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Foreword

“Österreichische Geodätische Kommission” (ÖGK), the Austrian Geodetic Commission, is a group of experts in the field of geodesy and geoinformation. The vision of ÖGK is to contribute to the well-being of society and economy through research. In the digital era accurate, reliable, up-to-date and context sensitive information has become indispensable for our daily lives, for business processes, and in the interaction between individuals, authorities, and the private sector. On the occasion of the 27th General Assembly of IUGG, held in Montreal (Canada), ÖGK traditionally organizes a special issue to reflect on the state of Geodesy in Austria. This special issue of VGI, the Austrian Journal of Surveying and Geoinformation, showcases contributions of ÖGK members to realize ÖGK’s vision: through fundamental and applied research, through technical development, and through education.

Customized geoinformation enables each and every one of us to navigate not only abroad but also at home. Cartography, as the science of map-making and thus of representing and communicating geo-information, provides the user-centered perspective (Gartner, p. 95, Giannopoulos et al., p. 147). This geoinformation is provided by country-wide surveying from airborne platforms (Pfeifer, p. 136) complemented by finding the own location from satellite positioning with GPS or generally Global Navigation Satellite Systems (Weber et al., p. 78, Uros Bokan et al., p. 83, Titz et al., p. 109, Zahn, p. 119). Domain specific geoinformation is obtained by terrestrial surveying for detailed plans, engineering constructions, and cadastral information. Since space is a limited and thus precious, it needs to be used efficiently, and thus cadastral information becomes more and more important, therefore needs to be more and more accurate, and eventually also has to consider the changing nature of our environment, e. g. due to subsidence or sliding slopes. The interdisciplinary nature of ÖGK, comprising experts from geoinformation, geodesy, the national mapping and cadastral agency BEV (Federal Office of Surveying and Metrology), geophysics, and the private sector of surveying (Bundeskammer der ZiviltechnikerInnen, Federal Chamber of Architects and Chartered Engineering Consultants), allows advising policy in such multi-faceted legal-technical-environmental cases (Höggerl et al., p. 124).

Precise geoinformation, be it on local level as in the example above, and all the more globally, like continental droughts or sea level rise, are provided by Earth observation satellites (e. g. the European Copernicus program). It enables and drives digitization processes from data collected from outer space to localized geoinformation. Both, the global view and the localized information can only be provided on the backbone of stable reference systems. These are systems of time (Nießner et al., p. 74) and systems for 3D space. The spatial reference systems do not only provide coordinates systems for measuring on the Earth and of the Earth (Böhm et al., p. 70), but also its regular motion and irregular deviations thereof need to be understood. These motions are monitored across a range of scales, from the body of the Earth, via the tectonic plates, to individual stations (Sehnal et al., p. 115). The Earth’s gravity field, and observations of its change, (Meurers, p. 101), complements the geodetic model of our planet, comprising space, time, and gravity. For realizing these global reference systems outer space is either used by the measurement instruments on satellites facing the Earth, or outer space is exploited as stable source in the form of distant stars, while the measurements are performed – for the time being – on the Earth’s surface.

ÖGK would like to thank the Austrian Society of Surveying and Geoinformation für the publication of this volume of VGI and wishes all readers a large gain in information.

Vorwort

Die Österreichische Geodätische Kommission (ÖGK) versteht sich als eine Gruppe von Expertinnen und Experten auf allen Gebieten der Geodäsie und Geoinformation. Vision der ÖGK ist es, zum Wohlergehen der Gesellschaft und der Wirtschaft durch Forschung beizutragen. Im digitalen Zeitalter ist genaue, zuverlässige, aktuelle und Kontext-sensitive Information für unser tägliches Leben unersetzlich – für Geschäftsprozesse ebenso wie für den Austausch zwischen Einzelpersonen, Behörden und dem privaten Sektor. Anlässlich der 27. Generalversammlung der IUGG (Internationale Union für Geodäsie und Geophysik), die in Montreal, Kanada, abgehalten wird, stellt die ÖGK traditionell einen Band der vgi zusammen, um den aktuellen Forschungsstand zur Geodäsie in Österreich zusammenzufassen. Dem wissenschaftlichen Standard folgend, mit dem Ziel der internationalen Sichtbarkeit und Einbindung, sind die Artikel in Englisch abgefasst. Alle Artikel haben eine deutschsprachige Zusammenfassung. Diese Ausgabe der „Vermessung und Geoinformation" zeigt aktuelle Beiträge der ÖGK-Mitglieder. Sie sind ein Beitrag zur Realisierung der Vision der ÖGK, durch Grundlagen- und angewandte Forschung, durch technische Entwicklung, und durch Weitergabe des Wissens.

Maßgeschneiderte Geoinformation ermöglicht jedem von uns sich zurechtzufinden und die kürzesten Wege zu nehmen, nicht nur im Ausland, wie z. B. in Montreal, sondern auch Zuhause. Kartographie, als die Wissenschaft des Landkarten-Machens, und daher die Wissenschaft zur Repräsentation und Kommunikation von Geoinformation, bietet eine Nutzer-zentrierte Sicht auf Geoinformation (Gartner, S. 95, Giannopoulos et al., S. 147). Diese Geoinformation selbst wird durch landesweite Vermessung von luftgestützten Plattformen aus gewonnen (Pfeifer, S. 136), vervollständigt durch die eigene Positionierung mittels GPS bzw. Globalen Satellitensystemen für Navigation (Weber et al., S. 78, Uros Bokan et al., S. 83, Titz et al., S. 109, Zahn, S. 119). Spartenspezifische Geoinformation wird durch terrestrische Vermessung gewonnen, für Detailpläne, für Ingenieurbauwerke und für den Kataster.

Der Raum, in dem wir leben, ist eine begrenzte Ressource. Daher muss er effizient genützt werden, und Katasterinformation, zur räumlichen Darstellung der Eigentumsverhältnisse und Beschränkungen, wird damit immer wichtiger. Dementsprechend muss diese Information auch immer genauer werden und letztendlich auch die sich verändernde Natur, z. B. Hangrutschungen und kriechende Hangbewegungen, berücksichtigen. Gerade die interdisziplinäre Zusammensetzung der ÖGK, mit Experten und Expertinnen aus den Bereichen Geoinformation, Geodäsie, staatliche Vermessung (Bundesamt für Eich- und Vermessungswesen), Geophysik und Vermessungsbüros (Bundeskammer der ZiviltechnikerInnen) erlaubt es, die Politik in solchen vielschichtigen Fällen mit technischen, gesetzlichen und naturbedingten Aspekten zu beraten (Höggerl et al., S. 124).

Präzise Geoinformation, als lokale Information wie oben beschrieben, und umso mehr global, z. B. Meeresspiegelanstieg oder kontinentale Dürren, wird durch Erdbeobachtungssatelliten zur Verfügung gestellt, z. B. durch das Europäische Copernicus-Programm. Das erlaubt und befördert die Digitalisierung, von der Datengewinnung im Weltraum bis zu punktbezogener Information auf der Erdoberfläche. Sowohl die globale Sichtweise als auch die lokale Information benötigen als Basis stabile Referenzsysteme. Dies sind Zeitsysteme (Nießner et al., S. 74) und Systeme zur Beschreibung des 3-dimensionale Raums. Die räumlichen Referenzsysteme erlauben nicht nur die Messung auf der Erde und der Erde selbst (Böhm et al., S. 70), sondern auch die Erfassung ihrer Bewegung und der unregelmäßigen Komponenten der Erdrotation. Diese Bewegungen werden über einen großen Maßstabsbereich hinweg beobachtet, von der Form der Erde, über die tektonischen Platten hin bis zur Bewegung einzelner Stationen (Sehnal et al., S. 115). Das Schwerkraftfeld der Erde, und die Beobachtung seiner Veränderungen (Meurers, S. 101), vervollständigt das geodätische Modell unseres Planeten (Raum, Zeit und Gravitation). Für die Realisierung dieser globalen Referenzsysteme wird der Weltraum einerseits für die Messinstrumente genutzt, durch Satelliten, die zur Erde gerichtet sind. Andererseits bietet der Weltraum stabile Punkte (ferne Sterne), wobei die Messungen – vorerst – von der Erdoberfläche aus durchgeführt werden.

Die Österreichische Geodätische Kommission bedankt sich bei der Österreichischen Gesellschaft für Vermessung und Geoinformation für die Herausgabe dieses vgi-Bandes und wünscht allen Lesern viel Informationsgewinn bei der Lektüre der Beiträge.

Norbert Pfeifer
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Technische Universität Wien,
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Vermessung & Geoinformation 2/2019, S. 70 – 73, 3 Figs.

Very Long Baseline Interferometry for Global Geodetic Reference Frames








Johannes Böhm, Sigrid Böhm, Jakob Gruber,
Andreas Hellerschmied, Hana Krásná, Daniel Landskron,
David Mayer and Matthias Schartner, Wien

Abstract

Geodetic Very Long Baseline Interferometry (VLBI) is the only technique for the determination of the full set of Earth orientation parameters and for the realization of the International Celestial Reference Frame (ICRF) at radio wavelengths. Furthermore, it is making essential contributions to the determination of the scale of the International Terrestrial Reference Frame (ITRF). Based on a Memorandum of Understanding between TU Wien and the Federal Office of Metrology and Surveying (BEV), a Vienna Analysis Center (VIE) of the International VLBI Service for Geodesy and Astrometry (IVS) is jointly run by both organizations. The main focus of these activities is on the routine determination of Earth orientation parameters as well as the estimation of global reference frames.

Keywords: Very Long Baseline Interferometry (VLBI), Global Geodetic Reference Frames (GGRF), Earth Orientation Parameters (EOP)

Kurzfassung

Die geodätische Very Long Baseline Interferometry (VLBI) ist das einzige Verfahren zur Bestimmung aller Erdorientierungsparameter und für die Realisierung des International Celestial Reference Frame (ICRF) im Radiowellenbereich. Weiters liefert die VLBI essentielle Beiträge für die Bestimmung des Maßstabs des International Terrestrial Reference Frame (ITRF). Basierend auf einem Memorandum of Understanding zwischen dem Bundesamt für Eich- und Vermessungswesen (BEV) und der TU Wien wird nun ein gemeinsames Wiener Analysezentrum (VIE) des International VLBI Service for Geodesy and Astrometry (IVS) betrieben. Der Fokus liegt dabei auf der operationellen Bestimmung von Erdorientierungsparametern und der Bestimmung von Globalen Referenzrahmen.

Schlüsselwörter: Very Long Baseline Interferometry, globale geodätische Referenzrahmen, Erdorientierungsparameter

1. Introduction

Global Geodetic Reference Frames (GGRF) are fundamental for monitoring changes to the Earth, including the continents, oceans, polar ice caps, or the atmosphere. Furthermore, they are fundamental for mapping, positioning, and navigation on Earth and in space, as well as for timing applications. The importance of GGRF has been recognized by the United Nations General Assembly in February 2015 by adopting the Resolution „A Global Geodetic Reference Frame for Sustainable Development“[1].

Very Long Baseline Interferometry (VLBI) plays a key role for the realization of terrestrial and celestial reference systems (TRF, CRF) as well as for the determination of Earth orientation parameters (EOP). The measurement principle is rather simple, observing the difference in arrival time of the signals from extragalactic radio sources

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[1] https://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/69/266

(mostly quasars) at two sites equipped with radio telescopes and very accurate clocks (see Figure 1). Since this delay τ can be represented as the scalar product of the baseline vector $\underline{b}$ with the unit vector to the source $\underline{s}_0$ (divided by the velocity of light), VLBI observations can be used to determine baseline vectors and directions to extragalactic radio sources and thus make essential contributions to the TRF and CRF. The EOP constitute the transformation between these frames and are, therefore, another result of VLBI. For more information on geodetic VLBI, see e.g., [8] Schuh and Böhm (2013).

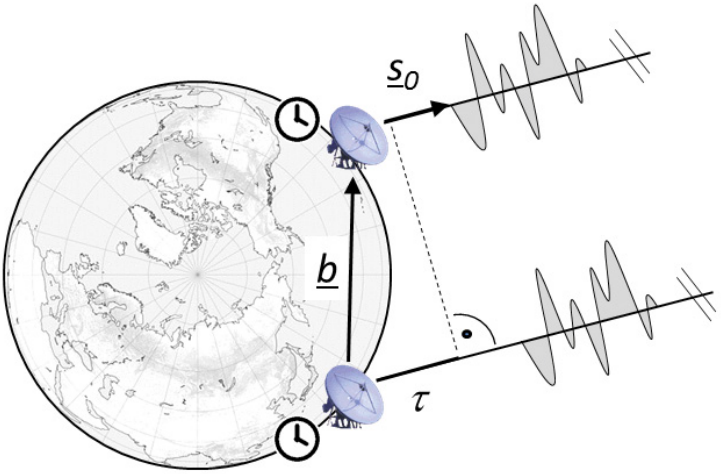

Fig. 1: Measurement principle of VLBI: The primary observable is the difference in arrival time t of the signal from the quasar at two radio telescopes. The observable τ can also be written as the scalar product of the baseline vector $\underline{b}$ with the unit vector to the source $\underline{s}_0$.

Typically, there are about three 24 hour sessions per week with six to eight radio telescopes observing a pre-defined sequence of sources. Additionally, once per day, there are so-called 1 hour Intensive sessions on a single baseline with a long east-west extension for the observation of UT1-UTC, which is the Earth orientation parameter reflecting the Earth rotation angle (see Nießner et al., this issue). UT1-UTC is a primary product of VLBI, because Global Navigation Satellite Systems (GNSS) are dependent on this information.

The complete process chain of VLBI comprises the scheduling, i.e., the preparation of the observation plans, the observations at the stations with radio telescopes, correlation and fringe-fitting to derive the group delays τ, as well as the analysis of the observations for the determination of geodetic and astrometric parameters. In July 2018, TU Wien and the Federal Office of Metrology and Surveying (BEV) signed a Memorandum of Understanding for joint work in the field of VLBI analysis. In the following sections, we describe the VLBI activities in more details.

2. Scheduling

VLBI observation plans, commonly referred to as schedules, define which antennas simultaneously observed a radio source at a particular time, i.e. which antennas of the network form a scan. Since the observation constellations defined in a schedule determine its applicability for the estimation of specific target parameters, e.g. EOPs, schedules have to be prepared carefully by applying dedicated optimization approaches.

Most of the geodetic schedules for the International VLBI Service for Geodesy and Astrometry (IVS; [6] Nothnagel et al., 2017) are prepared with the software *sked*. In Vienna, we use VieSched++ ([7] Schartner and Böhm, 2019) developed in C++, which is part of the Vienna VLBI and Satellite Software (VieVS; [2] Böhm et al., 2018). VieSched++ has already been used for the scheduling of Australian sessions, T2 sessions, INT3 sessions, OHG, sessions, or European sessions. The ability to use the Monte Carlo method in a feedback loop allows the VieSched++ software to produce schedules that are based on a rigorous simulation approach. More information about the session types can be found at: *https://ivscc.gsfc.nasa.gov/sessions/*

3. Correlation and fringe-fitting

All participating stations in a session pick up the schedule file and observe the sequence of sources with the defined observing mode. Typical data rates are 512 Mbit/sec or 1024 Mbit/sec. These streams of raw data then need to be (e-) transferred to a powerful supercomputer where the initial processing of the recorded raw observation data is conducted - the correlation. As VLBI correlation is very CPU intensive, powerful computer clusters are used in order to derive results in a reasona-

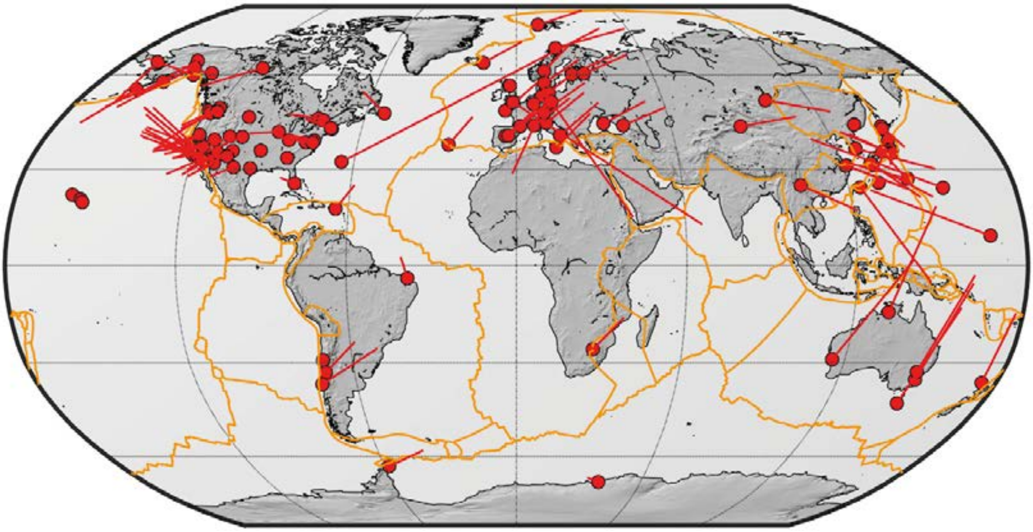

Fig. 2: Distribution of IVS radio telescopes with estimated velocities. Session-wise normal equations from all VLBI sessions until the end of 2014 as set up at TU Wien went into the combination process of ITRF2014.

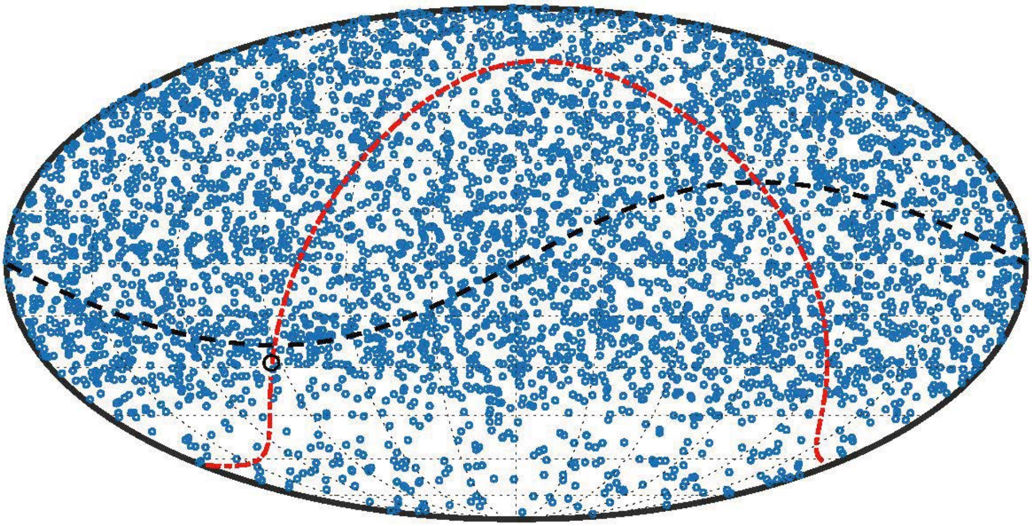

Fig. 3: Source distribution of the Vienna prototype solution for the ICRF3 ([5] Mayer, 2019). The ecliptic is depicted as a black dashed line, the galactic plane is illustrated as a red dashed line and a black circle in the bottom left part of the figure marks the Galactic center.

ble time. In Vienna, we use the Vienna Scientific Cluster 3 (VSC-3), which provides in total 2020 processing nodes. In 2019, we will move our correlation activities to the VSC-4, where we will have 10 private nodes and about 1 PByte storage capacity. Currently, we are correlating Australian sessions, European Intensives and K-band sessions for astrometry. Correlation and fringe-fitting, which is needed to determine the group delays that are then used in the VLBI analysis, are carried out with the software packages DiFX ([4] Deller et al., 2011) and HOPS/Fourfit[2], respectively.

4. LBI Analysis

Since July 2018, BEV and TU Wien form a Special IVS Analysis Center. We plan to become an Operational Analysis Center of the IVS, which means that we will operationally analyze all 24 hour R1- and R4-Sessions on Mondays and Thurs-

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[2] https://www.haystack.mit.edu/tech/vlbi/hops.html

days, respectively. The results (normal equations) are submitted to the IVS Combination Center at BKG in Frankfurt/Main with a short latency. This submission contains the Earth orientation parameters, which will then go into the products of the International Earth Rotation and Reference Systems Service (IERS).

For VLBI analysis, we use the VLBI module of the Vienna VLBI and Satellite Software (VieVS). VieVS is developed in Matlab and is publicly available at https://github.com/TUW-VieVS. We want to highlight that a Vienna solution with VieVS went into the combination for the ITRF2014 ([1] Altamimi et al., 2016) (see Figure 2) and we provided solutions for the International Celestial Reference Frame 3 (ICRF3; [3] Charlot et al., 2019) (see Figure 3), which was officially approved by the International Astronomical Union (IAU) in August 2018.

5. Summary and Outlook

The joint IVS Analysis Center VIE (TU Wien/BEV) is contributing to a variety of tasks in the field of Very Long Baseline Interferometry, comprising scheduling, correlation, and the analysis of VLBI observations. By doing so, BEV and TU Wien are also making an important Austrian contribution to the realization of Global Geodetic Reference Frames as requested by the UN General Assembly Resolution.

Acknowledgements

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Austrian contributions to the realization of time systems



Anton Nießner, Robert Edelmaier and Johannes Böhm, Wien

Abstract

The realization of accurate time scales is an important task for a country and worldwide because it is needed for many applications, such as financial transactions or positioning. The Federal Office of Metrology and Surveying (BEV) is in charge of the realization of the Coordinated Universal Time (UTC) for Austria and it is contributing to the realization of UTC globally. On the other hand, TU Wien and BEV are involved in the determination of UT1 with Very Long Baseline Interferometry (VLBI) observations. UT1 corresponds to the Earth rotation angle and is indispensable for any kind of satellite-based positioning and navigation. The difference between both time scales does not exceed 0.9 second because leap seconds are introduced in UTC to keep the difference below one second.

Keywords: Atomic Time, Universal Time, Earth Rotation

Kurzfassung

Die Realisierung von Zeitsystemen ist eine wichtige Aufgabe für ein Land und weltweit, da eine genaue Zeit für viele Aufgaben gebraucht wird, wie zum Beispiel Finanztransaktionen oder Positionierung. Das Bundesamt für Eich- und Vermessungswesen (BEV) ist mit der Realisierung der Coordinated Universal Time (UTC) für Österreich beauftragt und das BEV trägt auch zur globalen Realisierung von UTC bei. Andererseits sind die Technische Universität Wien (TU Wien) und BEV involviert in der UT1-Bestimmung mit dem Verfahren der Very Long Baseline Interferometry (VLBI). UT1 ist mit dem Winkel der Erdrotation verknüpft und unabdingbar für satellitenbasierte Positionierung und Navigation. Die Differenz zwischen diesen beiden Zeitskalen wird nicht größer als 0.9 Sekunden, weil immer rechtzeitig vorher eine Schaltsekunde bei UTC angebracht wird.

Schlüsselwörter: Atomzeit, Universalzeit, Erdrotation

1. Introduction

For a long time only astronomic observations to stars, planets, and the Moon could provide sufficient accuracy for forming accurate time scales. Then in the middle of the 20th century, the technical progress of the development of frequency standards, which are based on atomic physics processes (atomic clocks), gave a good precondition for a new quality of time scales and could reveal the irregularity of Earth rotation. By this new quality of time measurement, the definition of the second in the International System of Units (SI) could be revolutionized in 1967 on one hand and on the other hand, a uniform stable time scale, the International Atomic Time (TAI), could be launched in 1971. Additionally, the Coordinated Universal Time (UTC) has been implemented as new time scale. It guarantees the stability of an atomic time scale and is adjusted to the rotating Earth. In irregular intervals leap seconds are added according to the difference between the Earth rotation angle as defined with Universal Time (UT1) and UTC, so that the difference between these two amounts to a maximum of 0.9 s.

In this paper, we present Austrian contributions to the realization of UTC and UT1. In particular, Section 2 describes the observation of UT1 with geodetic Very Long Baseline Interferometry (VLBI) observations, and Section 3 provides an overview of the Austrian contribution to the national and international realization of UTC. Finally, we provide some information on leap seconds.

2. Observation of UT1 with Very Long Baseline Interferometry (VLBI)

The Universal Time 1 refers to the Greenwich hour angle of the mean Sun plus 12 hours corrected for polar motion (see Figure 1). Since the movement of the mean Sun in the equator with respect to the stars is exactly known, stars could be observed instead of the Sun.

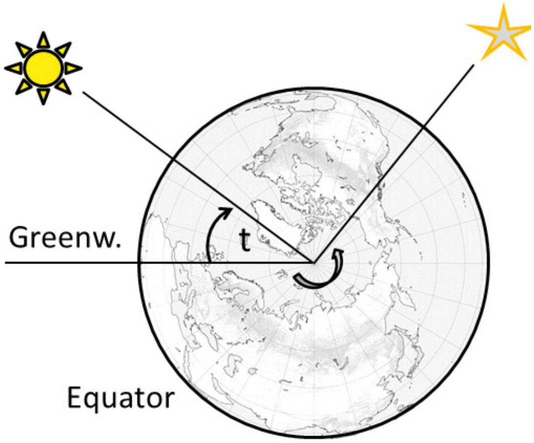

Fig. 1: UT1 refers to the Greenwich hour angle t of the mean Sun plus 12 hours. "1" denotes the correction for polar motion. Since the right ascension of the mean Sun with respect to the stars is exactly known, stars could be observed instead of the Sun.

Today, we do not observe stars but we use VLBI with radio telescopes to observe quasars, extragalactic radio sources billions of light years away. This measurement technique is a thousand times more accurate than the classical observations to stars. Essentially, geodetic VLBI is based on the observation of the difference in arrival time of signals from quasars at two sites which are equipped with atomic clocks ([1], Schuh and Böhm, 2013).

Internationally, geodetic VLBI activities are organized by the International VLBI Service for Geodesy and Astrometry (IVS; [2], Nothnagel et al., 2017), a Service of the International Association of Geodesy (IAG) and the International Astronomical Union (IAU). The Federal Office of Metrology and Surveying (BEV) and TU Wien are forming a joint analysis center of the IVS, and they are involved in scheduling observations, correlation, and the analysis of VLBI observations to determine geodetic products (see Böhm et al, this issue). The IVS organizes two different types of observing session. On the one hand, there are about three 24 hour sessions per week with six to eight stations participating to derive various geodetic parameters like Earth orientation parameters (nutation, polar motion, UT1-UTC) or station coordinates with highest accuracy and a latency of 10 to 14 days. UT1-UTC, which is essentially the difference between the Earth rotation angle and atomic time, can be derived with an accuracy of about 5 microseconds from these sessions, which corresponds to about 2-3 millimeters at the Earth surface.

Then, on a daily basis, there are 1 hour long so-called Intensive sessions with two or three stations, ideally with a long east-west baseline. UT1-UTC can be derived with an accuracy of about 20 microseconds (less than one centimeter at the Earth surface) from these sessions and is already available one or two days after the observation. This aspect is important because UT1-UTC cannot be predicted with sufficient accuracy over longer time spans and Global Navigation Satellite Systems (GNSS), such as GPS and Galileo, require exact information about UT1-UTC from VLBI for positioning and navigation purposes. Thus, it is essential that VLBI delivers these parameters with high accuracy and short latency.

As IVS analysis center, BEV and TU Wien are analyzing VLBI sessions from the IVS, thereby routinely providing UT1-UTC next to other parameters. We submit our estimates to the International Earth Rotation and Reference Systems Service (IERS) for combination. Additionally, we are developing and organizing special Intensive sessions such as European Intensives on the baseline Wettzell (Germany) to Santa Maria (Azores) and we are scheduling INT9 sessions between Wettzell and AGGO in Argentina.

3. Austrian realization of UTC at BEV

The Bureau International des Poids et Mesures (BIPM) in Sèvres close to Paris organizes the international network of time links to compare local realizations of UTC in contributing laboratories and uses them in the calculation of TAI and UTC. This network of time links used by the BIPM relies on observations of GNSS satellites and on two-way satellite time and frequency transfer (TWSTFT). TAI and UTC are formed monthly by a combination of data from about 500 atomic clocks operated by more than 80 timing centres which maintain a local UTC(k). BEV participates in these comparisons with its three atomic clocks (two caesium standards and one hydrogen maser, see Figure 2) and realizes UTC(BEV) valid as official time scale for Austria.

Most time links are based on GPS satellite observations and the data from multi-channel dual-frequency GPS receivers are regularly used in the calculation of time links, in addition to that acquired by a few multi-channel single-frequency GPS time receivers. For those links realized using more than one technique, one of them is

Fig. 2: *Laboratory with atomic clocks at BEV*

considered official for UTC and the others are calculated as back-ups. GPS links are computed using the method known as “GPS all in view”, with a network of time links that uses the *Physikalisch-Technische Bundesanstalt (PTB)* as a unique pivot laboratory for all the GPS links. GPS data are corrected using precise satellite ephemerides and clocks produced by the International GNSS Service (IGS). The links between laboratories equipped with dual-frequency receivers providing Rinex format files are computed with the Precise Point Positioning (PPP) method. GLONASS links are computed using the “common-view” method. GLONASS data are corrected using the IAC ephemerides SP3 files and the CODE ionospheric maps. A combination of individual TWSTFT and GPS PPP links and of individual GPS and GLONASS links are currently used in the calculation of TAI and UTC.

Once a month the BIPM informs the individual institutes in the publication *Circular T* about the deviations of UTC(k) to UTC (see Figure 3). By occasional corrections the deviations of UTC(BEV) to UTC are always kept smaller than 100 ns.

Additionally the weekly rapid solution UTCr is published by the BIPM. It allows weekly access to a prediction of UTC for about 50 laboratories which also contribute to the regular monthly publication. However, the final results published in *Circular T* remain the only official source of traceability to the SI second for participating laboratories.

4. Leap seconds

Due to tidal friction, Earth rotation is slowing down. As a consequence, leap seconds have to be inserted in UTC to keep the difference between UTC and UT1 smaller than one second. The last leap second had to be set at the end of 2016 (see Figure 4). In general, leap seconds cannot be predicted, but UT1-UTC needs to be observed with VLBI. It should be mentioned that there is an ongoing discussion about the abolition of leap seconds, but no decision has be taken.

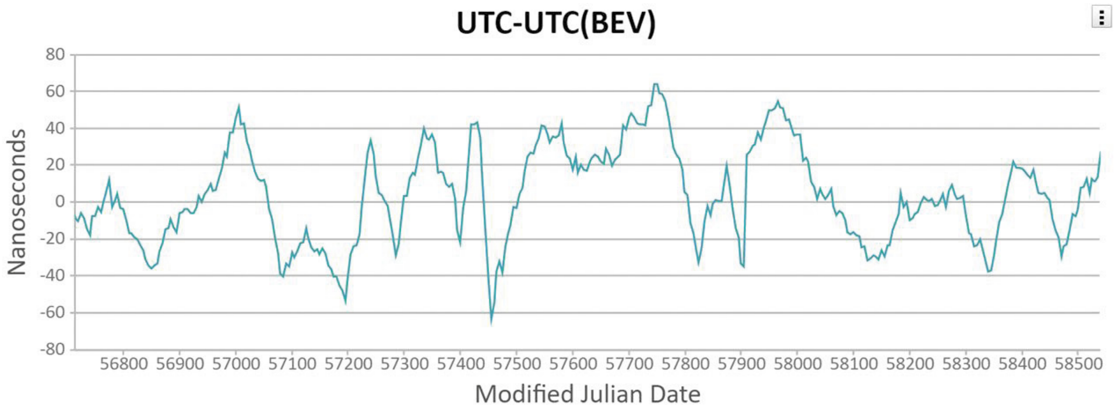

Fig. 3: UTC minus UTC(BEV) in nanoseconds as provided in Circular T *over the past five years (2014 - 2019) [from https://www.bipm.org/en/bipm-services/timescales/time-ftp/Circular-T.html]*

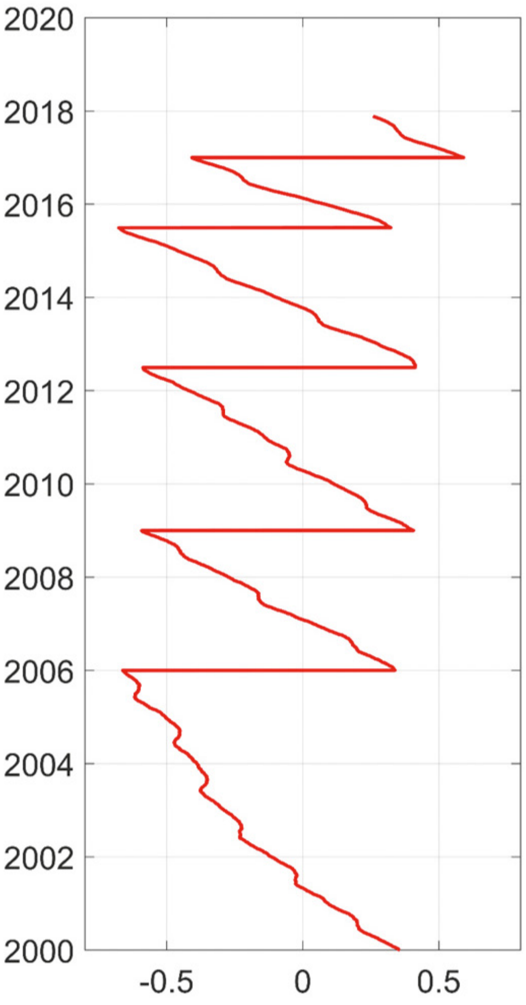

Fig. 4: UT1-UTC in seconds as observed with VLBI and leaps seconds since 2000.

5. Summary and outlook

BEV and TU Wien are making very valuable contributions to the realization of UTC and UT1, at a national and an international level. The reliable realization of those time scales is indispensable for a large variety of tasks. In future, it will certainly be important to also follow modern developments such as new optical clocks or new VLBI observing scenarios.

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Vermessung & Geoinformation 2/2019, S. 78 – 82, 2 Figs.

Atmosphere Monitoring by means of GNSS – Research Activities at TU Wien

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Abstract

GNSS signals experience delays as well as bending effects when passing the atmospheric layers. Both effects usually are summarized under the term atmospheric refraction. While the troposphere is a non-dispersive medium for microwaves the ionosphere is dispersive and therefore causes so-called code signal delays as well as phase advances. The multitude of nowadays available GNSS satellites and signals allows to choose among signal linear combinations preferable for atmosphere monitoring as well as an optimized observation geometry. GNSS signals are therefore excellent sensors to describe the state and variability of the ionospheric and tropospheric layers. Modelling the tropospheric and ionospheric refraction by means of GNSS signals constitutes an essential scientific core area at the research division Higher Geodesy of the Department of Geodesy and Geoinformation at TU-Vienna since 20 years. This article outlines some of the related research projects.

Keywords: GNSS Atmosphere Modelling, Tropospheric Refraction, Ionosphere Modelling

Kurzfassung

GNSS-Signale erfahren beim Durchlaufen der atmosphärischen Schichten abhängig vom variablen Refraktionsindex Verzögerungen bzw. Beschleunigungen im Vergleich zu einer Ausbreitung im Vakuum als auch eine veränderliche Krümmung des Strahlenweges. All diese Effekte werden üblicherweise unter dem Begriff atmosphärische Refraktion zusammengefasst. Die Vielzahl der heute verfügbaren GNSS-Satelliten und Satellitensignale erlaubt Optimierungen der Beobachtungsgeometrie und der verwendeten Signal-Linearkombination. GNSS-Signale stellen somit hervorragende Sensoren zur Beschreibung des Zustandes und der Variabilität der ionosphärischen und troposphärischen Schichten dar. Aus diesem Grund ist die Modellierung der troposphärischen und ionosphärischen Refraktion mit Hilfe von GNSS-Signalen seit fast 20 Jahren ein wesentlicher wissenschaftlicher Schwerpunkt am Forschungsbereich Höhere Geodäsie des Departments für Geodäsie und Geoinformation der TU-Wien. Der vorliegende Artikel gibt einen Überblick über eine Auswahl dieser Forschungsarbeiten.

Schlüsselwörter: GNSS-Atmosphärenmodellierung, Troposphärische Refraktion, Ionosphärenmodelle

1. Tropospheric Delay

Based on multi-frequency observations from a GNSS reference station network with adequately dense spatial resolution, both the hydrostatic as well as the wet component of the tropospheric delay can be estimated. In most cases the mostly stable hydrostatic part is covered by a model and therefore just the highly variable wet part is usually subject of the estimation process. The model parameters are so-called zenith wet delays as well as tropospheric gradients which describe the non-asymmetry of the delay with respect to the zenith. The relation between the zenith delays and the delays in line of view is determined by so-called mapping functions. The most precise mapping functions are derived from numerical weather models and can be used also for other space techniques than GNSS.

1.1 Tropospheric Mapping Functions

With the publications of the Vienna Mapping Functions (Böhm and Schuh, 2004, [1]) and the Global Mapping Functions (Böhm et al., 2006, [2]), the Department of Geodesy and Geoinformation at TU Wien has become a prime address in the modeling of troposphere delays for space geodetic techniques. The troposphere delay products had been determined on a daily basis and made available to the public via the server *ggosatm.hg.tuwien.ac.at* for more than 15 years. Thus, research institutes, organizations as well as private companies all over the world could use these products in their analyses and computations.

In April 2019, a new era has begun for the Vienna troposphere delay products. The GGOSATM server was replaced by the new, more comprehensive VMF data server, available at *vmf.geo.tuwien.ac.at*. This step was associated with a set of innovations:

- The latest model for the provision of discrete troposphere delays, the Vienna Mapping Functions 3 (VMF3; Landskron and Böhm, 2018a, [5]), is provided for all GNSS, VLBI and DORIS stations on Earth as well as on a global grid in two different horizontal resolutions. Just like VMF1, it is computed by means of ray-tracing through numerical weather models (NWMs) by the European Centre for Medium-Range Weather Forecasts (ECMWF), based on considerably more sophisticated algorithms though. VMF3 is available for three different NWM representations: the standard product (Operational) is published always one day in retrospect, while the forecast product comes one day in advance. In addition, there is also a VMF3 for re-analysis NWMs starting in 1980.
- A new model for horizontal troposphere gradients referred to as GRAD (Landskron and Böhm, 2018b, [6]), provided for the same NWMs and spatial representations as VMF3, models the variation in troposphere delay with azimuth. This is particularly important for observations at low elevation angles.
- The new empirical troposphere delay model Global Pressure and Temperature 3 (GPT3; Landskron and Böhm, 2018a, [5]) is a refined version of GPT2w and is fully consistent with VMF3. In addition to empirical mapping function coefficients and a number of meteorological parameters, it contains also empirical horizontal gradients on a global grid, available in 5°x5° as well as 1°×1° horizontal resolution.
- Ray-traced delays for every single VLBI observation since the advent of geodetic VLBI in 1980 are provided and regularly updated on the VMF server as well. Being the most rigorous and direct representation of troposphere delays, ray-traced delays may help to further improve output quantities of VLBI analyses such as Earth Orientation Parameters, in particular the irregularity of Earth rotation, dUT1.
- For GNSS and DORIS users, an individual ray-tracing tool constitutes a handy instrument to obtain accurate troposphere delays at arbitrary observation angles and times.
- Our ray-tracing software RADIATE (Hofmeister and Böhm, 2017, [4]), being the basis for the determination of all abovementioned troposphere models, is henceforth freely available via GitHub at *github.com/TUW-VieVS/RADIATE*. Thus, users can extend the range of applications by means of autonomously creating ray-traced delays for any NWM and any point on Earth.
- In the near future, RADIATE will also be capable of computing ray-traced delays for optical wavelengths and thus allowing for optical versions of VMF3, GPT3 and GRAD. This will help further improving the accuracy of tropospheric delay modeling in SLR.

Older troposphere delay models such as VMF1, GMF or GPT are provided on the VMF server further on. In addition to the troposphere delay models, there are also atmospheric pressure loading datasets on a global 1°×1° grid, updated on a daily basis as well. With this abundance of realizations and models, the Department of Geodesy and Geoinformation at TU Wien substantiates its position as a main provider of troposphere delay models for space geodetic techniques.

1.2 GNSS Tropospheric Parameters for NWP

In cooperation with the Austrian Central Institute for Meteorology and Geodynamics (ZAMG), the Department of Geodesy and Geoinformation investigates the benefits of using tropospheric GNSS products in Numercial Weather Predicition (NWP) models. Hourly Zenith Total Delays (ZTDs) and gradients are estimated from double-differenced network solutions using the Bernese software (Dach et. al, 2015, [3]). The station network used in the processing includes 71 stations, operated by different national GNSS reference stations providers or from the International GNSS service (IGS).

The tropospheric estimates are provided to ZAMG in near real-time (approximately 45 minutes delayed) via the department's web server on a regular basis. At ZAMG the data is used for assimilation into the Austrian version the NWP model AROME. After a series of case study model runs and subsequent forecast verifications, the assimilation of ZTD is now ready for operational mode. Several studies and tests have shown the benefits of ZTD assimilation into AROME, especially for precipitation forecasts.

A current cooperation between ZAMG, ETH Zurich and our research division within the ASAP14 project *GNSSnow* investigates the impact of Slant Total Delay (STD) assimilation in NWP. A major goal is to assess the benefits of using STDs instead of ZTDs. Furthermore a closer to real-time (less than the 45 minutes delay) processing and data delivery to ZAMG is strived for. This would improve data availability of short-time forecasts and nowcasting with AROME.

1.3 Troposphere Tomography

GNSS troposphere tomography is a technique that aims to obtain 3D information about humidity in the lower atmosphere based on GNSS signal delays. For tomography the three dimensional domain above the area of interest is usually subdivided in cuboids (voxels) with a horizontal resolution of a few tens of kilometers and a vertical side length of about 1 km. As the slant wet delay (SWD) observations gathered from a network of GNSS reference stations can be interpreted as the integral of the wet refractivity along the ray path, the inversion of the SWDs can lead to the estimation of the wet refractivity distribution.

Nevertheless, GNSS tomography suffers from several problems. What is most striking is that not all voxels of interest are covered by intersecting signal rays. This leads to ill-conditioned normal equation systems to recover the refractivity coefficients. Various algorithms have been established to solve these ill-posed equation systems. Appropriate inversion methods are described in the PhD-thesis of G.Möller [8] and will be further studied at our research division. Currently another PhD-thesis studies the combination of refractivity fields obtained from tomography and radio occultation profiles. These improved fields are assimilated and tested in numerical weather models. The authors assume that GNSS-tomography, potentially supported by Radio-Occultation profiles and radiosonde observations, will very soon become the standard technique to process GNSS observations for troposphere sounding.

2. Ionosphere Modelling

The ionosphere is usually indicated as the atmospheric layer comprising a large number of ions and free electrons. The lower bound of the ionosphere is located about 60 km above the Earth's surface and reaches the largest electron density at about 300 km – 350 km (F2 layer). The ionosphere extends up to 1000 km before it migrates there into the plasmasphere. The ionospheric delay essentially affects the GNSS-range measurement and therefore positioning with GNSS. While the ionospheric delay can be almost eliminated by the dual-frequency ionospheric-free linear combination, single frequency receivers have to apply ionospheric models.

2.1 Regional Ionospheric Model

The Research Division Higher Geodesy conducts also a number of studies in ionosphere modelling. Based on dual-frequency phase observation data of Austrian GNSS reference stations as well as some further international stations, a regional VTEC-model is calculated on an hourly basis for post-processing applications. The model can be employed by any user located within the Austrian territory providing corrections to low elevation angles down to 5 degrees. Comparisons with reference models certify our model an accuracy of about +/-1 TECU. Moreover another global model especially developed for real-time applications is made available. This model referred to as GIOMO (Magnet, 2019, [7]) is based on phase-smoothed pseudo-range observations and performs slightly worse than the previous one. Nevertheless, GIOMO parameters can be easily predicted and the model allows to correct about 70 % of GNSS-range measurements with sub-meter accuracy even down to low observation angles.

2.2 Galileo Reference Center

Since 2018 the Department of Geodesy and Geoinformation is partner in the GRC (Galileo Reference Centre) Member States consortium established by the GSA (European GNSS Agency). The aim of this activity is to study and analyze the performance of the broadcast NeQuick-Gal and Klobuchar ionospheric models in different latitudinal regions. Regular reports are issued to the Galileo Reference Center (GRC) since October 2018. Based on multi-GNSS observations from sites of the IGS, IGS-MGEX and EPOSA networks, maps of VTEC differences with respect to an internal and an external reference model (CODE) are established. For example, bi-hourly VTEC difference graphs of DOY 274, 2018 are visualized in Figure 2.

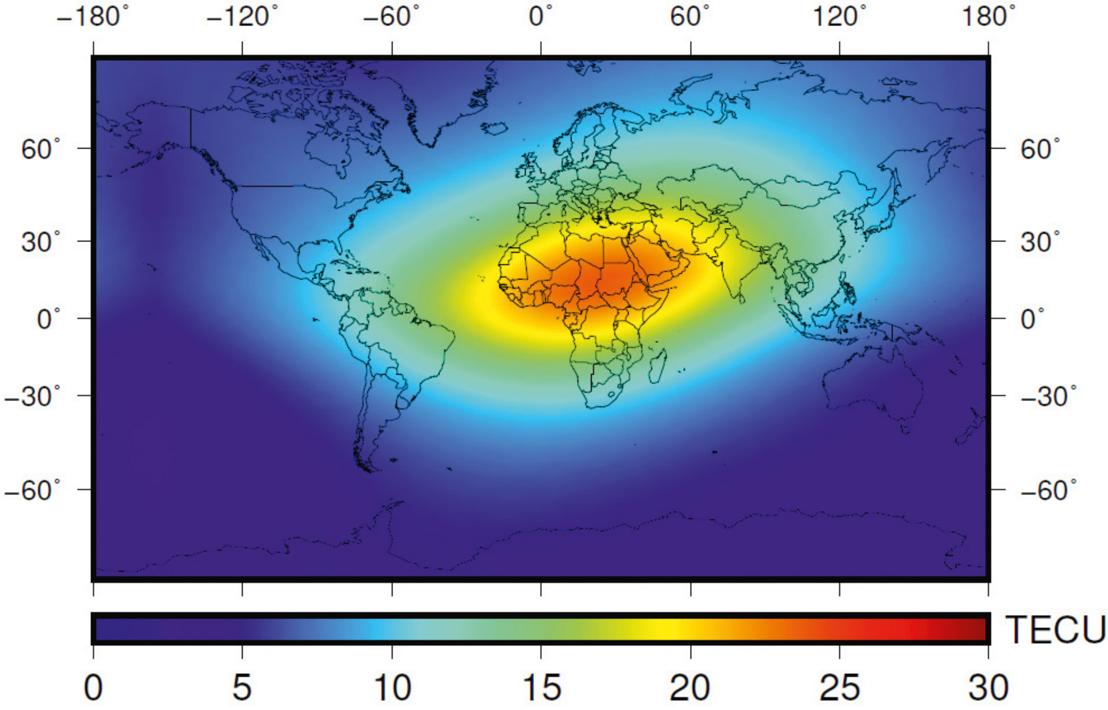

***Fig. 1:** VTEC map, May 1st, 2018, 14 UTC modelled by GIOMO*

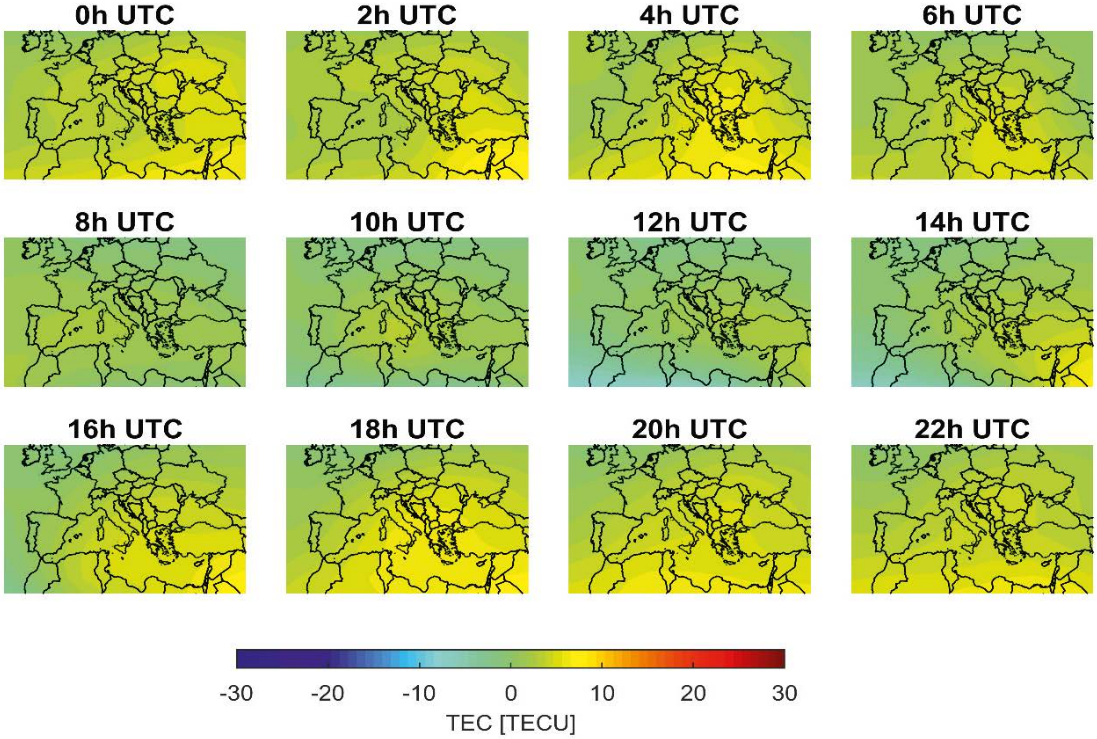

***Fig. 2:** Daily VTEC difference maps DOY 274/2018 - CODE minus NeQuick-Gal*

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Vermessung & Geoinformation 2/2019, S. 83 – 94, 18 Figs.

Detection and mitigation strategies for GNSS interference attacks

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Abstract

The use of global navigation satellite systems (GNSS) and the associated potential of the permanent availability of position and precise time measurements as well are playing a more and more important role in many areas of our daily life. With the steadily increasing number of applications and users, it is mandatory to think not only about the opportunities, but also about the weaknesses and risks of satellite-based positioning. Many users are currently unaware of the potential threats and their effects. In recent years, GNSS applications have become increasingly the target of deliberate interference attacks. This paper describes the impact of intentional interference (i.e., jamming and spoofing) on a software-defined receiver. In case of jamming, two state-of-the-art mitigation strategies focusing on adaptive filtering and blanking are explained in detail and their benefits are shown using simulated interference signals. In case of spoofing, different detection and mitigation techniques are discussed and two algorithms and their results are presented in detail.

Keywords: GNSS, jamming, spoofing, antenna array, notch filter, pulse blanking

Kurzfassung

Die Verwendung von globalen Satellitennavigationssystemen und das damit verbundene Potential der ständigen Verfügbarkeit einer Position sowie einer genauen Zeitmessung spielen in vielen Bereichen des täglichen Lebens eine immer größere Rolle. Durch die stetig steigende Zahl von Anwendungen und Nutzerinnen sowie Nutzern wird es zunehmend wichtiger, sich nicht nur über die Chancen, sondern auch über die Schwächen und Risiken einer satellitengestützten Positionsbestimmung Gedanken zu machen. Viele Anwenderinnen und Anwender sind sich des damit verbundenen Gefahrenpotentials und dessen Auswirkungen derzeit nicht bewusst, obwohl in den letzten Jahren GNSS-Anwendungen vermehrt das Ziel von Störattacken wurden.

In diesem Beitrag werden die Auswirkungen beabsichtigter GNSS Interferenz (d.h. Jamming und Spoofing) auf einen softwarebasierten Empfänger beschrieben. Im Fall von Jamming werden zwei unterschiedliche Mitigationsstrategien basierend auf adaptiver Filterung und Blanking im Detail erläutert sowie deren Leistungsfähigkeit anhand simulierter Interferenzsignale gezeigt. Im Fall von Spoofing werden unterschiedliche Detektions- und Mitigationsstrategien diskutiert und zwei ausgewählte Algorithmen präsentiert.

Schlüsselwörter: GNSS, Jamming, Spoofing, Antennenarray, Kerbfilter, Impulsunterdrückung

1. GNSS jamming

Jamming denotes the operation of drowning the navigation signals in high-power signals to cause loss of tracking lock and to prevent reacquisition so that a GNSS receiver cannot calculate a correct position solution. GNSS signals are particularly vulnerable to interference due to their low transmit power and the large distance between satellite and receiver. Theoretically, a 10 milliwatt jammer at a distance of 10 kilometres would be sufficient to prevent a Global Positioning System (GPS) C/A-code receiver from calculating a position solution [5]. In the civilian area, jammers, also called personal privacy devices (PPDs), are used by a wide variety of user groups to protect privacy, to shadow criminal activities or even to protect critical infrastructure. For many years, the availability and faultless operation of GNSS has been taken for granted. Jamming as well as spoofing concerned military users only. However, recent events started a gradual paradigmatic shift [6]. For example, the ground-based augmentation systems (GBAS) near airports of the United States and Taiwan were disrupted up to 117 times a day, mostly caused by truck and taxi drivers trying to hide their routes using PPDs. In 2007, a US warship entered San Diego Harbour, still activating its jammers. This resulted in failing emergency pagers, disruption and failure of the traffic management system. Jammers are cheap, easy to buy and very effective. The jamming impact of intentional interference depends on the one hand on the interference signal power and on the other hand on the spectral characteristics of the jamming signal where different types of jamming signals can be distinguished. Based on the bandwidth of the jamming signal, they can be divided into narrowband, wideband and continuous-wave interference. Based on the frequency and amplitude characteristics, a classification into continuous wave (CW), swept-continuous wave (SCW), frequency modulated (FM) and amplitude modulated (AM) jammer is possible.

According to [7] most jammers, available on the market, jam the GNSS L1/E1 band using a SCW signal. SCW signals are characterized by a constant amplitude but a periodically changing frequency using a saw tooth function. Apart from continuous jamming signals, pulsed interference signals exist. Following [8], pulsed signals are characterized by an on-off status of short duration and are mainly caused, in case of GNSS, by aeronautical radio navigation services (ARNS) like distance measuring equipment (DME) and tactical air navigation (TACAN). Pulsed signals can be described by the pulse width (length of a pulse), duty cycle (percentage of time that is occupied by the pulses) and the pulse repetition rate (number of pulses per second). More about the classification of interference can be found in [9].

1.1 Impact of GNSS jamming

Jamming signals affect both the received signal strength and the signal quality. In a first step, within the receiver internal signal processing chain, it causes a saturation of the analogue-to-digital converting (ADC) process which may result in clipping (signal amplitude exceeding the hardware capability). The automatic gain control (AGC) causes a further degradation of the useful authentic signal, reducing the signal-to-noise ratio (SNR) as well as the carrier-to-noise-density ratio (C/N0). This increases the time needed for signal acquisition (if the acquisition possible at all) and, thus, the time-to-first-fix. In addition, the number of satellites in the signal tracking is reduced and, consequently, fewer observations are available for the position calculation. The low C/N0 also causes the demodulated navigation bits to flip and therefore the decoding of the navigation message may become unsuccessful. The accuracies of the pseudorange and phase measurements are significantly reduced, due to the lower C/N0, causing a significant deterioration of the positioning accuracy up to the total failure of the positioning. In case of phase measurements, cycle slips occur more often.

1.2 Jamming detection and mitigation

A reliable detection of jamming signals is the first step towards successful mitigation. There exist different detection strategies, which are based on observing different quantities at different stages of signal processing, like AGC monitoring, monitoring of the spectral behaviour of the received signal, C/N0 monitoring, pseudoranges or Doppler monitoring or position, velocity, and time (PVT) monitoring. In order to increase the detection probability, different algorithms should be combined. After the detection, a classification is performed to obtain the spectral characteristics in order to select the most proper mitigation strategy. The methods for classification comprise short-time Fourier transform analysis as well as frequency response analysis. Once the interfering signal is detected and classified, mitigation strategies can be applied. According to literature, mitigation strategies can be defined in the frequency, in the time, and in the space-time domain, where each domain offers its advantages and disadvantages. In general, the frequency domain is used to filter out harmonic components of the interfering signal but preserving as far as possible the authentic signal. It is effective if the interfering signal occupies only a limited portion of the spectrum. The time domain is useful in case of pulsed interference. One technique, called Pulse Blanking (PB), monitors the quantized digital signal values. If a sample exceeds a defined threshold, the affected samples are set to zero. Other methods are clipping, limiting, or adaptive analogue-to-digital conversion, which are used to prevent the digital receivers from saturating, and mitigate in particular the influence of high energetic pulsed interferences. The performance of these algorithms is limited by the duty cycle. Time-space domain techniques use multiple antennas (i.e., antenna arrays) to perform a digital beamforming or null steering in order to virtually make the antenna insensitive towards the direction of interference signal arrival. Since most of the jamming signals are either SCW or pulsed, this paper focuses on the frequency and time domain, investigating the performance of Adaptive Notch Filter (ANF) and the PB algorithms.

A notch filter is a band-stop filter with a large passband frequency response and a very narrow portion of a rejection spectrum [8]. The frequency response of a notch filter is shown in Figure 1.

The notch filter is characterized by the attenuation bandwidth, which defines the bandwidth of the rejection spectrum. A low-bandwidth notch filter removes only a narrow portion of the spectrum, while the remaining signal is not or only by a few dB suppressed. If the attenuation bandwidth is set too large, the interfering signal will be attenuated and also parts of the useful signal may be suppressed. The NF represents a good strategy for mitigating interference if the jamming frequency is known and constant. In most cases, however, the frequency is an unknown parameter that changes its value over time. In this case, the ANF can be used. Adaptive notch filtering aims to estimate the unknown frequencies of periodic components buried in noise and/or retrieve such periodic components [10]. To estimate the (changing) frequencies, an adaptive unit is used. The basic structure for the bipolar ANF with an adaptive unit is shown in Figure 2.

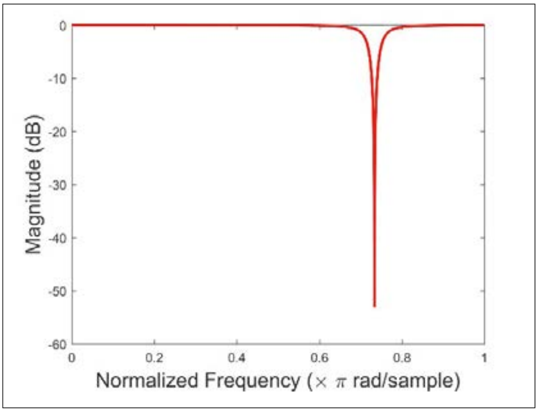

Fig. 1: *Frequency response of the notch filter*

In Figure 2, $y_{IF}(\mathrm{n})$ represents the input signal sample and $x_{IF}(\mathrm{n})$ denotes the filtered output signal. The numerator of the filter transfer function is defined as a moving average block and the denominator represents the autoregressive (AR) block [8]. The jammer frequency detection algorithm is based on the removal of the constraint on the location of the filter zeros in the complex plane. According to [8], their amplitude is adjusted by the adaptive unit. More information on the ANF design and implementation methods is provided in [10], [11] and [12].

Beside the attenuation bandwidth, the ANF uses an additional input parameter, called forgetting factor. The forgetting factor, which has to be chosen between zero and one, determines how fast the filter can react to frequency changes and, thus, how stable the notch frequency can be estimated over time. A forgetting factor of zero means that the ANF uses no information of the previous notch frequency estimation for the computation of the actual frequency. A forgetting factor close to one means that the ANF uses only information from the previous epoch to compute the current notch frequency. A smaller forgetting factor causes a faster reaction on frequency changes, which is very important for jammers with fast frequency changes like SCW or FM jamming signals. On the other hand, the variance of the notch frequency is increased resulting in a lower stability of the ANF

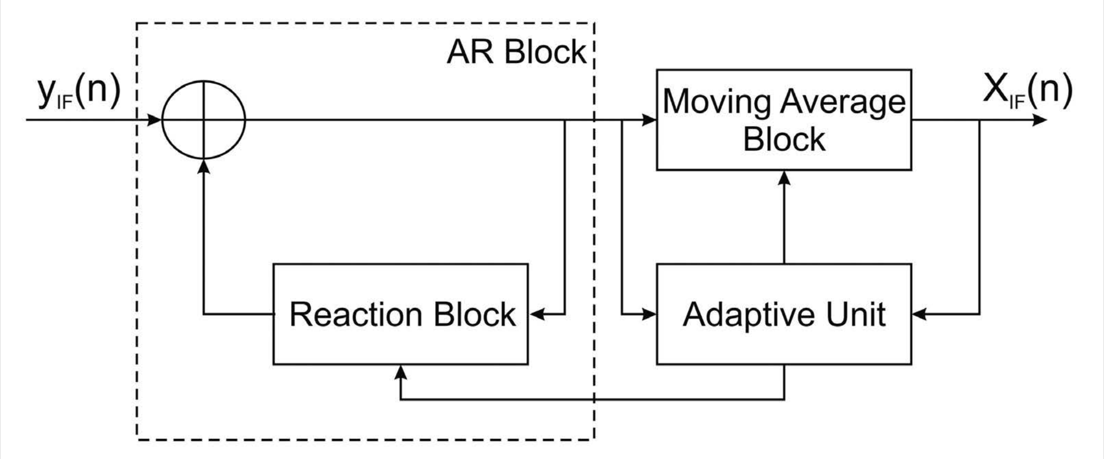

Fig. 2: *Basic structure of the adaptive notch filter*

and a lower quality of estimation. A larger forgetting factor will result in a more stable solution but may respond to the frequency changes with some delay. This is usually used in case of AM or CW signals.

As mentioned before, ANF is mainly used in case of continuous interfering signals. In case of pulsed interference, a time domain approach – pulse blanking (PB) – is more suitable. The PB technique is a low-cost and low-complexity pre-correlation technique that is applied on the data after the ADC and prior to the AGC and acquisition.

The quantized incoming digital signal values are constantly monitored and if a sample, containing interference, exceeds a defined threshold, the affected samples are set to zero. The pulse detection relies on the fact that the pulses are short and have a significant higher amplitude than the GNSS signal. The pulse detection may be done using different techniques, like analogue power measurements, analysing the histograms of the ADC output levels or by instantaneous power estimates [13]. From the input samples, the received power can then be calculated and compared to a decision threshold. The data can be additionally smoothed using a filter or a moving average. Furthermore, the setting of a threshold is important. The threshold has to be chosen low enough to detect (weak) pulsed interference signals, but it has to be chosen high enough to not zero too much of the useful signal. Therefore, a plausible threshold for suppression has to be found. [14] investigated the choice of a decision threshold for pulse blanking. The smallest signal degradation (-8.1 dB) happened at a decision threshold of -117.1 dBW. The PB method shown in Figure 3 demonstrates the impact on the complex signal.

The pulse blanking is not the perfect technique because during the pulse zeroing not only the pulse is suppressed, but also the useful GNSS signal. Many pulsed signals have a Gaussian

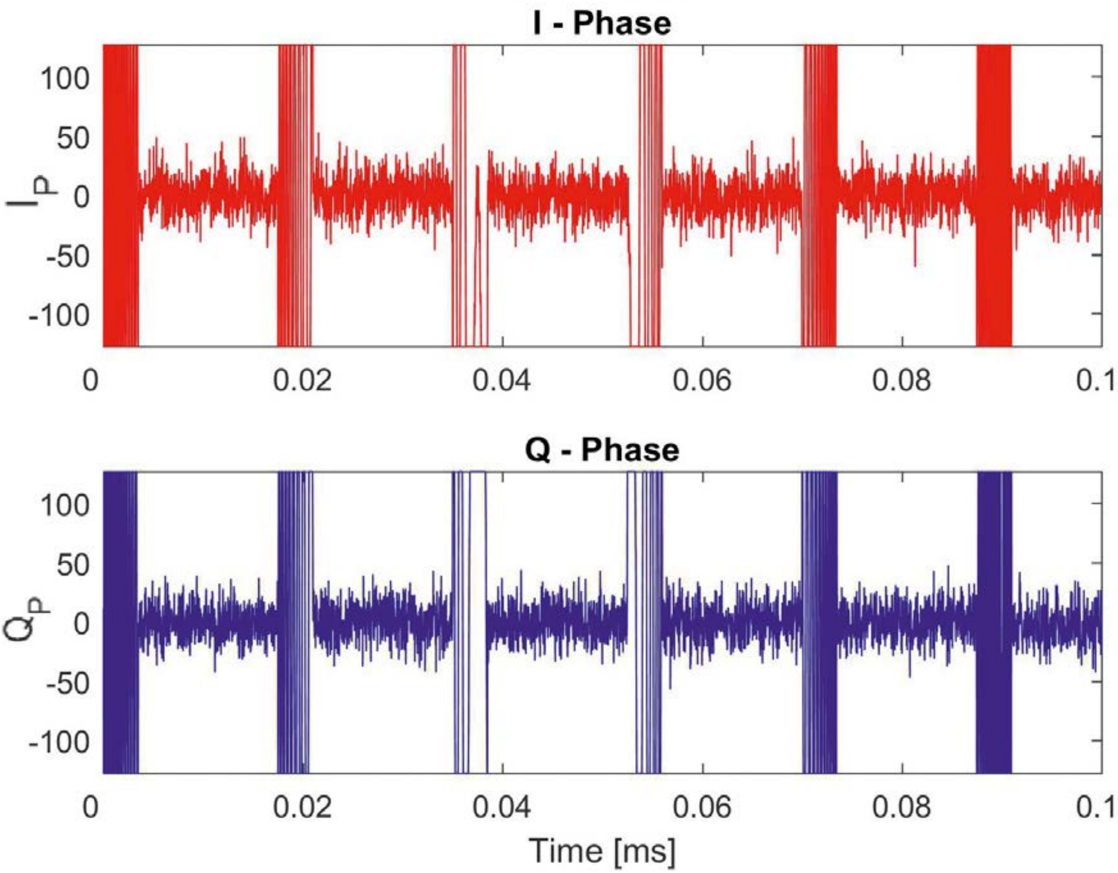

***Fig. 3:** The principle of pulse blanking (left without PB and right after PB)*

shape, which means that the pulse borders having a smaller power and amplitude are not suppressed at all [8]. Pulse blanking has to be done using a multi-bit ADC. If a single bit ADC is used, all samples have the same magnitude and it is not possible to distinguish between interference and useful signal. Furthermore, the pulse blanking should happen before the AGC. The AGC equals the signal samples and, thus, no pulse detection by amplitude discrimination is possible after that. The pulse blanking is widely-used in aviation scenarios.

2. GNSS spoofing

Spoofing denotes the manipulation, deception, or counterfeiting of GNSS signals with the aim to set a receiver to a wrong position by means of deliberately manipulated signals or to manipulate the time signal in a targeted manner. Meaconing can be considered as the simplest form of spoofing. In this case, the attacker records real GNSS signals and reradiates them again with a minor delay and with a slightly higher signal power compared to the original signal. As a result, the attacked receiver processes the delayed signals instead of the true ones and, thus, calculates an incorrect position solution. In contrast, a spoofer generates GNSS signals that match a previously set receiver position and transmits them at a slightly higher power. Depending on the effort, spoofing is classified into simple, advanced, and sophisticated attacks [8], depending on the equipment used and sophistication of the take-over algorithms.

For performing a spoofing attack, a GNSS signal simulator, sometimes in combination with a reference receiver, is used to generate and broadcast the counterfeit signals of visible satellites that are in the victim's view. In a first step, the spoofer tries to alter Doppler and code-offset of its broadcast signals to align with the ones from the real satellites. After a successful alignment, the correlation peak of the fake signal overlays with the authentic one. At this point, the power of the spoofing signals is still kept low, showing no indications to the victim. Now the attacker slowly increases the power of its signals until the victim's receiver tracking loop locks onto them. Once the receiver has been taken over, the spoofer can drag away its correlation peak by altering the broadcast signal properties as desired, yielding a false PVT solution for the victim's receiver.

Figure 4 shows the correlation function of one tracking channel of a victim receiver during a spoofing sequence. The blue line shows the correlation function of the authentic signal with the generated replica signal within the receiver. The three red dots indicate the early, prompt and late (EPL) correlation values. The green line represents the correlation function of the spoofing signal with the replica, while the red line shows the correlation function of the sum of the authentic and spoofing signal. At the beginning, no spoofing signal is present. At a certain point of time, the spoofing signal is visible but does not influence the EPL correlation values. Once the spoofing signal starts to interact with the authentic signal, the EPL values are affected and the power of the spoofing signal is increased. After the EPL correlations values have been taken over, a drag-off is done and the spoofer has gained control over the tracking loop. The threat of spoofing is no fiction but has rather become reality in recent years. Referring to [15] and [16], several incidents have been reported in the past.

2.1 Spoofing detection and mitigation

As in the case of jamming, detection of counterfeit signals is a prerequisite for mitigation algorithms and serves as a warning to the user not to trust the PVT solution any longer. Mitigation algorithms aim at maintaining the nominal receiver operations and trying to guarantee that no hazardously misleading information (HMI) is produced and used. In addition, some strategies aim at locating the source of the emitted false signals so that appropriate action can be taken. There exist different state-of-the-art spoofing detection methods that use different results of the internal receiver signal processing for detection. In case of static

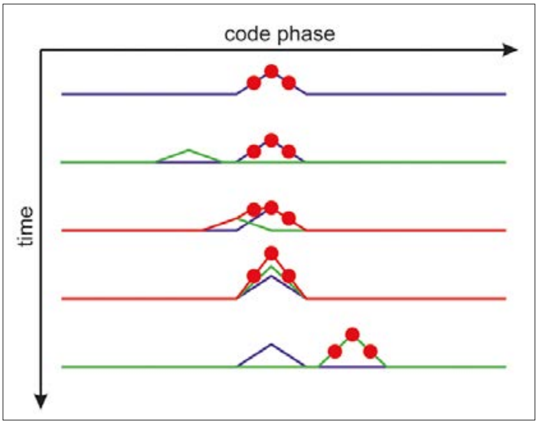

Fig. 4: Spoofing attack seen from victim's tracking channel point of view

applications, the PVT output can be monitored. Since a spoofing signal must have higher power compared to the authentic signal to successfully spoof the receiver, the received signal power can be used as an indicator. Also, the estimated SNR and C/N0 values can be used for detection since, in case of spoofing, they are expected to be higher due to the increased signal power. In case of a dynamic application, the carrier phases of different authentic satellite signals vary differently based on the motion of the receiver and the associated direction of signal arrival. This is not the case if the spoofing signals are transmitted from a single antenna since during a spoofing attack the authentic signal is still present (cf. Figure 4). By monitoring the full cross-correlation function, instead of EPL values, multiple correlation peaks appear. Another detection and mitigation method is based on estimating the direction of the spoofing signal arrival. This can be achieved by a combined signal processing of multiple antennas, as will be described later. Other methods rely on receiver autonomous integrity monitoring (RAIM), consistency checks with other sensors (e.g., inertial measurement units) or cryptographic authentication of the satellite signal.

Within [17] a detection method based on spatial correlation of Doppler residuals was investigated. This principle exploits the property of high correlations between signals emitted by the same source. Referring to [18], measurements coming from a single source have essentially the same power spectral density and virtually the same channel gain for any space-time point. If a receiver is static, all channel gains of the authentic and spoofed signal pairs are similar and, thus, highly correlated. But as soon as the receiver starts moving, the gains based on the authentic satellites quickly de-correlate over time. This enables a distinction between authentic and spoofed signals. [17] investigated this method using Doppler measurements. By comparing the measured Doppler frequency and the theoretical one, the spatial correlation of the spoofing signals is high in case the receiver is moving. Figure 5 shows the residual Doppler values (differences between measured Doppler frequencies and theoretical ones) during a spoofing event, where only two satellites (i.e. PRN8 and PRN21) out of eight have been spoofed for a kinematic receiver.

While the residual Doppler values sourcing from the authentic satellites randomly scatter around 0 Hz, the two spoofed satellite signals show deviations of up to 80 Hz. As shown in Figure 6, the correlation values are high during the whole time span of around two minutes due to the same relative movement of the receiver. The cross-correlation coefficient between PRN8 and PRN21 is 1, while the other values are close to zero. Note that the correlation for every signal with itself (auto-correlation) also yields 1.

By using multi antenna arrays, the direction of arrival of incoming signals can be estimated. Some algorithms offer the estimation of several signal sources simultaneously depending on the number of array elements. For the case of authentic GNSS satellites, every signal is received from a different direction at the antenna. There are several types of antenna arrays. Uniform linear arrays or uniform circular arrays are the most popular ones.

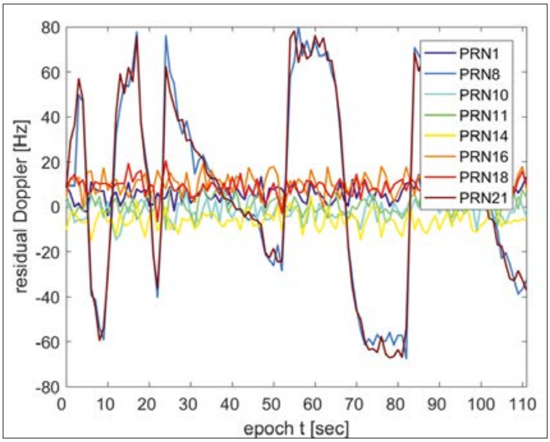

Fig. 5: Difference between measured and theoretical Doppler

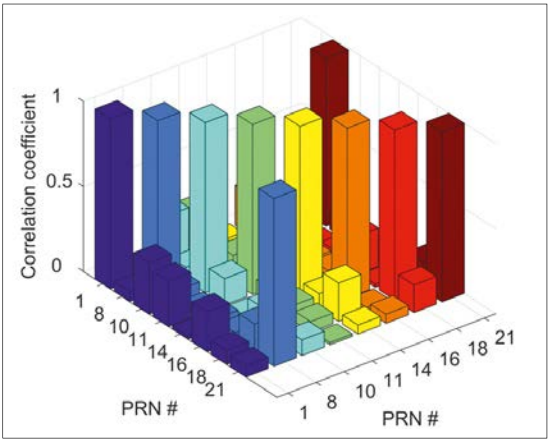

Fig. 6: Spatial correlation coefficients for residual Doppler

The more elements an array contains, the more stable is the estimation of the direction of arrival parameters. Referring to [19], the element spacing is important to avoid ambiguities in the estimated direction angles. For proper results, a spacing of equal or less than half the wavelength λ of the incoming signal is preferred. This limits the size of arrays in case of GNSS, where high frequencies for signal propagation are used. [20] describes several techniques for direction of arrival estimation. As examples, beamforming techniques and subspace-based methods are mentioned. The latter one has proven to deliver reliable results in case of closely spaced signal sources. One of these subspace-based methods is the multiple signal classification (MUSIC) algorithm. In case the algorithm detects an attack, the multi-antenna array can be utilized to determine the direction of arrival of the spoofing signals and, thus, perform a null steering. More information on the MUSIC algorithm is provided in [17].

3. Results

To evaluate the described detection and mitigation strategies, the GNSS multisystem performance simulation environment (GIPSIE®), developed by TeleConsult Austria GmbH, was used. The software is capable of simulating GNSS intermediate frequency (IF) signals. It supports all GNSS, regional and augmentation systems, which are currently available for satellite-based navigation. It enables the simulation of IF signals of multiple systems on different signal bands, the simulation of tropospheric and ionospheric path delays, and the simulation of jamming, spoofing and multipath signals. Furthermore, different RF front-ends with arbitrary settings can be simulated. It was used for this work for simulating different jamming and spoofing signals for GPS L1 C/A and Galileo E1B signals. Figure 7 illustrates a part of the graphical user interface, where the satellite systems and signals can be selected for simulation. More information on GIPSIE® can be found in [21].

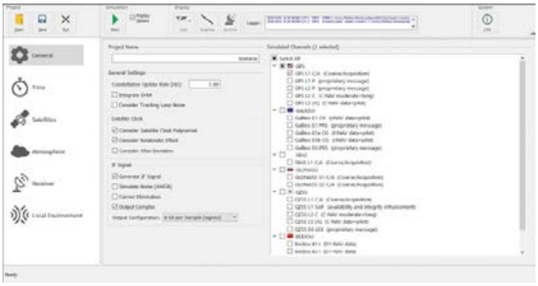

Fig. 7: Graphical user interface of GIPSIE®

3.1 Results of jamming mitigation

To evaluate the previously described jamming mitigation techniques, two simulations using the GIPSIE® simulator were made. In the first simulation, a swept-continuous wave jammer was simulated to evaluate the performance of an ANF. The IF signal was simulated using a sampling frequency of 40 MHz and an intermediate frequency of 0 MHz. The number of the quantization bits was set to 8. Altogether nine GPS and ten Galileo satellites were simulated. The SCW jammer has a frequency offset of 0 Hz, a sweep bandwidth of 40 MHz and a sweep duration of 18 µs. The jamming event has a duration of 10 seconds. To evaluate the effect of the jammer power on the results, the jammer power was varied. At the beginning it was set to -120 dBW. Then it is increased in the first five seconds to -110 dBW and then stays constant till the end of the interference event. The spectrogram of the simulated signal is shown in Figure 8.

The simulated signal was then processed within a software-defined GNSS receiver [22]. The C/N0 during the interference event for Galileo is presented in Figure 9.

During the interference event the C/N0 decreases depending on the jamming signal power: the stronger the jamming power, the lower the C/N0. The receiver loses track of some satellites, due to the jamming signal characteristics and the high power. Figure 10 shows the differences of the

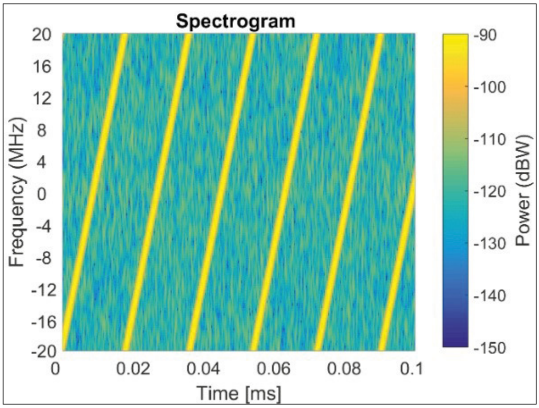

Fig. 8: Spectrogram of the simulated SCW jammer

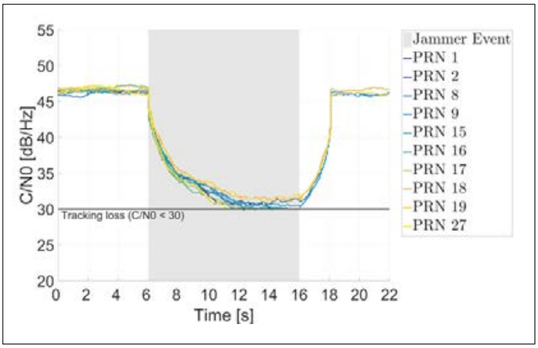

Fig. 9: *C/N0 of the Galileo satellites without activating the ANF*

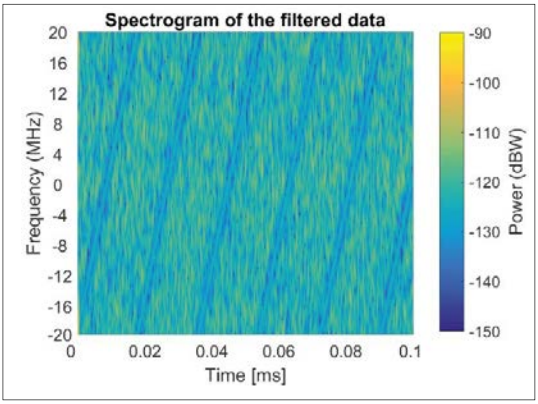

Fig. 11: *Spectrogram of the filtered data*

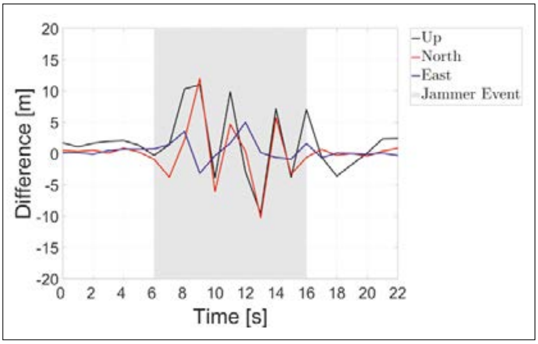

Fig. 10: *Difference to the reference position during the SCW jamming event*

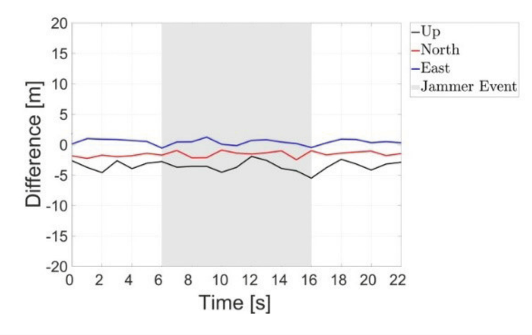

Fig. 12: *Coordinate differences to the reference position after filtering out the jamming signals*

computed positions with respect to the simulated reference position during the jamming event.

The coordinate differences to the reference position get higher during the interference event. Due to the low C/N0, the tracking gets inaccurate resulting in erroneous pseudorange measurements for all satellites. Furthermore, the tracking to some satellites is lost, which means that less observations for the least-squares-adjustment are available, worsening the geometry. In the next step, the ANF was applied on the simulated signal. Different combinations of the input parameters were tested. The optimum solution – chosen for further calculations – was achieved using a forgetting factor of 0.3 and an attenuation bandwidth of π/3. The spectrogram of the filtered signal is shown in Figure 11.

Figure 12 shows the coordinate differences of the obtained position solution with respect to the reference after applying the ANF.

The ANF filters out the interference part of the incoming signal which increases the C/N0 values. This prevents the receiver from losing tracking to satellites; therefore a stable PVT solution can be obtained. However, the C/N0 is slightly lower compared to the interference-free event. The reason for that is that the ANF suppresses not only the interfering signal, but it suppresses also a part of the useful signal. This reduces the carrier power and decreases the C/N0.

For evaluating the PB algorithm, a pulsed jamming signal was simulated using the GIPSIE® simulator, with a pulse width of 3.5 µs and a duty cycle of 0.6. The effect of PB on the simulated signal was already shown in Figure 3. First, the data were processed using the software-defined receiver without applying the pulse blanking algorithm. The C/N0 during this interference event is shown in Figure 13.

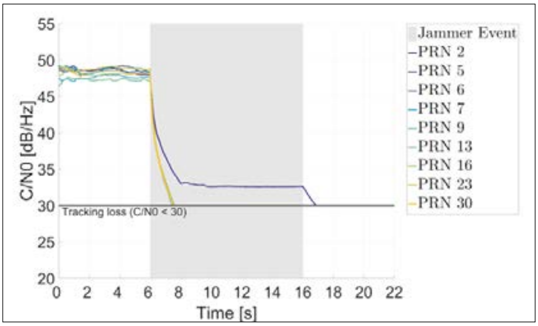

Fig. 13: *C/N0 of the pulsed interferer without pulse blanking*

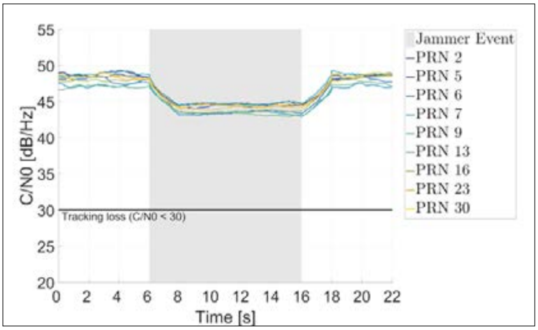

Fig. 14: *C/N0 after pulse blanking*

Due to the high duty cycle, the receiver loses track of all satellites. After applying the BP algorithm on the simulated signal, every satellite could be kept in tracking and only a small reduction of the C/N0 is visible, as shown in Figure 14.

It has to be mentioned that the duty cycle is an important parameter for the signal processing. The higher the duty cycle, the smaller is the amount of useful received signal, which causes worse tracking and positioning quality. The main problem of the pulse blanking algorithm is the pulse detection, especially the choice of the decision threshold.

3.2 Results of spoofing detection

Based on the investigation of residual Doppler correlations, an effective detection and mitigation algorithm has been developed and presented in [17]. For investigating the performance of the proposed algorithm, a scenario has been simulated within the software GIPSIE®. For this scenario, eight authentic GPS C/A-code satellite signals on the L1 frequency have been simulated together with the same set consisting of spoofed signals. Furthermore, a receiver movement with an arbitrary motion pattern was simulated. These two sets imitated all signals tracked inside a software-defined radio during an attack. Based on the proposed algorithm in [17], a coarse classification of the individual signals is performed by using the measured C/N0 values. In case a false classification was made, a further distinction through iteration was executed. For this test, a worst case scenario has been generated, where two sets (eight satellites per set) were misclassified by the algorithm. This resulted in sets consisting of four authentic and four spoofed signals each.

Figure 15 shows the resulting Doppler residuals for a time span of about two minutes, where the theoretical Doppler values were processed using a spoofed PVT output due to misclassification. PRN1 to PRN11 are authentic satellites, whereas PRN14 to PRN21 are spoofed. Afterwards, the algorithm started its sorting process. The whole time series was divided into data snapshots of equal length, where each snapshot was processed individually. Figure 16 shows Doppler residuals of the two processed data sets, where the first half of the time series has already been sorted correctly.

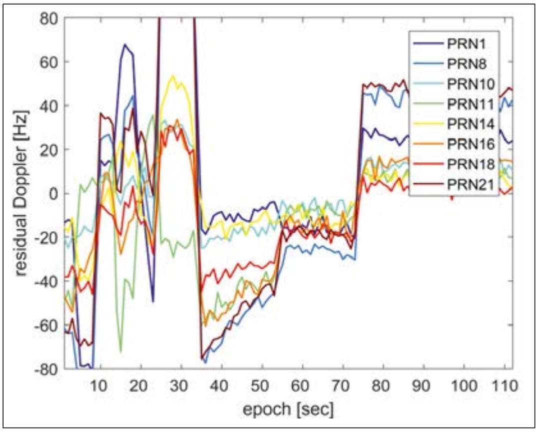

Fig. 15: *Doppler residuals for misclassified PVT set (50% authentic, 50% spoofed)*

As can be seen on the left, no correlations between the single signal pairs are present. After 55 seconds, the Doppler residuals on the right exceed the values of 80 Hz due to the inconsistency of the data sets. Figure 17 shows the final result after the algorithm has processed all data snapshots. As expected, the algorithm has correctly classified the signals. The Doppler residuals show a highly correlated pattern for the spoofed set, representing the relative motion of the receiver

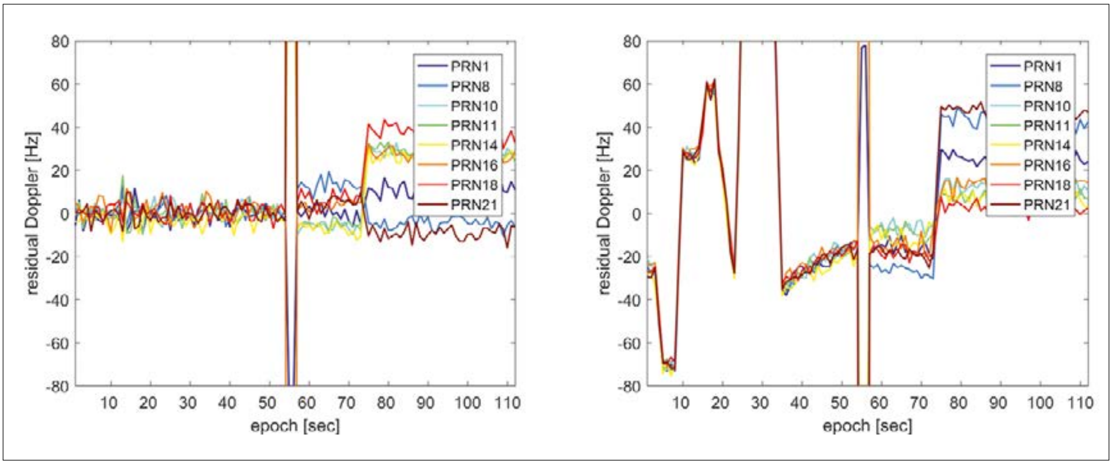

Fig. 16: Rearranging misclassified authentic (left) and spoofed (right) PVT set

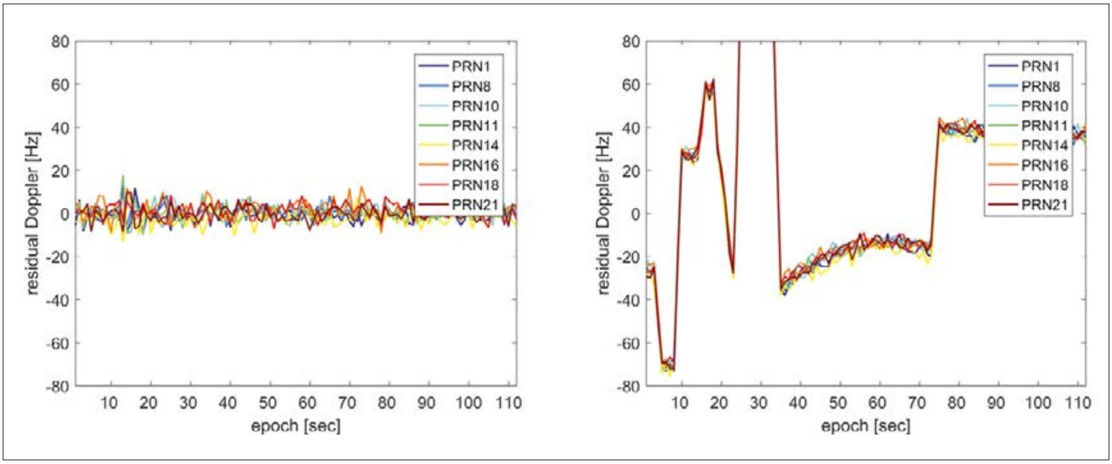

Fig. 17: Correctly sorted authentic (left) and spoofed (right) PVT set

with respect to the spoofer. The sudden jumps in the values occur when the receiver changed its direction in the trajectory.

For assessing the performance and accuracy of the previously discussed MUSIC algorithm, three spatial distributed spoofing signals were simulated using GIPSIE®. The uniform circular array was simulated as eight individual receivers within a radius of 9 centimetres.

The reference azimuth and elevation between the centre of the uniform circular array and the respective spoofer are listed in Table 1. Furthermore, the relative power between the emitted counterfeit signals and the authentic ones is given along with the distances. As can be seen, the distances between every spoofer and the centre of the uniform circular array is the same.

A MUSIC estimation has been performed where signals from the three spoofing signals where

	Azimuth [°]	Elevation [°]	Rel. power [°]	Distance [m]
Spoofer 1	136	36	20	1000
SP2	45	85	16	1000
SP3	295	12	18	1000

Tab. 1: direction of arrival properties of simulated spoofing signals

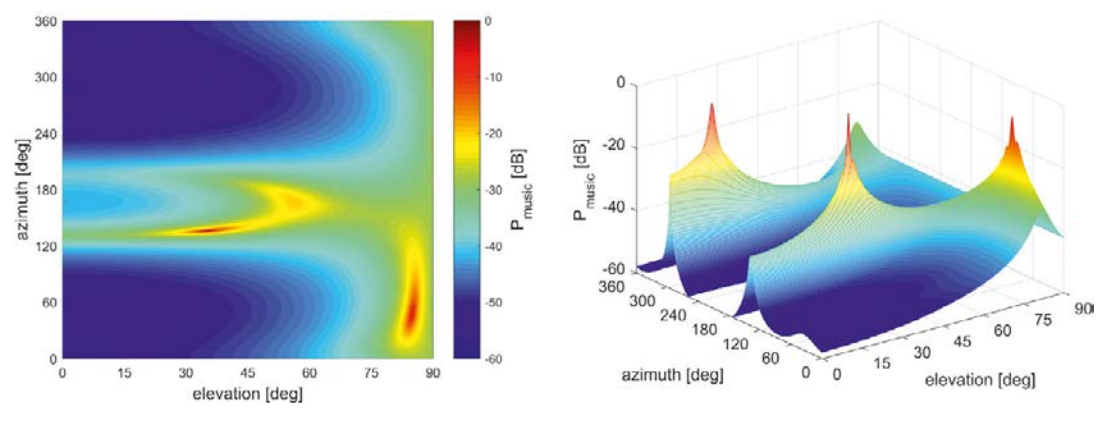

Fig. 18: *2D (left) and 3D (right) MUSIC spectrum for three spoofing signals*

arriving at the array. For peak searching, a grid resolution of 0.5 degrees was used. Beamforming was applied, to increase the performance of the algorithm as well as the spatial resolution of the spectrum in case of coherent signals. Figure 18 shows the respective 2D and 3D MUSIC spectrum in the presence of the three spoofing signals.

On the 3D spectrum, the x- and y-axis denote the azimuth and elevation angle respectively, while the z-axis shows the spectrum power in decibel. The algorithm had no problem determining the correct angle pairs of the sources when compared to Table 1, where peaks close to the reference values for azimuth and elevation are visible. It is remarkable that the second spoofer has the worst resolution, especially in its azimuth. The reason for this is the weaker power of this spoofer compared to the others (4 dB weaker as compared to Spoofer 1 and 2 dB weaker as Spoofer 3). All present spoofing signals are correlated with a connecting region where the spectrum is around -30 dB.

4. Conclusions

The impact of jamming and spoofing is described. In order to provide a reliable and robust PVT solution, GNSS interference caused by jamming and spoofing has to be detected, classified and then mitigated.

Referring to jamming, the adaptive notch filter (ANF) and pulse blanking (PB) successfully suppress the jamming signals. This results in a reduction of the noise level of the signal and causes an increase of the C/N0 and a more accurate PVT solution. In addition, in many cases it prevents the receiver from losing the tracking to the satellites and enables a calculation of the PVT solution.

The ANF estimates the interfering frequency and filters it out. The choice of the input parameters of the ANF, the forgetting factor and the attenuation bandwidth, is very important.

The PB algorithm shows good results for mitigating pulsed interference. The main problem of PB is the pulse detection, which might reduce the performance of the algorithm.

Referring to spoofing, the correlations of Doppler residuals have been exploited to successfully detect an ongoing spoofing attack and further mitigate it by correctly classifying the tracked signals into authentic and spoofed sets. A direction of arrival estimation based on multiple signal classification (MUSIC) for several spoofing signals has been successfully demonstrated with a simulated antenna array. With the simulated eight-element array, directions of arrival for three spoofing signals were simultaneously determined without performance losses in terms of accuracy and computation time.

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The research work described here was carried out within the scope of the projects "Detection, countermeasures and demonstration of GNSS spoofing" (DECODE) [23] and "Impacts and countermeasures of Austrian PRS application scenarios in GNSS denied environments (PRSAustria)" [24]. The projects DECODE and PRSAustria were successfully completed in 2018 and received funding from the Federal Ministry of Transport, Innovation and Technology (BMVIT) under the responsibility of the Austrian Research Promotion Agency (FFG) within the framework of the Austrian Space Application Program (ASAP). The authors would like to thank BMVIT for the financial support, FFG for the profes-

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The relevance of Modern Cartography and the demand for contemporary education: The International MSc Cartography

Georg Gartner, Wien

Abstract

Since the winter term 2011/2012 the International Master´s Program *Cartography* is offered. It lasts two years and is a cooperation between the Technical University Munich (TUM, Germany), the Technical University Vienna (TUM, Austria), the Technical University Dresden (TUD, Germany), and the University of Twente (UT, The Netherlands).
The aim of this Master´s Program is to educate specialists who are able to face the challenges of modern cartography and to help in forming the future of cartography. *Cartography* is supported within the scope of "Erasmus Mundus Joint Master Degree" of the Erasmus+ Program since October 2014. In this context highly qualified international students, who have been selected for this program, get scholarships.

Keywords: Cartography, Education

Kurzfassung

Seit dem Wintersemester 2011/2012 wird der internationale Masterstudiengang *Cartography* angeboten. Das zweijährige Masterprogramm ist eine Kooperation der Technischen Universität München (TUM, Deutschland), der Technischen Universität Wien (TUW, Österreich), der Technischen Universität Dresden (TUD, Deutschland) und der Universität Twente (UT, Niederlande).
Das Ziel des Studienganges ist es Spezialisten auszubilden, die den Herausforderungen der modernen Kartographie gewachsen sind und die Zukunft der Kartographie mitgestalten. Der MSc *Cartography* wird seit Oktober 2014 als „Erasmus Mundus Joint Master Degree" des Erasmus+ Programmes gefördert. Damit verbunden ist die Stipendienvergabe an hochqualifizierte internationale Studierende, die für dieses Programm ausgewählt werden.

Schlüsselwörter: Kartographie, Ausbildung

1. The relevance of modern cartography

Maps and cartographic forms of expression are gaining currently increasing popularity. This can be indicated by the enormous number of map-based applications in the Internet and the mobile Internet. Maps as interfaces to abundant information systems as well as presentation forms of spatial-related information are offered ubiquitously, either through their application on mobile input- and output devices or on the Internet. Though number and usage of cartographic presentation forms increase, many of these popular applications partly arise without considering fundamental theories and methods of cartography. Therefore a characteristic of modern cartography is the ambivalence between the popularity of applications in the field of new technologies and the role of traditional cartography. This apparent discrepancy can be solved by understanding maps as medium for communicating spatial information that has various possibilities to cover users' requirements. In the context of modern cartography this involves the increasing aspect of entertainment, though the function of the information transfer by maps remains constantly important. As a result we can state two major paradigms in modern cartography: the artefact-oriented cartography as well as a service-oriented cartography. In this respect we can argue, that the role of the map has changed. Maps used to be artifacts. They had to look beautiful and be well designed. They had to store information for a long time because that information was needed for a long time. In modern cartography, the map has an increasing number of functions. Besides being an artifact, a modern map is also an interface that gives people access to information stored in the map and – beyond the map – in databases, thus it can rather be best described as a service [1].

That's why a modern cartographer needs to be an interdisciplinary professional. For a cartographer, it is most important to know about methods and techniques of computer sciences, as well as GIS, data acquisition methods, design, art, data modelling and analysis techniques. A cartographer must be able to adopt new technologies as well as to be able to handle newest media becoming available. All these fields influence the end product of the cartographer. This triangle formed by art, research, and technology makes the best cartographic products. The modern cartographer is in the middle – better yet at the heart – of that triangle. He is skilled, trained, and able to deal with geodata, design principles, and the newest technologies [2].

Unfortunately there are fewer and fewer cartographers who have this mix of skills. Rather, there are experts in geodata handling who lack design skills. There are programmers who lack a profound understanding of "geo". There are journalists or designers which lack knowledge of cartographic methodology and spatial data characteristics. This is caused by the lack of dedicated cartographic education as well as due focus on particular skills. It was due to this situation that some years ago cartographers from Munich, Vienna and Dresden, namely Prof. Liqiu Meng (TU München), Prof. Georg Gartner (TU Wien) and Prof. Manfred Buchroithner (TU Dresden) decided to join forces and to try to establish a collaborative international master program with two main aims: focus on the triangle of competences needed for modern cartographers, namely competence in data handling, media usage and design skills for artefact and service-oriented cartography; and secondly focusing clearly on the role of user-centered cartographic communication concepts.

2. Building an International MSc Cartography

Since the winter term 2011/2012 the International Master´s Program *Cartography* is offered (cartographymaster.eu). It lasts two years and is a cooperation between the Technical University Munich (TUM, Germany), the Technical University Vienna (TUM, Austria), the Technical University Dresden (TUD, Germany), and the University of Twente (UT, The Netherlands) [3].

The aim of this Master´s Program is to educate specialists who are able to face the challenges of modern cartography and to help in forming the future of cartography. TUM coordinates the Master´s Program, the other three universities are called partner in consortium (partner universities). The full time study contains 120 ECTS. The students get 30 ECTS per term/at each university as well as 30 ECTS for the master thesis. The program is strongly structured. The students remain as group during the whole studies and switch together to the next university after each term. The corporate feeling and collegiality are especially supported within this program. A survey among the students showed that the students prefer this model. The studies last 4 terms and begin in each winter term at TUM. The students pass the second term at TUW and the third at TUD. They can choose at which of the four cooperating universities they want to complete their master thesis in the forth term.

Additionally to the mentioned physical mobility the master‘s program supports the virtual mobility of the students. The integration of two online modules of UT enables the students to get ECTS-points virtually at each location with free timing. In this way they acquire knowledge and skills about various methods in learning and working in the context of cartography. The online modules of UT can be taken separately or together in each winter term.

By means of these mobile study phases each partner of the consortium is actively involved in the education of the students and brings in his own expertise in the program. Only the cooperation of the universities can achieve the required high quality and the broad spectrum of studies in the scope of cartography. Furthermore synergies of the partners can be of use and the cooperation of the European universities sustained. *Cartography* pushes the internationalisation of the universities. It animates students to study cartography at different locations in Europe and therefore supports the exchange activities for students and scientists in the field of cartography on an international level.

Master theses are disseminated to the four involved universities in equal shares as possible. In case of approx. 25 students approx. 5-7 students will conduct their master thesis at one university at the same time.

UT is responsible for the coordination of the fourth term regarding quality, organisation and execution. Themes for master theses are suggested by all members of the consortium and published on a website. Associated partners from industry or administration and the students themselves can suggest themes too. All master theses are written, presented and discussed in English. The examiner (first supervisor) belongs to that university at which the student conducts the master thesis. The second supervisor "reviewer" comes from one of the other three partner universities. All graduates become "Master of Science in Cartography" and get a common university diploma "Joint Degree".

Every year approximately 25 students are selected for the international studies. An excellently completed Bachelor (180 ECTS-points at least) or an equal degree in a nature or engineering science such as cartography, geography, geodesy, geomatics or informatics is the precondition. Furthermore the applicants have to provide very good knowledge in English.

In the first nine years 185 students from 64 different countries have started the studies. The quote of graduates is near to 98 %. Due to the cooperation of four European universities the graduates have built up a big network and therefore have an optimal basis for starting a scientific career. Due to the mobility between the universities the graduates possess great organisational skills, self-reliance and flexibility.

3. Experiences and operational aspects

Cartography is a non-consecutive, independent master‘s degree course. There is no comparable degree course, neither in Germany, nor in Europe, nor worldwide. As English degree course with the focus on cartography, the master‘s degree course has a substantial unique feature. Due to the cooperation of four famous universities in the field of cartography, long time experience in education and research is accessed and a unique curriculum can be offered to the students.

The study contents include methods and applications in the field of spatial data modelling, data analysis and visualisation of geographic information based on the communication of spatial information and therefore provide a manifold contribution to the interdisciplinary portfolio of disciplines of TUM.

In the first term basics of cartography and geovisualisation are conveyed. In the second term the students gain knowledge in multimedial cartography, especially in the field of Web Mapping and Location Based Services (LBS). The students specialize in the field of mobile and 3D-cartography in the third term.

Students of the master degree course *Cartography* are matriculated at the coordinating university TUM during the whole duration of study. The partner universities afford the students a multiple matriculation at the particular university during the term. This means, for each term the students are matriculated at TUW, TUD or UT beside TUM. The same is valid for that term in which the master thesis is composed.

TUM undertakes the student‘s management as well as the application and admission procedure. All cooperation partners have accepted the procedure for the assessment of the ability of TUM. The preconditions for a successful execution of the common master‘s degree course were documented in a cooperation contract. TUM overtakes the compilation of the certificate documents as well. The coordinator of the master‘s degree course overtakes the organisation and is supported by the matriculation department and the examination office of TUM.

The master‘s degree course is following the quality management system of TUM. Furthermore, all parties accept the equality of quality protection procedures of every institution. At the end of every module the students are asked to evaluate each module by means of a questionnaire. Each lecturer and the local coordinator get the feedback results for each module. The students evaluate the whole term as well before they move to the next university (including non-academic aspects like mobility, organisation, mentoring and infrastructure). Each graduate evaluates the whole master‘s degree course at the end of the studies.

The master‘s degree course *Cartography* gives valuable impulses to the university education of the four involved universities. It guarantees the education of highly qualified junior scientists and pushes the research in the field of cartography and other related sciences. Furthermore, the cooperation of the universities is strengthened and exchange activities for students and scientists are supported on an international level. Due to the required mobility and the restricted number of students, the students are a team with great solidarity. The students as well as the lecturers profit by the intercultural exchange. In spite of the successes and positive experiences, the administrative work of such a master‘s degree course should not be underrated. Especially the consideration of four study guidelines requires great coordinational and organisational efforts. The handling of the applications and the common selection of students require much time too. The supervision of the students outside the university, for example with official, cultural or linguistical problems is only manageable by great engagement.

The administrative structure and responsibility assignment in the scope of the master‘s degree course *Cartography* have proved themselves. All involved universities nominate a local director. The directors work together in affairs concerning degree program, ratings, learning progress, quality issues and sustainability of the program. The local director of each institution makes sure that the studies at each university correspond with the aims of the whole program. The director of the coordinating university TUM overtakes the role of the program director for the whole master‘s degree course at the same time. In addition, each university nominates a coordinator on site. The program coordinator is responsible for course guidance supported by the local coordinators. All coordinators support the students intensively and individually in mobility matters, for example help with house-hunting, legal issues, visa, organisation of re-examinations etc.

4. The Erasmus Mundus Programme of Excellence

The MSc Cartography is supported within the scope of "Erasmus Mundus Joint Master Degree" of the Erasmus+ Program since October 2014. In this context highly qualified international students, who have been selected for this program, get scholarships.

Among nine degree programs in Europe *Cartography* was selected in 2014 and since then is supported within the Erasmus+ program of "Education, Audiovisual and Culture Executive Agency (EACEA)" of the European Union. Among the nine selected degree programs *Cartography* was the only master program with a German university as coordinator. Furthermore, the Master was the first Erasmus Mundus degree program coordinated by TUM.

The five-year support of the degree program *Cartography* totally contains approximately 1,65 Mio. Euro, which cover a year for preparation (October 2014 – September 2015) followed by three cohorts of students (2015-2017, 2016-2018 und 2017-2019). During this time 38 highly doped scholarships could be given to the best students. Thus, the master‘s degree course allows the best international students to visit universities, offers a unique curriculum and increases the competences and employability of the graduates in economy and science.

In spring 2017 a new proposal for support of the master program was successfully submitted. The support for further 5 years (including a year for preparation 01.10.2017-30.09.2018) covers approximately 2,11 Mio. Euro and 48 scholarships for the best qualified applicants from all over the world (cohorts of students 2018-2020, 2019-2021, 2020-2022). A direct prolongation of support in the scope of Erasmus Mundus is rare and eventually an indicator that the master program *Cartography* is a very innovative, future-oriented, well structured, coordinated and successful degree program. Once again 2017 *Cartography* was the only successful degree program among the applicants with a German university as coordinating university.

In its reasoning the Education, Audiovisual and Culture Executive Agency of Erasmus+ stated, that the MSc Cartography is a programme of excellence due to its excellent match of the required criteria, such as quality criteria, internationalisation, quality of partners, structure and management.

5. Summary and Outlook

Reacting on the changed but increasing demand on education programmes for modern cartography, thus embracing competences of data handing, media handling and design skills in the context of map making and map usage, the International MSc Cartography of TU München, TU Wien, TU Dresden and University Twente has been set up. After several successful intakes it received twice the highly competitive Erasmus+ label of a MSc programme of excellence. The focus of the involved universities is the continuing improvement of the degree program. The contents of teaching are adapted regularly and completed with newest research results. Before end of the first supporting period (September 2019) University Twente will be included in the "Joint Degree". The accreditation of Joint Degree is pushed in The Netherlands and University Twente takes care of the administrative steps. TUM, TUW and TUD already award a common Joint Degree. The consortium is developing the cooperation further and considers building on top of the MSc programme an international PhD school on cartography.

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Illustrations1)

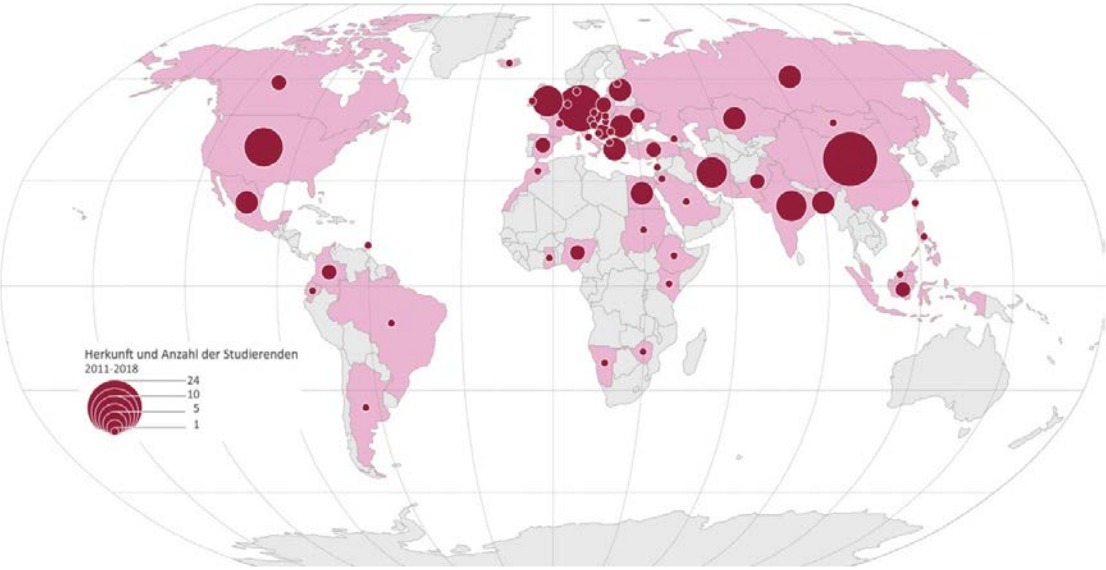

Fig. 1: *MSc Cartography Student's origins (1st to 8th Intake)*

Fig. 2: *Expectations of new intake students when starting the programme*

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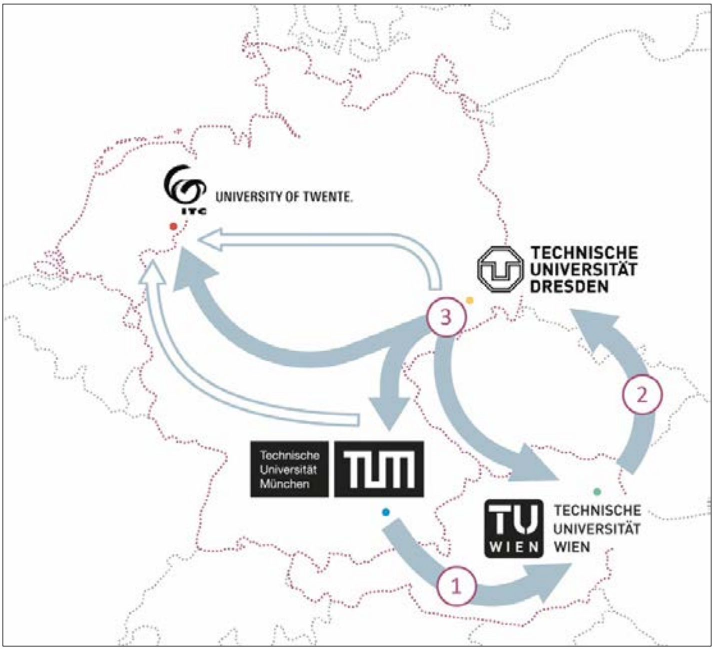

Fig. 3: *Phases of mobility*

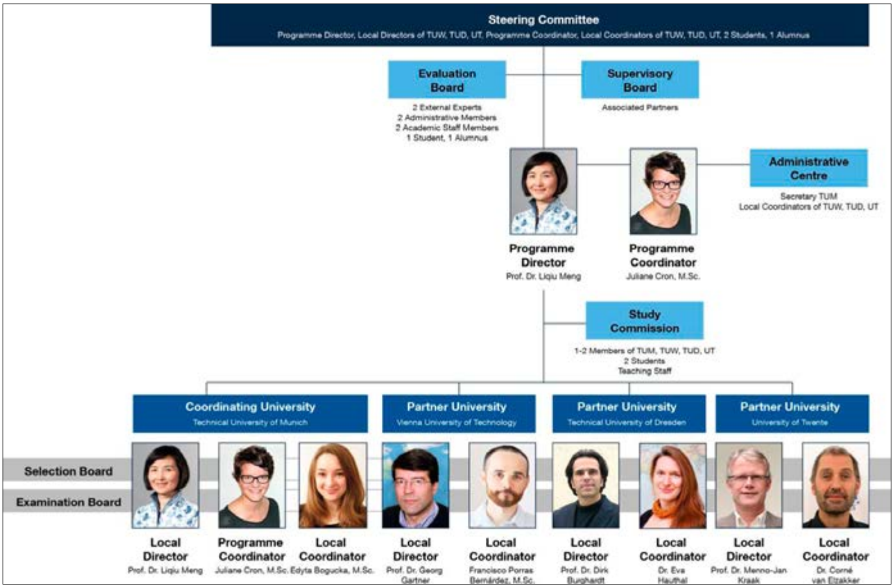

Fig. 4: *Organigram of MSc Cartography*

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Monitoring time variable gravity – bridging Geodesy and Geophysics

Bruno Meurers, Wien

Abstract

The gravity field of the Earth changes with time due to external forcing, but also due to direct gravitational effects of mass variations in the entire Earth system, which are mostly associated with deformation effects caused by loading. Temporal variations of the Earth rotation vector contribute to gravity changes as well. Time variable gravity therefore opens a research field, where Geodesy and Geophysics are closely linked. Today, superconducting gravimeters (SG) provide high accurate gravity time series that allow for monitoring and interpreting of physical signals reflecting a wide range of geodynamical phenomena like Earth tides, Earth rotation, normal modes and environmental gravity effects on all spatial and temporal scales. For more than 20 years, the SG GWRC025 has been operating in Austria, embedded in international projects. This paper presents a review of some important scientific achievements, to which the GWRC025 data contributed essentially.

Keywords: Time variable gravity, geodynamic processes, superconducting gravimeter

Kurzfassung

Das Schwerefeld der Erde ändert sich ständig durch die Gezeiten, aber auch durch direkte Gravitationseffekte von Massenverlagerungen im gesamten System Erde, die meist mit Deformation durch Auflast verbunden sind. Zeitliche Variationen des Erdrotationsvektors tragen ebenfalls zur Änderung der Schwerebeschleunigung bei. Die Untersuchung dieser zeitlichen Variationen eröffnet ein Forschungsfeld, das Geodäsie und Geophysik eng miteinander verbindet. Heute liefern supraleitende Gravimeter (SG) hochgenaue kontinuierliche Zeitreihen, mit denen physikalische Signale überwacht und interpretiert werden können, die eine Vielzahl von geodynamischen Phänomenen wie Erdgezeiten, Erdrotation, Eigenschwingungen und Massentransport auf allen räumlichen und zeitlichen Skalen widerspiegeln. Seit mehr als 20 Jahren ist das SG GWRC025 in Österreich im Einsatz und stellt wertvolle Messreihen für nationale und internationale Projekte zu Verfügung. Dieser Aufsatz gibt einen Überblick über einige wichtige wissenschaftliche Erkenntnisse, zu denen die Daten des GWRC025 wesentlich beigetragen haben.

Schlüsselworte: Schwerefeld, Supraleitende Gravimeter, zeitliche Schwereänderungen, geodynamische Prozesse

1. Introduction

Temporal variations of the gravity field are mainly caused by external forcing (tides). In addition, mass transports within the earth system on all spatial and temporal scales make the gravity potential time-dependent because they mostly change the density distribution of the earth. Finally, time variable earth rotation is involved as well. Therefore, changes in the mass distribution of the earth (mass transport) as well as changes of the earth rotation will directly influence the gravity of the earth and its figure. Mass transports also change the inertia tensor and hence contribute to the time variability of the earth rotation. On a non-rigid earth, they always cause a direct Newtonian effect as well as deformation due to time-dependent loading and inertial effects. Due to its direct link to the mass distribution, investigating the gravity field helps to understand both the structure and dynamical processes of the earth.

Superconducting gravimeters (SG) are currently the most accurate sensors for continuous observation of temporal gravity variations. In the time domain, they have a resolution less than 1 nm/s^2, and in the frequency domain 0.01 nm/s^2 resolution is achievable at tidal and normal mode frequencies under optimum site conditions (Warburton and Brinton, 1995; Richter and Warburton, 1998). The instrumental drift of SG sensors is well below 50 nm/s^2 per year and in most cases a linear function of time. Therefore, the drift can be well modeled based on co-located absolute gravimeter observations, which, in addition, provide the SG scale factor with an accuracy at the 1 per mille level. These characteristics qualify SGs as a unique tool for investigating short- and long-term geodynamic phenomena and make them capable to detect tiny gravity signals both in frequency and in time domain (e.g. Crossley et al. 1999, Hinderer et al. 2007). SG gravity time series contribute to give answers to many problems spanning from earth tides, earth rotation and normal modes to atmospheric or hydrological mass transports and global climate change.

In Austria, the Central Institute of Meteorology and Geodynamics (ZAMG) operates the SG GWR C025 since 1995 in close co-operation with the Department of Meteorology and Geophysics (University of Vienna) and the Federal Office of Surveying and Metrology (BEV). In the beginning, the SG was installed in an underground laboratory of the main ZAMG building in Vienna (VI, Austria) for more than 12 years. The station VI is located at the margin of the Vienna Basin at about 190 m altitude within late Tertiary sediments. In autumn 2007, the SG was moved to its final destination at Conrad observatory (CO), a geodynamical research facility situated at 1045 m a.s.l. within the Northern Calcareous Alps, 60 km SW of Vienna. CO is an underground installation as well.

The research objectives of GWRC025 are focused on earth tides and the impact of atmospheric and hydrological processes on temporal gravity variations. The knowledge of these environmental effects is indispensible for separating gravity signals of different origin. The CO site is co-located with a permanent GPS station operated by BEV. This opens the possibility to interpret long-term deformation at the Eastern margin of the Alps. Main task of this paper is presenting some of the scientific achievements where the VI and CO gravity time series provided important contributions.

2. Earth Tides

The elastic response of the Earth to tidal forcing depends on density and elastic properties in the Earth interior. Tidal parameters derived from observed tidal gravity variations at the Earth's surface relate the true tidal acceleration to that of a rigid, non-deformable planet. They can be described by Love-numbers, which depend on the degree of the spherical harmonic expansion of the tide generating potential. Our knowledge of the interior structure is mainly based on seismology which allows for modeling the physical properties of the Earth. Validating the theoretical Earth models can be done by comparing observed tidal parameters with model predictions (Baker and Bos 2003). The most recently developed body tide models (e.g. Dehant et al. 1999, Mathews 2001) differ by about 1 per mille only. Therefore, highly accurate sensor calibration is a mandatory requirement. In addition, the tidal amplitude factors and phases must be corrected for ocean loading effects which are provided by ocean tide models. The most recent validation has been presented by Ducarme et al. (2014) based on the average of load vectors from 8 different ocean tide models provided by the Free Ocean Tide Loading Provider (Scherneck and Bos, 2014). To keep the load calculation small, three European mid-continental stations at Pecny (PE, Czech Republic), Vienna (VI, Austria) and Conrad observatory (CO, Austria) have been selected, based on gravity time series over 5-12 years obtained from two well calibrated SGs. The agreement of the corrected gravimetric factors at these 3 stations is better than 0.04% in amplitude and 0.02° in phase. Their weighted means confirm previous results obtained from 16 stations in Europe (Ducarme et al. 2009) but with higher precision. They fit best to the theoretical body tide model DDW99/NH (Dehant et al. 1999) for M2 (Figure 1) and MATH01/NH (Mathews 2001) for O1.

The calibration accuracy and the quality of ocean load models and/or the load vector computation scheme are limiting factors for body tide model validation. SGs are commonly calibrated by co-located absolute gravity meters (Hinderer et al. 1991). This method provides calibration accuracy at the 1 per mille level. This accuracy can be increased by performing repeated calibration experiments (e.g. Van Camp et al. 2015, Crossley et al. 2018). Well calibrated spring gravimeters

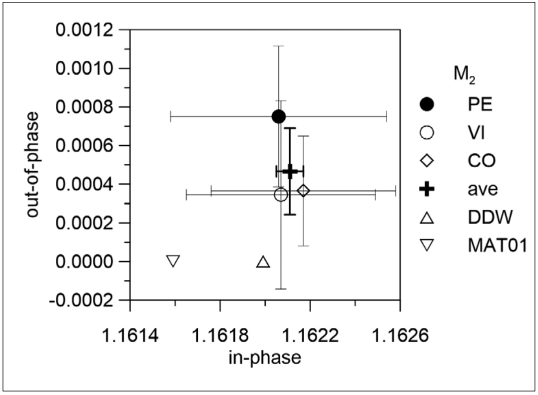

***Fig. 1:** In-phase and out-of-phase M2 tidal parameters after correcting for ocean tide loading derived from SG gravity time series at Pecny (PE), Vienna (VI) and Conrad observatory (CO) and comparison with theoretical body tide models DDW/NH and MAT01/NH. The average (bold cross) of the three stations deviates from the DDW prediction by less than 0.1 per mille.*

can be used alternatively provided the irregular instrumental drift of the reference sensor is properly adjusted (Meurers 2012). The temporal stability of the SG scale factor can be assessed by comparing the modulation of the M2 gravimetric factor derived from successive 1-year tidal analyses at nearby SG stations (Meurers 2017). This modulation is mainly due to the inherently limited frequency resolution of tidal analyses, because limited time series never allow for separating all tidal constituents of the tidal spectrum (Meurers et al. 2016). It must appear similarly in tidal analysis results from neighboring stations or synthetic tidal time series including ocean loading.

Because SGs exhibit low and regular instrumental drift, they are most suitable for investigating the gravimetric factors of constituents within the long-period tidal frequency band. Ducarme et al. (2004) analyzed an average gravimetric factor of 1.163 ± 0.001 derived from 9 SG stations after correcting for ocean loading. This number deviates from body tide models by 0.6 %. Also the phase differs significantly from zero. The transfer function of the SG sensors is known with much higher accuracy. This indicates that the oceanic loading correction is still not accurate enough. Comparing the tidal parameters corrected for ocean loading therefore provides a valuable tool for assessing the accuracy of ocean load models derived from satellite altimetry and calculation procedures.

3. Earth Rotation

Four eigenmodes are expected for a rotating elliptical planet with liquid outer and solid inner core: the Chandler wobble, free core nutation (FCN) or Nearly Diurnal Free Wobble (NDFW) in an Earth fixed reference frame, free inner-core notation and inner-core wobble (e.g. Rosat et al. 2017). While the two first rotational modes are clearly visible in high accurate gravity time series, the inner-core related modes are hard to detect. The gravimetric factors in the diurnal band obtained from tidal analyses are strongly influenced by resonance effects of the NDFW close to the NDFW frequency at about 1.005 cpd. Ducarme et al. (2007) retrieved the FCN eigenperiod from records of 21 globally distributed SG stations as 429.7 sidereal days with a 95% confidence interval of (427.3, 432.1) sidereal days. This number is close to the estimate of 431.18 ± 0.10 sidereal days obtained from VLBI data spanning over 27 years (Krásná et al. 2013).

Ducarme et al. (2006) analyzed tidal records of nine SG stations and determined the gravimetric amplitude factor of the polar motion (Chandler and annual wobble) by applying a regression analysis on the gravity residuals after removing the tides and air pressure effects. They obtained an average factor for the Chandler wobble of 1.179, which differs considerably from predictions by Earth response models at the Chandler wobble frequency due to the indirect effects of ocean tides. The correction based on equilibrium ocean pole tides reduced the arithmetic mean to 1.1605, which is much closer to the model predictions.

4. Normal Modes

SGs perform better than modern seismological instrumentation at frequencies lower than about 0.8 mHz (Widmer-Schnidrig 2003) and hence are widely used for normal mode studies. The gravity records of GWRC025 with 1Hz sampling both from VI and CO have been intensively incorporated in numerous free oscillation investigations because of the high quality of the acquired data. The research focus in this field is widely spread. Based on data of the 2004 Mw = 9.3 Sumatra-Andaman earthquake acquired by 18 world-wide distributed SGs, Xu et al. (2008) determined the eigenfrequency, initial amplitude, and Q of the radial mode ${}_0S_0$ with high accuracy as 0.8146565 $\pm 1.2 \cdot 10^{-6}$ mHz, 1.582 ± 0.054 nm/s^2, and 5400 ± 22 respectively. They confirm the numbers obtained by Rosat et al. (2007), who provided observational evidence of geographical variations of ${}_0S_0$ amplitude due the ellipticity and rotation of the Earth for the first time. While for a spherically symmetric Earth the ${}_0S_0$ amplitude is independent of the location at Earth's surface, theoretical predictions indicate a 2 % amplitude increase from the equator to the poles (Rosat et al. 2007). The observation of the frequency splitting of low frequency (< 1 mHz) normal modes helps to constrain 1D-density models of the Earth. Rosat et al. (2003) report on the first clear observation of the ${}_2S_1$ mode based on a stack of 5 SG stations after the Peru Mw = 8.4 earthquake in 2001. Again from the Sumatra event, ${}_2S_1$ splitting frequencies have been determined from 11 SG records (Rosat et al. 2005).

A still open problem in global geodynamics is the detection of the frequency triplet of the Slichter mode ${}_1S_1$. Knowledge of the Slichter mode frequencies would constrain the core's density structure and the density jump at the inner core boundary of the Earth. However, it is challenging to retrieve the Slichter triplet from SG records, because their amplitudes are close to the SG noise level in the corresponding frequency band. The detection has been claimed by some authors in the past but later on not confirmed by many others using multi-station stacking techniques in order to improve the detection capability based on SG data (e.g. Guo et al. 2006).

5. Environmental Effects in Gravity Time Series

Environmental effects in gravity time series are mainly caused by mass transport phenomena within atmosphere and hydrosphere and superimpose each other. In case of the atmosphere the resulting temporal gravity change is closely related to the air pressure variation observed at a station. Therefore it is possible to remove air pressure effects to a high extent (> 90 %) in order to retrieve the sensor response to geodynamical processes that would be masked otherwise.

5.1 Atmospheric Signals

The direct Newtonian effect dominates at lower frequencies and is partly compensated due to the displacement caused by surface loading of the air pressure. Atmospheric gravity signals are not always associated with air pressure variations because pure Newtonian effects can be caused also by vertical air mass redistribution whereby the surface air pressure does not change (Meurers 2000).

At higher frequencies the inertial effect gets important as well and leads to a sign reversal of the air pressure admittance function (Zürn and Wielandt 2007), which was proven to appear in gravity time series (Zürn and Meurers 2009). For removing the gravity effect of the atmosphere, operational 3D weather models (Klügel and Wziontek 2009) are combined with admittance approaches using the air pressure admittance to gravity in the tidal frequency band. The Federal Agency for Cartography and Geodesy (BKG) in Germany offers an atmospheric attraction computation service (ATMACS) which provides correcting time series based on regional and global models.

At higher frequencies, a frequency dependent admittance function derived from cross spectrum analysis must be used. This function is site-dependent. Figure 2 compares the admittance function beyond 0.1 mHz at VI and CO. Zürn and Wielandt (2007) developed simplistic models for explaining the admittance function: the inverted Bouguer plate (IBPM) and the atmospheric gravity wave (AGW) approach for an elastic crust. At CO, the AGW model matches the observation qualitatively while the IBPM model fits better at VI, at least at frequencies below 2 mHz.

For providing de-aliasing products used for satellite gravity missions like GRACE (Gravity Recovery and Climate Experiment) different approaches for modeling the atmospheric gravity effect are successfully applied by using spherical harmonic coefficients. Karbon et al. (2014) proved them to perform similar to the ATMACS products.

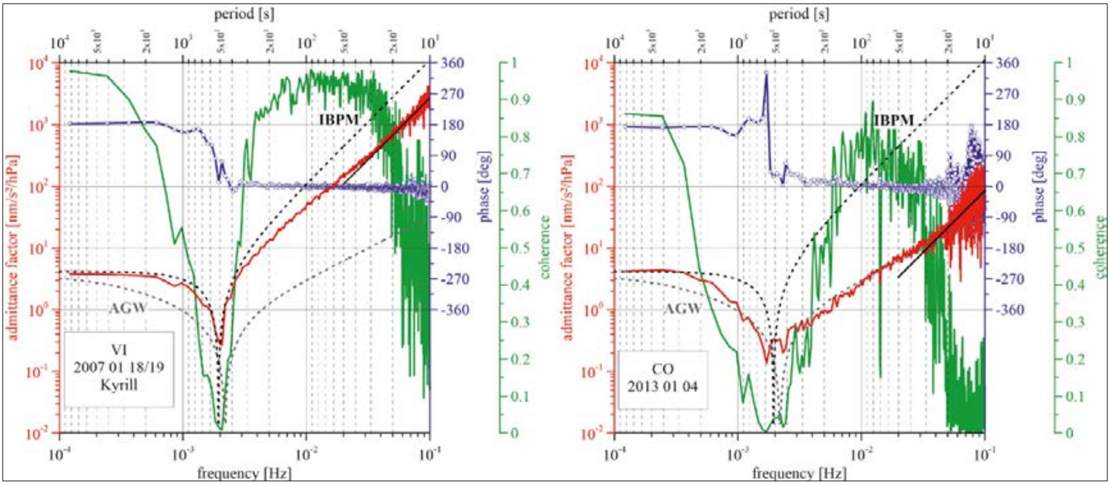

Fig. 2: Frequency dependent admittance function at Vienna (left panel) and Conrad observatory (right panel). The admittance factor is displayed in red; phase in blue and coherency in green. The sign-reversal at about 2 mHz is clearly visible. In both cases, high-frequency air pressure variations were caused by heavy storm events.

5.2 Hydrological Signals

In order to retrieve gravity signals caused by hydrological mass transport (precipitation, soil moisture, ground water table etc.) the gravity time series has to be corrected for tides (body tide and ocean loading), the atmospheric effect and the pole motion effect. The tidal analysis provides a tidal model including the ocean loading as well as the air pressure admittance within the tidal frequency band taken into account. The pole motion effect is based on earth rotation data provided by the international earth rotation service (IERS). Figure 3 compares the gravity residuals obtained by this procedure for the stations VI and CO. For clarity, a same time period of about 4 years has been selected. Figure 3 shows clearly, that hydrological processes at CO are much more complex than at VI. This is mainly due to water mass transport from topography downwards to below the SG sensor happening in case of heavy rain or rapid snow melt events. Gravity immediately reacts on precipitation events by a sudden gravity decrease, because both VI and CO are underground installations and therefore the precipitation within the dominating close surrounding is located above the sensors. The precipitation effect can be almost perfectly modeled by an equivalent water sheet spread over the topography of a terrain model with high spatial resolution (Meurers et al. 2007).

Figure 4 presents an example of a heavy rain event at CO. Even very little rain fall is retrieved by the SG in the time domain and shows up in gravity changes of 1 nm/s^2 and less. The sudden residual drop due to heavy rain can be well explained by the simplistic water sheet model. This example proves the high quality of the correction procedures applied for removing environmental effects from gravity time series based on modern meteorological instrumentation. A small-amplitude residual disturbance is visible between 10 and 11 UTC (Figure 4). Distrometer data provide the SYNOP code and allow for classifying the precipitation type. At the beginning, precipitation consists of a mixture of hail and rain. The SG experiences the Newtonian effect immediately. However, solid hail particles need some time for melting before they are monitored by the rain gauge, i.e. their contribution is apparently delayed during the hail phase. Later, the rain gauge indicates ongoing rain fall although rain has stopped as shown by the distrometer. The rain gauge obviously reflects the ice melting process at this moment. Vertical air mass redistribution could contribute to the residual disturbance as well.

Mikolaj et al. (2015) calculated the short- and long-term hydrological gravity effects at the Vienna station in spite of the fact that in situ soil moisture measurements were not available. The approach they applied combines gravity residuals, a priori soil moisture information from global hydrological models and in situ meteorological data like temperature, precipitation and snow height, i.e. missing soil moisture data is replaced by the response of a properly calibrated model based on the meteorological time series. The method is applicable for all stations where in situ soil moisture data are lacking provided they are located in relatively flat terrain. Figure 5 shows the mean global hydrological effect of several different global land surface models of the GLDAS (Rodell et al. 2004)

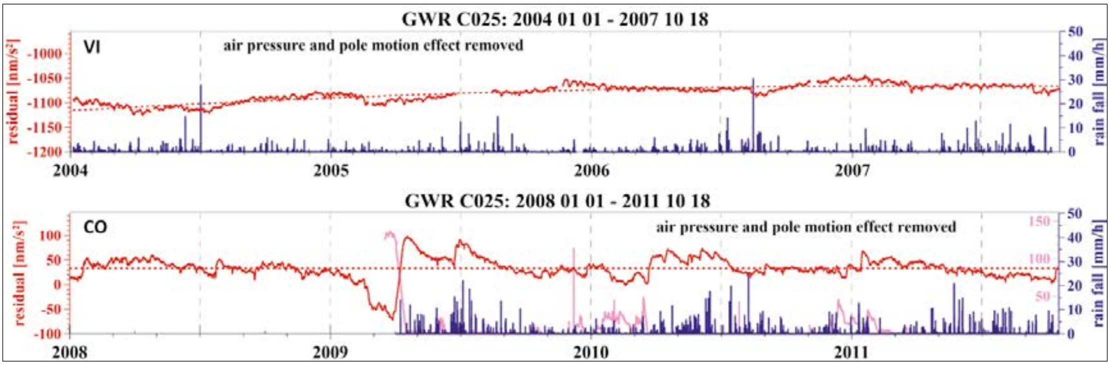

Fig. 3: Gravity residuals (red) at the stations VI (upper panel) and CO (lower panel) after subtracting the tides, atmospheric effects and the pole tide from the observation. Rain fall is displayed in blue, height of snow cover in pink. Dashed lines represent a low polynomial drift. Sections of same time interval have been selected for both stations for easier comparison.

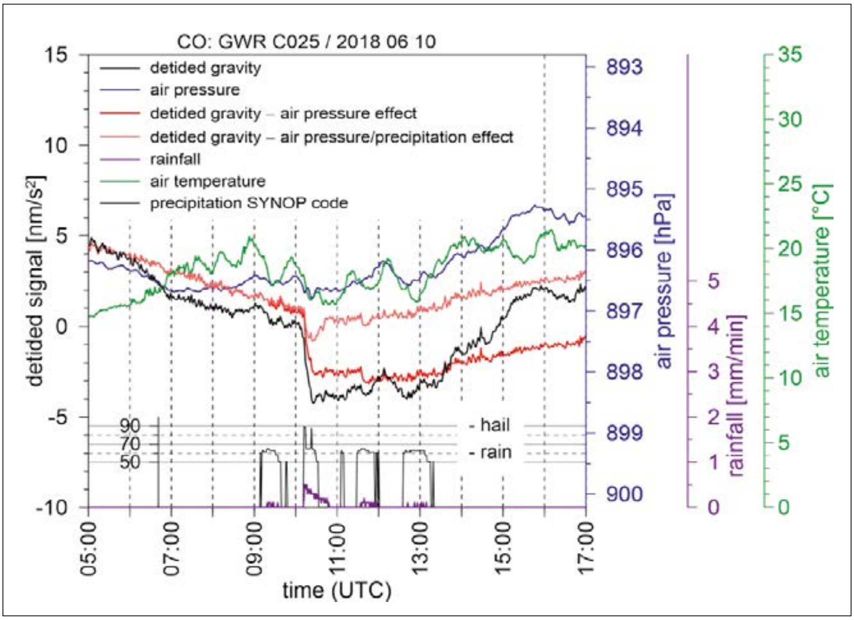

Fig. 4: *Gravity residuals corrected for the precipitation effect during a heavy rain event at CO in June 2018. The light red solid line shows the gravity residuals after subtracting the precipitation effect.*

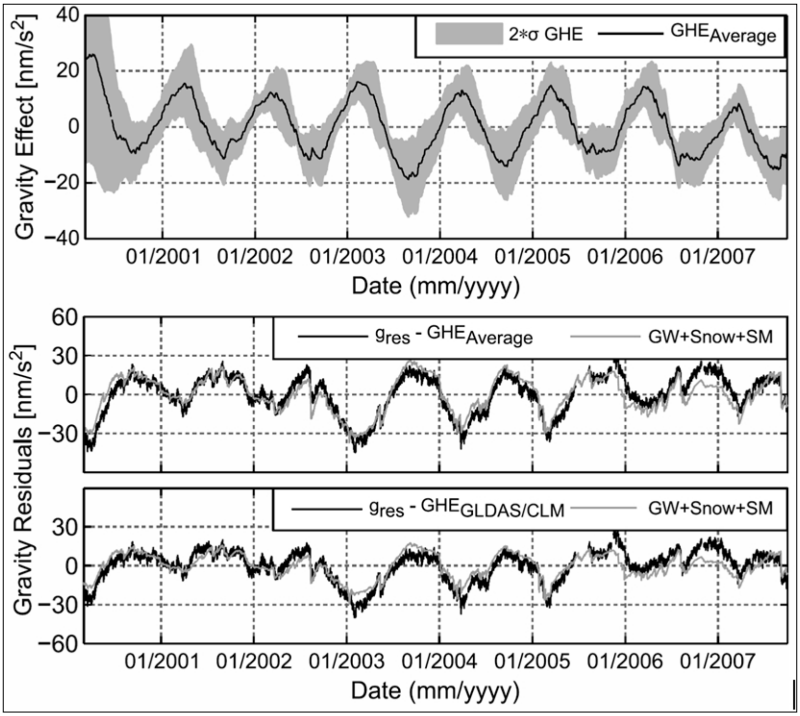

Fig. 5: *Global and local hydrological effect and gravity residuals at VI. The uppermost panel shows the average ($GHE_{average}$) of five different global hydrological models und its uncertainty. The local gravity effect combines local models of soil moisture (SM), groundwater (GW) and snow water equivalent. The middle and lower panels display the gravity residuals after subtracting the global part ($GHE_{average}$) and the GLDAS/CLM global model respectively (black solid line) compared to the contribution of the local hydrology model (grey solid line).*

and compares the gravity residuals corrected for the global contribution with the response of the local model which partly compensate each other. This is typical for underground installations like VI (Longuevergne et al. 2009). The gravity residuals are reduced by about 30% after applying the global and local hydrological correction.

Hydrological signals separated from SG gravity time series can be used successfully in hydrological research as they provide an integrated view in particular on local hydrological processes. Using these signals as a ground truth for global signals retrieved from satellite missions like GRACE (e.g. Crossley et al. 2012) turns out to be very problematic, in particular if surface and underground installations are mixed, given the complexity of local hydrology varying from station to station and the different sensitivity of space borne and ground based gravity sensors with respect to the spatial scale of the hydrological phenomena (Van Camp et al. 2014a, 2014b).

6. Conclusion

Superconducting gravimetry is an important pillar supplementing the investigation of the Earth's gravity field, its temporal changes and low-frequency geodynamics based on geodetic techniques like space gravity field missions, satellite altimetry or Very Long Baseline Interferometry (VLBI). The few examples of successful cooperation of the geophysical and geodetic scientific community, not only in Austria but world-wide, prove the necessity of modern research facilities providing the most modern instrumentation. They also show the importance of collaboration across the scientific disciplines. Conrad observatory is an excellent example of a research facility supporting the research interests of geophysics and geodesy and connecting involved scientists in Austria.

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Improving GNSS Realtime Height Measurements in Mountain Areas – Activities of the D-A-CH Group in the Alpine Region


Helmut Titz, Wien and Martin Freitag, München

Abstract

Heights are the weakest part of GNSS realtime measurements but modern applications more and more require very accurate height results at the user segment. Realtime height timeseries show short term and annual systematic signals that are connected to remaining neglected tropospheric effects. The D-A-CH group in the Alpine Region in Europe proved the correlation between height differences and differences of tropospheric zenith total delays (ZTD) between reference stations on mountain tops and in the valleys using special realtime monitoring stations. Combining near realtime ZTD values and VRS (virtual reference station) data in postprocessing showed the potential for improving the accuracy of realtime height measurements. The new concept was implemented into commercial software and is able to remove the systematic height errors in realtime systems.

Keywords: GNSS, APOS, SAPOS, SWIPOS, RTK – Monitor, RTK, Troposphere

Kurzfassung

GNSS Echtzeitmessungen sind für Höhenbestimmungen nicht besonders gut geeignet, da die erzielten Höhenresultate oft nicht die erforderliche Genauigkeit erreichen. Spielte das in der Vergangenheit eine eher untergeordnete Rolle, so erfordern neue Anwendungen doch vermehrt eine Verbesserung der erzielbaren Höhengenauigkeit. Zeitserien von mit Echtzeitsystemen gemessenen Höhen zeigen aber kurzzeitige und jahreszeitliche Schwankungen auf, welche mit der Vernachlässigung von Troposphäreneffekten in den Tälern in Zusammenhang stehen. Mit Hilfe eines speziellen Echtzeit Monitoring Konzepts gelang den Mitgliedern der D-A-CH Gruppe der Nachweis des Zusammenhangs zwischen Echtzeit Höhendifferenzen und vertikalen Laufzeitunterschieden in der Troposphäre (ZTD). Die Kombination von ZTD Werten aus „near real time" Postprozessing Analysen mit gespeicherten VRS-Daten eines Echtzeitsystems zeigte sich als sehr geeignet für die Erhöhung der Genauigkeit von Echtzeit Höhenmessungen. Dieses neue Konzept wurde in einer kommerziellen Software umgesetzt und ist in der Lage, die systematischen Höhenfehler von Echtzeitmessungen zu beheben.

Schlüsselwörter: GNSS, APOS, SAPOS, SWIPOS, RTK – Monitor, RTK, Troposphäre

1. The D-A-CH Cooperation - Introduction and Background

In the year 2003 the six German national mapping agencies (NMAs) of Bavaria, Baden-Württemberg, Hesse, North Rhine-Westphalia, Saxony and Thuringia, together with Swisstopo Switzerland and the Federal Office of Metrology and Surveying in Austria (BEV) decided to interconnect their upcoming GNSS realtime services SAPOS (Satellite Positioning Service of Germany), SWIPOS (Swiss Positioning Service) and APOS (Austrian Positioning Service) and started an intensive co-operation to benefit on different layers. The D-A-CH consortium has been founded consisting of the NMAs of the 3 adjacent countries Germany (D), Austria (A) and Switzerland (CH) in Europe. In the beginning the driving ideas behind the collaboration were simple. Costs should be reduced by using GNSS reference stations on both sides of the state borders in common and satellite data should be exchanged across borders in realtime via the internet. By coordinating the locations of the border stations the total number of required reference stations could be reduced. On the other hand the extended station distribution avoids extrapolation in the VRS (virtual reference station) generation at the borders and improves the quality of the measured realtime coordinates at border regions. Using the same reference frame ETRF89 (European Terrestrial Reference Frame) and identical coordinates in the realtime software gives the service providers the opportunity to provide a seamless and harmonised service. One of the aims of the D-A-CH providers was to set up a virtual reference system and users should be able to measure in that system with identical accuracy independently from the service provider that they may use. These early reference station networks and the first realtime services were build up mainly to be used for cadaster measurements. To achieve the required accuracy in the horizontal direction of nearly ±1 cm was the major priority of the systems. The accuracy of height results was not really important at the beginning because results have been locally transformed into projection coordinate systems and the height accuracy of the control points was at the same level of accuracy or even worse than the measured realtime height coordinates.

The members of the D-A-CH group meet annually in Munich. Up to now the cooperation evolved to a very close collaboration and exchange of information and experiences with the focus on the following common topics:

- Dataformats and open standards (RTCM, RINEX, NTRIP, NMEA)
- Quality checking and monitoring
- Reference systems and local transformations to cadaster systems
- New satellite systems and signals (GLONASS, GALILEO, BEIDOU)
- Service improvements
- Coordination of support meetings with software producers
- Development of software tools

Depending on the interests, priorities and possibilities of the colleagues involved in the D-A-CH group special working teams have been formed and the developed tools and solutions have been exchanged.

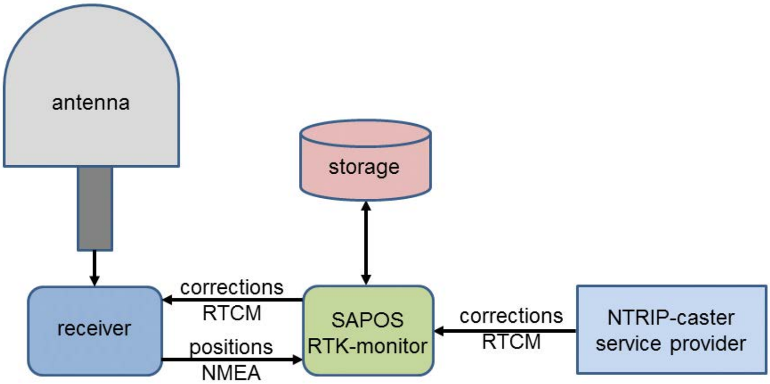

Fig. 1: RTK-monitor concept

2. From Quality Monitoring to Height Improvement

GNSS realtime service providers typically want to know if their service is operating correctly. They want to see if the required or guaranteed accuracy can be reached and if the VRS generation is producing reliable results. The behavior of the service, the correct operation or malfunction of the VRS-software should be documented and be ready to be useful in support cases. The generation of alarms should be possible too by the software. All these requirements were aimed in the development of a special Rover - Monitoring Concept. Independent reference stations beside the VRS network calculation that behave like roving users should be used to evaluate the required performance and availability parameters. A special RTK – Monitor Software, developed by Martin Freitag from SAPOS Bavaria from 2006 on, fulfills all the requirements and allows visualization of timeseries and longterm analyses of coordinate deviations. The software is situated between the hardware GNSS receiver of the monitoring station and the NTRIP-caster (Network Transport of Reference station Data over the Internet Protocol) of the provider that delivers the correction data (Figure 1). By regularly interrupting the correction data stream to the GNSS receiver the RTK – Monitor forces the receiver to reinitialise the ambiguity fixing algorithm and to produce a sequence of coordinates and other information with an interval of typically a few minutes. Comparing these coordinates to high precision reference coordinates calculated by using postprocessing methods allows the production of residual coordinate timeseries and the calculation of statistical parameters.

In the past each member of the D-A-CH group has established a more or less dense network consisting of up to 3 independent monitoring stations. When comparing the height timeseries of all the monitoring stations a systematic different behavior of the realtime heights could be detected depending on the location of the monitoring stations. In plain areas the accuracy requirements could be achieved and the timeseries showed a typical random behavior. In mountainous areas where height differences between rover and the surrounding reference stations are often more than 1000 m the heigths showed systematic disturbances of short term and long term characteristics. These height variations were supposed to be correlated to local troposphere variations. To analyse them in detail and to find a way to improve the achieved height accuracy in realtime systems special monitoring scenarios have been set up in the Alps. On the German-Austrian border 3 regions have been selected for further investigations (Figure 2). The Austrian monitoring station INBK in Innsbruck has been built up in 2011 especially to study the height variations (Figure 3). The height difference to the surrounding reference stations PAT2 (Patscherkofel) and HFL2 (Hafelekar) is approximately 1700 m (Figure 4).

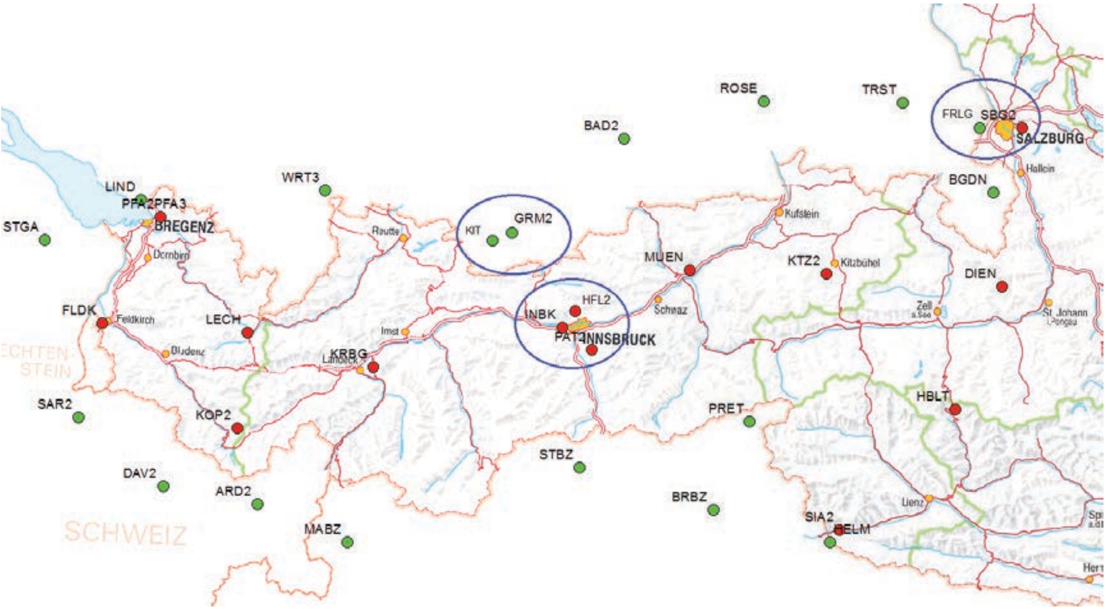

Fig. 2: *Monitoring station distribution for studying the height variations*

Fig. 3: *The monitoring station INBK in Innsbruck (H = 664 m, ellipsoidal height – ETRS89)*

Fig. 4: *The APOS reference station PAT2 at Patscherkofel (H= 2298 m, ellipsoidal height – ETRS89)*

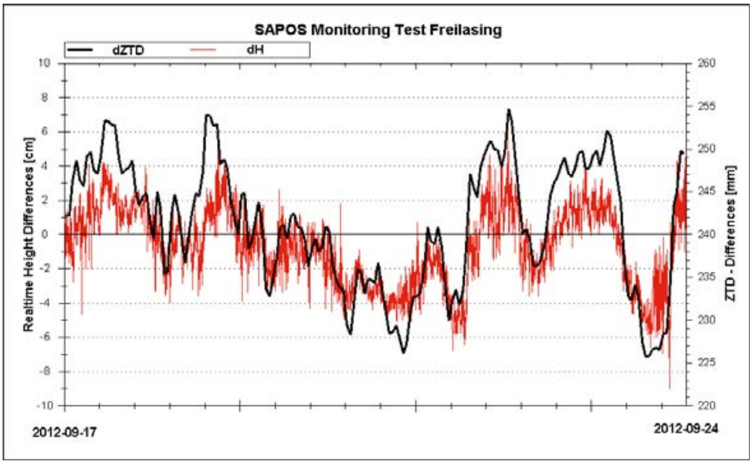

Fig. 5: Realtime height deviations and Zenith Total Delay (ZTD) differences at the monitoring station FRLG Freilassing [1]

3. Chronology of the Activities on Improving Realtime Height Measurements

3.1 Proof of the Correlation between Realtime Height Differences and ZTD-Differences

The height difference of the ellipsoidal heights (ETRS89) between the Bavarian reference station FRLG Freilassing (H = 481 m) and the Austrian reference station SBG2 Salzburg/Gaisberg (H = 1323 m) is 842 m. The horizontal distance between the two stations is only 11 km. These two nearby stations fulfill the requirements for an ideal testbed for first investigations in the analyses of height variations in the mountains. A special GNSS receiver with a so-called monitoring option has been temporarily installed at Freilassing in September 2012. The station Freilassing excluded from the VRS calculation in a test environment allowed the use of Freilassing as an independent realtime monitoring station. The measured realtime height differences of one week of testing (September 17, 2012 – September 24, 2012) were stored using the SAPOS RTK Monitor software and are shown in Figure 5. Systematic height variations of a few centimetres can be easily realised (see dH in Figure 5). Neglected remaining tropospheric effects in the VRS calculation as well as in the rover software were assumed to be the reason for that.

The BEV calculates coordinates and troposphere parameters routinely using stored raw measurements of all APOS sites. These results are produced using the Bernese GNSS Software and are saved in daily and weekly files. To verify the relation between height deviations and the actual troposphere status the hourly zenith total delay (ZTD) parameters calculated for both stations have been used. The differences between the ZTD values between the stations Freilassing and Salzburg/Gaisberg were meant to possibly be a value for the neglected tropospheric influence on the rover height variations and are shown in Figure 5 together with the height differences (see dZTD). Comparing the two curves in Figure 5 shows the very strong correlation between the realtime height differences and the differences of the hourly calculated zenith total delays (ZTD). Deviations of the troposphere status in the height layer between the nearest reference station of the network and the rover station from the implemented troposphere models may therefore lead to systematic height effects in the realtime solutions.

3.2 Detection of an Annual Signal at the Monitoring Station INBK (Innsbruck)

For more systematic studies of the influence of neglected tropospheric effects in realtime measurements the BEV decided in 2011 to build up a new GNSS permanent station at the Leopold Franzens University in Innsbruck (Figure 3). Innsbruck is situated in a deep valley called Inntal at the height of 664 m. The surrounding APOS reference stations that are used in the realtime system are nearly 1700 m higher on top of the mountains (Figure 6).

Fig. 6: Height profile through the Inntal at Innsbruck

Using the SAPOS RTK – Monitor Software the station was used for realtime monitoring from 2012 on. The height differences of the stored realtime measurements compared with high precision coordinates from a longterm postprocessing solution for the period of the year 2013 are shown in Figure 7. An annual signal of up to 16 cm can easily be seen. The figure shows the influence of the variation of atmospheric water vapour. The dry air in the cold winter has nearly no influence on the heights. Maximum height differences due to neglected tropospheric effects can be recognised in summer.

Height measurements in mountainous areas therefore may be time dependent.

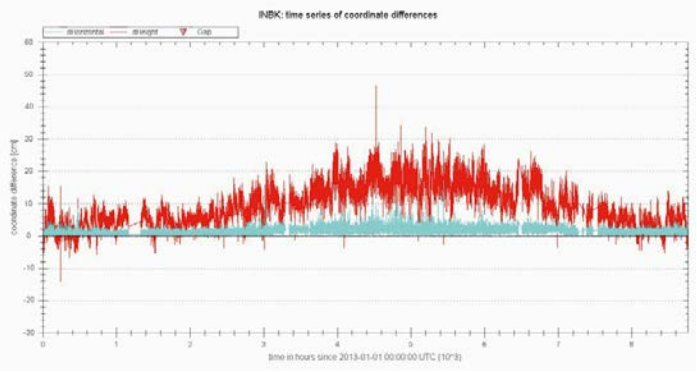

Fig. 7: *Realtime height differences at the monitoring station Innsbruck during the year 2013*

3.3 Improving the Realtime VRS Computation by using Near Realtime Troposphere Parameters

It is possible to store VRS data streams as files and to use these files for the calculation of rover coordinates in standard postprocessing applications. This is useful for example in cases, when an online connection to a realtime service provider is impossible. These VRS-RINEX-files may be corrected for ZTD differences to get improved height accuracies. This can easily be done in postprocessing if the required reference stations are available.

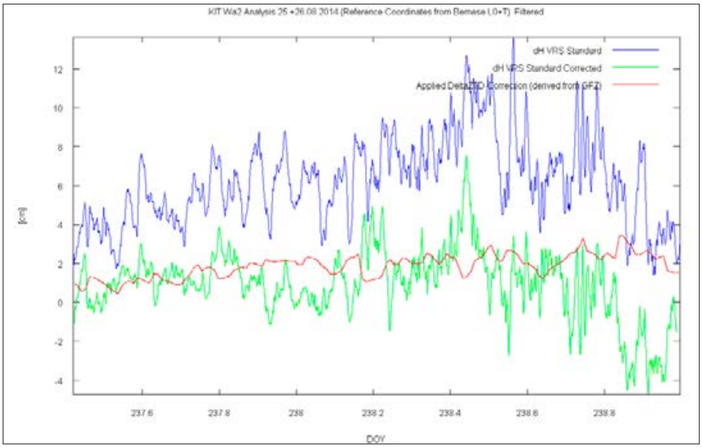

Fig. 8: *ZTD corrected VRS postprocessing height results processed by SAPOS Bavaria and KIT [2]*

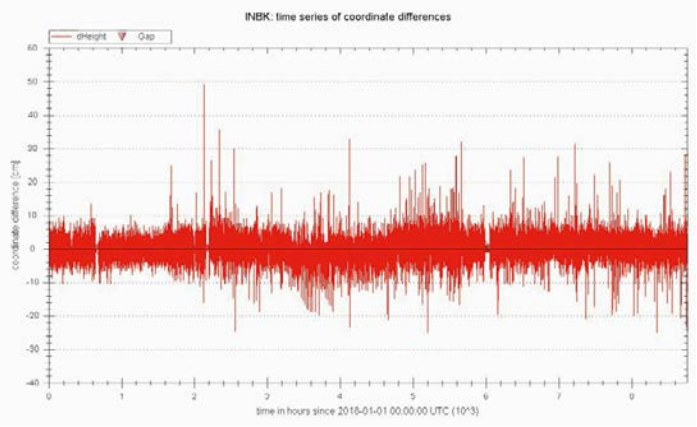

Fig. 9: *Height deviations at the APOS monitoring station in Innsbruck in the year 2018 using the 3D troposphere interpolation model*

Nearby the German SAPOS station GRM2 in Garmisch-Partenkirchen the Karlsruher Institute of Technology (KIT) which is part of the Geoforschungszentrum Potzdam (GFZ) operates a GNSS-teststation in the valley. The height difference to the SAPOS station is 1034 m, the horizontal difference is only 8 km. High accurate ZTD values with 15 minutes interval were calculated for a two day test period on August 25, 2014 – August 26,

2014. During a project cooperation of the KIT and SAPOS Bavaria a prototype software has been developed that allows the ZTD correction of stored VRS files. These corrected files may then be used in standard software to calculate rover positions in postprocessing. A simple ZTD correction model is used. Slant GNSS observations are corrected by using the Dry Neill Mapping Function for the ZTD values and ZTD differences are calculated by a simple linear height dependent function of the original ZTD values.

This simulation project showed that the realtime height measurements could benefit from the introduction of externally calculated troposphere parameters into the realtime VRS creation. It could also have been proved that a simple linear interpolation algorithm is able to deliver improved height accuracies and that due to the spatial correlation of the troposphere parameters good height results are obtained within a radius of 15 km to the KIT station. Nevertheless an interface to feed near realtime ZTD values into existing realtime software is not available.

3.4 Implementing the new concept into commercial software

The idea of using externally computed near realtime ZTD values in commercial realtime software has been discussed with different software developers. The use of these ZTDs seemed to be problematic because of quality and availability concerns. Nevertheless the 2D tropospheric model that represents the height layer of the included reference stations was not sufficient for achieving centimetre level accuracy in the height component at the user locations. A new 3D interpolation approach should be developed to improve the height measurements. Based on a set of raw datastreams of selected SAPOS- and APOS- stations the new concept includes an extended realtime troposphere calculation. To allow interpolation in the height direction reference stations on different height levels were requested. The simple linear interpolation function was replaced by a more complex prediction function to get representative ZTD values. First tests of the new concept have started in 2015. Figure 9 shows the results obtained at the APOS monitoring station in Innsbruck in 2018.

From January 1, 2018 to December 31, 2018 there have been 391018 realtime measurements registered. The achieved mean accuracy has been ± 1.5 cm in the horizontal direction and ± 4.0 cm in the vertical direction. Systematic height variations especially the annual signal could be successfully removed.

4. Summary and Outlook

The D-A-CH consortium consists of a high-grade group of experts that work together very successfully and share information, experiences and tools on various topics related to GNSS realtime systems on a routinely basis. The SAPOS RTK – Monitor software is an excellent tool for service providers to check the quality and the operational status of their realtime systems. Systematic height variations could be detected and analysed using the RTK – Monitor and the correlation between realtime height deviations and neglected tropospheric effects in mountainous areas has been proved. A new and improved concept of handling these unmodelled tropospheric influences in the realtime processing has been developed and has been implemented into commercial software. This leads to better height results and the remaining systematic height errors could be removed.

For further testing of algorithms and to establish a test environment for the future, Innsbruck has been equipped with a second GNSS receiver connected to the same antenna as the existing one using an antenna splitter in August 2018. This will allow the comparison of two different tropospheric approaches in parallel in the future.

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EUREF Analysis and Data Center at BEV Vienna

Martin Sehnal, Philipp Mitterschiffthaler and David Mayer, Wien

Abstract

Reliable data infrastructure components are the fundamental background for scientific work with global distributed geodetic GNSS permanent stations. Therefore, the Federal Office of Metrology and Surveying (BEV) in Vienna decided to contribute to these long term activities on different levels. Besides creating one of the Data Centers within EUREF we also established an Analysis Center which processes one of the biggest network parts of the European Permanent Network EPN. This is a valuable contribution to the international reference frame community. In addition to the European Network we also monitor a dense Austrian network which is used for the determination of intraplate velocities.

Keywords: EUREF, GNSS, Data Center, Analysis Center, Reference System

Kurzfassung

Um im wissenschaftlichen Bereich mit global verfügbaren GNSS Permanentstationen arbeiten zu können ist eine verlässliche Dateninfrastruktur notwendig. Das Bundesamt für Eich- und Vermessungswesen (BEV) in Wien hat sich dazu entschlossen dauerhaft dazu auf mehreren Ebenen beizutragen. Neben dem Betreiben eines von zwei EUREF Datenzentren wurde ein Analysezentrum aufgebaut, in dem eines der größten EPN (European Permanent Network) Teilnetzwerke ausgewertet wird. Das stellt einen wertvollen Beitrag zur internationalen Gemeinschaft der Referenzsysteme dar. Zusätzlich zum europäischen Netzwerk wird ein verdichtetes österreichisches Netzwerk ausgewertet, um Geschwindigkeiten auf der europäischen Erdplatte zu bestimmen.

Schlüsselwörter: EUREF, GNSS, Datenzentrum, Analysezentrum, Referenzsystem

1. Introduction

The Reference Frame Sub-Commission for Europe (EUREF) of the International Association of Geodesy (IAG) was established in the year 1990. EUREF main goals are the definition, realisation and maintenance of the European Geodetic Reference Frame, which includes the 3D European Terrestrial Reference Frame (ETRF89) as well as the 1D European Vertical Reference System (EVRS).

For realising 3D reference frames a combination of data all over Europe is important. The European Permanent Network (EPN) was established to connect the data of GNSS permanent stations all over Europe and to make the data available to the whole community. EPN monitors the availability of the data and the metadata while the quality of the data is monitored by a combination of the network solutions of several analysis centers.

Austria acts as a Data Center (DC) as well as an Analysis Center (AC). Our contribution has a long tradition starting in the 90s of the last century. The Austrian Academy of Sciences (AAS) and the Federal Office of Metrology and Surveying started their contribution under the name Observatory Lustbühel Graz (OLG). OLG got one of the biggest ACs and one of two DCs as well. Nevertheless, AAS decided in 2016 that they will stop their contribution to the GNSS community. Consequently, BEV migrated these services from the AAS IT Infrastructure in Graz to the BEV Infrastructure in Vienna. The transition phase was used for a complete redesign of the services embedded in the new infrastructure in order to reach a better level of security and higher service availability. In the beginning of 2017 (day of year 100) the transition was completed. The higher service level and the improvement of our solutions were shown at the EUREF symposium 2019 in Tallinn, Estonia.

For the public the Data Center of BEV consists of one ftp server, which is accessible via *ftp://gnss.bev.gv.at*. RINEX files can be down- and uploaded there. In the background an admin server is among other things responsible for the verification of these files. In addition to this IT infrastructure a couple of servers were installed

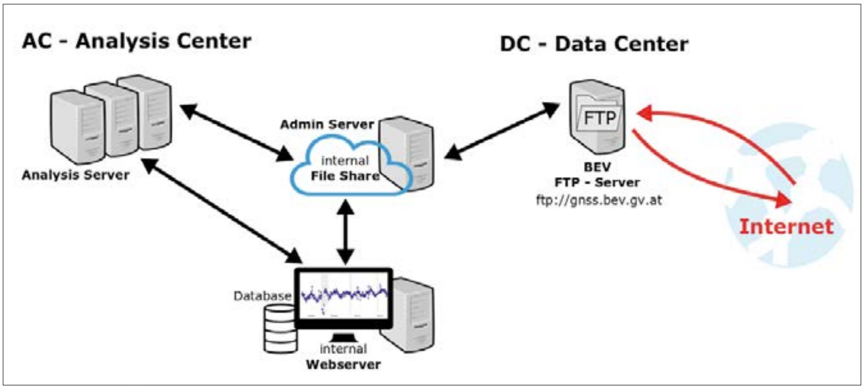

Fig. 1: *Overview of IT infrastructure of Analysis and Data Center in BEV*

for processing within the Analysis Center. Last but not least an internal webserver is used for an easy monitoring of AC and DC. Figure 1 shows a simplified overview of this IT infrastructure.

2. Data Center DC

A EUREF Data Center is responsible for collecting GNSS data, which are observed by the EPN. Further, it has to insure that the data provided satisfy certain standards, such as naming conventions, compression types etc. The Data Center connects the stations, which collect the data, with the analysts, which produce the final results in the Analysis Center. Therefore, it is a pivotal point in the processing chain and demands high reliability and redundancy. The EUREF community insures this by operating two completely independent Data Centers. They are managed by the Bundesamt für Kartographie und Geodäsie (BKG) in Germany and by the BEV in Austria. The Data Centers can be accessed at *ftp://gnss.bev.gv.at* and *ftp://igs.bkg.bund.de* respectively.

The BEV operates the EUREF Regional Data Centers for more than 20 years. During the migration from OLG to BEV the infrastructure of the Data Center was renewed completely and the data processing was brought up to current standards. However, the whole processing chain that downloads, checks and uploads the data was implemented in a serial fashion, which led from time to time to unforeseen availability delays of a couple of minutes at our ftp server. In order to address this issue the processing chain of the Data Center was parallelised. This was realised with the state of the art message broker RabbitMQ [1] which distributes incoming files to so called consumers, which process the data in parallel. The old Data Center was replaced in May 2019.

The BEV Data Center processes about 45,000 files per day, which amounts to about 2.7 GB of data. Since near real time products are derived from the uploaded data the Data Center is time sensitive. In practice this means that hourly as well as daily files, which contain data from the last hour and day respectively, are uploaded to the Data Center. In particular, the hourly files should be available within the first ten minutes after the finished hour. Data is provided in the standardised RINEX 3 as well as RINEX 2 format [2]. In total more than 4 million daily RINEX files (1.6 TB) and 42 million hourly RINEX files (1.2 TB) from 1996 until now are available at BEV Data Center (see Figure 2).

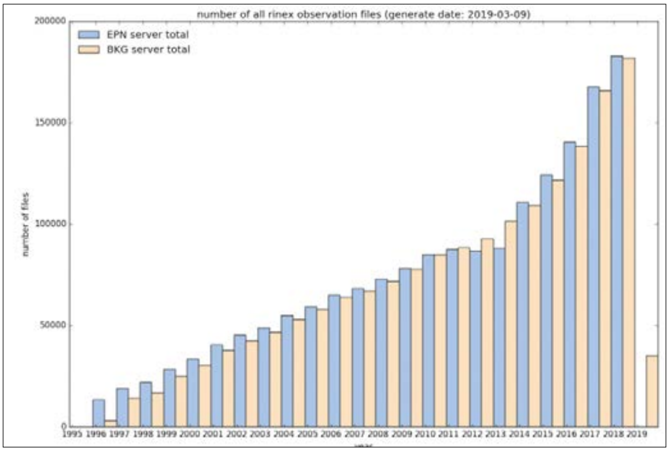

Fig. 2: *Growing number of daily RINEX files in BEV Data Center*

3. Analysis Center AC

After terminating the joint cooperation OLG between the Austrian Academy of Sciences and BEV in 2017 the BEV also took over parts of the OLG Analysis Center. In the Analysis Center RINEX observation files are evaluated in post-processing. For this process the worldwide known high-precision multi-GNSS software BERNESE (Version 5.2) is used [3]. OLG has analysed five networks in total. Besides the Austrian sub-networks of EPN (EUREF Permanent GNSS Network) and AMON (Austrian Monitoring Network), which are designed to realise the reference system ETRS89 in Austria, three other networks were processed with a geo-kinematic focus. These are CERGOP (Central European Geodynamics, 85 stations, started 1999), GREECE (120 stations, started 2013) and MON (Plate Boundaries in the Eastern Mediterranean, 70 stations, started 2000). In the new Analysis Center of BEV the focus is on the main two networks (EPN, AMON) and therefore CERGOP, GREECE and MON are no longer processed.

Fig. 3: EPN stations in sub-network of BEV Analysis Center [4]

3.1 EPN - EUREF Permanent GNSS Network

The EUREF Permanent GNSS Network (EPN) consists of more than 340 permanent GNSS tracking stations. The BEV operates one of the 16 EPN Analysis Centers and therefore contributes to the realisation of the reference system ETRS89 [4]. In 1996 the OLG started analysing a sub-network, which was taken over by BEV in 2017. At GPS week 1954, after a test phase of several weeks with the Analysis- and the Troposphere-Coordinator, the first contribution from BEV was submitted.

The sub-network from OLG has consistently been extended and currently consists of 115 stations (see Figure 3). The processing of RINEX files with the BERNESE software starts automatically when final satellite orbits are available. This automatic solution is then reviewed and, if necessary, reprocessed. In the end a daily and weekly solution of the BEV's sub-network is submitted to the BKG server in SINEX file format. The solutions of all EPN Analysis Centers are combined by the EPN ACC (Analysis Combination Center) in Poland to get a complete solution of the whole EPN network. In the final solution every station will have been analysed by at least three Analysis Centers.

In 2019 (GPS week 2044) the BEV Analysis Center started the processing of GALILEO data in addition to GPS and GLONASS data. In order to accommodate GALILEO data the workflow was adapted by using MGEX (Multi-GNSS Experiment) orbits and RINEX 3 data now. This resulted in an improvement of up to 30 % in accuracy compared to the mean solution of all ACs. In the near future it is also planned to derive a daily solution with rapid orbits and an hourly solution with ultra rapid orbits.

3.2 AMON – Austrian Monitoring Network

BEV generated an Austrian realisation of ETRS89 called "ETRS89/ETRF2000 Austria 2002.56", which was approved by the EUREF governing board in 2003. This solution was derived with 14 GPS stations during a one week measurement campaign. Just seven of these stations are also part of the Austrian RTK service APOS (Austrian Positioning Service) [5]. The APOS network consists currently of 65 stations, 36 of these are in Austria.

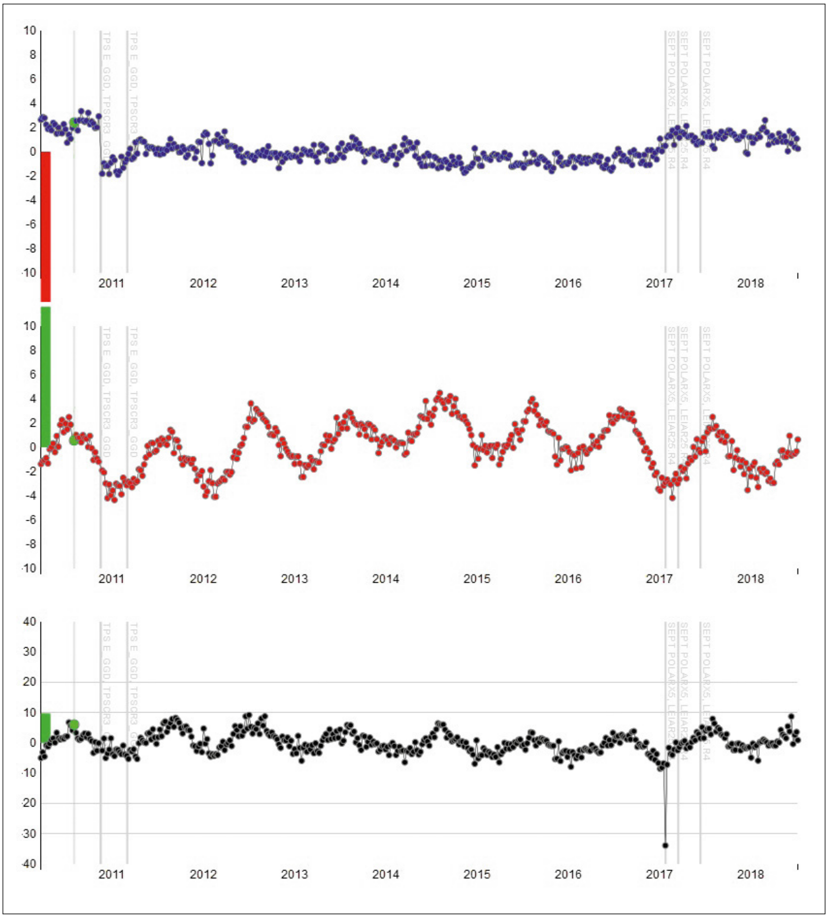

Fig. 4: Variation (mm) in time of AMON station WIEN in north (blue), east (red) and up (black) component

The AMON (Austrian Monitoring Network) was established in 2001 to monitor the Austrian ETRS89 realisation and consequently also all APOS stations. This denser Austrian network is used to derive a time series of all stations for the determination of intraplate velocities. Figure 4 illustrates the coordinate changes of the station WIEN. This station in particular experiences seasonal changes in east and up component in the range of a view millimeter.

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APOS – Austrian Positioning Service on the Way to Multi GNSS

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Abstract

The GNSS GALILEO (EU) und BeiDou (China) are in their final phase to reach their Full Operational Capability (FOC) by 2020. In combination with GPS and GLONASS they will build the so called „Multi GNSS“ for all Positioning, Navigation and Timing (PNT) - applications. The Austrian Federal Office of Metrology and Surveying (BEV) with its GNSS Real Time Service APOS (Austrian Positioning Service) have been adressed this issue since 2016 procuring essential equipment to be ready for the switch to „Multi GNSS“ (GPS, GLONASS, GALILEO) in May 2019.

Keywords: APOS, Multi GNSS, Galileo, FOC, PPP, Troposphere - Correction, Clients

Kurzfassung:

Die GNSS - Systeme GALILEO (EU) und BEIDOU (China) befinden sich in der finalen Phase ihres Vollausbaues (Full Operational Capability – FOC), welcher für das Jahr 2020 geplant ist. Gemeinsam mit den bekannten Systemen GPS (USA) und GLONASS (Russland) wird in absehbarer Zeit ein „Multi GNSS – System“ für sämtliche PNT - Anwendungen (Positioning, Navigation and Timing) zur Verfügung stehen. Das BEV trug mit seinem GNSS-Echtzeitpositionierungsservice APOS (Austrian Positioning Service) diesem Umstand bereits seit geraumer Zeit Rechnung indem 2016 mit den ersten Anschaffungen begonnen wurde und heuer, im May 2019, der Umstieg auf „Multi GNSS“ (GPS, GLONASS, GALILEO) abgeschlossen werden konnte.

Schlüsselwörter: APOS, Multi GNSS, Galileo, FOC, PPP, Troposphärenkorrektur, Kunden

1. GALILEO and BeiDou on the Way to FOC

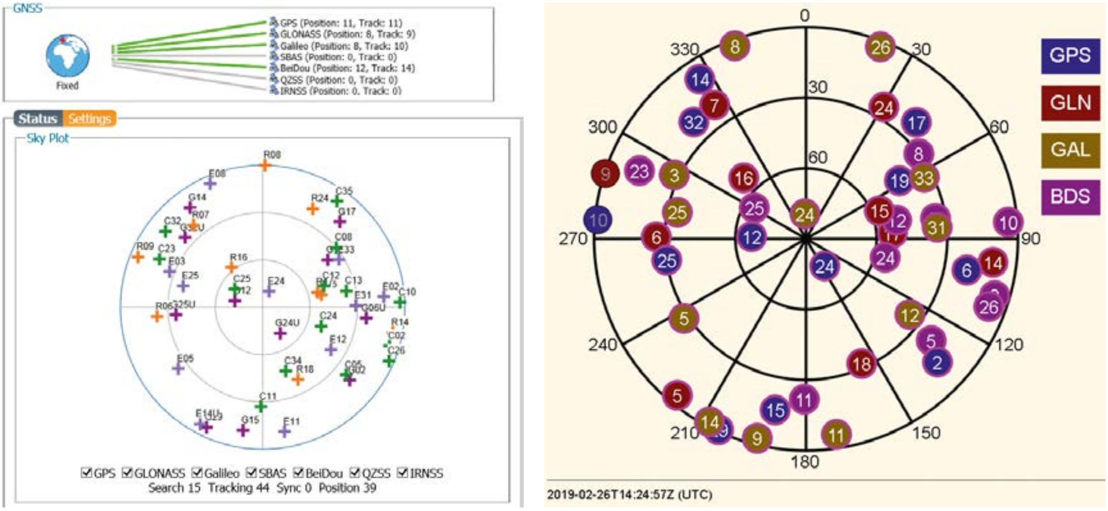
Parallel to the modernisation of GPS and GLONASS the additional systems GALILEO (EU) and BeiDou (China) are straight on their way to Full Operational Capability (FOC). Up to now GALILEO counts 26 satellites (nominal 24), whereas global 22 satellites are already usable. Additionally a new global operating BeiDou-Generation (BeiDou-III) recently is under construction aiming FOC also by 2020. With the development of a „Multi-GNSS“ basically in terms of increasing stability on signals using more frequency ranges than ever to get better availability etc. new user perspectives can be expected.

2. The Challenging Task to integrate GALILEO into the APOS Services

In GNSS real time positioning APOS and some of its international partners (providers) are using TRIMBLE® – software for their real time network-services, also in combination with 3rd-party receivers. Recently this has caused massive problems due to software bugs and incompatibilities. Roll-outs unfortunately had to be stopped or postponed; scheduled services could not be activated. Meanwhile most problems have been solved. Since begin October 2018 APOS has been ready for processing GALILEO signals. For all clients the service eventually was available at 28th May 2019. Due to the ongoing development of the new generation BeiDou-III and its upcoming implementation possibilities the APOS team decided to extend its services only with GALILEO - corrections in the first run.

3. Multi GNSS on PPP-Basis – A Challenge for Developers and Providers

The future of GNSS-real time services will be determined by the PPP (Precise Point Positioning) -technology. Meanwhile PPP has been implemented in Trimble®‘s new „RTX“-Modul as part of the new Trimble® TPP (Trimble Pivot Platform®) processing software and will replace the traditional processing based on base-line differences. This approach requires continuously corrections of satellite-orbits and -clocks of all GNSS as well as operating CORS-receiver code-bias calibrations. For the „APOS Real Time“ service Trimble® provides data and calibration services at a high availability-level.



GNSS

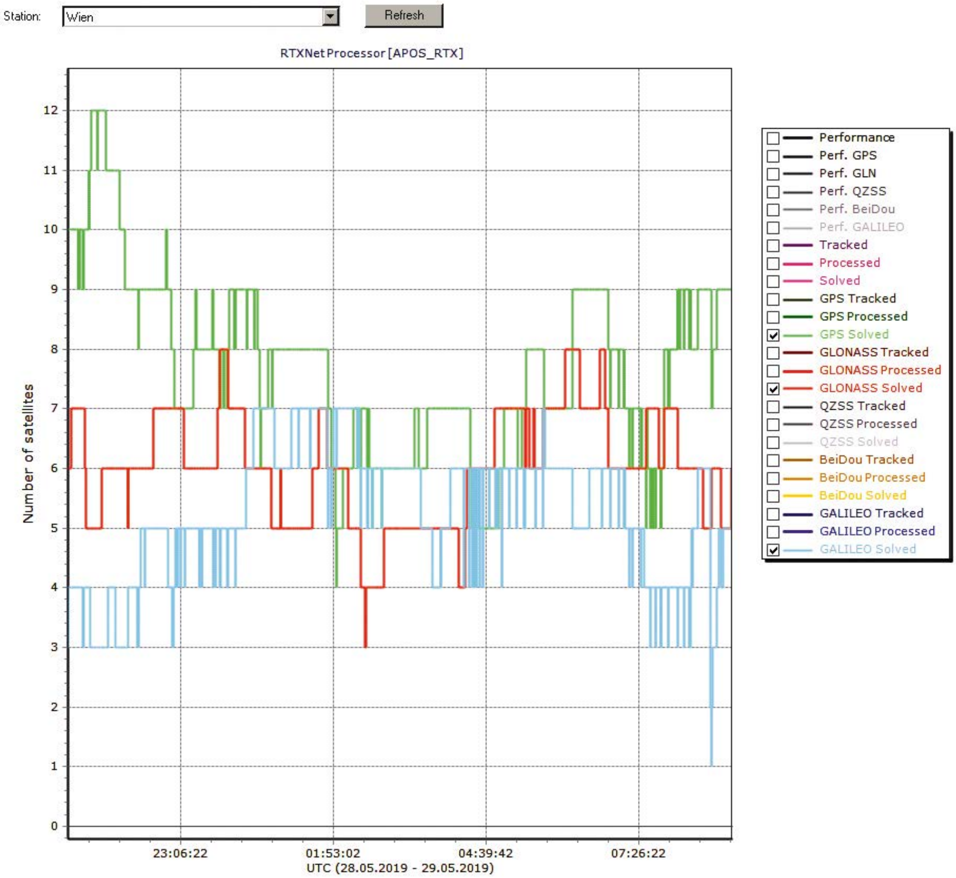
Fixed

GPS (Position: 11, Track: 11)
GLONASS (Position: 8, Track: 9)
Galileo (Position: 8, Track: 10)
SBAS (Position: 0, Track: 0)
BeiDou (Position: 12, Track: 14)
QZSS (Position: 0, Track: 0)
IRNSS (Position: 0, Track: 0)

☑GPS ☑GLONASS ☑Galileo ☑SBAS ☑BeiDou ☑QZSS ☑IRNSS
Search 15 Tracking 44 Sync 0 Position 39

2019-02-26T14:24:57Z (UTC)

__Fig. 1:__ Sky plots of the multi GNSS - receivers Septentrio® „PolaRX5“ (left) and Trimble® „Alloy“ (right) on 26th Feb. 2019, approx. 14:24 UTC at APOS teststation WIEN



Station: Wien

☐ Performance
☐ Perf. GPS
☐ Perf. GLN
☐ Perf. QZSS
☐ Perf. BeiDou
☐ Perf. GALILEO
☐ Tracked
☐ Processed
☐ Solved
☐ GPS Tracked
☐ GPS Processed
☑ GPS Solved
☐ GLONASS Tracked
☐ GLONASS Processed
☑ GLONASS Solved
☐ QZSS Tracked
☐ QZSS Processed
☐ QZSS Solved
☐ BeiDou Tracked
☐ BeiDou Processed
☐ BeiDou Solved
☐ GALILEO Tracked
☐ GALILEO Processed
☑ GALILEO Solved

__Fig. 2:__ Trimble® performance plot on 28th/29th Feb. 2019 between approx. 11:00 PM (UTC) and 7:30 AM (UTC) at APOS station Wien/Vienna equipped with Leica GR30

4. The Upgrade of the APOS Real Time Network / APOS Processing Centre

The APOS Real Time Network (Figure 3) actually consists of 65 GNSS-reference stations in Austria and abroad whereas 35 are owned and operated by BEV. All stations have high accuracy ETRS89 (European Terrestrial Reference System)-coordinates and are part of the official ETRS89-realisation in Austria [3]. On a contractual basis between the Leopold Franzens University Innsbruck (LFUI) and the BEV the station Innsbruck was raised and owned by LFUI and is operated by the BEV. Mutual contracts for co-operation between the BEV and all neighbouring national mapping agencies were signed years ago and are essential for the data-exchange across the boundaries between the providers‘ processing centres. As for the APOS processing centre in 2018 the testing of the Trimble® TPP 3.10.5 processing-software by the APOS team eventually was successful and consequently the roll out of the new multi GNSS-able CORS-receivers, mostly Leica GR30, was completed on schedule. The APOS real time service in general guarantees a homogenous RTK-accuracy in ETRS89 over the whole national territory of Austria.

At the same time a multi GNSS-testbed with Trimble®‘s new „RTX“-Modul, based on PPP, has been installed (Figure 4). After the necessary update of the APOS processing center’s operating system in December 2018 full redundancy of the „APOS Multi GNSS – production system“ has been reached from February 2019.

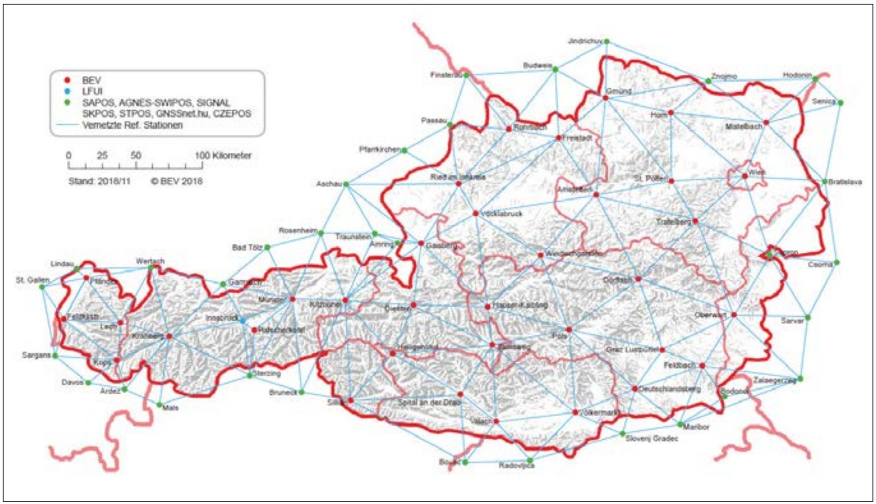


Fig. 3: APOS Real Time Network (Status 2018/11)

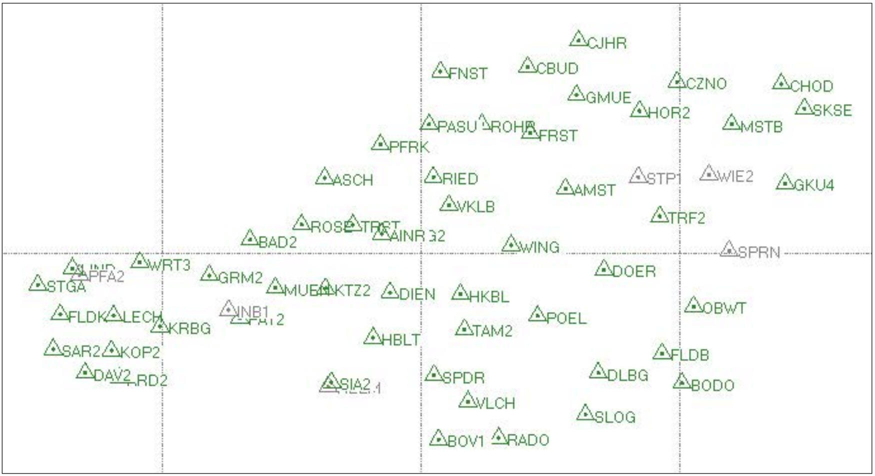


Fig. 4: APOS multi GNSS-testbed covering Austria

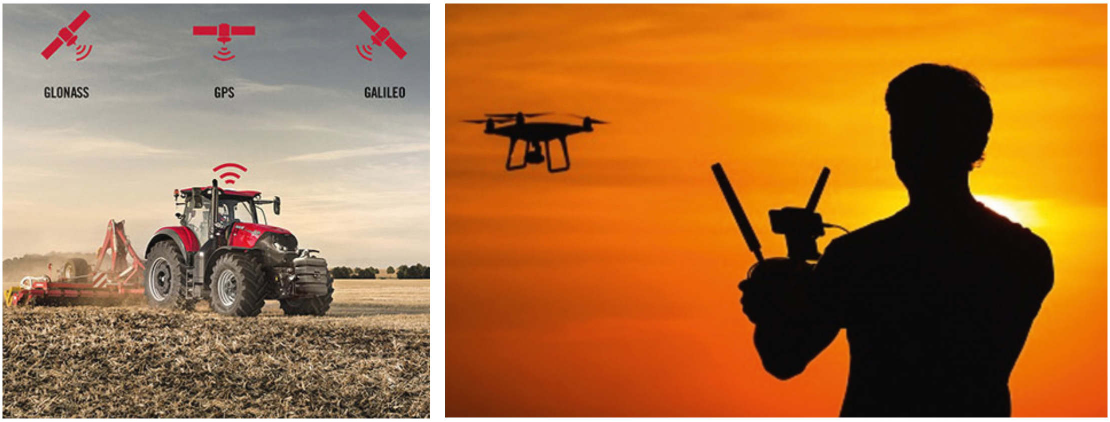


***Fig. 5:** User-subjects from Case IH (left) and Federal Aviation Administration (FAA) (right)*

5. APOS Multi GNSS - Testbed including Troposphere - Correction

The implementation and upcoming release of a multi GNSS-capable system includes the evaluation of nearly countless sensor-configuration possibilities in advance followed up by meaningful testing and analysing, as well as risk estimation of possible problems on clients‘ side. Over the years we became also aware of height accuracy decreases in alpine regions depending on weather situations (e. g. water vapour differences) in conjunction with greater differences in height between local APOS CORS-stations and clients‘ rovers. To avoid that in future Trimble® developed and implemented a special troposphere correction-module for better 3D-interpolation. APOS together with their partners SAPOS-BY and SWIPOS in advance gave support e. g. by routing raw data streams of some of the most relevant alpine APOS CORS-stations (all heights in meter above Adria sea level) for this issue like Innsbruck (615 m, Inn-Valley), the nearby situated Patscherkofel (2249 m, mountain top), Münster (551 m, Inn-Valley) and Krahberg (2208 m, mountain top) to the Trimble®.development division.

As soon as Trimble® released their new module in 2018 the APOS team carried out performance tests using a Trimble® R10 GNSS-rover connected with APOS‘ alternate testmountpoints providing RTCM 3.2 MSM5 (GPS,GLONASS,GALILEO) with and without 3-D interpolation which led to the following questions: firstly, will bring GALILEO‘s recent status a significant additional benefit for e. g. TTFX (time to first fix), availability etc. and secondly, will the 3-D interpolation/troposphere correction module improve height-accuracy. For the latter case the „dual-receiver-CORS-station“ Innsbruck served as a continuous monitoring system, equipped with a Leica AR25.R4 antenna which has been split with two CORS-receivers (Trimble® NetR5 and Trimble® NetR9). The receivers themselves emulated RTK rovers for the alternate dialling into „APOS Real Time“. In both cases the APOS station Patscherkofel served as physical base within the APOS real time network, situated high above Innsbruck-town. Actually an improvement up to 100 % throughout the year was observed despite the fact that the seasonal change of water vapour can infect height accuracy up to several decimetres in alpine regions. Related to that obviously a decrease of accuracy in position has to be taken into account (up to 100 %; for further information see [1]). A remaining activation of the Trimble® troposphere correction-module during testing in eastern parts with lesser alpine character on the other hand showed no bad effects at all.

To summarise the testing the results concerning „Multi GNSS“ with/without GALILEO show no significant differences in performance and accuracy. Measurements were taken in Innsbruck and Wipptal, in the north of Lower Austria and around the Neusiedler See in the eastern part of Austria. In 2018 APOS could not yet reach full „multi GNSS“ (GPS, GLONASS, GALILEO) - coverage because of the APOS partners‘ different GNSS extension (mainly rover-types) levels. So with slight limitations near the national boundaries to South Tyrol and Hungary (Figure 4) the APOS GNSS network is ready for production anyway. To get meaningful results the APOS team and their APOS clients have to look forward to the GALILEO/BeiDou FOC as of 2020 as well as the remaining CORS stations‘ upgrade.

APOS Real Time	Dataformat/ Modus	Mobile Internet Mountpoint (MP)	GPS GLONASS	GALILEO	GIS Grid	Acc. Position ETRS89	Acc. Position MGI	Acc. Height ETRS89	Acc. Height MGI	3D-Inter polation
APOS - DGPS	RTCM 2.3 (VRS)	APOS-DGPS	✓			±0,5 m		±0,5 m		
APOS - RTK	RTCM 2.3 (VRS)	APOS_VRS	✓			±1,5 cm	<15,0 cm	±4,0 cm	<15,0 cm	
	RTCM 3.1 (VRS)	APOS_VRS3	✓		✓	±1,5 cm	<15,0 cm	±4,0 cm	<15,0 cm	
	RTCM 3.1 (MAC)	APOS_NET3	✓		✓	±1,5 cm	<15,0 cm	±4,0 cm	<15,0 cm	
		APOS_VRS32_MSM	✓	✓	✓	±1,5 cm	<15,0 cm	±4,0 cm	<15,0 cm	
	RTCM 3.2 MSM5 (VRS)	APOS_VRS32_MSM_3D	✓	✓	✓	±1,5 cm	<15,0 cm	±4,0 cm	<15,0 cm	✓

Tab. 1: APOS Real Time - product portfolio (extract) [2]

6. APOS – Clients and their recent and future Requirements

For a growing number of APOS clients real time GNSS-based height measuring in practise already became more and more important. Applications include e. g. lift operators in skiing areas using snow-height measurement systems mounted on snowgrooming vehicles in combination with GIS-based snow management systems, the construction industry which requires better real time height results for road construction, the agriculture with its special ICT applications as well as the automotive and UAV sector, etc.. The miniaturization of GNSS-devices with its goal to reach centimetre-accuracy is a steady ongoing development process and should be in our focus.

7. APOS – What is coming up next?

In a first step the „APOS Real Time“ service started to provide additionally GALILEO-corrections in May 2019 (Table 1). Further developments comprise the integration of BeiDou III and a renewed multifunctional „BEV Shop APOS“ within the „APOS Postprocessing“ service including e. g. the online provision of RINEX 3 (incl. GALILEO), an online baseline calculation tool, a new user interface for better handling, APOS system's performance information, etc..

8. APOS – Statistics

From the statistic side of view the RINEX availability for all 36 BEV/APOS CORS stations was 99.96 percent (06:00-19:00 CET) resp. 99.99 percent on average (00:00-06:00 / 19:00-24:00 CET) with status November 2018. As of April 2019 APOS serves more than 1150 clients with more than 1900 accounts in all areas of applications, and the number of clients is steadily growing.

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[2] http://www.bev.gv.at/

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Österreichische Geodätische Kommission – Beratungsorgan der Politik in Österreich – Aufgaben und Arbeitsweise

Austrian Geodetic Commission – Advisory Body of Policy in Austria – Tasks and Functioning

Norbert Höggerl, Florian Helm und Norbert Pfeifer, Wien

Kurzfassung

Die Österreichische Geodätische Kommission (ÖGK) hat im Jahr 2014 ihre Statuten erneuert und in diesem Zuge präzisiert. Ausgehend von den Statuten wird die Arbeitsweise vorgestellt und aktuelle Beispiele dafür werden präsentiert. Dies reicht von der Stellungnahme zu formulierten Gesetzesvorhaben, über wissenschaftliche Expertise zu ausgesuchten Fragestellungen bis hin zu Vorschlägen für die Weiterentwicklung von Geodäsie und Geoinformation in Österreich.

Schlüsselwörter: Österreichische Geodätische Kommission (ÖGK), Aufgaben der ÖGK, Massenbewegungen, Grenzkataster

Extended Abstract

In the year 1862 the "Kommission für die Mitteleuropäische Gradmessung" was founded by Prussia and Saxony, marking the begin of international cooperation in geodesy. It was recognized, that the figure of the Earth could only be determined by cooperating, as the necessary works were not only in their volume, but also spatially extended. Austria became the third member in 1863. The actual work was in the responsibility of the "Österreichische Kommission für die Mitteleuropäische Gradmessung". Two years later, the commission had already 16 European members and "Mitteleuropäische Gradmessung" became "Europäische Gradmessung" in 1867. What was former the „Österreichischen Kommission für die Mitteleuropäische Gradmessung" became the „Österreichische Geodätische Kommission (ÖGK)", the Austrian Geodetic Commission, in 1996 [1].

The current statutes, enacted in 2014, define ÖGK as an advisory organ of the "Bundesministerin für Digitalisierung und Wirtschaftsstandort", the Federal Minister of Economy. In the English summary of this article the tasks and working principle of the ÖGK are presented.

The statues are preceded with a Vision and Mission Statement, declaring the aim to sustainably support society and economy, through research in all fields of geodesy. It should do this by developing, coordinating and executing geodetic and interdisciplinary projects.

Based on its broad expertise, ÖGK is actively advising decision makers in politics, especially the Federal Minister of Economy. It seeks to strengthen the role of Austria in international research in all fields of geodesy. This mission is underlined by the participation in IAG, the International Association of Geodesy, and IUGG, the International Union on Geodesy and Geophysics. ÖGK is the adhering organization for IUGG in Austria, representing the geosciences [2].

Beyond the tasks originating in advising the Minister and from the membership in IAG and IUGG, ÖGK is reaching out to public through various activities. The "Friedrich Hopfner" medal is presented each four year period to honour Austrian geodesists for their life achievements in all fields of geodesy and geoinformation. Latest awardees are Robert Weber (2018), Franz Leberl (2014) and Manfred Buchroithner (2010) for their works in positioning and monitoring of Earth rotation, in photogrammetry and computer vision, and in cartography, respectively. The "Karl Rinner" price is awarded to young geodesists, who have concluded a major publication or a comparable achievement, often given to PhD students after finalizing their PhD thesis. The last awardees were Matthias Ehrhart (2017), Michael Schindelegger (2016), Philipp Berglez (2015), Andreas Roncat (2014), and Hana Krásná (2013), for their works in image assisted total stations, atmospheric and oceanographic influence on Earth orientation, vulnerability of GNSS, full waveform laser scanning, and VLBI, respectively. In addition, the geodetic research is presented at national and international meetings, including "Österreichischer Geodätentag" (Austrian Day of Geodesists, held every 3 years) and the DACH-Meetings (German, Swiss, Austrian meetings of the respective commissions). Most of ÖGK's publications appear in the "Zeitschrift für Vermessung und Geoinformation (vgi)",

which is published by the "Österreichische Gesellschaft für Vermessung und Geoinformation (OVG)", the Austrian Society for Surveying and Geoinformation.

The working domain of ÖGK reaches from outer space (e. g. stellar reference systems), via Earth observation with satellite imaging, to works on the Earth surface and below (e. g. surveying in tunneling). There was always discussion, if one term can be used to summarize all fields of work: surveying, geodesy, geoinformation, geomatics, etc. In the statutes of 2014 the following solution has been found. The terms "all fields of geodesy" and "geodesy and geoinformation" are used, and in the respective paragraph of the statutes, geodesy is defined for the commission. The ÖGK shall advise the minister in:

- Fundamental surveying and reference systems,
- Time systems,
- Satellite navigation services,
- Cadastre,
- Engineering geodesy,
- Acquisition and analysis of topographic data and basic geo-data,
- Modelling and publication of spatially referenced data,
- Geo-data infrastructure.

The last three items include, at least partly, remote sensing and photogrammetry, on the one hand, and geoinformation and cartography, on the other hand. The last years clearly show the dynamic developments within geodesy and neighboring fields. It may become necessary to adapt those statues considering, e. g., that tasks in autonomous or automated driving require contributions from geodesy.

The Austrian Commission of Geodesy has ordinary, corresponding and extra-ordinary members. The ordinary members are appointed by the responsible minister every four years. These are professors in the fields of geodesy and geoinformation at Austrian universities and, in addition, representatives of

- the Federal Minister of Economy,
- the Federal Minister of Education, Science and Research,
- the Federal Office of Surveying and Metrology (BEV),
- the "Zentralanstalt für Meteorologie und Geodynamik" (the Austrian meteorological and geophysical service),
- the Space Research Institute of the Austrian Academy of Sciences, and
- the "Bundeskammer der Architekten und Ingenieurkonsulenten (BAIK)" (Chamber of Architects and Chartered Engineering Consultants), obviously from the group of Chartered Engineering Consultants for Surveying.

The corresponding members are selected based on their service to geodesy in Austria, see [3]. ÖGK has therefore not only competence in difference scientific disciplines, but also in the sectors of science, applied science, industry, and public administration. This allows to cover the fields listed above.

ÖGK is meeting typically twice per year, discussing legal, organizational, and scientific developments in geodesy. Additionally to these internal meetings, public meetings are held in the course of awarding prices and for presentations. The focal points of ÖGK's work are:

- Comments to laws and regulations, in the course of reviewing planned legislation
- Provision of expertise in scientific questions, e. g., on abolishment of the leap second
- Opinion building on technical developments
- Generating and maintaining a network of geodetic experts

The most recent work was on the question of how to deal with the cadastre in regions of ground movement. A small group was built which met three times. It resulted in a suggestion to the Minister of Economy on how to handle property borders, fixed by coordinates, in the area of landslides. This was considered in subsequent legal norms. As this matter reaches beyond technical questions, the reader is referred to the German version of this article.

Concluding, the reader is referred to the vision of the Austrian Geodetic Commission, which is to support science, society, and economy. The structure of ÖGK allows to elaborate statements on proposed legislation and provide scientific expertise for narrow, clearly defined questions (e. g. continuation with the leap second or not). To provide expertise on large questions are a challenge for ÖGK. Its members work voluntarily and can only support projects, if an immediate additional value for their very own field of work is realistic. Especially in an

interdisciplinary context the ÖGK provides a platform which brings together different competences (e. g. group for ground movement and cadastre).

Awarding prices supports young scientists and generates notable interest for these public lectures. This is successful outreach, but within science, economy and administration. A wider public can only be reached with other format (e. g. Austrian Day of Geodesists). This is executed by ÖGK members, but in their role as representatives of universities, of authorities and as chartered surveyors.

The third large field of tasks is the representation of Austrian geodesy in international organizations. This volume of VGI is published on the occasion of the IUGG General Assembly 2019 and presents an important section of the current achievements and research. The embedding of Austria in international science, especially in organizations like IUGG, but also in ICA (International Cartographic Association) and ISPRS (International Society for Photogrammetry and Remote Sensing), finally also in ESA (European Space Agency), etc., is of uttermost importance for the science location Austria. It allows collaboration on important and big scientific challenges, which require international collaboration, e. g. satellite missions.

ÖGK is fulfilling the tasks defined in the statues. It is an important part of geodesy and geoinformation in Austria.

Keywords: Austrian Geodetic Commission, ÖGK-Tasks, Mass-Movements, cadastre

1. Einleitung

Im Jahre 1862 wurde durch die Gründung der „Kommission für die Mitteleuropäische Gradmessung“ durch Preußen und Sachsen die internationale Kooperation im Bereich der Geodäsie in Europa gestartet. Bereits zu dieser Zeit wurde erkannt, dass nur durch internationale Zusammenarbeit die Bestimmung der Erdfigur und aller damit im Zusammenhang stehender Arbeiten, möglich ist. Österreich trat 1863 als dritter Staat dieser Gradmessungskommission bei. Für die Durchführung der Arbeiten in Österreich war damals die „Österreichische Kommission für die Mitteleuropäische Gradmessung“ zuständig. Bereits zwei Jahre später gab es europaweit 16 Mitglieder und aus der „Mitteleuropäischen Gradmessung“ wurde 1867 die „Europäische Gradmessung“. In der Tradition der damaligen „Österreichischen Kommission für die Mitteleuropäische Gradmessung“ steht heute die „Österreichische Geodätische Kommission (ÖGK)“, die diese Bezeichnung seit 1996 führt [1].

Die im Jahr 2014 in Kraft getretenen Statuten der ÖGK stellen die Basis für die Arbeiten der ÖGK als beratendes Organ der Bundesministerin für Digitalisierung und Wirtschaftsstandort (BMDW) dar. Über Aufgaben und Arbeitsweise der ÖGK soll im Folgenden berichtet werden. Die aktuellsten Arbeiten der ÖGK zum Thema Kataster und Bodenbewegungen werden vorgestellt.

2. Rechtliche Grundlagen für die Arbeiten der ÖGK: Statut 2014

Die die Statuten einleitende Präambel führt bereits mit der Vision und Mission sehr klar die Zielsetzungen und Aufgaben der ÖGK an:

- einerseits durch Forschung in allen Bereichen der Geodäsie Gesellschaft und Wirtschaft nachhaltig zu fördern und
- andererseits geodätische Projekte entwickeln, koordinieren und durchführen, um darauf aufbauend Innovation für Gesellschaft und Wirtschaft zu kreieren.

Auf Basis ihrer umfassenden geodätischen Kompetenz berät die ÖGK aktiv Entscheidungsträger in der Politik, speziell die/den Bundesminister/in für Digitalisierung und Wirtschaftsstandort (BMDW). Darüber hinaus betreibt die ÖGK die Stärkung der Rolle Österreichs in der internationalen Forschung in allen Gebieten der Geodäsie, sowie auch der interdisziplinären Forschung. Diese Anliegen werden durch die Mitarbeit in der *Internationalen Assoziation für Geodäsie (IAG)* und der *Internationalen Union für Geodäsie und Geophysik (IUGG)* unterstrichen. Die ÖGK ist der internationale Ansprechpartner (Adhering Organisation) für die in der IUGG vertretenen Geowissenschaften in Österreich [2].

2.1 Aufgaben der ÖGK laut Statut 2014

Die Aufgaben der ÖGK sind im Jahre 2014 vom Bundesministerium für Wissenschaften, Forschung und Wirtschaft (jetzt: Bundesministerium für Digitalisierung und Wirtschaftsstandort) in den Statuten veröffentlicht worden und gliedern sich in folgende Bereiche [2]:

- Beratung der Bundesministerin/des Bundesministers für Digitalisierung und Wirtschaftsstandort in allen Angelegenheiten der Geodäsie,
- Vertretung Österreichs in der IUGG mit gleichzeitiger Koordination aller in der IUGG vertretenen Geowissenschaften in Österreich (mittels dem der ÖGK zugeordneten Österreichischen Nationalkomitee – ÖNK – für die IUGG),
- Öffentlichkeitsarbeit zur Förderung der Geodäsie durch die Vergabe der Friedrich Hopfner

Medaille und des Karl Rinner Preises [3]. Zur Förderung junger Wissenschaftlerinnen und Wissenschaftler wird letzterer jährlich vergeben, zuletzt an Matthias Ehrhart (TU Graz) für seine Arbeiten zu trackenden Totalstationen. Auszeichnungen haben sich in der Wissenschaft als ein Maß für die Exzellenz von jungen Wissenschaftlerinnen und Wissenschaftlern etabliert, und in diesem Sinne ist eine eigenständige österreichische Auszeichnung von großer Bedeutung.

Die Hopfner-Medaille wird alle vier Jahre für das „Lebenswerk“, konkret laut Statuten für hervorragende wissenschaftliche Leistungen eines österreichischen Geodäten/einer österreichischen Geodätin vergeben. Zuletzt wurde sie an Robert Weber von der TU Wien vergeben.

Darüber hinaus wird über die Arbeiten aus dem Bereich der Geodäsie in Österreich bei nationalen Veranstaltungen (z. B. Österreichischer Geodätentag) und bei internationalen Tagungen (z. B. DACH-Tagung der Geodätischen Kommissionen aus Deutschland, Schweiz und Österreich) referiert und auch publiziert. Diese Publikationen erfolgen überwiegend in der Österreichischen Zeitschrift für Vermessung und Geoinformation (vgi) die von der Österreichischen Gesellschaft für Vermessung und Geoinformation (OVG) herausgegeben wird.

2.2 Arbeitsbereich Geodäsie

Die Arbeitsbereiche der Geodäsie reichen vom Weltraum (stellare Referenzsysteme), über Erdbeobachtungen mittels Satellitenverfahren zu den Arbeiten an der Erdoberfläche bis hin zu Arbeiten untertags, wie Tunnelmessungen oder Vermessungen in Bergwerken. Es gab daher schon immer Diskussionen, ob ein umfassender Begriff all diese Arbeitsgebiete zusammenfassen kann. Mit Bezug auf die deutsche Sprache wird eine Vielzahl von Begriffen verwendet: Vermessungswesen, Geodäsie, Geoinformation, Geomatik, etc.

In den Statuten 2014 wird der Begriff *Geodäsie* verwendet, und um Diskussionen auszuschließen, beinhalten die Statuten eine Aufzählung der betroffenen Bereiche, für die die ÖGK als Beratungsgremium zuständig ist:

- Grundlagenvermessung und Referenzsysteme,
- Zeitsysteme,
- Satellitennavigationsdienste,
- Kataster,
- Ingenieurvermessung,
- Aufnahme und Analyse von topographischen Daten und von Geobasisdaten,
- Modellierung und Veröffentlichung von raumbezogene Daten,
- Geodateninfrastruktur.

Die letzten drei Punkte schließen zumindest teilweise die Fernerkundung und Photogrammetrie, einerseits, und die Geoinformation und Kartographie, andererseits, mit ein. Die letzten Jahre zeigen jedoch sehr deutlich, dass es eine dynamische Entwicklung innerhalb der Geodäsie und benachbarter Bereiche gibt, sodass die o. a. Aufzählung auch immer wieder zu adaptieren sein wird. Zum Beispiel werden Aufgabenstellungen aus dem Bereich autonomer Fahrzeugsteuerung verstärkt an Experten aus dem Bereich Geodäsie herangetragen.

3. Wissenspotentiale, Expertisen und Kompetenzen der ÖGK-Mitglieder

Der Kommission gehören ordentliche, korrespondierende und außerordentliche Mitglieder an, wobei die beiden erstgenannten alle 4 Jahre durch den/die zuständige/n Minister/in ernannt werden.

Die ordentlichen Mitglieder sind einerseits Vertreter aller auf dem Gebiet der Geodäsie und Geoinformation an österreichischen Universitäten tätigen Professorinnen und Professoren, anderseits Vertreterinnen und Vertreter aus:

- BM für Digitalisierung und Wirtschaftsstandort (BMDW)
- BM für Bildung, Wissenschaft und Forschung (BMDW)
- Bundesamt für Eich- und Vermessungswesen (BEV)
- Zentralanstalt für Meteorologie und Geodynamik (ZAMG)
- Institut für Weltraumforschung der ÖAW (IWF/ÖAW)
- Bundeskammer der Architekten und Ingenieurkonsulenten (BAIK)

Bei den korrespondierenden Mitgliedern handelt es sich um Persönlichkeiten, die sich um Belange der Geodäsie in Österreich verdient gemacht haben. Details sind ersichtlich in [4].

Diese Vielfalt in der Mitgliederstruktur innerhalb der ÖGK aus den Bereichen Wissenschaft, Forschung, angewandte Wissenschaft, Praxis und Verwaltung erlaubt es, die unter 2.2 angeführten

Arbeitsbereiche sehr gut abzudecken. Darüber hinaus erweitern und ergänzen die speziellen Erfahrungen und Fachbereiche der korrespondierenden Mitglieder noch die der ordentlichen Mitglieder.

Einige Beispiele für die Anerkennung der Leistung einzelner Mitglieder der ÖGK seien hier kurz angeführt: **Wiener Ingenieurpreis 2014** an Prof. Böhm/TU Wien für die *„Entwicklung von Projektionsfunktionen“* zur Steigerung der Positionierungsgenauigkeit von GPS [5]; **Österreichischer Staatspreis Patent 2018** (Nominierung) an Prof. Lienhart/TU Graz für *„Tübbingelement: Tunnelelement das mitdenkt und bei Gefahr warnt“* [6]. Diese Tübbingelemente werden bereits in der Praxis eingesetzt (Koralmtunnel der ÖBB). **Descartes Preis 2003 der EU** an Weber, Schuh, et.al/ TU Wien für das Thema *„New Non-rigid Earth Nutation Model“*.

Die wirtschaftliche Kompetenz wird in erster Linie durch den Vertreter/die Vertreterin der BAIK eingebracht. Zu ergänzen ist hier außerdem die Leistung des ÖGK Mitglied Prof. Leberl/TU Graz, der die Firma Vexcel Corp. aufgebaut hat, die für die Produktion der Internetkarte BING zuständig ist. Die Firma wurde später durch Microsoft gekauft.

Darüber hinaus sind bzw. waren zahlreiche Mitglieder der ÖGK in diversen nationalen und internationalen Gremien in führenden Positionen tätig (z. B. International Association of Geodesy/ IAG, International Cartographic Association/ICA, International Society for Photogrammetry and Remote Sensing/ISPRS, Österreichische Akademie der Wissenschaften, ...).

4. Arbeitsweise der ÖGK

Grundsätzlich gibt es für die Durchführung der Arbeiten innerhalb der ÖGK zwei jährliche Treffen, zu denen neben allen ÖGK-Mitgliedern bei Bedarf auch Experten zu bestimmten Fachgebieten eingeladen werden können. Zusätzlich zu diesen internen Sitzungen der ÖGK, gibt es auch öffentliche Sitzungen, die vor allem der Durchführung von Preisverleihungen, Vorträge und anderen öffentlichkeitswirksamen Veranstaltungen dienen, wie es im §2 (4) der Statuten vorgesehen ist. Im Folgenden soll kurz auf die Schwerpunkte der Arbeiten der ÖGK eingegangen werden: Stellungnahmen zu Gesetzesvorschriften, Expertisen zu Fachfragen, Meinungsbildung zu aktuellen technischen Entwicklungen im Bereich der Geodäsie und ganz allgemein Schaffung eines Netzwerkes geodätischer Experten.

4.1 Stellungnahmen zu Gesetzen und Verordnungen

Schwerpunkt der Beratungstätigkeiten sind vor allem Gesetze, Gesetzesnovellen, Verordnungen und Novellen zu Verordnungen, die sich auf den Bereich der Geodäsie beziehen, vor allem auf das Vermessungsgesetz (VermG) mit zugehörigen Verordnungen. Für die Erarbeitung von Stellungnahmen durch die ÖGK waren oft die Besprechungen innerhalb von Sitzungen nicht ausreichend, sondern oft war es auch erforderlich Arbeitsgruppen zu bilden, die dann die notwendigen Grundlagen für eine Abstimmung innerhalb der ÖGK lieferten. Erwähnt seien hier vor allem die Arbeitsgruppen für die Novellen der Vermessungsverordnungen (VermV2010, VermV1994 und VermV1976) welche sich mit den Themen Messmethoden, Festpunktfeldanschluss und Fehlergrenzen beschäftigt haben.

Bei der Erarbeitung der Stellungnahmen stand nicht alleine die bestmögliche technische Lösung zu finden im Vordergrund, sondern es war oft wichtiger eine Lösung zu finden, die allen beteiligten Spartenvertretern innerhalb der ÖGK gerecht wurde. Die ÖGK Mitglieder kommen einerseits aus der Wissenschaft, aus dem Bereich der Verwaltung aber auch die österreichischen Ingenieurkonsulenten für Vermessungswesen sind in der ÖGK vertreten. Aus dieser Konstellation heraus sind folgerichtig Interessensgegensätze zu erwarten. Diese auszugleichen war und ist eine wichtige Aufgabe der ÖGK.

Bei manchen Themen bestand allerdings von Seiten der Verwaltung (BMDW, BEV) die Notwendigkeit sich einer Stellungnahme innerhalb der ÖGK zu enthalten, um nicht in einen Interessenskonflikt als weisungsgebundene Mitglieder der ÖGK zu kommen.

4.2 Nationale und internationale Expertisen

Wie in §2 (3) der Statuten angeführt, ist es eine der Aufgaben der ÖGK internationale Entwicklungen und Anforderungen im Bereich der Geodäsie frühestmöglich wahrzunehmen und daraus mögliche Auswirkungen auf Österreich abzuleiten. Als im 19. Jahrhundert (1863) der Vorläufer der ÖGK, *„Die Kommission für die Mitteleuropäische Gradmessung“* gegründet wurde, war die Internationalisierung der Vermessungsarbeiten in Mitteleuropa der Anlass. Im ausgehenden 20. Jahrhundert kam der nächste Schritt aus dem Bereich der Satellitennavigationssysteme, welche in letzter Konsequenz zu einer weltweiten Globalisierung der Vermessung führten. Das begann mit dem Aufbau weltweiter Referenzsysteme, welche schrittweise auch als nationale Referenzsysteme verwendet werden. Die innerhalb der ÖGK erforderlichen Beratungen, Diskussionen und Schlussfolgerungen wurden meist in Arbeitsgruppen oder Subkommissionen ausgelagert, um entsprechende Ressourcen dafür aufbringen zu können. Zwanglos seien hier die wichtigsten angeführt:

- Neugestaltung des Österreichischen Höhensystems (1983)
- GPS Kommission (1984)
- Digitale Geländehöhen- und Dichtemodelle (1985)
- Geoidkommission (1992)
- AGREF (Austrian Geodynamic Reference Frame)
- AREF (Austrian Reference Frame)
- Homogenisierung Festpunktfeld
- Kataster und Landinformation (2010)
- Auswirkungen von Massenbewegungen auf den Grenzkataster (2017).

Diese Auflistung zeigt wieder einmal ein geodätisches Prinzip auf: vom Großen ins Kleine – von den weltweiten Referenzsystemen die durch GPS einen wesentlichen Auftrieb erhielten, hin zu den nationalen 3D-Referenzsystemen (AGREF, AREF), ebenfalls auf GPS-Basis. Begleitend dazu läuft die Verbesserung der Höhensysteme und der Geoidmodelle, wofür auch verbesserte Dichte- und Geländemodelle erforderlich sind. Zuletzt stand die Problematik der Homogenisierung des vorhandenen Festpunktfeldes in Hinblick auf den verstärkten Einsatz von Satellitennavigations-Messgeräten in der täglichen Vermessungspraxis im Vordergrund der Beratungstätigkeiten.

Hervorgehoben sei die Empfehlung der ÖGK hinsichtlich der Auswirkungen von Massenbewegungen auf den Grenzkataster. Die Details über die Erarbeitung und die Ergebnisse dieser Empfehlung werden exemplarisch im Punkt 5 dieses Artikels dargelegt.

Neben den o. a. Beratungs- und Koordinierungstätigkeiten gab es auch Anfragen internationaler Organisationen. Erwähnt sei hier die Stellungnahme für die *World Radio Conference* zur Beibehaltung oder zur **Abschaffung der Schaltsekunde**. Als Schlussfolgerung aller Für und Wider wurde seitens der ÖGK eine Abschaffung empfohlen, jedoch mit einer entsprechend langen Übergangsfrist von 5-8 Jahren.

4.3 Wissenstransfer, Kooperationen und Vernetzung

Neben den unter 4.1 und 4.2 beschriebenen Tätigkeiten, die auch explizit in den Statuten angeführt werden, ergeben sich durch die Zusammenarbeit der ÖGK-Mitglieder noch weitere positive Effekte: Verbesserung des Transfers von Wissen, Schaffung von Grundlagen für Kooperationen zwischen den in der ÖGK vertretenen Institutionen, sowie eine Verbesserung der Vernetzung im Bereich der Geodäsie, aber auch darüberhinausgehend aller Geowissenschaften. Als Beispiel dafür seien die jährlichen Treffen und Exkursionen des Österreichischen Nationalkomitees (ÖNK) für die IUGG angeführt, die eine wichtige Grundlage für einen Wissenstransfer für alle in der IUGG vertretenen Geowissenschaften darstellen: Conrad Observatorium (COBS/Trafelberg) der ZAMG, Institut für Kulturtechnik und Bodenwasserhaushalt (Petzenkirchen), Department für Meteorologie und Geophysik (IMGI) in Innsbruck, Department für Geodäsie und Geoinformation, Forschungsgruppe Höhere Geodäsie der TU Wien, Studienzentrum für Naturkunde des Universalmuseums Joanneum/Geologie & Paläontologie (Graz und Kapfenstein) und Zentralanstalt für Meteorologie und Geodynamik (Wien) [7].

5. Aktuelle Expertise: Bodenbewegungen und Grenzkataster

Die Problematik der Veränderung von Grenzen durch das Auftreten von Massenbewegungen in der Natur wurde immer wieder in juristischen oder technischen Publikationen behandelt [8], [9].

Ausgangspunkt für die Arbeiten der ÖGK betreffend die Problematik von Bodenbewegungen in Gebieten mit Grenzkatastergrundstücken war einerseits die Novelle zum Vermessungsgesetz 2015 (VermG2015) mit dem neuen §32a, der auf diese Problematik Bezug nimmt. Andererseits die auf das VermG2015 aufbauende Novelle der Vermessungsverordnung 2016 (VermV 2016), die nähere Aussagen zur Vorgangsweise bei Vermessungen in Gebieten mit Bodenbewegungen macht. Um Aspekte im Zusammenhang von Massenbewegungen und Grenzkatastergrundstücken umfassend zu untersuchen, installierte die ÖGK im Jahre 2016 die Arbeitsgruppe „Bodenbewegungen und Kataster“.

In dieser Arbeitsgruppe, die unter der Leitung von Dr. Helm stand (Vertreter der BAIK in der ÖGK), konnten die verschiedenen Kompetenzen der ÖGK, wie Ingenieurgeodäsie, Geophysik, Kataster, Photogrammmetrie und Fernerkundung gebündelt werden. Zusätzlich wurde die benötigte geologische Kompetenz durch die Geologische Bundesanstalt (GBA) und eine Landes-Geologie-Behörde in die Arbeitsgruppe integriert.

5.1 Datenquellen und Methoden zur Erhebung von Daten über Bodenbewegungen

Ein erster wesentlicher Schritt bestand in der Schaffung einer Übersicht über verfügbare Daten. Daten über Veränderungen der Erdoberfläche sind bei den unterschiedlichsten Verwaltungs- und Forschungsbereichen in Österreich verfügbar:

- Geologische Bundesanstalt (GBA),
- Wildbach- und Lawinenverbauung, Forsttechnischer Dienst,
- Geologische Landesdienststellen,
- Bundesamt für Eich- und Vermessungswesen (BEV),
- Forschungsstellen: Joanneum Research, AlpS-Zentrum für Naturgefahren Management, Bundesforschung- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft (BFW), Institut für Geographie und Regionalforschung der Uni Wien,
- weitere Institutionen in ihrem jeweiligen Wirkungsbereich, z. B. ÖBB, ASFINAG

Dabei handelt es sich um äußerst heterogene Datensätze, welche unterschiedlich strukturiert sein können:

- von Punkt- über Linien- und Polygon- bis zu Flächeninformationen,
- kleinräumig (projektbezogen) bis flächendeckend für Österreich,
- zeitlich große Differenzen in der Auflösung (Jahre bis Jahrhundert)
- von Zentimeter- bis Metergenauigkeit,
- frei verfügbar oder mit Restriktionen belegt.

Eine Zusammenstellung der Methoden zur Bestimmung von Bodenbewegungen mit den zugehörigen Eigenschaften ist in Tabelle 1 enthalten. Als Resümee dieser Erhebung kann gesagt werden, dass

- flächendeckend für Österreich keine Informationen mit einem einheitlichen Qualitätsniveau verfügbar sind,
- Informationen aus Einzelprojekten nur nach Qualitätsbeurteilung übernommen werden können,
- Orthophotos, Laserscans und InSAR verwendet werden können, aber von automatisierten Prozessen z. T. noch weit entfernt sind.

5.2 Datenbank „Ermittlungsflächen für Bodenbewegungen“ (DB EF-BBW)

Unter „Ermittlungsflächen für Bodenbewegungen“ werden jene Bereiche der Erdoberfläche verstanden, in denen ausreichend Informationen vorliegen, um eine geometrische Veränderung der Erdoberfläche annehmen zu können, wobei die Mindestgröße der Veränderung größer als die geforderte Genauigkeit von Grenzpunkten im Kataster (± 5 cm, vergl. VermV, § 6, Abs. 2) sein muss.

Die Ermittlungsflächen werden in der Datenbank flächenhaft, durch Angabe von Umgrenzungspolygonen beschrieben sein. Weitere Attribute betreffend Genauigkeit, Herkunft usw. (siehe Tabelle 1) erscheinen ebenfalls sinnvoll.

Bei der Bereitstellung von Informationen in dieser Datenbank ist zu beachten, dass zu Beginn nur ein sehr eingeschränkter Benutzerkreis Zugriff haben soll (Planverfasser gem. § 1, Abs (1) LTG, Datenlieferanten, ...). Erst nach dem Aufbau der Datenbank und entsprechenden Erfahrungen im Umgang mit den Informationen, könnten diese - oder Teile davon - auch einem erweiterten Benutzerkreis zur Verfügung gestellt werden. Um zu gewährleisten, dass die enthaltenen Informationen den erforderlichen Qualitätskriterien entsprechen und der Inhalt der Datenbank aktuell gehalten wird, sollte diese Datenbank beim Bundesamt für Eich- und Vermessungswesen eingerichtet werden. Jedenfalls wird für die Erstellung der Datenbank EF-BBW eine intensive Zusammenarbeit der unter 5.1 angeführten Institutionen erforderlich sein.

5.3 Bodenbewegungen

5.3.1 Klassifikation von Bodenbewegungen

Grundstücksgrenzen werden einerseits durch klar erkennbare Markierungen im Boden und andererseits durch Koordinaten in einem geodätischen Bezugssystem festgelegt. Solange horizontale Relativbewegungen des Bodens im gewählten Referenzsystem vernachlässigbar sind, ist die Wiederherstellung einer physischen Grundstücksgrenze durch Koordinaten eindeutig lösbar. Sobald sich der Boden aber signifikant bewegt, ist

	Erhebung im Gelände	Archivrecherche	BEV	Orthofoto / Luftbild	Airborne Laser Scanning (ALS)	SAT	
						Optical	InSAR
Methodencharakteristika	direkt	indirekt					
		visuell-kognitiv	automatisch	a) visuell-kognitiv, b) semiautomatisch	visuell-kognitiv	a) automatisch, b) semiautomatisch	a) automatisch, b) semiautomatisch
Verortungsgenauigkeit	je nach Erhebungs- und Zielmaßstab (1:5.000 – 1:25.000)	Karten: Je nach Darstellungsmaßstab; Foto- und Textinformationen: unterschiedlich (1:1.000–1:200.000)	Lage: +/- 2 cm (1σ) Höhe: +/- 4 cm (1σ)	sehr genau – mäßig genau (z. B. aufgrund Abschattungen), ca. 1 GSD (20 cm)	sehr genau, Abgrenzung z. B. 1-2 m	sehr genau – mäßig genau (z. B. aufgrund Abschattungen), GSD 10 m (Sentinel-2)	sehr genau – genau, GSD 10 m (Sentinel-1), Höhenänderung aber im cm-dm-Bereich
Vertrauenswürdigkeit	hoch – sehr hoch	gering – hoch	sehr hoch	mäßig – sehr hoch	hoch	hoch	hoch
Datenverfügbarkeit	bundesweit, bereichsweise sehr unterschiedlich	bundesweit, selektiv/nicht flächendeckend	bundesweit, punktuell	bundesweit, flächendeckend	bundesweit, flächendeckend	bundesweit, flächendeckend	bundesweit, (stark) abhängig von Hangexposition
GIS-Darstellung	Punkt, Linie, Polygon	Punkt, Linie, Polygon	Punkt	a) Punkt, Linie, Polygon b) Punkt (manuelle Auswahl, automatische Verfolgung)	Punkt, Linie, Polygon	Punkt, Linie, Polygon	Punkt, Linie, Polygon
Charakteristika der gravitativen Massenbewegungen	flach bis tiefgreifend, spontan/schnell bis progressiv/langsam	flach bis tiefgreifend, spontan/schnell bis progressiv/langsam	tiefgreifend, progressiv/langsam	zumeist spontan/schnell, flachgründig	zumeist tiefgreifend, progressiv/langsam	zumeist spontan/schnell, flachgründig	tiefgreifend, progressiv/langsam
Daten-Periodizität/-Frequenz	einmalig	einmalig	unterschiedlich	3(-5) Jahre	flächendeckende Wiederholung noch offen	6-10 Tage (aber beschränkt durch Wolken)	6-10 Tage

Tab. 1: Erfassungsmethoden von Bodenbewegungen. Erstellt durch AG „Bodenbewegungen und Kastaster“ der ÖGK (2017-01)

zu entscheiden, wo die Grundstücksgrenze zum Folgezeitpunkt tatsächlich verläuft.

Prinzipiell sind hier zwei Lösungsansätze möglich: Neuordnung im ortsfesten System (Euler) oder Nachjustierung im bewegten (materiefesten) System (Lagrange) - oder anders ausgedrückt: Festhalten der Eigentumsgrenzen an den Koordinaten der Grenzpunkte bzw. Veränderung der Eigentumsgrenzen gemeinsam mit der Verschiebung der Grenzsteine (siehe Abbildung 1).

Zur Entscheidungsfindung zwischen den beiden Lösungsansätzen ist eine Analyse der Massenbewegungen hilfreich. Es besteht die Möglichkeit einer Generalisierung der Massebewegungen in konstruktive, konservative und destruktive Abschnitte, wobei es sich bei den konstruktiven Abschnitten um den Abbruchbereich, bei den konservativen Abschnitten um den sich üblicherweise homogen ändernden Kernbereich und bei den destruktiven Abschnitten um den zerstörten Abschnitt (Überschiebungen und Erosion am Fuß) einer Massenbewegung handelt.

Während Grenzen innerhalb inhomogener Massenbewegungen (konstruktive und destruktive Abschnitte gem. Abbildung 2) als ortsfest zu betrachten sind, wird üblicherweise bei homogenen Bewegungen (konservative Abschnitte) eine materiefeste Lösung heranzuziehen sein.

Für die Beantwortung der Frage, ob ein ortsfestes System nach Euler oder ein materiefestes nach Lagrange herangezogen wird, sollte u. a. auch gelten:

- bleibt Lebensraum erhalten?
- sind wirtschaftliche Auswirkungen (Wertverlust) relevant?

Das Schweizer ZGB (Art. 660 ff) beispielsweise stellt als Entscheidungsgrundlage auf „Bodenbeschaffenheit, Nutzung und Wert des Grundstücks“ ab.

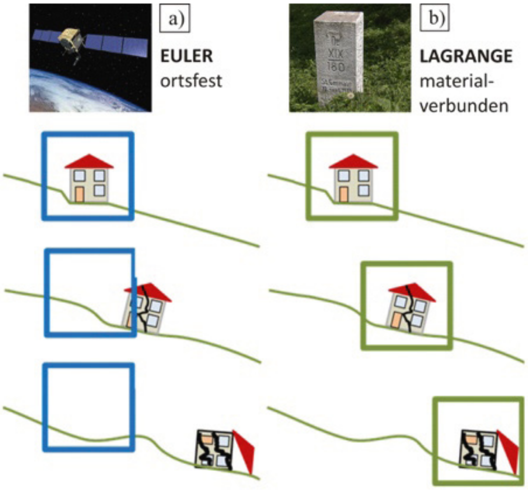

Abb. 1: Neuordnung der Koordinaten nach Euler oder nach Lagrange [10]

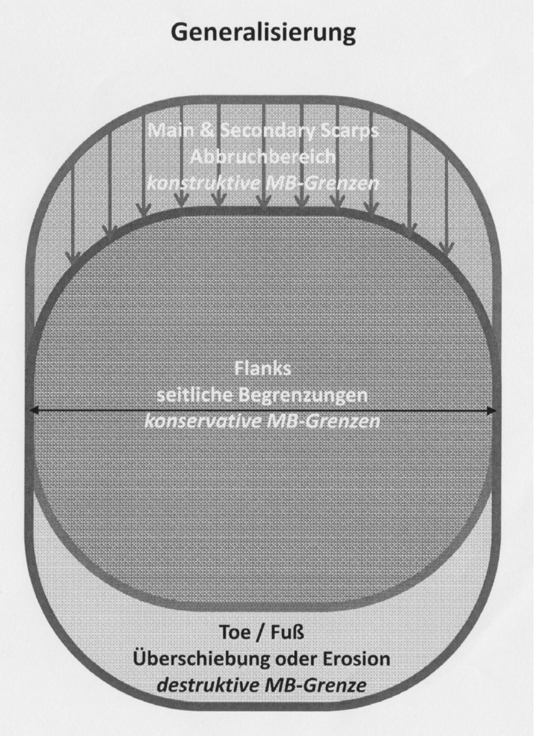

Abb. 2: Generalisierung von Massenbewegungen [11]

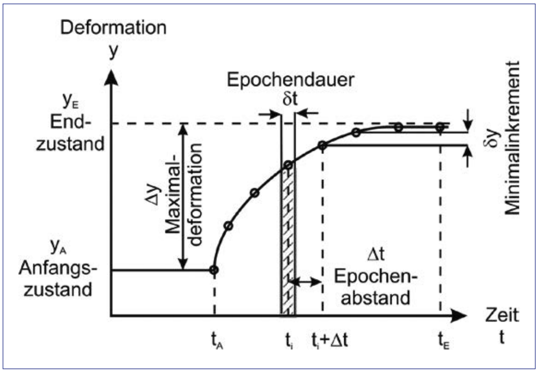

Abb. 3: Starrkörperbewegungen-Begriffsdefinitionen (Neuner)

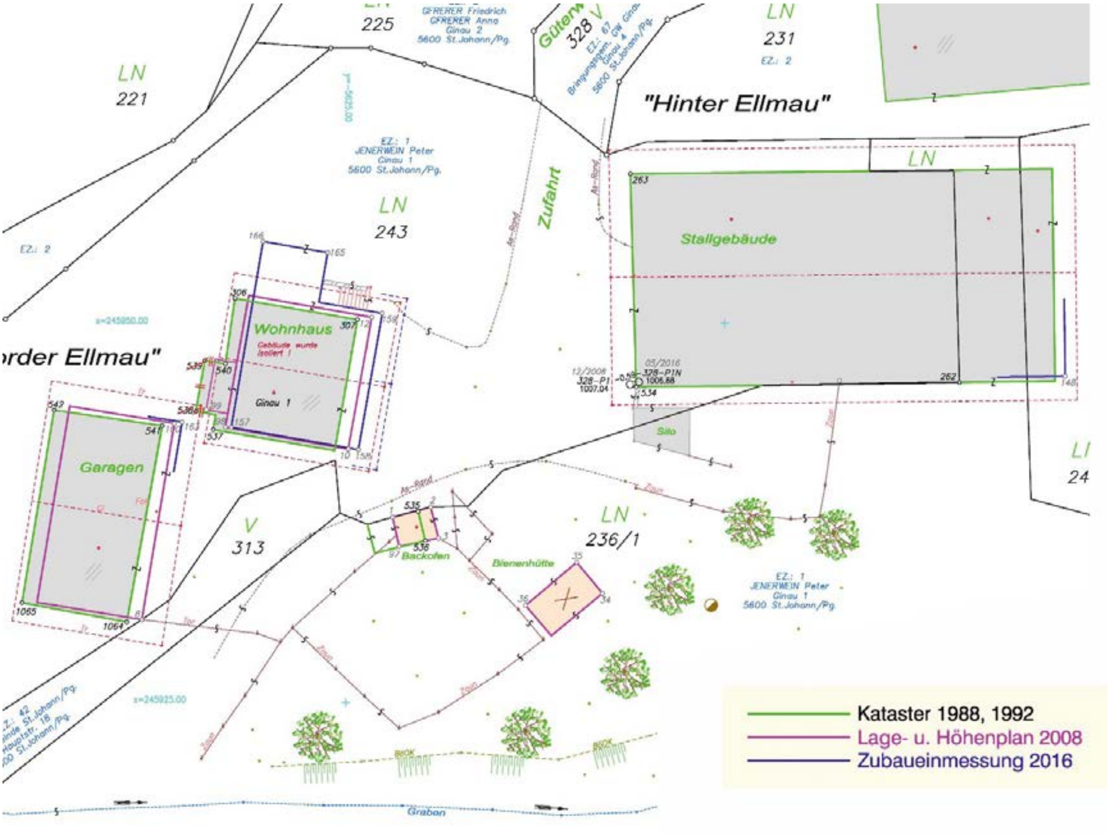

Abb. 4: *Beispiel für ein materiefestes System (Ginau/St. Johann/Pongau, Braunstingl)*

5.3.2 Starrkörperbewegungen und Messpläne

Lösungsansätze zur Analyse und Berechnung homogener Massenbewegungen basieren auf Punktmessungen zu verschiedenen Epochen. Dabei wird ausgehend von Informationen bezüglich der geforderten minimalen Detektierbarkeit einer Änderung und der linearen Änderungsgeschwindigkeit des Messobjektes auf die erforderliche Messpräzision, die Wahl des Epochenabstandes und die Epochendauer geschlossen.

5.3.3 Beispiel materiefestes System

Als Beispiel für ein materiefestes System werden Grundstücke in der Katastralgemeinde Ginau, *(Gemeinde St. Johann/Pg.)* herangezogen. Ein Vergleich des Katasters aus den Jahren 1988 und 1992 mit Messungen in den Jahren 2008 und 2016 zeigt Verschiebungsvektoren von 4 – 5 cm/Jahr (siehe Abbildung 4). Ein weiterer Vergleich mit dem Franziszeischen Kataster (vor etwa 170 Jahren in dieser Gemeinde angelegt) ergibt Differenzen von 10 – 20 m. Der Großteil der Gebäude zeigt keinerlei Schäden, nur das Wirtschaftsgebäude hat Risse.

Es handelt sich um eiszeitliche Sedimente die in Bewegung sind. Diese Bewegungen verlaufen ziemlich gleichmäßig und beeinträchtigen die Bewirtschaftung keineswegs, es besteht auch keine unmittelbare Gefahr für Menschen oder Gebäude. D. h. in diesem Fall könnte bzw. sollte bei vermessungstechnischen Arbeiten der Ansatz des materiefesten Systems nach Lagrange zum Einsatz kommen.

5.4 Empfehlung der ÖGK für die Erstellung von Plänen gem. §32a des VermG

Ausgangsbasis für eine Vermessung lt. § 32a VermG und VermV §15 sollte die unter 5.2 angeführte Datenbank für die „Ermittlungsflächen für Bodenbewegungen“ (DB EF-BBW) sein. Befindet sich das von der Vermessung betroffene Gebiet innerhalb oder teilweise innerhalb einer von der DB EF-BBW ausgewiesenen Fläche, dann hat die Vermessung nach § 15 der VermV zu erfolgen. Neu dabei ist, dass in diesem Fall für alle gemessenen Fest-, Mess-, Grenz- und sonstigen Punkte des vermessenen Bereiches, zusätzlich zu den bisher üblichen Koordinaten des nationalen Systems MGI, auch die Koordinaten im europäischen Referenzsystem ETRS89 anzugeben sind. Erst die Dokumentation in diesem, lediglich durch Satelliten, und unabhängig vom physischen Festpunktfeld, realisierten System eröffnet bei einer Folgemessung die Möglichkeit eindeutige Rückschlüsse über das Ausmaß erfolgter Bodenbewegungen in den Grenzpunkten zu ziehen.

In Hinblick auf die Entlassung aus dem Grenzkataster geht die Arbeitsgruppe der ÖGK davon aus, dass diese nur anlassbezogen und nur grundstücksweise erfolgen wird. Für die Entlassung aus dem Grenzkataster wird Folgendes empfohlen:

- Festlegung eindeutiger Grenzwerte, unter Berücksichtigung der Genauigkeitsmaße im Grenzkataster
- Vorliegen von Messungen an mindestens 2 Messepochen bei koordinativ gesicherter Festpunktlage
- Vorgabe der Punktdichte zur Erfassung der Bewegungen.

Für Grenzpunkte, welche Teil eines Grenzkatastergrundstückes sind (Indikator „G“ gem. VermV, § 1, Abs.13) sollte nach der Entlassung des Grundstückes aus dem Grenzkataster ein eigener Indikator vergeben werden (z. B. Indikator GB), damit die Information der Wertigkeit, insbesondere die Zustimmung der beteiligten Eigentümer zum Grenzverlauf zu einem bestimmten Zeitpunkt (im Falle des Grenzkatasters materie- und ortsfest), nicht verloren geht.

In gleicher Weise sollte für Grenzpunkte, welche durch erfolgreiche Grenzverhandlung und Anschluss an das Festpunktfeld gem. VermV, § 1, Abs. 13 mit dem Indikator „V“ versehen sind, bei zweifelsfreier Feststellung der Lageveränderung durch Bodenbewegungen ein eigener Indikator vergeben werden (z. B. Indikator VB).

Diese Empfehlungen der ÖGK wurden Anfang des Jahres 2017 an das damals zuständige Ministerium für Wissenschaft, Forschung und Wirtschaft übersendet.

6. Zusammenfassung

Die ÖGK ist ein Gremium, dass die Geodäsie und Geoinformation fördern soll zum Wohl von Gesellschaft, Wirtschaft und Wissenschaft. Die Struktur der ÖGK erlaubt es Stellungnahmen zu Gesetzesvorhaben abzugeben und ebenso zu eng umgrenzten Fragestellungen wissenschaftliche Expertisen abzugeben. Im Artikel sind beispielhaft die Novelle zu den Vermessungsverordnungen und die „Schaltsekunde“ angegeben.

Größere Fragestellungen stellen die ÖGK aber vor eine Herausforderung. Die Mitglieder der ÖGK arbeiten ehrenamtlich, und können somit nur dann an Projekten teilnehmen, wenn sich ein Mehrwert für das jeweils eigene Arbeitsfeld abzeichnet. Speziell im interdisziplinären Umfeld bietet hier die ÖGK ein Gremium, das verschiedene Kompetenzen zueinander führt. Die Arbeitsgruppe zu Bodenbewegungen und Grenzkataster ist solch ein Fall.

Die Vergabe von Preisen unterstützt junge Wissenschaftlerinnen und Wissenschaftler und stößt auf großes Interesse bei den Festvorträgen. Dies ist eine erfolgreiche Öffentlichkeitsarbeit innerhalb von Wissenschaft, Wirtschaft und Verwaltung. Eine breitere Öffentlichkeit wird und kann nur durch andere Formate (Geodätentag, Tag der Geodäsie, GEO-Tag) erreicht werden [12]. Daran sind natürlich auch Mitglieder der ÖGK beteiligt, jedoch in ihrer jeweiligen Rolle als Vertreter bzw. Vertreterinnen von Universitäten, Behörden und Ingenieurkonsulenten.

Der dritte große Aufgabenbereich ist die Vertretung der österreichischen Geodäsie in internationalen Organisationen. Das vorliegende Heft wird anlässlich der IUGG-Jahrestagung 2019 herausgebracht und stellt einen bedeutenden Ausschnitt der aktuellen Leistungen dar. Die Einbettung Österreichs in die internationale Wissenschaft, gerade auch in Organisationen wie IUGG, aber ebenso ICA und ISPRS, letztendlich aber auch z. B. ESA (European Space Agency) etc., ist von größter Bedeutung für den Wissenschaftsstandort Österreich. Sie ermöglicht die Mitarbeit an großen wissenschaftlichen Vorhaben die eine weltweite Zusammenarbeit erfordern, z. B. Satellitenmissionen.

Die ÖGK wird ihren, in den Statuten festgelegten, Aufgaben gerecht. Sie ist ein wichtiger Bestandteil der Geodäsie und Geoinformation in Österreich.

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Lidar and Photo: differences and integrated processing

Norbert Pfeifer, Wien

Abstract

The differences between Lidar and photo observations are discussed on a sensor level. This highlights the similar and complimentary aspects of both data acquisition methods. A method for the integrated orientation of photo and Lidar observations is presented and its effectiveness is shown. It is argued that integrated acquisition and processing will become a standard for topographic data acquisition. The article is based on the research and experience of the photogrammetry group at Technische Universität Wien.

Keywords: Lidar, Camera, Laser Scanning, Photogrammetry, Complimentarity

Kurzfassung

Für die Erfassung topographischer Information über größere Bereiche stehen praktisch zwei Messkonzepte zur Verfügung: Lidar (Light Detection And Ranging), auch unten dem Namen Laserscanning bekannt, misst direkt 3D und ist die jüngere Technologie und die 3D-Rekonstruktion aus Photographien, die auf bereits 150 Jahre Erfahrung zurückgreift. Beide Technologien entwickeln sich rasch weiter. Anhand der Gemeinsamkeiten und der Unterschiede der beiden Messkonzepte, untersucht auf dem Sensor-Niveau, wird gezeigt, wie sehr sich diese beiden Methoden ergänzen. Eine gemeinsame Prozessierung kann potentiell genauere, zuverlässigere und vollständigere Modelle unserer Umgebung liefern, die noch dazu effizienter erstellt werden können. Eine solche integrierte Verarbeitung ist aber nur für wenige Aufgaben entlang der Prozessierungskette von der Datenaufnahme bis zum 3D-Modell realisiert. Ein Ansatz zur gemeinsamen Orientierung wurde bereits vorgeschlagen und praktisch eingesetzt. Dieser Artikel soll die Komplementarität der beiden Sensoren stärker herausarbeiten und dazu beitragen die integrierte Aufnahme und Prozessierung von Lidar- und Photo-Aufnahmen als Standard etablieren.

Schlüsselwörter: Laserscanning, Kamera, Lidar, Photogrammetrie, Komplementarität

1. Introduction

Technische Universität Wien (TU Wien) has 8 faculties, among it the faculty of „Mathematics and Geoinformation“. This faculty has four institutes, three in mathematics and the “Department of Geodesy and Geoinformation”. With more than one hundred employees it is, also considering international standards, a large group in this domain, reaching from engineering and advanced geodesy, via remote sensing, geophysics and photogrammetry to geoinformation and cartography.

The photogrammetry research unit has built up a reputation in airborne laser scanning research, including full waveform analysis (Wagner et al., 2006; Schwarz et al., 2019), sensor orientation (Kager et al., 2004; Glira et al., 2016), and terrain modelling (Kraus et al., 1998) as well as vegetation modeling (Hollaus et al., 2006) and hydrography (Mandlburger et al., 2015). The scope of research is, however, wider and reaches from the sensor to the application. The photogrammetric aspect in this research is that i) the method of data collection is concentrated in the optical part of the electromagnetic spectrum (using Photons), thus the visible and near infrared light. It means further that geometrical optics (line of sight, lenses) is in most cases sufficient to explain the imaging process. A further photogrammetric aspect in the research is, that ii) the sensors are imaging, which means that the entire scene is recorded in a profile- or area-wise image (referring to graphic recording), as it is typically acquired by a camera or a laser scanner. Thus no interpretation of the scene is performed during data acquisition, e. g. by measuring “only” specific object points like corners. Finally, the aim is iii) a metric exploitation of those measurements, in order to build georeferenced models of our environment from those images. Applications play an important role in the research work of the group. This steers the basic research into directions relevant for society, public administration, and economy.

The most important sensors in topographic photogrammetry are cameras and pulsed laser scanners. In this article the research work of the photogrammetry group w.r.t. the mutual differences of those two data acquisitions methods and the current state of joint processing are presented 1). Such a combined exploitation of photographic images and Lidar (light detection and ranging) sensors is not an aim per se, but has to support more efficient, reliable, complete, and accurate extraction of 3D information.

The aim of this article is to study the differences between photo and Lidar observations on a fundamental, sensor-oriented level and present one domain, i. e. orientation, in which a successful integrated processing has been established. This builds the basis to formulate expectations for future developments.

2. Photos and Lidar

Photos are taken by cameras and have been studied in photogrammetry since roughly 150 years (Albertz, 2007). They operate by recording reflected sunlight, which is focused by the lens system onto a matrix arrangement of light sensitive elements (pixels) in the focal plane. Scanning Lidar is comparatively newer and is applied since roughly 30 years in photogrammetry (Kilian et al., 1996). Lidar operates by emitting a short laser pulse in a specific direction, which then travels through the atmosphere, is scatted back at objects, and the (small fraction of the) signal that travels back to the sensor is detected to record the time lapse between emission and detection. With the known speed of light this is converted to a range measurement. Both sensors, cameras and Lidars, are typically used to acquire area-wide data from either static or mobile (e. g. airborne) platforms. Lidar and photos, through dense image matching (e. g. Hirschmüller et al., 2008), can both be used to provide a point cloud describing the recorded object surfaces.

2.1 Comparison

Considering that both sensors use either visible light or the near infrared, also different objects (building, streets, terrain, etc.) are measured in a similar way. The density of measurements scales with flying height above ground for both sensors, and also does the swath width. However, there is also a list of differences, which originates in the physical measurement principles and has effect on measured objects. Understanding those differences and exploiting them is part of the fundamental research in the photogrammetry group of TU Wien. It has impact on applications, e. g. when mapping vegetation, water bodies or urban regions, but also influences the possible deployment of these sensors. Practical differences between Lidar and photo point clouds are presented, e. g., in Mandlburger et al. (2017), Ressl et al. (2016) and Otepka et al. (2013), see also Figure 1.

Photos record simultaneously the entire field of view, which depends on the focal length and the opening angle, respectively, of the lens system. The simultaneous recording also means, that the incoming radiation is recorded for all pixels simultaneously, which is a large advantage when it comes to georeferencing. For modern photogram-

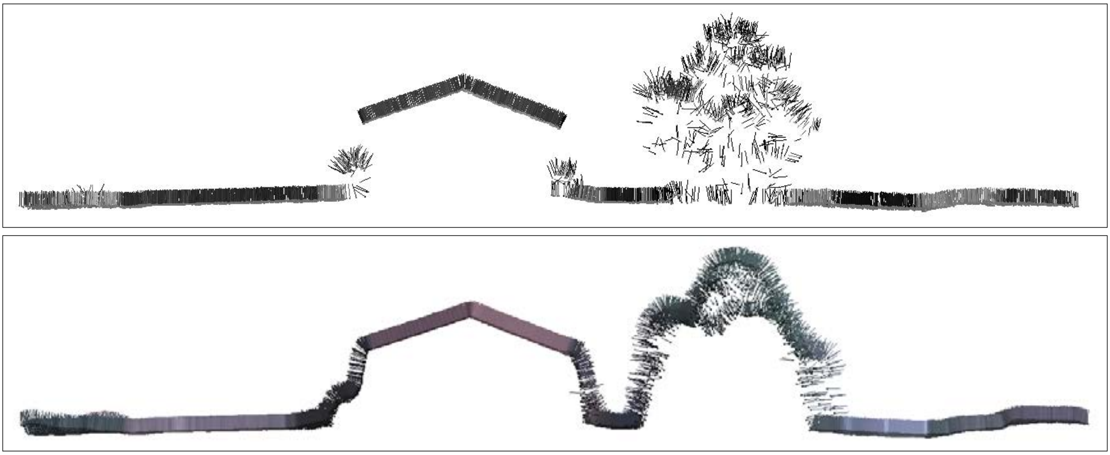

Fig. 1: Lidar (top) and photo (bottom) point clouds showing a profile with open ground, a house and tall vegetation. Additionally to the points, estimated normal vectors are shown. The Lidar point cloud shows as grey value the amplitude of the detected signal, whereas the photo point cloud has the color of the corresponding images. (Figure taken from Otepka et al., 2013)

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1) As this article presents the research work from one group, the list of references is somewhat imbalanced.

metric cameras this means that 100 million pixels of one image – or for the newest cameras rather a few 100 million pixels – have the same exterior orientation. Acquiring overlapping photos leads to overdetermination, and by bundle block adjustment the exterior orientation can be estimated using only a few ground control points. There are some limits, e. g. motion blur, which can partly be compensated, or special mechanisms, like, e. g., the rolling shutters. The latter are not advisable for moving platforms or capturing non-static scenes. Professional aerial photogrammetric cameras have a fixed focal length (and a fixed focus), which means that their field of view is constant.

Lidar, on the other hand, is a **sequential measurement** technology. The measurements are performed one after another. For mobile platforms this means, that each measurement has its own exterior orientation, and thus direct georeferencing using, e. g., GNSS and INS (Global Navigation Satellite System and Inertial Navigation System) are mandatory. In earlier commercial systems only one pulse was in the air traveling from sensor to object and back. This limited flying height or the pulse repetition frequency and the effective scan rate, respectively. Newer systems are not limited in that sense and can have multiple (e. g., 5 and more) pulses simultaneously in the air. Additionally, multiple laser range finders can be mounted in one scanner, using the same or different beam deflection devices. In this way the scan rate is further increased. Additionally this starts (at a very low level) introducing within-strip overdetermination, because the same location is measured more than once. The palmer scanners (using a nutating mirror or a rotating wedge prism for beam deflection), effectively producing a circular scanning pattern on the ground, naturally provides this. Other methods to increase the number of beams operate by splitting each emitted beam into beamlets, using, e. g., diffractive optical elements (DOE). All these beamlets are released simultaneously, therefore having the same exterior orientation. Such DOEs are planned, e. g., for NASA´s Lidar swath imaging space mission LIST (Yu et al., 2010), but is currently also employed in topographic scanning (Degnan et al., 2016). Those methods increase the number of observations with one exterior orientation.

A physical limit to the **resolution** is given by diffraction. For photos this means, that an ideal point is imaged onto a circle, which is in the order of the unit-less aperture number interpreted in µm. Thus, pixel size is accordingly in the order of 5 µm or somewhat smaller. Opening angles for individual pixels can, in tele configuration, be below 0.02 mrad. For wide angle cameras these values naturally go up. The ground sampling distance (GSD) is obtained by the multiplication of the pixel size with the image scale. Typically the entire sensor area is sensitive to light, e. g. with the help of micro lenses that focus the entire light of one pixel in the focal plane onto a smaller, photo sensitive region. Thus, the ground is covered contiguously with pixels, which are spaced at the GSD.

For Lidar the beam width (or beam divergence) is typically higher, in the order of 0.2 mrad. It is in the order of λ/D, with λ the wavelength and D the aperture diameter of the emitter. For cameras the limiting aperture is given by the lens system. The area illuminated with one laser shot of an airborne laser scanner, the footprint, is thus typically larger than the GSD of the panchromatic image acquired by a professional photogrammetric camera flown at the same height (see also Figure 5). A smaller opening angle of the laser beam would increase the resolution, but focus more energy into a smaller region, which can become problematic w.r.t. eye safety. Also, repetition frequency, flying speed, and footprint size should be chosen to map the entire ground (contiguously) in airborne operation. In terrestrial laser scanner systems correlated sampling (i. e. overlapping footprints) is possible. In that case the “GSD” (i. e. the linear point spacing) is smaller than the footprint (see, e. g., Milenković et al., 2018). The footprint can also be tailored to applications, e. g., forming an elliptic footprint with its longer axis orthogonal to the flying direction, in order to increase the chance of mapping linear elements in flying directions (e. g. power lines).

Color can be recorded in photos using multiple (lens) cones, and therefore multiple cameras, thus providing multiple photos in different parts of the electromagnetic spectrum, e. g., blue, green, red, and near-infrared. These cameras do typically have lower resolutions than their pan-chromatic counter parts, and pan-sharpening is used to fuse the higher resolution pan-images to the lower resolution color images. An alternative, found more often in consumer cameras and in professional “mid-format” cameras used for photogrammetry, are color filter arrays as the Bayer pattern. Each light sensitive pixel in the focal plan is covered with either a red, a green, or a blue filter. To obtain the “full” resolution, the colors are interpolated from the respective recordings to obtain red, green, and blue values for each pixel. It is noted that both approaches lead to a lower resolution of the color information, often by factors between 2 and 4 (linear), in comparison to the pan-chromatic recordings. The grey or color values are often provided as digital numbers, i. e. not in a physical unit like radiance at the sensor. If multiple objects are within the instantaneous field of view of one pixel, they all contribute in an integral way to the sensor reading.

In contrast, a Lidar measures in a very narrow spectral band (around the wavelength of the Laser), opposed to the (broad) color bands of a camera. Assuming that only one target is within the instantaneous field of view of the laser beam, the amount of diffuse reflection towards the sensor, and the loss due to spreading of the reflected signal into the entire (half-)space, influences the amount of recorded energy. As the amount of emitted energy can be or is often known for laser scanners, also the amount of received energy can be expressed in physical units. Because of the active system and the very narrow spectral band of the detector, radiometric calibration is straightforward for Lidar observations in comparison to photos, for which the solar illumination and the composition of the atmosphere play a more important role. Currently, the number of laser scanners operating at multiple wavelengths is increasing. While commercially available ALS sensors feature two or three wavelengths, experimental terrestrial systems have eight and more channels (Hakala et al, 2012).

Photographic imaging is singular, which means that the process of focusing the incoming radiation onto the focal plane reduces the 3D object space to a 2D image. This mapping cannot be inverted, and thus – at least – one additional photo is required to reconstruct a scene in 3D from photos. Matching of homologous points is necessary, which requires computing resources. In a practical investigation Tran et al. (2018) have shown, that computation time grows with decreasing resolution, specifically it grows with current standard approaches stronger than linear with the number of points that can be reconstructed. Furthermore, the matching process, although featuring overdetermination, can also lead to matching of non-homologous points, and wrong points in object space. Additionally, matching requires that the same texture is recorded (and recognized) from different exposure positions, which are furthermore illuminated by the sun. Thus at least three rays have to hit a point, two directly from the camera projection centers and one from the sun, at least indirectly. Therefore, reconstruction of the ground below forest cover is in general not possible from photos (see also Figure 1). This demand for at least two viewpoints in order to reconstruct a 3D point also means that narrow alleys are more difficult to reconstruct, because a correspondingly dense strip layout in the flight plan is necessary to reconstruct especially those alleys that are parallel to the flying direction. Finally, this singularity also means that multiple objects along the instantaneous field of view of one pixel are recorded at the same position.

Laser scanners use a polar measurement technique, recording range and direction to the measured targets simultaneously. Obviously, this brings an advantage in computation time. The measurement to a single object point is, however, not controlled. This becomes obvious in multipath situations, caused by specular reflecting surfaces (e. g. glass façades), which lead to an additional mirrored image of the mapped objects (see Figure 2).

Fig. 2: *Due to multi-path, the polar measurement method generates a mirrored image of a real object. The building glass façade is acting as mirror. Class labels (building, ground, vegetation) were derived automatically (Tran et al., 2017).*

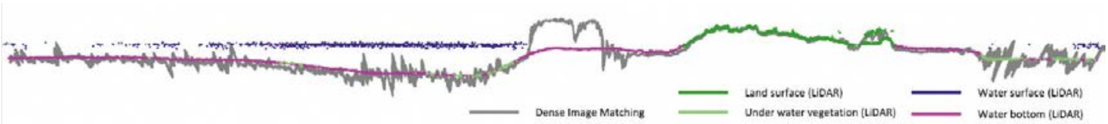

Fig. 3: A comparison of Lidar measurements and a point cloud reconstructed from photos. The left part of the profile is acquired over water surface, and the Lidar sensor provides both, water surface and water bottom. As the water is clear, dense image matching through water can be performed, also providing an estimate of the bottom surface, but not the water top surface. It is noted that the noise of the image matching point cloud is larger than of the bathymetric Lidar point cloud. Over open land, both datasets show the same surface. (Figure taken from Mandlburger, 2018)

The ranging capability of Lidar means that range-resolved measurements are possible. Under the assumption that a short signal of laser light (often <10ns) is used to scan (and therefore illuminate) the object surface, targets that are further apart (along the beam direction) can be discriminated. Each target causes an individual echo. This **multi-target capability** is especially advantageous over tall vegetation, because it allows measuring the crown (first echo), vegetation elements below (intermediate echoes), and the ground (in an ideal but not untypical situation the last echo, see also ground points below vegetation in Figure 1). The polar measurement technique is also advantageous in urban canyons or under semi-transparent objects (tree canopy), as only one beam has to reach the lower surfaces to record a position. A further example, in which this is exploited, is the bathymetric measurement with Lidar. Using a suitable wavelength (green light, e. g. 532nm) allows to record a range measurement to the water surface, but also a further measurement to the bottom of the water body (see Figure 3). Also laser scanning can deliver wrong points in object space. They originate from multiple targets along the laser beam, which are spaced so close together, that the returning signals overlap strongly and only one point in a middle (and therefore wrong) distance is recorded.

Lidar is an active measurement method. It records the backscatter from a signal that was emitted by the very same system. This makes it independent from illumination conditions. The atmosphere must, however, be clear for both, Lidar and photos. This makes data acquisition during night time possible. **Photos are passive sensors**, recording (at least outdoors) the backscattered radiation of the sun. This means, that they are affected by shadows, which leads to a lower precision in matching of points located in shadow areas

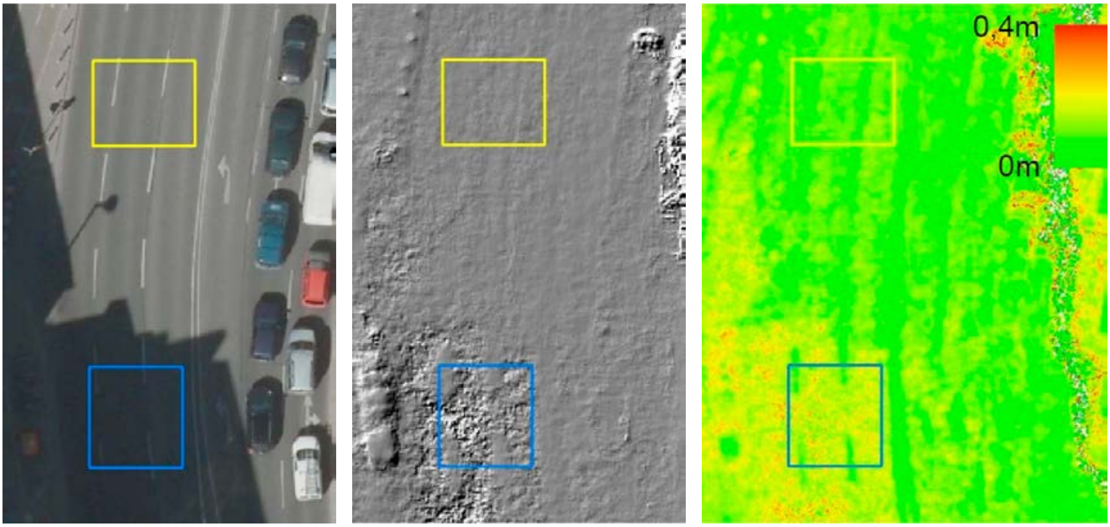

Fig. 4: Shadows in the original image (here orthophoto for comparison), DSM derived robustly from dense image matching, and std.dev. of heights originating from multiple image pairs. The higher std.dev. in the shadow areas is highlighted. Data provided by Stadt Wien, MA41.

(see Figure 4). Recording reflected sun light has the advantage that no power source is needed as it is required in Lidar to generate Laser pulses. This leads to a lower weight for the sensor, which is notable for terrestrial, static systems, and for operation on unmanned, light weight platforms.

Pulsed Lidars emit a short beam. This is in contrast to the sun continuously illuminating a target, which reflects a constant stream of light to the sensor (i. e. the camera). The Lidar signal scattered back to the sensor, on the other hand, is the convolution of the emitted pulse shape (more correctly the system waveform) with the differential target backscatter cross section. This differential cross sections contains information on the location of reflection along the beam as well as the brightness at the wavelength of the laser. There are different possibilities to **detect and process this returning signal**. Recording of the full waveform provides information on the elongation of objects along the laser beam. While strongly inclined surfaces stretch the returning signal. However, it is especially the occurrence of distributed targets with similar but not identical range along the beam axis, which causes a widening of the returning pulse. The echo-widening, typically high over tall leaf-on vegetation for footprints in the order of some dm, can thus be used to detect vegetation. This also applies to low vegetation, which is otherwise hard to discriminate from ground echoes. Recording and analyzing this full-waveform has led to an increased number of (discrete) echoes in vegetation. For denser media, e. g. water, an exponential decay of the returning energy can be expected. This technology allows ranging over long distances (km) with precision in the order of cm. It requires, however, that the returning signals are sufficiently strong. Detection of weaker signals becomes possible using so-called single photon detection (Degnan et al, 2016). In this case, one photon (or a very small number of photons) is sufficient to detect a returning pulse. This may cause false detections, and a relatively high number of erroneous points, which have to be eliminated in further post-processing. An example of single photon Lidar, an aerial photo, and full wavefrom Lidar is shown in Figure 5.

While some of the differences between photos and Lidar elaborated above are governed by physical principles, the effects on the recorded measurements are depending on the current state-of-the-art in the sensor technologies. For both, laser scanners and cameras, the last years have provided an ever increasing density of measurements and thus higher productivity. The advantage of cameras lies mainly in the smaller (planimetric) GSD, whereas Lidar provides multiple echoes and higher precision in range, which is basically the vertical direction for airborne acquisition. Some developments in Lidar technology, e. g. bathymetric measurements using a green Lidar, are already established, while multi-wavelength Lidar has not yet found a wide area of application in surveying.

Both technologies can be expected to develop further, and they are complimentary, as shown above. It thus stands to reason to ask, how can the datasets be used together in the best possible way?

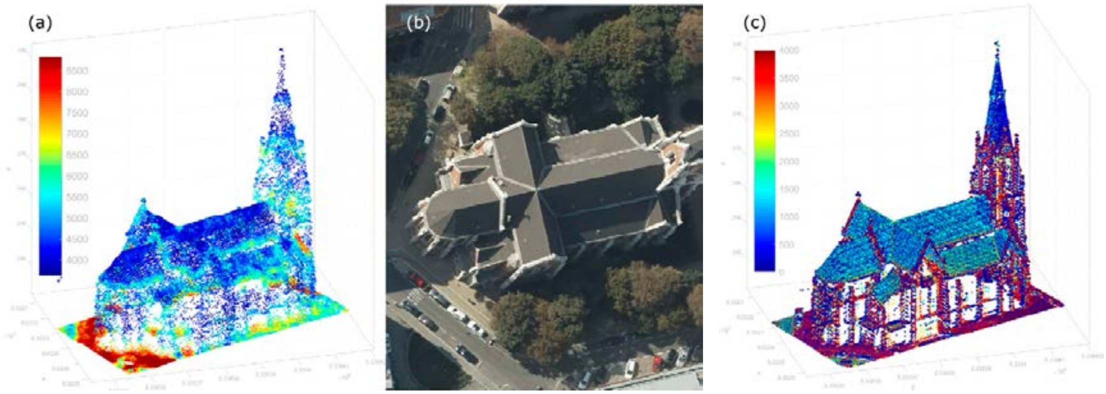

Fig. 5: *Left the point cloud from single photon Lidar is shown, in the middle an aerial image, and right the point cloud from full-waveform Lidar. All sensors were flown at the same height. (Figure taken from Mandlburger et al., 2019)*

2.2 Integrated orientation

Fusing Lidar and photo observations can occur on different levels, either in the orientation phase, in the 3D modeling phase, or in the application phase. Obviously, fusing data from both sensors in earlier stages of the workflow will provide higher accuracy and reliability, as the entire information is available in all subsequent stages. The disadvantage is that current workflows or algorithms have to be adapted to accommodate both sources.

The integration of Lidar and photo observations is suggested by integrating strip adjustment and bundle block adjustment. The aim of strip adjustment is to determine improved trajectories (improved w.r.t. the direct georeferencing solution) and to estimate calibration parameters (e.g. misalignment between laser scanner and INS). Subsequently, new 3D object point coordinates are computed. The optimization principle minimizes the distances between overlapping laser strips and the differences to ground control data (points or point clouds). Bundle block adjustment operates in a similar way, estimating exterior orientation, camera calibration parameters, and – in contrast – also the tie point coordinates. The optimization minimizes the offsets between the rays of corresponding points, as well as the offset between ground control points and corresponding ray(s).

The equation relating the unknown exterior orientation, the unknown tie point, and the measured image point to each other is the collinearity.

$$(\boldsymbol{X}_i - \boldsymbol{O}_j) = m\mathrm{R}_j(\boldsymbol{x}_{ij} - \boldsymbol{o}) \qquad (1)$$

Here the terms have the following meaning: $\boldsymbol{x}_{ij}$ are the observed point coordinates in the image plane, and $\boldsymbol{X}_i$ is the object point; o is the interior orientation, possibly augmented by the distortion; $\boldsymbol{O}_j$ and R_j are the exterior orientation of image j; m is image scale, individual for each point measurement and eliminated by dividing the first two rows of this vector valued equation by the third row. The index i is specific for each point, the index j for each photo.

The direct georeferencing equation of airborne lidar is:

$$\boldsymbol{X}(t) = \boldsymbol{G}(t) + \mathrm{R}^n(t)\mathrm{R}^b(t)(\boldsymbol{a}^m + \mathrm{R}^m\,\boldsymbol{x}(t)) \qquad (2)$$

Also, this equation relates the measurement of a point in the laser scanner coordinate system $\boldsymbol{x}(t)$, thus a range and two angle measurements, to the object point $\boldsymbol{X}(t)$. Here the index pair (i, j) is replaced by the time of the measurement (t). The other parameters are: the mounting, consisting of the bore sight (mis)alignment R^{m} and the lever arm $\boldsymbol{a}^m$, which rotate and shift the vector $\boldsymbol{x}(t)$ into the system of the INS; $\mathrm{R}^b(t)$ describes the rotation from this body system to the navigation frame and is provided by the Kalman filter output of the GNSS and INS observations, typically designated as roll, pitch and yaw angle; $\mathrm{R}^n(t)$ rotates from this frame, the local horizon or navigation frame, to an earth centered earth fixed system (e.g. WGS84), which depends on the current latitude and longitude; $\boldsymbol{G}(t)$ finally is the vector denoting the position of the GNSS antenna.

Bringing those equations, photo collinearity and Lidar direct georeferencing, together, requires interchange between the paradigm of observing key points in multiple images $\boldsymbol{x}_{ij}$ and a continuous stream of point measurements $\boldsymbol{x}(t)$. The concepts of exterior orientation are comparable: $\boldsymbol{O}_j$ and $\boldsymbol{G}(t)$ for the location and R_j and $\mathrm{R}^n(t)\mathrm{R}^b(t)$ for the angular attitude. Because of direct georeferencing, the mounting parameters $\boldsymbol{a}^m$ and R^m are necessary, but this would equally apply if integrated georeferencing (i.e. ground control points, tie points, and direct georeferencing) is performed for photos. Similar to the case of photos, calibration parameters may be added to the Lidar observations $\boldsymbol{x}(t)$, as functions of the observed range and angles.

In the bundle block adjustment, the residuals $\boldsymbol{\nu}_{ij}$ are added to each point, and their square sum is minimized in order to determine the unknown parameters. The homologous points do not exist in laser scanning. The solution suggestion by Kager (2004) uses homologous planar patches, which have three unknowns, similar to the tie points of the bundle block. The alternative solution suggested by Glira et al. (2016) replaces the exact correspondence between points by approximate correspondence, as applied in the ICP algorithm (Besl et al., 1992). For relative orientation of 3D point clouds, the formula is:

$$\sum_{i=1}^{n}\left[\left(T(\boldsymbol{Y}_i) - \boldsymbol{X}_{c(\boldsymbol{Y}_i)}\right)^{\mathrm{T}} \boldsymbol{n}_{c(\boldsymbol{Y}_i)}\right]^2 \xrightarrow{T} Min \qquad (3)$$

Here, $\boldsymbol{X}_j$ is an individual point of a fixed point cloud, and $\boldsymbol{n}_j$ is its normal vector. $\boldsymbol{Y}_i$ is a point of the second point cloud with n points, which is to be transformed, e.g. by a Euclidean transformation, $T(\boldsymbol{Y}_i) = \boldsymbol{Y}_0 + \mathrm{R}\boldsymbol{Y}_i$, in order to fit as good as possible to the first (i.e. the fixed) point cloud. The function $c(\boldsymbol{Y}_i)$ delivers the index of the points $\boldsymbol{X}_j$

which is spatially closest to $\boldsymbol{Y}_i$. Alternatingly the transformation parameters are determined and the correspondences for the transformed points $T(\boldsymbol{Y}_i)$ are computed. Each transformation brings the points $\boldsymbol{Y}_i$ closer to $\boldsymbol{X}_j$ until an optimum is reached. The optimum is that the square sum of the orthogonal distances d_i (the term in the square brackets above) is minimal.

The principle of the joint strip and bundle block adjustment is to simultaneously minimize the distances between overlapping strips, the residuals of the tie point observations, and the distances of the tie points to the strips. Furthermore, deviations between photo/Lidar measurements to the control points or control point clouds, respectively, are minimized. The residuals of the tie points are formulated in image space, whereas the strip-to-strip differences with their observed value zero ($d(t,t')$ in Figure 6), are formulated according to the ICP principle in object space. The transformation T is not the Euclidean transformation, but rather the direct georeferencing equation of Lidar. Its unknowns are the mounting parameters and corrections for the rotation and the GNSS antenna phase center. Likewise, the tie points from the bundle block are formulated to have a distance of zero to the Lidar strips (d_i in Figure 6).

More complex models linking both, photos and Lidar, to a common trajectory, and improving a given trajectory from direct georeferencing with time dependent correction functions (e. g. splines) are presented in Glira et al. (2019).

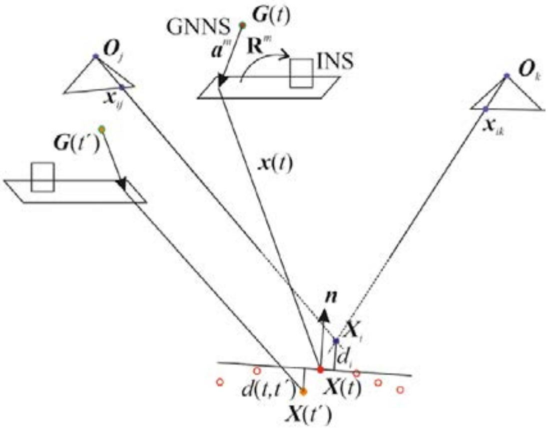

Fig. 6: Integrated orientation of Lidar and photo observations. The normal vector $\boldsymbol{n}$ in $\boldsymbol{X}(t)$, solid red point, is estimated from its neighbors measured within the same Lidar strip (red circles). The Lidar point $\boldsymbol{X}(t')$ is measured typically in another strip. The point $\boldsymbol{X}_i$ is measured in at least two, but preferably more, photos. Airborne scanning Lidar requires direct georeferencing (GNSS, INS) and the corresponding mounting parameters.

An integrated orientation of Lidar and photo observations triggers the question for the homologous elements. As shown in Figure 7, only "hard" surfaces should be used, whereas surfaces covered with grass feature already a height differences between Lidar and photo point cloud.

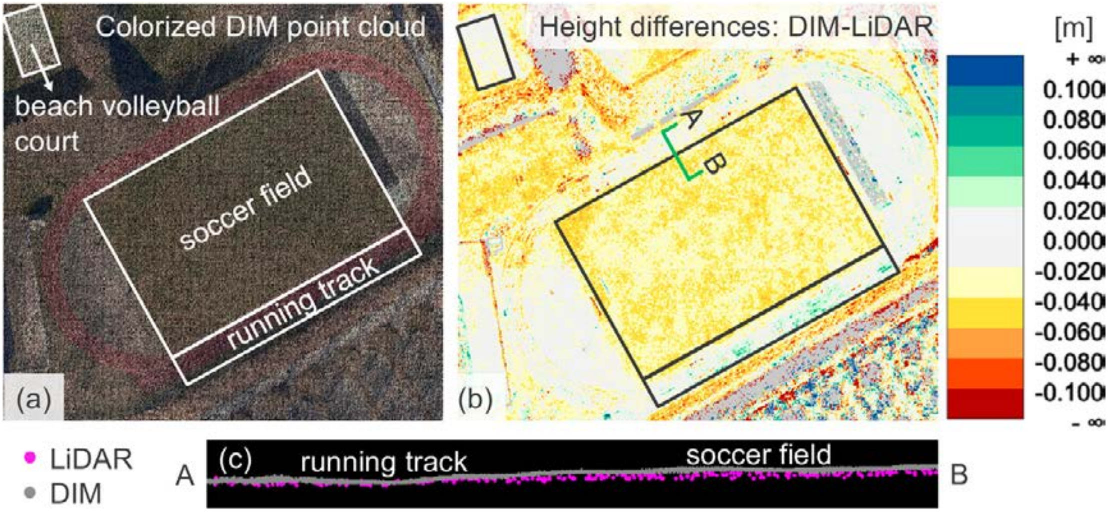

Fig. 7: Difference between points clouds from dense image matching and from Lidar. Data was acquired from the same platform. Left the situation is shown, right the height difference, which is zero up to the single centimeter for solid surfaces (running track) and above 2 cm for the grass surface (soccer field). (Figure taken from Mandlburger et al., 2017)

Fig. 8: Differences between dense image matching and Lidar point cloud before (left) and after (right) integrated orientation. For solid surfaces the improvement from above 6 cm to below 3 cm can be seen. For inclined surfaces (roofs) the improvement is bigger, because the alignment is also improved in the horizontal component. (Figure taken from Mandlburger et al., 2017)

The benefit of integrated processing is demonstrated with one example. Using photos and Lidar data acquired from one platform, at first independent orientation was performed for either dataset: the bundle block adjustment with ground control points for the photos and strip adjustment with ground control patches for the Lidar data. Both datasets exploited direct georeferencing, but for the photos it is "only" an observation stabilizing the bundle, whereas for the Lidar data it is indispensable. Subsequently, a dense image matching was performed to obtain a dense point cloud. The differences between those point clouds are expected to be high over tall vegetation or other rough surfaces, but zero at solid surfaces (street roofs, etc.). Within each single sensor orientation result, no inaccuracy could be detected. However, as shown in Figure 8, over street surfaces larger differences appear. This indicates that at least one source features internal, undetected errors. A joint orientation successfully removes those biases.

2.3 Integrated Point Cloud Processing

While the integrated orientation and calibration of measurements from Lidar and photos is already suggested and operational, there is comparatively little work so far on how to optimally use the point clouds for deriving 3D models or classifying the point cloud.

- Mandlburger et al. (2017) have suggested to derive better surface models by using the higher reliability of Lidar point clouds and the higher density of photo point clouds.
- The process of ortho photo generation can be speeded up with a concurrently acquired Lidar data. The surface model comes from Lidar and the image content from photos. If the data are acquired simultaneously, changes in the objects are minimized (excluding, e. g., the effect of growth or wind on vegetation). Also the higher resolution of images fits favorably to the observation that the texture of a surface is varying faster than its geometry. This benefit is already exploited today.
- Lidar data can also be used to constrain image matching. Given approximate exterior orientation of images, the search space can be reduced to the epipolar line. If the position of the surface is already known from Lidar, the search space can be further reduced to a short line segment. Ideally, only a small area, depending on the relation between Lidar footprint size and photo GSD, will have to be investigated to pinpoint the location of edges and corners through corresponding image points.
- Certain objects can be acquired better with a Lidar sensor, e. g., power lines or the ground below vegetation. Independent thereof, color and near infrared information from photos provide a valuable input to classify the entire area. The different appearance (see Figure 7) of some objects in the point cloud can support classification.

3. Discussion

As shown in Section 2.1, there are not only many similarities between Lidar and photo observations, but also some differences. For many object classes (vegetation, solid earth, water) the impact of those differences and the similarities are clear. However, a model to quantify those differences has not yet been established. Such a model would predict the (vertical) difference between, e. g., a crown surface over a certain tree species from airborne photo to airborne Lidar data. It is rather the case that for specific experiments the differences in the height estimation are reported (e. g., Ressl et al. 2016).

Both technologies, Lidar and photographic imaging, are developing. Also within each technology different concepts, e. g. full waveform recording vs. single photon counting Lidar, are competing. In imaging an example is the standard nadir imaging concept, augmented by oblique imaging, and moving more and more towards omnidirectional imaging as in backpack solutions. Predicting the trends of the past into the future means, that we will witness a further increase in density of measurements (or point clouds) with more and more directly measured attributes (reflectance in a number of spectral bands or single wavelengths). Those three trends, i) higher density, ii) multidirectionality, iii) directly measured attributes, will allow to replace multiple measurement tasks performed currently with terrestrial devices and especially with tactile measurement by (low flying) airborne sensors. One current limit is the accuracy and the reliability of direct georeferencing. Additionally, legal restrictions (operation of UAVs) will need to change to enable this.

The joint orientation of Lidar and photo observations as described in Section 2.2 is to be considered as one formulation for a (relatively) rigorous joint orientation of Lidar and photo observations. The principle can be applied to terrestrial data as well. It is highly automated by relying only on points, which are restricted to those areas, where both sensors provide comparable results, i. e. within smooth surfaces. While the formulation and implementation of the strip and bundle block adjustment is operational and effective, improved models may be developed in future. These models could, e. g., minimize residuals only in the Lidar observations ($\boldsymbol{x}(t) + \boldsymbol{v}(t)$ rather than $d(t,t')$), and especially models that integrate GNSS and INS observations. The current 2-stage approach (first georeferencing, inevitably producing some errors, and subsequently sensor calibration to minimize discrepancies) is not optimal and can lead to locally wrong trajectories, which need to be repaired by complicated re-computation. Instead, the overlap and identity at the ground level should support the derivation of the trajectory from the very beginning. However, the joint photo Lidar orientation, together with technological developments of Lidar sensors w.r.t. internal overdetermination, will (or should allow to) decrease requirements on very precise direct georeferencing.

Finally, the joint processing of Lidar and photo data to derive 3D models is not far developed yet. Given the development of sensors, more and more sensor systems acquiring simultaneously high quality photogrammetric images and Lidar data are becoming available. It is expected, that simultaneously acquired Lidar and photo data becomes the standard for topographic acquisition, thus representing a technology push leading to new methods of integrated processing.

The point cloud will play a decisive role, as it offers the possibility to have a common data model for data coming from various sources. Thus, the development of versatile tools for the orientation and processing of point clouds is necessary and they will gain more importance in future. At the photogrammetry research unit of TU Wien the point cloud processing software OPALS is developed (Pfeifer et al., 2014).

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Geoinformation Research Directions

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Abstract

This article introduces the research directions of the Geoinformation Research Group at the Vienna University of technology. When we walk in a real or virtual environment as well as when we interact with our surroundings, e. g., buildings, we produce geospatial traces. By analyzing this human generated, but also urban environment data in an efficient and effective way, we are able to answer several research questions of the field. For instance, we can reveal the structure of the environment we live in, investigate the effects of the environment on human decision-making, we can understand how humans interact with the environment as well as enable novel geospatial visualizations and interaction dialogues. Emerging technologies such as virtual and augmented reality as well as eye tracking allow us to go a step further and perform complex experiments in order to generate relevant spatial data that will allow us to investigate and understand the decision making process of humans in controlled environments. Furthermore, due to current technological advances of the Geoinformation Research Group, we can now use the AR technology also in outdoor spaces in order to visualize georeferenced objects in real-time. This provides us the ability to perform experiments also in natural environments, altering the spatial information that the humans can perceive while using our developed technology.

Keywords: Urban Computing, Geospatial Machine Learning, 3D-Cadastre, Outdoor Mixed Reality, Navigation

Kurzfassung

Dieser Artikel stellt die Forschungsrichtungen der Forschungsgruppe Geoinformation an der Technischen Universität Wien vor. Wenn wir uns in einer realen oder virtuellen Umgebung bewegen und mit unserer direkten Umgebung, z. B. Gebäuden, interagieren, produzieren wir raumbezogene Spuren. Durch die effiziente und effektive Analyse dieser vom Menschen erzeugten Daten, aber auch von der städtischen Umwelt, sind wir in der Lage, mehrere Forschungsfragen des Bereichs zu beantworten. Zum Beispiel können wir die Struktur der Umwelt, in der wir leben, aufdecken, die Auswirkungen der Umwelt auf die menschliche Entscheidungsfindung untersuchen, verstehen wie Menschen mit der Umwelt interagieren, sowie neue raumbezogene Visualisierungen und Interaktionsdialoge ermöglichen. Neuartige Technologien wie Virtual and Augmented Reality sowie Eye Tracking befähigen uns, einen Schritt weiter zu gehen und komplexe Experimente durchzuführen, um relevante raumbezogene Daten zu generieren, die es uns ermöglichen, den Entscheidungsprozess des Menschen in kontrollierten Umgebungen zu untersuchen und zu verstehen. Darüber hinaus können wir aufgrund des aktuellen technologischen Fortschritts der Forschungsgruppe für Geoinformation die AR-Technologie nun auch im Außenbereich einsetzen, um georeferenzierte Objekte in Echtzeit zu visualisieren. Dies erlaubt uns, Experimente auch in natürlicher Umgebung durchzuführen und die räumliche Information, die der Mensch mit Hilfe unserer entwickelten Technologie wahrnehmen kann, zu verändern.

Schlüsselwörter: Städtisches Computing, Räumliches maschinelles Lernen, 3D-Kataster, gemischte Realität, Navigation

1. Introduction

The Geoinformation Research Group works at the intersection of Computer Science, Mathematics, Geography as well as Cognitive Sciences. The research focus lies on the development of novel algorithms that enable to deal with geospatial data in an efficient and effective way. These algorithms ultimately advance the state-of-the art computational theories concerned with the wide range of geospatial data and information. The addressed aspects include but are not limited to representation, storage, visualization, analysis, reasoning, semantic, integration, sharing, and prediction.

The research and technological advances of the last years allow us to deal with highly complex problems and pursue research questions that could not be answered in the past. Our work aims at extracting, analyzing and understanding the structure of urban environments by utilizing intelligent algorithms (see Sections 2.1 and 2.5) and further combine this knowledge with human mobility patterns and geospatial semantics in order to develop prediction models (see Sections 2.2 and 2.3) or even generate collective spatial solutions based on artificial intelligence methods (see Section 2.4).

An additional focus of our work is on user centric aspects, investigating how humans interact with their surrounding environment as well as with spatial information communicated through a digital device. For our research in this domain we utilize emerging technologies such as Augmented and Mixed Reality as well as Eye Tracking and perform experiments in order to investigate optimal visualization techniques (see Sections 3.1 and 3.4) and interaction dialogues between the user and the environment (see Sections 3.2, 3.3). Furthermore, we perform several experiments in the area of Navigation since it provides a content and context rich environment that allows us to investigate how humans consume and use spatial information for decision-making (see Section 4).

2. Geographic Information Science

2.1 Urban Computing

Urban Computing is an interdisciplinary research field that concerns the study and application of computing technologies to urban environments. It leverages concepts of ubiquitous computing, geographic information science, data science, cognitive science, and computer science to answer questions related to urban space, to conceive new urban analytical tools, and to provide services for supporting and enhancing urban studies.

In [1] an urban computing framework[1] has been introduced that provides information about the urban structure of most cities in the world. This framework provides a base for further research which ultimately enables to represent urban structures and their complex nature in a more complete and accurate way. An analysis of the street intersections has been carried out that resulted in a formal definition and categorization of intersections based on the number of their branches and the similarity to the corresponding “regular intersection”. As argued in [1], this new insight on the structure of the street network of a city can serve multiple goals. For example, it can be used in navigation studies and spatial analysis for choosing representative paths in an urban environment. Furthermore, the availability of this data allows for studying the structural similarity of different cities or for comparing and harmonizing spatial studies carried out in multiple areas.

The urban computing framework is designed to be extended with additional information concerning urban structures, such as geospatial semantics as well as different spatial relations, such as topology, orientation, distance and visibility. The framework will be extended with novel data computed from the ones that are already available in the framework. An example is given in [2] where the basic information about intersection classification is used to study and compute the distribution of sequences of intersections of different types. The higher the amount of available information, the more detailed the characterization of the urban structures. This rich source of information can ultimately be used as input for machine learning algorithms (as discussed in more detail in Section 2.3) in order to automatically detect different place classes such as historic or touristic areas, business districts, etc. Furthermore, spatial similarity can be computed, for example, by representing different spatial objects and the relations among them as a graph and by tuning graph isomorphism algorithms. Finally, the availability of formal and structured descriptions of urban environments can be used in the context of simulation and synthetic dataset generation. Indeed, the graph representation of a city can be used as a template to generate similar graphs and, therefore, virtual look-alike cities.

2.2 Human Mobility Patterns

What can human mobility patterns reveal? Currently, one of our latest research projects deals with identifying the familiarity level of pedestrians with their surrounding environment. Through multiple experiments we try to collect data that can be used as input for machine learning in order to classify urban familiarity. In our experiments, pedestrians have to navigate in urban environments they are familiar with, but also in environments they have never been before. A snapshot of the collected spatial data includes the location of the pedestrian, the movement trajectory as well as the head movements. The basic assumption, which we used in order to approach this problem, is that, if a pedestrian is not familiar with the cur-

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1) The resulting data is made available at http://intersection.geo.tuwien.ac.at

rent surrounding environment, there is a higher probability that the search behavior will differ compared to pedestrians that are familiar with it. Thus, this different behavior should be reflected in the measured head movements and mobility pattern in general.

2.3 Geospatial Semantics and Machine Learning

Geospatial semantics reflect how humans see the world. A geo-object can be a restaurant, a forest, a bar, a river, etc. These values are referred to as geospatial semantics. Some semantics describe concepts which are more generic than others, such as “restaurant” versus “china restaurant”. Geospatial semantics exhibit a geospatial autocorrelation. It might be more likely to find a bar in a city than in the middle of a forest for example. Machine Learning on the other hand aims at determining functional relationships between parameters. It therefore enables to predict phenomena based on a set of given parameters. The Geoinformation Research Group at TU Wien researches how to predict spatial phenomena, such as urban growth or land covers, based on geospatial semantics. Thus, a machine learning algorithm is trained to detect patterns in the spatial distribution and configuration of geospatial semantics and ultimately aims at predicting the urban growth of cities or to classify land covers. This approach presents an alternative to using remotely sensed imagery, which is traditionally used for such prediction tasks, and reveals geospatial semantics as potent geodata source. In order to perform spatial predictions, the data is firstly preprocessed and then passed to the machine learning algorithm. For machine learning a specific type of algorithm is used: Deep Learning. The preprocessing step transforms the geospatial semantics and their geospatial configuration into a matrix. This matrix reflects distances and angles from a given set of locations to geospatial semantics.

Figure 1 illustrates how the geospatial configuration with respect to the geospatial semantics of a single location is presented: distances and angles to geo-objects with specific semantics define the geospatial semantic configuration for a single point (center of the Figure 1).

The Deep Learning algorithm takes this matrix as an input and predicts spatial phenomena for a set of other locations. Specifically the algorithm determines the urban growth or land cover type based on the geospatial semantic configuration [3]. However, other types of spatial phenomena can be predicted as well. Within this scope, we developed one of the most accurate urban growth models. Our results show that predictions can be performed with high overall accuracy as well as high kappa coefficients based on geospatial semantics only. This newly obtained knowledge enables us to understand complex spatial phenomena in a better way and to ultimately model them.

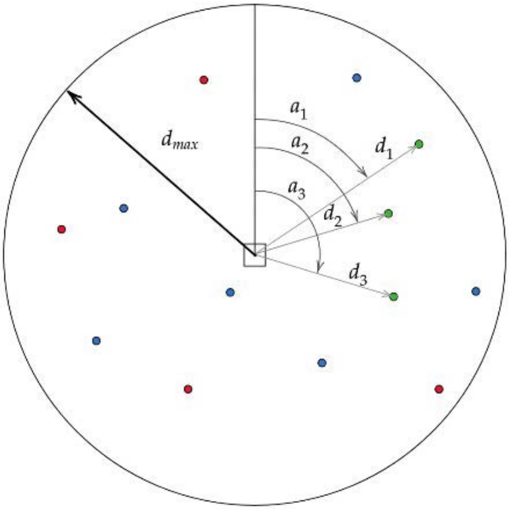

Fig. 1: Geospatial semantic configuration for a single location. This configuration can hold implicit knowledge on the type of land cover the location is in or if it will be subject to urban growth.

2.4 Qualitative Spatial Reasoning for Collective Plans

Cities are evolving, as complex systems composed of many integrated components. The management and planning of these components requires robust and constantly updated spatial data, local knowledge, as well as the skills to integrate and transmit this information to the planning processes. Therefore, urban planning should refer to an interactive process that involves bilateral information flow and goes beyond the required framework of current applications with a strong focus on the community in order to improve the decision-making process and the final design solutions. In parallel to the increasing mobility, developments in the GIScience field provide an important opportunity for a shift from conventional planning methods to socially inclusive and flexible processes in which users can directly intervene. From the perspective of an experienced urban planner with the main focus of participatory urban design and neighborhood sustainability assessment, the quantitative representation of large amount of qualitative social data is always a requirement to be able to create responsive environments that meet the local needs and priorities and to compare, assess, and monitor the improvements in time. In this scope, there are many recognized methodologies to obtain social data, such as workshops, focus group meetings, gamification, and Web GIS. On the other hand, interpretation of this qualitative data into a collective plan remains a big challenge.

In order to provide a solution to this problem, we developed a geospatial methodology for a collective design solution based on Qualitative Spatial Reasoning (QSR), which is an automated methodology for understanding spatial patterns and spatial relations. Currently, we are conducting experiments in a 3D GIS environment created based on the plan of a courtyard at the Vienna University of Technology. The participants of the experiment can modify the 3D environment based on their individual preferences and with given constraints. In the first phase of the experiment, the user-generated plans were collectively analyzed regarding location, scale, and number of the design elements. The first results of our experiment revealed that the design process helped participants to develop a better understanding of the environment, increase the sense of belonging as well as their acceptance towards a collective plan. Currently, we are applying QSR to each user-generated plan for the computation of the relative location and orientation of the design elements towards each other and within the designated area. This approach provides an efficient methodology to define ontological, topological, and geometrical relationships as well as the spatial patterns in each plan. The overall process will provide an optimal configuration for a collective plan, which will guide designers and urban planners to provide a responsive solution.

2.5 Cadastre

One of the oldest research areas of the Geoinformation Research Group is the cadastre. It started with the implementation of the first curriculum on practical geometry in 1819 [4]. The goal of a cadastre is the creation of land parcel identifiers and the documentation of the land parcel's boundaries and use [5]. The cadastre is closely connected to the land register, the documentation of rights, restrictions, and responsibilities connected to land parcels. In the 200 years of cadastral development in Austria, the system was continuously improved and this process is still ongoing [6].

Our research covers different fields connected to the cadastre and most of them are connected to quality. The simplest case is the quality of existing cadastral maps. Questions like "How to determine quality?" [7], [8] "How to communicate quality?" [9], or "What quality is required?" [10] are essential for the development of applications based on cadastral data. Extensions of the current scope of the cadastre were developed in cooperation with students, e. g., [11] or fellow researchers, e. g., [12]. Finally, connections to the legal domain [4], [13] or design questions [14], [15] were also investigated. Our goal is to provide input for national and international discussions on future cadastral developments.

3. Geographic Human Computer Interaction

3.1 3D Data Visualization

Appropriate visualization is key for making sense of and analyzing data. Specifically, we argue that 3D data can be more easily consumed if presented to the user through a proper 3D visualization. For instance, this can be the case with 3D city models and 3D building models that aim at mapping real spatial objects at different levels of detail. This is also the case of more abstract structures aimed at correlating different primitive concepts in a unified 3D representation, such as space-time cubes: 3D tools for spatio-temporal analysis where the two horizontal dimensions are used to represent the spatial footprint of some phenomenon or object and the vertical dimension is used to denote time.

While it is possible to visualize and interact with 3D data in classical computer environments, this is not optimal as those offer only a 2D representational space and non-natural interactions. That is, the 3D model is to be projected on a 2D plane (the display) and the user can only interact with the object via classical input devices such as mouse and keyboard. As a result, at each point in time the user is presented with a 2D snapshot of the 3D data and she has to move, rotate, and scale the projected model in order to observe the model from different perspectives. After each interaction, the 2D snapshot changes and the user has to mentally stitch those together in order to obtain a complete 3D mental representation of the object.

Conversely, we argue that the cognitive load necessary to create a full 3D mental representa-

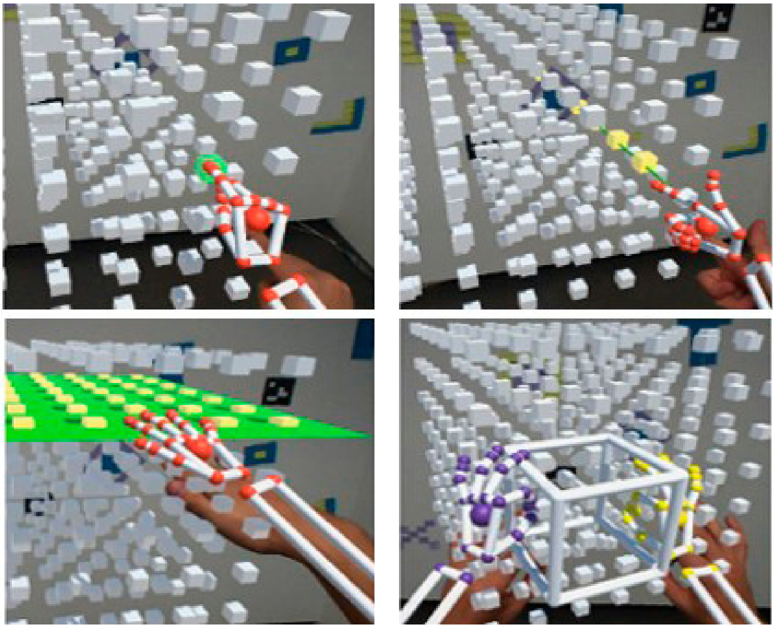

Fig. 2: An implementation of ESRI's space-time cube in a mixed reality environment. The user can perform single-element selection by touching, multi-element selection via predefined gestures and scaling via two-hand pinching.

tion can be significantly reduced by presenting the model in an immersive 3D environment such as a Virtual or Mixed reality environment. Indeed, these environments allow for presenting the model to the user in a much more natural way. The 3D model is presented to the user as if it is a real object embedded in the real space. This allows for leveraging the spatial cognition abilities of the user that does not have to learn and apply artificial mapping techniques to survey and make sense of the model. Finally, interaction modalities can be implemented that resemble and increase the natural interaction capabilities that one has with physical objects. For example, the user can select an element by simply touching it with a finger or can move the object by grabbing or even scale it by stretching or squeezing it in order to obtain a panoramic or detail view.

3.2 Outdoor Mixed Reality

Mixed reality is everything where real and virtual environments (Virtual Reality) are combined [16]. Virtual Reality is an artificial, immersive environment, which the user can interact with. It can be similar to the real world, but does not have to (other definitions of space, time, or physics in general are possible) [16]. Hence, Mixed Reality means either a combination of the real world with virtual objects or a virtual environment enhanced with real world objects. One of our research topics is the use of Augmented Reality (AR) outdoors. AR refers to the real world with virtual objects enhancing (augmenting) it [16].

Augmenting our reality gives us several new possibilities. It is possible to visualize information which otherwise is hidden. The hiddenness of information can be caused, among other things, by physical occlusion (e. g. underground structures like gas or water pipes are occluded by the ground surface) and by its non-physical character (e. g. attributes of physical objects like age). Another application of AR is the inspection if measured entities are placed where they should be (e. g. according to guidelines or a database). This allows an instantaneous correction of both the real world objects' position and virtual objects' attributes. A further use case of AR, not only outdoors, is data collection. The user can immediately create or add data to existing objects. Regarding metadata, this is a big advantage as opposed to adding it later in the office, where memory can fail you or adding metadata based on satellite images, where additional attributes are often not deducible.

While the concept of VR and MR dates back to the 1970's, we are finally witnessing in the last years their actual implementation towards affordable and functional devices. However, these devices and the algorithms they rely upon are mainly conceived for working indoors. One goal of our research group is to investigate and implement the use of MR in outdoor environments (see Figure 3). To this end, it is necessary to merge together indoor and outdoor localization and tracking techniques. In an ongoing project we have implemented a novel approach to create a transformation among the local coordinate system of a MR headset and a geographic reference system. Preliminary experiments were very promising, with a localization accuracy between 2 and 3 cm within

Fig. 3: Both users are interacting with the surrounding environment through a mobile display: on the left side in the form of a tablet and on the right side in form of a glass display (i. e., Microsoft Hololens). We equipped both devices with all the necessary sensors and algorithmic solutions in order to be able to display georeferenced virtual objects in the real environment, thus, enabling outdoor Mixed Reality applications.

the chosen calibration area. Outside of the calibration area, we lose 5 cm of every 10 m of distance from the boundary of the calibration area. Our approach enables users to interact with the surrounding environment in a multitude of ways. In our research we investigate which interaction modalities are better suited for which interaction with the environment. For instance, next to haptic interaction modalities, our focus lies also on gaze-based interaction (e. g. the user can interact with an object by looking at it [17]).

3.3 Gaze-Based Interaction

Our eye movements and where we look at while interacting with spatial elements provide important insights that can help us optimize the (gaze-based) interaction dialogues. In our research we focus on the one hand on eye movements [18] and gaze analysis [19] in order to understand how we interact with our surrounding environment (i. e., real environment, virtual reality and mixed reality) and spatial data visualizations. On the other hand, we utilize the eye movements and the gaze of the user in order to enable novel implicit and explicit interaction dialogues [20]–[23].

3.4 3D-Cadastre

At the end of the 20th century, it became obvious that the traditional cadastral systems have increasing difficulty to cope with the growing density of urban infrastructure (compare [24]). Subways are an example of vertical separation between different types of use. In the last 20 years, airspace above public roads was used for a growing number of development projects and correct documentation of these constructions was problematic at least. In rural areas, it was mainly road and railway tunnels that could not be documented in a legally and graphically convincing way. This resulted in a series of international workshops in the Netherlands, China, United Arab Emirates, and Greece since 2011, supported by a working group of the International Federation of Surveyors (FIG). The Geoinformation Research Group contributed to both, the working group and the workshop series. The discussions include legal (e. g., [25]), technical (e. g., [26], [27]), and usability aspects (e. g., [28]).

Recently, usability aspects of 3D cadastres received more attention than the other aspects. The reason is that the technical questions are discussed extensively in the last 15 years and they are already part of the ISO standard 1952 Land Administration Domain Model (see [29]) and the legal questions will require real cases as further research input. Since there are already several countries with and existing 3D cadastre (e. g., Israel, Sweden, and The Netherlands), such cases should become available. This leaves the problem of usability that has not yet been discussed sufficiently, since it is assumed that 3D CAD solutions will be sufficient for visualization. However, users of a 3D cadastre that are not trained in 3D CAD (e. g., lawyers or politicians) will have difficulties to work with a 3D software. On a 2D map it is simple to indicate a proposed boundary with a

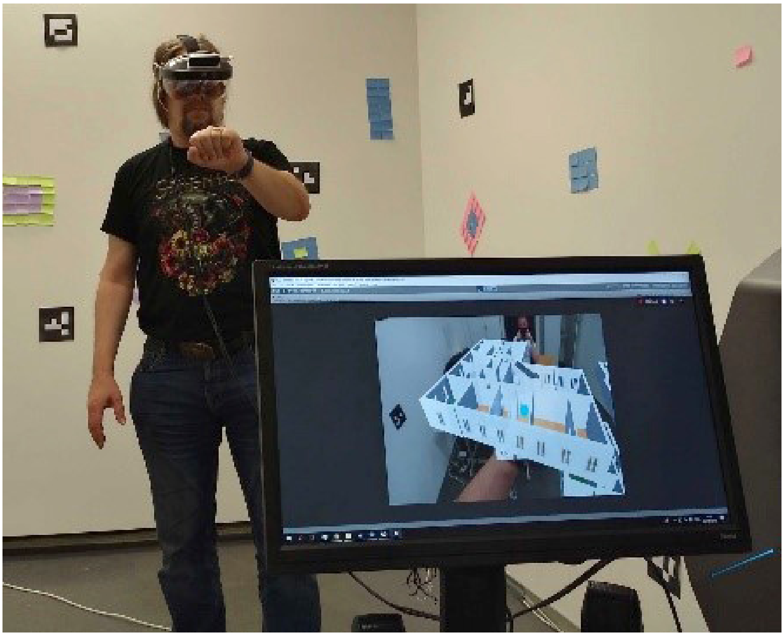

Fig. 4: Working with the first model of an apartment building in mixed reality.

In our work, we perform empirical experiments in order to observe how wayfinders act in real, but also in virtual and mixed environments. These experiments result is multiple spatial data that have to be efficiently analyzed (often in real time) as well as interpreted in order to understand the underlying human processes.

Currently, next to wayfinding assistance systems we are focusing on modeling the complexity of a decision situation [32] as well as on the implementation of a prediction model for optimal timing of pedestrian navigation instructions [33].

pencil line. Our goal is to develop a similarly simple system for 3D models. This requires a simple user interface to work with 3D data in a mixed reality (see Figure 4). First experiments with an apartment building generated promising results regarding user frustration [28].

4. Navigation

According to Montello [30], navigation is composed of two components, locomotion and wayfinding. In our work we focus on the second and most important component, wayfinding. During navigation, we have to make a series of correct spatial decisions in order to reach the desired destination from an origin. Wayfinding can be separated into four processes namely orientation, route planning, route monitoring and recognition of the destination [31]. In most cases during wayfinding we use assistance aids in order to ease the decision-making process, such as cartographic maps or other digital devices such as mobile navigation systems.

The Geoinformation Research Group tries to get insights and unfold the process of wayfinding. We aim at understanding the problems that might occur and at the same time reveal successful strategies that wayfinders use in order to successfully reach their destination.

4.1 Wayfinding Complexity and Assistance

In order to reach a target destination, we have to make a series of wayfinding decisions of varying complexity. Previous research has focused on classifying the complexity of these wayfinding decisions, primarily looking at the complexity of the decision point itself (e. g., the number of possible routes or branches). In our research, we are also incorporating user, instructions, and environmental factors into our modeling process in order to assess the Complexity of a wayfinding decision.

Pedestrian navigation systems help us make a series of decisions that will eventually lead us to the desired destination. Most current pedestrian navigation systems communicate using map-based turn-by turn instructions. This interaction mode suffers from ambiguity, its user's ability to match the instruction with the environment, and it requires a redirection of visual attention from the environment to the screen. In our research, we focus on Navigation Assistance for pedestrian navigation aiming at overcoming these problems and at the same time increase the user experience and decrease the cognitive load.

Assistance systems help wayfinders by providing relevant information within the context of their surroundings, e. g., landmark-based instructions of the type "turn left at the church". Next to the instruction type and content, also the timing of the instruction must be considered in order to facilitate the wayfinding process. In our research we also focus on the user and environmental factors that have an impact on the timing of instructions. We perform experiments in real, but also in realistic virtual environments in order to analyze the expected distance to the decision point until instructions are needed.

The Geoinformation Research Group has opened three research labs (i. e., The VR Lab, The SpatialHCI Lab and The Eye Tracking Lab) in order to investigate all these topics under controlled conditions and in depth. The VR Lab can be used to simulate specific environments as well as specific conditions. For instance, an urban environment can easily be developed and altered to meet the necessary conditions to answer the relevant questions. Furthermore, weather conditions, light conditions as well as pedestrian and automotive traffic can be controlled and manipulated based on user interaction. The SpatialHCI Lab provides us the ability to investigate novel interaction dialogues between a user and the surroundings, e. g., enable interaction modalities that will allow us to interact with a facade of a building, but also with new technologies that can be utilized as assistance systems. Finally, through our research in the Eye Tracking Lab we can collect data that will allow us to investigate the decision making process in depth. Where are humans looking at when making spatial decisions, which environmental aspects are considered important and what strategies can be revealed by analyzing eye movement data.

4.2 Location Based Services

We are constantly interacting with our surrounding environment, either to find our way through the city, to find something we are looking for or just out of curiosity, trying to learn what is around us. Location based services provide us with information and many types of services based on our location. These services, when delivered in an optimal way, i. e., relevance and right amount of information, can be very beneficial for our tasks. In our work, we are focusing on retrieving the right moment to deliver the information/service based on user and environment characteristics as well as on the optimal interaction with the device and environment. For instance, we are focusing on novel interaction dialogues (mostly gaze-based and AR-based) between the user and the surrounding environment [34]. Furthermore, we are aiming at optimizing the amount of information to be delivered based on several user characteristics, such as familiarity with the environment.

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Veranstaltungskalender

AGIT 2019

03.07. – 05.07.2019 Salzburg, Österreich
http://www.agit.at

ESRI USER CONFERENCE

08.07. – 12.07.2019 San Diego, CA, USA
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7. Bayerische Woche der Geodäsie

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www.bwdg.bayern.de

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24.09. – 27.09.2019 Florence, Italy
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15.05. – 26.05.2020 Montreal, Canada
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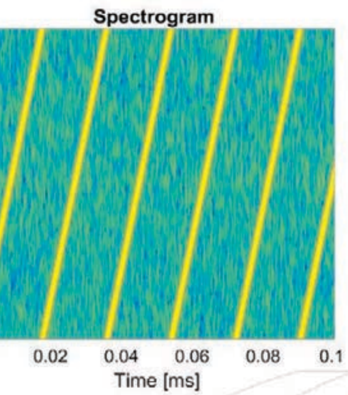
Geodätisches Kolloquium – Winter 2019/20

Mittwoch, 16. Oktober 2019	„VGOS-Teleskope im Fokus“ Prof. Dr.-Ing. Cornelia ESCHELBACH Frankfurt University of Applied Sciences - Vermessung und angewandte Geodäsie
Mittwoch, 13. November 2019	“Monitoring kontinuierlich in Raum und Zeit: die Alpen kriechen & Kräne schwingen" Dr.-Ing. Christoph HOLST Rheinische Friedrich-Wilhelms-Universität Bonn - Institut für Geodäsie und Geoinformation
Mittwoch, 4. Dezember 2019	"Transformation durch Digitalisierung – Chancen und Gefahren" Dr.-Ing. Jürgen DOLD, Präsident Hexagon Geosystems
Mittwoch, 22. Jänner 2020	„Hochpräzises Monitoring von Infrastrukturbauwerken mit geodätischen Sensoren“ Dr.-Ing. Jens-André PAFFENHOLZ Leibniz Universität Hannover - Geodätisches Institut

Alle Veranstaltungen finden im HSB6 der Universität Innsbruck, Technikerstraße 13, Innsbruck statt.
Beginnzeit der Vorträge: 18 Uhr 15

Um Ihnen in Zukunft Mitteilungen über die Veranstaltungsreihe rascher und aktueller zukommen lassen zu können, bitten wir Sie um Bekanntgabe Ihrer E-Mail Adresse: vermessung@uibk.ac.at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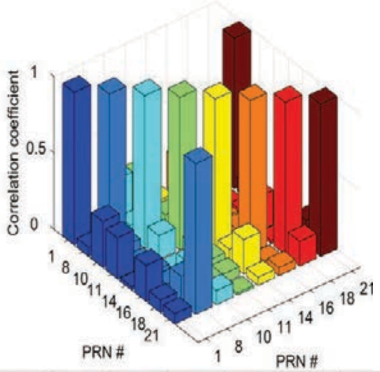
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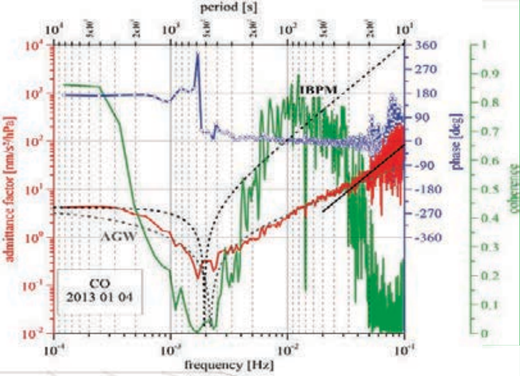
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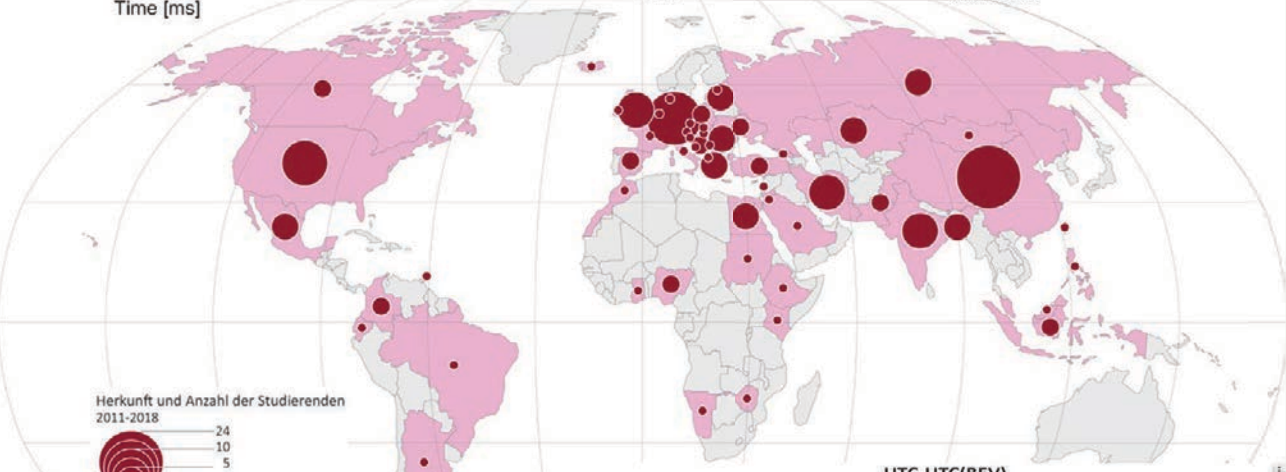
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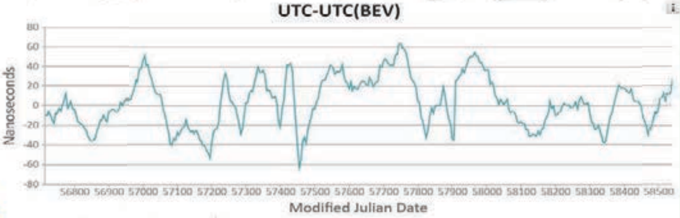
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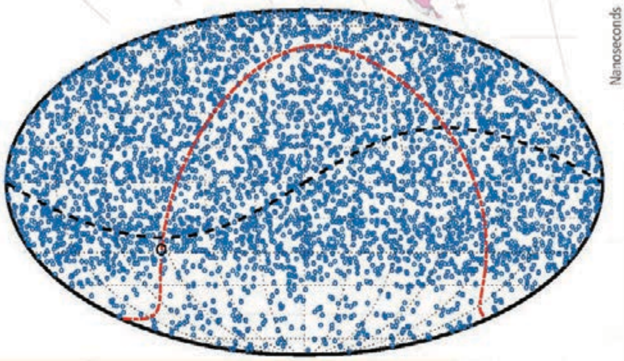

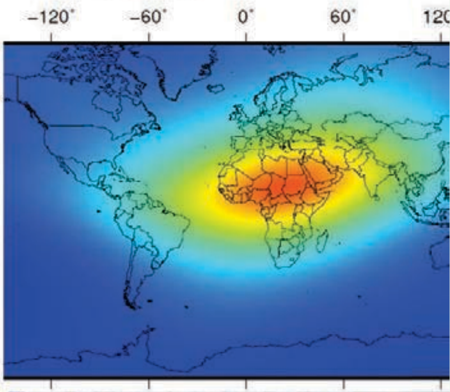
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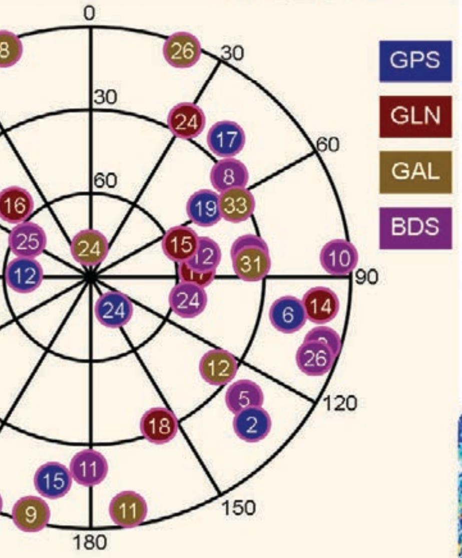
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