error, $\sigma_{T_{\mathrm{A}}}$ is the receiver clock error, σ_{N_i} is the ambiguity error, and λ_f is the wavelength of frequency f.

The Earth's ionosphere contains enough electrons to significantly delay the propagation of a GNSS signal. Normally an ionospheric-free linear combination is used to remove the first order ionospheric delay, which normally accounts for $\sim 99.9\,\%$ of the total delay. Despite this, the second order delay can have a significant impact on the ZTD $(0.6$ to $4)\,\mathrm{mm}$, particularly during strong solar activities such as ionospheric storms (Fritsche *et al.*, 2005). Third order and higher terms are insignificant over long time series and therefore need not be corrected for.

The errors arising from signal multi-path are dependent on the elevation angle of the observation and vary from site to site based on the electromagnetic environment. For better QA/QC issues regular multi-path analysis is recommended at/for a site, recording the results in site metadata (at least temporarily). In addition, the electromagnetic environment can vary temporally at a site due to changes in soil moisture and growing vegetation (Larson *et al.*, 2010; Pierdicca *et al.*, 2014). Therefore, it is very difficult to create a general model to account for signal multi-path errors. Instead, for all GRUAN GNSS-PW sites, it is highly recommended that a microwave absorbing material, such as ECCOSORB (http://www.eccosorb.com/), is installed on the antenna to minimize the impact of multi-path effects.

Antenna-related errors arise from Phase Centre Variations (PCV) and radome effects. PCV corrections are normally always applied to eliminate this source of error and must be used at GRUAN GNSS-PW sites. Different shaped radomes create different effects, though hemispheric radomes minimize the effect. Therefore, GRUAN recommends hemispheric radomes if a GNSS site is going to install one. A radome calibration in the data processing is necessary in order to reduce the impacts. The IGS provides and updates radome calibration tables for particular antenna and radome pairs.

Finally, the Mapping Functions (MF) that convert the slant path delay to the equivalent ZTD can provide uncertainty to the measurement of ZTD. These errors are exacerbated at low elevation angles, and at such angles are difficult to distinguish from other sources of error such as signal multi-path. Therefore, rather than quantifying the uncertainty for GRUAN data products, it is best to choose a slightly higher elevation cut-off angle, such as $>10°$, for the GPS data processing to significantly reduce the MF induced uncertainty.

In summary, the uncertainty of ZTD is primarily derived from the errors associated with the GNSS satellite orbit. While there are other errors and uncertainties associated with the Earths ionosphere (signal multi-path, antennas effects and MF), these can largely be reduced to an acceptable level by taking the actions described in Section 4.3.

Uncertainties of Zenith Hydrostatic Delay

The uncertainties of the ZHD can arise from the uncertainty of the inputs: the ground pressure measurement, the latitude, height above the geoid, and the constant of the model (see Section 4.2). The uncertainty of both the height and the latitude of the site are essentially negligible such that the uncertainty of the ZHD is defined by:

$$\sigma_{\text{ZHD}} = \sqrt{\left(\frac{2.2767\sigma_{p_0}}{f(\lambda, H)}\right)^2 + \left(\frac{p_0\sigma_c}{f(\lambda, H)}\right)^2}, \tag{4.9}$$

where σ_{p_0} and σ_c are the one-sigma uncertainties of the surface pressure (p_0) and the constant in the derivation in ZHD (see Section 2.2). $f(\lambda, H)$ is defined in Eq. (2.2).

All GRUAN GNSS sites should be equipped with a barometer that provides accuracy better than $0.5\,\text{hPa}$. The uncertainty of these barometers will be assessed based on the protocols in Immler *et al.* (2010).

Uncertainty of the Conversion Factor Π

The uncertainty of the conversion factor, σ_Π (see Eq. 4.6), is sourced largely from the uncertainties in the estimation of T_m and the constants formula used for refractivity (see Section 2.2). While the uncertainties of the density of liquid water (p_w) and specific gas constant (R_w) for water vapour impact the uncertainty of Π, it is insignificant ($<0.1\,\%$ of the total uncertainty).

The uncertainty of the constants used in the formula of refractivity (${k_2}'$ and k_3) has been reported in Bevis *et al.* (1994) (see Table 5 on page 19). The value of ${k_2}'$ and k_3 was defined at the time and is changing as the atmosphere changes. New experimental work is awaited to update these values, however, the changes are expected to be small and will not drastically affect the uncertainty budget of GNSS-PW (Ning *et al.*, 2016b). Globally, T_m can be derived from NWP models. A Root Mean Squared (RMS) difference of $1.3\,\text{K}$ in T_m was claimed by (Wang *et al.*, 2005) based on global comparisons between the NCEP/NCAR reanalysis and the radiosonde measurements using 6 years of data. The authors also found a better agreement ($1.1\,\text{K}$) in T_m obtained from the ECMWF reanalysis product. There is normally a difference between the horizontal, vertical, and temporal resolution of the ECMWF data and the GNSS site, therefore an interpolation is necessary. Such an interpolation is described in Heise *et al.* (2009).

4.2 Reporting Measurement Uncertainty

Pressure and temperature uncertainties are taken as documented for the instruments used at the site, and the site is responsible for regular calibration by certified metrology services. If the site operator notices a problem with any of the pressure or temperature instruments, actions must be taken to handle the problem and GRUAN (LC + GFZ) must be informed as soon as possible.

The theoretical method (Section 4.1.2) will be implemented in GRUAN GNSS central data processing. Firstly, all GRUAN GNSS data will be processed by the GFZ using GFZs in-house GNSS software package, the Earth Parameter and Orbit determination System (EPOS) (Dick *et al.*, 1999, 2001; Gendt *et al.*, 2004), where only the PPP approach will be implemented in the data processing. The formal error, provided for each time epoch by the estimation process of PPP, is only dependent on the amount of carrier phase measurements and the constellation of the satellites for a given site (Byun, 2009). In order to take systematic measurement errors in the GNSS orbit into account, the method discussed in the paragraph on the uncertainties of ZTD (Section 4.1.2) will be applied and the calculated ZTD error for each time epoch will be added to the corresponding formal error. In order to reduce ZTD uncertainty due to the other factors discussed above, the conditions listed in Section 4.3 must be fulfilled in GNSS data processing. Secondly, the ZHD uncertainty is obtained using uncertainty of ground pressure, estimated using the method presented by Immler *et al.* (2010), and the uncertainty in the constant in Eq. (2.2). Thirdly, the uncertainty for the conversion factor Π is calculated using the uncertainties of the mean temperature, ${k_2}'$ and k_3 listed in Table 5. Finally, the total PW uncertainty for each data point is calculated using the uncertainties for the ZTD, the ZHD, and the conversion factor Π using Eq. (4.5). The final uncertainty for each data point will be distributed by the appropriate GRUAN data centre (GFZ).

4.3 Reducing Measurement and Operational Uncertainty

Greater than $75\,\%$ of the total PW error derives from the error in ZTD (Ning *et al.*, 2016b). Much of the ZTD error can be minimized through a series of operational procedures. In addition, errors arising from the uncertainty of surface meteorological instruments, while not the dominant source of error, are easy to minimize through operational procedures. The following procedures from Ning *et al.* (2016b) are the best method to reduce the total uncertainty of GNSS-PW data products:

- Corrections for the second order of the ionospheric delay must be applied.
- Final orbit/clock products from IGS or equivalent must be used.
- Absolute satellite and ground antenna PCV models and radome calibrations must be implemented.
- An ECCOSORB (http://www.eccosorb.com) high-loss microwave absorber plate is recommended.
- A radome is not recommended, however this is left at the discretion of the site operator as one may be required for operational reasons.
- Signal multi-path effects must be minimized either by implementing microwave absorbing material to the antenna, and/or by locating the GNSS antenna in a favourable place with excellent monumentation (see Sections 7.1.1 and 7.1.2).

- An elevation cut-off angle of $10°$ or higher must be used. A higher elevation cut-off angle will degrade the geometry and increase the formal error of the ZTD estimate. However, this may still be desired for applications where long-term trends are estimated and systematic measurement errors such as signal multi-path rather than formal errors are the limiting factor (Ning *et al.*, 2012).
- Increased accuracy of the site barometer will decrease the uncertainty associated with the estimate of ZHD.
- Change to the site must be managed (see Section 3.2) to minimize the introduction of systematic measurement errors.
- Routine calibration of surface meteorological instruments must be completed.

4.4 Validating Measurements

Measurements for each measurement system must be validated, either against duplicate measurement systems or through laboratory analysis (GCOS-171). As laboratory validations of GNSS-PW measurement techniques are not feasible, the GNSS-PW system will be validated against similar techniques measuring PW. The most likely candidate for GNSS-PW validation is the required daily radiosondes flights at each GRUAN Site. When using radiosondes as validation for the measurement, it is important to incorporate the known biases of radiosonde sensors and the added uncertainty from instrument co-location, as radiosondes may drift a few $100\,\mathrm{km}$ away from the launch point. Where present, validation with additional measurement systems (e.g., MWR) will help constrain uncertainties and biases of the GNSS-PW measurement system. Validations are done by collaborations of GFZ, Lead Centre, sites and the GRUAN community, and must take place at a minimum every year and be reported at GRUAN Implementation and Coordination Meeting (ICM). The GTT recommends that GFZ and Lead Centre set up automatic tools to display PWs from GNSS, radiosondes and other GRUAN instruments, and for routine data QA and validating PWs from redundant measurements. Then at end of year, statistics can be generated and reviewed by GTT.

5 Measurement Scheduling

Measurements of GNSS-PW are essentially a continuous measurement technique. Measurement scheduling therefore consists of sampling and data submission intervals. For scheduling the change of antennas or other instrumentation see Section 3.2. Both sampling and data submission intervals are prescribed in the GRUAN Guide (GCOS-171):

- The GNSS receivers at GRUAN sites shall track GNSS satellites with a sampling interval of $30\,\mathrm{s}$ or less.
- The minimum requirement for GNSS raw data submission is daily $(24\,\mathrm{h})$ files with a $30\,\mathrm{s}$ sampling interval.
- Surface meteorological observations shall be made at GNSS sites at intervals of no more than $60\,\mathrm{min}$. An observation interval of $10\,\mathrm{min}$ is preferred.
- An hourly sampling interval is required for GNSS tropospheric products and associated supplemental data, including ZTD, ZWD, precipitable water, surface pressure, and atmospheric water-vapour-weighted mean temperature.

6 Data Management

6.1 Data Flow

This chapter describes the data flow from GRUAN GNSS sites to the GNSS data processing and analysis centre, GRUAN Lead Centre and users, over the data distribution channels.

Raw GNSS data collected at the GRUAN sites is initially recorded in its proprietary binary format at the site's local servers file system (or database). As a next step it is transferred via FTP to the GRUAN GNSS Data Processing Centre (Figure 2). Raw GNSS data is sent together with its accompanying site meteorological data and metadata. Site surface meteorological data (surface pressure and temperature) are collected/recorded from Automatic Weather Stations installed together with the GNSS receiver or interpolated from the nearest possible meteorological stations (preferably in radius up to $50\,\mathrm{km}$). Each site collects and sends meteorological data from the site.

Site metadata consists of site IGS-style log files and any additional supporting information describing the conditions of measurements at the site according to this technical document (GRUAN-TD6). Further information on IGS style log files can be found at https://kb.igs.org/hc/en-us/articles/203402393-IGS-Site-Log-Manager-User-Guide.

The data (GNSS data binaries, site meteorological data and metadata) are archived, pre-processed (including format conversion if necessary), processed and quality-checked at the GRUAN GNSS Data Processing Centre (GFZ). Due to practical reasons, raw GNSS data is not directly sent to GRUAN Lead Centre, but to the GFZ (i.e., for GNSS the data processing/-analysing institution acts also as a collector of the data from the sites).

After processing, the GRUAN GNSS data product, accompanied by its raw and converted data and metadata, is sent to GRUAN Lead Centre for archiving (backup) and storing in the database of GRUAN GNSS products.

The GRUAN Lead Centre also supports monitoring of the data (and data flow), generates statistics and keeps the reports.

GRUAN Lead Centre is the only party that delivers GRUAN products to the end user.

6.2 Centralized Data Processing

The German Research Centre for Geosciences (GFZ) in Potsdam, Germany is the GRUAN GNSS-PW centralized data processing centre. Operational GNSS data processing for GRUAN at GFZ is performed in NRT. GRUAN GNSS Data Product (GDP) is a result of post-processing.

There are a number of software packages used to calculate ZTD. The most widely used commercial GNSS data processing package is `Bernese` (http://www.bernese.unibe.ch), which can handle both the Double Difference (DD) and PPP methods of calculating the GNSS antenna position. There are a number of free of charge GNSS software packages typically used for research: GIPSY/OASIS,GAMIT/GLOBK, and RTKLIB. GIPSY/OASIS is often preferred because of its better computational efficiency associated with the PPP method, which also helps avoid error propagation from malfunctioning or poorly functioning sites/stations within the net-

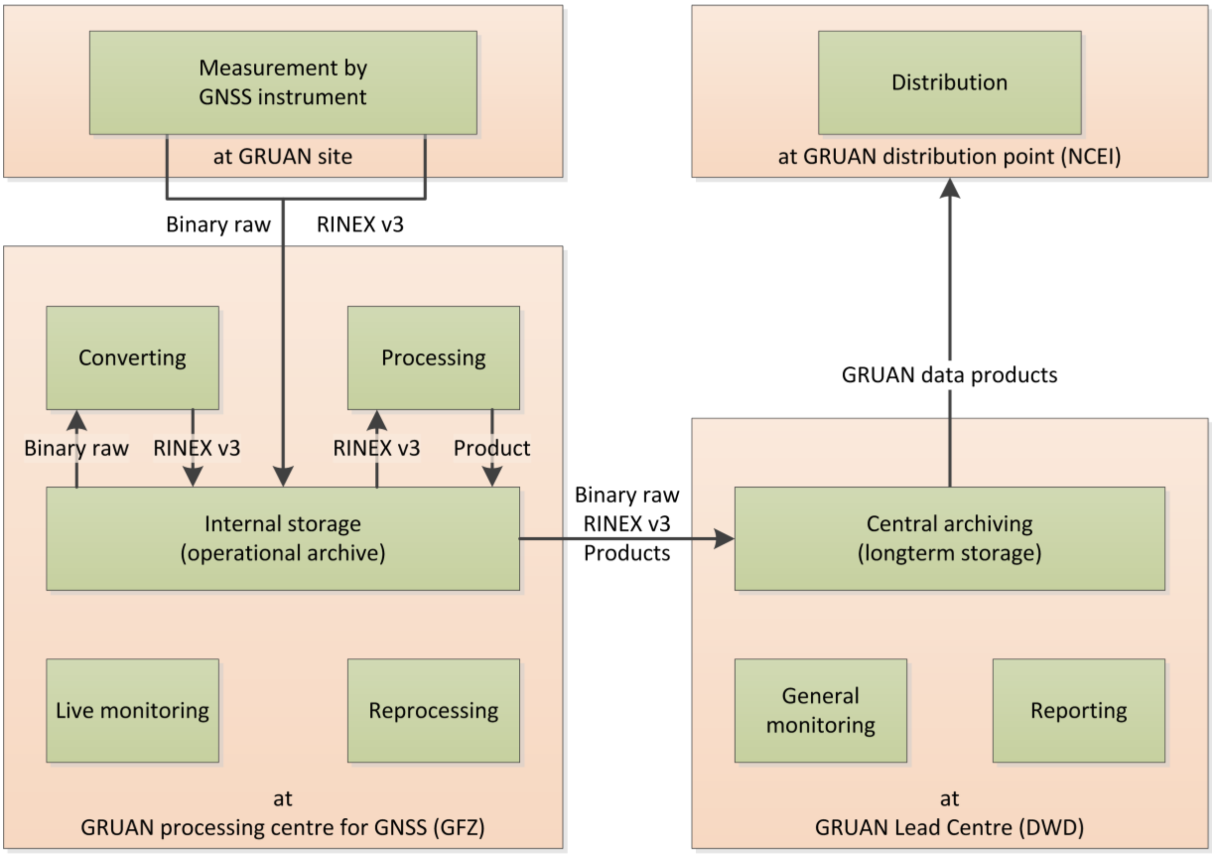

Figure 2: GNSS Data Flow.

work. GAMIT/GLOBK does not support PPP, and thus uses only DD. The three abovementioned software packages are used by a number of GNSS analysis centres (COST Action 716 Final Report). It is beyond the scope of this document to provide a full assessment of each package but further information about data processing software can be found from IGS-TECH.

GNSS data processing at GFZ is based on GFZ EPOS8 software, which is based on least squares adjustment using a sliding window approach and makes use of the IERS standards. Operational GPS data processing at GFZ is performed in PPP mode and provides all tropospherical products: the Zenith Tropospheric Delay (ZTD), the Integrated Water Vapour (IWV), the Slant Total Delay (STD), and tropospheric gradients in near-real time and in post-processing.

PPP strategy is chosen because of its advantages. One of the main advantages is the possibility of investigations of site-dependent effects, because the sites are processed independently.

PPP strategy:

The main idea of the PPP strategy is the processing of each site separately, fixing the high quality GPS orbits and clocks. The NRT processing is split into two steps:

1) "Base cluster" analysis: estimation of high quality GPS orbits and clocks from a global network (using approximately 100 IGS sites), where an orbit relaxation starting with the Ultra Rapid GFZ predictions is performed. Among the estimated parameters for the "base cluster" step are (1) GPS orbits with predicted Ultra Rapid orbits from GFZ used

as initials, (2) Satellite clocks, and (3) ZTDs for 4 h intervals.

2) PPP analysis: estimation of ZTDs/IWV/STD using parallel processing of stations in clusters with PPP based on fixed orbits and clocks from Step 1): (1) the ZTDs are adjusted with a resolution of 15 min; and (2) tropospheric east and north gradients with hourly resolution.

The GFZ final orbits and clocks are used to get the best possible absolute accuracy of ZTDs for GRUAN GNSS products. Using the orbits and clocks produced with the same software and with high accuracy guarantees the most consistent results in PPP analysis. For this reason GFZ uses GFZ final orbits and clocks (and not IGS finals) in PPP processing.

The main characteristics of GFZ EPOS8 software processing include:

1) Use of sliding 24 h data window.
2) Elevation cut-off angle: 7° (10° for GRUAN data processing).
3) Sampling rate of observations is 30 s and for data processing 150 s.
4) Reference frame:
   - Earth rotation parameters: GFZ GPS solution/prediction.
   - The station coordinates are held fixed, once determined with sufficient accuracy within ITRF.

GRUAN GNSS-PW data products will be provided to users in the COST716 and SINEX_TRO formats. NetCDF is planned for the future. Links to the technical descriptions of these formats can be found at ftp://ftp.gfz-potsdam.de/pub/GNSS/products/nrttrop/FORMATS/.

6.3 Data Quality Assurance and Control (QA/QC)

The GRUAN quality management policy is to achieve a level of data quality that allows the primary goals of GRUAN to be met for all potential users of GRUAN data products. Quality assurance (implementing systems to ensure quality), and quality control (monitoring the results to ensure that the systems implemented are adequate to the task), are both required at all stages of GRUAN GNSS-PW data production. Because GRUAN GNSS-PW data products are intended to be used for long-term trend detection, quality assurance and control are further extended to data re-processing and to the management of long-term consistency and stability.

QA and QC of the GRUAN GNSS-PW data product will be achieved through routine yearly maintenance, regular calibration of the surface meteorological instruments, and through frequent inter-comparisons with independent techniques. These actions are presented in the standard operating procedures detailed in Section 7.2.

To ensure good data quality for GNSS-PW, we need to perform both "on site" (hardware) and "data processing" quality assurance. For "on site" practice it is recommended not to touch a well-performing system, with no interactions without clear technical reasons. However, regular monitoring and maintenance are recommended (see Section 7.2). Major GNSS receiver updates should be installed if available, and those changes must be reflected in the site logs. Whenever the visibility of the sky is restricted (e.g., erection of new buildings near the antenna), this should also be mentioned in the site logs. While processing the data a routine quality check using teqc (https://www.unavco.org/software/data-processing/teqc/teqc.html) is recommended and is already performed at GFZ central processing facilities. Significant changes of data quality indicators (overall availability, latency, multi-path indicators) should be reported.

6.4 Data Archiving and Distribution

The GRUAN products are available both in EGVAP-II NetCDF and SINEX_TRO formats and can be accessed on the GFZ ftp-server by following the instructions below. All products are also delivered to the GRUAN LC in Lindenberg.

- server: ftp.gfz-potsdam.de
- user: anonymous
- for ZTD/IWV in COST716 format:

```
cd "/GNSS/products/nrttrop/product_COST_GRUAN_EPOS8/y****/m**"
```

- for ZTD/IWV in SINEX_TRO format, sorted by GPS weeks:

```
cd "/GNSS/products/nrttrop/sinex_trop_GRUAN_EPOS8/w****"
```

As of March 2019 the following GRUAN sites are included in operational processing at GFZ:

- Lindenberg (LDB0, LDB2),
- Ny-Alesund (NYA2),
- Payerne (PAYE),
- Sodankyla* (SODF),
- Lauder (LDRZ),
- Lamont* (SGPO),
- Barrow (UTQI).

*GNSS data processing is operational, but meteorological data is still missing for calculating GNSS-PW.

6.5 Data Policy

The GRUAN data policy is available on https://www.gruan.org/data/data-policy/. It applies to all GRUAN GNSS-PW data products.

7 Site Assessment and Certification

7.1 Criteria

7.1.1 Strictly required characteristics

The GNSS equipment and its surroundings (up to a radius of $\sim 100\,\mathrm{m}$), must not be disturbed or changed unless a clear benefit from the change under consideration outweighs the potential for discontinuities in the time series. Obvious examples include replacing failed equipment, a planned replacement of obsolete equipment, clearance of encroaching vegetation, and the routine installation of vendor-recommended firmware updates. All changes should follow the guidelines detailed in Section 3.2 "Managing Change". The following requirements are for geodesy use and adopted from the "IGS site guidelines" (IGS-GL). They might be revised in the future based on GRUAN specific analyses by the GTT specifically to meet GRUAN needs.

(1) **GNSS receiver requirements**
In general, the requirements specified below are typical equipment and operating characteristics of geodetic quality GNSS sites.

a) The receiver must track both code and phase on L1 and L2 under non-AS (anti-spoofing) as well as AS conditions (Hofmann-Wellenhof *et al.*, 1992). Required observables are L1, L2, P2, and at least one of C1 or P1. Equipment capable of reporting both C1 and P1 should do so. A full description of GNSS observables can found through the RINEX data format specification (see Table A1 on IGSCB-R210).
b) The receiver must be capable of, and set to, record data simultaneously from at least 8 satellites in view.
c) The receiver must track with a sampling interval of $30\,\mathrm{s}$ or smaller.
d) The receiver should be configured (suggested by IGS) with an elevation mask of $0°$.
e) Synchronize the actual instant of observation with true GNSS time to within $1\,\mathrm{ms}$ of the full second epoch.

(2) **GNSS antenna requirements**

a) Have well-defined phase (and gain) pattern to allow mixing with other standard antennas with negligible errors. The antenna phase centre variation should be reproducible, with absolute phase centre repeatability of $0.5\,\mathrm{mm}$ in the horizontal and $1\,\mathrm{mm}$ in the vertical. The antenna type should be approved by the IGS antenna working group and have its phase centre variation calibrated and available following IGS guidelines (see IGSCB-AR and IGSCB-08).
b) Be levelled and oriented to True North using the North reference mark and/or antenna cable connector.
c) Be rigidly attached, such that there is not more than $0.1\,\mathrm{mm}$ motion with respect to the antenna mounting point under all circumstances.
d) The eccentricities (easting, northing, height) from the primary station marker to the antenna reference point (defined for the antenna type in IGSCB-A) must be surveyed and reported in site logs and RINEX headers to $1\,\mathrm{mm}$ accuracy. Each eccentricity component must be less than $5\,\mathrm{m}$.

e) When antenna changes are planned, operate both the new and old antennas at the same time first (if an additional monument and receiver are available), and announce to the Lead Centre how users may get the test data set. Such changes have to follow the guidelines from Section 3.2.

(3) **Antenna radome requirements**

a) The use of radomes should be avoided unless required operationally, for instance due to weather conditions, antenna security or wildlife concerns.
b) Non-hemispherical radomes especially must be avoided when the shape is not required by site characteristics (e.g., for snow rejection).
c) If a radome must be used, the antenna and radome pair used must be documented in the IGS phase centre variation file (see IGSCB-08), with zenith- and azimuth-dependent calibration values down to the horizon. If it is not, contact the GRUAN Lead Centre. An absolute calibration from an independent recognized laboratory is required (see IGSCB-AR).
d) If you remove an uncalibrated antenna and radome pair, please make it available to a calibration laboratory for calibration. Contact the GRUAN Lead Centre for assistance.
e) Only radomes directly connected to the antenna are allowed.

(4) **Surface meteorological instrument requirements**

a) The minimum set of observables is pressure and temperature.
b) Pressure sensor accuracy must be at least $0.5\,\mathrm{hPa}$.
c) Temperature sensor accuracy must be at least $0.1\,\mathrm{K}$.
d) Instrument drift and bias must be minimized through routine calibration as specified in the manufacturer's recommendations and any supplementary GRUAN procedures.
e) Temperature effects on the pressure measurements should be minimized, e.g., with solar shielding or by placing the sensor in a nearby building if necessary.
f) Data are to be prepared in RINEX files. See the RINEX specification (IGSCB-R210).
g) Observation interval must be no more than $60\,\mathrm{min}$.
h) Meteorological data is to be transmitted with the same schedule and method as the RINEX observation files (hourly for hourly sites; otherwise daily).
i) The height difference between the surface pressure sensor and the GPS antenna must be measured with an accuracy of $1\,\mathrm{m}$ or better.

(5) **Required data reporting characteristics**

a) The agency operating the station will archive the raw (native binary) GNSS data, or arrange for this archiving to be undertaken at GFZ and the Lead Centre.
b) GNSS data (observations and broadcast ephemeris) are to be prepared and distributed in the RINEX format, version 2.11 or greater, as specified in IGSCB-R210 or IGSCB-R2, IGSCB-R3.

c) Observation files will normally be exchanged in the Hatanaka Compact format. See the RINEX specification IGSCB-R210 and confirm with GRUAN Lead Centre.
d) All files are ordinarily Unix compressed (“*.Z”).
e) File naming conventions set forth in the RINEX specification IGSCB-R210, Section 4, “The Exchange of RINEX files”, will be followed.
f) The RINEX header information, especially the 4-character site ID, receiver and antenna information, and antenna eccentricities, must be up-to-date and strictly follow the agreed-upon conventions.
g) Specifically, they must match the information in the GRUAN GNSS-PW site log and therefore observe the same equipment naming conventions found in IGSCB-RA.
h) A radome identifier code from IGSCB-RA must be found in the ANT TYPE field, in columns 17 to 20 of this field.
i) The RINEX headers must be updated to reflect actual times of all equipment changes.
j) If an advisory of RINEX header inconsistencies is received from the GRUAN Lead Centre, the headers must be corrected as soon as possible.
k) The minimum requirement for data submission is daily ($24\,\mathrm{h}$) files with a $30\,\mathrm{s}$ sampling interval.
l) Metadata correctness for daily ($24\,\mathrm{h}$) data files must be verified prior to transmission to the GRUAN Lead Centre. This includes verification of site name, observation types, time of first epoch, epoch interval, equipment types, as well as station and antenna eccentricities.

(6) **Required site log characteristics**

a) Whenever there is a change to the site information as documented in the station log, the log must be updated. Refer to Appendix B for detailed site log preparation instructions.
b) Include the URL to a web page for the site, if one exists. Contact the GRUAN Lead Centre if you have site photos that cannot be made available on a web page.
c) Site photos should include a panorama photograph of the entire site (see an example given in Fig. 3) and instrument photos (receivers, antennas, radomes, surface met sensors and other relevant instruments).
d) Updates must be sent to the GRUAN Lead Centre within one business day of any change. If an advisory of site log inconsistencies are received from the GRUAN Lead Centre, the site log must be corrected as soon as possible.

(7) **Additional requirements for GRUAN GNSS-PW sites with GPS/GLONASS receivers**

a) The receiver must tag observations in GNSS time (not UTC or GLONASS), and time tags for all satellites must be identical (simultaneous observations).
b) Data must be submitted in M(MIXED) RINEX files. See the RINEX specification at IGSCB-R210.

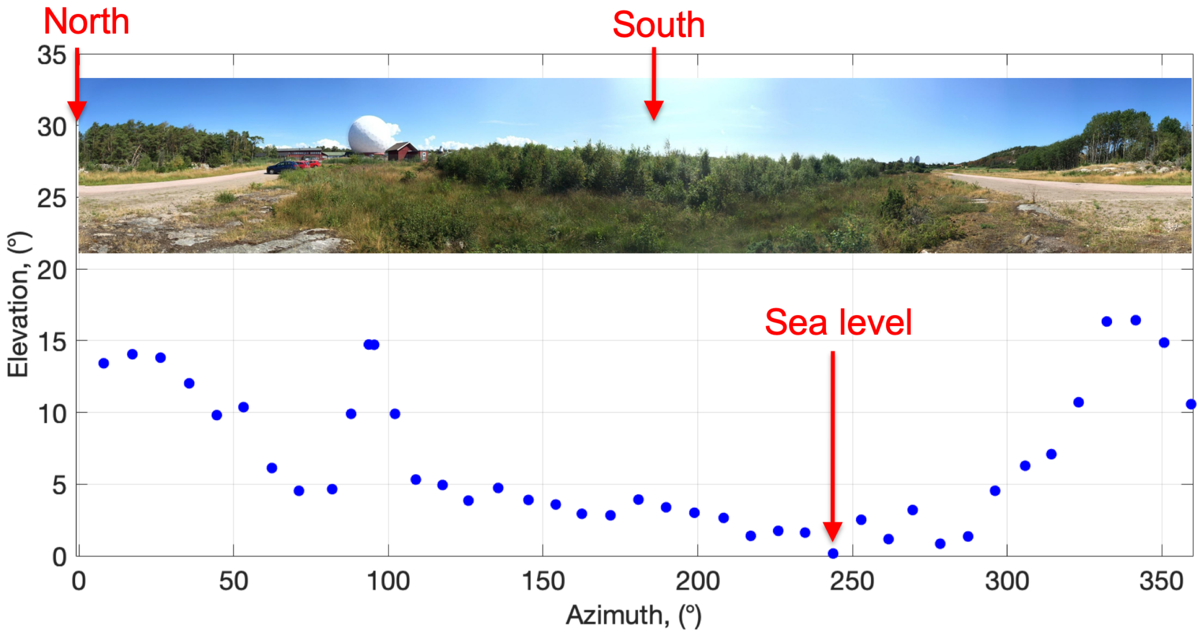

Figure 3: A panorama photography of the new Onsala site with elevation information shown in the lower panel. Photos courtesy of Gunnar Elgered.

7.1.2 Optional, but desired characteristics

While not being strict requirements for each GRUAN GNSS-PW site, detailed care regarding the physical and equipment characteristics of a site improves its overall value as a long-term monitoring location. The following specifications should be considered for both the planning of new sites and the long-term improvement of existing sites. Agencies are encouraged to select potential new sites that have the majority of these features, and work toward these characteristics at existing sites.

(1) **Desired equipment characteristics**

a) Receiver should support "all-in-view" tracking.
b) The receiver tracking cut-off should be set to zero. The elevation of satellites actually processed however is dictated in the GNSS processing setup. For GRUAN data processing the elevation cut-off angle is $10°$.
c) GNSS receivers and ideally other station equipment such as computers should be protected against power failures by providing surge protection and backup power wherever feasible.
d) Antenna types which are already present in the GRUAN GNSS-PW network in reasonable numbers are generally preferred over novel types (a list of acceptable antenna types can be found in IGSCB-08).
e) Radomes uniformly manufactured with less than $1\,\mathrm{mm}$ variability in thickness are preferred.
f) Support for Multi-GNSS observations is desirable.
g) Equipment never used before in the GRUAN GNSS-PW should be avoided until tested and approved by the GRUAN Lead Centre. The Lead Centre should be imme-

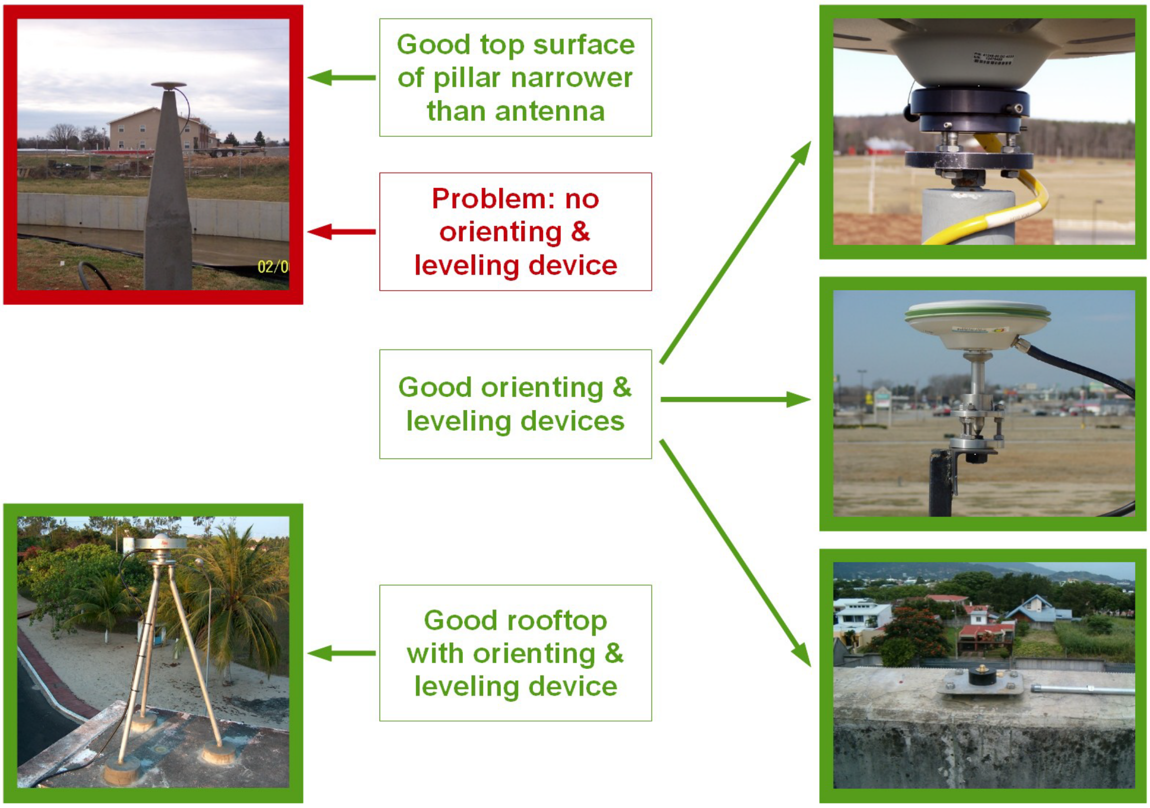

Figure 4: Example of 'good' and bad 'GNSS' sites. Pictures courtesy of NGS (Giovanni Sella)

diately informed of instances where new equipment (receiver or antenna and radome combination) is used that are not contained in IGSCB-RA. Situations where unapproved equipment is used should only occur when a parallel site (within $100\,\mathrm{m}$) operates with an approved equipment configuration.

h) Test data sets, and analysis of test data, will be helpful. Inform the GRUAN Lead Centre whether these will be available.

i) The antenna reference point ideally will be mounted directly vertically above the marker (i.e., horizontal eccentricities ideally are zero).

(2) **Desired characteristics of site location**

a) The site should be on a stable regional crustal block, away from active faults or other sources of deformation, such as subsidence. Contact the GRUAN Lead Centre for assistance in determining the stability of a particular area if it is not clear.

b) The site should be on firm, stable material, preferably a bedrock outcrop. The site should not be located on soil that might slump, slide, heave, or vary in elevation (e.g., because of subsurface liquid variations).

c) The site should have a clear horizon with minimal obstructions above $5°$ elevation.

d) The site should not have significant changes to the surroundings (for example changes to buildings or trees; new construction), foreseen or likely.

e) The site should not have excessive radio frequency interference.

f) The site should not have excessive radio frequency reflective surfaces (e.g., fences, walls) and other sources of signal multipath. See Teunissen and Montenbruck (2017) for more information concerning site multi-path.

g) The site should not have excessive natural or man-made surface vibrations from, for instance, ocean waves or heavy vehicular traffic.

(3) **Desired characteristics of monument**

a) The monument should be of ultra-stable design. See IGSCB-M for additional information. See Fig. 4 for examples of sites with good and bad monumentation.

b) The monument should be isolated from unstable surface material (e.g., freezing/melting cycles in cold climates) and extend into stable subsurface formation.

c) The monument should remain durable, maintainable, accessible, and well-documented.

(4) **Desired station infrastructure**

a) The station should have reliable power and communications (preferably Internet) to enable consistent data transfer.

b) The station should have appropriate security to ensure uninterrupted operation and prevent vandalism.

(5) **Desired surface meteorological instrumentation characteristics**

a) An observation interval of $10\,\mathrm{min}$ or less is preferred.

b) Calibration, operation, and uncertainty assessment for temperature and pressure sensors adheres to GRUAN guidelines for temperature and pressure measurement.

c) Regular water vapour profiling measurements are made with a measurement system (sonde or remote-sensed), operating according to GRUAN recommendations and located within a distance which makes sense climatologically to ensure a meaningful collocation for inter-comparison.

(6) **Other desirable instrumentation**

a) Other geophysical systems (such as SLR, VLBI, DORIS, absolute or superconducting gravimeters, Earth tide gravimeters, seismometers, strain meters, ocean tide gauges) are also desirable and will enhance the value of the station for multi-disciplinary studies.

b) Co-location with scientific systems that rely on accurate positioning, such as timing labs, is recommended when feasible.

7.2 Standard Operating Procedures

All GRUAN GNSS-PW sites must be adequately maintained and upgraded. As mentioned in Section 6.3:

> Quality assurance (QA) and quality control (QC) of the GRUAN GNSS-PW data product will be achieved through routine yearly maintenance, regular calibration of the surface meteorological instruments, and through frequent inter-comparisons with independent techniques.

Software-based QC and regular hardware monitoring/maintenance

Software-based QC is regularly performed by the operators at the central GNSS data processing centre. Expecting that several hardware-related problems can be detected remotely (software-based observational data analysis) by experienced technical personnel, it is necessary to have good communication between the data processing centre and site operators (for example, in a case of sudden and remarkable change noticed in signal/noise ratio, the antenna cleanliness should be checked). Usually, each site belongs to some national or larger network and each network has its own practices for maintaining/monitoring the sites (including firmware and hardware changes). The operating agency shall take responsibility for GNSS-PW instruments operated at the GRUAN site. The following procedures are required:

a) The operating agency must always have the capability to repair, upgrade and maintain the station and its software systems, including if the original technical staff are no longer available. However, because all maintenance of an instrument can also introduce discontinuities and systematic measurement errors in measurement series, maintenance shall not be conducted more frequently than is necessary.

b) Maintenance schedules must be developed for all instruments and all maintenance actions shall be documented as part of the metadata of that instrument.

c) Maintain an accurate calibration for the station antenna, antenna and radome pair, if using a radome, and for all surface meteorological instrumentation relating to the GNSS-PW data product.

d) Ensure that the GNSS equipment, and its surroundings, is not disturbed or changed unless a clear benefit outweighs the potential for discontinuities in the time series. Examples include: equipment failure, planned upgrade of obsolete equipment or vendor-recommended firmware updates.

e) Regularly check the antenna/radome for cleanliness and remove any environmental contamination (e.g., bird droppings, snow, ice, algae, guano, etc.) if necessary.

f) Check the monument, fixings and antenna position with respect to the site marker and antenna tilt (recommended during rainy days only, to avoid any changes due to thermal expansion of metal constructions due to the sun).

g) Check the antenna cable (isolation, connection and moisture).

h) Archive the stations data (preferably in its native format) in case it is needed for data recovery or engineering purposes.

i) Download raw data from the receivers of the local network.

j) Perform a data quality check on the data using a utility such as TEQC, on a station-by-station basis (https://www.unavco.org/software/data-processing/teqc/teqc.html).

k) Take appropriate action if the station performance degrades. E.g., alert/engage onsite staff.

l) Ensure full responsibility for reliable data handling and transmission to GFZ and Lead Centre.

7.3 Criteria for Assessing Added Value

The criteria for assessing added value of a site is defined in Section 5.4 of the GRUAN-Guide (GCOS-171). The added value of a site must be considered in the context of the geographical co-location of similar measurements. For instance, all things being equal, a site which conducts GNSS-PW measurements in an area of the globe with relatively few similar measurements will be of considerably more added value to GRUAN than a site which is closely co-located to another GRUAN site. In addition, sampling in regions of atmospheric phenomena which are not currently sampled adds considerable value to the prospective site. Specifically, the addition of a GNSS-PW measurement system creates several added values for a potential GRUAN Site. It provides an additional measurement of the priority one variable, water vapour. The GNSS-PW measurement is particularly valuable as it fulfils both the minimum requirement of greater than 2 measures of PW per day and the fully operational requirement of hourly observations of PW. Meeting these requirements is a significant portion of the minimum requirements for the inclusion in GRUAN (see Section 5 of GCOS-171). GNSS-PW also adds value by allowing frequent inter-comparisons with other instruments capable of measuring PW. Finally, a site which is seeking entrance into GRUAN that currently operates a GNSS-PW measurement system may have an existing series of historical measurements which adds greater value to GRUAN than sites which do not have such a record. To fulfil this added value, detailed documentation of the measurement system (e.g., standard operating procedures, calibration history, changes to instrumentation) must be available.

7.4 Auditing

Auditing of the GNSS-PW measurement systems shall occur every 3 to 4 years. Auditing can entail a review of annual reports, a written report from the site, and/or a visit by selected members of the WG-GRUAN and the GRUAN Lead Centre. For a description of the GRUAN Site auditing process see Section 5.6 in GCOS-171. An audit must ensure that the site is meeting the minimum requirements for inclusion in GRUAN detailed in Sections 7.1.1 and 7.1.2. Where the site is deviating from standard operational procedure, the nature, extent and duration of the deviation must be documented. Such deviations must be justified or corrected at the discretion of the GRUAN Lead Centre. During such an audit all changes made to the stations must also be documented unless they have been previously documented in the appropriate fashion.

Appendix

A Guidelines for New GRUAN GNSS-PW Sites

Agencies proposing new GRUAN GNSS-PW sites, and existing GRUAN participants that are installing new GNSS equipment, should follow these instructions when proposing that a new station be considered as a GRUAN GNSS-PW site. The proposing agency should carefully review the guidelines in Section 7 to determine the suitability of the location as a potential GRUAN GNSS-PW site.

A.1 Qualification

- Carefully review the GRUAN GNSS-PW Site Guidelines detailed in Section 7.
- The responsible agency must have every expectation that the station will operate for at least 3 years.
- Confirm that the proposed station meets the requirements and adds value to the GRUAN GNSS-PW network.

A.2 Questions for New GRUAN GNSS-PW Sites

Contact the GRUAN Lead Centre (email to gruan.lc@dwd.de) with a message addressing the following questions and additional ones listed in the "GRUAN site assessment and certification" document (Bodeker, 2016).

- Where is the station located?
- Is the station currently operating, or planned? If planned, when will it become operational? Does it operate additional equipment? Is this equipment already GRUAN certified? If not, is it planned to incorporate these measures into GRUAN also?
- What agencies are responsible for installing, managing, operating, and maintaining the station?
- Is there a GRUAN quality upper air sounding station within a reasonable distance of the GRUAN GNSS-PW site? Are there any studies on PW comparisons between radiosonde and GNSS data to quantify the influence of spatial separation between the radiosonde and GRUAN GNSS-PW site?
- What is the expected operational lifetime of the station? How secure is the funding?
- Will the station replace an existing GRUAN GNSS-PW station? If so, what is the scheduled date of decommissioning? Does the new station offer more capability than the old one? Will there be an overlap period and analysis undertaken?
- Does/will the station meet all of the strictly required GRUAN GNSS-PW site guidelines specified in Sections 2 and 3 of this document?
- What is the data delivery schedule?

- Can the receiver be configured to operate in an "all-in-view" tracking mode (including tracking of satellites flagged as unhealthy)?
- What GRUAN GNSS-PW product or project will this site benefit, based on its location, instrumentation, and latency?
- Is there a web page associated with this site (please specify)? If not, please include a site photo or two with this application, including a 360° panorama picture.
- Is data available on a public server (please specify)? Does data also contribute to other networks, and if so which?
- Please complete and include a draft site log according to the instructions given in Appendix B.
- The proposed unique four-character identifier should also be included, but it remains proposed until confirmed by the GRUAN Lead Centre and the IGS. Allowed characters are A–Z and 1–9 (numerals may not be used in the first character).
- A new four-character ID is required if a site is moved to a new monument. The four-character ID has a one-to-one relationship with a monument, except in the case that more than one receiver records data from one antenna.
- A unique DOMES number should be applied for from the ITRF (http://itrf.ign.fr/domes_request.php). More information can be found here: http://itrf.ign.fr/domes_desc.php.

A.3 Technical Iterations of Documentation

Following technical iterations of documentation with the Lead Centre the WG-GRUAN will be notified of the proposal as outlined in the site assessment and certification documentation. IGS style log files should be created and kept up-to-date for all GRUAN GNSS sites when possible. Log files contain metadata concerning site information, station operator as well as GNSS antenna and receiver history. An example log file can be found in Appendix B. Instructions for filling out IGS style log files can be found at ftp://igscb.jpl.nasa.gov/pub/station/general/sitelog_instr.txt.

A.4 Additional Questions

If the site requested is certified to be added by the WG-GRUAN, you will be asked to:

- Contact the GRUAN Lead Centre to confirm that they can accept the data and learn about the transfer mechanisms.
- Revise the site log, if necessary. Logs should then be sent to the GRUAN Lead Centre as plain ASCII text. Notify the GRUAN Lead Centre where a recent RINEX file may be downloaded, or include a sample RINEX header (**header only**) in the email to the GRUAN Lead Centre.
- When the site log becomes available, the GRUAN Lead Centre will announce the station to the GRUAN community and the data will be added to the GRUAN data stream served through National Centers for Environmental Information (NCEI).

B Instructions for Completing GRUAN GNSS Site Logs

These instructions are modelled after IGS site log instruction (IGSCB-SL). Modifications will be made to this instruction in order to be specialized to GRUAN GNSS sites in the future after some of GRUAN unique practices are established. You can find a blank log form at IGSCB-SLB and an example at IGSCB-SLE. A practical on-line tool – the IGS Site Log Manager SLM – can be used for validation of new log files. The SLM is a web based online application designed for the purpose of managing the meta data of IGS GNSS ground based sites. The site log file for Lindenberg (LDB2) can be found at the end of this section.

Web link for SLM:
https://slm.igs.org/login.php.

Instructions for using:
https://kb.igs.org/hc/en-us/articles/203402393-IGS-Site-Log-Manager-User-Guide.

B.1 General

B.1.1 Format and line length

- Prepare site logs in plain ASCII
- Line length is limited to 80 characters
- Date and time
  - Date and time formats within the site log follow the basic format from ISO 8061: "CCYY-MM-DDThh:mmZ"

CC	century (e.g., 20); 2 digit
YY	year (00-99); 2 digit
MM	month (01-12); 2 digit
DD	day of month (01-31; depending on month)
T	date/time separator
hh	hour (00–23); 2 digit
mm	minutes of hour (00–59); 2 digit
Z	UTC indicator
/	separator when begin and end times are given

  - A date without a time is specified thus: "2003-07-30", not "2003-07-30Thh:mmZ"
- Latitude/Longitude
  - Latitude/Longitude formats are aligned to ISO 6709:

Lat	±DDMMSS.SS
Long	±DDDMMSS.SS

  - A '+' or '−' sign is required. Leading zeroes must be used as appropriate to maintain the DDMMSS and DDDMMSS format. Valid latitude range is from −180° to (infinitesimally less than) +180°. Valid longitude range is −90° to +90°.
- "etc"

  - "etc" indicates you may enter any relevant answer, not just a choice of the suggestions shown.
- FORTRAN-style format
  - "F7.4", "A4" and so on indicate the FORTRAN-style format which the response should have. Example:

F7.1	12345.7
A4	ABCD

  - Blocks which have a "N.x" definition (namely sections 3-10) should always have the complete historic set of information; when a change is made, the previous information is left (for example in section 3.1) and the new information is placed in a new block numbered 3.2. Please leave the .x sections uncompleted to remind yourself of the format when the next change occurs. Please remove the response hints such as "(F7.4 N/S)" as you fill out the log (except in the .x sections and Date Removed fields for currently installed equipment, which you will not alter).
  - If an answer for an optional field is unknown, try to learn the answer for the next log update.

B.1.2 Submission of site logs

When ready, submit site logs by sending as a plain text email message to GRUAN Lead Centre (email to gruan.lc@dwd.de). Site logs are usually handled by the GRUAN Lead Centre within approximately one business day.

B.1.3 Questions

If you have any questions not answered here, please feel free to contact the GRUAN Lead Centre at gruan.lc@dwd.de).

B.2 Form

B.2.1 Previous Site Log

: (ssss_CCYYMMDD.log)

An overview of existing log files at the GRUAN Lead Centre archive can be found at https://www.gruan.org/data/metadata/gnss-site-log-files/. Files can be downloaded according to the following link scheme:

https://www.gruan.org/gruan/downloads/gnss-site-logs/ssss_CCYYMMDD.log

with 'ssss' the 4-character site name.

B.2.2 Modified/Added Sections

: (n.n.n.n, ...)

Enter the sections which have changed from the previous version of the log.

B.3 Site Identification of the GNSS Monument (1.)

B.3.1 Monument Description

: (PILLAR/BRASS PLATE/STEEL MAST/FICTIVE/etc)

Enter one or more elements as necessary to describe the monument.

B.3.2 Additional Information

: (multiple lines)

Suggestions are electrical isolation.

B.4 Site Location Information (2.)

Approximate Position (ITRF) should be given to a precision of one-meter (`F7.1`) at a minimum. The elevation may be given to more decimal places than `F7.1` with a maximum of `F7.4`. `F7.1` is a minimum for the SINEX format.

B.5 GNSS Receiver Information (3.)

B.5.1 Receiver Type

: (A20, from rcvr_ant.tab; see instructions)

Please find your receiver in file *"rcvr_ant.tab"* (IGSCB-RA) and use the official name, taking care to get capital letters, hyphens, etc. exactly correct. If you do not find a listing for your receiver, please notify the GRUAN Lead Centre at gruan.lc@dwd.de.

B.5.2 Serial Number

: (A20)

Keep the 5 significant characters of the serial number field in SINEX in mind: do not enter "`S/N 12345`" instead of "`12345`" since valuable information will be lost.

B.5.3 Firmware Version

: (A11)

Keep the 11 significant characters of the field in SINEX in mind.

B.5.4 Elevation Cut-off Setting

: (deg)

Please respond with the tracking cut-off as set in the receiver, regardless of terrain or obstructions in the area.

B.5.5 Temperature Stabilize.

: (none or tolerance in degree Celsius)

This refers to the temperature of the room in which the receiver is housed.

B.5.6 Date Removed

: (`CCYY-MM-DDThh:mmZ`)

In the block for the receiver currently in operation, leave this line as is to remind yourself of the format when the next receiver change is made.

B.6 GNSS Antenna Information (4.)

B.6.1 Antenna Type

: (A20 from "*rcvr_ant.tab*"; see instructions)

Please find your antenna in file *"rcvr_ant.tab"* (IGSCB-RA) and use the official name, taking care to get capital letters, hyphens, etc. exactly correct. If you do not find a listing for your antenna, please notify the GRUAN Lead Centre at gruan.lc@dwd.de. Please do not use antenna names from a "Previously valid" section. Choose the corresponding new antenna name instead. The radome code from IGSCB-RA must be indicated in columns 17-20 of the Antenna Type, use "`NONE`" if no radome is installed. The antenna+radome pair must have an entry in IGSCB-05 with zenith- and azimuth-dependent calibration values down to the horizon. If not, notify the GRUAN Lead Centre at gruan.lc@dwd.de.

B.6.2 Serial Number

: (A20)

Keep the 5 significant characters of the serial number field in SINEX in mind: do not enter "`S/N 12345`" instead of "`12345`" since valuable information will be lost.

B.6.3 Antenna Reference Point

: (BPA/BCR/XXX from *"antenna.gra"*; see instructions)

Locate your antenna in the file *"antenna.gra"* (see IGSCB-A). Indicate the three-letter abbreviation for the point which is indicated equivalent to ARP for your antenna. Contact the GRUAN Lead Centre at gruan.lc@dwd.de if your antenna does not appear.

B.6.4 Marker → ARP Up Ecc (m)

: (`F8.4`)

This is the antenna height measured to an accuracy of 1 mm and defined as the vertical distance of the ARP from the marker described in Section 4.1 in the site log file (example in Appendix B.12).

B.6.5 Marker → ARP North Ecc (m)

: (F8.4)

B.6.6 Marker → ARP East Ecc (m)

: (F8.4)

These must be filled in if non-zero.

B.6.7 Alignment from True North

: (deg; "+" is clockwise/east)

The positive direction is clockwise, so that due east would be equivalent to a response of "+90".

B.6.8 Antenna/Radome Type

: (A4 from rcvr_ant.tab; see instructions)

Place a radome code from file *"rcvr_ant.tab"* (IGSCB-RA). "NONE" indicates there is no external radome. If an antenna has a cover which is integral and not ordinarily removable by the user, it is considered part of the antenna and "NONE" is to be used for the radome code. The radome code used here has to be the same as the one in the columns 17–20 of the antenna type.

B.6.9 Date Removed

: (CCYY-MM-DDThh:mmZ)

In the block for the antenna currently in operation, leave this line as is to remind yourself of the format when the next antenna change is made.

B.7 Surveyed Local Ties (5.)

Local ties to other markers on the site should be determined in ITRF coordinates to 1 mm precision in all 3 dimensions. Offsets are given in geocentric Cartesian coordinates (ITRF).

B.8 Meteorological Instrumentation (8.)

B.8.1 Height Difference to Antenna

: (m)

The difference in height between the GNSS antenna and the pressure sensor for the meteorological instrument should be measured and supplied. Positive numbers indicate that the pressure sensor is ABOVE the GNSS antenna.

B.9 Responsible Agency (12.)

The primary contacts listed here should always be the first choice for questions about operation of the site. This person will receive automated emails regarding site log or RINEX errors and should be someone who can answer questions about the configuration and data delivery for this site.

B.10 More Information (13.)

B.10.1 Primary Data Centre (DC)

- Please list the DC where the station's data ordinarily goes first as "Primary".

B.10.2 Secondary Data Centre

- Use "Secondary" either for a second location where the station's data always goes, or would go in the case of a long-term failure with the Primary DC.
- Select primary and secondary data centers via the centers html-pages and enter the abbreviation of the DC name.
- A geographically- or functionally-related center is generally preferred.
- The secondary DC is where data would be sent if the primary were unavailable for an extended period.
- The switchover does not need to be automated, but data transfer procedures should be verified.

B.10.3 URL for more information

- This will be linked to the GRUAN Lead Centre page for this site.
- It is not necessary to include "`http://`".
- Photos are mandatory. See section 7.1.1 on requirements for site photos. Send all available photos of antenna, radome, placement and all relevant photos to the GRUAN Lead Centre at gruan.lc@dwd.de.
- Contact the GRUAN Lead Centre at if you have photos which cannot be hosted on a site web page.

B.11 Additional Information

- Anything you feel is important.
- Some possibilities to consider are
  ◦ Elevation mask table, indicating physical mask effects such as listed in Table 6
- This could also be kept at your local website and referred to by URL in the log.

Table 6: Elevation mask table

AZ	ELEV	AZ	ELEV	AZ	ELEV	AZ	ELEV
10	8	20	12	30	10	40	8
50	5	60	12	70	8	80	8
90	5	100	5	110	5	120	5
130	5	140	5	150	8	160	8
170	5	180	3	190	5	200	8
210	8	220	8	230	5	240	5
250	5	260	8	270	10	280	12
290	12	300	12	310	12	320	8
330	5	340	5	350	5	360	8

B.12 Example IGS-style Site Log file (e.g., for Lindenberg, 4-character GNSS Identifier LDB2)

```
LDB200DEU Site Information Form (site log)
     International GNSS Service
     See Instructions at:
       ftp://igscb.jpl.nasa.gov/pub/station/general/sitelog_instr.txt


0.   Form

     Prepared by (full name)  :  Peter Franke
     Date Prepared            : 2018-05-09
     Report Type              : UPDATE
     If Update:
      Previous Site Log       : ldb200deu_20170411.log
      Modified/Added Sections : 3.7,3.8


1.   Site Identification of the GNSS Monument

     Site Name                : Lindenberg
     Four Character ID        : LDB2
     Monument Inscription     :
     IERS DOMES Number        : 14114M002
     CDP Number               : (A4)
     Monument Description     : steelpipe with heat protection
       Height of the Monument : 1.7 m
       Monument Foundation    : 2005
       Foundation Depth       : 10 m
     Marker Description       : SURVEY MARKER BOLT ON THE PILLAR
     Date Installed           : 2005-09-28
     Geologic Characteristic  : CENOZOIC QUATERNARY
       Bedrock Type           : (IGNEOUS/METAMORPHIC/SEDIMENTARY)
```

```
        Bedrock Condition      : (FRESH/JOINTED/WEATHERED)
        Fracture Spacing       : (0 cm/1-10 cm/11-50 cm/51-200 cm/over 200 cm)
        Fault zones nearby     : NO
          Distance/activity    : (multiple lines)
      Additional Information   : Antenna mounted with a special
                               : screw adapter on a rivet thread of a
                               : circular tube of steel filled with concrete,
                               : 11,7 m length.


2.   Site Location Information

     City or Town             : Lindenberg
     State or Province        : Brandenburg
     Country                  : Germany
     Tectonic Plate           : EURASIAN
     Approximate Position (ITRF)
       X coordinate (m)       : 3798345.260
       Y coordinate (m)       : 955552.840
       Z coordinate (m)       : 5017221.540
       Latitude (N is +)      : +521232.84
       Longitude (E is +)     : +0140715.31
       Elevation (m,ellips.)  : 159.5
     Additional Information   : (multiple lines)


3.   GNSS Receiver Information

3.1  Receiver Type            : JPS LEGACY
     Satellite System         : GPS+GLO
     Serial Number            : AG2A5QEYQDC
     Firmware Version         : E_GGD_2.5p1
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2005-10-25T10:00Z
     Date Removed             : 2007-11-22T12:30Z
     Temperature Stabiliz.    : none
     Additional Information   : (multiple lines)

3.2  Receiver Type            : JPS LEGACY
     Satellite System         : GPS+GLO
     Serial Number            : AG2A5QEYQDC
     Firmware Version         : 2.6.0 APR,18,2007
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2007-11-22T12:30Z
     Date Removed             : 2008-01-29T09:15Z
     Temperature Stabiliz.    : none
     Additional Information   : (multiple lines)

3.3  Receiver Type            : JPS LEGACY
     Satellite System         : GPS+GLO
     Serial Number            : AG2A5QEYQDC
     Firmware Version         : 2.6.1 JAN,10,2008
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2008-01-29T10:00Z
     Date Removed             : 2015-03-24T09:00Z
     Temperature Stabiliz.    : none
```

```
     Additional Information   : (multiple lines)

3.4  Receiver Type            : LEICA GR25
     Satellite System         : GPS+GLO+GAL+SBAS
     Serial Number            : 1831169
     Firmware Version         : 3.11.1639
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2015-03-24T12:00Z
     Date Removed             : 2016-05-06T06:00Z
     Temperature Stabiliz.    : none
     Additional Information   : ME serial number BDU14060417

3.5  Receiver Type            : LEICA GR25
     Satellite System         : GPS+GLO+GAL+SBAS
     Serial Number            : 1831169
     Firmware Version         : 3.22.1818
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2016-05-06T06:00Z
     Date Removed             : 2016-07-20T09:00Z
     Temperature Stabiliz.    : none
     Additional Information   : ME serial number BDU14060417

3.6  Receiver Type            : LEICA GR25
     Satellite System         : GPS+GLO+GAL+BDS+SBAS
     Serial Number            : 1831169
     Firmware Version         : 4.00.335
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2016-07-20T09:00Z
     Date Removed             : 2017-04-11T06:45Z
     Temperature Stabiliz.    : none
     Additional Information   : ME serial number BDU14060417

3.7  Receiver Type            : LEICA GR25
     Satellite System         : GPS+GLO+GAL+BDS+SBAS
     Serial Number            : 1831169
     Firmware Version         : 4.11.606
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2017-04-11T06:45Z
     Date Removed             : 2018-05-09T10:00Z
     Temperature Stabiliz.    : none
     Additional Information   : ME serial number BDU14060417

3.8  Receiver Type            : LEICA GR50
     Satellite System         : GPS+GLO+GAL+BDS+SBAS
     Serial Number            : 1870606
     Firmware Version         : 4.20.232
     Elevation Cutoff Setting : 0 deg
     Date Installed           : 2018-05-09T10:00Z
     Date Removed             : CCYY-MM-DDThh:mmZ
     Temperature Stabiliz.    : none
     Additional Information   : (multiple lines)

3.x  Receiver Type            : (A20, from rcvr_ant.tab; see instructions)
     Satellite System         : (GPS+GLO+GAL+BDS+QZSS+IRNSS+SBAS)
     Serial Number            : (A20, but note the first A5 is used in SINEX)
     Firmware Version         : (A11)
```

```
     Elevation Cutoff Setting : (deg)
     Date Installed           : (CCYY-MM-DDThh:mmZ)
     Date Removed             : (CCYY-MM-DDThh:mmZ)
     Temperature Stabiliz.    : (none or tolerance in degrees C)
     Additional Information   : (multiple lines)


4.   GNSS Antenna Information

4.1  Antenna Type             : TPSCR3_GGD      CONE
     Serial Number            : 217-0244
     Antenna Reference Point  : BPA
     Marker->ARP Up Ecc. (m)  :   0.0470
     Marker->ARP North Ecc(m) :   0.0000
     Marker->ARP East Ecc(m)  :   0.0000
     Alignment from True N    : 0 deg
     Antenna Radome Type      : CONE
     Radome Serial Number     :
     Antenna Cable Type       : AIRCOM+
     Antenna Cable Length     : 18 m
     Date Installed           : 2005-10-25T10:00Z
     Date Removed             : 2011-09-28T09:00Z
     Additional Information   : Antenna individual calibrated
                              : absolute by GEO++

4.2  Antenna Type             : LEIAR25.R4      LEIT
     Serial Number            : 725072
     Antenna Reference Point  : BPA
     Marker->ARP Up Ecc. (m)  :   0.0470
     Marker->ARP North Ecc(m) :   0.0000
     Marker->ARP East Ecc(m)  :   0.0000
     Alignment from True N    : 0 deg
     Antenna Radome Type      : LEIT
     Radome Serial Number     :
     Antenna Cable Type       : AIRCOM+
     Antenna Cable Length     : 18 m
     Date Installed           : 2011-09-28T10:00Z
     Date Removed             : CCYY-MM-DDThh:mmZ
     Additional Information   : Antenna individual calibrated
                              : absolute by GEO++

4.x  Antenna Type             : (A20, from rcvr_ant.tab; see instructions)
     Serial Number            : (A*, but note the first A5 is used in SINEX)
     Antenna Reference Point  : (BPA/BCR/XXX from "antenna.gra"; see instr.)
     Marker->ARP Up Ecc. (m)  : (F8.4)
     Marker->ARP North Ecc(m) : (F8.4)
     Marker->ARP East Ecc(m)  : (F8.4)
     Alignment from True N    : (deg; + is clockwise/east)
     Antenna Radome Type      : (A4 from rcvr_ant.tab; see instructions)
     Radome Serial Number     :
     Antenna Cable Type       : (vendor & type number)
     Antenna Cable Length     : (m)
     Date Installed           : (CCYY-MM-DDThh:mmZ)
     Date Removed             : (CCYY-MM-DDThh:mmZ)
     Additional Information   : (multiple lines)
```

```

5.   Surveyed Local Ties

5.x  Tied Marker Name         :
     Tied Marker Usage        : (SLR/VLBI/LOCAL CONTROL/FOOTPRINT/etc)
     Tied Marker CDP Number   : (A4)
     Tied Marker DOMES Number : (A9)
     Differential Components from GNSS Marker to the tied monument (ITRS)
       dx (m)                 : (m)
       dy (m)                 : (m)
       dz (m)                 : (m)
     Accuracy (mm)            : (mm)
     Survey method            : (GPS CAMPAIGN/TRILATERATION/TRIANGULATION/etc)
     Date Measured            : (CCYY-MM-DDThh:mmZ)
     Additional Information   : (multiple lines)


6.   Frequency Standard

6.1  Standard Type            : INTERNAL
       Input Frequency        : (if external)
       Effective Dates        : 2000-09-29/CCYY-MM-DD
       Notes                  : (multiple lines)

6.x  Standard Type            : (INTERNAL or EXTERNAL H-MASER/CESIUM/etc)
       Input Frequency        : (if external)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Notes                  : (multiple lines)


7.   Collocation Information

7.x  Instrumentation Type     : (GPS/GLONASS/DORIS/PRARE/SLR/VLBI/TIME/etc)
       Status                 : (PERMANENT/MOBILE)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Notes                  : (multiple lines)


8.   Meteorological Instrumentation

8.1.1  Humidity Sensor Model  : HMP45ASP
       Manufacturer           : Vaisala Oyi
       Serial Number          : A2110014
       Data Sampling Interval :    10 sec
       Accuracy (% rel h)     : 1 % rel h
       Aspiration             : CAPACITIVY THIN FILM POLYMER
       Height Diff to Ant     : -0.5 m
       Calibration date       : 2005-05-23
       Effective Dates        : 2005-10-25/2017-01-26
       Notes                  : The humidity sensor is 0,5 m
                              : below the antenna.

8.1.2  Humidity Sensor Model  : HMP45A-P
       Manufacturer           : Vaisala Oyi
       Serial Number          : W5040013
       Data Sampling Interval :    10 sec
```

```
       Accuracy (% rel h)     : 1 % rel h
       Aspiration             : CAPACITIVY THIN FILM POLYMER
       Height Diff to Ant     : -0.5 m
       Calibration date       : 2015-11-23
       Effective Dates        : 2017-01-26/CCYY-MM-DD
       Notes                  : The humidity sensor is 0,5 m
                              : below the antenna.

8.1.x  Humidity Sensor Model  :
       Manufacturer           :
       Serial Number          :
       Data Sampling Interval : (sec)
       Accuracy (% rel h)     : (% rel h)
       Aspiration             : (UNASPIRATED/NATURAL/FAN/etc)
       Height Diff to Ant     : (m)
       Calibration date       : (CCYY-MM-DD)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Notes                  : (multiple lines)

8.2.1  Pressure Sensor Model  : PTU200
       Manufacturer           : Vaisala Oyi
       Serial Number          : X4150003
       Data Sampling Interval :  10 sec
       Accuracy               : 0.1 hPa
       Height Diff to Ant     : -0.8 m
       Calibration date       : 2002-10-11
       Effective Dates        : 2005-10-25/2017-01-26
       Notes                  : The pressure Sensor is
                              : 0,8 m below the antenna.

8.2.2  Pressure Sensor Model  : PTU200
       Manufacturer           : Vaisala Oyi
       Serial Number          : X2930004
       Data Sampling Interval :  10 sec
       Accuracy               : 0.1 hPa
       Height Diff to Ant     : -0.8 m
       Calibration date       : (CCYY-MM-DD)
       Effective Dates        : 2017-01-26/CCYY-MM-DD
       Notes                  : The pressure Sensor is
                              : 0,8 m below the antenna.

8.2.x  Pressure Sensor Model  :
       Manufacturer           :
       Serial Number          :
       Data Sampling Interval : (sec)
       Accuracy               : (hPa)
       Height Diff to Ant     : (m)
       Calibration date       : (CCYY-MM-DD)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Notes                  : (multiple lines)

8.3.1  Temp. Sensor Model     : HMP45ASP
       Manufacturer           : Vaisala Oyi
       Serial Number          : A2110014
       Data Sampling Interval : 10 sec
       Accuracy               : 0.2 deg C
```

```
       Aspiration             : RESISTIVE PLATINUM PROBE
       Height Diff to Ant     : -0.5 m
       Calibration date       : 2005-05-23
       Effective Dates        : 2005-10-25/2017-01-26
       Notes                  : The temperature sensor is
                              : 0,5m below the antenna.

8.3.2  Temp. Sensor Model     : HMP45A-P
       Manufacturer           : Vaisala Oyi
       Serial Number          : W5040013
       Data Sampling Interval : 10 sec
       Accuracy               : 0.2 deg C
       Aspiration             : RESISTIVE PLATINUM PROBE
       Height Diff to Ant     : -0.5 m
       Calibration date       : 2015-11-23
       Effective Dates        : 2017-01-26/CCYY-MM-DD
       Notes                  : The temperature sensor is
                              : 0,5m below the antenna.

8.3.x  Temp. Sensor Model     :
       Manufacturer           :
       Serial Number          :
       Data Sampling Interval : (sec)
       Accuracy               : (deg C)
       Aspiration             : (UNASPIRATED/NATURAL/FAN/etc)
       Height Diff to Ant     : (m)
       Calibration date       : (CCYY-MM-DD)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Notes                  : (multiple lines)

8.4.x  Water Vapour Radiometer :
       Manufacturer           :
       Serial Number          :
       Distance to Antenna    : (m)
       Height Diff to Ant     : (m)
       Calibration date       : (CCYY-MM-DD)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Notes                  : (multiple lines)

8.5.x  Other Instrumentation  : (multiple lines)


9.   Local Ongoing Conditions Possibly Affecting Computed Position

9.1.x  Radio Interferences    : (TV/CELL PHONE ANTENNA/RADAR/etc)
       Observed Degradations  : (SN RATIO/DATA GAPS/etc)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Additional Information : (multiple lines)

9.2.x  Multipath Sources      : (METAL ROOF/DOME/VLBI ANTENNA/etc)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Additional Information : (multiple lines)

9.3.x  Signal Obstructions    : (TREES/BUILDINGS/etc)
       Effective Dates        : (CCYY-MM-DD/CCYY-MM-DD)
       Additional Information : (multiple lines)
```

```


10.  Local Episodic Effects Possibly Affecting Data Quality

10.x  Date                   : (CCYY-MM-DD/CCYY-MM-DD)
      Event                  : (TREE CLEARING/CONSTRUCTION/etc)


11.  On-Site, Point of Contact Agency Information

     Agency                  : Bundesamt fuer Kartographie
                             : und Geodaesie
                             : Department of Geodaesie
     Preferred Abbreviation  : BKG
     Mailing Address         : Bundesamt fuer Kartographie
                             : und Geodaesie
                             : Department of Geodaesie
                             : Richard Strauss Allee 11
                             : D 60598 Frankfurt / M.
                             : Germany
     Primary Contact
       Contact Name          : Peter Franke
       Telephone (primary)   : (0049)-69-6333-279
       Telephone (secondary) : (0049)-69-6333-1
       Fax                   : (0049)-69-6333-425
       E-mail                : peter.franke@bkg.bund..de
     Secondary Contact
       Contact Name          : see section 12
       Telephone (primary)   :
       Telephone (secondary) :
       Fax                   :
       E-mail                :
     Additional Information  : (multiple lines)


12.  Responsible Agency (if different from 11.)

     Agency                  : Bundesamt fuer Kartographie
                             : und Geodaesie
                             : Department of Geodaesie
     Preferred Abbreviation  : BKG
     Mailing Address         : Bundesamt fuer Kartographie
                             : und Geodaesie
                             : Branch Leipzig
                             : Karl Rothe Str. 10-14
                             : D 04105 Leipzig
                             : Germany
     Primary Contact
       Contact Name          : Matthias Groeschel
       Telephone (primary)   : (0049)-341-5643-432
       Telephone (secondary) : (0049)-341-5643-0
       Fax                   : (0049)-341-5643-415
       E-mail                : matthias.groeschel@bkg.bund.de
     Secondary Contact
       Contact Name          :
       Telephone (primary)   :
```

```
       Telephone (secondary)  :
       Fax                    :
       E-mail                 :
     Additional Information   : (multiple lines)


13.  More Information

     Primary Data Center      : BKG
     Secondary Data Center    : OLG
     URL for More Information : www.bkg.bund.de
     Hardcopy on File
       Site Map               : (Y or URL)
       Site Diagram           : (Y or URL)
       Horizon Mask           : (Y or URL)
       Monument Description   : (Y or URL)
       Site Pictures          : Y
     Additional Information   : Data center Bundesamt fuer
                              : Kartographie und
                              : Geodaesie
                              : Department of Geodaesie
                              : Referat G2
                              : Richard Strauss Allee 11
                              : D 60598 Frankfurt / M.
                              : Germany
                              : http://www.bkg.bund.de
     Antenna Graphics with Dimensions

TPSCR3_GGD
                        ---------
                      /     +     \                       <--  0.104  = L2
                     |      +      |                      <--  0.081  = L1
   +---------------------------------------------------+    <--  0.071  = TCR
   |                                                   |
   |                                                   |
   |                                                   |
   |                                                   |
   +-----------------+-------------+-------------------+    <--  0.003 = BCR
                      +-----x-----+                       <--  0.000   BPA=ARP

   <--                    0.326                     -->





LEIAR25.R4

                       +-------+                         <--  0.1995
                      /         \
                +---+-------------+---+                  <--  0.1606  TCR
                |                     |
             |---------------------------|
          |---------------------------------|
       |----------------------------------------|
    +----------------------------------------------+
```

```
  |                                             |
  |                                             |
+-+---------------------------------------------+-+
+-----------------+-------------+-----------------+     <--  0.0320  BCR
                  |             |
                  |             |
                  +------x------+                       <--  0.0000  BPA=ARP

<--                    0.3802                   -->


 ARP: Antenna Reference Point
 L1 : L1 Phase Center                   L2 : L2 Phase Center
 TCR: Top of Chokering                  BCR: Bottom of Chokering
 TGP: Top of Ground Plane               BGP: Bottom of Ground Plane
 TPA: Top of Preamplifier               BPA: Bottom of Preamplifier
 TOP: Top of Pole

 All dimensions are in meters.
```

Acronyms

AGNES	Automated GNSS Network for Switzerland
AOPC	Atmospheric Observation Panel for Climate
ARP	Antenna Reference Point
ASCII	American Standard Code for Information Interchange
CIMO	Commission for Instruments and Methods of Observation
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
DC	Data Centre
DORIS	Doppler Orbitography Radiopositioning Integrated by Satellite
ECMWF	European Centre for Medium-Range Weather Forecasts
EPN	EUREF GNSS Permanent Network
EPOS	Earth Parameter and Orbit determination System
E-GVAP	EUMETNET GPS Water Vapour Program
ERA-Interim	ECMWF global atmospheric reanalysis from 1979 until 31 August 2019
ETRF	European Terrestrial Reference System
EUREF	Reference Frame Sub Commission for Europe
FGI	Finnish Geospatial Research Institute
GAMIT/GLOBK	A comprehensive suite of programs for analyzing GPS measurements, developed by MIT, Scripps Institution of Oceanography, and Harvard University with support from the National Science Foundation
GFZ	German Research Centre for Geosciences
GHG	GreenHouse Gas
GIPSY/OASIS	GNSS-Inferred Positioning System and Orbit Analysis Simulation Software, developed by Jet Propulsion Laboratory, Californian Institute of Technology
GLONASS	GLObalnaja Nawigazionnaja Sputnikowaja Sistema
GNSS	Global Navigation Satellite System
GCOS	Global Climate Observing System
GPS	Global Positioning System
GREF	Integrated German Geodetic Reference Network
GRUAN	GCOS Reference Upper-Air Network
GTT	GRUAN GNSS-PW Task Team
ICM	GRUAN Implementation and Coordination Meeting
IERS	International Earth Rotation and Reference Systems Service
IGS	International GNSS Service
ITRF	International Terrestrial Reference Frame
IWV	Integrated Water Vapour
LC	Lead Centre
MF	Mapping Functions
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NetCDF	Network Common Data Format (Unidata)
NWP	Numerical Weather Prediction
MWR	Microwave Radiometer

NRT	Near Real Time
PBO	Plate Boundary Observatory
PCV	Phase Centre Variations
PPP	Precise Point Positioning
RINEX	Receiver Independent Exchange Format
RMS	Root Mean Squared
RTKLIB	An Open Source Program Package for GNSS Positioning, developed by Tomoji Takasu from the Tokyo University of Marine Science and Technology
SI	International System of Units
SINEX	Solution (Software/technique) INdependent EXchange Format
SLM	IGS Site Log Manager
SLR	Satellite laser ranging
SOP	Standard Operating Procedure
STD	Slant Total Delay
PC	Processing Centre
PW	Precipitable Water
QA	Quality Assurance
QC	Quality Control
UCAR	University Corporation for Atmospheric Research
UTC	Coordinated Universal Time
UTLS	Upper Troposphere / Lower Stratosphere
VLBI	Very Long Baseline Interferometry
WCDMP	World Climate Data and Monitoring Programme
WCRP	World Climate Research Programme
WDAC	World Climate Research Programme Data Advisory Council
WIGOS	WMO Integrated Global Observing Systems
WG-GRUAN	The GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC) Working Group on GRUAN
WMO	World Meteorological Organization
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Tropospheric Delay
ZWD	Zenith Wet Delay

Links to Relevant Documents and Websites

- ANTEX - ftp://ftp.igs.org/pub/station/general/antex14.txt
- COST Action 716 Final Report: Exploitation of ground-based GPS for climate and numerical weather prediction applications
  https://e-services.cost.eu/files/domain_files/METEO/Action_716/final_report/final_report-716.pdf
- COST-Format: File Specification for Ground-based GNSS Delay and Water Vapour
  Version 1.0 - 2000
  Version 2.0 - 2003
  Version 2.1 - 2008
  Version 2.2a – 21 Oct 2013 – http://egvap.dmi.dk/support/formats/egvap_cost_v22a.pdf
- E-GVAP NetCDF File Specification for GNSS Water Vapour Data
  ftp://ftp.gfz-potsdam.de/pub/GNSS/nrttrop/diverses/egvap_netcdf_v02.pdf
- SINEX_TRO Specification
  http://twg.igs.org/documents/sinex_tro_v2.00.pdf
- GCOS 161 GRUAN ICM-4
  https://www.gruan.org/gruan/editor/documents/gcos/gcos-161.pdf
- IGS Homepage of International GNSS Service - http://igs.org
- IGS-GL IGS Site Guidelines
  ftp://ftp.igs.org/pub/station/general/IGS%20Site%20Guidelines%20July%202015.pdf
- IGSCB-05 - Satellite antenna and receiver antenna corrections (as ANTEX file: The Antenna Exchange Format, Version 1.4)
  ftp://ftp.igs.org/pub/station/general/igs05.atx
- IGSCB-08 - GPS/GLONASS satellite antenna and receiver antenna corrections (as ANTEX file: The Antenna Exchange Format, Version 1.4, see ANTEX)
  ftp://ftp.igs.org/pub/station/general/igs08.atx
- IGSCB-A - Definition file for antenna reference points and physical antenna dimensions
  ftp://ftp.igs.org/pub/station/general/antenna.gra
- IGSCB-AR - Readable summary of all IGS antenna files (13 Sep 2011)
  ftp://ftp.igs.org/pub/station/general/antenna_README.pdf
- IGSCB-M - Monumentation Design and Implementation Recommendations
  https://www.unavco.org/instrumentation/monumentation/monumentation.html
- IGSCB-R2 - RINEX: The Receiver Independent Exchange Format Version 2
  ftp://ftp.igs.org/pub/data/format/rinex2.txt
- IGSCB-R210 - RINEX: The Receiver Independent Exchange Format Version 2.10
  ftp://ftp.igs.org/pub/data/format/rinex210.txt
- IGSCB-R3 - RINEX: The Receiver Independent Exchange Format Version 3
  ftp://ftp.igs.org/pub/data/format/rinex303.pdf
  ftp://ftp.igs.org/pub/data/format/rinex303_update1.pdf
- IGSCB-RA - Naming conventions for IGS equipment descriptions in site logs, RINEX headers, and SINEX
  ftp://ftp.igs.org/pub/station/general/rcvr_ant.tab

- IGSCB-SL - Instructions for filling out IGS site logs (Apr 2011)
  ftp://ftp.igs.org/pub/station/general/sitelog_instr.txt
- IGSCB-SLB - Blank Site Information Form (site log)
  ftp://ftp.igs.org/pub/station/general/blank.log
- IGSCB-SLE - Site information (logfiles)
  ftp://ftp.igs.org/pub/station/log
- IGS-TECH - Technical Report 2012
  ftp://ftp.igs.org/pub/resource/pubs/2016_techreport.pdf

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