Annual Report 2021
Institute of Navigation

INS

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Annual Report 2021

of the

Institute of Navigation (INS)

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Staff in 2021

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.Sc. Dagmar Epple	Institute management and translation
Helga Mehrbrodt	Secretary

Academic Staff	Research Focus
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	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

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

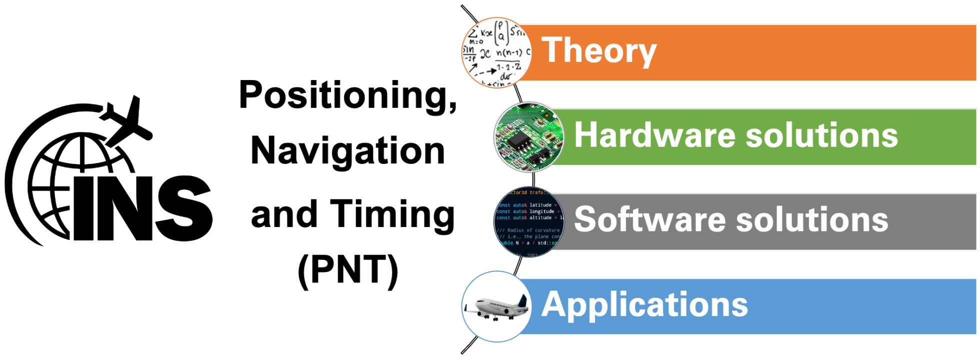


Figure 1: INS focus areas to which the institute is actively contributing with research projects.

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.

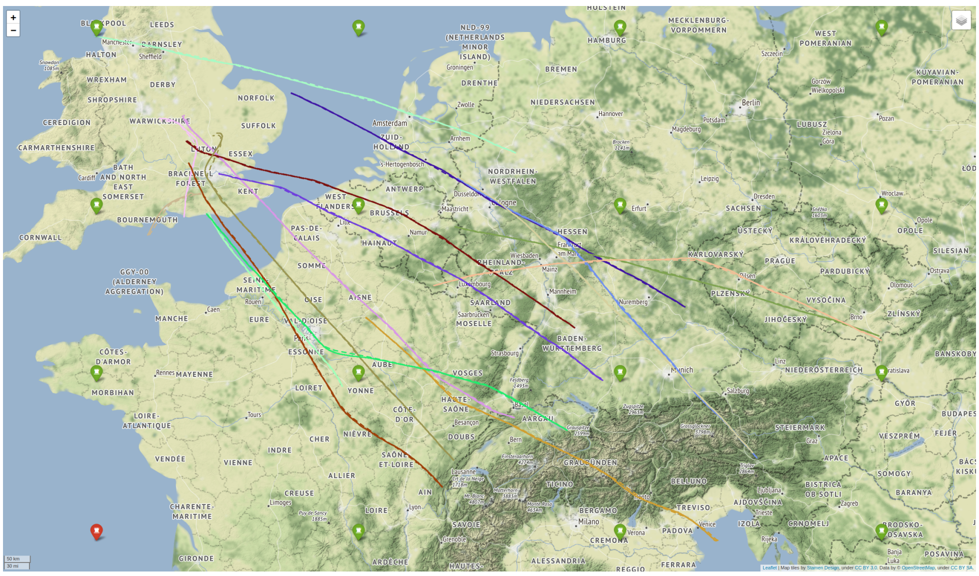


Figure 2: Map view of the ADS-B software. It shows results of the in-house developed flight path tracking software in comparison to their broadcasted one.

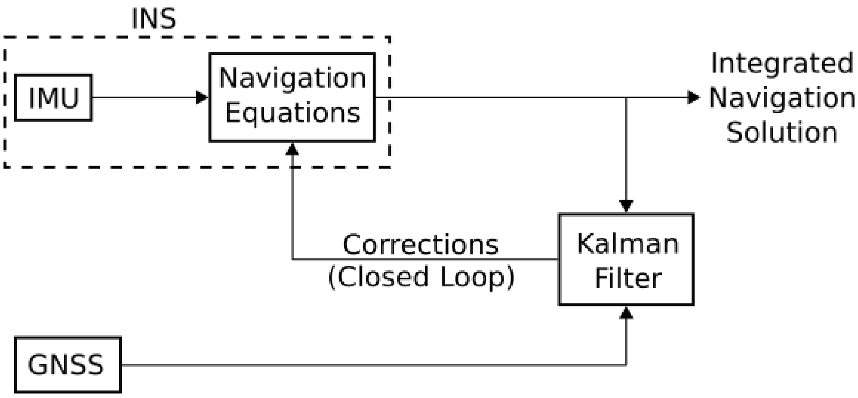


Figure 3: Loosely Coupled Kalman Filter for INS/GNSS sensor fusion

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 3.

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 (s. fig. 4) 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.

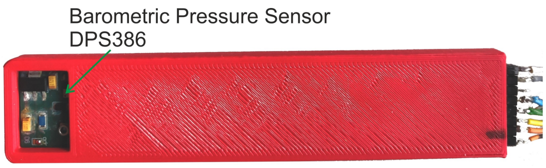


Figure 4: Sensor head

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. 5

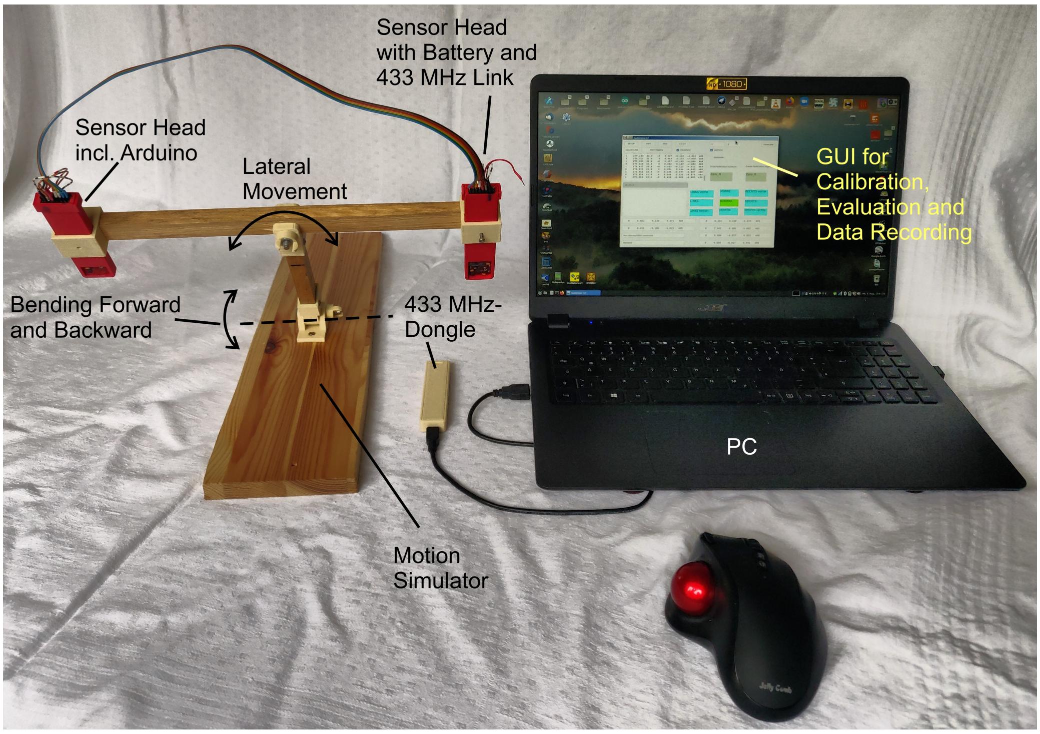
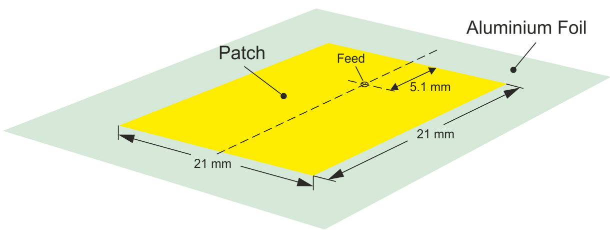


Figure 5: Simulation setup

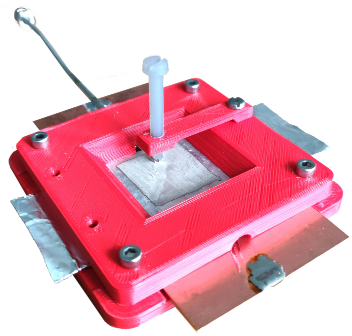
This setup was first used to determine the decision-tree. Here, many data were gathered starting with an upright position followed by e.g. forward, backward and lateral movements and dipping into water. These data were processed by WEKA, which generated a decision-tree regarding the sensor data of IMU, 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. 6a) and manufactured by DITF. The DITF patch antenna was tested by the setup depicted in fig. 6b. 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 6: 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℃ during three minutes for achieving a better conductivity (s. fig. 7). 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.

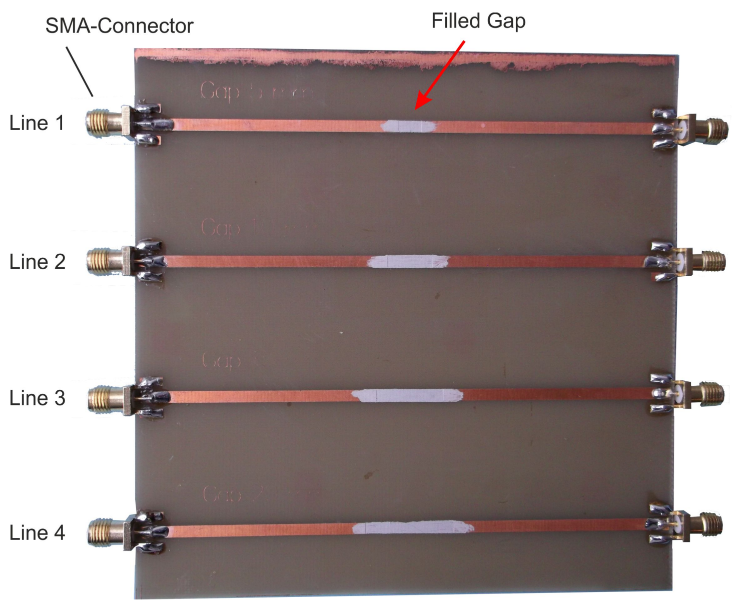


Figure 7: Test PCB

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 OpenSky 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.

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 (also see section Testfeld eFliegen BW on page 17).

Figure 8: High grade ADS-B antenna on the roof of the building in Breitscheidstraße 2.

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

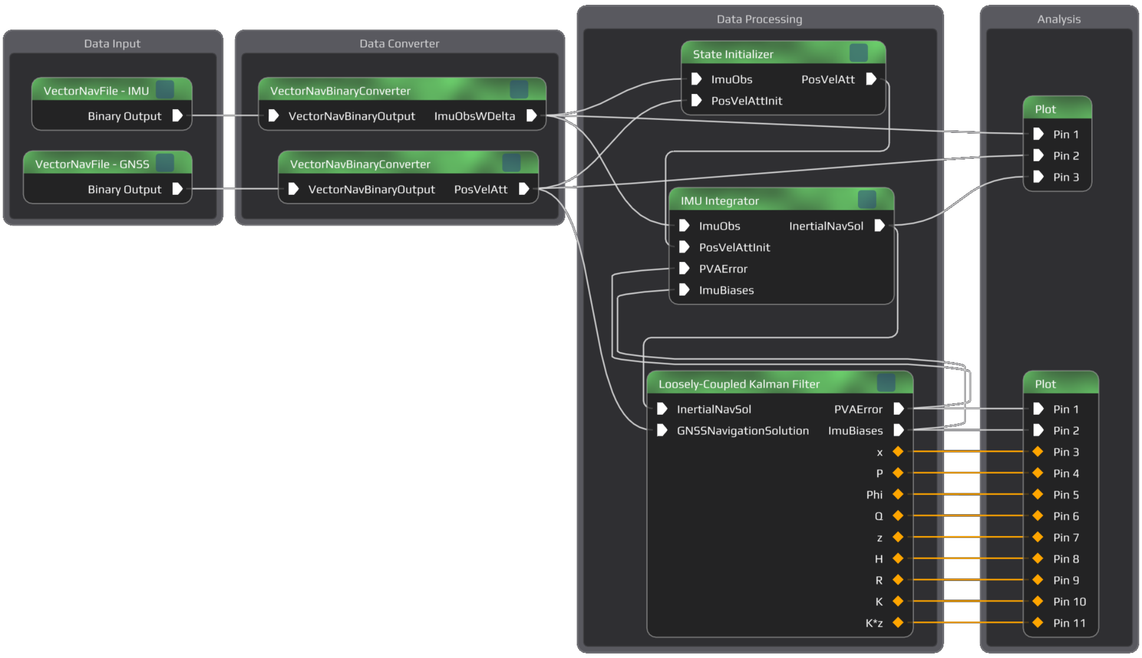


Figure 9: INSTINCT dataflow for an INS/GNSS loosely-coupled Kalman filter algorithm.

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 9 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 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.

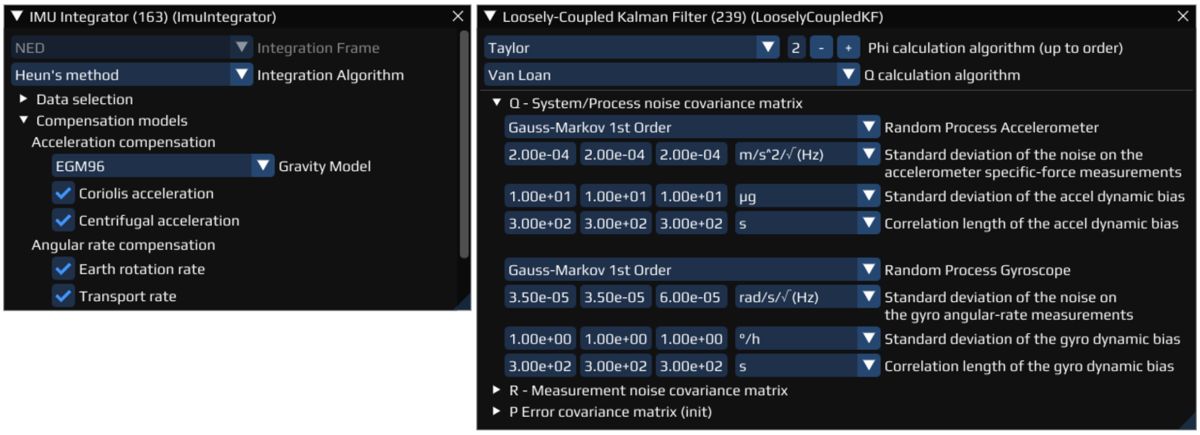


Figure 10: Configuration windows for the IMU Integrator and loosely-coupled Kalman filter nodes.

All algorithms and their options can intuitively be configured inside graphical windows, which can be seen in figure 10. 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.

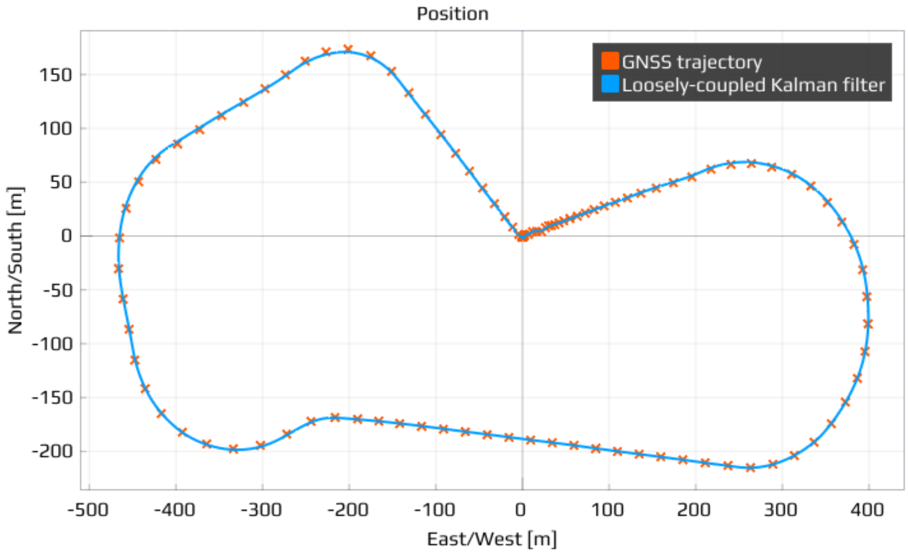


Figure 11: Plot from INSTINCT

Over the last year, INSTINCT was used in multiple test campaigns onboard of UAVs and also onboard of manned aerial vehicles. Figure 11 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 12).

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 13), 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.

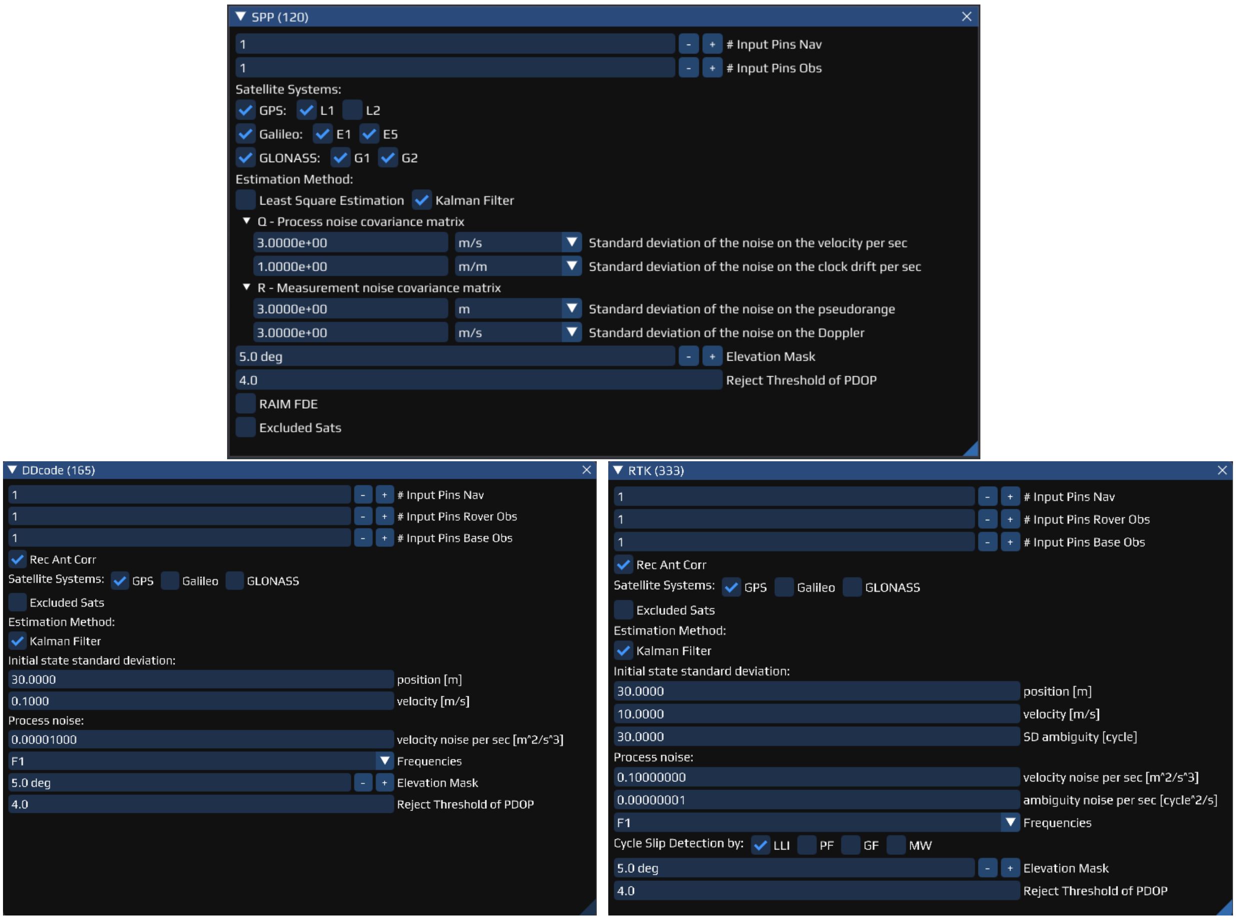


Figure 12: Config windows for the SPP, DDcode, RTK node

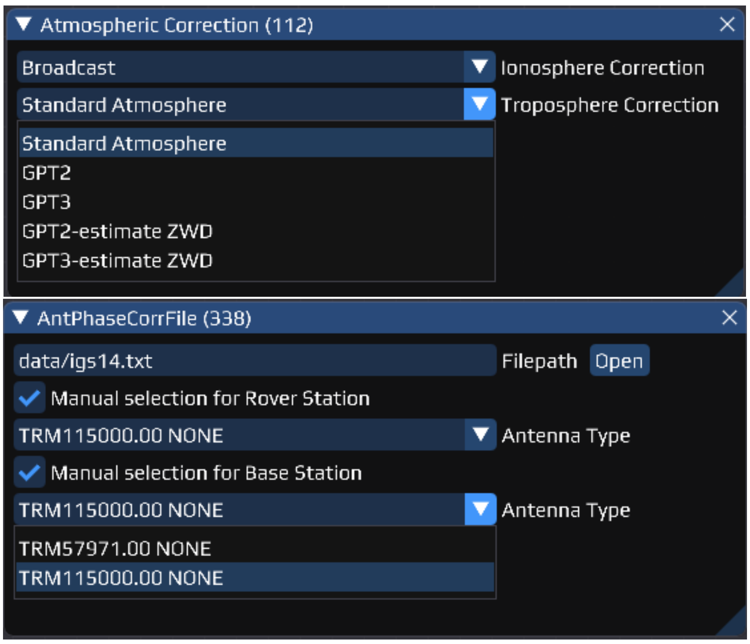


Figure 13: Config windows for the nodes about the atmospheric and antenna phase center correction

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 14 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.

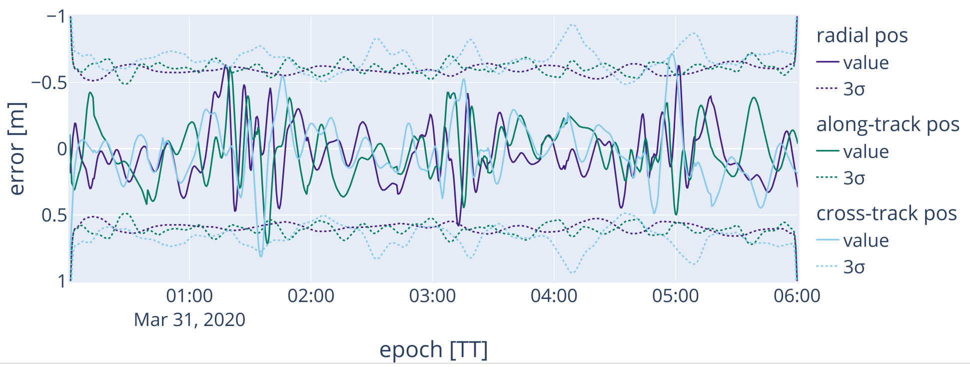


Figure 14: Estimation error of a satellite's position in the radial, along-track, cross-track reference frame

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.

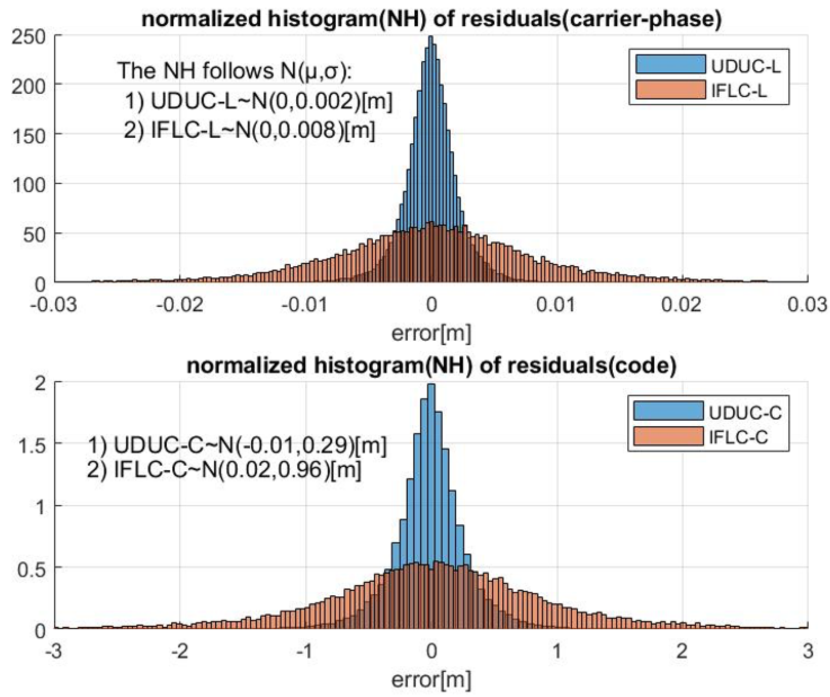


Figure 15: Example for obtained distributions of residuals, depicted as normalized histograms or code(C) and carrier-phases(L)

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.

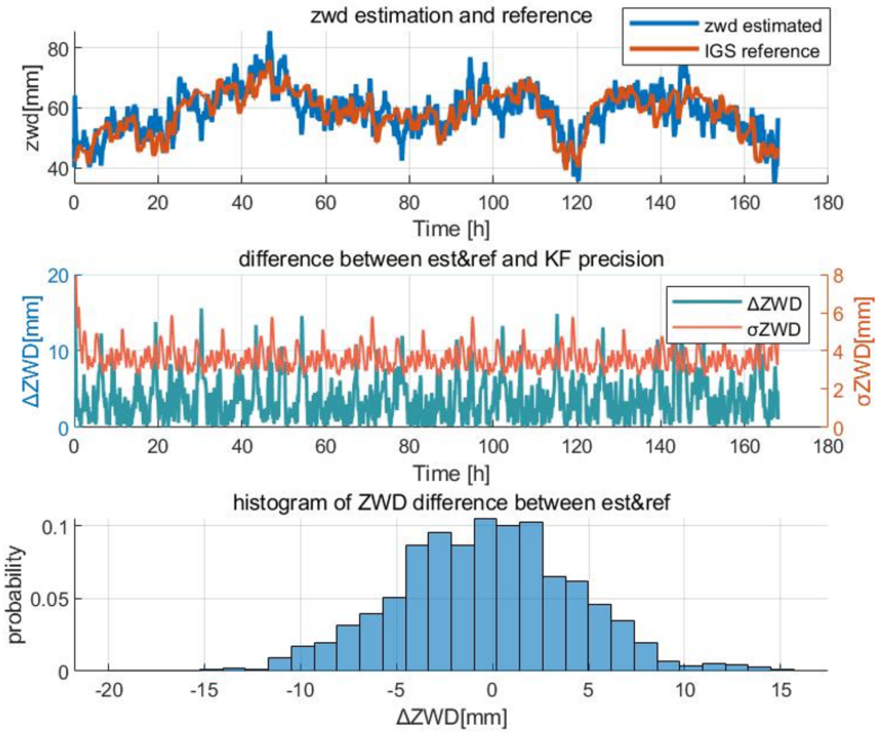


Figure 16: Troposphere analysis for IGS station Wettzell, Germany(WTZR) for 7 days

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 $60\,\mathrm{km\,h^{-1}}$. 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 9).

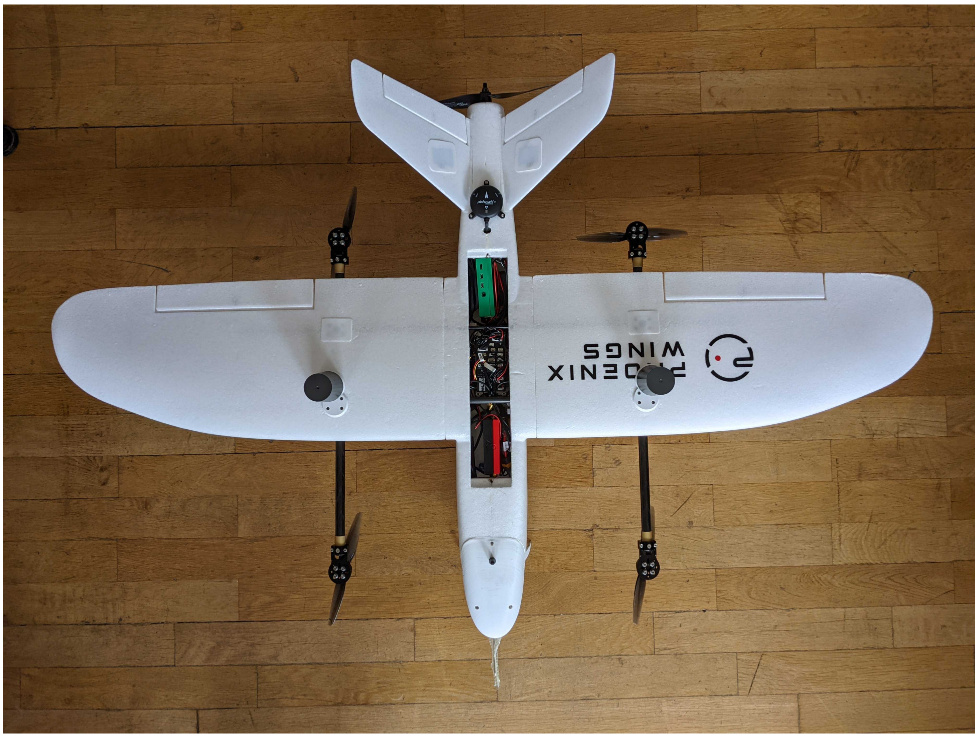


Figure 17: Top view of the VTOL vehicle PWOne with the integrated navigation platform.

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 18). 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 19) and the collected flight data is currently being made available to the INSTINCT project (see page 9). 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 18: The two Holybro QAV250 racing drones in the drone laboratory.

Figure 19: 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)

Lectures offered

Lecture name	BSc /MSc	Person responsible	Lecture (h)	Exercise (h)
Bachelor Geodesy & Geoinformatics:				
Adjustment Theory I	BSc	Hobiger, Hobiger, T.J.	2	1
Adjustment Theory II	BSc	Hobiger, Hobiger T.J.	2	1
Fundamentals of Navigation	BSc	Hobiger, Wang	2	2
Integrated Fieldwork	BSc	Hobiger T.J., Sonnleitner	10 days	
Introduction of Geodesy and Geoinformatic	BSc	Hobiger, Becker	2	2
Measurement Techniques II	BSc	Wehr, Sonnleitner, Klink	2	2
Valuation	MSc	Bolenz	1	0
Master Geodesy & Geoinformatics:				
Filtering Techniques	MSc	Hobiger, Topp	1	1
Inertial Navigation	MSc	Hobiger, Becker	1	1
Inertial Sensors	MSc	Hobiger	1	0
Integrated Navigation	MSc	Hobiger, Topp	1	1
Measurement Techniques in Navigation	MSc	Wehr, Sonnleitner	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, Topp, Maier	2	1
Object-oriented Programming in C++	MSc	Hobiger, Sonnleitner, Topp	1	3
Project	MSc	Sonnleitner	6	0
Property Valuation	MSc	Bolenz	1	0
Simultaneous Localization and Mapping (SLAM)	MSc	Hobiger, Maier, Klink	1	1
Master GeoEngine:				
Dynamic System Estimation	Msc	Hobiger, Hobiger T.J.	2	1
Integrated Positioning and Navigation	MSc	Hobiger, Wang, Maier	2	1
Satellite Navigation	MSc	Hobiger, Wang	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 “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