Annual Report 2023

Institute of Navigation

INS

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Annual Report 2023

of the

Institute of Navigation (INS)

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Staff in 2023

Management	**Role**
Prof. Dr.techn. Thomas Hobiger	Head of the institute, Dean of Studies (since Oct. 2021)
Dr.-Ing. Aloysius Wehr (until Dec. 2023)	Deputy
Prof.i.R. Dr.-Ing. Alfred Kleusberg	Retired professor
Mina Sungur	Secretary

Academic Staff	**Research Focus**
M.Eng. Vanessa Bär (from Sep. 2023)	Digital Electronics
Dipl.-Ing. Doris Becker	Navigation Systems
Dipl.-Ing. (FH) Martin Thomas (until Jul. 2023)	Digital Electronics and Hardware Programming
Dr.-Ing. Aloysius Wehr	Optical and Wireless Communication

PhD students	**Research Focus**
M.Sc. Kevin Gutsche	Precise orbit determination
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
M.Sc. Bayram Stucke	Precise orbit determination
M.Sc. Thomas Topp	Navigation Software Development
M.Sc. Rui Wang	GNSS, RTK, PPP, Integrity

IT	**Responsibility**
Regine Schlothan	Computer infrastructure and programming

Electr. and Mech. Workshop (ZLW)	**Expertise**
Dr.-Ing. Aloysius Wehr (until Dec. 2023)	Head of ZLW
Michael Pfeiffer (until Jun. 2023)	Mechanician Master
Sebastian Schneider	Electrician
Dipl.-Ing. (FH) Martin Thomas (until Jul. 2023)	Electrical engineer

External lecturers	**Affiliation**
Dr. Toni Caesperlein	Dr. Koch Immobilienbewertung, Esslingen

Preface

This report summarizes the activities of the Institute of Navigation (INS) in the year 2023.

Looking back on the past year we can state that we definitely saw very positive developments in many of our research projects, some of them are also being highlighted in this report. We also increased our efforts to write proposal which were submitted to different funding agencies and are currently being reviewed. Maybe the biggest highlight concerning the acquisition of highly competitive funding, was the successful evaluation of the DFG-funded Collaborative Research Centre "ATLAS" to which we are going to contribute with one sub-project from 2024. We also saw several projects reaching their nominal end and we are very happy that we could acquire funding so that the initiated research activities could continue in follow-on projects. The outcome of our research has not only become visible in different reviewed publications and reports, but found its recognition by two awards which were presented by two of our PhD students. Clemens was presented an "Outstanding presentation award" at the European Navigation Conference 2023 for his ground-breaking work on making airspace surveillance possible with low-cost hardware. Kevin, who attended the ION's GNSS+ conference in fall 2023 received "Best Presentation Award" for his work on "Addressing Inaccurate Phase Center Offsets in Precise Orbit Determination for Agile Satellite Missions".

In terms of teaching, we finalized our internal Git repository that includes now all lecture materials in LaTeX and we revised the contents of the "Measurement Techniques II" in order to equip our students with the necessary basic skills concerning electrical engineering and electronics. Facing significantly lower course students than in the years before required to optimize our course program and offer courses to those interested even when the required minimum number of students could not be reached.

Concerning staffing, the year 2023 was one in which we saw three of our colleagues entering retirement. We wish them all the best for their new stage of life and face the situation that they left a void which will take some time to be filled.

Prof. Dr. Thomas Hobiger
(Head of the Institute of Navigation)

Research

The INS identifies new fields of applications, develops and tests navigation solutions, and assigns research projects according to four "focus areas", which were originally defined in 2018. Considering the way the institute is organized and its participation in different research projects, those areas reflect most of the activities of the INS. Moreover, the teaching activities, which are described later in this report, also reflect the research activities that the INS is involved in. Figure 1 depicts those focus areas, which are grouped around the topics of "positioning, navigation, and timing".

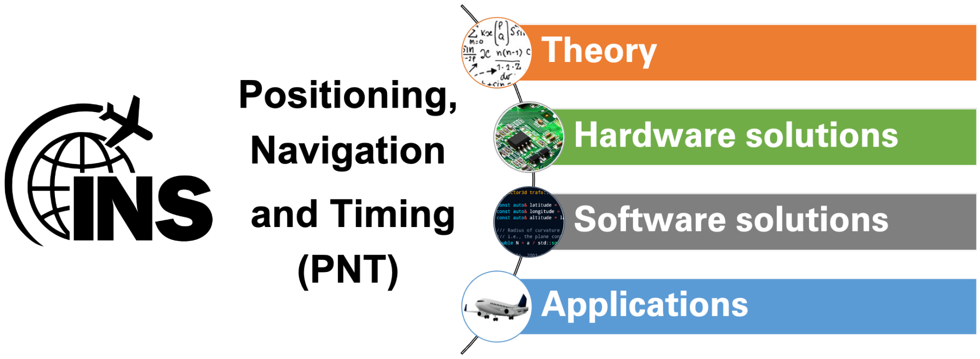


Figure 1: INS focus areas to which the institute is actively contributing in the form of research projects.

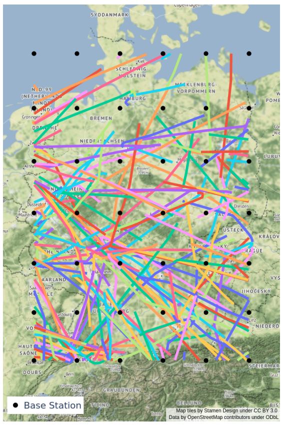
While most of the current research projects can be clearly assigned to one or two focus areas shown in the figure, larger research projects, described later in this report, usually fall under the category "applications" but require intense input from the other three research areas. In the following,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

Research focus: Theory

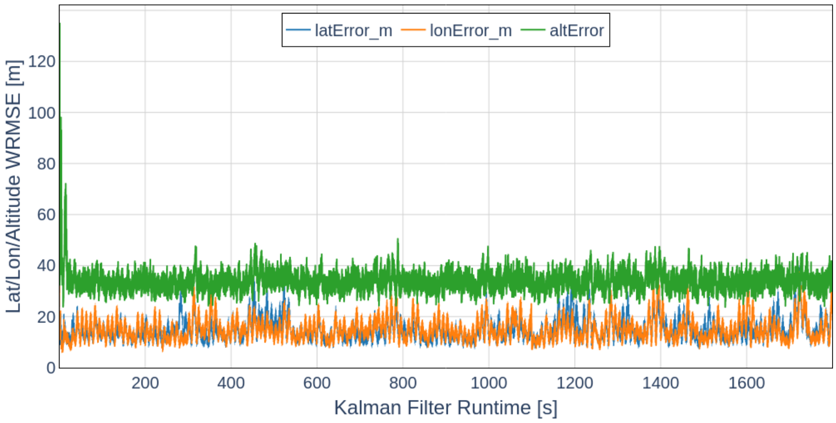
The following sections describe theoretical work that was conducted in 2023.

ADS-B

The Automatic Dependent Surveillance - Broadcast (ADS-B) standard allows airspace operators to monitor their area of responsibility with a high precision and update rate in a very cost efficient way. As is is a quite old protocol, without any modern security measurements in mind, it is prone to attacks which can degrade the airspace security and potentially lead to fatal accidents. Wide-Area Multilateration (WAM) systems, that can mitigate these attack vectors, are usually very expensive and require a complex clock synchronization.
At the institute we investigate a novel approach in which additionally to the aircraft position and velocities the relative clock offsets of the receivers are estimated in an Extended Kalman Filter (EKF). First simulation results, that were presented at the ENC2023, indicate that the system performs very well and might remove the requirement of an external clock synchronization. In Figure 2 some results of a simulation for the German airspace and aircraft trajectories based on data from the OpenskyNetwork are given.
Further work will focus on spoofer and outlier detection and the scalability of the system.



(a) The simulated aircraft trajectories and receiver placement.



(b) The Weighted Root Mean Square Error (WRMSE) of all tracked aircraft positions over time.

Figure 2: ADS-B MLAT simulation setup and results.

Robust Kalman filtering and integrity monitoring for GNSS positioning

Based on the enhanced performance of RTK algorithms in robust Kalman filtering referring to R. Wang et.al. (2023), the robust estimation is further applied to PPP applications. In the continuing work, we focus not only on the adjustment of the measurement noise matrix in stochastic modeling, but also on the confidence domain of estimated states, which is expected to contain the so-called true value under a pre-defined Integrity Risk (IR). Therefore, we exploit the interval bounding analysis for a more realistic assessment of GNSS measurement uncertainties and propagate them from the range-domain into the state-domain. In practice, GNSS measurements are inevitably contaminated by outliers (e.g., multipath effects), resulting in a degradation of Kalman filtering.

Thus, we utilize the polytope-based bounding method for quality control in both pseudorange and carrier-phase measurements. In the fault detection procedure, this polytope bounding method enables to offer geometric constraints by means of the convex optimization. Once an outlier exists, i.e., the remaining residual is beyond the interval error bound, which is derived by a specified IR, the polytope solution can yield an empty set in such faulty case. This property is similar but superior to the classical fault detection commonly using the Chi-square test.

The comparison of these two fault detectors and their performances was shortly presented at the ENC conference. Figure 3 illustrates an example of two bounding methods (i.e., zonotope and polytope) in the interval bounding analysis. Unlike the polytope boundary taking measurement residuals into account, the shape of the zonotope is always centred at the estimated position, and relies only on the satellite geometry and the interval error bound. Subsequently, the polytope bounding method is integrated into a designed Receiver Autonomous Integrity Monitoring (RAIM) framework based on a robust Kalman filter, which involves the protection level computation as well. To validate the effectiveness of this complete RAIM framework, multiple scenarios with simulated and real data have been conducted. The relevant research paper is considered to be submitted to an academic journal in 2024.

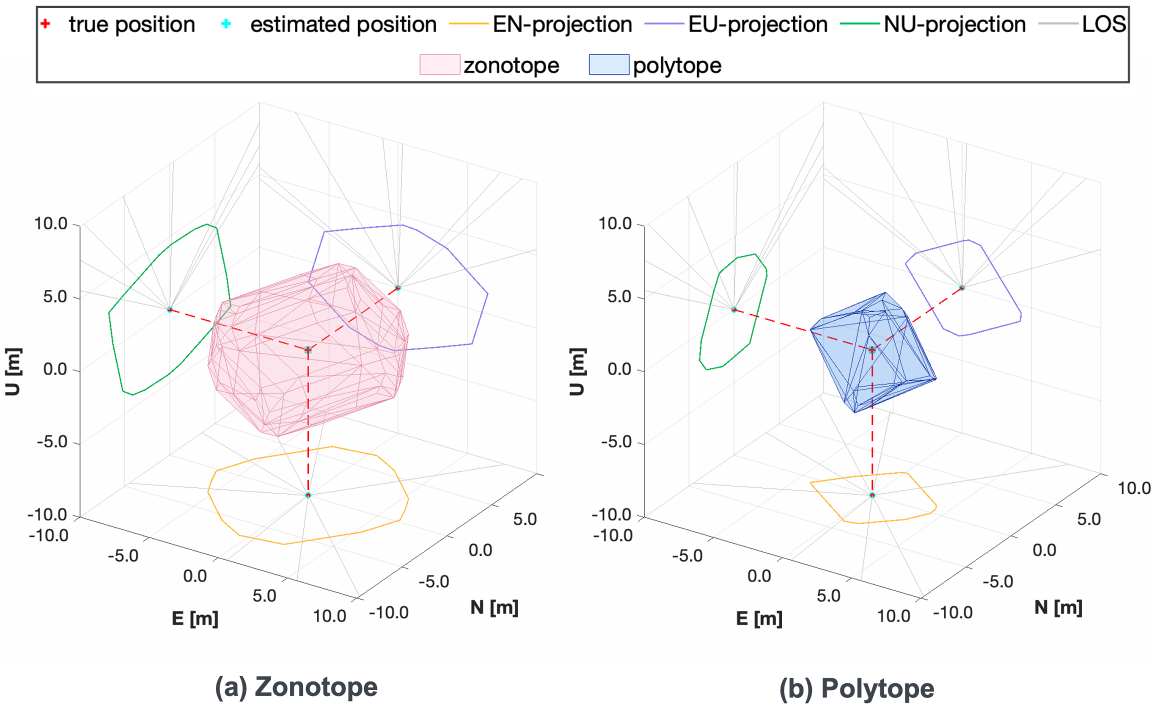


Figure 3: 3D example with respect to the zonotope and polytope solution

Measurement fusion using co-located receivers for improving GNSS meteorology

In 2023, we refined the fusion algorithm on the observation level for the Zenith Wet Delay (ZWD) estimation, and developed a novel model to provide common ZWD estimates on a local scale for our joint Polish-German research project "Simultaneous Troposphere Estimation with Precise Point Positioning" (STEPPP), funded by Deutsche Forschungsgemeinschaft (DFG). The related research has been reported at the EGU conference and submitted to an academic journal with a current status of undergoing review. Considering that tropospheric estimation is prone to be limited due to receiver noises and systematic biases, the proposed fusion model is intended to estimate one common ZWD parameter with less noise for co-located receiver sites.

According to experimental results from simulations and low-cost GNSS receiver field tests, the fusion model outperforms the single receiver PPP model in terms of precision, accuracy and noise level in tropospheric estimation. As depicted in figure 4 for investigating the stability of Zenith Total Delay (ZTD) time series by the overlapping Allan deviation (ADEV), when averaging out more stochastic processes, the fusion curve gradually converges towards the reference curve of Near Real-Time (NRT) ZTDs, and both are more stable than the radiometer curve. On the basis of this fusion approach, further study is in progress.

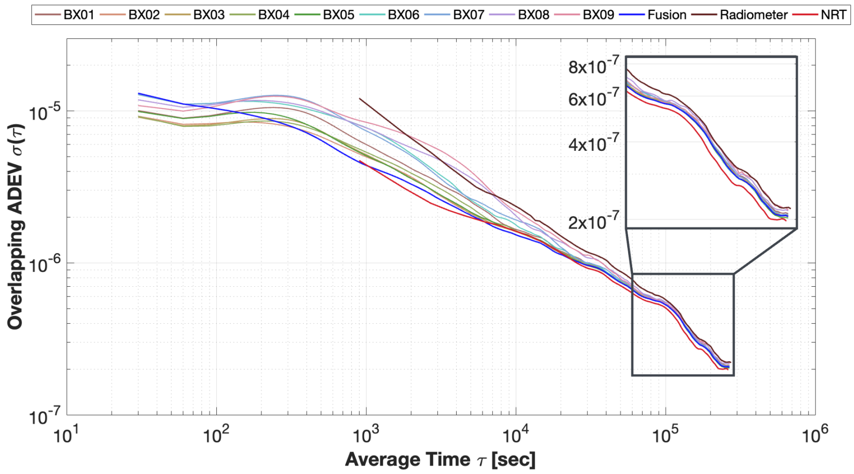


Figure 4: Low-cost demonstration test for 13 days with respect to reference values from the radiometer and NRT ZTDs

Multi-Receiver Precise Baseline Determination

Within the last year, we finished our development on the Multi-Receiver Precise Baseline Determination (MR-PBD) and published it in the Proceedings of the 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023) (M.B. Stucke et al. (2023)). The developed algorithm is capable of fusing the observations of multiple receivers distributed on two spacecraft to a single estimator. We were able to recover extremely precise baselines using this algorithm. Using the MR-PBD, we performed a simultaneous estimation of the inter-spacecraft baseline with either each attitude of the spacecraft or each lever arm of the antennas. This simultanous estimation was not possible before. We analyzed the simultaneous estimation of the inter-spacecraft baseline and both attitudes of the spacecraft and presented the outcomes at the ION GNSS+ 2023 (M.B. Stucke et al. (2023)). Figure 5 depicts the improve of the accuracy of the baseline estimate with an increasing number of antennas mounted on each spacecraft. The results of the simultaneous estimation of the inter-spacecraft baseline and the antenna off-sets of all included antennas were presented at the German Aerospace Congress (DGLRK 2023) (M.B. Stucke et al. (2023)). However, the algorithm appears to diverge if all three of the parameters, the baseline, the attitudes, and the antenna off-sets are estimated at once.

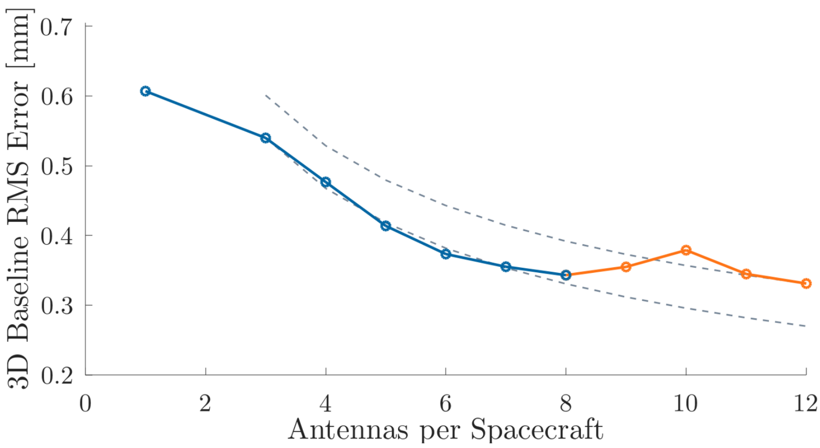


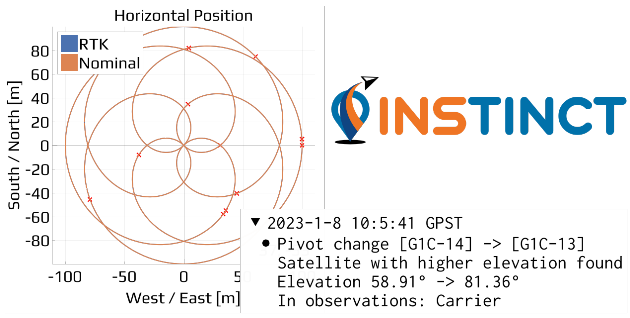
Figure 5: 3D RMS of an inter-spacecraft baseline over the number of included antennas per spacecraft

Research focus: Software development

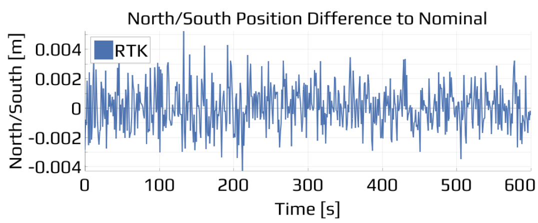
The following sections describe the institute's software development activities in the year 2023.

INSTINCT - INS Toolkit for Integrated Navigation Concepts and Training

After making INSTINCT available to the public last year on GitHub[1], development progressed steadily. New algorithms like an INS/GNSS Tightly-coupled Kalman Filter (TCKF) were developed. Furthermore, the Real-Time Kinematic algorithm is approaching it's final stages of testing and will be released in a big update later in 2024 on GitHub. The documentation will also receive a big overhaul to explain better how to use the software to users and developers.
Apart from algorithms, there were a lot of other improvements. Figure 6a shows the new event system. Algorithms can raise events which can be directly shown in the plots. This provides an easy way to spot problems during algorithm development. When comparing position solutions, it's quite hard to see improvements in plots such as figure 6a. That is why INSTINCT now can plot the difference between solutions, which is shown in figure 6b. The innovative part about this is, that it also works with signals at different data rates. Interpolation of the data is automatically performed in a way which reduces interpolation errors without any need for user input.
Another feature implemented during last year which will be released in the next update is an ublox file reader, so ublox GNSS observations as well as navigation data can be read and used in navigation algorithms. Moreover the ublox observations can be fed into another new node, the RINEX data logger, to write out RINEX obs files. With this, ublox to RINEX conversions can be performed closing a big gap in GNSS processing tooling, as such converters are not widely available.
If you want to stay informed about the development of INSTINCT and not miss updates, please feel free to start the GitHub repository. GitHub releases with changelogs and precompiled executables are planned, so it is worth adding the repository to the watch list to get notified when the update is happening.



(a) Plot with events showing when hovering with mouse



(b) Plotting of differences

Figure 6: New features of INSTINCT

PODCAST - Precise Orbit Determination for Complex and Agile Satellite Technology

POD - Precise Orbit Determination

Within the last year, significant progress was achieved with respect to the Precise Orbit Determination (POD) of non-agile and agile satellites. First, the modeling of the forces that Low Earth Orbit (LEO) satellites experience in orbit was partially reworked and fully validated. Additional changes include time-variable gravity potentials, new tide models, as well as highly precise non-gravitational models based on ray-tracing. Figure 7 depicts the error of the orbit propagation of Sentinel-6A for 24h in

[1] https://github.com/UniStuttgart-INS/INSTINCT

radial, along-track, and cross-track direction. This demonstrates the good performance and validity of the implemented models.

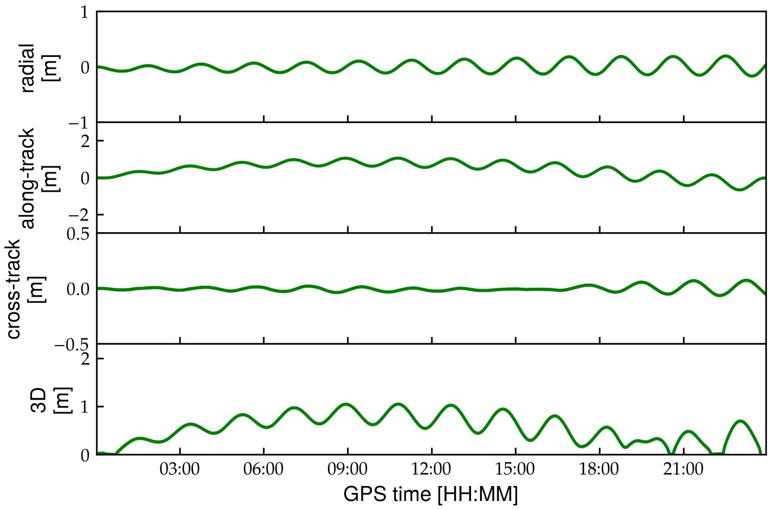


Figure 7: Error in the fully propagated trajectory of Sentinel-6A compared to the POD solution.

The POD of agile satellites was investigated in-depth based on HIL simulations and realistic missions scenarios. The main results of this study were presented at the ION GNSS+ 2023 (K. Gutsche et. al. , 2023). Additionally, the POD of agile satellites was demonstrated using a low-cost GNSS receiver (K. Gutsche et. al. , 2023).
Finally, the POD of non-agile satellites was further validated based on in-orbit data from both Sentinel-3 and Sentinel-6. The improvements in the software lead to a significant reduction in the estimation error, which is now below 2 cm 3D RMS. Figure 8 displays this error in radial, along-track, and cross-track direction for Sentinel-6A.

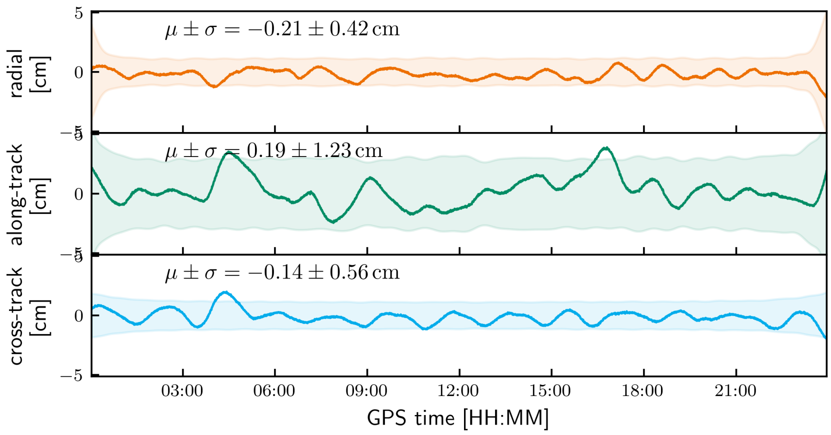


Figure 8: Estimation error of Sentinel-6A with respect to the solution of the Copernicus POD Quality Working Group on 19th of November 2021.

PBD - Precise Baseline Determination

The precise baseline determination part within our in-house estimator PODCAST was enhanced by algorithms of the MR-PBD introduced in the subsection Multi-Receiver Precise Baseline Determination. Furthermore, the development of the PBD solution is at the final stage. The validation with in-orbit data is coming in the first quarter of 2024.

Development of a new mapping function for troposphere studies

To overcome the limitations in the traditional two-axis gradient model, we proposed the B-spline Mapping Function (BMF) as an alternative to represent the asymmetry of the tropospheric delay. After experimental verification with a large amount of data, BMF turns out to have the following advantages:

- It can improve the repeatability of PPP positioning results, whereby the repeatability is about twice as high as with the gradient model. Under extreme weather conditions, this improvement is even higher.
- BMF can significantly reduce the correlation between weather conditions and positioning accuracy, which leads to weaken the adverse impact of extreme weather conditions on the positioning accuracy.
- BMF can normalize the distribution of post-fit residuals and make it closer to Gaussian distribution.
- After applying the azimuth-dependent weighting model, BMF can accelerate the convergence time of PPP.
- BMF can provide rich atmospheric information, allowing the tropospheric gradient to be expanded into divergence to more accurately describe tropospheric asymmetry.

In figure 9 representative BMF results in comparison with results of standard strategies, e.g. NONE (no troposphere model), GRAD (two-axis gradient model) and GRD2 (2nd-order gradient model) are given.

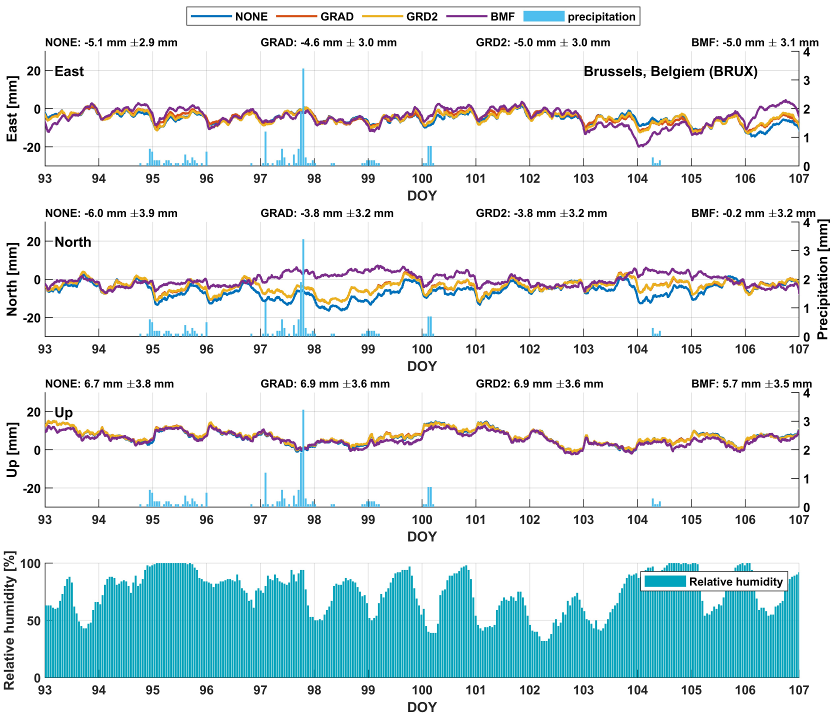


Figure 9: Coordinate time series of IGS stations in Brussels, Belgium (BRUX, upper) during 2.Apr. - 16.Apr, 2022. Right y-axis refers to the hourly-average precipitation during the timespan. The accuracies are shown in “NAME: bias ± uncertainty”

Sensor fusion of multiple inertial measurement units

Urban air mobility has stringent requirements on accuracy, reliability and integrity of a navigation solution, while also keeping costs low. Therefore, a fusion algorithm for multiple low-cost inertial measurement units (IMUs) was developed. In our approach, the IMUs are fused by assuming acceleration and angular rate as integrated random walk processes. Additionally, relative biases between each IMU and a reference IMU are estimated. Figure 10 shows the corresponding filter architecture. As can be seen, the IMUs receive a common time stamp from GPS. This is necessary for synchronization of the IMUs. Each IMU provides specific force and angular rate measurements to the "Multi-IMU Fusion Filter". The output of the fusion filter is virtually the same as from a single-IMU, which is therefore called "Virtual IMU" (VIMU). Its output is then fed into a Tightly Coupled Kalman Filter (TCKF), where it is fused with GPS observations to calculate a navigation solution.

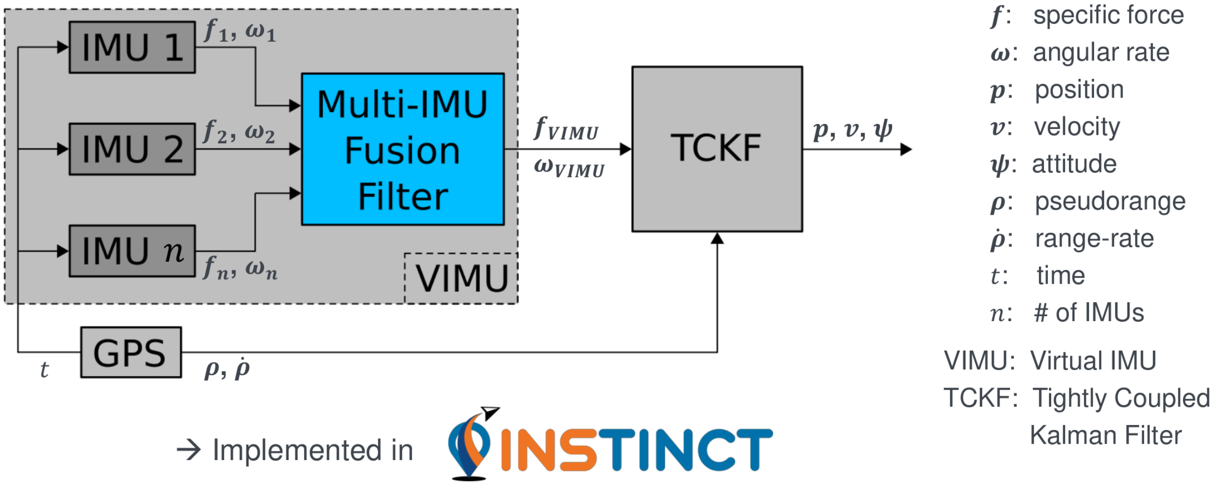


Figure 10: Multi-IMU filter architecture.

This filter architecture was implemented in INSTINCT and validated in simulation at first, using GPS observations generated by the institute's Spirent SimGEN simulator.

Research focus: Applications

The following sections describe applications on which the INS worked on in the year 2023.

Flight Test with the multiple inertial measurement unit setup

After the successful validation of the multiple inertial measurement unit concept, flight tests were performed. The test setup consisted of:

- Multi-IMU: consisting of five identical low-cost IMUs (developed at the institute)
- VectorNav VN310E: high-grade IMU as a reference
- Emlid Reach RS2 + M2: post-processed kinematics, also as a reference

These sensors and receivers were flown on the institute's Prism Coaxial X8 drone at the Ihinger Hof. The gathered data were then post-processed in INSTINCT, where the TCKF-VIMU solution is compared to another solution with the TCKF, that is calculated using only a single-IMU of the Multi-IMU array. Figure 11 shows the altitude and the altitude error of the test flight. The latter shows the differences of each TCKF solution to the PPK solution. After take-off the TCKF solutions converge quickly and both, the VIMU and single-IMU cases, are close to the PPK solution. Comparing the position errors, the TCKF-VIMU is in Lat/Lon/Alt better than the TCKF-single-IMU by 2% / 1% / 3%. Despite the slightly reduced position errors, the Multi-IMU's filter architecture is resilient regarding the loss of one of the low-cost IMU.

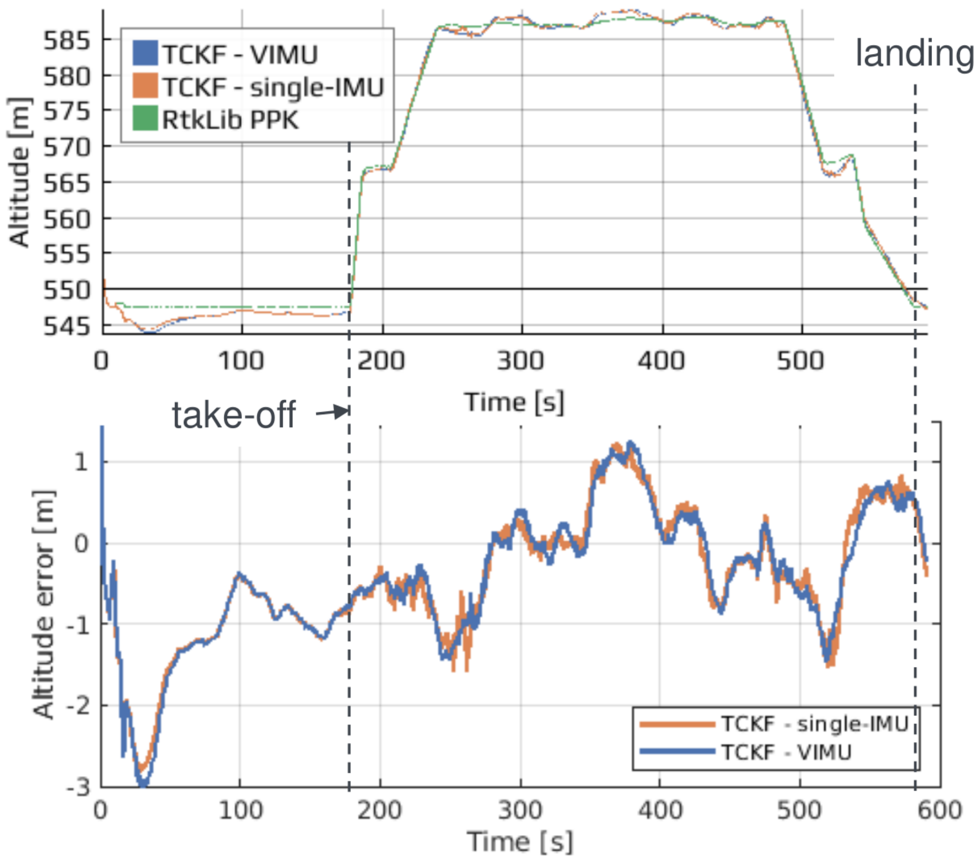


Figure 11: Altitude and altitude error of TCKF-VIMU and TCKF-single-IMU.

List of Publications

Gutsche K., Hobiger T., Winkler S., *Addressing Inaccurate Phase Center Offsets in Precise Orbit Determination for Agile Satellite Missions*, Proceedings of the 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023), 3082-3095, Denver, USA.

Stucke M.B., Hobiger T., Möller G, Gutsche K., Winkler S, *Multi-Receiver Precise Baseline Determination: Coupled Baseline an Attitude Estimation with a Low-Cost Off-The-Shelf GNSS Receiver*, Proceedings of the 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023), 3082-3095, Denver, USA.

Wang R., Becker D., and Hobiger T., *Stochastic modeling with robust Kalman filter for real-time kinematic GPS single-frequency positioning*, GPS Solutions, vol. 27, no. 3, p. 153, 2023.

List of Presentations

Gutsche K., Hobiger T., Möller G, Winkler S., *Precise Orbit Determination of Agile LEO Satellites Using Simulations with a Low-Cost Commercial Off-the-Shelf Receiver*, German Aerospace Congress (DLRK) 2023, Stuttgart, Germany.

He S., Becker D., Hobiger T. *Modelling asymmetric troposphere delays by means of B-splines*, 28th IUGG General Assembly 2023, Berlin, Germany.

Maier M., Hobiger T., Topp T. and Thomas M., *Resilient navigation through a novel fusion approach for multiple inertial measurement units*, European Navigation Conference 2023, Noordwijk, Netherlands.

Stucke M.B., Hobiger T., Möller G, Gutsche K., Winkler S, *Exploitation of a Low-Cost Off-The-Shelf GNSS Receiver for Coupled Baseline and Attitude Estimation*, German Aerospace Congress (DLRK) 2023, Stuttgart, Germany.

Wang R., Becker D., and Hobiger T., *Interval bounding analysis for precise point positioning*, European Navigation Conference 2023, Noordwijk, Netherlands.

Wang R., Becker D., and Hobiger T., *Stochastic modeling with robust Kalman filter for real-time kinematic GPS single-frequency positioning*. GPS Solutions, 27(3), Article 3. https://doi.org/10.1007/s10291-023-01479-5.

Wang R., Hobiger T., Marut G., and Hadas T., *Improving GNSS meteorology by fusing measurements of multi-receiver sites on the observation level*, EGU General Assembly 2023, Vienna, Austria.

Teaching and Supervision

During the past year, the downward trend in the number of students in the three geodesy degree programs has unfortunately continued. This has various effects on the form of teaching. In foundation courses with few participants, students have an excellent student-to-staff ratio. Elective subjects offered the opportunity to teach content individually and to support the students. In the navigation specialization module, e.g. we were able to cater specifically to students' wishes and combine the theory of filter techniques with practical exercises on the industry-standard GNSS simulators that are available through Spirent's Academia Programme and Orolia's Academic Partnership Program. Ideas on navigation topics were developed to give geodesy students an insight into non-standard disciplines. This allowed a small group to focus specifically on signal propagation and antenna technology, topics that are essential in the practice of navigation. In future, the focus will be on skills in electronics and electrical engineering.

The following parts of this section list student thesis projects which were completed in 2023 and summarize the teaching activities of the institute.

Bachelor Theses

- NONE

Master Theses

- Ghribi, Adam: *Adaptive Kalman Filtering for Precise Orbit Determination of Low Earth Satellites* (Supervisor: K. Gutsche)
- Lauterbach, Mike: *Evaluation von RTK-Szenarien durch Generation an verschiedenen GNSS-Simulatoren* (Supervisor: D. Becker)
- Seyfried, Michael: *Echtzeit-Charakterisierung von IMUs für hochgenaue Sensorfusionsalgorithmen* (Supervisors: M. Maier, T. Topp)

Lectures offered

Lecture name	BSc /MSc	Person responsible	Lecture (h)	Exercise (h)
Bachelor Geodesy & Geoinformatics:				
Adjustment Theory I	BSc	Hobiger, Becker	2	1
Adjustment Theory II	BSc	Hobiger, Becker	2	1
Fundamentals of Navigation	BSc	Hobiger, Becker, Stucke	2	2
Integrated Fieldwork	BSc	Sonnleitner, Topp	10 days	
Introduction of Geodesy and Geoinformatic	BSc	Hobiger, Becker	2	2
Measurement Techniques II	BSc	Wehr, Sonnleitner, Klink	2	2
Valuation	BSc	Caesperlein	1	0
Master Geodesy & Geoinformatics:				
Filtering Techniques	MSc	Hobiger, Topp	1	1
Inertial Navigation	MSc	Hobiger, Topp	1	1
Inertial Sensors	MSc	Hobiger	1	0
Integrated Navigation	MSc	Hobiger, Topp, Becker	1	1
Measurement Techniques in Navigation	MSc	Wehr, Klink	1	3
Satellite Navigation	MSc	Hobiger, Becker, Gutsche	1	1
Signal Propagation and Antenna Theory	MSc	Hobiger, Becker, Klink	1	1
State Estimation in Dynamic Systems	MSc	Hobiger, Maier, Gutsche	2	1
Object-oriented Programming in C++	MSc	Hobiger, Sonnleitner, Topp	1	3
Property Valuation	MSc	Caesperlein	1	0
Simultaneous Localization and Mapping (SLAM)	MSc	Hobiger, Maier, Klink	1	1
Master GeoEngine:				
Dynamic System Estimation	Msc	Hobiger, Maier, Stucke	2	1
Integrated Positioning and Navigation	MSc	Hobiger, Topp	2	1
Satellite Navigation	MSc	Hobiger, Becker, Stucke	2	1
Master Aerospace Engineering:				
Inertial Navigation	MSc	Hobiger	2	0
Satellite Navigation	MSc	Hobiger	2	0
Master Electromobility:				
Navigation of Surface Vehicles	MSc	Becker	2	0
Satellite Navigation	MSc	Hobiger	2	0

Activities in National and International Organizations

- Prof. Hobiger
  - 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