Annual Report
Institute of Navigation
2022

INS

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Annual Report 2022

of the

Institute of Navigation (INS)

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Staff in 2022

Management	**Role**
Prof. Dr.techn. Thomas Hobiger	Head of the institute, Dean of Studies (since Oct. 2021)
Dr.-Ing. Aloysius Wehr	Deputy
Prof.i.R. Dr.-Ing. Alfred Kleusberg	Retired professor
M.A. Dagmar Epple (until Feb. 2022)	Secretary
Mina Sungur (from July 2022)	Secretary

Academic Staff	**Research Focus**
Dipl.-Ing. Doris Becker	Navigation Systems
Dipl.-Ing. (FH) Martin Thomas	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 (from May 2022)	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	Head of ZLW
Michael Pfeiffer	Mechanician Master
Sebastian Schneider	Electrician
Dipl.-Ing. (FH) Martin Thomas	Electrical engineer

External lecturers	**Affiliation**
Dipl.-Ing. Steffen Bolenz	Stadtmessungsamt, Stuttgart
Dr. Toni Caesperlein	Dr. Koch Immobilienbewertung, Esslingen

Guests	**Affiliation**
M.Sc. Grzegorz Marut (11.7.-5.8.2022)	University of Wroclaw, Poland
Dr. Gregor Möller (12.-13.9.2022)	ETH Zürich, Schweiz

Preface

This report summarizes the activities of the Institute of Navigation (INS) in the year 2022. With COVID-19 in the past and all restrictions for teaching and office work lifted, we returned to operating like before the pandemic. Thus, meetings could be held in person, conference attendance became possible again, and social activities in our group were recommenced.

We also saw our research team grow and new projects could be acquired, paving the way for a sustainable growth of our group in the next years. We could also streamline some of our internal processes and reduce administrative burdens by making use of agile planning tools, self-hosted cloud solutions, and a flexible version control system. This system also allows us to deliver clean and well-tested code, that complies with industry standards. Research highlights, which are described in greater detail in this report, cover a wide range of topics, including GNSS, sensor fusion, precise orbit determination, airspace monitoring, robust real-time kinematic GNSS positioning, precise point positioning, troposphere estimation.

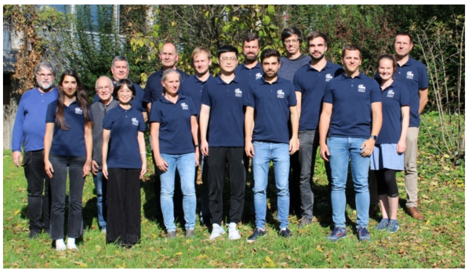

Figure 1: Group photo of almost all INS members.

GNSS simulators

The Institute of Navigation currently operates an industry-compatible hardware GNSS simulator and an additional GNSS simulator, which can be used for educational purposes or testing. While the hardware-GNSS-simulator from Spirent Communications is used heavily in research projects dealing with precise orbit determination, autonomous flight, and GNSS studies dealing with the atmosphere, the Skydel simulator, which is provided under the Orolia Academic Partnership Program (OAPP), is mostly being used for educational purposes.

In order to intensify the cooperation with the manufacturer of the hardware simulator, the Institute of Navigation has joined the Spirent Academia Programme in 2022 under which both partners will cooperate on research and educational topics related to the simulation of real-world GNSS scenarios. The program will provide PhD students and researchers from the Institute of Navigation exclusive insights into Spirent's simulation tools and algorithms while providing feedback to Spirent engineers to further enhance their software and hardware suites. Figure 2 shows the usage in hours of both simulators. While the Spirent hardware simulator was used in total for more than 47 days, the Orolia solution was only used for about a week of computation time. The heavy load of the first can be explained by very extensive simulations of LEO spacecrafts and unmanned aerial vehicles, whereas the Skydel simulator was only used in smaller students' projects and bachelor or master thesis projects.

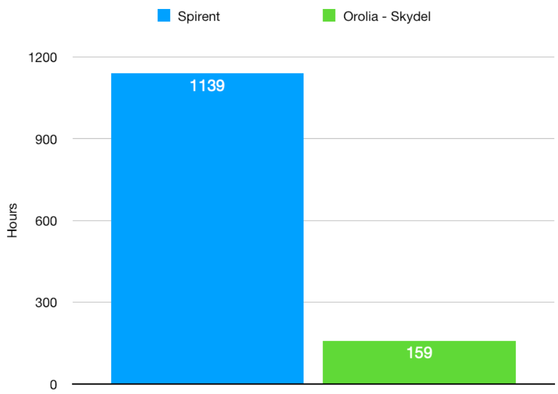

Figure 2: Usage (in hours) of the two GNSS simulators in 2022.

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 3 depicts those focus areas, which are grouped around the topics of "positioning, navigation, and timing".

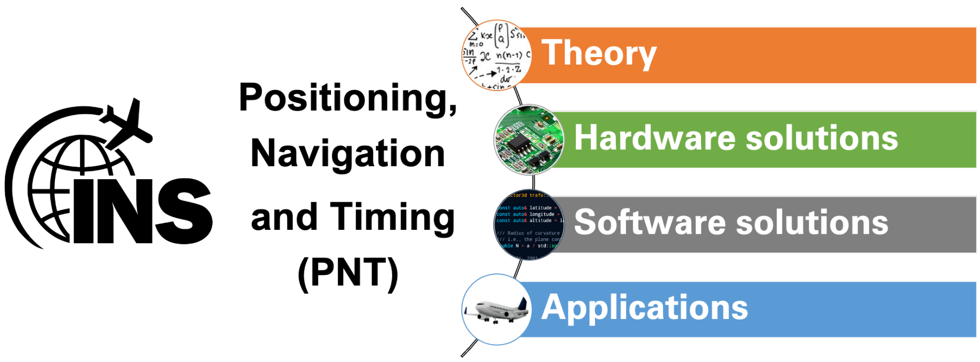

Figure 3: INS focus areas to which the institute is actively contributing in the form of research projects.

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 2022.

ADS-B

Since the end of the year 2020, a large portion of commercial aircraft operating in the European sky airspace have to be equipped with an Automatic Dependent Surveillance - Broadcast (ADS-B) transponder. This obligation has pushed forward the amount of performed flights during which ADS-B messages were broadcasted to about 94 % at the end of 2022. Besides professional dedicated receivers, these signals can be detected and decoded by low-cost general-purpose hardware as installed on the roof of the institute[1]. The institute and many others feed the gathered data into the OpenSky Network database, building up an immense open-access dataset of real-world air traffic control data.

[1] `https://opensky-network.org/receiver-profile?s=-1408232197`

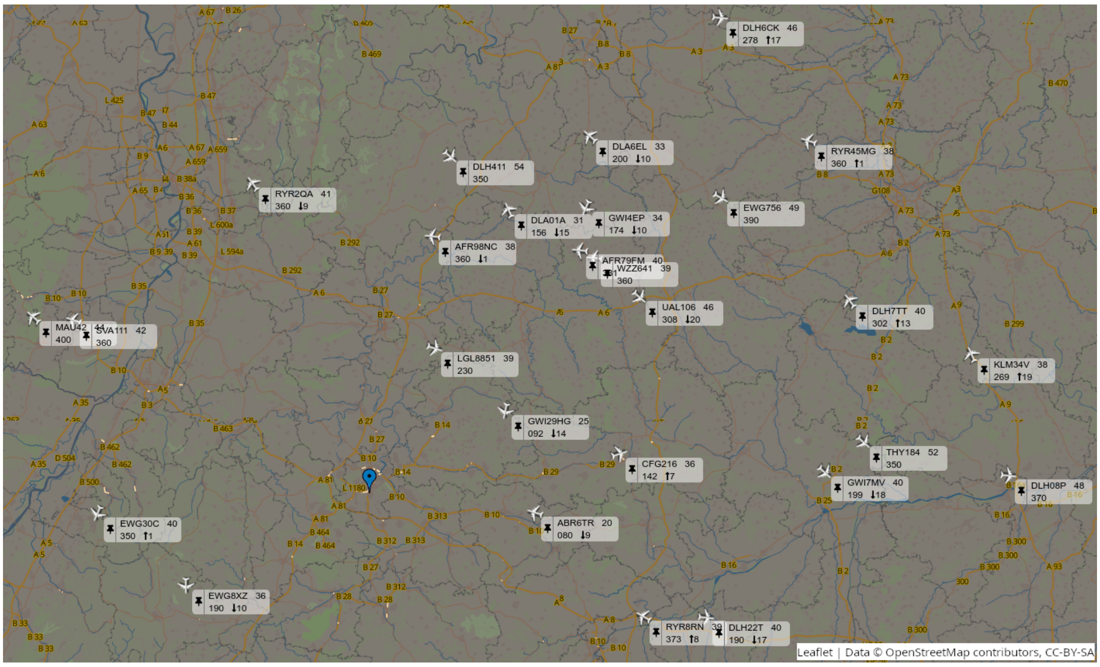

Figure 4: Snapshot of the airspace around Stuttgart monitored by the ADS-B receiver on the roof of the institute and fed into the open-access OpenSky Network database.

This data can be used for a large variety of research purposes. At the institute, it is used as a basis for in-depth performance analysis of a Time-Differential-Of-Arrival (TDOA) localization system built upon the emitted ADS-B messages of aircraft. One of the research focuses is the low-cost clock synchronization of the receiver network. Another focus is the development of a precise, reliable solution that can detect and mitigate attempts of spoofing.

Stochastic modeling with a robust Kalman filter for RTK positioning

In standard Real-Time Kinematic (RTK) processing, the measurement noise Variance-Covariance (VC) matrix is based on the satellite elevation-dependent function. However, this stochastic model cannot always be appropriate in challenging environments, such as urban areas. To improve the reliability of ambiguity resolution and the positioning accuracy in dynamics, the adaptation of the measurement noise VC matrix is applied by choosing a moving estimation window. Besides, the performance of Kalman filtering is prone to degrade when measurements are contaminated by outliers. To resist such effects, the Institute of Geodesy and Geophysics (IGG) III scheme is utilized. In both simulated and practical tests, this proposed approach can enhance the robustness of filtering, as well as achieve higher ambiguity fixing rates. The relevant research paper has been submitted to an academic journal and is currently undergoing review.

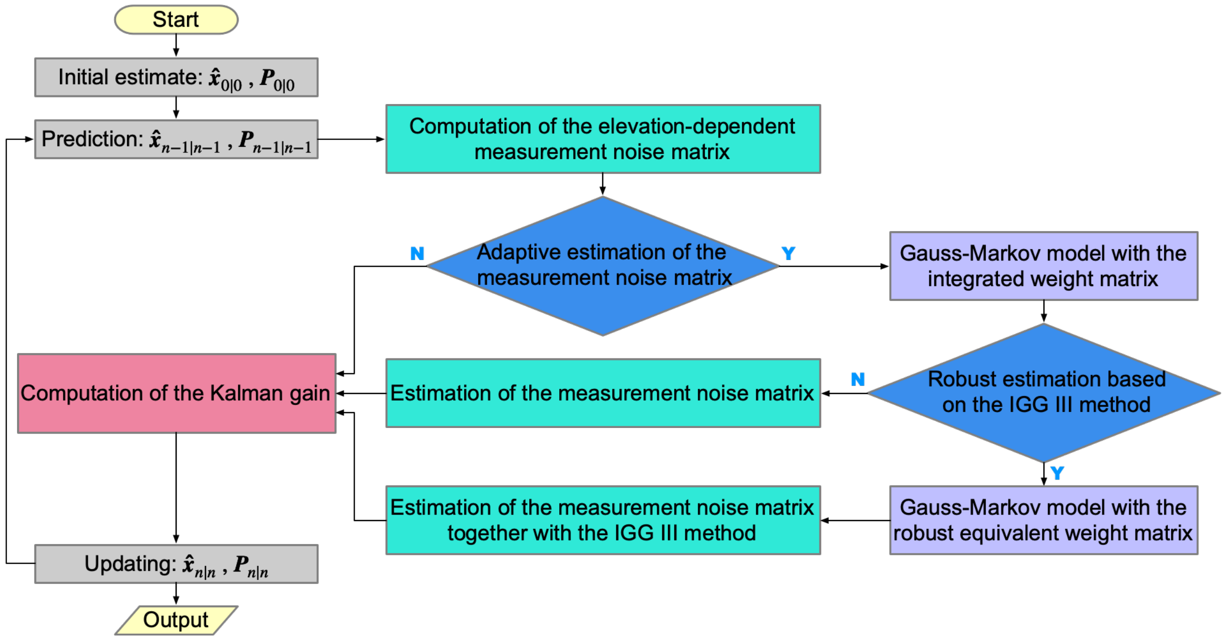

Figure 5: Filter flowchart with three different measurement noise VC matrices

Multi-Receiver Fusion for Improved Tropospheric Modeling

In the STEPPP project, a Precise Point Positioning (PPP) algorithm based on an Extended Kalman Filter (EKF) has been implemented. The EKF can achieve millimeter-accurate positioning results, as well as provide time series of Zenith Wet Delay (ZWD) for meteorologic applications. However, either the precision or accuracy of such ZWD estimates is limited due to receiver noise and system characteristics like cycle slips. Thus, the INS developed a novel approach that combines observations from multiple receivers to estimate a common ZWD parameter, which is superior compared to single receiver estimates in terms of precision and accuracy. This approach can be extended to larger networks and also have broader implications for GNSS analysis, such as improving positioning accuracy and precision in challenging environments. More research on this topic is undergoing.

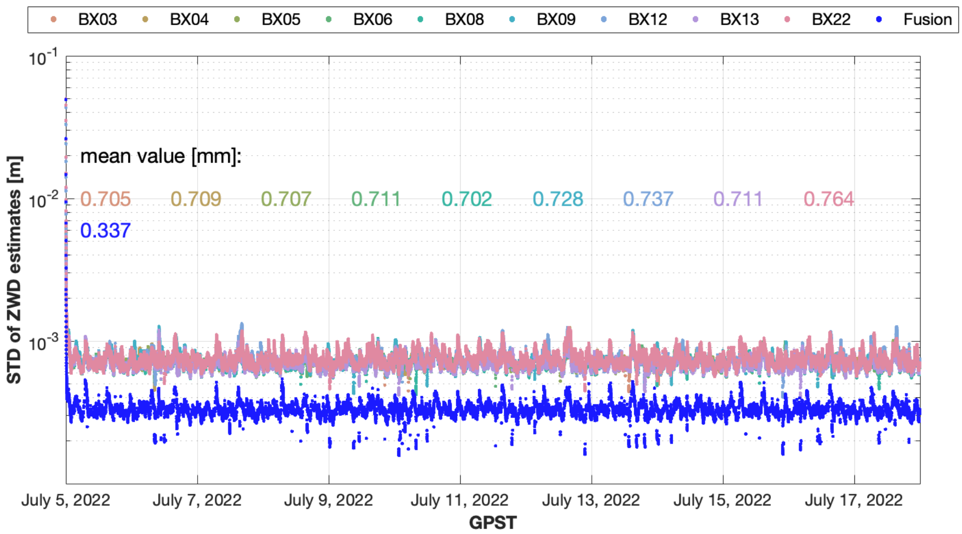

Figure 6: Standard Deviations (STD) of ZWD estimates from PPP and Fusion solutions for multiple low-cost receivers

Research focus: Hardware development

The following sections describe the institute's hardware development activities in the year 2022.

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

The development of a subsystem to aid in the autonomous landing, which is a requirement for the project CNSAlpha, was continued with hardware improvements and simulation tests. In 2022 the demonstration hardware was completed comprising the RF- input/output module, the IF- and digitizer board, and the logic board (see Figure 7). Both the RF- input/output module and the digitizer board were developed and manufactured by the INS, whereas the logic board is the commercial FPGA development board Arty Z7 with Xlinx ZYNQ XC7Z020. Signal processing algorithms were implemented in the logic board's FPGA and tested.

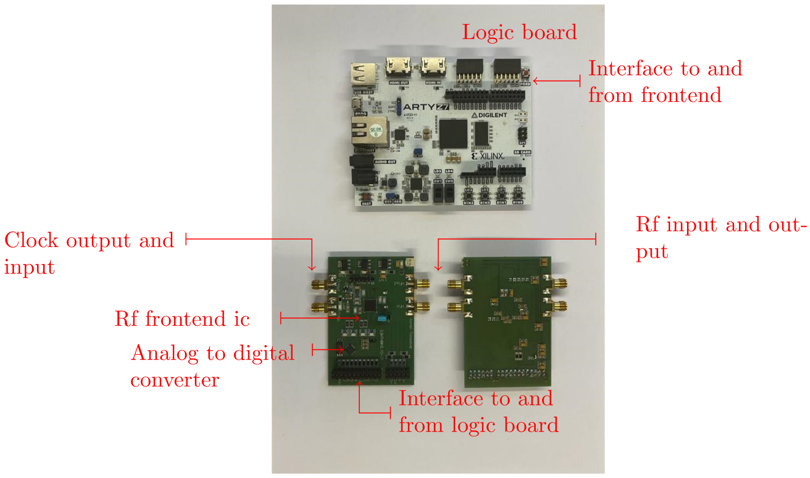

Figure 7: Demonstration hardware, comprising the RF- input/output module, the IF- and digitizer board, and the logic board.

Parallel to this work, various direct and iterative algorithms for the position calculation were studied by running simulations concerning the achievable positioning accuracy. Simulations evidenced that both, the geometric placement of the transmitters and the slant range measurement accuracy, primarily determine the system positioning performance. To underline the simulation results, experiments will be conducted with the hardware shown in Figure 7 in the year 2023. A one-way slant ranging testbed for a free space signal transmission will be set up. Here the receiver and its antenna will be mounted on a linear motion unit and moved with a resolution better than a tenth of a millimeter, whereas the antenna of the transmitter remains at a fixed position. Measured phase differences between the transmitted and received signal, together with moving steps of the linear motion unit, will be logged in a file. This data will be used to determine the ranging performance achieved by the hardware and the software programming of the FPGA of the logic board. After successfully completing the laboratory tests, field tests will be carried out with a multiple transmitter setup.

Time synchronization of different independent IMUs using GPS time

Setting up multi sensor systems on mobile platforms requires accurate time synchronization for accurate measurements. Therefore, the INS developed a software-based synchronization using a microcontroller and a GNSS receiver. The GNSS receiver provides a GPS time that is very accurate, but only available once a second. In contrast, the sensors offer much higher sampling rates of more than 100 kHz but do not exhibit any timing as accurate as GPS time. The developed very sophisticated time synchronization concept is exemplified based on a cluster of five Inertial Measurement Units (IMUs), each set up in micro-electro-mechanical systems technology (MEMS technology). The synchronization problem is solved by using a fast hardware counter for generating the time stamps of the sensor measurements. The values of the counter are synchronized to the GPS time by the pulse per second pulses (PPS) output by the GPS receiver. As PPS is directly linked to GPS time, the user now obtains measurement data in the GPS timeframe. This synchronization works either online or offline. In the offline case, the datasets' counter values of the measurements and the measurements themselves, as well as the counter values of the PPS pulses and the associated GPS time can be stored in separate files. The synchronization is carried out offline by the same algorithm used in the online case, i.e. by linking the counter values of the measurements to the PPS and by that also to GPS time. Figure 8 shows an experimental setup comprising five IMUs (MPU 6050, TDK InvenSense), a GPS receiver (LEA 6T, ublox) with antenna, as well as the microcontroller board Arduino MEGA 2560 based on the ATmega2560 with Arduino shield and with interfaces to the IMUs and the GPS receiver. Figure 9 shows a typical synchronized data output of an IMU.

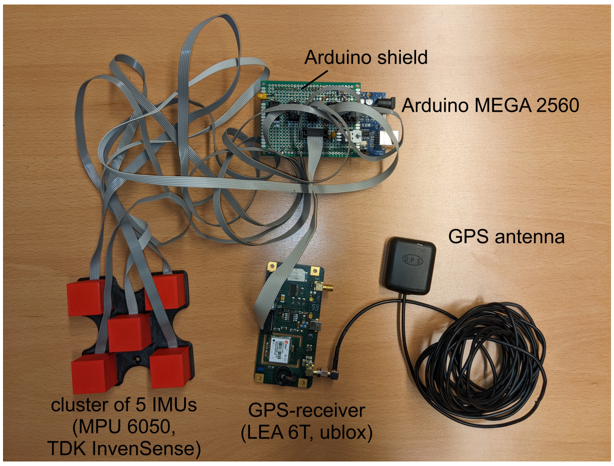

Figure 8: Experimental setup for the verification of the synchronization method

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PPS 1000408
62899.019531 ACX 1.205 ACY 0.129 ACZ 10.802 GyX -507.000 GyY 315.000 GyZ -53.000
62899.070312 ACX 1.174 ACY 0.139 ACZ 10.556 GyX -504.000 GyY 278.000 GyZ 12.000
GPGGA,172819.00,4854.00945,N,00912.28280,E,1,09,1.15,323.0,M,47.6,M,,*5C
gps-sekunden  62899
62899.121093 ACX 1.154 ACY 0.117 ACZ 10.656 GyX -501.000 GyY 289.000 GyZ -82.000
62899.171875 ACX 1.157 ACY 0.081 ACZ 10.719 GyX -511.000 GyY 306.000 GyZ -10.000
62899.218750 ACX 1.166 ACY 0.151 ACZ 10.671 GyX -517.000 GyY 309.000 GyZ -59.000
62899.269531 ACX 1.107 ACY 0.122 ACZ 10.592 GyX -504.000 GyY 299.000 GyZ -7.000
62899.320312 ACX 1.186 ACY 0.115 ACZ 10.692 GyX -513.000 GyY 301.000 GyZ -67.000
62899.371093 ACX 1.140 ACY 0.069 ACZ 10.731 GyX -538.000 GyY 305.000 GyZ -3.000
62899.421875 ACX 1.164 ACY 0.125 ACZ 10.702 GyX -498.000 GyY 305.000 GyZ -47.000
62899.468750 ACX 1.150 ACY 0.115 ACZ 10.632 GyX -519.000 GyY 306.000 GyZ -28.000
62899.519531 ACX 1.164 ACY 0.081 ACZ 10.738 GyX -511.000 GyY 309.000 GyZ 4.000
62899.570312 ACX 1.162 ACY 0.132 ACZ 10.707 GyX -520.000 GyY 309.000 GyZ -43.000
62899.621093 ACX 1.128 ACY 0.134 ACZ 10.690 GyX -501.000 GyY 302.000 GyZ -14.000
62899.671875 ACX 1.219 ACY 0.125 ACZ 10.750 GyX -534.000 GyY 318.000 GyZ -29.000
62899.718750 ACX 1.071 ACY 0.050 ACZ 10.723 GyX -493.000 GyY 273.000 GyZ -10.000
62899.769531 ACX 1.162 ACY 0.115 ACZ 10.769 GyX -508.000 GyY 326.000 GyZ -67.000
62899.820312 ACX 1.131 ACY 0.091 ACZ 10.654 GyX -527.000 GyY 307.000 GyZ 6.000
62899.871093 ACX 1.138 ACY 0.137 ACZ 10.695 GyX -531.000 GyY 304.000 GyZ -55.000
62899.921875 ACX 1.133 ACY 0.149 ACZ 10.695 GyX -520.000 GyY 301.000 GyZ -2.000
62899.968750 ACX 1.147 ACY 0.105 ACZ 10.690 GyX -516.000 GyY 297.000 GyZ -40.000
synchr. time            accelerations                      angular rates
```

Figure 9: Typical synchronized data output

Research focus: Software development

The following sections describe the institute's software development activities in the year 2022.

INSTINCT - INS Toolkit for Integrated Navigation Concepts and Training

The in-house navigation software framework INSTINCT continues to improve. The focus of last year's efforts was reliability, extensibility, and performance. To achieve this, INSTINCT utilizes the "Flow-based Programming" paradigm (FBP). The paradigm is described in more detail in older annual reports of the institute. In short, functionality is bundled into modules, so-called nodes, which communicate over links between each other. Data flowing over the links trigger calculations in the nodes, which is the reason why it is called flow-based programming. FBP was used inside INSTINCT from the start, but now we completely utilize its benefits. The additional abstraction layer of FBP enables us to run all nodes in parallel. This is especially useful when running INSTINCT on Single-board Computers like a Raspberry Pi, which has multiple but slow CPU cores. Now we can read data from sensors, pre-process them, and run the final sensor fusion algorithm in parallel. This increases the performance depending on the used nodes by more than a factor of 2.

Moreover, INSTINCT was finally publicly released on the institute's GitHub (`https://github.com/UniStuttgart-INS/INSTINCT`). There, information on how to build the software and also its documentation can be found. The institute will continue to maintain the repository and update it with new functionality such as RTK, tightly-coupled INS/GNSS, and multi-IMU sensor fusion algorithms, which are already available on our internal development version but not yet publicly available. Further, with the publicly available GitHub repository, we hope to enable future collaboration and attract developers who make pull requests to fix bugs and/or to add new functionality.

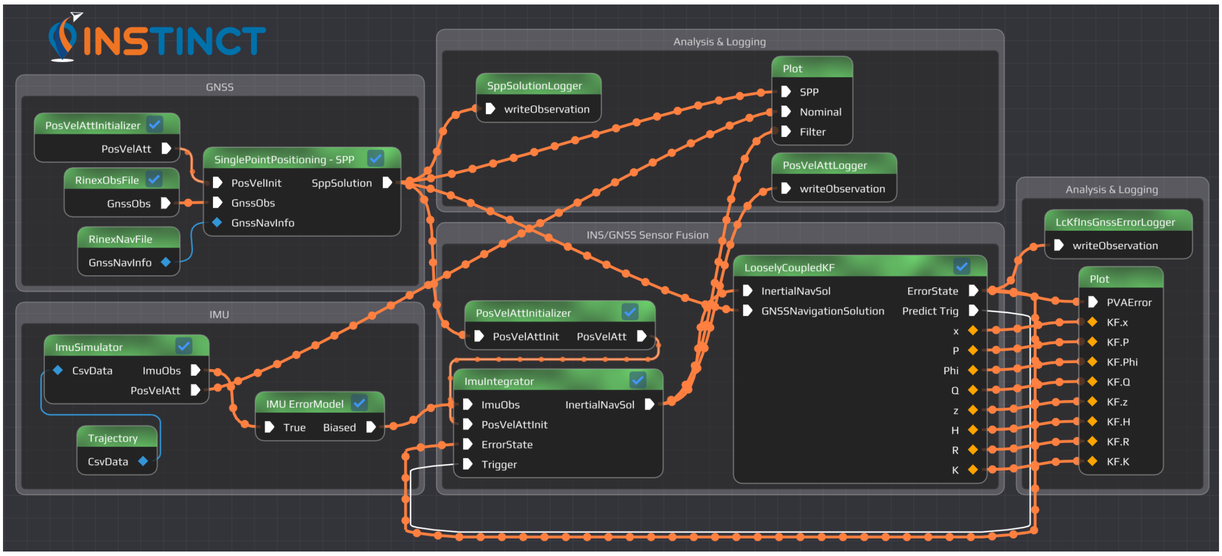

Figure 10: An example flow inside INSTINCT of an INS/GNSS loosely-coupled sensor fusion algorithm

PODCAST - Precise Orbit Determination for Complex and Agile Satellite Technology

In the previous year, the Precise Orbit Determination (POD) capabilities of PODCAST have been significantly improved. The main progress with respect to the previous year was the incorporation of carrier-phase measurements. To utilize these highly precise measurements, PODCAST now features all measurement models needed for this type of measurement. Additionally, the associated carrier-phase ambiguities can be estimated in the orbit determination process as float values. The precise

GNSS products from the International GNSS Service (IGS) can now also be used within PODCAST to further improve the POD performance. To validate the POD within PODCAST, we used a Sentinel-3A trajectory and simulated corresponding measurements using our Spirent simulator. The resulting POD accuracy based on the ionosphere-free combination of these simulated pseudorange and carrier-phase measurements is depicted in Figure 11. A second POD solution based on in-orbit measurements is displayed in Figure 12. Further improvements that are expected to benefit the POD performance are planned for the coming year. These include a robust outlier detection, cycle slip detection, as well as an investigation of POD for agile satellite missions.

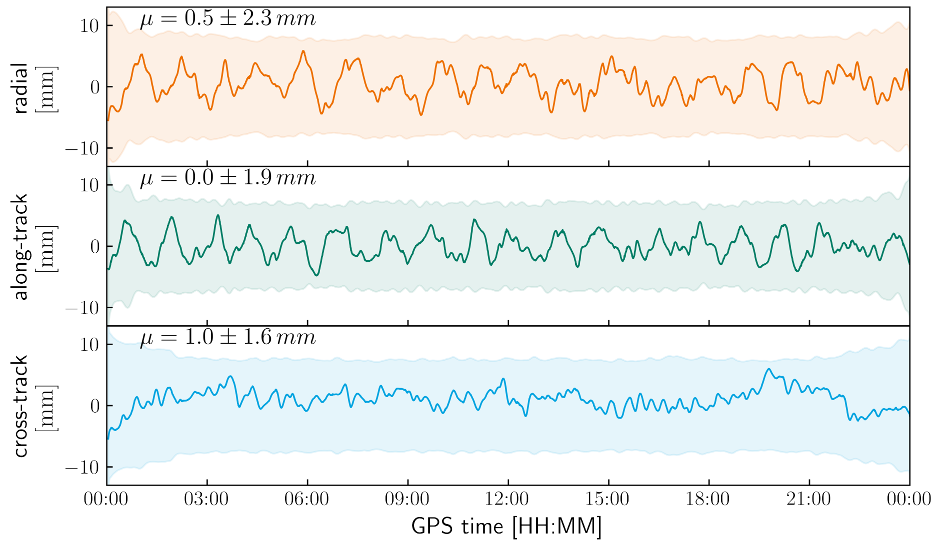

Figure 11: POD accuracy and 3-sigma bounds (shaded area) in radial, along-track, and cross-track direction for simulated pseudorange and carrier-phase measurements based on a Sentinel-3A trajectory.

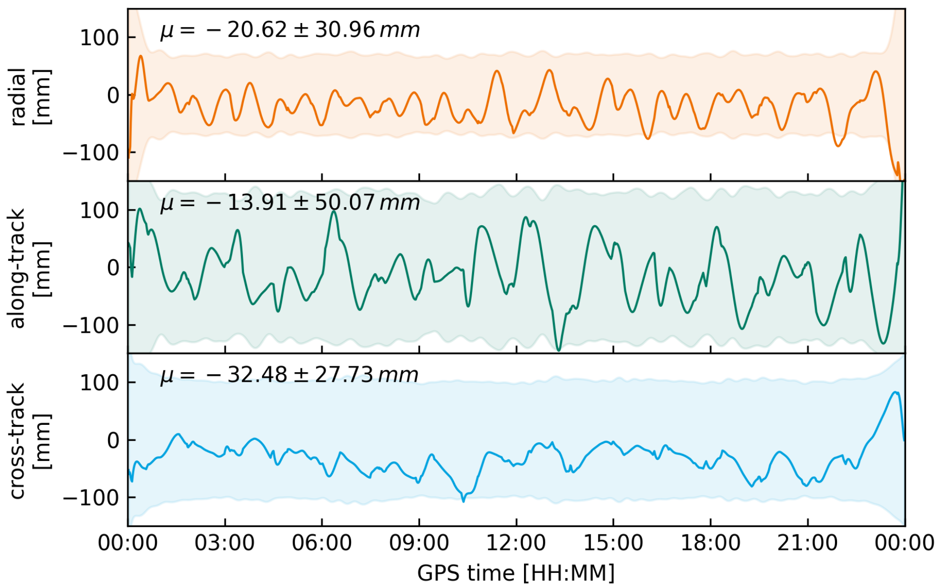

Figure 12: POD accuracy and 3-sigma bounds (shaded area) in radial, along-track, and cross-track direction for in-orbit pseudorange and carrier-phase measurements of Sentinel-3A.

PBD - Precise Baseline Determination

As a new functional aspect of PODCAST, the topic of Precise Baseline Determination (PBD) was introduced. PBD refers to the estimation of the 3D relative position of a rover spacecraft with respect to a base spacecraft with the utmost precision. The precise determination of inter-spacecraft baselines is a key technology for Low Earth Orbiting (LEO) satellite missions featuring formation flying satellites. These formations allow for advanced mission profiles that would not be possible with a single spacecraft. Applications are gravimetry and Synthetic Aperture Radar (SAR) missions, such as along-track interferometry for traffic monitoring, and cross-track interferometry for deriving accurate Digitial Elevation Models (DEM). One example is the German mission TanDEM-X, where the twin satellites TerraSAR-X and TanDEM-X perform measurements of the digital elevation of the Earth's surface. In contrast to gravimetry missions, SAR missions do not feature an inter-satellite laser ranging system but rely solely on GNSS-based baseline determination. The TanDEM-X mission requires a precision of 1 mm with the confidence of 68% for the projected baseline in the cross-track direction. The latest available advancements in PBD are utilized to achieve the necessary estimation quality and it is aimed to also reach these precisions within the in-house software PODCAST.

While state-of-the-art PBD techniques are suitable for meeting the current requirements, future SAR missions will demand higher baseline precisions for more challenging mission profiles. Especially the upcoming trend for agile missions holds multiple challenges that have to be overcome. Therefore, PODCAST takes a significant step to improve the PBD precision of inter-spacecraft baselines for future agile and non-agile formation flying spacecraft missions.

Within the last year, the software framework for PBD was implemented within PODCAST. The implementation obeys the overall concept of PODCAST, enabling flexible testing of the software for novel approaches related to Precise Orbit Determination. Topics related to PBD that were finalized were the detection of cycle slips of GNSS carrier phase observations, algorithms to recover the integerness of the ambiguities of said carrier phase observations, and the overall estimation tool chain. A Kalman-Filter-based approach was selected for the PBD estimation. As the Kalman Filter profits considerably from a good initialization, a least squares estimate is calculated before the start of the actual estimation loop. The following Kalman Filter estimation consists of the smoothed result of a forward and a backward Kalman Filter estimate.

In test scenarios, the state-of-the-art precision of 1 mm could be reached. The results can be seen in Figure 13. The continuous line indicates the errors in the radial, along-track, and cross-track direction of the satellites and the dashed lines indicate the confidence of different levels. The grey dashed lines indicate the estimated 3-sigma confidence of the filter, while the blue and green dashed lines indicate the empirical 1- and 3-sigma bounds, recovered from the knowledge of the true error. Moreover, it was possible to verify the capabilities of PODCAST regarding PBD by processing observations from a low-cost off-the-shelf GNSS receiver. The test setup consisted of the aforementioned receiver, which was plugged into a GNSS signal stimulator. The orbit for the simulated scenario was propagated by the in-house Precise Orbit Propagator (PrOP). The PBD scenario consisted of two spacecraft that were simulated consecutively, which resulted in asynchronous observations of the GNSS satellites. After the re-synchronization of the observed signals, the former claimed precision of 1 mm could again be reached, as shown in Figure 14. Upcoming challenges are the introduction of agility, the mitigation of the ionospheric influence, and the improvement of robustness. Furthermore, tests for in-orbit satellite observations are still pending.

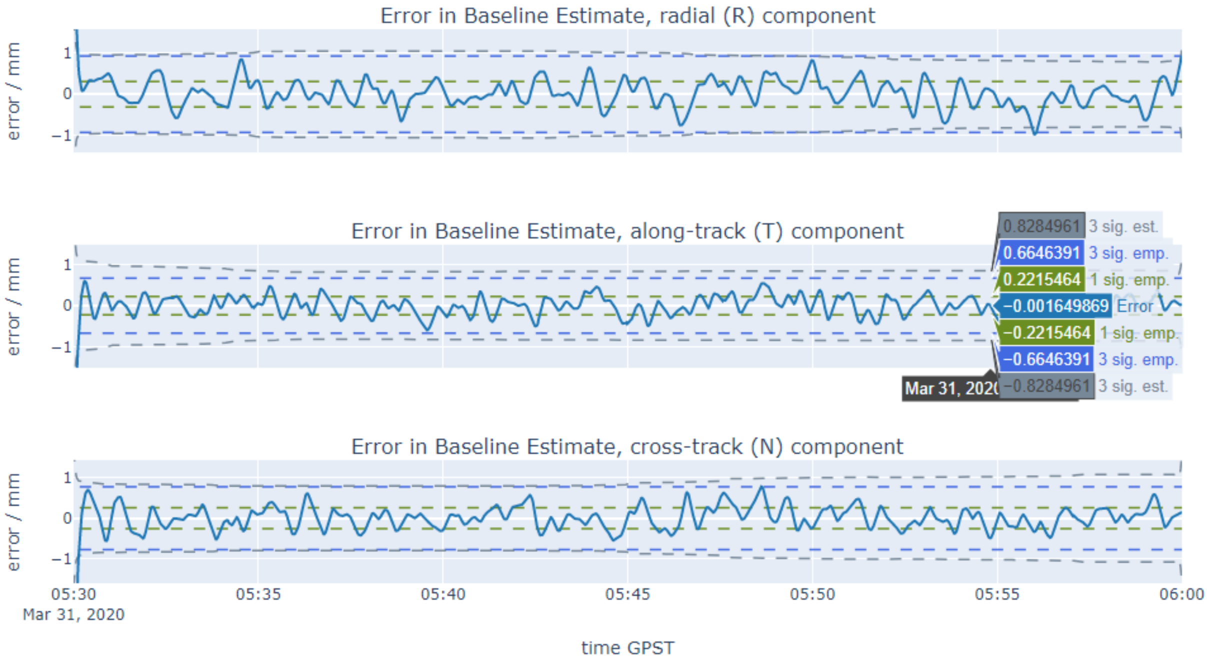

Figure 13: PBD accuracy, estimated 3-sigma bounds (grey dashed line), and empirical 1- and 3-sigma bounds (blue and green dashed lines) in radial, along-track, and cross-track direction for simulated pseudorange and carrier-phase measurements of two chasing satellites with a baseline length of about 7 km.

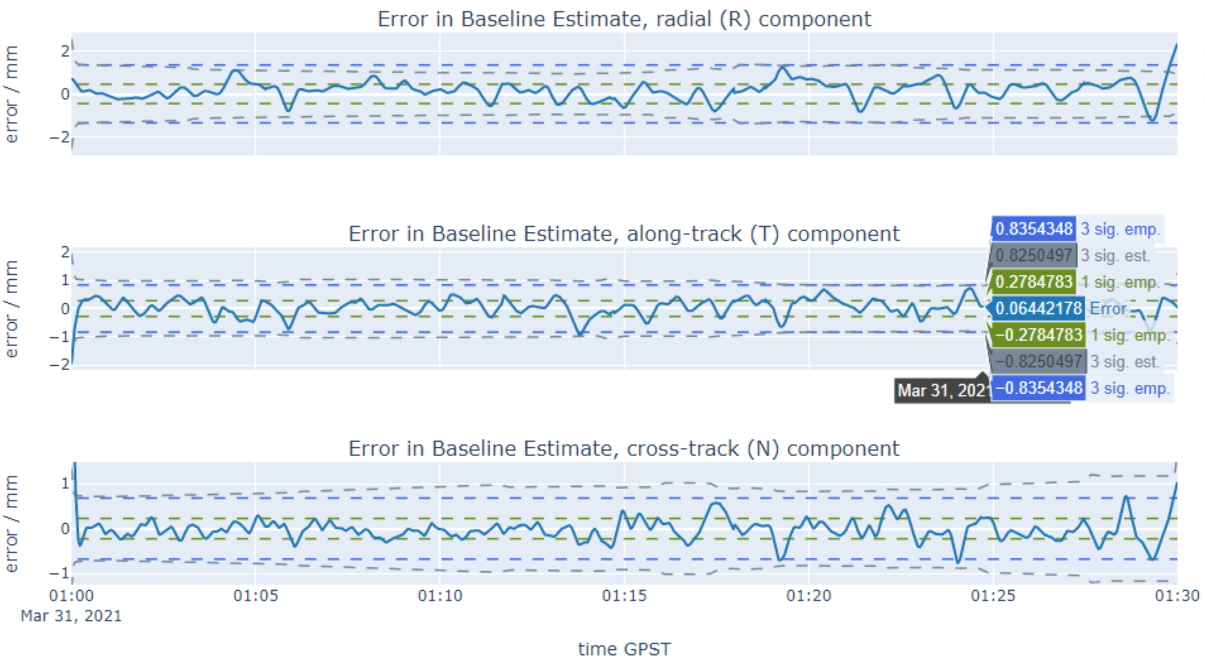

Figure 14: PBD accuracy, estimated 3-sigma bounds (grey dashed line), and empirical 1- and 3-sigma bounds (blue and green dashed lines) in radial, along-track, and cross-track direction for simulated and hardware received pseudorange and carrier-phase signals of two chasing satellites with a baseline length of about 7 km.

Development of a PPP Software for Troposphere Studies

Troposphere delays are usually regarded as isotropic in PPP applications. However, in reality, the troposphere is inhomogeneous and can cause considerable errors in extreme weather and terrain conditions, sometimes up to ten centimeters. Researchers proposed two-axis gradient models to compensate for this disparity, but the model does not have such a good performance concerning accuracy and flexibility. In order to overcome the shortcomings in existing models, we proposed a new troposphere model based on B-splines. In this model, the troposphere delays at specific elevations are modeled as a circular B-spline curve, so that we can get the troposphere information at random azimuth angles.

The new model has benefits in the following points:

- Better coordinate repeatability. We compare the estimated coordinates with ITRF20 and the results show that the new model brings a significant improvement compared to traditional models: up to $30\,\%$.
- More accurate and flexible. The new model is more capable in modeling real troposphere wet delays. The post-fit residuals in the EKF show that the new model has $10\,\%$ improvement compared to traditional models.
- More realistic. The new model can get more realistic troposphere results because the B-spline can fit the real troposphere delay better.

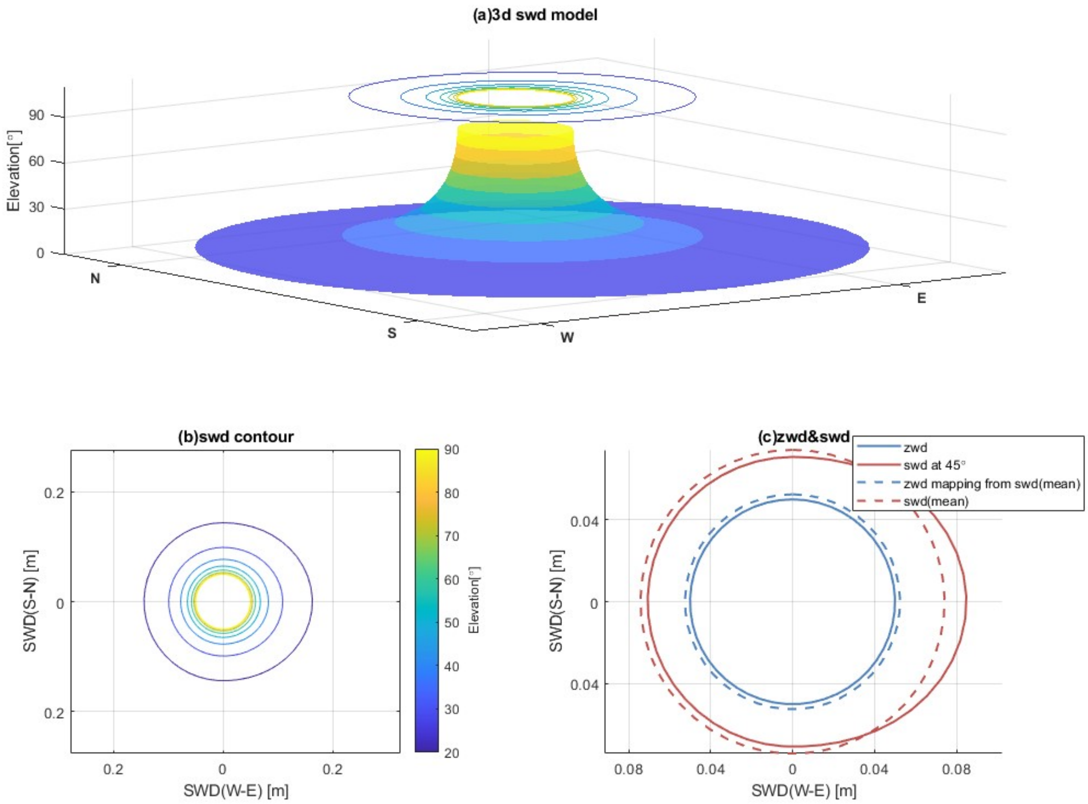

Figure 15: Figures (a) and (b) show daily averages of the troposphere wet delay around the IGS geodetic station at Wettzell (WTZR) on January 1st 2022. The contours are constructed by the B-spline model. (c) shows a simulated B-spline curve and reveals the relation between the SWD and ZWD.

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 significantly lowered with respect to today's launchers. In recent years, the industry has identified that micro launchers may satisfy this task. Micro launchers are small rockets carrying about 500 kg of payload into Low-Earth orbit. To achieve the objective of low cost, the rocket design is focused on modularity and reuse. This 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 designs in this area, too. Therefore, ESA initiated a project called "Generic Guidance and Navigation Onboard Software for Microlauncher" with ASTOS Solutions GmbH as the contractor. Here, a software library with guidance and navigation algorithms has to be established that makes a flexible software implementation possible and can be optimized to the particular launcher by auto coding. As a subcontractor, the INS is concerned with the navigation part and develops off-the-shelf navigation algorithms. The integrated navigation algorithm implemented in 2021 was finalized, verified and extensively 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 computes integrated navigation estimates in real-time by reading the outputs of GNSS receivers and several IMUs distributed in the launcher in parallel. The company ASTOS verified the auto coding performance using the Matlab/Simulink script of the INS. Figure 16 shows deviations in position and orientation during lift-off between the simulated trajectory and the computed trajectory using dedicated simulated GNSS and IMU data. The accuracy of the filter is within the requirements specified within the project for a nominal injection accuracy.

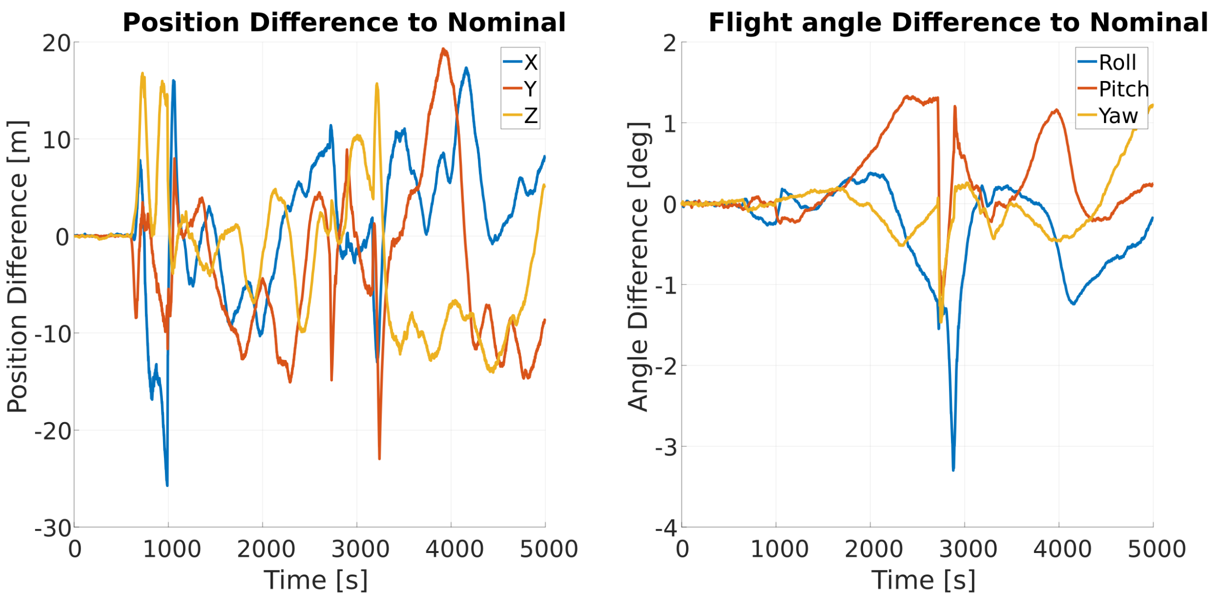

Figure 16: Filter performance

Sensor fusion of different independent IMUs

The combination of multiple IMUs yields redundancy and increased accuracy compared to a single IMU. For the use on a mobile platform, a sensor fusion algorithm was implemented in INSTINCT and subsequently tested on the experimental setup shown in Figure 8. The algorithm reads the data output as shown in Figure 9 and sorts each sensor's measurements before they are fused. The principle behind the fusion algorithm is shown in Figure 17. The IMUs measurements have a common time base realized through the GPS module. A Kalman filter then combines the measurements and provides a measurement from a virtual single IMU. This combined output can then be fed into further INS-/GNSS-fusion. In comparison to simple averaging of the IMUs measurements, the Kalman filter is capable of considering the IMUs dynamics. These are modeled by integrated random walk on the accelerometer and gyro measurements, respectively. Results from a static test are shown in the Allan deviation plot in Figure 18 (here, only the angular rate's vertical component is shown as the other components, and the accelerations are similar). The Allan deviation is reduced significantly for small averaging periods τ. For rising τ, the combined solution converges into IMU 1, which acts as the reference sensor in the tested configuration, because of effects that are not modeled by the Kalman filter. In conclusion, the lowered Allan deviation implies that the accuracy of IMU measurements can be improved when combining multiple IMUs measurements.

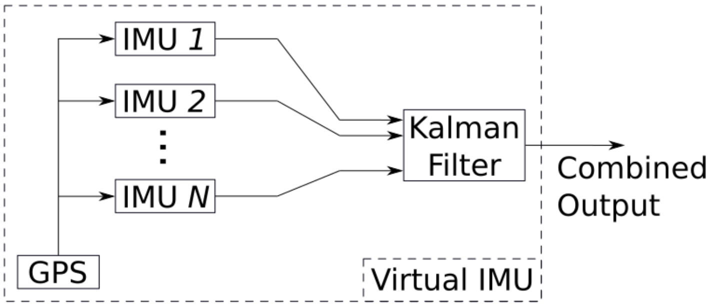

Figure 17: Sensor fusion principle

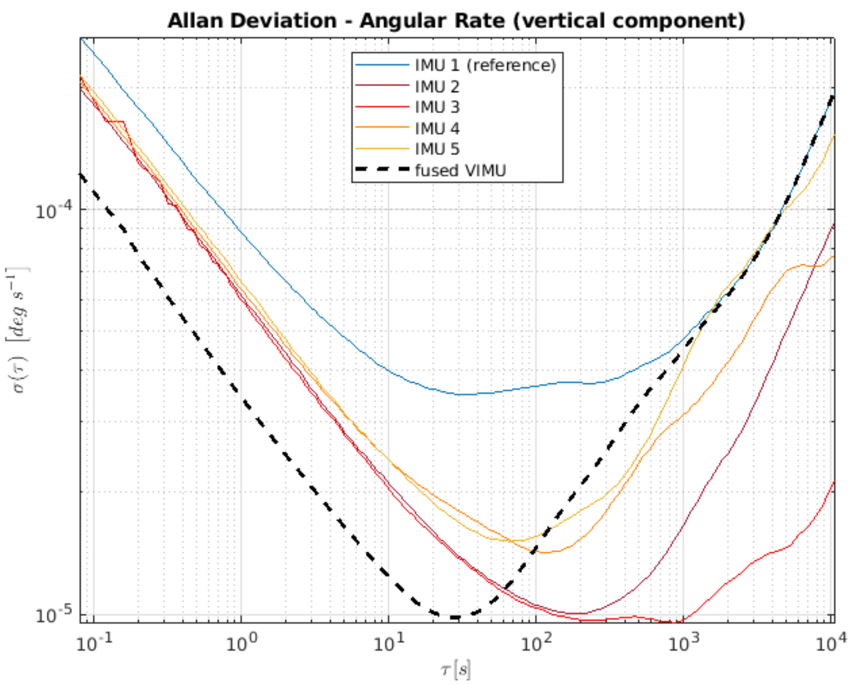

Figure 18: Allan deviation of gyroscope measurements of the single IMUs and the combined virtual IMU (VIMU)

Research focus: Applications

The following sections describe applications on which the INS worked on in the year 2022.

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”) alongside partners from industry under the lead of the iFR (Institut für Flugmechanik und Flugregelung der Universität Stuttgart). All information on the operation, tests, and other news can be found on the homepage `https://area-bw.de/`, which is maintained by the institute.

Customized research platform Prism Coaxial X8

In 2022 the institute purchased a *Prism Coaxial X8* drone from *Watts Innovations* and customized it for the usage as a research platform for navigation solutions. Figure 19 shows the drone after its first flight, which was conducted at ”Ihinger Hof”, one of the institute’s primary testing sites. This addition to the institute’s fleet of drones provides much more capacity regarding mass (up to 11 kg) and space for sensors, compared to the other available drones. Therefore, we are now able to test multiple sensors simultaneously and thereby compare measurements of the same flight trajectory. The institute’s mechanical workshop has constructed an adapter plate that can carry a range of sensors and equipment as shown in Figure 20. This adapter plate can be mounted on top of the drone using the four grey screws as shown in Figure 21.

Figure 19: Prism Coaxial X8 after its first flight

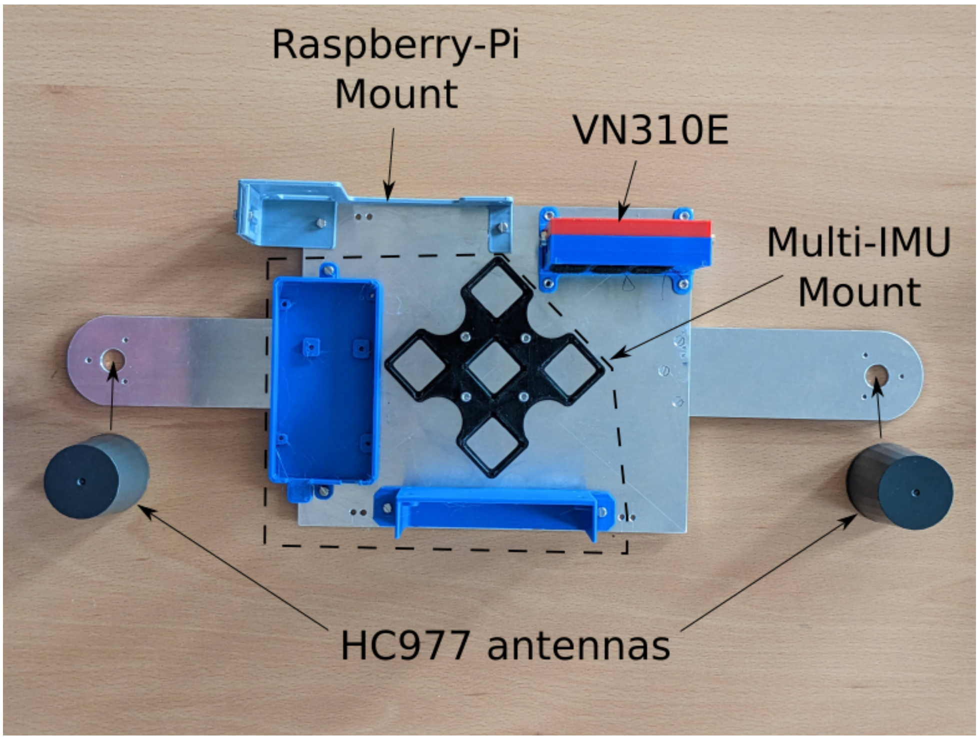

Figure 20: Adapter plate for the Prism Coaxial X8, constructed at the institute's mechanical workshop

Figure 21: Mounting points for the adapter plate of the Prism Coaxial X8

List of Publications

Gutsche K., Hobiger T., Winkler S., and Stucke B., *PODCAST: Precise Orbit Determination Software for LEO Satellites*, Proceedings of the 35th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2022), 3707–3719, Denver, USA.

Topp T., and Hobiger T. *Flow-Based Programming for Real-Time Multi-Sensor Data Fusion*, Proceedings of the 35th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2022), 2492–2502, Denver, USA.

List of Poster Presentations

He S., Becker D., Hobiger T. *The impact of GNSS multipath errors on ZTD estimates based on PPP*, 2nd IAG Commission 4 Symposium (IAG C4 Symp 2022), Potsdam, Germany, https://doi.org/10.5281/zenodo.7326315.

Gutsche K., Hobiger T., Winkler S., *Adaptive Extended Kalman Filtering for Precise Orbit Determination*, Poster presented at the 8th International Colloquium on Scientific and Fundamental Aspects of GNSS, Sofia, Bulgaria.

Research Stays

Wang, Rui (20.5.2022 – 18.6.2022)
Visiting PhD student at Wrocław University of Environmental and Life Sciences, Poland, to work on the implementation of PPP algorithms and the development of a mathematical framework that includes functional and stochastic models. This research stay allowed for close collaboration with researchers at the host institution, the exchange of different research approaches, and a deeper understanding of various error sources in GNSS positioning, which expanded the PPP applications based on EKF, especially in the field of improved tropospheric modeling.

Teaching and Supervision

With the COVID-19 restrictions on lectures and exercises completely lifted, we saw an almost normal year in all our educational activities. A smaller number of students in elective courses posed certain challenges so that exercise formats had to be slightly adapted to accommodate smaller groups and achieve the learning objectives that are based on problem based learning or group work. The availability of two GNSS simulators allows us to implement realistic GNSS scenarios and even deal with threats like jamming or spoofing without the need to transmit signals over the air. Through Spirent's Academia Programme and Orolia's Academic Partnership Program, we have access to industry-standard GNSS simulation tools in undergraduate and graduate courses and train our students with the tools they might encounter at their future workplaces. We also saw an increasing number of master's students from different curricula at the University of Stuttgart, who carry out their projects with several of our industry partners. This turned out to be mutually beneficial - students can get in close contact with potential employers and present themselves, and companies might find the right well-educated and trained employees.

Bachelor Thesis

- Ertmann, Richard: *Nachweis der dynamischen Leistungsfähigkeit verschiedener GNSS-Empfänger durch Simulation* (Supervisor: D. Becker)

Master Thesis

- Stucke, Bayram: *Development of a Satellite Trajectory Generator for Precise Orbit Determination* (Supervisor: Y. Enginger (Airbus))

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	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	1	1
Measurement Techniques in Navigation	MSc	Wehr, Klink	1	3
Satellite Navigation	MSc	Hobiger, Becker	1	1
Signal Propagation and Antenna Theory	MSc	Hobiger, Becker	1	1
State Estimation in Dynamic Systems	MSc	Hobiger, Sonnleitner, Maier	2	1
Object-oriented Programming in C++	MSc	Hobiger, Sonnleitner, Topp	1	3
Project	MSc	Sonnleitner	6	0
Property Valuation	MSc	Caesperlein	1	0
Simultaneous Localization and Mapping (SLAM)	MSc	Hobiger, Maier, Klink	1	1
Master GeoEngine:				
Dynamic System Estimation	Msc	Hobiger, Wang, Maier	2	1
Integrated Positioning and Navigation	MSc	Hobiger, Topp, Maier	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