University of Stuttgart
Germany

Faculty 6: Aerospace Engineering and Geodesy

Annual Report **2021**

Geodesy & Geoinformatics

IIGS GIS INS ifp

editing and layout:
volker walter, markus antoni, martin metzner, aloysius wehr

Dear friends and colleagues,

It is our great pleasure to present to you this annual report on the 2021 activities and academic highlights of the Department of Geodesy and Geoinformatics of the University of Stuttgart. The Department consists of the four institutes:

- Institute of Geodesy (GIS),
- Institute for Photogrammetry (ifp),
- Institute of Navigation (INS),
- Institute of Engineering Geodesy (IIGS),

and is part of the Faculty of Aerospace Engineering and Geodesy.

Preface

The 2nd year of the Corona pandemic had also its influence on the way how we could interact with our students, deliver our lectures or carry out practical exercises. While we were able to hold most of the labs and exercises in presence, most of the lectures from the summer semester of 2021 were given in virtual environments. However, we were fortunate that circumstances changed in the winter semester 2021/22, and we were allowed to return to classroom teaching for almost all of our courses.

Concerning research, it can be stated that the cumbersome adoption to the circumstances of the Corona pandemic in the previous year has prepared us well for the year 2021. All institutes could carry out their planned research work, apply for new research projects and establish new collaborations, which kept increasing the visibility of the Department of Geodesy and Geoinformatics of the University of Stuttgart on national and international levels.

Research

This annual report documents our research contributions in many diverse fields of Geodesy and Geoinformatics: from satellite and physical geodesy through navigation, remote sensing, engineering surveying and telematics to photogrammetry, geographical information systems and location based services. Detailed information on projects and research output can be found in the following individual institutes' sections.

Teaching

We were able to welcome 14 new BSc students in winter term 2020/2021. For the first semester of the MSc program for Geodesy and Geoinformatics we welcomed 15 students. Please visit our website www.geodaesie.uni-stuttgart.de for additional information on the programs.

Our successful international MSc program Geomatics Engineering (GeoEngine) exists already 16 years. Probably due establishment of tuition fees for non-EU students in 2018, we saw a decline of new students since then. We welcomed only 11 students in 2021. We believe one reason for the decline in the number of students actually showing up could be a general reluctance to study abroad in times of pandemic.

Awards and Scholarships

We want to express our gratitude to our friends and sponsors, most notably:

- Verein Freunde des Studienganges Geodäsie und Geoinformatik an der Universität Stuttgart e.V. (F2GeoS),
- Ingenieur-Gesellschaft für Interfaces mbH (IGI),
- DVW Landesverein Baden-Württemberg,

who support our programs and our students with scholarships, awards and travel support. Below is the list of the recipients of the 2021 awards and scholarships. The criterion for all prizes is academic performance; for some prizes GPA-based, for other prizes based on thesis work. Congratulations to all recipients!

Thomas Hobinger, Associate Dean (Academic)

thomas.hobiger@ins.uni-stuttgart.de

Award	Recipient	Sponsor	Programme
Karl-Ramsayer Preis	Ms. Franziska Nied	Department of Geodesy & Geoinformatics	Geodesy & Geoinformatics
BSc Thesis Award	Mr. Junyang Gou	F2GeoS	Geodesy & Geoinformatics
MSc Thesis Award	Mr. Lukas Lansche	F2GeoS	Geodesy & Geoinformatics

Institute of Engineering Geodesy

Geschwister-Scholl-Str. 24 D
70174 Stuttgart
Germany
Tel.: +49 711 685 84041
Fax: +49 711 685 84044
sekretariat@iigs.uni-stuttgart.de or
firstname.secondname@iigs.uni-stuttgart.de
http://https://www.iigs.uni-stuttgart.de/

Head of Institute

Prof. Dr.-Ing. habil. Dr. h.c. Volker Schwieger

Secretary

Elke Rawe
Désirée Schreib

Scientific Staff

M.Sc. Laura Balangé	Quality Modeling
M.Sc. Urs Basalla	Terrestrial Laser Scanning
Dipl.-Ing. Lyudmila Gorokhova (since 15.10.2021)	Kinematic Positioning
Dipl.-Ing. Susanne Haußmann	Kinematic Positioning
M.Sc. Gabriel Kerekes	Terrestrial Laser Scanning
Dr.-Ing. Otto Lerke	Machine Guidance
M.Sc. Philipp Luz	Digital Map
Dr.-Ing. Martin Metzner	Engineering Geodesy
M.Sc. Christoph Sebald (since 01.11.2021)	GIS for Climate Data
Dr.-Ing. Li Zhang	Engineering Geodesy
Dr.-Ing. Yin Zhang (until 31.05.2021)	Monitoring

Technical Staff

Dipl.-Ing. (FH) Andreas Kanzler
Martin Knihs, Mechanikermeister
Dipl.-Geogr. Lars Plate

External Teaching Staff

Dipl.-Ing. Jürgen Eisenmann	Geschäftsbereichsleiter Landratsamt Ostalbkreis, Geoinformation und Landentwicklung
Dr.-Ing. Frank Friesecke	Prokurist der STEG Stadtentwicklung GmbH
M.Eng. Jonas Stadler	Landratsamt Alb-Donau-Kreis Flurneuordnung der Landkreise Alb-Donau-Kreis und Biberach
Dipl.-Math. Ulrich Völter	Geschäftsführer der Fa. Intermetric - Gesellschaft für Ingenieurmessung und raumbezogene Informationssysteme mbH
Dr.-Ing. Thomas Wiltschko	Daimler AG, Mercedes-Benz Cars; Research and Development

PhD-Students

M.Sc. Julia Aichinger	Terrestrial Laser Scanning
M.Sc. Alexandra Avram	GNSS
M.Sc. Marko Gasparac	GNSS and Digital Map
Dipl.-Ing. Patric Hindenberger	Location Referencing
M.Sc. Yu Li	Digital Map
M.Sc. Dung Trung Pham (until 28.05.2020)	Kinematic Positioning
M.Sc. Annette Schmitt	Multi-Sensor-Systems
M.Sc. Tobias Schröder	Automation of Production Process
M.Sc. Yihui Yang	Multi-Sensor-Systems
M.Sc. Christian Bader	Kinematic Laser Scanning

General View

The Institute of Engineering Geodesy (IIGS) is directed by Prof. Dr.-Ing. habil. Dr. h.c. Volker Schwieger. It is part of Faculty 6 "Aerospace Engineering and Geodesy" within the University of Stuttgart. Prof. Schwieger holds the chair in "Engineering Geodesy and Geodetic Measurements". Until October 2021, he was Dean of Faculty 6.

In addition to being a member of Faculty 6, Prof. Schwieger is co-opted to Faculty 2 "Civil and Environmental Engineering". Furthermore, the IIGS is involved in the Center for Transportation Research of the University of Stuttgart (FOVUS). Thus, the IIGS actively continues the close collaboration with all institutes in the field of transportation, especially with those belonging to Faculty 2.

Since 2011, Prof. Schwieger is a full member of the German Geodetic Commission (Deutsche Geodätische Kommission – DGK). Furthermore, he is head of the section "Engineering Geodesy" within the DGK since 2020.

The institute’s main tasks in education focus on geodetic and industrial measurement techniques, kinematic positioning and multi-sensor systems, statistics and error theory, engineering geodesy and monitoring, GIS-based data acquisition, and transport telematics. Here, IIGS is responsible for the above-mentioned fields within the curricula of “Geodesy and Geoinformatics” (Master and Bachelor in German) and for “GEOENGINE” (Master for Geomatics Engineering in English). In addition, the IIGS provides several courses in German for the curricula of “Aerospace Engineering” (Bachelor and Master), “Civil Engineering” (Bachelor and Master), “Transport Engineering” (Bachelor and Master) and “Technique and Economy of Real Estate” (Bachelor and Master). Furthermore, lectures are given in English to students within the Master course “Infrastructure Planning”.

The cluster “Integrative Computational Design and Construction for Architecture” (IntCDC), that is part of the excellence strategy to strengthen cutting-edge research in Germany, was awarded funding in 2018 for the next seven years. The cluster IntCDC aims to harness the full potential of digital technologies in order to rethink design and construction, and enable ground breaking innovations for the building sector through a systematic, holistic, and integrative computational approach. As a member of the cluster (IntCDC), the institute’s research in the field of new construction methods is intensified in cooperation with architects, civil engineers, computer scientists, production engineers, and other scientists from various research institutions within and outside the University of Stuttgart.

The current research and project work of the institute is expressed in the course contents, thus always presenting the actual state-of-the-art to the students. As a benefit of this, student research projects and theses are often implemented in close cooperation with the industry and external research partners. The main research focuses on kinematic and static positioning, analysis of engineering geodetic processes and construction processes, machine guidance, monitoring, transport and aviation telematics, process and quality modeling. The daily work is characterized by intensive co-operation with other engineering disciplines, especially with traffic engineering, civil engineering, architecture, and aerospace engineering.

Again, this year was marked by the corona pandemic in research and teaching. In research, almost all face-to-face meetings were cancelled and in teaching, lectures were held digitally. Laboratories and exercises were mainly carried out presence. In the winter semester all lectures taught by the institute are given in presence.

Research and Development

Precise Seamless 6-DoF Positioning for Georeferenced Assembly Control - Project Advancement

Within the framework of the Cluster of Excellence IntCDC, the research project (RP) 16 investigates automated and semi-automated assembly processes of long span buildings. The geodetic contribution is the provision of 6-DoF pose (position and orientation) of the assembly robot's (mini-crane) jib, by a real time robotic total station network (RTS-N). After the completion of the methodical preparations on data fusion procedures and pose determination, the realization phase is currently in progress. Therefore, the appropriate RTS-N control scheme has been developed and implemented. The scheme is depicted in Figure 1.

Gefördert durch
DFG Deutsche Forschungsgemeinschaft
IntCDC
CLUSTER OF EXCELLENCE

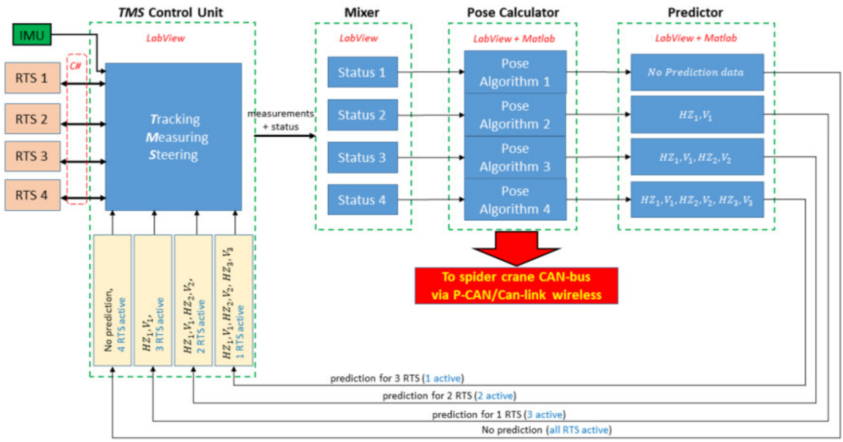

Figure 1: RTS network control scheme

The four items TMS control unit, mixer, pose calculator, and the predictor handle the measurement data in order to provide the position and orientation (pose) to the construction robot in real-time. Dependent on the number of RTSs, which are actively contributing to the pose determination and have the line-of-sight to the robot, appropriate pose algorithms and predictor states are chosen. The real-time capability requires temporal synchronisation between different RTSs. Two different synchronisation issues are present which are 1) between different RTSs (extrinsic) and 2) between individual RTS functionalities, as angle and distance measurement (intrinsic). Among these, the extrinsic issue is solved. The intrinsic issue is stil under investigation.

The network performance has been evaluated in real-world tests, where the construction robot picked a payload from and transported it to a certain position. The RTS-N pose has been processed within the robot control-loop to position its tool center point (TCP), according to the planned trajectory. The results showed satisfactory accuracy levels for positions and orientations in both implemented configurations, which are: configuration A - 4 RTSs – 1 prism, for position + IMU for orientation and configuration B - 4 RTSs – 2 prisms, for position and 2 orientation angles, 3rd orientation angle is stil provided by the IMU.

Config A	**4 RTSs**	**3 RTSs**	**2 RTS**	**1 RTS**	**IMU (data sheet)**
	2.1 mm	2.6 mm	3.0 mm	3.1 mm	0.05° Pitch/Roll, 0.8° Yaw
Config B	**2 RTS per prism**		**1 RTS per prism**		**From RTS-N**
	2.2 mm		3.3 mm		0.03° - 0.1° Pitch/Yaw

Table 1

These values confirm and partly overtop the simulated results from the preparation phase, as published in Lerke and Schwieger (2021).

Supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618.

Holistic Quality Model for IntCDC Building Systems

The research project "Holistic Quality Model for IntCDC Building Systems" is part of the cluster of excellence for Integrative Computational Design and Construction for Architecture (IntCDC). In this project, a Holistic Quality Model regarding social, environmental and technical quality characteristics is developed in cooperation with the Institute of Acoustics and Building Physics (IABP) and the Institute of Social Sciences (SOWI). Together, a holistic quality assessment, which takes into account the individual aspects as well as the interdependencies between the disciplines, was carried out within the framework of a graded concrete case study.

In the case of technical quality, the focus is on an assessment of the geometric quality. Compared to conventional construction methods, a standardized nominal/actual comparison is often not possible for the construction systems developed in the project. The focus of the research here was on generating a measurement and evaluation workflow to estimate the geometry of fiber composite systems. Here, on the one hand the position and orientation of the individual fibers is of major importance, and on the other hand the shape of the fiber itself with a special focus on the cross-sectional area is needed. Therefore, two different experiments were carried out to determine the change in geometry during the manufacturing process as well as the shape of the individual fiber bundles after the production process.

For the monitoring of the fiber interaction, laser scanner measurements were taken after each fiber was added. In each epoch the intersection point of several fibers is calculated and then assigned to the corresponding intersection of the following epoch. This can then be used to determine the deformation within the production process.

Another important point is the determination of the final geometry of the components after production. In addition to the position of the individual fiber bundles, their cross-sectional area is of great interest here, too. For this purpose, TLS measurements were carried out, as shown in Figure 2, and the cross-sectional area was estimated using various methods.

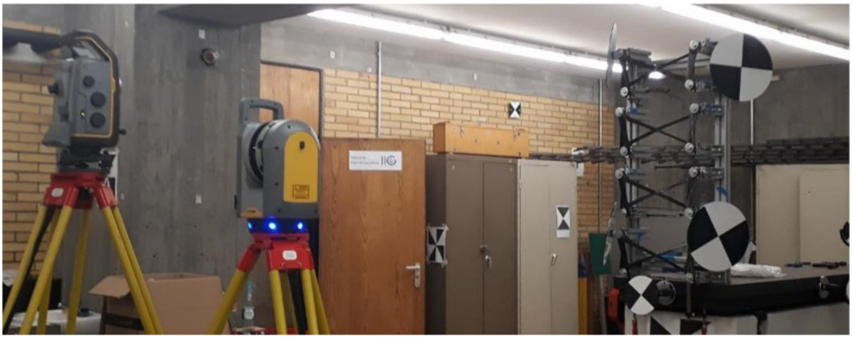

Figure 2: Measuring set-up for the geometric quality control after the production.

Supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy – EXC 2120/1 – 390831618.

Freiburg Pavilion

The Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) have constructed the LivMatS Pavilion at the botanical garden in Freiburg. It consists of a load-bearing structure that is entirely made of robotically wound flax fibre. The pavilion was scanned twice by the IIGS. The pavilion was scanned in June after construction and again in July after the acrylic glass façade had been installed. A fixed point field was installed on site to allow an easier comparison of the scanning epochs. The HDS7000 from Leica was used for on-site scanning, and the TS16 (Leica) was used for measuring the fixed point field. These two epochs were then compared to each other and to the CAD (Fig. 3).

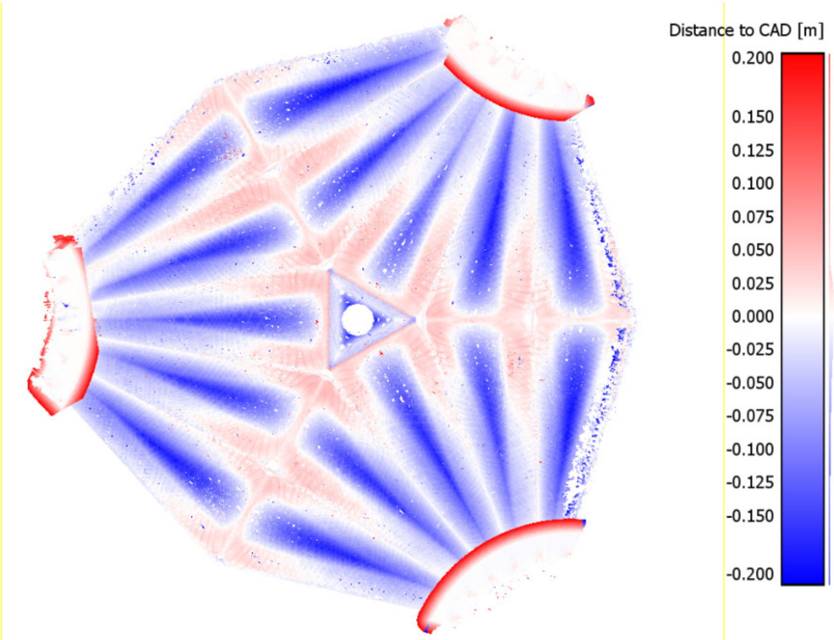

Figure 3: Cloud to mesh distance between measurements of epoch 1 and the designed CAD

The comparison of the two epochs was considerably simplified by the fixed point field. The comparison between the epochs shows almost no change. Deviations between the epochs are less than 3 mm. Unfortunately, the fixed point field could not be applied for the comparison with the CAD, as the CAD does not have the same fixed points. In this case, the foundation blocks were initially matched by hand. This could then be more accurately oriented using ICP. Again, only the foundation blocks and the lowest section of the pavilion up to a height of 0.5 m were used for orientation. With the transformation now known, the entire pavilion can be oriented to the CAD and compared to it. Here, the deviations are in the range of up to 15 cm (fig. 3). These deviations are mainly in the middle of the curved structure of the individual beams. These were constructed with more curvature than was originally planned in the CAD. However, this does not affect the stability of the structure.

The next and final scan is scheduled for March/April 2022 to assess the stability of the building over a longer period of time. For better comparability the same equipment will be used here as well.

Collaborative Scanner Test and Calibration at Bonn Reference Wall

Within the framework of the project "Collaborative Scanner Test and Calibration at Bonn Reference Wall" (COLLECTOR) carried out by the Society for Calibration of Geodetic Devices (SOGD) a comparison of various laser scanners from different universities should be carried out. Therefore, a reference wall in Bonn was measured with a predefined set-up. The set-up can be seen in Figure 4. In addition, calibration measurements were done inside the hall. In total, measurements were carried out with approximately 20 different devices and then a predefined evaluation process was carried out. Our institute participate in this project with four laser scanners (HDS7000, BLK, X7, Riegel2000V). All four scanners were used to measure the exterior of the Bonn wall. The results of all institutes are now compared and questions like "What is the real reference of the wall?", "What is the effect of calibration?" or "How can we describe cyclic effects?" raised and are still part of the current research.

Figure 4: Measurement set-up at Bonn reference wall

Targetless Registration and Identification of Stable Areas for Deformed TLS Point Clouds

Accurate and robust 3D point cloud registration is the crucial part of the processing chain in terrestrial laser scanning-based (TLS-based) deformation monitoring that has been widely investigated in the last two decades. For the scenarios without signalized targets, however, automatic and robust point cloud registration becomes more challenging, especially when significant deformations and changes exist between the sequence of scans which may cause erroneous registrations. A fully automatic registration algorithm for point clouds with partially unstable areas is proposed, which does not require artificial targets or extracted feature points. In this method, coarsely registered point clouds are firstly over-segmented and represented by supervoxels based on the local consistency assumption of deformed objects. A confidence interval based on an approximate assumption of the stochastic model is considered to determine the local minimum detectable deformation for the identification of stable areas. The significantly deformed supervoxels between two scans can be detected progressively by an efficient iterative process, solely retaining the stable areas to be utilized for the fine registration. The proposed registration pipeline is demonstrated on the TLS point cloud dataset (with two-epoch scans) of the Nesslrinna landslide close to Obergurgl, Austria. The experimental results show that the proposed algorithm exhibits a higher registration accuracy and thus a better detection of deformations in TLS point clouds compared with the existing voxel-based method and the variants of the iterative closest point (ICP) algorithm. Figure 5 shows the identification results of stable areas within the TLS point clouds of Nesslrinna landslide from July 2015 to July 2017.

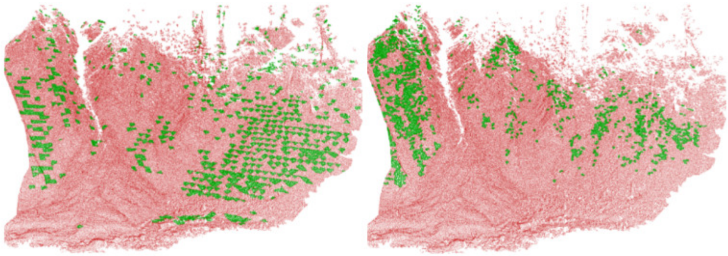

Figure 5: Identification of stable (green) and unstable (red) areas of the TLS point clouds of Nesslrinna landslide by the voxel-based method (a) and the proposed method (b).

Integrated Space-Time Modeling based on Correlated Measurements for the Determination of Survey Configurations and the Description of Deformation Processes (IMKAD II)

Within the DFG (Deutsche Forschungsgemeinschaft) project IMKAD II, further steps have been made towards establishing a stochastic model for Terrestrial Laser Scanner (TLS) monitoring. This project is carried out in cooperation with research division Engineering Geodesy at the department of Geodesy and Geoinformation at the TU Vienna.

Gefördert durch DFG Deutsche Forschungsgemeinschaft

TLS point clouds acquired under laboratory conditions of a B-spline specimen (test object) were used to understand and validate the role of the stochastic model in the estimation process. Specifically, the stochastic model was represented by the synthetic variance covariance matrix (SVCM). It was used as a weighting matrix for the estimated B-spline control points. Different versions of the same matrix (e.g. fully populated SVCM and diagonal matrix D) were used and compared with the identity matrix.

The magnitude of the elementary errors that are introduced in the SVCM was verified w.r.t. a reference scan of the same test specimen within the same coordinate system. The focus was set on instrument (TLS) specific errors. Results indicate that TLS non-correlating errors, here angular and range noise had the biggest impact on the accuracy of the estimated control points. Detailed findings are presented in Raschhofer et al. (2021). The complete workflow is shown in figure 6.

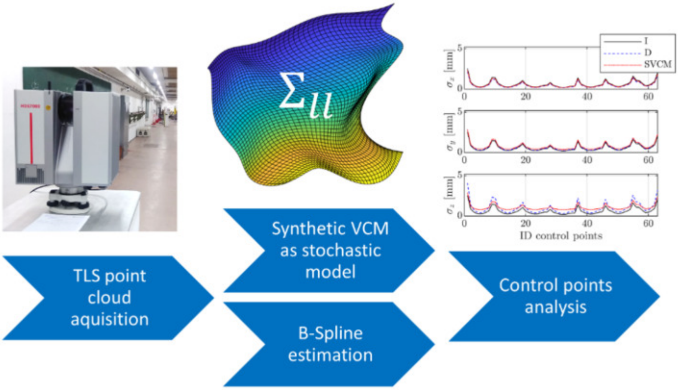

Figure 6: Workflow used for the validation of the SVCM for a B-spline test specimen in laboratory conditions.

This research was funded by DFG (German Research Foundation), SCHW 838/7-3.

B-spline Curvature Matching based on Rank Correlation Analysis

Terrestrial laser scanning offers the possibility of scanning objects by means of high-resolution object discretization. However, the acquisition of identical points over multiple epochs is not possible, and therefore object deformations cannot be detected directly. As a consequence, a method is developed to generate and overlay B-spline curves from laser scan data in order to detect differences in the object shape over multiple epochs.

One step of this method is to perform a correlation analysis using curvature values of the B-spline curve points to obtain a 1D shift position of two B-spline curves to be compared. The curvature values are calculated using the second derivative of the B-spline curve, which can be generated by the second derivative of the B-spline basis functions. In the correlation analysis, Spearman's rank correlation coefficient is applied, where the rank of the curvatures is used instead of the curvature value itself. In contrast to the Pearson correlation coefficient, Spearman's rank correlation coefficient offers the advantage of evaluating non-linear but monotonic relationships.

Map-supported Road Boundary Detection from 3D Point Cloud

This research is the result of a partnership between the Institute of Engineering Geodesy (IIGS) at the University of Stuttgart and the Daimler Truck AG. Road detection is a fundamental task for vehicle autonomy. In most of the well-constructed urban areas, road curb is usually regarded as a representative road boundary feature as it separates a road into driveable and non-driveable areas. One key hardware component used in a typical autonomous vehicle is the Lidar sensor, which is capable of measuring precisely the surrounding environments in a 3D manner. This property makes it suitable for detecting the road boundaries surrounding the ego vehicle, especially the road curbs with significant height jump from road surface. During the last decades, different work pipelines have been developed to detect curbs from 3D point cloud. However, most of the works focus mainly on the simplified driving scenarios, e.g., straight road without complex intersections, with less or even no other road participators, and ego vehicle (assumed) with ideal sensor mounting position. These simplifications rule these methods out of situations where traffic condition becomes complicated, or when the sensor-to-ground geometry changes drastically.

To overcome the limitations of the existing approaches, several improvements have been proposed in this study. Firstly, a fast and efficient range image based object detection module was adapted to remove the noisy object points from the given 3D point cloud. This results in a “clear” point cloud where the points are mainly lying on the ground. Then, a curb detector with adaptive threshold was applied, to detect and extract all curb candidates from the point cloud. In order to cope with curvy roads and intersections, the existing road geometry and topology information from a standard definition (SD) map is also retrieved and utilized. In particular, the map geometry is used as an approximation of the actual road geometry, thus helps to filter out noisy curb candidates from the second step; while the map topology can help the detection system to adapt its searching strategy at a road intersection. The overall system is implemented using C++ in Linux ROS environment, and a preliminary evaluation shows that the developed system can run at 50 fps on a single CPU core, which meets the real-time requirement given that the typical data rate of a Lidar sensor is 10Hz.

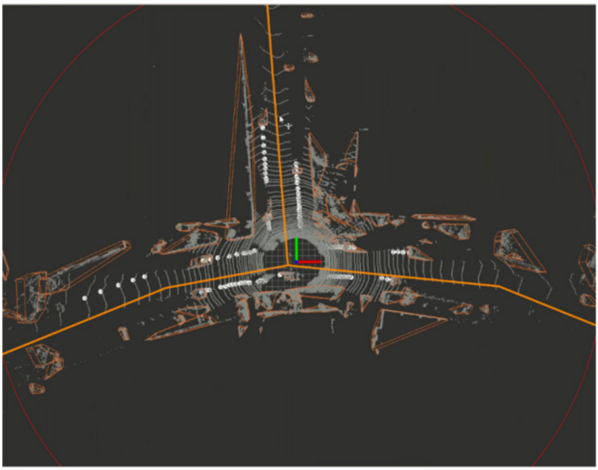

Figure 7: Detected road curbs at an intersection. White dot: detected road curbs; dark orange polygon: detected 3D object; bright orange polyline: map geometry; red circle: 50 meter range.

Dynamic Location Referencing: Probability- and Fuzzy Logic-based Decision Systems

Dynamic (on-the-fly, map-agnostic) Location Referencing is a well-known methodology for sharing geo-objects between digital maps, used in such cases when there are no common databases and/or common structures between the systems (maps) to be exchanged. Here, dynamic methods are developed to share Location References (LR, digital-map based geo-objects) between different, non-corresponding maps.

Generally, Location Referencing Methods follow a one-dimensional three-step process of encoding the LR in the sender system, transfer and decoding the LR in the receiver system without any iterations and typically limited bandwidth. Given the fact, that there are no dedicated links/common data structures between the maps, the key issue for Dynamic Location Referencing is to find the correct LR in the target map which corresponds to the LR in the source map (see Figure 8).

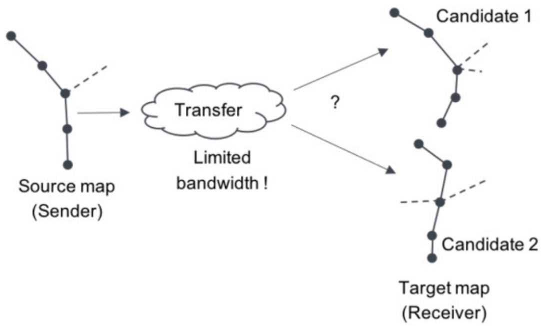

Figure 8: Identification of Location Reference

Typically, deterministic algorithms are defined and implemented in nearly all known methods developed and implemented so far.

Based on the fact that there are uncertainties in matching geospatial data matching methods, uncertainty-based decision systems are in the research process and the thesis of the research work. That means in specific, a probability-based and a fuzzy-based approach were specified and investigated in detail as two different uncertainty-based concepts. For both, a set of decision criteria (geometrical, topological, syntactical and semantical) were defined and the decision algorithms were formulated. Both approaches were implemented in an evaluation system and analyzed.

As a result, the probability-based and fuzzy-based approaches show similar results with an average hit rate up to 90% and improve the results of a comparable deterministic approach (OpenLR) by 12 percentage points in average.

The new research approaches formulated in the last report, which resulted from the previous state of research, were continued and brought to an intermediate state. New principles have been developed that provide a broader basis for the previous approaches and help to validate the results and place them in a broader context. This will be continued in the course of the year and implemented in the existing methods.

Ghosthunter II and its Successor Ghosthunter III

The aim of the Ghosthunter II project and its successor Ghosthunter III is to develop an app for Android smartphones that can be used for to reliably detect of wrong-way drivers on highways and their ramps. In addition, both the wrong-way drivers themselves and other drivers, are to be warned. This project is carried out in cooperation with the Institute of Space Technology and Space Applications at the University of the Federal Armed Forces Munich and the company NavCert.

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

In the Ghosthunter II project, an app for Android smartphones was developed for this purpose. A warning case, which was recognized by the app is shown in Figure 9. The app's wrong-way driver detection was extensively evaluated with real and simulated trajectories during the course of the project. Using simulated trajectory data, it was also possible to test trajectories of wrong-way driving. In its final state, the app achieved a false alarm probability of $7 * 10^{-4}$ % and a sensitivity of 98.89 %.

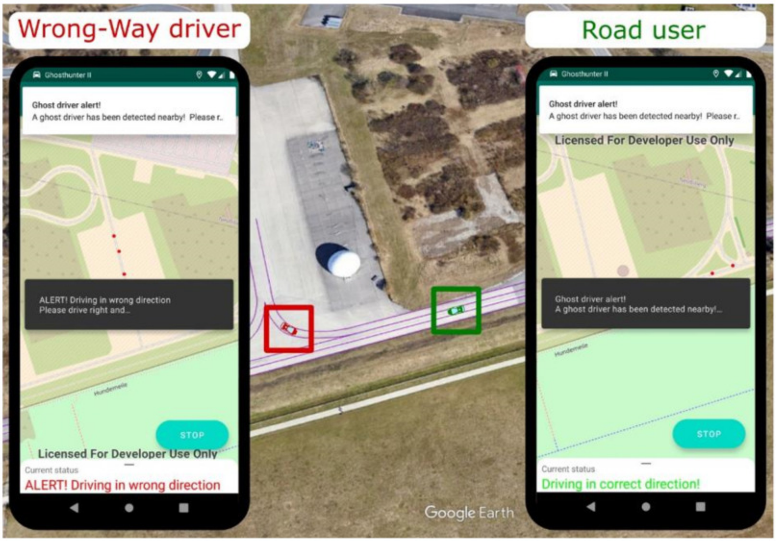

Figure 9: Ghosthunter app for wrong-way driver detection. The wrong-way driver (red car, left smartphone) generates a warning. Both the wrong-way driver and another road user (green car, right smartphone) are warned.

In the follow-up project Ghosthunter III, the goal is to develop this app from its function as a demonstrator to a ready-to-use product. A crucial aspect is the exchange of commercial map data with freely available open source data. Here, OSM (Open Street Maps) data will be used to generate a map specifically adapted to our use case. In the next steps, the algorithms of the app will be adapted to these map data.

The Ghosthunter II and Ghosthunter III research project are funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) and the German Aerospace Center (DLR) under grant number 50 NA 1802 resp. 50 NA 2109.

The CoKLIMAx Project

The CoKLIMAx project started in November 2021 it deals with the use of COPERNICUS data for climate-relevant urban planning by the example of water, heat and vegetation. The project consortium consists of the City of Konstanz as consortium leader, supported by the Institute of Engineering Geodesy (IIGS) at the University of Stuttgart, the Konstanz University of Applied Sciences forTechnology, Economics and Design (HTWG) Konstanz, and the Climate Service Center Germany (GERICS) at the Helmholtz Center Hereon. At the municipal level only a low utilization of the available data has been observed so far. In this context, it is difficult for potential users from municipal administrations to identify the data sets relevant for them from the extensive offer of the C3S Climate Data Store and to recognize the interpretability/meaning. In the everyday application context of urban planning, practical tools are needed that serve to merge and meaningfully combine Copernicus data with local data and to further process and use the results in municipal planning activities.

Supported by:

Federal Ministry for Digital and Transport

on the basis of a decision by the German Bundestag

Based on this background, CoKLIMAx aims to develop new products and procedures, such as the development of practice-oriented technical tools for data acquisition from Copernicus services and merging with heterogeneous locally available data sets.

CoKLIMAx envisions to develop an Advanced Municipal Climate Data Store toolbox (AMCDS Toolbox) and make it available as a freely available software kit. The implementation will be exemplary based on the concrete local needs of the city of Konstanz in the above mentioned focus areas water, climate and vegetation. Relevant data and products will be developed for concrete applications in these areas and implemented, applied and validated in a practice-oriented manner.

During November and December 2021, architectural planning and development took place on how to structure and install the CoKLIMAx ArcGIS Enterprise platform in the CODE-DE IT infrastructure. As of today, the GIS Enterprise Platform is fully installed and functional. It consists of ten instances (virtual machines), which are connected for overall functionality. The installation is made up of an ArcGIS Base deployment with additional server capabilities, such as the ArcGIS Data Stores (relational and spatio temporal), a GeoEvent, GeoAnalytics, and Notebook Server. From a technical point of view, these components shall be in the center having ingoing and outgoing data streams and services available. At the same time, available tools, such as Survey123 or StoryMaps, and ArcGIS HUB (and SITES) are being used for later deployment and communication. For instance, Enterprise Sites is like a subset of the capabilities that is available with ArcGIS Hub. Sites simply provide the ability to create tailored websites and subpages and are more or less equivalent to ArcGIS Open Data. Meanwhile, the development to derive data from the Copernicus Climate Data Store (C3S) is under construction.

The CoKLIMAx research project is funded by the German Federal Ministry for Digital and Transport (BMDV) and the German Aerospace Center (DLR) as part of the “Climate Adaptation Strategies for Municipal Applications in Germany” under grant number 50EW2103C.

Evaluation of 5G Mobile Phone Positioning

As part of the cooperation with Nokia Bell-Labs, the position of an Omron robot is to be determined via the 5G mobile radio standard. In order to support the measurements of the position of the robot itself and the 5G position measurements, IIGS has been contracted to provide reference measurements. For this purpose, a 360° prism was positioned on the robot, which was mounted exactly under the mobile phone antenna. This prism was tracked by a tachymeter (TS16) and thus a position was provided for reference. The measurements took place entirely in ARENA2036, in which a local fixed point field was installed. All elements such as robots, mobile radio and total stations operate in this fixed point field, which simplifies the comparison of the data. Both static and kinematic tests were performed in Arena2036 and will be evaluated and published next year. The ARENA2036 project was the winner in the ”Research Campus Public-Private Partnership for Innovation” competition of the Federal Ministry of Education and Research. In order to make room for the newly emerging Research Campus, a new building was constructed, which offers a production environment in which approaches, ideas and results from researches can be tested and directly converted into practicable prototypes for industrial purposes. The total construction costs of the new building were equally shared between the European Union (EFRE funds) via the state of Baden-Württemberg and the University of Stuttgart.

Advanced Automated Gap and Flush Measurement Assisted by a High Flexible and Accurate Robot System

This research is the result of a partnership between the Institute of Engineering Geodesy (IIGS) at the University of Stuttgart and the Mercedes-Benz AG. Mercedes is responsive in fulfilling the market needs in SUV cars. The expected market-share of SUVs in the United States is 75% in the year 2021. The autonomous mobile robot system with triangulation scanners to measure gap and flush between car-parts (SME-S) that was presented in the last year’s annual report, operates in production sites within Europe and China. However, it is not able to capture every measurement position, especially considering the dimensions of a modern SUV vehicle and is not capable to measure on every surface finish.

We evolved the SME-S in two main directions to cope with the two new requirements regarding reachability of measurement points and the new surface finishes.

The first direction is selecting the hardware (manipulator, platform and sensor) driven by the application but with an independent and easy-to-use human machine interface and an orchestration platform for programming and commissioning. The robot and platform selection is determined by reachability requirements. The vehicle-surface leads to the sensor selection. The second direction delivers the same high precision with more inaccurate robot-hardware that includes a non-holonomic platform (MIR) and a new manipulator (Doosan).

Overall, the SME-S and SME-SL share the same user-interaction and orchestration platform with hardware selection based on business-requirement firsts. In addition, with the new hardware-setup, the SME-SL is capable of performing gap and flush measurements at any position on the vehicle surface on any surface finish with the same precision as the previous SME-S. The next steps include a fully autonomous measurement of different vehicles in different locations. Therefore, the SME-SL must move autonomously outside its working cell and interact with other systems and unknown dynamic environments on the shop floor to perform its measurement task in another working cell.

Combining Geometric and Neural Network Approaches for Lidar Environment Perception

For modern advanced driver assistant systems (ADAS) and automated vehicles, a comprehensive environment perception is necessary. More and more systems use lidar sensors, since they offer high spatial precision. Using the point clouds, neural networks nowadays achieve high accuracies on object detection datasets, like the KITTI benchmark, but may fail to detect objects of untrained classes or in untrained environments. To overcome this issue, the detection pipeline is split into a geometric segmentation approach and a neural network for classification and bounding box regression. In the first step, a traditional geometric approach segments the point cloud into physical objects and thus generates a point cloud segment for each object, as shown in figure 10.

Figure 10: Segmentation of lidar scan into point cloud segments using a geometric approach

The second step is based on a neural network, since these are the most accurate solutions for classification and regression on point clouds. The network architecture is shown in figure 11 and consists of three parts. Three encoder networks of different grid sizes extract voxel features from the point cloud segment. A point based implementation is used, so no prior data transformation has to be applied.

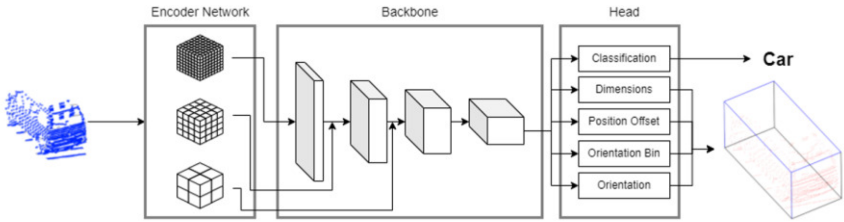

Figure 11: Network architecture for classification and bounding box regression

The backbone consists of a 3-dimensional convolution and pooling layers, while the voxel features from the encoder networks are injected at the corresponding stages. The head is then spitted into multiple branches with different tasks. The classification head is responsible to distinguish between the classes "car", "pedestrian", "cyclist" and "background". The other branches together regress the oriented bounding box. The classification is evaluated separately on the real world lidar segments of the Stanford Track Collection and achieves a classification accuracy of 96.8 %. The regressed bounding boxes are further evaluated on the KITTI 3D detection benchmark where a mAP score of 79.3 % is achieved for cars using a custom data split. Both the segmentation and the neural network are capable of running in real time. Overall, this combination of a geometric segmentation approach and a neural network for refinement offers high classification and regression performances combined with the safety of a geometric detection.

Perceived Space Representation using Brain Activity Analysis, Eye-Tracking and Terrestrial Laser Scanning (Brain TLS)

This RISC (Research Seed Capital – Blue Skies Research) project aims to use brain activity and eye movement of humans to represent the perceived space and possibly replace or enhance existing reality capture methods. The project is funded by the Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg.

Up to now, the conducted experiments yielded some interesting findings. Eye-tracking data are used obtained with a Pupil Core eye-tracker and brain activity was recorded with an 8-chanel electroencephalography (EEG) brain computer interface (BCI) from Neuroelectrics. The experiments can be briefly described as follows: a person equipped with the BCI and Eye-tracker stands in front of a wall at short distance ($\sim$ 4m) with small black & white targets fixed on it. While BCI and eye-tracker data is recorded, the subject focuses on each target in succession. The goal is to reconstruct the position of targets using EEG and eye-tracking data. Based on eye tracking, the position of each target can be reproduced with differences w.r.t. the true position in lower dm-level (< 20 cm) on the observed wall. The EEG data shows interesting artifacts when the person changes his or hers gaze point. It is possible to interpret if a target is on the left or on the right side w.r.t. an egocentric coordinate system based on the signal patterns (see figure 10). Data from further experiments with different subjects is still being analyzed.

All in all, the project reflects an old saying of the pre-Socratics - “Man is the measure of all things ...”, this time literally.

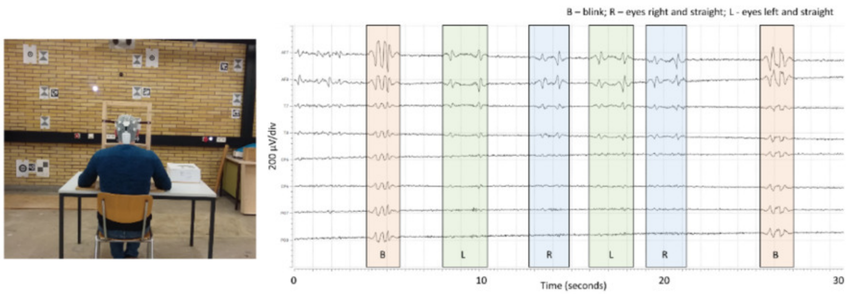

Figure 12: Left: person during the experiment; right: EEG Signals and patters for different eye movements (see legend)

PhD Seminar

The 11th Doctoral Seminar of the Engineering Geodesy Section of DGK was organized by the Institute of Geodesy of Leibniz Universität Hannover. Although the entire scientific community was confronted with challenging times and overwhelmed by digital events, the DGK PhD Seminar of Engineering Geodesy Section was organized as a live event. It took place from October 6 to 7, 2021, under strict 3G rules and an appropriate hygiene concept at the Royal Horse Stables (Königlicher Pferdestall) in Hannover, a communication and meeting center of Leibniz Universität Hannover for science and culture. A total of 12 presentations mirrored the work of PhD candidates from Austria, Switzerland, and Germany. Fruitful discussions between the 50 participants were possible during the coffee breaks and in the evening at the much anticipated get-together for “Beer & Brezel”. After the successful participation of the IIGS members with contributions from Christian Bader and Julia Aichinger, a long minibus ride back to Stuttgart crowned the experience.

Publications

Refereed Publications

Bader, C.; Dingler, S.; Schwieger, V. (2021): PVENet: Point Voxel Encoder Network for Real-Time Classification of Lidar Point Cloud Segments. In: 2021 20th International Conference on Advanced Robotics (ICAR), pp. 492-498, https://doi.org/10.1109/ICAR53236.2021.9659376

Balangé, L.; Zhang L.; Schwieger V. (2021): First Step Towards the Technical Quality Concept for Integrative Computational Design and Construction. In: Kopácik A., Kyrinovic P., Erdélyi J., Paar R., Marendic A. (eds) Contributions to International Conferences on Engineering Surveying. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-51953-7_10;

Bühler, M.; Sebald, C.; Rechid, D.; Baier, E.; Michalski, A.; Rothstein, B.; Nübel, K,; Metzner, M.; Schwieger, V.; Harrs, J.; Jacob, D.; Köhler, L.; Panhuis, G.; Tejeda, R.; ;Herrmann, M.; Buziek, G (2021): Application of Copernicus data for climate-relevant urban planning using the example of water, heat, and vegetation. Remote Sensing, 13(18), 3634; https://doi.org/10.3390/rs13183634

Kerekes, G.; Schwieger V. (2021): Determining Variance-Covariance Matrices for Terrestrial Laser Scans: A Case Study of the Arch Dam Kops. In: Kopácik A., Kyrinovic P., Erdélyi J., Paar R., Marendic A. (eds) Contributions to International Conferences on Engineering Surveying. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-51953-7_5

Lauer, A. P. R., Blagojevic, B., Lerke, O., Schwieger, V., Sawodny, O. (2021): Flexible Multibody System Model of a Spider Crane with two Extendable Booms. In Proceedings of the 47th Annual Conference of the IEEE Industrial Electronics Society.

Lerke, O., Bahamon-Blanco, S., Metzner, M., Martin, U., Schwieger, V. (2021): Vorarbeiten zur Entwicklung eines Gleisfehlerdetektionssystems mit Regelzügen und Low-Cost Sensorik. Zfv 3/2021. 10.12902/zfv-0339-2021

Lerke, O., Schwieger, V. (2021): Analysis of a kinematic real-time robotic total station network for robot control. Journal of Applied Geodesy 2021; 15(3). doi.org/10.1515/jag-2021-0016

Luz, P.; Zhang, L.; Wang, J.; Schwieger, V. (2021): Lane-Level Map-Aiding Approach Based on Non-Lane-Level Digital Map Data in Road Transport Security. Sustainability 2021, 13, 9724. https://doi.org/10.3390/su13179724

Raschhofer, J.; Kerekes, G.; Harmening, C.; Neuner, H.; Schwieger, V. (2021): Estimating Control Points for B-Spline Surfaces Using Fully Populated Synthetic Variance–Covariance Matrices for TLS Point Clouds. Remote Sensing. 2021; 13(16):3124. https://doi.org/10.3390/rs13163124

Scheider, A.; Hassan, A.; Brüggemann, T.; Schwieger, V. (2021): Lückenlose Positionsbestimmung zur Georeferenzierung von hydrographischen Messdaten. AVN, Heft 3, 123-132.

Yang, Y.; Balangé, L.; Gericke, O.; Schmeer, D.; Zhang, L.; Sobek, W.; Schwieger, V. (2021): Monitoring of the Production Process of Graded Concrete Component Using Terrestrial Laser Scanning. Remote Sens. 2021, 13, 1622. https://doi.org/10.3390/rs13091622

Non-Refereed Publications

Kerekes, G.; Schwieger, V. (2021): Towards Perceived Space Representation using Brain Activity, Eye-Tracking and Terrestrial Laser Scanning. In A. Basiri, G. Gartner, & H. Huang (Eds.), LBS 2021: Proceedings of the 16th International Conference on Location Based Services. https://doi.org/10.34726/1788

Wagner, H.-J., Aicher, S., Balangé, L., Basalla, U., Schwieger, V., Menges, A. (2021): Qualities of the Unique: Accuracy and Process-Control Management in Project-based Robotic Timber Constructions. WCTE 2021, Santiago de Chile, 9.-12. August 2021

Presentations

Balangé, L., Di Bari, R., Hos, P. D.: RP18: Holistic Quality Model for IntCDC Building Systems, Status Colloquium 2021, 26.02.2021

Balangé, L., Di Bari, R., Hos, P. D.: RP18: Holistic Quality Model, Status Seminar 2021 Bad Boll, 11.11.2021

Balangé, L., Di Bari, R., Hos, P. D.: RP18: Holistic Quality Model, Joint Meeting RPA-B1, RPA-C, RP18, 02.03.2021

Balangé, L.: Results of the University of Stuttgart in the framework of the COLLECTOR ring trial, COLLECTOR Workshop 1 and 3, 27.05.2021 and 16.11.2021

Faulkner, R., Gong, Y., Javot, B., Lerke, O., Lauer, A., Mohan, M., Ortenzi, V., Sanchez, N.: Robotic Platform for Cyber-Physical Assembly of Long-Span Fiber-Composite Structures, IntCDC Status Colloquium 2021, 26.02.2021

Faulkner, R., Gong, Y., Javot, B., Lauer, A., Lerke, O., Mohan, M.: Robotic Platform for Cyber-Physical Assembly of Long-Span Fiber-Composite Structures, 2021 IntCDC Status Seminar Bad Boll, 11-12.11.2021

Kerekes, G.: Elementary Error Model for TLS Measurements, Workshop on Error Sources and Corrections in Permanent Laser Scanning, digital at Optical and Laser Remote Sensing Group, Department of Geoscience and Remote Sensing, Delft University of Technology, 18.03.2021.

Kerekes, G.: Perceived Space Representation using Brain Activity Analysis, Eye-Tracking and Terrestrial Laser Scanning, Strategiedialog 2021 Universität Stuttgart - Bold research, 20.04./03.05.2021.

Kerekes, G.: Presentation of work experience and research experience at the Polytechnic University of Timisoara for Geodesy Students, digital event, 17.05.2021.

Kerekes, G.: Successful Graduates Speech at the Polytechnic University of Timisoara – 100 years anniversary of the university and 80 year anniversary of the faculty of construction, digital at the Polytechnic University of Timisoara, 11.11.2021

Lerke, O.: Precise Seamless 6-DoF Positioning for Georeferenced Assembly Control, IntCDC RP16 Status Meeting, 08.01.2021

Lerke, O.: Quality aspects related to Engineering Geodesy, IntCDC Research project area (RPA - C) Meeting, 20.01.2021

Schwieger, V.: Beyond BIM – Integrative Computational Design and Construction, Jahressitzung des Ausschusses Geodäsie (DGK), Bayrische Akademie der Wissenschaften, 24.11.2021.

Schwieger, V.: Vorstellung der Abteilung Ingenieurgeodäsie, Jahressitzung des Ausschusses Geodäsie (DGK), Bayrische Akademie der Wissenschaften, 25.11.2021.

Schwieger, V.: Integrative Computational Design and Construction – Geodetic Contributions, Geodätisches Kolloquium der Universität Bonn, 02.12.2021.

Zhang, L.: Quality as Driver for Sustainable Construction — Holistic Quality Model and Assessment, IntCDC Best Publication Awards 2020/21, Status Seminar 2021 Bad Boll, 11.11.2021

Activities at the University and in National and International Organizations

Volker Schwieger

Full member of the German Geodetic Commission (Deutsche Geodätische Kommission – DGK)
Head of the section "Engineering Geodesy" within the German Geodetic Commission (DGK)
Chief Editor of Peer Review Processes for FIG Working Weeks and Congresses Member of the Editorial Board "Journal of Applied Geodesy"
Member of the Editorial Board "Journal of Applied Engineering Science"
Member of the Editorial Board "Journal of Geodesy and Geoinformation"

Martin Metzner

Member of the NA 005-03-01 AA "Geodäsie" at the DIN German Institute for Standardization
Course Director of the MSc Program GeoEngine at the University of Stuttgart

Li Zhang

Co-Chair of the Working Group 5.6 "Cost Effective Positioning" within the FIG Commission 5 (Positioning and Measurement)

Chair of the Working Group "Quality Assurance" within the Commission 3 "Measurement Methods and Systems" of "Deutscher Verein für Vermessungswesen (DVW)"

Doctorates

Scheider, Annette: Identifikation von Systemmodellen zur dreidimensionalen Zustandsschätzung eines Peilschiffs mit Propellerantrieb unter Verwendung eines Multi-Sensorsystems. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 868, ISBN 978-3-7696-5280-2, ISSN 0065-5325, Verlag der Bayerischen Akademie der Wissenschaften. https://dgk.badw.de/fileadmin/user_upload/Files/DGK/docs/c-868.pdf
Main reviewer: Prof. Dr.-Ing. habil. Dr. h.c. Volker Schwieger, Co-reviewers: Prof. Dr.-Ing. Harald Sternberg (HCU Hamburg), Prof. Dr.-Ing. Andreas Eichhorn (TU Darmstadt);

Alexandra Avram: A contribution to multipath modelling and simulation for kinematic trajectories. Universität Stuttgart: Universitätsbibliothek der Universität Stuttgart. https://elib.uni-stuttgart.de/handle/11682/11848
Main reviewer: Prof. Dr.-Ing. habil. Dr. h.c. Volker Schwieger, Co-reviewer: Univ.-Prof. Mag. Dr. habil. Thomas Pany;

Chaudhry, Sukant: Surface related uncertainties of laser scanning: a simulation-based and experimental study. ETH Zürich, Research Collection, Dissertation 2021. https://www.research-collection.ethz.ch/handle/20.500.11850/533401
Main reviewer: Prof. Dr. Andreas Wieser (ETH Zürich), Co-reviewers: Prof. Dr.–Ing. habil. Dr. h.c. Volker Schwieger, Dr. David Salido Monzu (ETH Zürich)

Master Theses

Ahmeti, Shkelqim: Improvements of lane exact Map-Matching by considering past GNSS epochs (Luz/Metzner)

Andrews, Akosah: Examining the pixel positions of the camera measurements of the crosshairs of the telescopic line of sight of the Leica TS16I (Basalla/Schwieger)

Buck, Maximilien: Prozessoptimierung beim Einsatz der Methode Building Information Modeling. (Metzner)

Li, Bilin: Radar-Sensorsimulation zur Validierung autonomer Fahrfunktionen (Schwieger)

Irslinger, Maximilien: Automatisierte Ermittlung des baulichen Nutzungsmaßes und der daraus resultierenden Wertunterschiede (Metzner)

Miseke, Ariane: The use of geospatial analysis to evaluate the locations and distribution patterns of COVID-19 in Baden-Württemberg (Metzner)

Xu, Bingqing: Development of a Map-based Constrained Extended Kalman Filter Algorithm for Train Positioning (Lerke/Schwieger)

Zheng, Yifei: Sensor integration with magnetic data and improvement of an extended Kalman filter (Luz/Zhang)

Bachelor Theses

Schmid, Frieder: Erfassung von Baustellenfahrzeugen mittels Verfahren der Bildverarbeitung (Basalla/Schwieger)

Speidel, Pauline: Evaluierung von unterschiedlichen Verfahren zur Bestimmung der Pose eines Bauroboters mittels eines RTS Netzwerks (Lerke/Schwieger)

Sprügel, Nadine: Detektion und Verfolgung eines Laserspots im Kamerabild eines TS16 (Basalla/Schwieger)

Tao, Yihan: Evaluierung der Möglichkeiten für die Erstellung eines BIM-Modells mittels Trimble X7 und der Software RealWorks (Balangé/Metzner)

Wilczynski, Martin Jan: Verwendbarkeit von mobilen Eye-Tracking Systemen in der geodätischen Messtechnik (Kerekes/Schwieger)

Education

SS21 and WS21/22 with Lecture/Exercise/Practical Work/Seminar

Bachelor Geodesy and Geoinformatics (German)

Basic Geodetic Field Work (Haußmann, Kanzler)	0/0/5 days/0
Engineering Geodesy I (Schwieger, Basalla)	4/2/0/0
Engineering Geodesy II (Schwieger, Lerke)	1/1/0/0
Geodetic Measurement Techniques I (Metzner, Haußmann)	3/1/0/0
Geodetic Measurement Techniques II (Haußmann)	0/1/0/0
Integrated Field Work (Kerekes, Metzner)	0/0/10 days/0
Reorganisation of Rural Regions (Stadler)	1/0/0/0
Statistics and Error Theory (Schwieger, Balangé)	2/2/0/0

Master Geodesy and Geoinformatics (German)

Deformation Analysis (L. Zhang)	1/1/0/0
Industrial Metrology (Schwieger, Gorokhova)	1/1/0/0
Land Development (Eisenmann)	1/0/0/0
Monitoring Measurements (Schwieger, Gorokhova)	1/1/0/0
Terrestrial Multisensor Systems (L. Zhang, Lerke)	1/1/0/0
Geomobility (L. Zhang, Luz)	2/2/0/0
Projekt Geodäsie und Geoinformatik (Schwieger, L. Zhang, Basalla, Haußmann)	0/0/0/6

Master GeoEngine (English)

Kinematic Measurement Systems (Schwieger, Basalla)	2/2/0/0
Monitoring (Schwieger, Balangé)	1/1/0/0
Thematic Cartography (L. Zhang, Sebald)	1/1/0/0
Transport Telematics (Metzner, Sebald)	2/1/0/0
Terrestrial Multisensor Systems (Lerke, Haußmann)	2/1/0/0

Bachelor and Master Aerospace Engineering (German)

Statistics for Aerospace Engineers (L. Zhang, Balangé)	1/1/0/0

Master Aerospace Engineering (German)

Industrial Metrology (Schwieger, Gorokhova)	1/1/0/0
Transport Telematics (L. Zhang, Luz)	2/2/0/0

Bachelor Civil Engineering (German)

Geodesy in Civil Engineering (Metzner, Luz, Kanzler)	2/2/0/0

Master Civil Engineering (German)

Geoinformation Systems (Metzner, Sebald)	2/1/0/0
Transport Telematics (L. Zhang, Luz)	2/1/0/0

Bachelor Technique and Economy of Real Estate (German)

Acquisition and Management of Planning Data and Statistics (Metzner, Luz, Kanzler)	2/2/0/0

Bachelor Transport Engineering (German)

Bachelor Transport Engineering (German): Statistics (Metzner, Luz, Kanzler)	0.5/0.5/0/0
Seminar Introduction in Transport Engineering (Basalla)	0/0/0/1

Master Infrastructure Planning (English)

GIS-based Data Acquisition (L. Zhang, Haußmann)	1/1/0/0

Institute of Geodesy

Geschwister-Scholl-Str. 24D
D-70174 Stuttgart
Tel.: +49 711 685 83390
Fax: +49 711 685 83285
gis@gis.uni-stuttgart.de
https://www.gis.uni-stuttgart.de

Head of Institute

Prof. Dr.-Ing. Nico Sneeuw
Prof. Dr. James Foster

Retired

Prof. Dr. sc. techn. Wolfgang Keller

Academic Staff

Dr.-Ing. Markus Antoni	Physical Geodesy, Satellite Geodesy
Dr.-Ing. Jianqing Cai	Satellite Geodesy, Adjustment Theory
Dr. Karim Douch	Physical Geodesy, Hydrogeodesy
Dr.-Ing. Omid Elmi	Remote Sensing, Hydrogeodesy
PD Dr.-Ing. habil. Johannes Engels	Physical Geodesy
M.Sc. Bruce Thomas	Physical Geodesy, Satellite Geodesy
Dr.-Ing. Mohammad Tourian	Satellite Geodesy, Hydrogeodesy
Ph.D. Rudolf Widmer-Schnidrig	Physical Geodesy

Research Associates

M.Sc. Sajedeh Behnia	Satellite Altimetry
M.Sc. Clara Bützler	Physical Geodesy, Seismology
M.Sc, Siqi Ke (since 11.2021)	Hydrogeodesy
M.Sc. Saemian Peyman	Satellite Geodesy, Hydrology
M.Sc. Bo Wang	Satellite Altimetry

Administrative/Technical Staff

Dipl.-Ing. (FH) Thomas Götz	IT System, Controlling
Dipl.-Ing. (FH) Ron Schlesinger	IT System, Technical Support, Gravimetry
B.A. Tamara De Francesco	Office Management

External Lecturers

Dipl.-Ing. Gerhard Grams	Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg, Stuttgart
Dipl.-Ing. Dieter Heß	Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg, Stuttgart

Guests

M.Sc Lang Liu	Tongji University, China (01.11–31.10.2022)
Assoc. Prof. Yi Lin	Tongji University, China (15.11–15.04.2022)
Dr.-Ing. Shuang Yi	China, Humboldt Fellow

Research

Seafloor Geodesy

The July 29, 2021 Mw 8.2 Chignik earthquake ruptured the Semidi segment of the Aleutian subduction zone megathrust. The Semidi section may have high tsunami generation potential, and could direct maximum tsunami wave amplitudes toward the U.S. west coast. Our team, consisting of scientists from the U.S. Geological Survey, University of California San Diego, Lamont Doherty Earth Observatory, University of Washington, and University of North Carolina at Wilmington, along with Professor James Foster from the University of Stuttgart, mounted a response to remeasure a GNSS-acoustic station located on the seafloor in the immediate vicinity of the Chignik rupture. This station, "SEM1", is located immediately up-dip of where the preliminary slip models tend to zero: thus a surface displacement measurement could place important constraints on the slip distribution nearest the trench. We made waveglider-based measurements in October 2021. We will use these measurements to determine the surface displacement for SEM1 and use this to improve the fault slip estimates and to assess the fault area available for potential future earthquakes and its tsunamigenic potential.

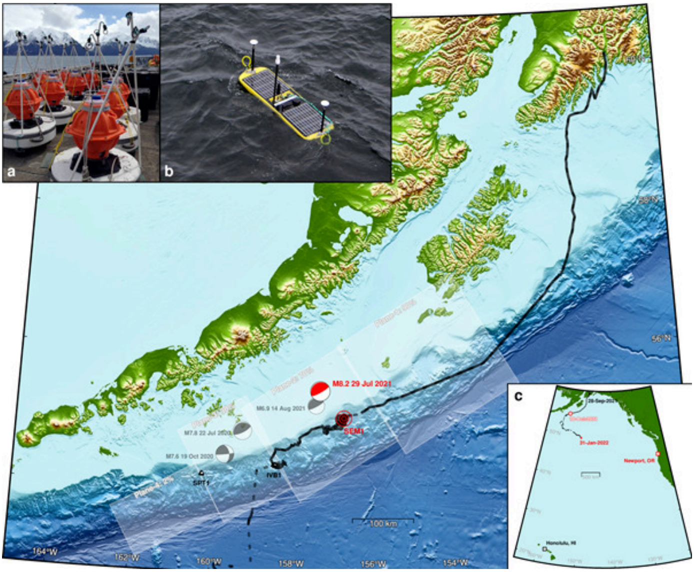

Figure 1: Map of the 2021 Waveglider Alaska Earthquake Response mission to re-measure the seafloor geodetic station SEM1 (in red) in response to the M8.2 Chignik earthquake (red “beachball”). Waveglider track (black line), previous recent large earthquakes (gray beachballs) and other 2 seafloor stations (black triangles) are shown. Different segments of the subduction zone megathrust fault are shown in white rectangles with the estimated degree of fault locking (which controls the rate of strain buildup). Insets: a shows the instruments that have been deployed to the seafloor (3 per station); b shows the Waveglider; c regional map showing current location of the Waveglider as it returns to Newport Or, for recovery.

The network of 3 seafloor station was originally deployed to improve our understanding of the frictional properties of this section of the Aleutian subduction zone megathrust fault. Previous research had estimated that this sequence of segments of the fault become increasingly less “locked” towards the west. This means less strain is built up as the Pacific tectonic plate moves under the North American plate. The details are crucial for our ability to determine earthquake and tsunami hazards from this region. Our team has been making measurements of the three seafloor geodetic sites using the Waveglider to allow us to improve estimates of the amount of locking. We also acquired extra measurements after the 2 large earthquakes in 2020 to determine the ground motions caused by these events.

Kīlauea volcano-tectonics

Global Navigation Satellite System (GNSS) data provide high accuracy measurements of ground motion. The University of Hawai’i (UH) and the Hawai’i Volcano Observatory (HVO) have installed, operated and maintained a network of continuous GNSS sites along with benchmarks for roving GNSS occupations on the Big Island of Hawaii. Data from these networks support a huge range of scientific investigations into the active volcanic and tectonic processes on Kīlauea and Mauna Loa. One key benchmark line runs from south of Kīlauea's caldera through the Koa'e fault zone. This area has experienced extreme historical extension connecting the east and southwest rift zones, and it is thought to have a key role in the overall tectonics of Kīlauea volcano.

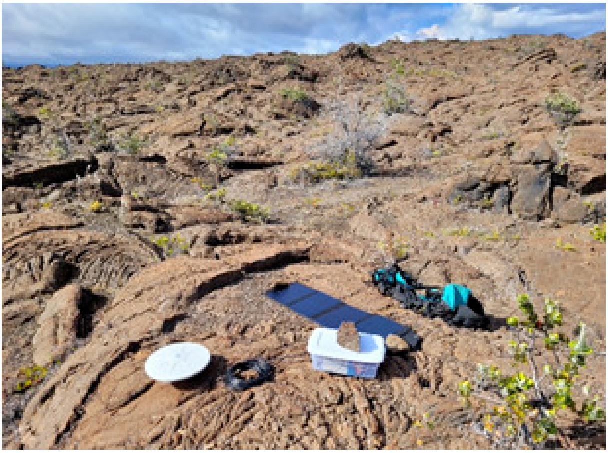

Figure 2: GNSS receiver, antenna and batteries installed by Bruce Thomas on a site on Koa'e fault zone, Hawaii, November 2021.

This line has been measured several times since it was installed in 2004, and University of Stuttgart PhD student Bruce Thomas re-occupied it in 2021 to extend our data-set to span the dramatic 2018 summit collapse. The 66 benchmarks were visited with Trimble GNSS receivers for at least 6 hours to obtain precise coordinates. This dataset will be augmented by continuous GNSS data from Kīlauea network, leveling records and fault maps and used to guide numerical models of the deformation. These models will help us understand how this area responds during the eruptive events, as well as to seismic and tectonic motions occurring under the mobile south flank of the volcano. We are especially interested in the ratio of elastic to inelastic deformation and the role of the fault system in accommodating or transfering stresses within the volcano.

Earthquake / Tsunami Early Warning

Earthquake early warning (EEW) systems aim to provide a few crucial tens of seconds warning of imminent shaking. This allows people to move to safer locations, utilities to shut off gas and generators, and emergency response teams to prepare. EEW have already been implemented in the USA and Japan but have very high equipment and maintenance costs. We follow the approach demonstrated by our successful ASTUTI project with our collaborators in the U.S. Geological Survey and the National University of Costa Rica, by testing compact low-cost sensors to create a pilot network for low-cost early warning for the Big Island in Hawai'i. The sensors chosen are Samsung J3 and Xiaomi 8 smartphones and the data used comes from the on-board accelerometers and GNSS chips. They use the cell network to notify our servers of any large earthquakes happening. The smartphones were configured and deployed by University of Stuttgart PhD student Bruce Thomas in locations close to previous earthquake swarms, and either in closed buildings around the island or in instrument boxes of continuous GNSS sites. The test period started in December 2021 and is planned to run for a least a year. The project aims to demonstrate the capability of this type of network to rapidly detect large earthquakes In Hawaii. We will test the implementation of a tsunami early tsunami approach using the ground motions determined from the dual frequency GNSS chips on the Xiaomi 8 smartphones to initiate numerical tsunami prediction models.

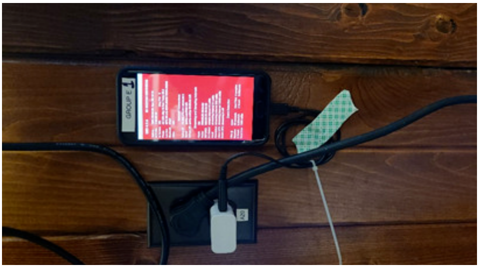

Figure 3: Smartphone for early earthquake warning installed in a building inside Hawai'i National Park, December 2021. Ship-based GNSS Tsunami Detection

Over the last decade several tsunamis have highlighted weaknesses in our understanding of earthquake and tsunami hazards, and emphasized the need for additional, more densely spaced observing capabilities, particularly for early warning. The recent Tonga volcano eruption caused a tsunami that was poorly monitored as it was unexpected, and had an unusual generating source. Unexpected slip magnitude (e.g. 2011 Tohoku-oki), location (e.g. 2012 Haida Gwaii), mechanism (e.g. 2018 Palu), all indicate more observations are needed for robust, comprehensive, regional and global tsunami warning. While the seismic network provides rapid event detection, and land-based GNSS offers improved rapid slip characterization, these techniques rely on proxy measurements to infer the existence and size of a tsunami. Direct measurements of the ocean gravity-wave are provided by tide-gauges and the DART array. Though crucial, these are sparse and may arrive too late for early warning. Ships with geodetic GNSS systems tracking changes in sea-surface height are able to detect even small, $\sim 10\,\mathrm{cm}$ amplitude, tsunamis. Commercial shipping lines provide excellent temporal and spatial coverage of the oceans globally and, critically for local and regional early warning, are at their most dense near coastlines. A collaboration between the Univ. of Hawaii, Matson and Maersk shipping companies, and the World Ocean Council, funded by NOAA, built a 10-ship pilot network operating across the North Pacific from 2015–2018. Each ship was equipped with a geodetic GNSS system and satellite communications, and streamed real-time kinematic positions to our server. Although there was no detectable tsunami event within the project period, the system demonstrated its capability as a monitoring network. A new phase of this project, led by the Univ. of Stuttgart with Fugro, Maersk, and Swire shipping, is deploying a revised package that offers a scalable operational solution. A ship-board PC pre-processes the data stream reducing its bandwidth and allowing the ships to host our data on their existing internet service, greatly reducing costs. With a unit price of ~5000 $ for each package and low monthly costs this new network can be expanded to exploit the excellent observational geometry of the shipping routes for the rapid detection and characterization of tsunamis. We are currently working with our "beta-test" collaborator, Fugro, to get the first ships in the new network providing live data to our server. Meanwhile, University of Stuttgart Masters student Yuke Xie is mining the GNSS data set collected during the pilot project to identify the signature of tsunamis in the ionosphere, and construct an analysis approach that will allow us to deploy this additional technique with our new network. This will further densify the observations available to detect and characterize tsunamis, and improve our ability to provide timely and accurate warnings to at-risk coastal communities.

Gravity gradients and gravity strain of prompt-elasto-gravity signals

When an earthquake happens elastic waves propagate inside the Earth. This changes gravity even at locations the waves have not reached yet. Why? The waves are compressing and dilating the Earth material. If a material is compressed its density increases, while dilatation decreases the material density. Therefore, the waves are changing the density distribution inside the Earth a little bit. As the gravity field of the Earth is governed by its density distribution the earthquake waves will cause a very tiny change in gravity everywhere on Earth. If we are too far from the earthquake this change cannot be measured because it is to small. However, in an appropriate distance from the earthquake, a gravity change can be measured before any of the waves has arrived. So it is the first signal of an earthquake which can be measured. In the future it might therefore be used for early warning systems for earthquakes and tsunamis. The mechanism of this prompt-gravity signal is further illustrated in Figure 4.

Prompt-gravity signals are very small: smaller than $2\,\mathrm{nm/s^2}$, which is a thousand times smaller than the daily gravity change caused by solid Earth tides. It is thus very difficult to measure them. Furthermore, there is a second reason why prompt-gravity signals are difficult to detect: When gravity is changing, this acts as a tiny new force at every point inside the Earth. These forces are much smaller than the force that originally caused the earthquake, but the effect is similar, only smaller: Caused by the gravity change "mini earthquakes" start at every point in Earth. For all points is close enough to the instrument the waves of these "mini earthquakes" will reach the instrument before the waves of the actual earthquake.

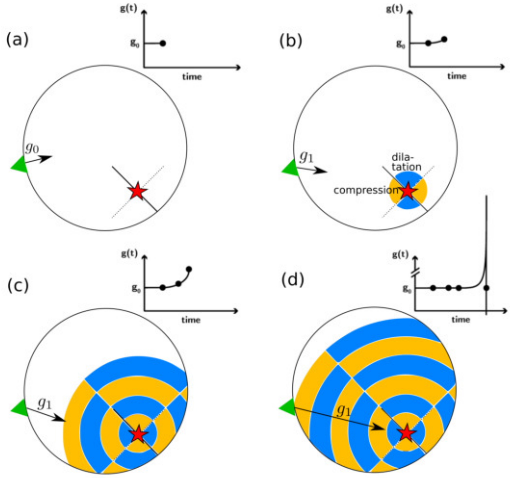

Figure 4: Mechanism of a prompt-gravity signal. In all four sketches you can see the Earth (circle). The hypocentre of an earthquake (the point where the rupture starts) is marked with a red star. In sketch (a) the earthquake has not started yet. With an instrument (red triangle) the undisturbed gravity is measured. In sketch (b) the elastic wave starts to propagate. There are two areas of compression and two areas of dilatation. As the compressed area is the closest to the instrument it has the main influence. In the compressed area density is rising and therefore also the measured gravity increases. When the wave further propagates (sketch (c)) the compressed area is coming closer to the instrument and the gravity change increases. So an increase in gravity is measured until the elastic waves reach the instrument. Afterwards, the gravity change cannot be measured anymore as the waves will make the ground shake and this causes a much bigger signal than the gravity change.

So, the ground on which the instrument is put down will be accelerated. Instruments built to measure gravity change (gravimeters) and those to measure ground acceleration (seismometers) are in reality sensitive to both of them, ground acceleration and gravity change. So, they will measure the prompt-gravity change and the "mini earthquakes" caused by the prompt-gravity change. Unfortunately, these two partly cancel each other. The remaining signal is called prompt-elasto-gravity-signal (PEGS) and it is even smaller than the prompt-gravity-signal: $\leq 1.6\,\mathrm{nm/s^2}$.

As a result, it would be of advantage to have an instrument, which is only sensitive to the prompt-gravity-signal, but not to the "mini earthquakes". One class of such instruments are called gravity gradiometers: They measure the difference of gravity at two points inside the instruments and they are designed in such a way that the ground acceleration cancels out when taking the difference. However, our research has shown that existing and under development gravity gradiometers are not sensitive enough to measure prompt-gravity signals. A more promising idea is to use gravity strainmeters, which are originally developed to measure gravitational waves. They have properties similar to the gravity gradiometers. Previous studies have shown that gravity strainmeters which are under development should be able to detect prompt-gravity signals. Recently, we have studied how realistic a model of the Earth has to be in order to model prompt-gravity signals in the measurements of gravity strainmeters correctly. We found that already the very simple model of a homogeneous infinite material gives surprisingly realistic results.

RiwiSAR-SWH: A data-driven method for estimating significant wave height using Sentinel-3 SAR altimetry

More than 600 million people (about 10 $\%$ of the world's population) live in coastal areas that are less than 10 m above sea level. Despite the urgent need to monitor coastal waters, in-situ measuring stations including wave buoys around the world do not provide sufficient insight into coastal water level variations, and in particular, they cannot provide sufficient information on one of the essential properties of water surfaces, namely the Significant Wave Height (SWH). Satellite altimetry plays an increasingly important role, especially after operating in Synthetic Aperture Radar (SAR) mode. However, due to the complexity of the coastal water surfaces, the performance of the satellite altimeters over the coastal area falls behind that over open ocean surfaces. In addition, the well-known direct relationship between waveform rise time and SWH does not hold for SAR waveforms due to a different processing scheme. Our study proposes a data-driven method to determine SWH using the Sentinel-3 data for both oceanic and coastal zones. For this purpose, we developed a method based on the rise time (δr) and the width of a waveform, called RiwiSAR-SWH (rise time width model for SAR-SWH), which is free from the complexity of the SAR physical model and estimates SWH over the coastal area and open ocean in a relatively straightforward manner.

The method is employed over six virtual stations, Sylt, Elbe#1, Elbe#2, Elbe#S3A, Spiekeroog, and Cuxhaven, defined along four selected Sentinel-3B passes (541, 655, 130, 244), and two selected Sentinel-3A passes (541, 130) in the North Sea (Figure 5). The results are validated against in-situ measurements available from three buoys on Sylt, Butendiek, and Elbe and compared with SWH estimates from SAMOSA+, SAMOSA++ and the Sentinel-3 Ocean retracker. The validation analysis for these six virtual stations is divided into two categories, namely along the coastlines and over the open water surfaces. RiwiSAR-SWH delivers reliable SWH estimates efficiently without considering the complicated physical model. Results over all selected virtual stations show considerable improvement in the $\mathrm{RMSE_i}$ up to 77 $\%$. Furthermore, RiwiSAR-SWH is more robust against non-standard waveforms because it does not rely on the whole waveforms. Overall, the validation shows that the proposed method can determine SWH with accuracy ranging from 0.25 m to 0.91 m for different locations in the North Sea. RiwiSAR-SWH estimates reliable SWH values starting from around 1 km distance from the coast, which is an improvement of more than 40 $\%$ compared to SAMOSA+ and the Ocean retracker.

The method can be potentially applied globally for all types of SAR waveforms over oceanic and coastal regions with necessary readjustments of the model. Moreover, the applicability

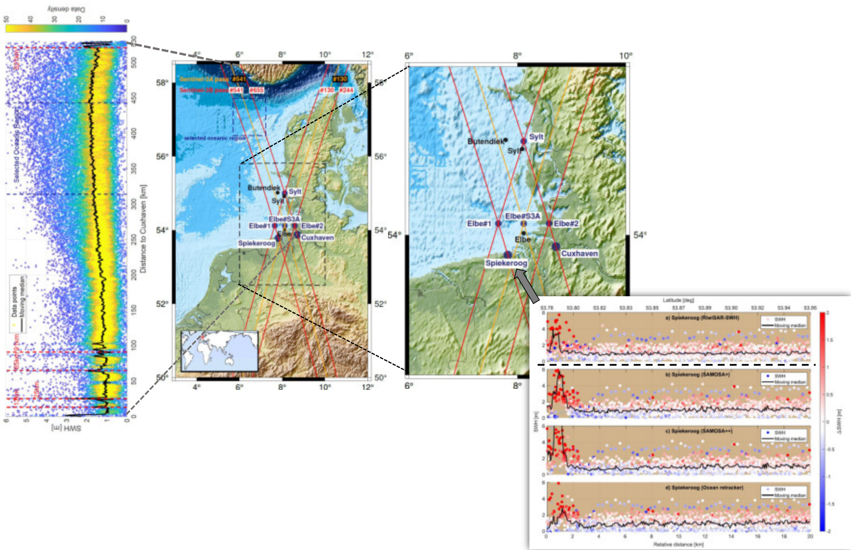

Figure 5: Virtual stations Sylt, Elbe#1, Elbe#2, Elbe#S3A, Spiekeroog, and Cuxhaven, defined along selected ground tracks of Sentinel-3A and Sentinel-3B.

of the proposed methods is independent of waveform derivation processing methods, as demonstrated by applying the RiwiSAR-SWH model on differently processed waveforms sampled in 512 bins instead of 128 bins. In addition, probably one of the main assets of the proposed method is its simplicity, which allows a fast and straightforward implementation at a global scale.

Sentinel-3 Topography mission Assessment through Reference Techniques – St3TART

St3TART is an ESA-funded project which aims at providing proof of concept for using Fiducial Reference Measurements (FRMs) in support of the validation activities of the Sentinel-3 (S3) radar altimeters. Given the variety of measurements for validation of S3, the project is being conducted within three thematic groups: hydrology, sea ice, and land ice.

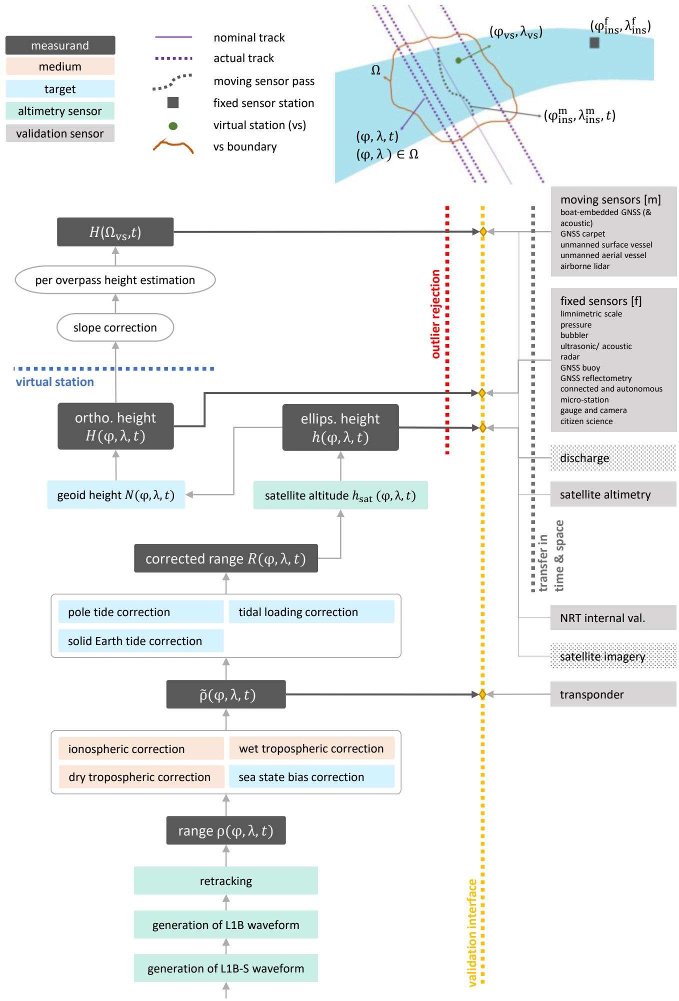

Figure 6: Conceptual flowchart of validation scenarios

Together with other partners, GIS is a member of the hydrology working group. Our goal is to define procedures and protocols for FRMs while campaigning over permanent and temporary validation sites. Figure 6 is a conceptual representation of different validation scenarios which are to be considered.

Leading Edge Identification with Prior Information (LEIPI): a new approach to retracking inland altimetry waveforms

Despite both theoretical and methodological developments, inland altimetry is still hindered by many factors, an important one being land contamination. Inland waveforms do not follow a typical shape. This effect complicates the retracking process, and plays a degrading role in the final accuracy and precision of the altimetry retrieved water heights. LEIPI is a new approach to retracking inland altimetry waveforms within the Bayesian framework. In this approach, an outlier identification analysis is performed over the altimetry driven water level time series. As a by-product, the analysis generates a reliable water level variation model which can be used as prior information. By deriving the likelihood function from the waveforms, and multiplying it by the prior, LEIPI chooses the Maximum A Posteriori (MAP) solution as an alternative retracking gate. Figure 7 shows an example of the improvement achieved by LEIPI in deriving water level time series using Jason-3, a pulse-limited radar altimeter.

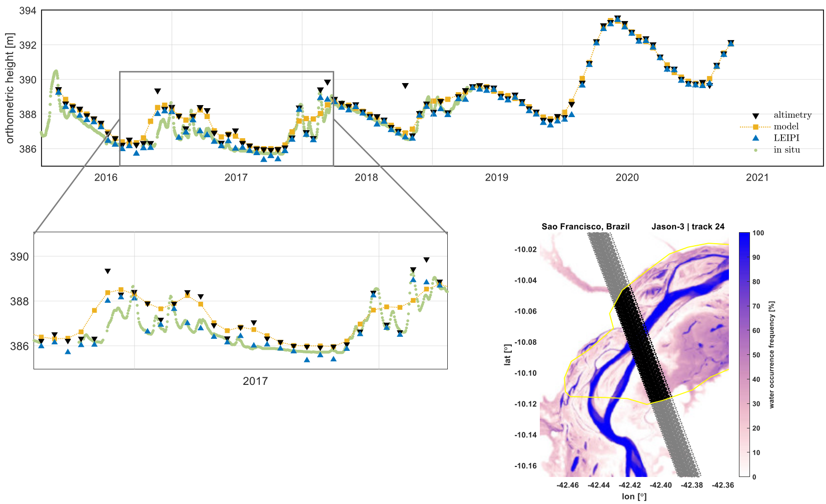

Figure 7: Altimetry water level time series generated based on the LEIPI retracking approach over the river mouth of Sao Francisco as it enters into the Sobradinho reservoir in Brazil.

Retrieving time series of surface water extent by enhancing existing surface water datasets

The accurate monitoring of surface water storage, an essential component of the global water cycle, requires a realistic representation of the surface water extent dynamic. The lack of such observations has obscured the proper quantification of freshwater storage and its spatio-temporal dynamics over many water bodies. Despite recent advances in satellite imaging sensors, water extraction algorithms, and big data processing capabilities, none of the available global water extent datasets can meet the accuracy and spatio-temporal resolution requirements. The inherent complexity of monitoring the surface water extent limits the previous efforts to develop either global water mask datasets just with a few temporal layers or water mask datasets at a regional scale.

Theoretically, the surface area of all inland water bodies can be extracted from any existing dataset. However, the temporal and spatial limitations of the initial dataset restrict the derived water extent estimates. Furthermore, since satellite optical imagery is the primary source of most water extent datasets, the obtained surface area estimates are subject to significant over- and underestimations mainly due to cloud contamination and misclassification.

We propose a region-based image restoration algorithm to obtain high-quality time series of water extent from pre-existing global water masks by incorporating additional constraints. To achieve this goal, we formulate the problem as a Maximum A Posterior estimation of a Markov Random Field. Within such a frame, the enhanced water mask is obtained by incorporating the temporal and spatial constraints as well as pixel labels. We employ the algorithm on the Monthly Water History maps of the Global Surface Water (GSW) dataset developed by The European Commission's Joint Research Centre.

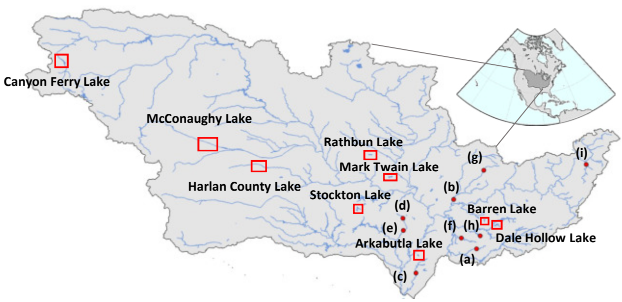

Figure 8: Selected lakes and river reaches in the Mississippi River Basin

To evaluate the algorithm's performance, we selected nine river reaches with an average length of 10 km in the Mississippi River Basin (cf. Figure 8). The time series of monthly river reach areas are compared with in situ discharge measurements in Figure 9 (top panel). In

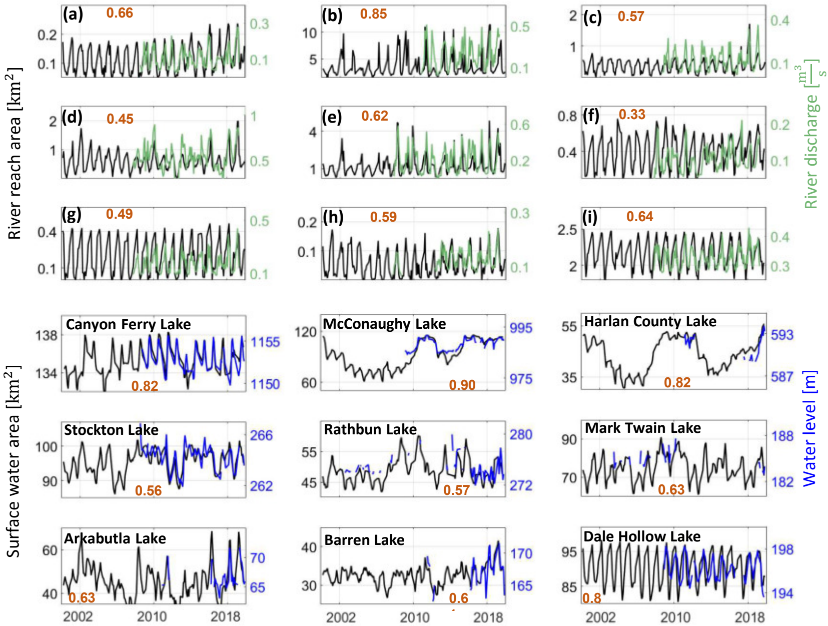

Figure 9: Time series of river reach area for the selected river reaches are compared to in situ river discharge time series (top panel). Lake water area time series are validated against altimetric water level time series (bottom panel).

most cases, we observe a high rank correlation, however some river reaches (like Figure 8(g, f)) are too narrow (about 40 m) to capture accurately from Landsat images. The bottom panel of Figure 8 shows the comparison between the surface water area and altimetric water level time series of nine lakes and reservoirs in the Mississippi River. In general, water level and surface water area variations show an excellent agreement with a high correlation level.

A probabilistic view to characterize drought using satellite gravimetry

Drought is an extreme event with far-reaching economic, social, and environmental impacts that can occur in all climatic regimes. Drought monitoring and forecasting is a proactive approach to managing the risks and mitigating the costs by tracking and evaluating our water resources and climate. In the recent past, the Gravity Recovery and Climate Experiment (GRACE) satellite mission and its successor GRACE Follow-On (GRACE-FO) have been used to characterize total water storage (TWS) drought. Left unaddressed, however, is the fact that different post-processing approaches, inaccurate modeling of high-frequency gravity field variations, and the uncertainty inherent in the GRACE data would lead to uncertainties in the final characterization of the drought.

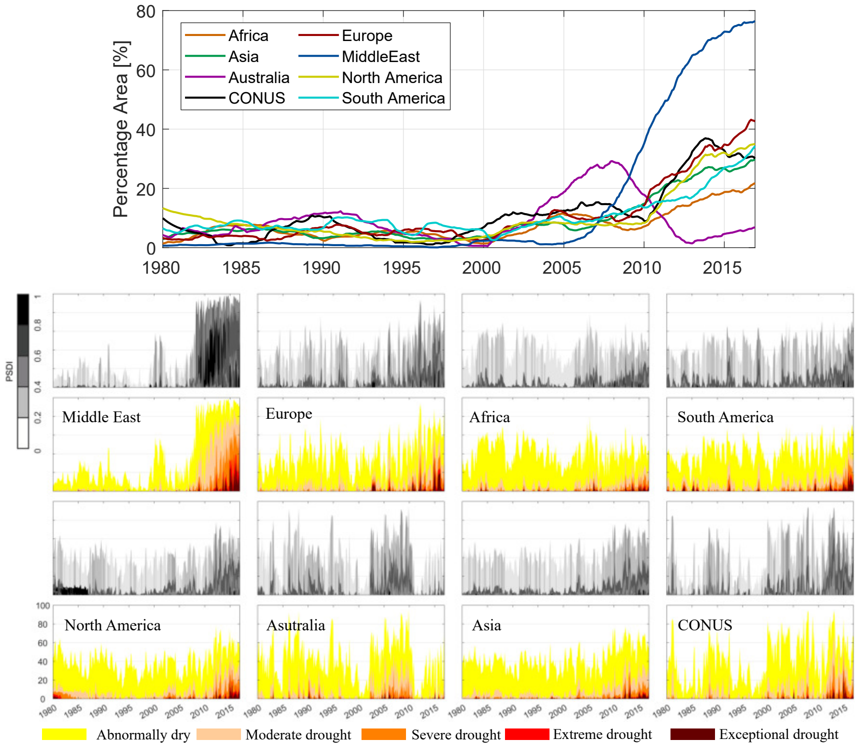

Figure 10: (Top) The time series of the SDI over the continents and the Contiguous United States (CONUS). The time series are smoothed by a moving average with a 4-year window to better represent the main fluctuations. (Bottom) PSDI-affected area by percentage with regard to different drought severity classes over the continents and the CONUS. For each region, the average probabilities associated with the different classes of drought are shown in grayscale.

We propose an approach to obtain the Probabilistic Storage-based Drought Index (PSDI) that accounts for the uncertainties and serves probability for the drought characterization. The stochastic process should be modeled properly in order to obtain a realistic uncertainty at each epoch. Our approach makes use of the Gauss-Markov process and Monte Carlo simulations to obtain the dependent sequence of possible events. The PSDI shows consistent results during the reported hydrological droughts including the 2000s Millenium drought over Australia. In contrast to the common deterministic view, the proposed probabilistic approach would serve a more realistic characterization of the TWS drought, making it more suited for realistic risk management.

The eruptions of Mount Pinatubo and Hunga-Tonga as observed in the far-field

This activity report summarizes a poster presented at the annual meeting of the 2022 German Geophysical Society (DGG) co-authored with my colleagues at the Black Forest Observatory (BFO): Thomas Forbriger and Walter Zürn. Even though Hunga-Tonga erupted in 2022 I take the liberty to report about it in the 2021 activity report simply because this is a once-in-a-century event.

The eruptions of Hunga-Tonga and Mount Pinatubo were of phreatic and plinian style respectively. They were the most explosive eruptions of at least the last 40 years.

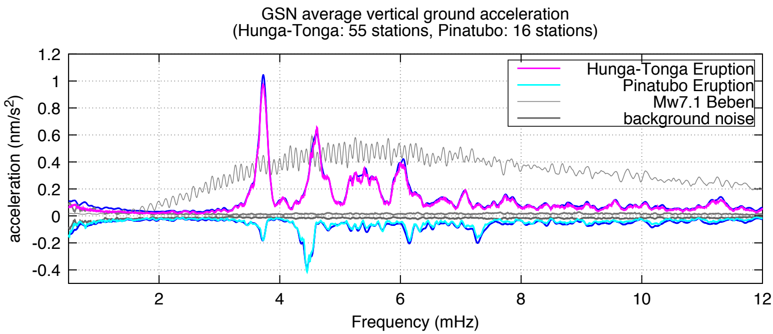

Figure 11: Comparison of Fourier amplitude spectra from two paroxysmal volcanic eruptions against an Mw7.1 earthquake with a shallow source. Shown are vertical ground acceleration spectra of the Hunga-Tonga and Pinatubo eruption observed and averaged over N globally distributed seismic stations with $N = 55$ and $N = 16$, respectively. Spectra from $N = 68$ seismic stations were averaged for the earthquake. For all spectra $6\,\mathrm{h}$ of data were used and a Hanning taper applied. The colors indicate the arithmetic mean (blue) and the median (megenta and cyan, respectively). The reason of the small but significant differences between the frequencies of the dominant lines in the Hunga-Tonga und Pinatubo spectra remains an open question. We can only speculate that it may be caused by a different temperature profile in the atmosphere over the two volcanoes.

We compare the energy radiated in the frequency band $1 - 12\,\mathrm{mHz}$: Rayleigh waves in the solid Earth and acoustic gravity waves (including Lamb waves) in the atmosphere. Both eruptions have in common that they only radiated Rayleigh waves in narrow frequency bands: Pinatubo near 3.7 and $4.4\,\mathrm{mHz}$, Hunga-Tonga additionally also near $5.2 - 5.7$ and $6.0\,\mathrm{mHz}$ (Figure 11).

If we consider a volcano as a point source in space such a narrow band frequency spectrum implies that the source itself must have acted like a small set of harmonic oscillators exciting the Earth with these frequencies. In this respect such large volcanic sources differ from earthquakes. The latter constitute a source which is localized both in space and time and hence they radiate energy over a broad frequency band (cf. Figure 11).

In the case of the Hunga-Tonga eruption higher orbit Rayleigh waves $R_1 - R_8$ could be clearly identified (Figure 12) from which a short duration can be inferred. This is in contrast to Pinatubo which radiated Rayleigh waves for at least 8 hour but no recurring Rayleigh waves could be identified.

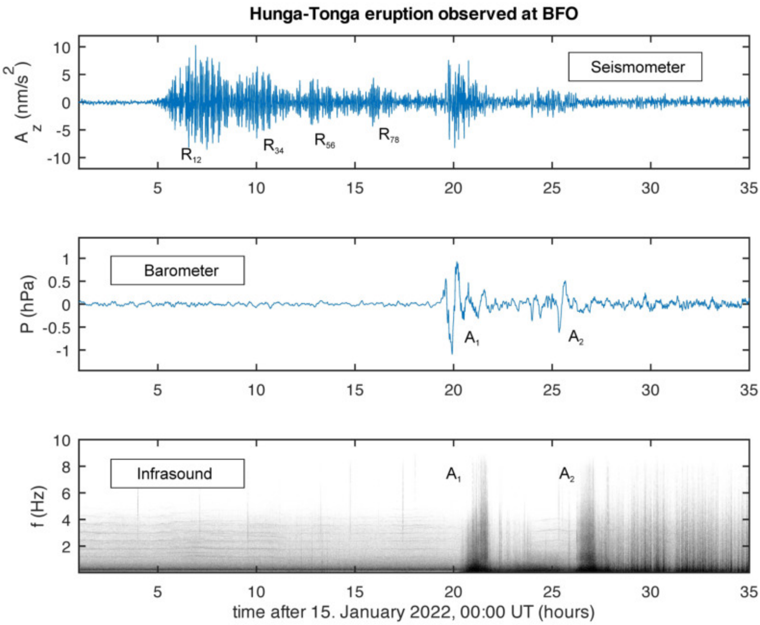

Figure 12: The Hunga-Tonga eruption recorded at the Black Forest Observatory (BFO) at a distance of $17000\,\mathrm{km}$. Shown is the vertical ground acceleration (top) and the atmospheric pressure (middle) which are both band-pass filtered between $3600\,\mathrm{s} - 200\,\mathrm{s}$. The bottom panel shows a spectrogram of the recorded infrasound. The beating pattern with $3\,\mathrm{h}$ period in the seismogram stems from the recuring Rayleigh waves R_{12}, R_{34}, R_{56} and R_{78} which take 3 hours for one full orbit. The air-wave A_1 passed over BFO around $19\,\mathrm{h}$ UT followed six hours later by A_2. The high frequency infrasound propagated at a slower speed: $\sim 293\,\mathrm{m/s}$ as opposed to the Lamb wave with $313\,\mathrm{m/s}$. Clearly, the frequency content of the Hunga-Tonga infrasound signal is limited by the band-width of the recording system: its Nyquist frequency is at $10\,\mathrm{Hz}$. (As an aside we note that infrasound recordings by our colleagues at KIT have energy at least up to $60\,\mathrm{Hz}$, thus well into the audible range). The vertical acceleration signal at the time of the passage of the air-waves A_1 and A_2 are produced by a local coupling of atmspheric pressure fluctuations into gravity: as the pressure changes the density of the atmosphere changes which leads to a subsequent change in Newtonian attraction of the atmosphere onto the proof mass in the seismometer. The harmonic lines in the infrasound spectrogram prior to the air-wave arrival A_1 are from wind turbines which are all at least $8\,\mathrm{km}$ away from BFO.

Harkrider[1] has shown that the fundamental acoustic gravity mode of the atmosphere is at $3.7\,\mathrm{mHz}$. We can thus identify the harmonic oscillator responsible for the excitation of the observed Rayleigh waves: its neither a resonance of the volcano or an underlying magma chamber but the atmosphere above the volcano: the eruption of the volcano has excited the acoustic gravity modes of the atmosphereand the pressure field at the Earth's surface of the oscillating atmosphere near the volcanos has excited Rayleigh waves in the solid Earth.

The atmospheric pressure waves excited by Hunga-Tonga could be observed worldwide with the leading pulse–the so called Lamb wave–having a period of approx. 30 minutes. The last time such a Lamb wave has been observed was after the 1981 Mount St Helens eruption. Presumably due to its long lasting paroxysmal eruption of 8 hours no Lamb wave has been reported after the Pinatubo eruption.

A historical review of mascons approaches

The geodetic and geophysical literature shows an abundance of mascon approaches for modeling the gravity field of Moon or Earth on global or regional scale. On the one hand, the term "mascon" is an abbreviation of the phrase "mass concentration" and it is introduced for describing the physical irregularities of the Lunar gravity field. On the other hand, also the localizing base functions of the gravity field modeling are labeled as mascons[2].

The first mascon approach in literature refers to a point mass model of the Lunar gravity field. Due to limited computational resources at the time, the parameters had to be estimated in North-South bands with maximum 100 parameters, and the partial solutions were later assembled. An interpretation of the physical mass anomalies close to Lunar marias and some drawbacks of point mass models — partly due to observation geometry in case of the Moon — leads to an improved idea of finite mass elements for field modeling. Closed formulas for the gravitational gradient are derived for oblique rotational ellipsoids. The planar disc mascons are obtained by squeezing the semi-minor axis of these ellipsoids to zero.

Finite mass elements are also the concept of the simple layer potential. In this approach, a reference field is removed from the investigated potential, and the remaining inhomogeneous mass distribution is condensated onto the (spherical) surface. The surface is then sub-divided into smaller surface elements $\mathcal{S}_q$, where the mass density σ_q can be assumed to be constant. The potential $V_q(x_P, y_P, z_P)$ of a single mascon is then calculated by a two-dimensional integration

$$V_q(x_P, y_P, z_P) = G\sigma_q \iint_{\mathcal{S}_q} \frac{1}{\sqrt{(x_P - x)^2 + (y_P - y)^2 + (z_P - z)^2}} \mathrm{d}\Omega \qquad (1)$$

with

[1] Harkrider, D.G. (1964): Theoretical and observed acoustic-gravity waves from explosive sources in the atmosphere, J. Geophys. Res.

[2] P. M. Muller and W. L. Sjogren (1968): Mascons: Lunar Mass Concentration, Science 161. pp. 680–684

- (x_P, y_P, z_P): evaluation point,
- G: gravitational constant,
- (x, y, z) points within the mascon element $\mathcal{S}_q$,
- $\mathrm{d}\Omega$, differential surface element.

The investigated mascon approaches differ in complexity of the surface elements (equal area, equal angular, shape of water basins, ...) but also in the calculation of the localizing base function:

i) The mascons are defined in the spectral domain via lumped spherical harmonics and differential Stokes coefficients. All field quantities can be derived from standard routines of spherical harmonic synthesis.

ii) Each mascon is derived in the spatial domain with closed expressions for the gradient of its gravitational potential. A prominent example are the spherical cap mascons of the JPL solution, where the two-dimensional integral is replaced in a rotated coordinate system by a one-dimensional integration in direction of the spherical distance. Also the planar disc mascons can be sorted into this category.

iii) The mascons can be defined in the spatial domain by numerical quadrature of formula (1). Variational equations must solved for each mascon base and each orbital arc to approximate the gradient. The method avoids truncation errors and aliasing in exchange of a high computational burden.

Another kind of mascon approach can be identified as post processing tool. The gravity field is analyzed in monthly data sets of spherical harmonic coefficients and an adequate field quantity is derived by spherical harmonic synthesis to generate pseudo observations in the region of interest. The pseudo observations are analyzed – in a least-square-estimation – by a set of localizing basis function with constant surface density per element.

Publications

(`https://www.gis.uni-stuttgart.de/en/research/publications/index.html`)

Refereed Journal Publications

Abedini, A., W. Keller and A. R. Amiri-Simkooei (2021). "On the performance of equiangular mascon solution in GRACE-like missions". In: Annals of Geophysics 64.2. DOI: `10.4401/ag-8621`.

Abedini, A., W. Keller and A. Amiri-Simkooei (2021). "Estimation of surface density changes using a mascon method in GRACE-like missions". In: Journal of Earth System Science 130.26. ISSN: 0973-774X. DOI: `10.1007/s12040-020-01535-5`.

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Poster Presentations

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Master Theses

(`https://www.gis.uni-stuttgart.de/lehre/abschlussarbeiten/`)

von Bloedau, Eric: Assessment of change to gravity field due to underground railroad tunnel construction

Cui, Bochen: Monitoring the ground environment around Black Forest Observatory using GNSS Interferometric Reflectometry technique

Ke, Siqi: Estimation of river discharge using SWOT: full catchment coverage with optimal space and time resolution

Saemian, Peyman: Characterizing storage-based drought using satellite gravimetry

Wei, Yi: Data-driven loading assessment: Green Function from satellite altimetry, imagery and InSar

Wu, Yuwei: Exploring the performance of SAR altimetry and improvements offered by fully focused SAR

Guest Lectures and Lectures on special occasions

Ghajarnia, Navid (Department of Physical Geography, Stockholm University): Is large-scale terrestrial hydrological cycling well represented in Earth System Models? (06.10.2021)

Lorenz, Christof (Karlsruhe Institute of Technology, Karlsruhe): Research data infrastructures and initiatives across Germany - towards an improved collaborative research in environmental sciences (16.12.2021)

Activities in National and International Organizations

Keller W.

Doctorate honoris causa, Wrocław University of Environmental and Life Sciences, Wrocław, Poland

Sneeuw N.

Distinguished Professor, Land Satellite Remote Sensing Application Center (LASAC), China (since 2019)
Professor h.c. (Luojia chair), Wuhan University, China (since 2018)
Adjunct Professor of the College of Engineering, University of Tehran (since 2015)
Fellow International Association of Geodesy (IAG)
Full Member Deutsche Geodätische Kommission (DGK)
Member of Gauss-Gesellschaft e.V. (since 2018)
Member of the editorial board of Surveys in Geophysics
Member of the editorial board of Studia Geophysica et Geodaetica (until 12.2021)

Research stays

Thomas B.

Visiting PhD student at Universidad Nacional de Costa Rica to work on a low-cost early earthquake warning project with the Volcano and Seismological Observatory (09.2021–10.2021)
Visiting PhD student at University of Hawai'i to realize fieldwork of roving GNSS occupations on Kīlauea volcano with collaboration with the Hawai'i Volcano Observatory (10.2021–12.2021)

Courses – Lecture/Lab/Seminar

Bachelor Geodesy & Geoinformatics (German):

Amtliches Vermessungswesen und Liegenschaftskataster (Grams)	2/0/0/0
Einführung Geodäsie und Geoinformatik (Sneeuw)	2/2/0/0
Integriertes Praktikum/Integrated Field Work (Sneeuw, Foster)	10 days
Landesvermessung (Foster, Thomas)	2/2/0/0
Physikalische Geodäsie (Sneeuw, Bützler)	2/2/0/0
Referenzsysteme (Sneeuw, Antoni)	2/2/0/0
Satellitengeodäsie (Sneeuw, Antoni)	1/1/0/0

Master Geodesy & Geoinformatics (German):

Aktuelle Geodätische Satellitenmissionen (Sneeuw)	2/2/0/0
Amtliche Geoinformation (Heß)	2/0/0/0
Ausgewählte Kapitel der Parameterschätzung (Tourian, Douch)	2/2/0/0
Geodätische Erdbeobachtungen (Tourian)	2/2/0/0
Hydrogeodäsie (Tourian, Douch)	2/1/0/0
Koordinaten- und Zeitsysteme in der Geodäsie (Sneeuw)	2/0/0/0
Marine-Geodäsie (Foster, Thomas)	2/2/0/0
Physikalische Geodäsie (Engels, Bützler)	2/2/0/0
Satellitengeodäsie (Tourian, Douch)	2/1/0/0

Master Umweltschutz (German):

Fernerkundung der Hydrologie und Wasserwirtschaft (Tourian)	2/2/0/0

Master GeoEngine (English):

Advanced Mathematics (Foster, Thomas)	3/2/0/0
Foundations of Satellite Geodesy (Sneeuw, Antoni)	2/1/0/0
Integriertes Praktikum/Integrated Field Work (Sneeuw, Foster)	10 days
Map Projections and Geodetic Coordinate Systems (Foster, Thomas)	2/1/0/0
Physical Geodesy (Sneeuw, Bützler)	2/1/0/0
Satellite Geodesy Observation Techniques (Foster, Thomas)	2/1/0/0
Statistical Inference (Tourian, Douch)	2/1/0/0

Institute of Navigation

Breitscheidstraße 2
D-70174 Stuttgart
Tel.: +49 711 685 83400
Fax: +49 711 685 82755
ins@ins.uni-stuttgart.de
http://www.ins.uni-stuttgart.de

Head of Institute

Prof. Dr. techn. Thomas Hobiger, Dean of Studies (since Oct. 2021)

Deputy:	Dr.-Ing. Aloysius Wehr
Institute management and translation:	M.A. Dagmar Epple
Secretary:	Helga Mehrbrodt
Retired Professor:	Prof. i.R. Dr.-Ing. Alfred Kleusberg

Academic Staff

Dipl.-Ing. Doris Becker	Navigation Systems
M.Sc. Kevin Gutsche	Precise orbit determination
Dr. Tomasz Hadas	GNSS troposphere
M.Sc. Shengping He	GNSS troposphere & PPP
M.Sc. Tomke Jantje Hobiger	Parameter Estimation in Dynamic Systems
M.Sc. Daniel Klink	FPGA design, autonomous flight
M.Sc. Marcel Maier	Navigation Software Development
M.Sc. Clemens Sonnleitner	Autonomous flight, ADS-B
Dipl.-Ing. (FH) Martin Thomas	Digital Electronics and Hardware Programming
M.Sc. Thomas Topp	Navigation Software Development
M.Sc. Rui Wang	GNSS, RTK, integrity
Dr.-Ing. Aloysius Wehr	Optical and Wireless Communication

IT

Regine Schlothan	Computer infrastructure and programming

Electr. and Mech. Workshop (ZLW)

Dr.-Ing. Aloysius Wehr	Head of ZLW
Michael Pfeiffer	Mechanician Master
Sebastian Schneider	Electrician
Dipl.-Ing. (FH) Martin Thomas	Electrical engineer

External lecturers

Dipl.-Ing. Steffen Bolenz	Stadtmessungsamt, Stuttgart

Preface

This report summarizes the activities of the Institute of Navigation (INS) in the year 2021. Despite the circumstances and challenges that came along with the COVID-19 regulations, we can look back on a rather successful year of research and education. As for teaching, all lesssons of the spring term had to be given in virtual environments, but the fall term could be started with class-room lectures adhering the university's COVID-19 regulations. Since business travel was still not possible, we were not able to present our results on national and international conferences. Most of the scientific exchange had to be done in the form of video conferences. Concerning research, we can state that we achieved most of the self-set goals and milestones and could acquire a couple of new externally funded projects with industry partners. We could grow our team by hiring two new full-time PhD students and a new management assistant who will steer and supervise the transformation of our internal and external processes so that we are becoming more effective in our adminstrative tasks. Research highlights, which are described in greater detail in this report, cover a wide range of topics, including sensor fusion, precise orbit determination, airspace monitoring, robust real-time kinemtatic GNSS positioning, troposphere estimation, among others.

GNSS simulators

With the start of 2021, INS at the University of Stuttgart also became the first German university to start participating in the Orolia Academic Partnership Program (OAPP) and thus working with the Skydel software-defined GNSS simulator. The simulation engine allows the students to carry out costly and time-consuming field tests, simulate laboratory scenarios in real time and use radio hardware to send signals to commercial receivers. It is possible to compare new navigation solutions with the simulated trajectories as well as being able to show the absolute accuracy of the developed algorithms. Additional plug-ins have been developed in order to extend the capabilities of testing the performance of our integrated navigation software toolkit INSTINCT, which will be described in a later section of the report.

At the end of the year, the installation and training of the long-awaited hardware-GNSS-simulator from Spirent Communications took place. The HW simulator, specially equipped for the institute's research, will be used in the coming year to support LEO satellite operations with GNSS. Thus, the INS is now equipped with one industry-compatible hardware GNSS simulator and an additional GNSS simulator, which can be used for educational purposes. This allows us to carry out our state-of-the-art GNSS research projects with industry and research partners, and verify functional elements of hard- and software components.

Research

The INS identifies new fields of applications, develops and tests navigation solutions and assigns research projects according to four "focus areas", which were defined in 2018. Figure 13 depicts those areas, which are grouped around the topics of "positioning, navigation and timing".

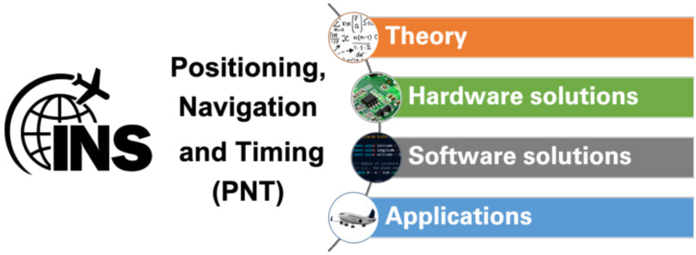


Figure 13: INS focus areas to which the institute is actively contributing with research projects.

While most of the current research projects can be clearly assigned to one or two focus areas shown in the figure, larger research projects, described later in this report, are usually falling under the category "applications" but require intense input from the other three research areas. In the following, the purpose and vision for each research area is presented together with examples of ongoing research projects.

Research focus: Theory

The following sections describe theoretical work that was made in 2021.

ADS-B

One of the research topics at the Institute of Navigation deals with Automatic Dependent Surveillance-Broadcast (short: "ADS-B"). A major problem of ADS-B is that the messages are neither authenticated nor encrypted. A new software-suite is developed in-house for investigation on enhanced approaches for airspace surveillance, which are more robust against system errors and malicious intent.

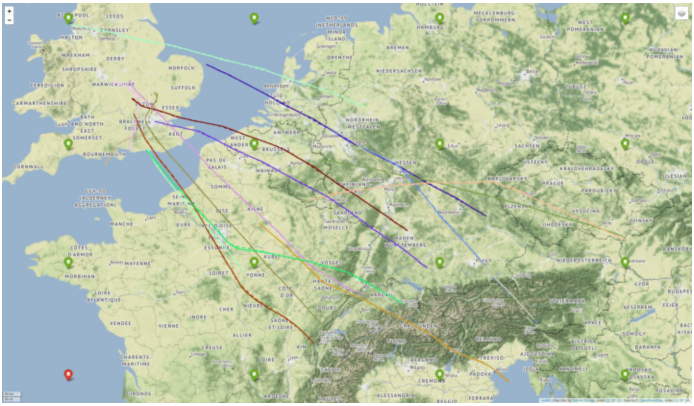


Figure 14: Map view of the ADS-B software. It shows results of the in-house developed flight path tracking software in comparison to their broadcasted one.

Sensor fusion algorithms

A navigation solution can be calculated from inertial sensor measurements or processing GNSS data. However, if a more precise, a safer or a more robust solution is required, data from different sensors can be fused in order to combine the advantages of different concepts. In the CNS/ALPHA project, the institute develops navigation algorithms for autonomous flight, hence, sensor fusion plays a critical part.

One of the most widely used concepts for sensor fusion is the Kalman filter. As a basis for more sophisticated algorithms, a Kalman filter has been developed in its fundamental form (see also subsection INSTINCT). The principle of a so-called Loosely Coupled Kalman filter is shown in figure 15.

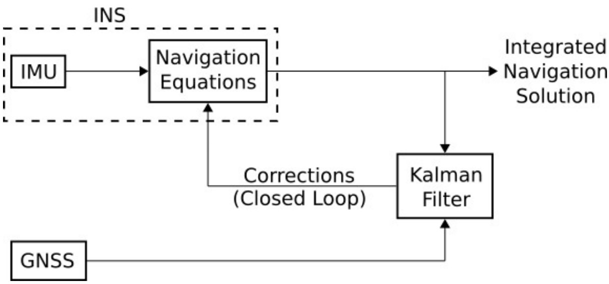


Figure 15: Loosely Coupled Kalman Filter for INS/GNSS sensor fusion.

A Kalman filter consists of two steps, the first being a prediction and the second a correction. The prediction step propagates a system's state vector with certain initial values. The underlying dynamical model, here the navigation equations, propagates a system's state vector based on certain initial values. Since after this principle the solution will drift away with time, the correction basically resets the predicted solution by applying measurements. Another advantage of a Kalman filter is its capability to consider stochastic properties of the model and the sensors. Thus, effects like sensor noise can be modelled.

In the context of navigation, one of the most widely used applications of a Kalman filter is the fusion of INS and GNSS. More specifically, the loosely coupled integration of INS and GNSS refers to fusing the respective navigation solutions. The output of the Kalman filter can then be corrections, which are fed back to the INS's solution. The corrected solution is then called the integrated navigation solution.

This fundamental framework for sensor fusion is currently advanced with regard to properties such as robustness and reliability. One approach is to incorporate more sensor types, such as magnetometer, DME or arrays of identical sensors. This redundancy would enable the navigation system to tolerate the failure of sensors. Another advancement is the consideration of other filtering algorithms. On the one hand, this can be advancements to the fusion scheme, namely tightly coupled or deeply coupled INS/GNSS fusion. In these variants the Kalman filter gets measurement data at an earlier stage of the processing, rather than navigation solutions directly. On the other hand, other types of filters like a particle filter will be considered. With the latter approach, certain disadvantages of a Kalman filter are adressed, such as the assumption that all errors are normally distributed.

Research focus: Hardware development

The following sections describe the insitute's hardware development actitivities in the year 2021.

Development of a ground-based landing aid for unmanned air vehicles

The development of a subsystem to aid in the autonomous landing, requirement for the project CNS-Alpha, has been started. The working principle follows the one used in the GPS system. Multiple transmitters are placed in stationary positions. Each one of them is sending out its own signal, which is comprised of a carrier onto which a pseudo-random code and subsequently a stream of data is modulated. These codes have a maximum autocorrelation only at zero shift additionally the crosscorrelation with other codes of the same kind is minimal. These properties allow for separation of the different signals at the receiver and also spread the power over a wider spectrum. A single receiver then is located on the air vehicle for the decoding of the data stream and the derivation of variables necessary for navigation. This mainly includes position, velocity and can, with the usage of additional receivers, be extended to also include attitude. For the demodulation to be possible, parameters like the frequency of the carrier and the phase of the code, have to be known at the receiver for each transmitter.

These values are influenced by Doppler effect, a frequency shift caused by relative motion between the receiver and the transmitters. Also they are influenced by a phase shift due to the absolute difference in position. Additional imperfections from the system, like oscillator drift, contribute to a deviance from the expected values. Nevertheless, they can be acquired by iterating through the search space either in time of frequency space. Once found, they will be tracked by two control loops. One for the carrier frequency and one for the code phase of each transmitter. These parameters allow the derivation of position and velocity. It is then also possible to carry out the demodulation by reversing the order of operations performed at the transmitter. Further the navigation data could be used to send information from the ground-based equipment and thus make the onboard solution even more robust.

The receiver and transmitters logic are being implemented on a field-programmable gate array. Special care is given to an efficient yet performant implementation. This logic interfaces to converters that change from digital to analog domain and vice versa. The mixing, filtering and the amplification is handled by an on-chip RF front end, to which in turn the antennas are connected. Prototype boards containing the RF front end and the converters have been implemented by the staff in the institute's workshop. First tests for the transmitters and the tracking loops of the receiver have been carried out. More time will be spent in the following year to complete and eventually add features to this system.

Sensors for an alarm system against drowning in a bathtub

Sensor with AI processing

This project was initiated by the company Horcher and has been supported by the Central Innovation Programme for small and medium-sized enterprises (SMEs). The project started in January 2019. Its objective was the development of a system preventing people from drowning in a bathtub in e.g. nursing homes for the elderly. Project partners were the company Horcher and the German Institutes of Textile and Fiber Research (DITF). INS was assigned the task to develop and realize the sensor system, which comprised MEMS-Inertial Measurement Units (MEMS-IMUs), air pressure sensors, humidity sensors and an Indoor Microwave Positioning and Data Transmission System (IMPDS). The sensors and the transmitters of IMPDS should be mounted on the patient's body. Therefore, the electronical items were developed in close cooperation with DITF regarding the requirements of so-called wearable electronics. In the year 2021, the project was completed successfully by delivering a compact sensor head (see fig. 16) with a wireless data link. In addition, supporting experimental studies were carried out concerning the high frequency properties of special print material for a wearable antenna manufactured by DITF.

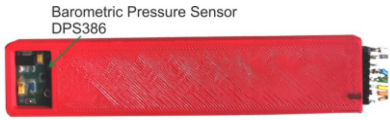


Figure 16: Sensor head.

The sensor head consists of a barometric pressure sensor, a humidity sensor, an inertial measurement unit (IMU), a wireless communication link working at 433 MHz, an Arduino controller and a lithium-ion cell. Using two sensor heads, a PC and applying artificial intelligence (AI) algorithms, an alarm system was built up, which detects the movements of a person in a bathtub, recognizes drowning situations and gives alarms. The idea of applying AI algorithms was born by the fact that the LSM6DSOX had available a machine learning core feature working by decision-tree logic. However, experiments with LSM6DSOX concerning AI showed that decisions-trees were derived by a public domain program WEKA of the University Waikato Hamilton in New Zealand, which used empirical measurement data of our setup and ran on a PC. This so externally generated decision-tree was stored in LSM6DSOX, which outputs the result in dedicated output registers. The main disadvantage of LSM6DSOX was, that it was impossible to store a set of calibration data concerning the orientation of the sensor in the chip. This means, that the decision-tree derived by WEKA stored in the machine learning core was only valid for a certain orientation of the sensor head on the body. As positioning the sensor head in exactly the same orientation in each session on the patient was not practicable, a calibration procedure was developed, which could be processed by a microcontroller already in use on the sensor board for sampling and managing the data of IMU, pressure and humidity sensors. By calibrating the sensor after attaching it to the body, the system could work with a decision-tree, which had been generated only by WEKA. A reprogramming with an external program like WEKA was not required anymore. As the microcontroller computed the calibrated IMU data, the decision-tree (AI) was implemented in this device, too. The described procedure was tested and verified by a simulation setup depicted in fig. 17

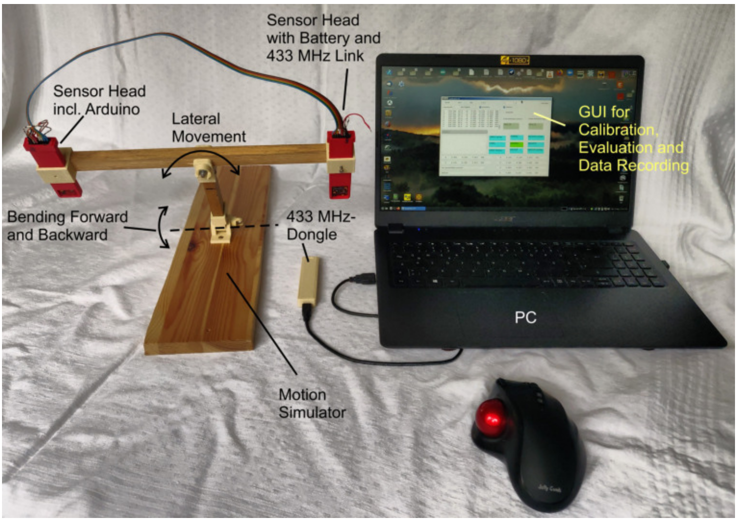
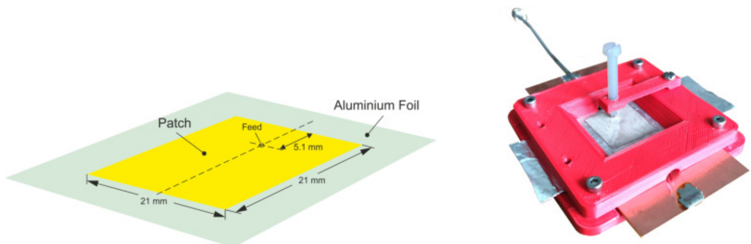


Figure 17: Simulation setup.

This setup was first used to determine the decision-tree. Here, many data were gathered starting with an upright position followed by e.g. forward, backward and lateral movements and dipping into water. These data were processed by WEKA, which generated a decision-tree regarding the sensor data of IMU, humidity and pressure sensors. This tree was implemented in a program written in Delphi/Lazarus-Object Pascal on a PC, which put out the actual drowning condition and calculated calibrated orientation data based on the IMU acceleration data. The calibration routine transformed all three-dimensional accelerometer data into the original coordinate system, in which the decision algorithm had been computed. The orientation was related to the gravity vector. For calibration the patient sat in an upright position first, after attaching the two sensor heads on its body. In this position the gravity vectors of both sensor heads were measured. In a second step the patient took a relaxed position. In this position again, the gravity vectors of both sensors were measured and transformation matrices for both sensor heads could be computed. After this calibration procedure, all IMU accelerations are available in the coordinate system valid for the decision-tree. This means, the requirements for attaching the sensor heads on the body were very relaxed concerning the orientation. However, they should be mounted very firmly on the shoulder to assure proper operation.

Supporting work for a wearable patch antenna

Based on the analytical experiments concerning the relative permeability determination (dielectric constant) of the special filling material between the fabric and the electrical conducting ink a patch antenna was dimensioned by INS (s. fig. 18a) and manufactured by DITF. The DITF patch antenna was tested by the setup depicted in fig. 18b. The measurements made clear that these patches were not functioning with high-frequency signals and did not show any antenna properties. Therefore, a high-frequency (HF) test was carried out to determine the HF performance of the used ink.



(a) Calculated patch antenna (b) Patch antenna setup

Figure 18: Patch antenna designed for the project.

In order to assure proper HF contacting and using known material as much as possible, two printed circuit boards (PCB) were manufactured: A reference PCB with different lines and a PCB, whose lines were interrupted. The discontinued line parts were filled with the special ink. However, this time the ink was heated at 140°C during three minutes for achieving a better conductivity (s. fig. 19). The HF connections were realized by SMA connectors soldered on PCB. All lines performed equal and exhibited the same performances as the lines of the reference PCB. The experiment verified that the selected ink could well be used and emphasised that HF contacting and base material demand special attention. Therefore, another experiment will be planned, printing a patch antenna with the well-tried ink and fixing it with heat on a PCB, and using soldered SMA connectors.

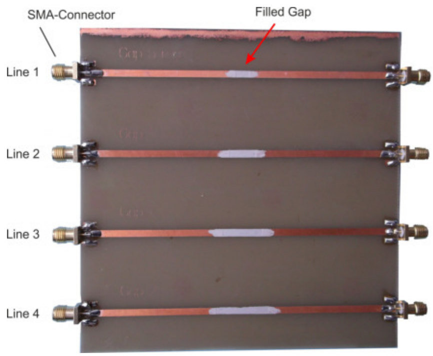


Figure 19: Test PCB

ADS-B

In 2021 the low cost ADS-B receiver on the roof of the building in Breitscheidstraße 2 has been connected to the non-profit Open-Sky Network (https://opensky-network.org). The collected ADS-B data is streamed to their servers and can now be used by researchers all over the world. Statistics about the INS receiver can be found at https://opensky-network.org/receiver-profile?s=-1408232197.

Figure 20: High grade ADS-B antenna on the roof of the building in Breitscheidstraße 2.

Additionally, a high-grade ADS-B receiver from Thales has been installed on a special mount. The ADS-B system is part of the devices designated as ground based equipment for the "Testfeld eFliegen BW". The preliminary installation at the institute makes it possible to test the equipment and use it for development purposes before it is placed at the test site in Mengen in 2022 (see page 70).

Research focus: Software development

The following sections describe the institute's software development actitivities in the year 2021.

INSTINCT - INS Toolkit for Integrated Navigation Concepts and Training

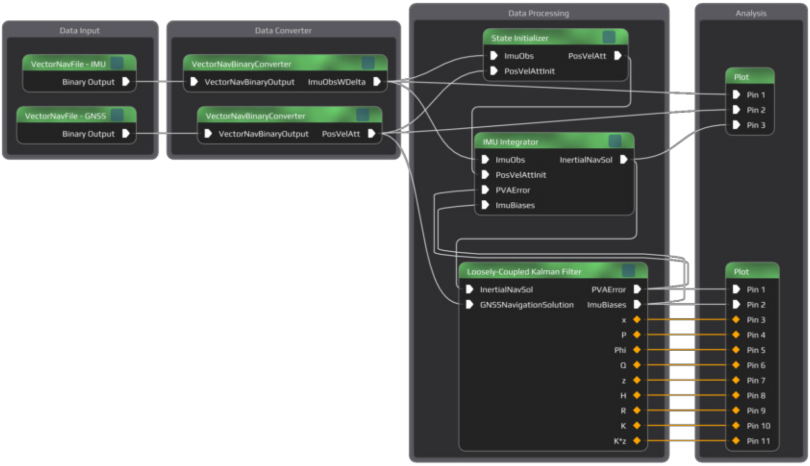


Figure 21: INSTINCT dataflow for an INS/GNSS loosely-coupled Kalman filter algorithm.

INSTINCT, the C++ navigation framework of the INS, made a lot of progress during the last year. It started as a general framework where functionality is bundled into nodes and data is exchanged over links between these nodes. Such a data-flow programming approach helps to keep clean interfaces between functions and is easily extendable. In figure 21 the GUI of INSTINCT for an INS/GNSS loosely-coupled Kalman filter can be seen. From the left to the right it is easy to understand which steps the data takes. First data is inputted from either data files or directly from sensors. Here the software now supports a huge variety of file formats like ublox, VectorNav or ulog and also the corresponding sensors for real-time processing of data are supported. After reading in the data, the necessary data gets extracted and converted into common structures, which can then be processed with nodes representing navigation algorithms. These range from different numerical integration algorithms, to demonstrate the effects on e.g. acceleration and angular velocity measurement integration, up to different variations of Kalman filters to estimate the navigation solution. After processing the data it is easy to plot the results without the need to use external tools.

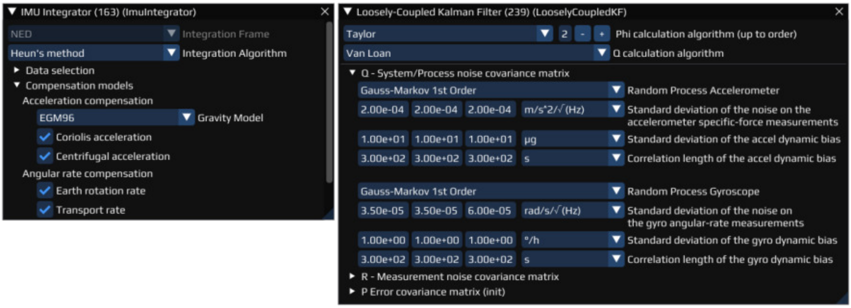


Figure 22: Configuration windows for the IMU Integrator and loosely-coupled Kalman filter nodes.

All algorithms and their options can intuitively be configured inside graphical windows, which can be seen in figure 22. On the left the configuration window for the IMU integration node can be seen. Over dropdown menus the integration frame and integration algorithm can be selected. Also it can be selected which compensation models should be applied. This can be used to demonstrate their effects when teaching students or also to disable effects when working with simulated data and we purposely do not want to simulate certain effects. In the right figure the configuration window for the loosely-coupled Kalman filter node can be seen. Here we have a lot more options, which allow to tune the filter. It is especially useful that for inputted values the units can be selected, which saves time for navigation engineers and also prevents easy-to-make mistakes.

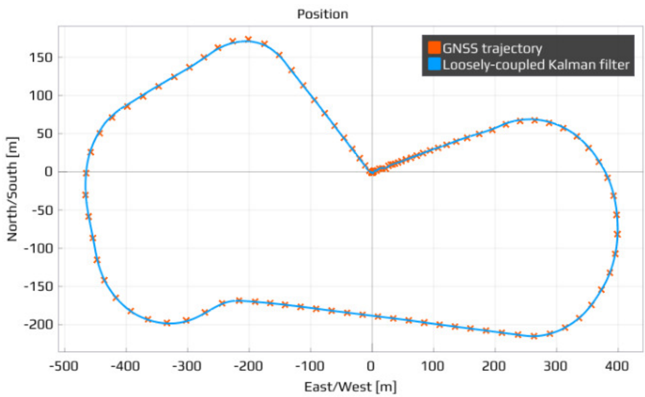


Figure 23: Plot from INSTINCT.

Over the last year, INSTINCT was used in multiple test campaigns onboard of UAVs and also onboard of manned aerial vehicles. Figure 23 illustrates the trajectory of such a test flight with the institute's new UAV, the PWOne (there will be more information given in the Testfeld eFliegen BW paragraph). During the flight INSTINCT was used to record the data from all sensors, afterwards the software calculated a navigation solution, which is displayed in the figure. The plot itself is also done within the INSTINCT software and could easily be used for publications due to the customization possibilities inside the GUI.

Based on the INSTINCT framework, the GNSS positioning algorithms have been extended, including the Single Point Positioning (SPP), double-differenced (DD) code positioning and Real-Time Kinematic (RTK) positioning (figure 24).

Using the GNSS positioning feature of INSTINCT, it is possible to post-process the raw GNSS data or estimate the position and velocity in real-time by connecting with the Ublox receiver. Considering the different observation conditions, including single and multi-GNSS constellations, the software can provide the user with various options under different positioning modes to choose from, like the satellite elevation cut-off angle, single or combined signal frequencies and the threshold of Dilution of Precision (DOP). Besides, the other nodes, such as the atmospheric and antenna phase center correction (figure 25), have their own user options, which on the one hand broaden the user's choices, on the other hand allow the algorithms to better adapt to the specific measurement environments and equipment. Moreover, the Autonomous Integrity Monitoring (RAIM) approach to fault detection and exclusion (FDE) has been developed and will continue to be enhanced later.

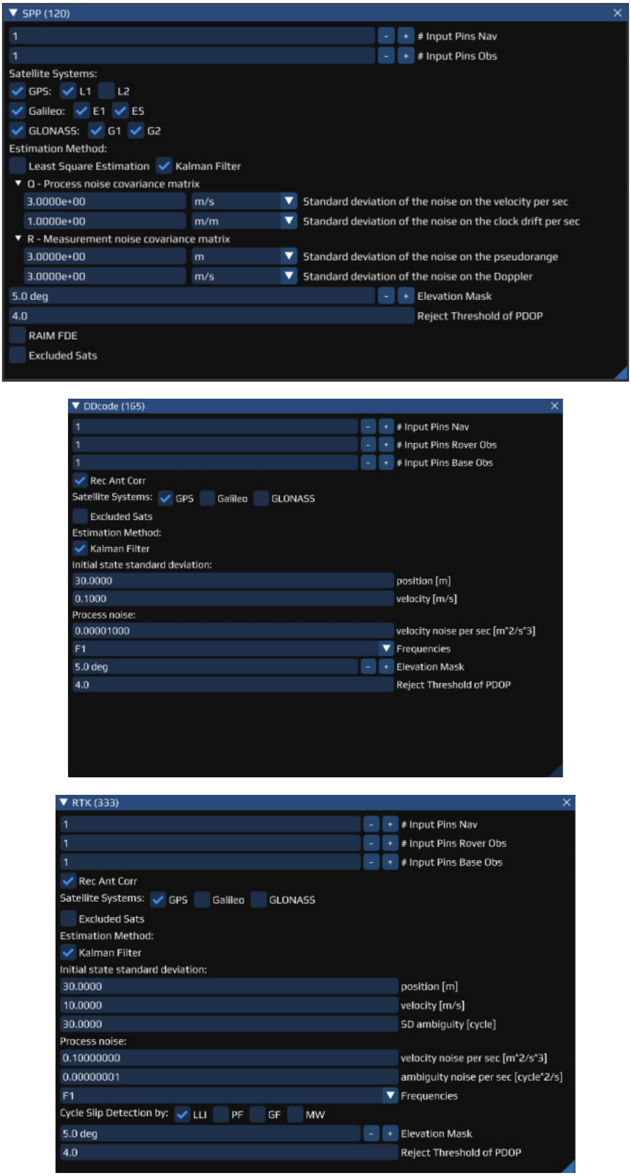


Figure 24: Config windows for the SPP, DDcode, RTK node.

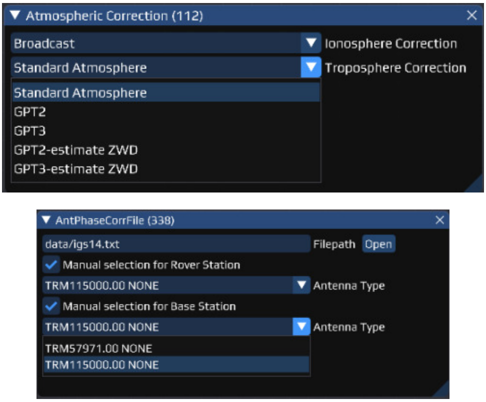


Figure 25: Config windows for the nodes about the atmospheric and antenna phase center correction.

PODCAST - Precise Orbit Determination for Cutting-edge Adaptive Satellite Technology

PODCAST is the Precise Orbit Determination (POD) software solution of the INS that is being developed in cooperation with Airbus. It aims to provide POD capabilities for LEO satellites while enabling research of new POD methods for agile satellites missions. In the past year the software has made considerable progress in reaching its first main goal - to provide orbit determination for non-agile LEO satellites.

Following its development start in late 2020, a resilient and flexible software framework has been developed and installed as a fundament of PODCAST. The software is developed in modern C++ and abides to object-oriented principles to ensure future extensibility and flexibility of the software's features. With this framework, PODCAST can be gradually improved, for instance by incorporating improved estimation algorithms and force models or new measurement types.
The underlying estimation process in PODCAST is performed by an Extended Kalman Filter (EKF). For this purpose, the EKF and a numerically more stable variation of the EKF have been added and can be selected in the configuration file.

For the utmost orbit determination accuracy, the estimation algorithm relies on models for the forces acting on the satellites. Therefore, detailed force models and precise integrators are required. All gravitational forces acting on LEO satellites and a number of non-gravitational forces have been implemented in the software. Missing and updated models will be continuously added in the future.

The implementation of numerous advanced integration algorithms has been completed. These integrators enable the generation of precise reference orbits and avoid estimation errors induced by the integrators.

PODCAST has been extended to process and utilize GPS and Galileo pseudorange measurements in the orbit determination process. In combination with the broadcast ephemeris or precise orbit products from the International GNSS Service (IGS), sub-meter accuracy can be reached. This is displayed in Figure 26 for pseudorange measurements created with the aid of a GNSS simulator at the INS.

Next steps include the incorporation of carrier-phase measurements in order to improve the orbit determination accuracy and dedicated hardware simulations to further validate the performance of PODCAST.

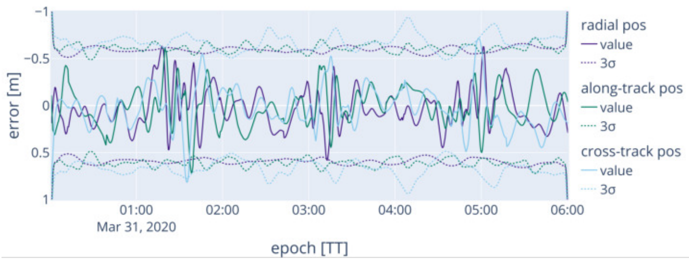


Figure 26: Estimation error of a satellite's position in the radial, along-track, cross-track reference frame.

Development of a PPP Software for Troposphere Studies

The accuracy of precise point positioning (PPP) is largely dependent on the troposphere model and, in turn, high-precision PPP software is also an important tool for analyzing the troposphere. In order to effectively analyze the performance of the tropospheric model and thus build new models, this high-precision PPP software is implemented. It supports multiple constellations (currently including GPS, GLONASS, Galileo), triple-frequency signals, fixed solutions, and multiple tropospheric models.

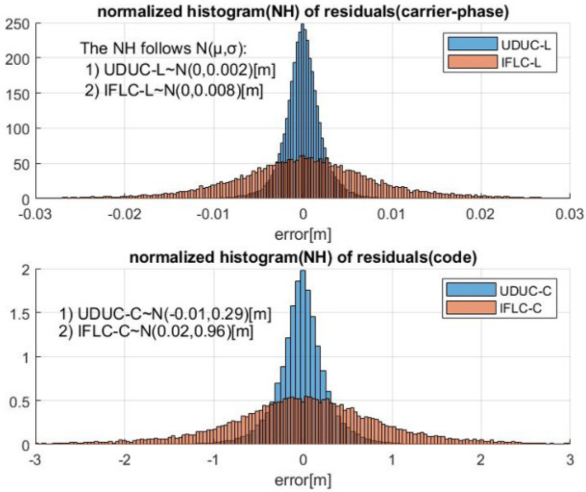


Figure 27: Example for obtained distributions of residuals, depicted as normalized histograms or code(C) and carrier-phases(L).

Compared with other standard PPP software tools, this PPP software introduces the algorithm of Undifferenced-Uncombined observation (UDUC) and ambiguity resolution (AR), and also takes into account some millimeter-level error terms, such as ocean loading, earth polar tide, atmospheric pressure loading etc. In general, the accuracy of the floating solution is 15 cm, the fixed solution can reach within 6 cm, and for some geodetic stations with stable state and good data, the accuracy can even reach within 3cm. Some other PPP software such as RTKLIB Post has an accuracy of about 20cm. In addition, for the needs of research, the software also supports multiple tropospheric models including VMF, NMF, GMF, GPT3, VMF3, which provides more options for tropospheric analysis. In comparison, this PPP software has been greatly improved in terms of accuracy, reliability and practicality.

The next step in the PPP software requires more improvement to the stochastic model to provide better results for dynamic solution and, more importantly, the analysis and study of new tropospheric models.

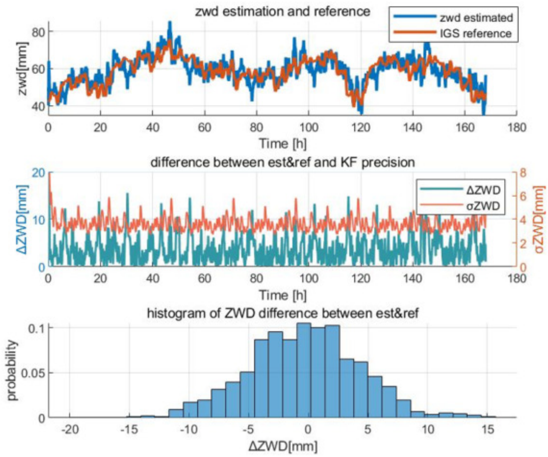


Figure 28: Troposphere analysis for IGS station Wettzell, Germany(WTZR) for 7 days.

Navigation Algorithms for Micro Launcher

The growing market for putting large numbers of small satellites into orbit requires new concepts for launch systems. The cost for those transportation systems should be located significantly below of today launchers. During the recent years industry has identified that micro launchers may do this task. Micro launchers are small rockets carrying about 500 kg of payload into low-earth orbit. Achieving the objective of low cost, the rocket design is focused on modularity and reuse, which results in modular design not only for engines and the structure but also for sensors, actuators and software. Concerning the guidance and the navigation software advanced development concepts have to be set up for underlining the modular design in this area, too. Therefore, ESA initiated a project called “Generic Guidance and Navigation Onboard Software for Microlauncher” with Astos Solutions GmbH as contractor. Here, a software library with guidance and navigation algorithms has to be established, which makes possible a flexible software implementation optimized to the particular launcher by auto coding. INS as subcontractor is concerned with the navigation part, designs and develops off-the-shelf navigation algorithms in Matlab/Simulink. The routines are verified and tested by ASTOS’s multi-purpose tool for space applications. The navigation is limited to the three-dimensional positioning and the orientation in three axes. The algorithm has to compute integrated navigation estimates in real time by reading parallelly the outputs of several GNSS receivers and IMUs distributed in the launcher. In 2021 INS studied existing integrated navigation algorithms and carried out a trade-off in determining the optimum one for a straightforward adaptation by potential customers to the specific characteristics of their own micro-launcher. A INS/GNSS loosely-coupled Kalman filter algorithm was selected and implemented in Matlab/Simulink.

Research focus: Applications

The following sections describe applications on which the INS worked on in the year 2021.

H2020-MSCA-IF project "Real-Time GNSS for European Troposphere Delay Model (ReS4ToM)" finished

The project „Real-Time GNSS for European Troposphere Delay Model (ReS4ToM)" aimed at developing "a novel real-time model of the troposphere by using Global Navigation Satellite Systems (GNSS) derived troposphere delays, gradient information and water vapor content". Remote sensing of the troposphere with GNSS, so-called GNSS meteorology, provides observations of spatial and temporal resolution higher than any other technique and operates under all weather conditions. Therefore, hundreds of permanent GNSS stations in Europe are used by several analysis centers to operationally sense the troposphere under the E-GVAP project for monitoring water vapor by the help of GNSS. Troposphere products estimated from GNSS observations from the two oldest systems (GPS, GLONASS) are delivered with a latency reaching one hour. A real-time service, rather than a delayed provision of accurate troposphere products, from quad-constellation GNSS remains a goal. In addition to zenith total delay (ZTD), advanced troposphere products like horizontal gradients and slant delays gain more attention over recent years.

The main product of GNSS meteorology, the ZTD, can be assimilated into numerical weather prediction (NWP) models in order to improve weather forecasting. This is particularly important for severe weather events (heavy rainfalls, hailstorms) for which reliable prediction remains a challenge. The dynamics of troposphere gradients can reveal additional information on troposphere asymmetry, and slant delays can be used to reconstruct the three-dimensional distribution of water vapor. With low-cost GNSS receivers, the tracking network can be densified and thus the spatial density of sensing the troposphere can be increased from tens to single kilometers. This allows to observe local dynamics of water vapor and increases the accuracy of forecasts for urban areas.

This MSCA has pushed the frontiers of real-time GNSS meteorology forward in numerous ways. The advanced GNSS data processing strategy has been developed, which exploits a quad-GNSS constellation, deals directly with all major signal propagation errors, provides advanced troposphere products, and is competitive with existing near real-time solutions in terms of accuracy, while also reducing the latency of products. The corresponding analysis software was developed and the service was established to process GNSS data from the European network of permanent GNSS stations. The accuracy of real-time ZTD in ReS4ToM is at the level of 5 to 8 mm, which corresponds to the accuracy of Integrated Water Vapor of 1.5 – 2.5 kg/m^2.

It was also proven that Galileo and supporting services are already mature enough to provide reliable information on the troposphere state in real-time. The combination of GPS and Galileo observations is superior to single-system processing, as it increases the accuracy and availability of troposphere products. Moreover, such a combination suppresses orbit-related artificial signals of high frequency in the ZTD time series.

Furthermore, it was demonstrated that horizontal gradients form consistent signatures during the presence of a severe weather event. Thus, such parameters represent relevant information on troposphere asymmetry, which should be exploited further in weather forecasting. Last but not least, the feasibility of using low-cost GNSS receivers for GNSS meteorology was also confirmed. Data from such devices leads to troposphere products, for which the accuracy is sufficient for assimilation into an NWP model. Therefore, densification of existing GNSS networks at a reduced cost is possible, thus allowing to observe local dynamics of water vapor content. This action did not only combine a manifold of recent advancements in GNSS but also demonstrates that the transition from well-established near real-time processing to real-time processing will bring benefits for GNSS meteorology. It is anticipated, that E-GVAP analysis centers will update their processing strategies, while weather services will increase their efforts in assimilating real-time and advanced troposphere products. The demonstration of benefits for GNSS meteorology coming from low-cost GNSS receivers should convince meteorological offices and GNSS service providers to densify tracking networks. More details can be found in the final report, which can be accessed under https://www.ins.uni-stuttgart.de/en/research/research-projects/2021-real-time-gnss/

Testfeld eFliegen BW

The INS is one of the institutes of the University of Stuttgart that is building up the "Testfeld für energieeffizientes, elektrisches und autonomes Fliegen" (short: "Testfeld eFliegen BW") together with partners from industry under the lead of the IfR (https://www.ifr.uni-stuttgart.de).

In 2021, a web presence has been created for the association "AREA B.W." by the Institute of Navigation. The website gives insight into the project and the activities at the test sites in Mengen and Lahr. It can be found at https://area-bw.de.

Furthermore, the planning of the infrastructure at the test site Mengen has made progress and the hangar with offices and a workshop is planned to be finished in the first half of 2022, which will allow the installation of the navigation and ADS-B equipment of the INS.

Customized research platform PWOne

In 2021 the institute purchased the VTOL solution PWOne from Phoenix Wings and customized it for the usage as a research platform for navigation solutions. The UAV can carry a payload of 0.5 kg over a distance of 20 km with an average cruise speed of 60 km h^{-1}. A tactical-grade high-performance dual antenna GNSS receiver together with an IMU consisting of a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer has been mounted on the drone by the institute. The setup allows extensive testing of in-house developed navigation solutions without any dependency on external partners.

In 2021 several flights have been performed at the "Ihinger Hof", providing sensor data for post-processing navigation algorithms. The data has already been used extensively for the development of different navigation algorithms and the project INSTINCT (see page 61).

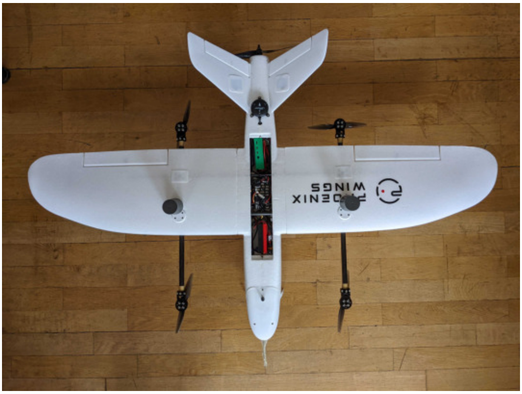


Figure 29: Top view of the VTOL vehicle PWOne with the integrated navigation platform.

Research platform Holybro

Flight tests are crucial in developing navigation for autonomous flight. Hence, the institute has acquired another platform, namely two “Holybro QAV250” racing drones (see figure 30). These are equipped with the off-the-shelf flight control computer “Pixhawk 4 Mini” that is not only capable of conducting automatic flights, but also to collect flight data, which is very valuable for the advancements of navigation software. The automatic flight capability of these drones has been proven in 2021 (see figure 31) and the collected flight data is currently being made available to the INSTINCT project (see page 61). Through this systematically different test platfrom - in addition to the PWOne - we are capable of developing navigation software that is not just tailored to one single platform. Therefore, the Holybro drones provide another opportunity to validate the algorithms developed for projects like CNS-ALPHA.

Figure 30: The two Holybro QAV250 racing drones in the drone laboratory.

Figure 31: One Holybro QAV250 airborne at Ihinger Hof during a flight demonstration.

List of Publications

Hadas T., M. Bender, G. Marut and T. Hobiger: Real-Time GNSS Meteorology in Europe-Hurricane Lorenzo Case Study, Proc. of the 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, pp. 8321-8323. https://ieeexplore.ieee.org/abstract/document/9554690, 2021.

Wielgocka N., T. Hadas, A. Kaczmarek and G. Marut: Feasibility of Using Low-Cost Dual-Frequency GNSS Receivers for Land Surveying, Sensors, vol. 21, iss. 6, https://www.mdpi.com/1424-8220/21/6/1956, 2021.

List of Presentations

Hadas T., G. Marut, J. Kapłon and W. Rohm: Real-time and near real-time ZTD from a local network of low-cost dual-frequency GNSS receivers, EGU General Assembly, Apr. 21, 2021.

Hadas T., G. Marut, J. Kapłon and W. Rohm: Determination of water vapor content using low-cost dual-frequency GNSS receivers, Scientific Assembly of the International Association of Geodesy (IAG), June. 21, 2021.

Hadas T., N. Wielgocka, A. Kaczmarek, and G. Marut: Precise positioning using low-cost dual-frequency GNSS receivers, Scientific Assembly of the International Association of Geodesy (IAG), June. 21, 2021.

Hadas T., M. Bender, G. Marut and T. Hobiger: Real-Time GNSS Meteorology in Europe-Hurricane Lorenzo Case Study, IGARSS 2021, Jul. 21, 2021.

Kaźmierski K., K. Dominiak, K. Sośnica, and T. Hadaś: Positioning performance with low-cost GNSS receivers., Scientific Assembly of the International Association of Geodesy (IAG), June. 21, 2021.

Teaching and Supervision

In 2021 the summer semester had to continue to take place in digital form under the university's regulations due to the ongoing COVID-19 pandemic. Thus again, all lectures had to be filmed and were then provided to the students so that they could attend classes virtually according to their own schedule and pace. Fortunately, most of the lectures and tutorials in the winter semester 2021/22 could take place in presence, so that lively scientific debates with the students were possible again. Some graduate projects in the field of GNSS could be organized with the help of remote access to the Skydel GNSS simulator. This made it possible to work in their home as well.

The following parts of this section list student thesis projects which were completed in 2021 and summarize the teaching activities of the institute.

Bachelor Thesis

Lintz, Roland: Modellierung von GNSS-Ausbreitungseffekten mit Hilfe eines GNSS-Simulators (Supervisor: D. Becker)

Peitschat, Paula: Lösung von GNSS-RTK-Phasenmehrdeutigkeiten mit Hilfe von Partikelfilter-Ansätzen (Supervisor: T. J. Hobiger)

Ruof, Aaron: Simulation von GNSS-Jamming- und -Spoofing-Attacken im Landeanflug von autonomen Flugzeugen (Supervisor: T. Topp)

Master Thesis

El Kassemi, Younes Rafael: Analysis of impact of performance based surveillance approach on multilateration and ADS-B real data performance (Supervisor: C. Sonnleitner, A. Shoshi (Thales), Dr. H. Neufeldt (Thales))

Thürsam, Janis: Implementierung und Analyse eines ARMA-Filters – angewendet auf Rohdaten einer inertialen Messeinheit (Supervisor: T. J. Hobiger, T. Topp)

Activities in National and International Organizations

Prof. Hobiger

Editorial board member "Journal of Geodesy"
Editorial board member "Earth, Planets and Space"
Editorial board member "Acta Geodaetica et Geophysica"
Member of the German Geodetic Commission
Corresponding member of the Austrian Geodetic Commission
Fellow of the International Association of the Geodesy
Member of the Institute of Navigation
Member of the Royal Institute of Navigation

Member of the German Institute of Navigation
Member of the American Geophysical Union

Prof. Kleusberg
Fellow of the International Association of the Geodesy
Member of the Institute of Navigation
Member of the Royal Institute of Navigation
Member of the German Institute of Navigation

Education - Lectures/Exercises

Bachelor Geodesy & Geoinformatics

Adjustment Theory I (Hobiger)	2/1
Adjustment Theory II (Hobiger)	2/1
Fundamentals of Navigation (Hobiger, Wang)	2/2
Integrated Fieldwork (Hobiger, Sonnleitner)	2/10 days
Introduction of Geodesy and Geoinformatic (Hobiger, Becker)	2/2
Measurement Techniques II (Wehr) 2/2	

Master Geodesy & Geoinformatics

Filtering Techniques (Hobiger, Topp)	1/1
Inertial Navigation (Hobiger, Becker)	2/1
Integrated Navigation (Hobiger, Topp)	2/1
Measurement Techniques in Navigation (Wehr, Sonnleitner)	1/3
Satellite Navigation Hobiger, Becker)	1/1
Signal Propagation and Antenna Theory (Hobiger, Becker)	1/1
State Estimation in Dynamic Systems (Hobiger, Topp, Maier)	2/1
Object-oriented Programming in C+ (Hobiger, Sonnleitner, Topp)	1/3
Project (Sonnleitner)	6/0
Property Valuation (Bolenz)	1/0
Simultaneous Localization and Mapping (SLAM) (Hobiger, Maier, Klink)	1/1

Master GeoEngine

Dynamic System Estimation (Hobiger)	2/1
Integrated Positioning and Navigation (Hobiger, Wang, Maier)	2/1
Satellite Navigation (Hobiger, Wang)	2/1

Master Aerospace Engineering

Inertial Navigation (Hobiger)	2/0
Satellite Navigation (Hobiger)	2/0

Master Electromobility

Navigation of Surface Vehicles (Becker)	2/0
Satellite Navigation (Hobiger)	2/0

Institute for Photogrammetry

Geschwister-Scholl-Str. 24D
D-70174 Stuttgart
Tel.: +49 711 685 83336
Fax: +49 711 685 83297
info@ifp.uni-stuttgart.de
http://www.ifp.uni-stuttgart.de

Head of Institute

Prof. Dr.-Ing. Uwe Sörgel

Deputy:	apl. Prof. Dr.-Ing. Norbert Haala
Personal Assistants:	Carmen Kaspar
	Ute Schinzel
Emeritus Professor:	Prof. Dr.-Ing. Dieter Fritsch

Academic Staff

M.Sc. Tobias Bolz	Object Reconstruction from SAR Images
Dr.-Ing. Michael Cramer	Photogrammetric Systems
Dipl.-Ing.(FH) Markus Englich	Laboratory, Computing Facilities
apl. Prof. Dr.-Ing. Norbert Haala	Photogrammetric Computer Vision
M.Sc. Lena Joachim	Integrative Computational Design
M.Sc. Michael Kölle	Crowd-based Data Collection
M.Sc. Dominik Laupheimer	Classification in Remote Sensing
M.Sc. Stefan Schmohl	Deep Learning in 3D Remote Sensing
M.Sc. Philipp Schneider	SAR Interferometrie
Dr.-Ing. Volker Walter	Geoinformatics

Stipendiaries and external PhD Students

M.Sc. Jonathan G. Santiago	Multimodal self-supervised Representation Learning
Dipl.-Phys. Hendrik Schilling	Classification of Hyperspectral Data
M.Sc. David Skuddis	LiDAR-based Mobile Mapping
M.Sc. Wei Zhang	Visual SLAM for Augmented Reality
M.Sc. Xinlong Zhang	Object Recognition from LiDAR Data

Guest Scientists

M.Sc. Ruihang Xue	Tree Detection from Laser Scanning

External Teaching Staff

Dipl.-Ing. Stefan Dvorak, Amt für Stadtentwicklung und Vermessung, Reutlingen

Research Activities in ifp organized in four thematic Groups

Geoinformatics	Dr.-Ing. Volker Walter
Photogrammetric Computer Vision	apl. Prof. Dr.-Ing. Norbert Haala
Photogrammetric Systems	Dr.-Ing. Michael Cramer
Remote Sensing	Prof. Dr.-Ing. Uwe Sörgel

In Memoriam Prof. Dr.-Ing. Dr. h.c. mult. Friedrich (Fritz) Ackermann 1929 - 2021

Em. Prof. Dr.-Ing. Dr. h.c. mult.

Friedrich (Fritz) Ackermann

Professor Emeritus of Photogrammetry and Surveying and Former Director of the Institute for Photogrammetry at the University of Stuttgart

We mourn the loss of our dear colleague and institute founder Friedrich (Fritz) Ackermann, who passed away on December 4, 2021. He founded the Institute for Photogrammetry with his appointment to the University of Stuttgart on April 1, 1966, and was its director until March 31, 1992. With his research and development work in the field of analytical and digital photogrammetry, he significantly influenced the developments and progress in these two fields and helped the Institute of Photogrammetry to achieve a worldwide reputation. For many younger photogrammetrists he was always a role model and stood for the close connection between basic research and application. With the software developments he initiated with his spin-off inpho GmbH, Stuttgart (today Trimble), he was able to drive very successful technology transfer from research to practice.

Fritz Ackermann was born on November 1, 1929 in Moosbeuren (Ehingen) on the Danube. As a result of the Second World War, his school education, like that of many of his generation, was not entirely easy. He attended the elementary schools in Moosbeuren and Ehingen (1936-1940) and then the grammar school in Ehingen, where he graduated in 1949. Few knew of his inclination towards physics - he enrolled in the same year at the University of Tübingen to study physics. A year later, he began studying surveying at the Technical University of Stuttgart - a stroke of luck for photogrammetry. He finished his studies in 1954 and decided to get his first taste of practical experience as a young graduate engineer. For this purpose, he joined Zeiss-Aerotopograph, Munich, and was able to help developing film-based aerial photogrammetry and photogrammetric evaluation equipment in analog photogrammetry. After almost four years of practical experience, he decided to enter international photogrammetry research and development and in 1958 applied to the International Training Center for Earth Sciences (ITC), which at the time was located in Delft (now Enschede and part of the University of Twente).

Here he also completed a master's degree in photogrammetry and got to know other recognized companions of photogrammetric research such as H.G. Jerie and C.M.A. Van den Hout, who at this time had already entered the field of analytical photogrammetry. The analytical formulation of the bundle block adjustment had just been worked out by D.C. Brown and published by H.H. Schmid, who used it to perform the first world-wide photogrammetric triangulation for geometric determination of the Earth's figure at the National Oceanic and Aeronatics Administration (NOAA) Institute. The analytical block adjustment also fascinated the young researcher Fritz Ackermann, who was able to write a doctoral thesis at the ITC on "Error-Theoretical Investigations on the Accuracy of Photogrammetric Strip Triangulations"

(DGK Series C, Issue No. 87) and defended it at the University of Stuttgart in 1964 - supervisor was Prof. E. Gotthardt. For this dissertation he was awarded the Otto-von-Gruber Award of the International Society for Photogrammetry (ISP). When Prof. E. Gotthardt was appointed to the Technical University of Munich in 1965, his professorship in Stuttgart was vacant and Fritz Ackermann was able to demand the foundation of a new Institute for Photogrammetry in his appointment negotiations - he took over its direction on April 1, 1966.

In research and development Fritz Ackermann has set standards worldwide. In analytical photogrammetry, the block adjustments according to the method of independent models (software PAT-M) and the ray bundle (software PAT-B) are associated with his name. It was he who published the method of image correlation by the method of least squares and transferred it into application (later software MATCH-T). In the late 1980s, he worked to integrate GPS into photogrammetry, thus introducing GPS-based aerotriangulation to measure directly projection centers by DGNSS - now a matter of course. With the advent of airborne laser profiling, high-accuracy laser profiles were successfully acquired and analyzed. In the early 1990s, he worked on digital aerotriangulation and transformed it into a fully automated workflow (software MATCH-AT). In total, 26 PhD students and 3 post-doctoral students were supervised by him, who went on to successful careers in administration, universities and colleges, and industry. No wonder that he was often called the "father of modern photogrammetry". In addition to research and development, technology transfer was always important to him: from 1973 to 1991, he organized the Photogrammetric Week symposia at the University of Stuttgart every two years, in cooperation with Carl Zeiss, Oberkochen.

With so many successes, honors were not lacking. In 1988, for example, the Helsinki University of Technology honored him with an honorary doctorate Dr. tek. h.c., and four years later the Vienna University of Technology awarded him the dignity of Dr. tech. E.h. The University of Wuhan awarded him an honorary professorship Prof. h.c. in 1989 - a distinction comparable to the honorary doctorates here. At the University of Hanover, he was awarded the Dr.-Ing. E.h. degree in 1995, and in 2009 he received the Dr.-Ing. E.h. award from the Moscow State University of Geodesy and Cartography (MIIGAiK). Furthermore, he was an honorary member not only of the German Society for Photogrammetry and Remote Sensing and the ISPRS, but also in the corresponding professional societies in the USA and Great Britain. With Fritz Ackermann we and the Institute for Photogrammetry at the University of Stuttgart lose an extremely successful scientist, academic teacher and a kind, friendly and humble colleague. He was always humorous in his dealings and, in addition to photogrammetry, especially loved music, including playing the piano. We fondly remember the 50th anniversary celebration of the Institute of Photogrammetry in April 2016, which he introduced with a piano sonata - at the age of more than 86. Besides his fondness for music, mountain hiking and skiing were important to him; he was almost 80 years old when he climbed Kilimanjaro. Until the end he tried to keep up professionally. At the photogrammetric weeks he was an honorary participant until the end. We will miss him very much and cherish his memory.

Dieter Fritsch and Uwe Soergel
Institute for Photogrammetry of the University of Stuttgart

Research Projects

CATEGORISE: An Automated Framework for Utilizing the Workforce of the Crowd for Semantic Segmentation of 3D Point Clouds

At latest since the emergence of Convolutional Neural Networks (CNNs), it has become clear that supervised machine learning (ML) systems are severely hindered by the lack of labeled training data. We meet this increased demand for annotated data by building the CATEGORISE framework, which is meant for establishing supervised ML models without i) the requirement of training labels generated by experts, but by the crowd instead and ii) the labor-intensive manual management of crowdsourcing campaigns. When crowdworking is involved, quality control of results is essential. This control is an additional overhead for an expert diminishing the attractiveness of crowdsourcing. Hence, the requirement for an automated pipeline is that both quality control of labels received and the overall employment process of the crowd can run without the involvement of an expert.

Automated quality control can be achieved by exploiting the phenomenon of the wisdom of the crowd. This means that aggregating answers of many yields to a result of similar quality compared to one given by a single dedicated expert. In our case, wisdom of the crowd can be translated to simple majority vote (MV) of class labels given by a group of crowdworkers. However, a drawback of this kind of quality control is increased costs due to multiple acquisitions. Therefore, it is beneficial to also employ quality control on task designing. In our case, this is realized by including check points in our tasks. Consequently, when combining these two control mechanisms, the question arises of how many crowdworkers are necessary to get results sufficient to train a ML model of desired quality. Hence, we designed a proper web-based categorization task (see Figure 1) and evaluated the results received by real crowdworkers. It can be observed that accuracy can be significantly improved by the aforementioned measures while minimizing the necessary number of multiple acquisitions.

Together with active learning (an iterative process where a ML model points out only the subset of instances that are worth to be included into the training data and which are to be labeled by the crowd), this technique represents the key module of the CATEGORISE framework for full automation capabilities of labeling campaigns. Its overall architecture is visualized in Figure 2.

Eventually, our framework is applied for semantic segmentation of 3D point clouds but can be easily mofified for other input data. ML models derived by our framework achieve state-of-the-art accuracies, while the operator solely monitors the progress of the iteration instead of fulfilling labeling or administrative responsibilities.

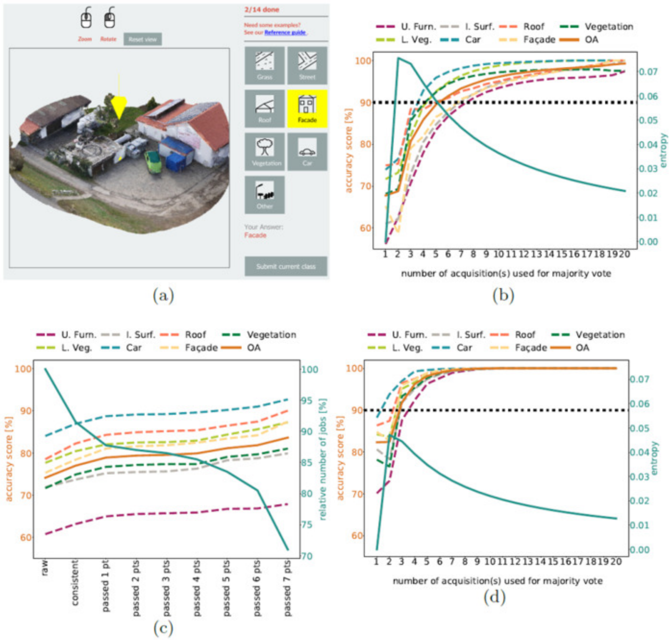


Figure 1: Developed web tool used by crowdworkers for labeling 3D points (a) and derived results with respect to individual class scores and overall accuracy (OA). We compare the result of pure MV (b) to the result of the same task when adding check points (d). The quality improvement by check points is displayed in (c). (Web tool can be tried out at https://crowd.ifp.uni-stuttgart.de/DEMO/index.php).

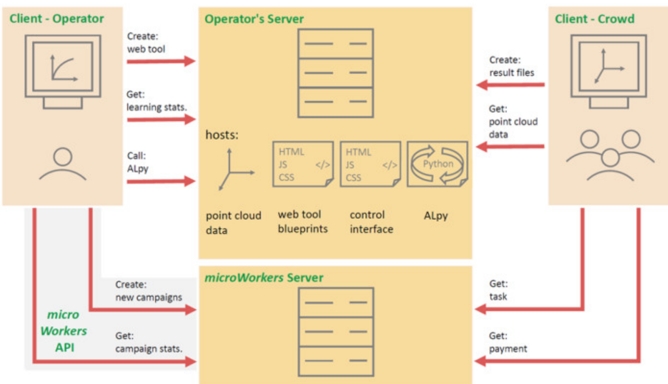


Figure 2: Architecture of the CATEGORISE framework.

IntCDC: Environment Monitoring for a Cyber-Physical Construction Platform

The Cluster of Excellence IntCDC (Integrative Computational Design and Construction for Architecture) of the University of Stuttgart aims to rethink design, fabrication and construction in order to tackle the current challenges of the building industry, such as the lack of sustainability and productivity. IntCDC is funded by the German Research Foundation (DFG).

One of the research activities within this interdisciplinary project is the development of a cyber-physical construction platform, namely a tower crane, for automated on-site assembly of prefabricated building elements. In cooperation with the Institute for System Dynamics, we are developing the control for the automated tower crane and the corresponding monitoring system. The goal is to enable a fully automated load handling including the pick and place processes and the transportation in between. Therefore, task scheduling, path planning and an online feedback for collision avoidance during transportation are needed.

As main data source for solving these tasks, we investigate an array of crane-mounted cameras, which take overlapping images of the workspace of the crane. We installed such a system at the IntCDC test site (see Figure 3) to be able to test different approaches for 3D reconstruction of the workspace and the integration of the generated data into the crane control. The cameras are used to generate a DEM (Digital Elevation Model) of the workspace, which is the basis for autonomous path planning. First investigations about the quality of such DEMs generated from crane camera images by classical photogrammetric processing showed promising results. However, as autonomous operations require real-time data to be able to react to any changes, the DEM has to be generated in real-time. Thus, our research currently focuses on the adaption of visual SLAM algorithms for the special crane camera use case.

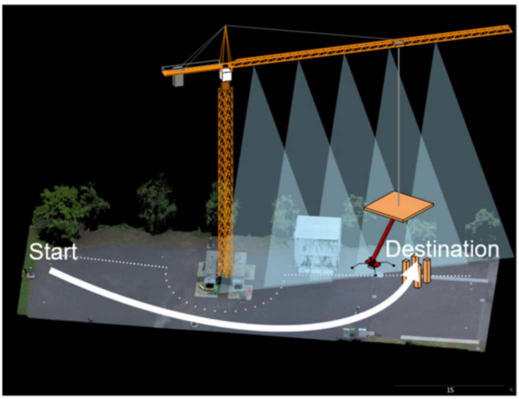


Figure 3: Point cloud of the IntCDC test site with the tower crane as part of a cyber-physical construction platform. The blue triangles show how the crane cameras take overlapping images of the site.

Comparison of different 2D and 3D Sensors and Algorithms for indoor SLAM on a low-cost Robotic Platform

Mobile robots are becoming a fairly important part of people's lives. Simultaneous localization and mapping (SLAM) is one of the most fundamental capabilities to perceive the surroundings and keep track of the robot's position while constructing a map incrementally. For this purpose, there is a wide range of products from different manufacturers. In practice, depending on the application requirements, different sensors are deployed for this task. Furthermore, with rapid development, more new methods have emerged and pushed the boundaries of sensor performance. Therefore, this work aims to compare different low-cost environmental sensors and different advanced algorithms for each of the sensors.

For the 2D Lidar, the Matlab Lidar SLAM and ICP graph SLAM methods are selected. As for visual SLAM methods, the representative methods which are the ORB-SLAM, the Stereo-DSO, and the DROID-SLAM are evaluated. For the experiment, a low-cost robotic platform is assembled, consisting of a 2D Lidar and a 3D depth camera. Additionally, to provide a reference for comparison, an ArUco marker is appended on top of the platform as illustrated in Figure 4.

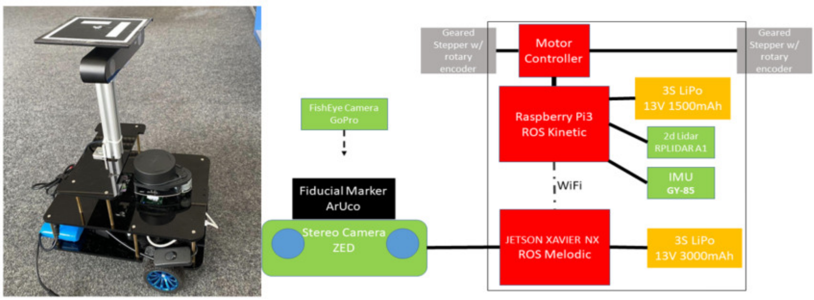


Figure 4: The low-cost robotic platform and the module diagram.

We employed a wide-view GoPro camera on the room's roof to keep tracking the position and orientation of the robot. The experimental results show that the recent deep learning-based DROID-SLAM method performs best with an ATE error of 2.9 cm. Nevertheless, thanks to the high precision of direct distance measurements, the 2D Lidar-based SLAM provides a more consistent 2D occupancy map (Figure 5 a). Besides, the Lidar map covers more spaces because of the greater measurement range. By contrast, the resulting 3D map (Figure 5 b and c) of the visual system contaminates more clutter due to the insufficient accuracy of stereo depth estimate.

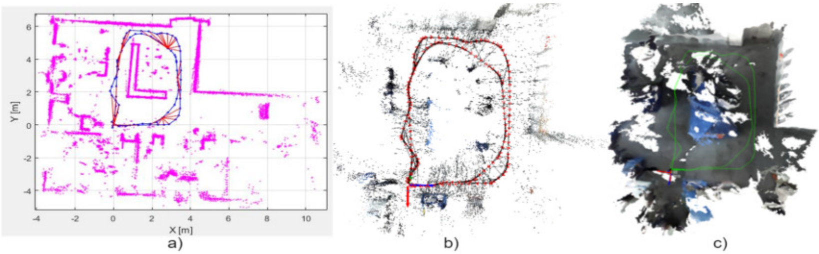


Figure 5: Different map representations, which are 2D Lidar map, 3D point cloud map, and 3D dense volumetric map respectively.

Towards the Integration of DInSAR Deformation Data into Building Information Modeling

In the last twenty years, the monitoring of deformation processes such as slow landslides, mining-induced subsidence, and post-earthquake tectonic movements has been more and more carried out by interferometric synthetic aperture radar (InSAR) techniques. When it comes to monitoring urban areas, persistent scatterer interferometry (PSI) has been proven to work reliably and is becoming a standard technique in the portfolio of monitoring. The availability of open space-born SAR data made nationwide deformation mapping services possible. However, the rather low spatial resolution of such data limits their applicability for monitoring at finer scales, for example, motion patterns of individual buildings.

High-resolution SAR data such as TerraSAR-X are suitable for this task but come with the downside of a limited acquisition capacity. In the future, upcoming SAR satellite constellations will provide greater availability of high-resolution SAR data, better than 1 m × 1 m. This enables officials the possibility to efficiently monitor smaller objects of interest, such as critical infrastructure like bridges and dams as well as single buildings.

The results of such monitoring can be handled either isolated or set in relation to other information related to the building. Such building information modeling (BIM) systems use sensors, meters, network infrastructure and 3D modeling to create a digital twin of the structure to inform decisions, such as predictive maintenance. PSI analysis of high-resolution SAR data often covers buildings with thousands of derived PSI points in the order of 1 PS per m^2 on the facades.

We are exploring a method to aggregate and cluster these scatterers into groups of points that show similar movements and therefore are assumed to be located on the same structural part of the building. These parts can be linked to actual structures of the building via a BIM or ALS point clouds and allow augmenting the information with deformation histories (see Figure 6).

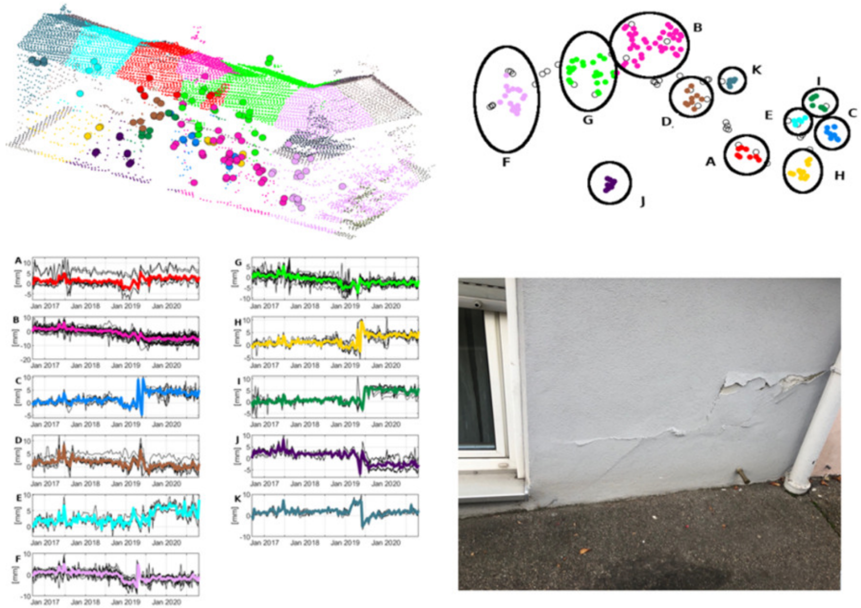


Figure 6: Top-left: PS-Point Distribution on a building. Top-right: Clusters In Deformation Space (embedded via a hybrid distance metric and a non-linear dimension reduction technique). Bottom-left: Corresponding deformation time-series for each extracted cluster. Bottom-right: Damage on the building, which overlaps with the area where Cluster D and H move in different directions.

Airborne (PolIn)SAR for Coastal Protection

The Wadden Sea covers large areas of the North Sea coast in Germany, the Netherlands and Great Britain and is exposed to the influence of tides and storm surges. To ensure the safety of seafaring traffic and the protection of the coastal areas among other things, up to date high-resolution geodata is required. This data includes digital surface and terrain models, digital imagery and a variety of 3D line geometry such as water-land-boundaries or 3D structural lines.

The GeoWAM (www.geowam.net) project investigates the possibility to replace state of the art laser scanning with airborne SAR. The use of SAR has some advantages, such as weather independence and larger strip width, but also comes with problems due to the specifics of the recording. Figure 7 shows the resulting DEM of the delayed flight campaign in summer 2020. As part of the project the ifp focuses on the reconstruction of 3D structures to monitor dikes and other coastal protection buildings.

After the investigation of structural edges in the first two years of the project, the focus has now turned to the classification of object edges. This plays a role especially in the evaluation of the current structural condition of the coastal protection structures. Driven by the results of the pure structural edge extraction, now more methods were investigated, which are not only able to classify existing lines, but also to detect them in the same course, if possible.

In order to keep the required computing power as low as possible for this project, hierarchical approaches were preferably investigated. One such approach is the use of attention-based neural nets. The approach is depicted in Figure 7.

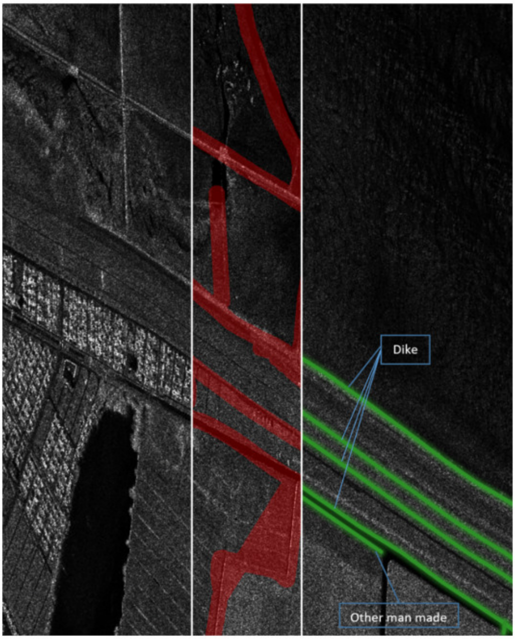


Figure 7: Left: radar image in slant range geometry; middle: overlaying a symbolic attention mask; right: extracted lines with class labels.

Fusing Top-View Point Cloud and SAR Image for Urban Classification

With high-resolution and altitude information, large-scale point clouds have played an important role in urban planning, ecosystem monitoring, and land resources analysing. Urban areas are complex scenarios consisting of large numbers of objects with various materials. This variety poses a challenge to any single-data classification scheme, for example, solely based on RGB point clouds. Synthetic Aperture Radar (SAR) images reflect the backscattering intensity of objects and show strong contrast between artificial materials and natural objects. Therefore, the RGB point clouds and the SAR images provide complementary features which is advantageous especially in urban areas. Fusing such data by deep networks with powerful capabilities of feature mapping could effectively improve the performance for urban classification.

We explore feature-level fusion on the RGB top-view point cloud and SAR images for urban classification. The challenges include that the aerial point clouds and the satellite SAR images have quite different scales and resolutions. The coherent sensor principle gives rise to speckle, which both renders visual interpretation and automated semantic segmentation to be hard tasks. In order to overcome these limitations, we propose a data-driven feature extraction and fusion network based on swin-Transformer.

The structure of proposed network is shown in Figure 8, which can be separated into four parts: data pre-processing, feature extraction, feature fusion and classification. Firstly, the point cloud is projected onto a horizontal plane, and the RGB value of each point is interpolated to pixels in the grid to obtain a top-view image. Afterwards, homologous points in the top-view image and SAR image are extracted for registration. Secondly, the top-view image together with the SAR registration image is fed into an asymmetric encoder for individual feature extraction. Thirdly, the features from top-view image and SAR image are concatenated along the channel dimension and fed into a fusing encoder. The asymmetric encoder and the fusing encoder are both realized by a 2-block swin-Transformer. Finally, the fused feature is decoded by an UperNet for generating the semantic labels. The proposed network is evaluated on a subset of the Hessigheim high-resolution 3D point cloud benchmark data and a TerraSAR-X image of same site. The overall precision achieves 87.25% and the mean intersection over union (mIOU) achieves 73.56%.

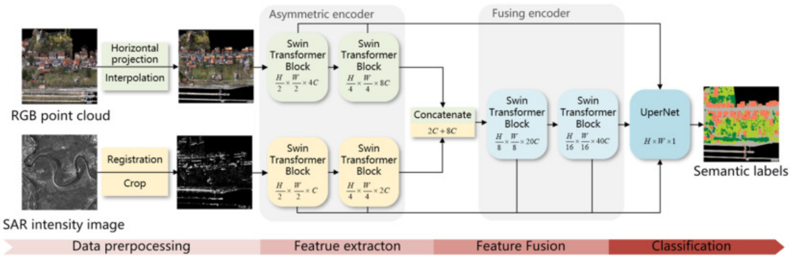


Figure 8: Structure of the proposed network.

A Two-Stage Approach for Fine-Grained Object Segmentation in Large-Scale ALS Point Clouds

Automated semantic segmentation of point clouds plays an indispensable role in many application areas such as autonomous driving, building information modelling and robotics. Compared with the regular grid structure of image data, the disordered distribution of point clouds makes 3D semantic segmentation a challenging task. In particular, the complexity of large-scale scenarios leads to difficulties in fine-grained object segmentation. We propose a two-stage segmentation framework for class-imbalanced fine-grained objects on the pipeline of general semantic segmentation. The overall structure is illustrated in Figure 9, which consists of two stages, the general semantic segmentation and the detection based refined semantic segmentation.

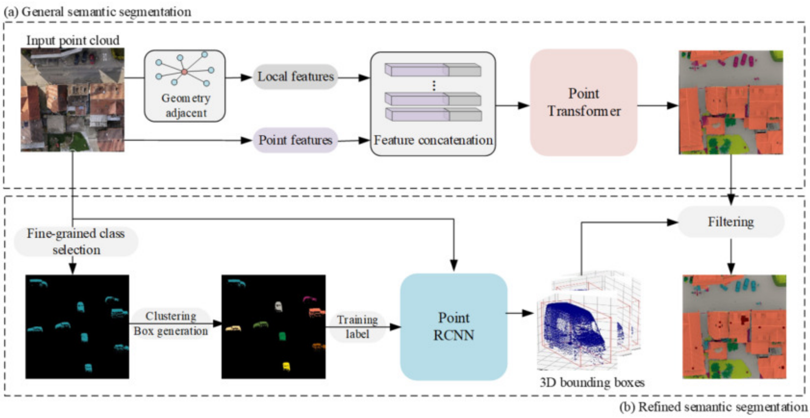


Figure 9: Structure of the proposed approach.

The proposed approach is evaluated on the Hessigheim High-Resolution 3D Point Cloud (H3D) Benchmark. The confusion matrix is shown in Figure 10 (b), where the overall accuracy achieves state-of-the-art 89.35% and the mean F1-score achieves outstanding 75.70%. Furthermore, comparing with the result without the refined stage, vehicle and chimney classes have achieved breakthroughs from zero in F1-score. It indicates that the proposed two-stage approach effectively improve the segmentation of fine-grained objects, i.e. vehicle class and chimney class.

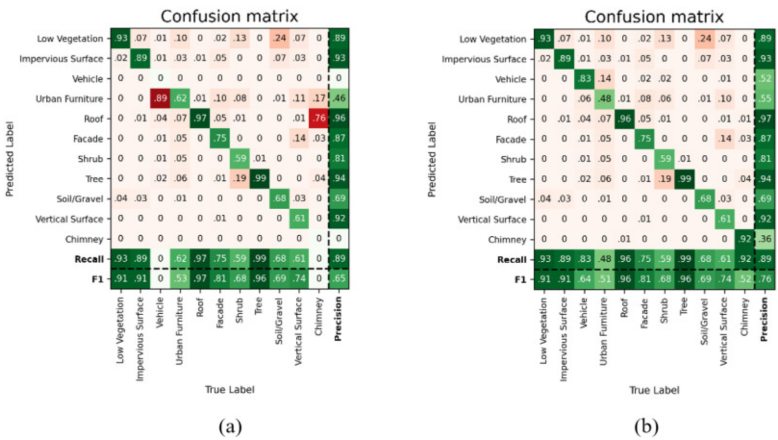


Figure 10: Confusion matrices on (a) segmentation without the refined stage, (b) the proposed two-stage segmentation.

LiDAR Scan-Matching for Simultaneous Localization and Mapping

In LiDAR-based SLAM algorithms, scan matching is required to align point clouds captured from different locations. This serves as a prerequisite for determining the respective sensor position and for finally combining multiple scans into a consistent scene. For this purpose, scan matching is required for consecutive scans, but is also used to provide so-called loop closures, when the scanner platform revisits known places. Figure 11 shows the SLAM result of a small sequence.

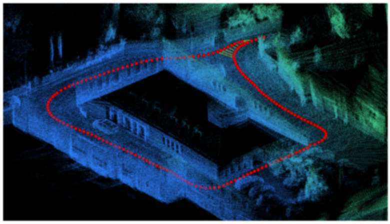


Figure 11: Composite scene as a result of a SLAM algorithm. Red dots indicate keyframe positions and yellow lines indicate loop closures.

The process is also named point cloud registration. Various scan matching algorithms have been developed over the past decades, but their accuracy and robustness can vary greatly depending on the nature of the environment and sensor configuration. Some methods rely on structured environments to find suitable landmarks, while still other methods rely on good approximations during initialization to converge.

In this project, novel scan matching algorithms for challenging environments are investigated and compared to known methods. Figure 12 shows an example of the merging of two scans with very low overlap using a novel method. In addition to the LiDAR sensor, the sensor system is also equipped with GNSS receivers. The goal of the project is to develop a system whose trajectory can be reconstructed and georeferenced even in very difficult environments where GNSS is temporarily unavailable.

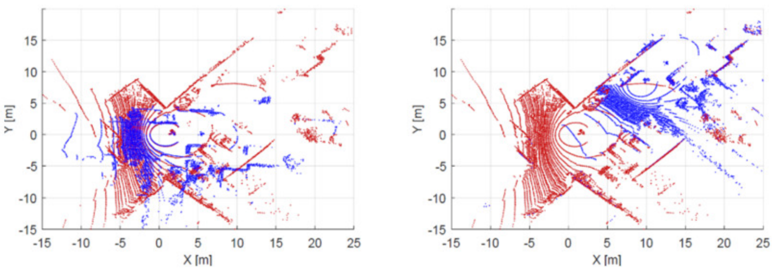


Figure 12: Scan matching example. Left: Initialization. Right: Result after scan matching.

Individual Tree Detection in Urban ALS Point Clouds with 3D Convolutional Networks

Since trees are a vital part of urban green infrastructure, automatic mapping of individual urban trees is becoming increasingly important for city management and planning. We exploit the full 3D potential of airborne laser scanning ALS point clouds by using a 3D neural network for individual tree detection in urban environments. Specifically, we use a 3D convolutional network for feature extraction combined with a subsequent single-shot region proposal network for the actual detection. Furthermore, results are refined through the combination with semantic segmentation results computed by parallel network branch, as well as a final region growing. Extensive ablation studies were performed to investigate the fine-tuned choice of hyperparameters and individual improvements of the network pipeline.

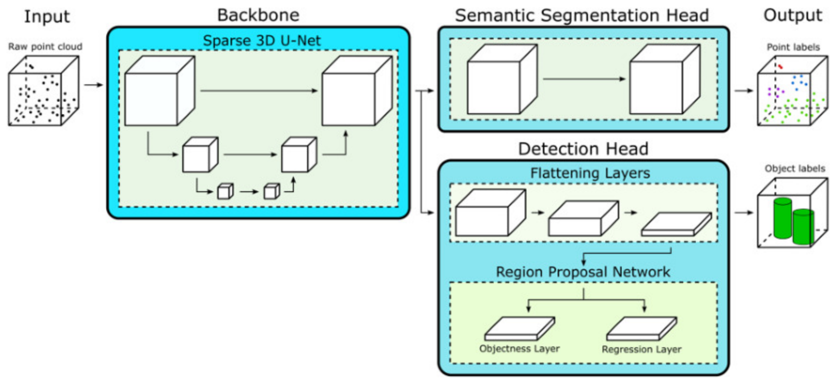


Figure 13: Network architecture.

Overall, our method achieves good results and outperforms the baselines in all metrics in terms of individual tree detection, stem detection, and tree canopy cover. Combining object detection with semantic segmentation improved precision and slightly enhanced radius estimates. However, if the goal is the estimation of tree canopy cover, 3D semantic segmentation alone is still the easier and faster alternative. Ablations show the positive effects of finely tuned loss weighting and data augmentation, as well as the benefits of a 3D backbone. Pre-training on a larger set of weak labels showed higher gains the less refined the algorithm. In the future, we expect 3D neural networks for object detection in topographic ALS point clouds to benefit even more from higher point densities compared to 2D detection networks in general but especially in individual tree detection due to better resolution of tree stems in the data.

Figure 14: Exemplarily results (white: ground truth; yellow: prediction).

Multi-Modal Semantic Mesh Segmentation in Urban Scenes

3D data acquisition and processing have increasingly become feasible and important in the domain of photogrammetry and remote sensing in the past decade. The 3D modalities Point Cloud (PC) and mesh are common representations.

PC processing and interpretation are currently very popular topics. PCs are unordered sets of points directly measured with Airborne Laser Scanning (ALS) or derived from images via Multi-Vision Stereo (MVS). In contrast, surface meshes are graphs consisting of vertices, edges, and faces that provide explicit adjacency information. The mesh is adaptive to the underlying geometry due to the non-uniformity and non-regularity of faces. This means planar surfaces are represented by a few large faces, whereas vivid areas are reconstructed by many small surface elements. Generally, the adaptiveness results in a less memory-consuming 3D representation compared to a PC. Another strength of meshes is the high-resolution texturing generating a realistic-looking 3D representation of the real world. In our opinion, the mesh may replace unstructured PCs as the final user product for urban scenes in the future. For these reasons, we strive for semantic segmentation of textured urban meshes.

With this work, we want to account for the current hybridization trend and aim at semantic segmentation integrating information from both modalities (hybrid semantics). Joint photogrammetric and LiDAR acquisition (hybrid acquisition) is state of the art for airborne systems and emerges for UAV-based systems. Since very recently, the hybrid orientation of complementary ALS PCs and aerial imagery is possible. The integrative character of the mesh facilitates data fusion "out-of-the-box" by utilizing LiDAR points and MVS points for the geometric reconstruction while leveraging high-resolution imagery for texturing (hybrid data storage). However, the information regarding the source modality is not encoded in the mesh vertices and hence, cannot be accessed in further processing steps, e.g., semantic segmentation. Therefore, we recover the explicit one-to-many relationship between a face and points with the so-called Point Cloud Mesh Association (PCMA). The association mechanism allows propagating information between PCs and meshes in a subsequent information transfer. The propagated attributes may embrace (manually attached) labels, sensor-intrinsic and handcrafted features, such as pulse characteristics and sophisticated engineered quantities.

Figure 15 proves its functionality in comparison to a simple nearest neighbor interpolation by showcasing the propagation of labels that have been assigned manually to the point cloud. The tile-wise procedure enables parallel processing and ensures processing within a reasonable period - even for large-scale data sets. We transfer information encoded in ALS PCs to meshes and enhance per-face descriptors to multi-modal feature vectors. We construct various descriptors considering features of different modalities, scales, and types (radiometry and geometry). Eventually, we perform an extensive ablation study on the ISPRS benchmark data sets Vaihingen3D (V3D) and Hessigheim3D (H3D) to investigate the impact of the deployed features. In particular, we analyze the benefit of the additional PC features by comparing the classifier performance with/without LiDAR support on the face level. We establish a feature-based pipeline for semantic mesh segmentation with well-established and fast Random Forest (RF) models. Figure 16 shows exemplary results for two dedicated feature vector compositions demonstrating the superiority of the multi-modal information integration.

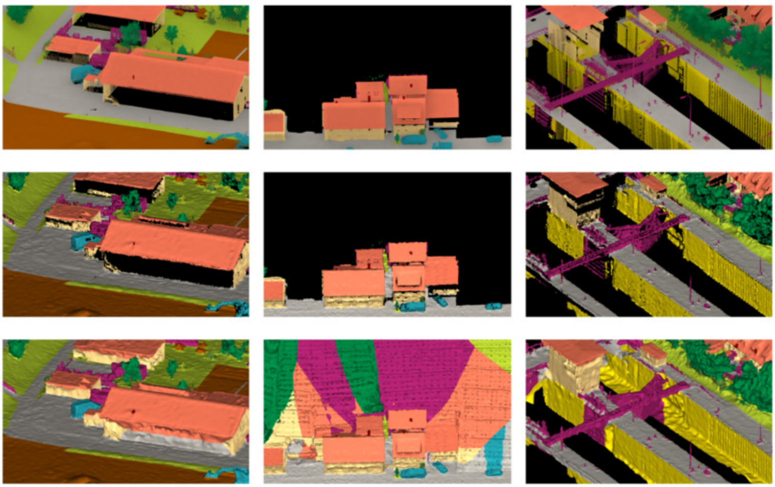


Figure 15: Effect of different propagation methods. The annotations of the manually labeled point cloud of H3D (top) are propagated to the mesh by a) PCMA-steered transfer (center) or b) nearest neighbor interpolation (bottom).

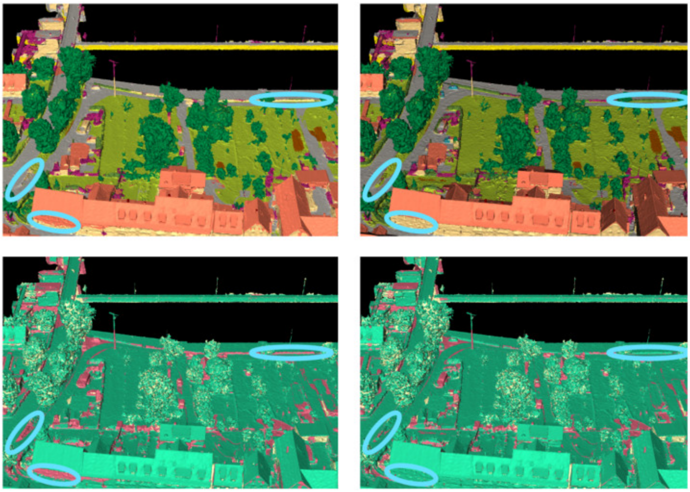


Figure 16: Semantic segmentation results on the mesh as achieved with RF classifiers trained with a) features derived from the mesh only (left) and b) multi-modal features derived from both the mesh and the point cloud (right). The top shows the prediction results, whereas the bottom shows the respective red-green plots indicating correct (green) and false (red) predictions. Faces with unknown ground truth are marked in yellow. The most obvious differences between the predictions are circled in sky-blue.

Evaluation of state-of-the art scanning station for analogue airborne image digitization

Since the early 20th century the use of airborne imagery to produce (photo-)maps is established. This not only was driven by military reconnaissance aspects. Already Nadar, the early photographer who took the first airborne image from balloon over Paris in 1858, recommended to use this new technology to replace the enormous work of classical land surveyors and mapping engineers. Since then an uncountable number of airborne imagery has been captured, many of them still available in different archives all over the world. This analog information conserves more than 130 years of land change. Historical aerial photographs therefore represent a unique cultural asset to enable long-term environmental monitoring studies and change detection based on the analysis and evaluation of time series of images. Still, the lack of digital availability hinders their wide-spread use so far. Not only because of this have organizations like National Mapping Agencies (NMAs) started initiatives to digitise their analogue film archives. This also is necessary to avoid the further damaging of film because of aging and especially due to wrong storage conditions. Considering the estimated remaining lifetime of aerial photographs and suboptimal archiving conditions, current estimates suggest that the digitisation process should be completed within the next 10-15 years to minimise irreversible loss and film deterioration. As of today, it should be more than 4.5 million analog airborne photogrammetric images in the archives of the sixteen German NMAs only!

The LGL Baden-Württemberg has initiated the project “Digitaler Luftbildatlas Baden-Württemberg” (DLBA) as part of the state’s digitisation strategy “digital@bw” to digitise large parts of the analogue aerial photo collection. As the “traditional” photogrammetric scanners from the 1990ies are almost not available anymore a new scanning approach was selected typically used for the scanning of (historic) document scanning in libraries. Different to the traditional photogrammetric scanners, this scanning stations captures the whole image with one single shot only. The main component therefore is a 150 MPix Phase One iXM-MV150F high performance camera combined with a HR Digaron-SW float 138 mm f/6.5 lens (see Figure 17). The preserving of spatial and radiometric resolution and geometric accuracy during scanning are the critical issues within this process. These effects have been thoroughly investigated in a student’s master thesis project, together with LGL team and support from the Bavarian NMA in Munich.

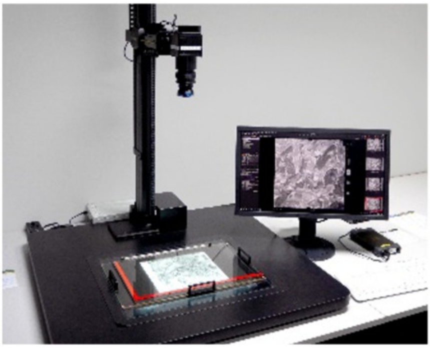


Figure 17: Digitization station used at LGL BW.

As Figure 18 shows, a reference resolution target, consisting out of 25 regularly distributed highest resolved Siemens stars has been used to analyse the resolution of the scanning station over the whole scanning window. In addition this target also is able to verify the correct alignment and focussing of the camera with respect to the scanning table. Small mis-alignments or non-parallelism of the focal plane of the sensor and the scanning plane will immediately influence the geometric resolution, which can be derived from the individual Siemens star pattern.

The Figure 19 shows the derived spatial resolution for two different epochs. The first epoch shows that the sensor is able to resolve minimal resolved pixel size around 25–28 μm. This quite nicely corresponds to the scanning pixel sizes from the photogrammetric scanners, which often were between 14–28 μm. The result from the second epoch shows significantly worse resolution. The resolved pixel are up to 35 μm now, in addition a systematic decrease of resolution from top to bottom can be noticed. This must be due to non-optimal re-focussing or even changes in the mechanical structure. With the Siemens star resolution pattern such issues can be easily detected and corrected afterwards.

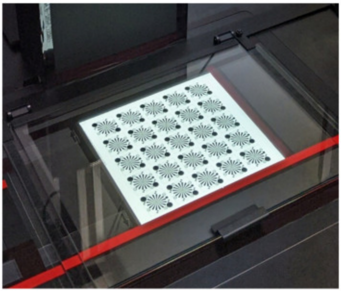


Figure 18: Resolution pattern arranged on the scanning station.

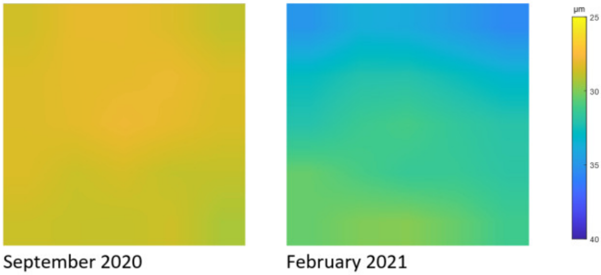


Figure 19: Evaluation of geometric resolution of scanning station, two different epochs shown.

A further issue not discussed so far is the effect of non-considered distortions in the scanning camera itself as these will be superimposed with the geometry of the scanned analogue image itself. This evaluation of geometric accuracy also relies on the individual calibration of the scanning head. Especially the in-situ calibration is demanding as the depth of field of the scanning station is in the very small due to the short focus distance, long focal length and pre-selected f-stop number, which limits the in-situ calibration to an almost flat field calibration, which is somewhat limited with respect to a full calibration in 3D test field. Still the refined calibration parameters of the scanning camera were used to create a new set of digitised images by correcting the originally scanned images with the determined interior orientation parameters of the digitising camera. This correction has a significant influence in later bundle adjustment. Comparing the results from aerial triangulation of non-corrected digitised analogue images with corrected ones, especially the height performance is much better than for the non-corrected ones. As these AT tests were done with image materials that previously had been scanned with traditional photogrammetric scanner already obtained results could be compared to the bundle adjustment with the traditionally photogrammetrically scanned images. The accuracy from check-point analysis using pre-corrected scanned images are fully comparable to the results from the images scanned by traditional photogrammetric scanners.

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Collmar, D.: Gamificationansätze für Crowdsourcing: Untersuchung anhand web-basiertem 3D-Labeling. Supervisors: Walter, V., Kölle, M.

Graf, F.: Methoden der photogrammetrischen Bildverarbeitung in der Automatisierungstechnik. Supervisors: Wagner. W., Haala, N.

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Höltzcke, R.: Remote Sensing-based Analysis of Absorbed Photosynthetic Active Radiation (APAR) on Land under Adaptive Multi-paddock Grazing. Supervisors: Schneider, P., Sörgel, U.

Mostafa, J.: Untersuchung der Wolkenbedeckung und weiterer meteorologischer Größen anhand von Kameraaufnahmen im sichtbaren und infraroten Spektralbereich. Supervisors: Kociok, T. (IOSB), Sörgel, U.

Nie, R.: Processing of Allied Air Forces World War II Strategic Air Reconnaissance Imagery. Supervisor: Cramer, M.

Rahn, A.: Auswertung historischer Luftbilder aus Flurbereinigungsverfahren. Supervisors: Wild, F. (Landratsamt Heilbronn), Cramer, M.

Roth, M.: Kalibrierung einer drohnenbasierten Multi-Sensorplattform. Supervisor: Cramer, M.

Schulz, J.: Qualitätsuntersuchung der Phase One iXM-MV150F Dokumentenkamera für die Luftbilddigitalisierung. Supervisor: Cramer, M.

Stelzer, R.: Entwicklung einer vollautomatisierten Pipeline zur qualitativ hochwertigen Erfassung von Fahrzeugen. Supervisors: Walter, V., Kölle, M.

Tan, X.: Semantic Segmentation of Urban Meshes Utilizing MeshCNN. Supervisors: Laupheimer, D., Haala, N.

Tsao, W.N.: Semantikbasierte Klassifikation von 3D-Punktwolken. Supervisors: Kölle, M., Walter, V.

Wang, Y.: Machine-learned 3D Building Vectorization from Satellite Imagery. Supervisors: Bittner, K. (DLR), Haala, N.

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Geiger, R.: Baumdetektion in luftgestützten Fernerkundungsdaten mittels Deep Learning. Supervisors: Schmohl, S., Haala, N.

Helber, L.: Crowdbasierte Erfassung von Fassadenelementen aus 3D-Meshes. Supervisors: Kölle, M., Walter, V.

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Rechtsteiner, H.: Extraktion von Liniennetzen aus hochaufgelösten SAR-Bildern des Wattenmeers. Supervisor: Sörgel, U.

Activities in National and International Organizations

Cramer, M.:

Co-Chair ISPRS WG I/9: Integrated Sensor Orientation, Calibration, Navigation and Mapping

Mitglied im DIN Normungsausschuss NA 005-03-02 AA "Photogrammetrie und Fernerkundung"

Secretary German Society for Photogrammetry, Remote Sensing and Geoinformation (DGPF)

Englich, M.:

Webmaster ISPRS

Haala, N.:

Chair ISPRS WG II/2: Point Cloud Generation

Chair EuroSDR Commission II: Modelling and Processing

Vorsitz DGPF Arbeitskreis Sensorik und Plattformen

Sörgel, U.:

President German Society for Photogrammetry, Remote Sensing and Geoinformation (DGPF)

Chair ISPRS WG III/3: SAR-Based Surface Generation and Deformation Monitoring

Walter, V.:

National Correspondent of the ISPRS Commission IV

Education - Lectures/Exercises

Bachelor "Geodäsie und Geoinformatik"

Geoinformatics I (Walter)	2/2
Geoinformatics II (Walter)	1/1
Image Processing (Haala)	2/1
Integrated Fieldworks (Haala, Hobiger, Sneeuw)	0/4
Introduction into Geodesy and Geoinformatics (Cramer, Hobiger, Sneeuw, Sörgel)	2/2
Photogrammetry (Cramer)	2/1
Remote Sensing (Sörgel)	2/1
Urban Planning (Dvorak)	2/0

Master Course "Geodäsie und Geoinformatik"

Aerotriangulation (Cramer)	1/1
Computational Geometry (Walter)	1/1
Computer Vision for Image-based Acquisition of Geodata (Haala)	1/1
Databases and Geographical Information Systems (Walter)	1/1
Fundamentals in Urban Planning (Dvorak)	2/0

Georeferencing of Photogrammetric Systems (Cramer)	1/1
Modelling and Visualisation (Haala)	1/1
Pattern Recognition and Image Understanding (Haala)	1/1
Photogrammetric Acquisition of 3D Geodata (Cramer, Haala)	2/2
Selected Chapters in Remote Sensing (Sörgel)	1/1
Simultaneous Localization and Mapping (SLAM) (Haala, Hobiger)	2/2
Web-based GIS (Walter)	1/1

Master Course GEOENGINE

Airborne Data Acquisition (Cramer)	2/1
Computer Vision (Haala)	2/1
Geoinformatics (Walter)	2/2
Integrated Fieldworks (Haala, Hobiger, Sneeuw)	0/4
Signal Processing (Sörgel)	2/1
Pattern Recognition (Sörgel)	2/1
Remote Sensing (Sörgel)	2/1

Master Course "Infrastructure Planning"

Introduction to GIS (Walter)	2/0

Master Course "Aerospace Engineering"

Image Processing (Haala)	2/1
Introduction to projective Geometry (Cramer)	1/0