Aviation Applications

Hybrid Navigation Techniques and Safety-of-Life Requirements Part 1


Dornier DO 128-6 research aircraft.

Drawing on authors from several German organizations, this two-part column describes some key results of the UniTaS IV project, a publicly funded effort to investigate special problems in the application of satellite navigation for aviation. Among the subjects covered: adaptive beamforming antennas, a GNSS landing system that incorporates inertial sensors with a ground-based augmentation system (GBAS), multi-constellation RAIM (receiver autonomous integrity monitoring), and jamming, spoofing, and authentication of signals.

ULF BESTMANN
MEIKO STEEN
PETER HECKER
TECHNISCHE UNIVERSITÄT BRAUNSCHWEIG
ANDRIY KONOVALTSEV
MARCOS V. T. HECKLER
GERMAN AEROSPACE CENTER (DLR)
FELIX KNEISSL
UNIVERSITY FAF MUNICH

The emergence of global navigation satellite systems, combined with the evolution of GPS, introduces new possibilities for the use of GNSS in aviation. A major gain in integrity, accuracy, and availability can be expected by using multiple GNSSes and augmented services.

The path from algorithm development to the derivation of standards for use in aviation is both enduring and widely distributed among various institutional stakeholders. International and national space and aviation agencies, such as the European Space Agency (ESA), the Deutsches Zentrum für Luft- und Raumfahrt (DLR, the German Aerospace Center), and their counterparts in regions outside Europe contribute to the development of new techniques.

This article shows how research for GNSS applications in civil aviation has found its way into the demonstration phase of the UniTaS IV project. (UniTaS is the German acronym for the "support program of industrial activities and technology transfer in the field of applied satellite navigation for aviation," a multi-phase project founded by the Bundesministerium für Wirtschaft und Technologie or BMWi, Federal Ministry for Economy and Technology and administered by the Agency of Aeronautics of the DLR in Bonn.)

In this two-part series, we will describe the goals and some results of this joint project, including the integration of GNSS and inertial technologies, antenna beamforming techniques and equipment design, spoofing detection and signal authentication, monitoring the Galileo system, and multi-constellation receiver autonomous integrity monitoring.

GNSS and Aviation

The UniTaS IV Project investigates technologies and methods to improve the practical use of satellite navigation in aviation. Hence integrity, continuity, and availability of navigation aids are a major focus of the project.

Key elements in the current evolution of the navigation technologies employed in the project include the ground-based augmentation system (GBAS), hybrid navigation using micro-electromechanical system (MEMS) inertial navigation sensors, use of Europe's Galileo system in aviation and associated safety-of-life requirements, and antenna beamforming techniques for GNSS navigation.

We investigate the engineering aspects of the foregoing topics beginning with the theoretical background and followed by the results of proof-of-concept demonstrations. Several demonstrations have been developed during our project using one or more of these technologies to characterize their practical use.

A team of academic and industrial partners led by the Institute of Flight Guidance (IFF) of the Technical University Braunschweig carried out the work on UniTaS IV. Our academic partners are the University of the Federal Armed Forces, Munich (University FAF Munich), the DLR Institute of Communication and Navigation (IKN), and the Institute for Navigation at Stuttgart University. Our industrial partners include Fraunhofer IIS, iMAR GmbH, Funkwerk Avionics, and messWERK GmbH.

The algorithms developed during the UniTaS IV project were field tested, in most cases including flight trials using a DO 128-6 research aircraft shown in the photo on the opening page.

Hybrid Navigation: GBAS/INS

GBAS is designed to support precision approach operations at airports within a coverage area defined by a nominal range of 23 nautical miles. It provides desired flight path information for approaches, landings, and other maneuvers within the terminal area, as well as determining ranging source errors using multiple ground reference receivers. Information on those errors is broadcasted via VHF data broadcast (VDB) to the users in the coverage area. The GBAS ground station also monitors the integrity of the GNSS signals-in-space.

High precision landing operations, such as Category II and III approaches, have very stringent integrity and continuity requirements. Without the availability of Galileo or the new GPS L5 frequency, single-frequency GNSS user equipment requires additional augmentation for GBAS equivalent approaches up to CAT IIIb (GBAS Approach Service Type D, GAST D).

Minimum Aviation System Performance Standards (MASPS) for GPS Local Area Augmentation System Airborne (LAAS) Equipment (RTCA Do-253C) requires several additional integrity augmentations. These augmentations include position solutions with various smoothing time constants, e.g., dual solution ionospheric gradient monitoring (DSIGM), fault detection before and during new satellite additions, satellite geometry screening, and optional on-board autonomous integrity monitoring.

In the course of the UniTaS IV project, an integrated GBAS/INS system was developed that uses the INS to help meet the Category II and III requirements. Such GPS/INS hybridizations are well known in the technical literature and demonstrated in practical applications. In these cases, inertial navigation systems (INS) use the basic principle of measuring a vehicle's accelerations, which can be integrated to velocity and position. In contrast to the long-term stable (but noisy) GNSS position solution, the INS solution only provides short-term accuracy. The complementary nature of these two systems is widely recognized.

A GNSS landing system (GLS) can benefit from the hybridization of GBAS with INS in two ways. First, the inertial information can be used to coast for a short time during GNSS signal outages, which may occur for some ranging sources due to shadowing by aircraft's wing or fin, or as a result of a signal-in-space being excluded from a position solution if a fault is detected. Second, the inertial information can be used to increase the ability of the system to detect and exclude ranging sources that are disturbed locally and thus cannot be detected by the GBAS ground station.

Figure 1 illustrates the basic GBAS/INS system layout. A GPS receiver delivers the raw pseudoranges and carrier phases. Pseudoranges are smoothed using the carrier phase according to the *Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment* (RTCA Do-253C).

A smoothing time constant of 100 seconds is used for GBAS Approach Service Type C (GAST C) and a time constant of 30 seconds for GAST D. A variable delay buffer (VDB) receiver delivers the message types from the GBAS ground station. The pseudorange and range rate corrections are then applied to the smoothed pseudoranges, and the GBAS corrected pseudoranges are used within the hybridization filter, which in this case is a total-state extended Kalman filter (EKF).

On the inertial side, the measured accelerations and turn rates are used together with an Earth gravity model in the propagation step of the EKF to calculate the predicted attitude, heading, velocity, and position of the vehicle. If GBAS-correct-

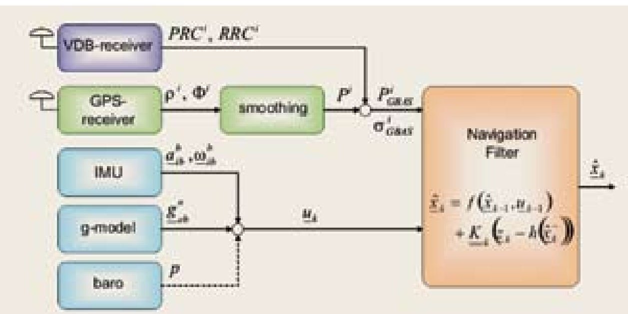


FIGURE 1 GBAS/INS system layout

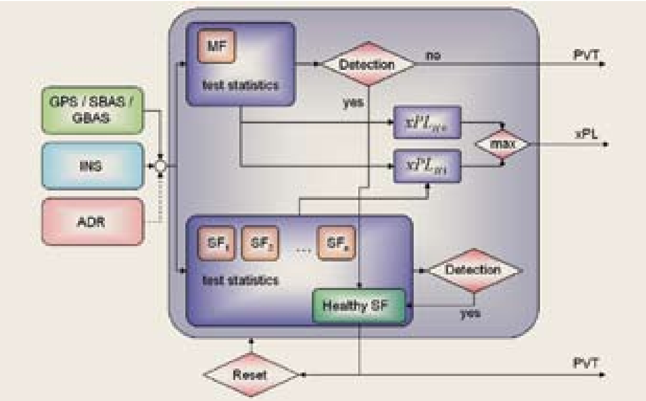
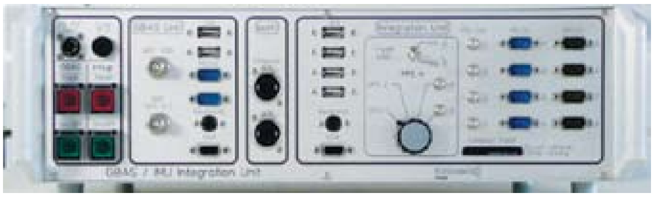


FIGURE 2 GBAS/INS integrity functions: ADR (air data reference), MF (main filter), SF (sub-filter), PVT (position, velocity, time), xPL_{H0} (horizontal/vertical protection level fault free hypothesis), xPL_{H1} (horizontal/vertical protection level single fault hypothesis)



GBAS/INS integration unit

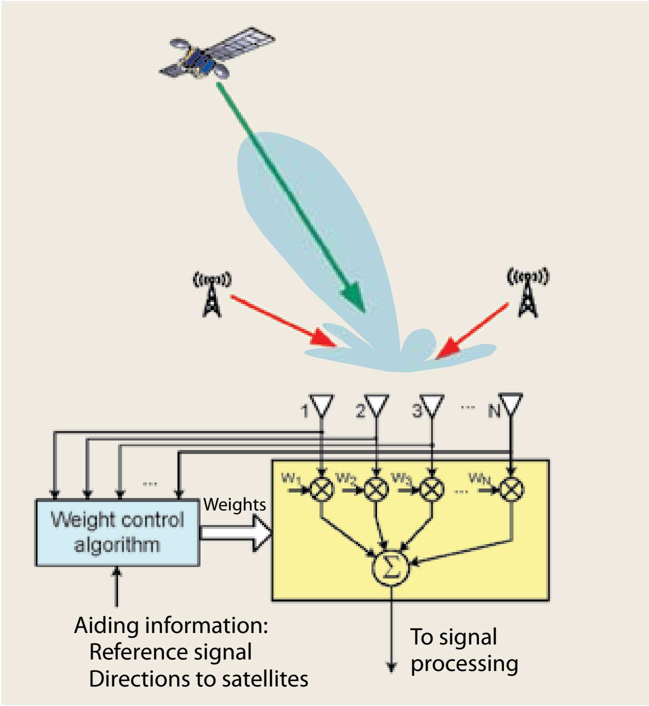


FIGURE 3 Adaptive antenna principle

ed pseudoranges are available, they are used in the correction step of the EKF in terms of a tightly coupled system.

As mentioned earlier, autonomous integrity monitoring can be used to attain the highest integrity requirements as reflected in the LAAS MASPS. The system developed during the UniTaS IV project uses such additional integrity monitoring by means of inertial reference systems. The basic architecture of this system is shown in **Figure 2**.

In the present system layout, GNSS, INS, and optional barometric data from an air data reference (ADR) system are fed into the system. Depending on service availability, the GNSS data can be either solely GPS or raw data corrected by space-based augmentation system (SBAS) or GBAS differential broadcasts.

A main filter (MF) uses all (n) available GNSS ranging sources, while a bank of n-1 sub-filters (SF_i) operates in parallel. Each sub-filter excludes one ranging source. Fault detection is performed by monitoring either the main filter's residuals or the solution separations in the horizontal and vertical domain between the main filter and sub-filters.

If a fault is detected, the healthy sub-filter – the one that is excluding the faulty ranging source – is used to reset the whole system. For the calculation of hybrid protection levels, the integrity monitor uses filter characteristics from the main and sub-filters.

For the purpose of testing and evaluating the basic functions and system performance, we performed several ground and flight tests. During the flight trials, various kinds of inertial measurement units (IMUs) were used, ranging from low-cost MEMS to tactical- and navigation-grade units.

For recording the raw data, we used hardware developed during the project and shown in the accompanying photo. In addition to the IMU, this unit contains a VDB receiver and two GPS receivers, one low-cost receiver and one OEM GPS/Galileo/SBAS receiver. First results are presented in the articles by M. Steen et alia and M. Steen and P. Hecker cited in the Additional Resources section at the end of this article.

Beamforming Equipment Design

Because signals from the navigation satellites arrive at the user receiver with extremely low power density, GNSS-based equipment is inherently vulnerable to the radio frequency interference (RFI). Due to the spread spectrum technology used by GNSS, some RFI robustness is provided by the de-spreading processing gain. However, this can easily become inadequate in case of strong interference. Of particularly great concern is the RFI problem in GNSS applications with safety-critical aspects, such as aircraft landing with GBAS.

The UniTaS IV project addressed the RFI challenge by using adaptive antennas. These are based on the same principle as phased-array antennas: the individual outputs of each array element are weighted and summed in order to produce a desired array radiation/reception pattern. The array weights are adaptively adjusted by a dedicated weight control mechanism for providing an optimum signal reception according to some criterion.

As shown in **Figure 3**, the main beam of the array reception pattern can be steered to a particular GNSS satellite while nulls are produced along the directions of arrival (DOAs) of interferers. The antenna array serves as a spatial filter for the incoming signals, which can be easily combined with the receiver-based mitigation techniques in

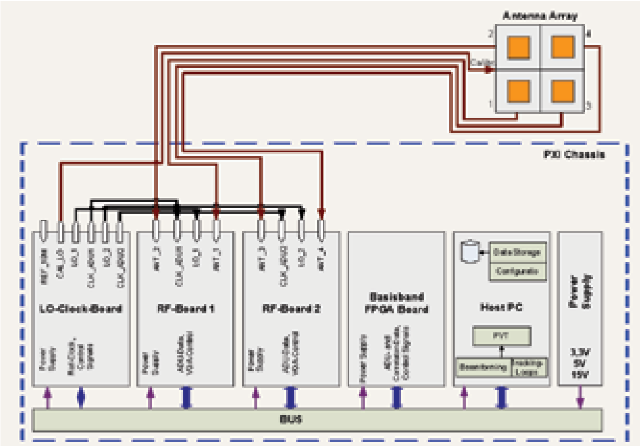
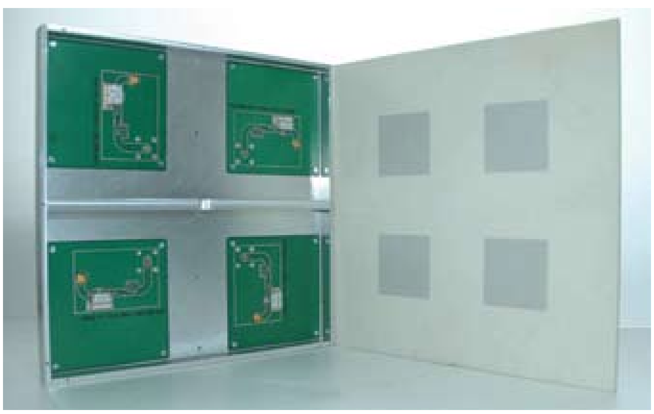


FIGURE 4 Block diagram of GNSS array demonstrator


2x2 antenna array

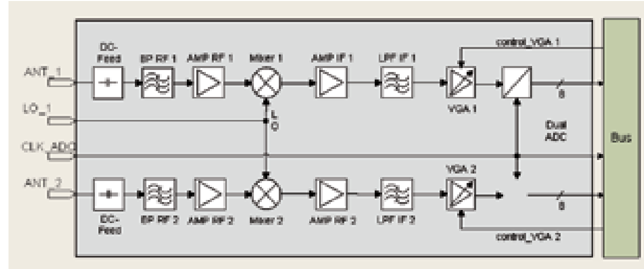


FIGURE 5 Block diagram of RF front-end

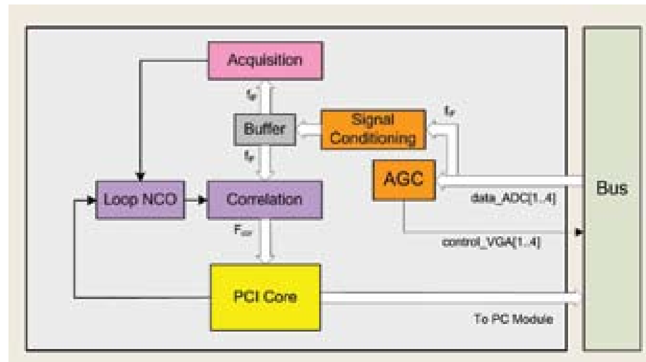


FIGURE 6 Block diagram of FPGA processing unit

the time-frequency processing domain. Similarly, spatial filter may also be used to minimize multipath error.

Our project also concentrated on the development of a Galileo/GPS L1 receiver that uses the adaptive antenna technology. The test platform receives GNSS signals by means of a 2×2 rectangular antenna array (shown in the accompanying photo) and uses digital beamforming in the signal processing software after the PRN-code correlation.

The adaptation of the array weights is performed individually for each satellite signal tracked by the receiver. The weight control algorithms for each satellite channel work independently from each other and produce multiple sets of weights. Each and every set is optimized for the reception of a given satellite. In other words, each satellite signal is received through its own array reception pattern.

Two low-noise amplifiers (LNAs) with total gain of 25 decibels are placed directly after each of the antenna elements in order to compensate for the losses in the cabling and to obtain an acceptable noise figure for the receiver.

For better out-of-band rejection, the array elements were designed to have frequency-selective antenna gain with the maximum at L1 and more than 15-decibel attenuation in the GSM band. For further details, see the articles by M. V. T. Heckler et alia and M. Cuntz et alia listed in Additional Resources.) Second-order pass-band filters with a 3 decibel bandwidth of 45 MHz are inserted after the first LNAs to provide additional out-of-band rejection.

As shown in **Figure 4**, the receiver hardware design for the test platform is based on a PCI eXtensions for Instrumentation (PXI) chassis hosting several boards (each consisting of four RF front-ends, **Figure 5**), a board to generate the clock for the analog-to-digital converter (ADC), a local oscillator (LO) and calibration signal, a field programmable gate array (FPGA) board for high-rate data processing, and a host PC for low-rate processing. The antenna array connects to the front-end boards through phase-stable cables.

The RF front-ends feature a low-IF architecture with a 21-megahertz bandwidth and 8-bit ADC with a 60 megahertz sampling rate. The high ADC resolution supports a wide dynamic range to prevent signal saturation in case of interference that would considerably degrade the beamforming performance.

The PC-module controls the following functions on the RF- and LO-clock-board:

- selecting the attenuation of the calibration signal in the range of 31decibels
- setting the duty cycle of the PWM source for each channel in 256 steps
- switching the antenna power supply on and off.

Figure 6 shows the block diagram of the FPGA processing unit. This digital baseband hardware provides the interface from the RF-boards to the PC, the digital signal conditioning, hardware correlators, and acquisition unit. The tracking loops are closed using the PC included in the PXI chassis communicating via the PCI-bus with the digital

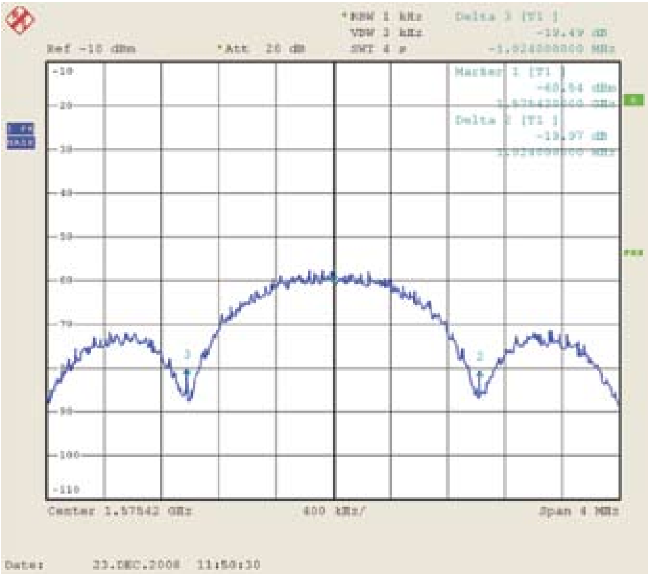


FIGURE 7 Spectrum of the calibration signal

FPGA receiver hardware.

The clock-board generates and distributes the clock signals for the ADCs and the LO-signal for the four analog mixers. A 10 megahertz oven-controlled crystal oscillator (OCXO) is used as the reference clock, and an external clock can also be applied.

The second task of the board is to provide the calibration signal for the antenna beamforming. A pseudorandom noise (PRN)-like signal is used instead of a common continuous wave (CW) signal to calibrate the RF front-end at their intended operation points.

Further, a PRN signal enables on-line calibration during operation because the signal is treated like a pseudolite with zero Doppler shift. Choosing an appropriate PRN sequence, such as the C/A-code of an unused satellite, a state-of-the-art correlator can be used to determine signal delay variations of various channels, such as those caused bytemperature shifts during operation.

Antenna array at site of static test

The signal is fed into the calibration network at the antenna array where it is distributed to the four reception channels via directional couplers. The unattenuated BPSK(1) modulated PRN-signal is shown in **Figure 7**.

Beamforming Techniques

The signal-processing software running on the host PC of the PXI chassis is basically a software receiver that implements all typical GNSS signal-processing functions after the PRN code correlation. The signal processing includes signal tracking by using code and carrier loops, navigation data decoding, and position determination.

For processing the signals from the antenna array, the software receiver also has blocks that implement the various algorithms used for adaptive array weight control and estimation of DOAs. The calculated array weights are applied in each receiver channel, and the beamformer output feeds into the tracking loops.

Using digital beamforming in the software receiver allows for fast implementation of the array processing algorithms and high flexibility. The UniTaS array receiver platform supports beamforming drawing on one of two types of aiding information:

- the satellite signal's known DOA, or
- highly correlated reference and GNSS signals, after PRN-code correlation.

In the first case, we may either calculate the DOA by using the broadcast ephemeris data of the navigation message or estimate it using a direction-estimation algorithm. The reference signal used with the second type of beamforming is a sequence of the navigation data bits estimated by the receiver-tracking block.

The weight control algorithms with the first type of beamforming are usually based on the minimum variance (power minimization) criteria, while the algorithms with the second type minimize mean square error between the beamformer output and the reference signal. (See the article by A. Konovaltsev et alia, 2007, for more details on this subject)

The use of the beamforming of the first type requires well-calibrated amplitude and phase transfer characteristics of array elements and RF front end of the receiver hardware. This can also be shown to be a prerequisite for determining the position of the phase center of the array antenna for given array weights, for which purpose the calibration signal is used.

The distribution of the signal with a calibration network is designed such that the signal appears in each array channel with almost equal phases and amplitudes. The calibration signal propagates through the entire processing chain and is individually processed in the receiver tracking part.

We can then use the phases and amplitudes of the calibration signals reported by the tracking algorithm to produce corresponding corrections for beamforming and direction estimation. This allows live calibration of the time-variant part of the receiver hardware with active elements, including amplifiers, mixers, and ADCs.

The signal enhancement introduced by beamforming appears in the results of UniTaS field trials, including a static test in which a dedicated tracking channel of the receiver was used to process the calibration signal and obtain the phase corrections. These corrections were then applied while performing beamforming and DOA estimation.

The system obtains the DOA in two steps by using the 2-D unitary ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) tech-

PRN	Azimuth error (deg)		Elevation error (deg)	
	Bias	Std	Bias	Std
9	-1.85	0.40	-2.06	0.26
12	-1.95	1.21	-3.05	0.92
15	-3.21	0.40	-3.49	0.39
17	0.66	0.33	2.17	0.48
18	0.92	0.40	-2.48	0.79
22	-3.68	0.81	-12.98	1.32
26	-9.12	0.54	-2.94	0.86
27	-2.20	0.61	0.67	0.27
28	-1.36	0.47	1.53	1.22

TABLE 1. Estimation error in Direction of Arrival (DOA)

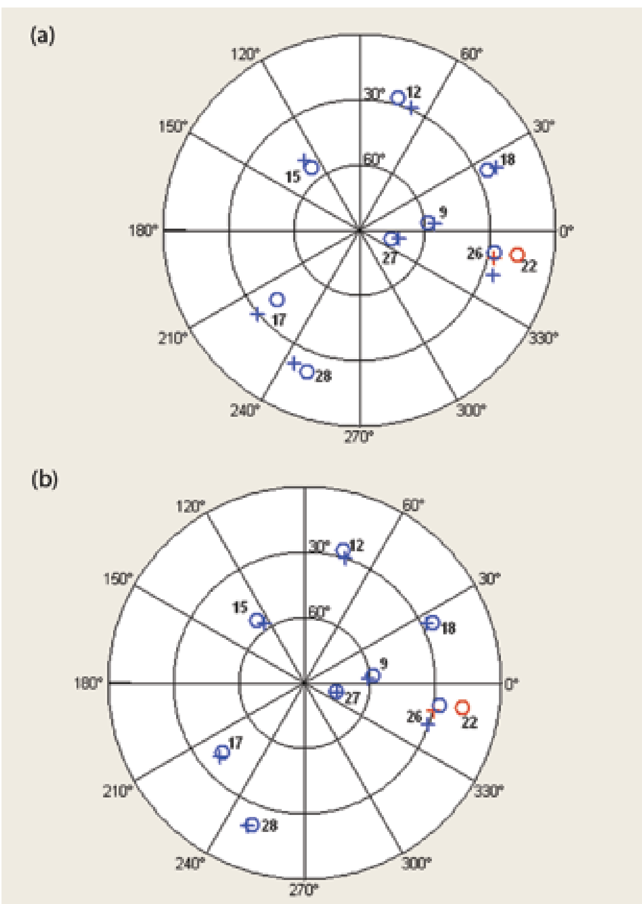


FIGURE 8 DOA results: (a) only RF front-end online calibration, no patterns of array elements used; (b) accounting for antenna patterns (circles denote true DOAs of satellite signals, crosses show the estimated DOAs).

nique. First, the DOAs of GPS satellites were estimated with the real-time calibration corrections but without accounting for the reception patterns of array elements (see **Figure 8a**). In the next step, estimated DOAs were used to find the corresponding phase responses of the array elements and take them into account in the second DOA estimation (see **Figure 8b**).

Table 1 summarizes the statistical characteristics of the

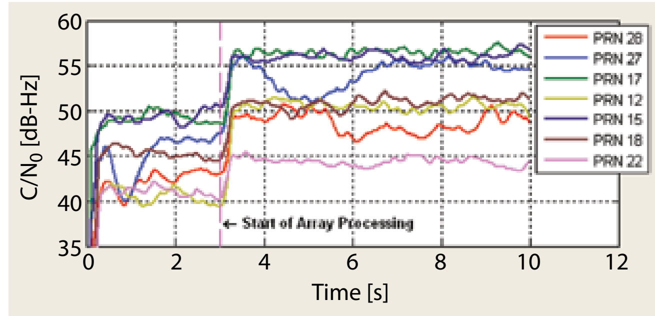


FIGURE 9 Beamforming gain for carrier-to-noise density ratio.

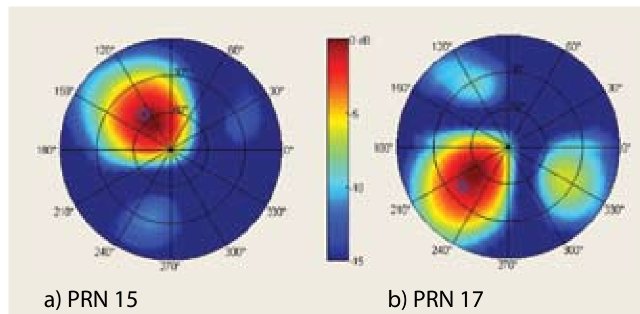


FIGURE 10 Array beam patterns for GPS satellites with PRN 15 and PRN 17 using the minimum mean square error beamforming technique

DOA estimation errors from more than 350 runs during seven seconds of signal tracking. The actual satellite DOAs are computed with the ephemeris information from the GPS system almanac.

We used two beamforming strategies: minimum mean square error (MMSE) beamforming with the temporal reference, a local receiver PRN code used in de-spreading process; and linearly constrained minimum variance (LCMV) beamforming with an estimated DOA of the GPS signal as the constraint for the maximum of the array gain patterns. **Figure 9** illustrates the improvement in the signal level in terms of carrier-to-noise density ratio (C/N_0).

Figure 10 shows the array beam patterns obtained after digital beamforming with the use of the phase calibration corrections for the satellites with PRN15 and PRN 17.

Post-processed field test data show promising results for beamforming and DOA estimation. We are planning further tests this summer (2010) of the GNSS adaptive antenna array systems in real-time mode.

High Dynamic GNSS/INS Testing Using Aerobatic Aircraft

We investigated the behavior of IMUs under high dynamic conditions using a double-equipped MEMS IMU that included two complete and dissimilar sensor sets of accelerometers and gyros, respectively. An additional MEMS was used for reference.

In order to ensure very high dynamic excitation of the IMUs, the trials employed an aerobatic aircraft equipped with a GPS receiver and a flight measurement computer with which to record data.

Laser 200 aerobatic aircraft.

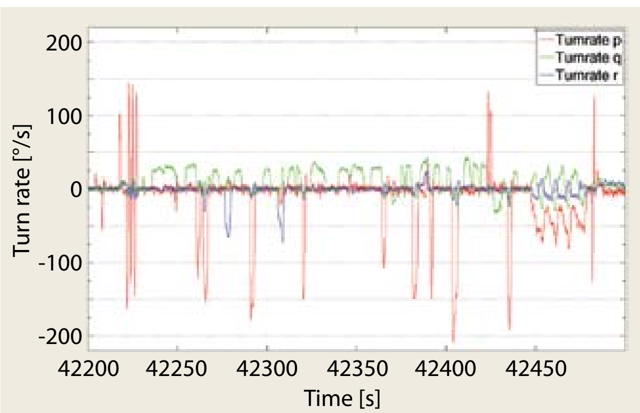


FIGURE 11 **Turn rates during aerobatic flight**

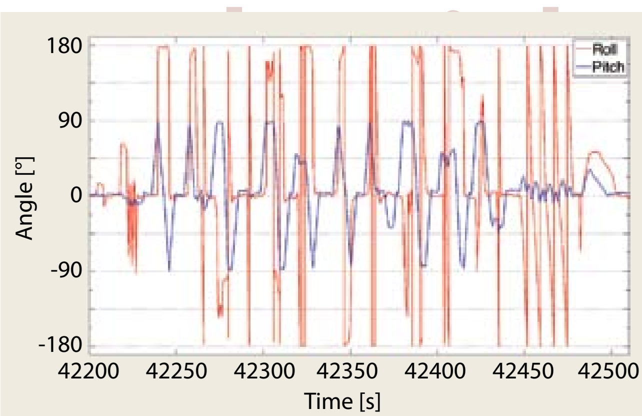


FIGURE 12 **Roll and pitch angle during aerobatic flight phase**

Two subjects were examined based on processing of the flight test data: the capability of the INS mechanization to handle discontinuities when using the classical Euler angle formulation and the performance of the MEMS inertial sensors themselves. Due to high acceleration und turn rates, the sensor stimulation is beyond the linear part of their characteristic curve. This leads to higher demands on the sensor calibration as well as the navigation filter.

The solution to the first challenge is the implementation of a quaternion reference frame, as is practiced widely. The solution to the second is a sophisticated calibration process and precise synchronization of IMU and GNSS data.

FIGURE 13 **Flight data visualization display**

Another challenge during aerobatic flight is the shadowing of the GNSS signals. Experiments showed that a low-cost automotive receiver has very short reacquisition times, but the tests revealed that expectations of the receiver's tracking performance were very optimistic.

Moreover, the receiver position is heavily filtered using dynamic models and therefore counterproductive for the aiding of the INS. This was not a problem in our case, because we used an "own-position" solution calculated from the receiver raw data in the Kalman filter's update step of the INS/GNSS integration. Finally, we found that in most cases a reliably tracked, but intermittent GNSS signal is more valuable than a signal that is more available but less accurate.

Figure 11 shows the turn rates during the aerobatic flight program. With maximum turn rates of more than 220 degrees per second, and maximum gravity load of 5.6 G's, the navigation system is highly stressed.

The resulting roll and pitch angles are shown in **Figure 12**. Because these values are difficult to interpret, we used a visualization tool (**Figure 13**) that displays views of the plane, its trajectory, and dashboards for data. The test flight can be replayed and wound forward and backward like a classical media player. This allows a better understanding of what happened during the maneuvers and may also be used for pilot training.

Conclusion

This first part of the article has shown techniques that are being evaluated or will be evaluated during real flight trial as part of the UniTaS IV project. The second part will concentrate ground based activities on theoretic investigations concerning aspects of the new GALILEO signals and multi-constellation GNSS. As part of this forthcoming discussion, we will also present a short overview of the the aviationGATE Galileo test infrastructure for airborne and apron applications, built as part of the UniTaS IV project.

Acknowledgements

The results presented here were developed during the IFF's UniTaS IV project founded by the Bundesministerium für Wirtschaft und Technologie (BMWi) and administered by the Agency of Aeronautics of the DLR in Bonn (FKZ 50 NA 0734). The IFF wants to thank all UniTaS IV scientific and industrial partners for the good cooperation and the excellent work performed during the UniTaS IV projects.

Manufacturers

The GBAS/INS unit contains an AsteRx1 GPS/Galileo/SBAS receiver from **Septentrio Satellite Navigation NV**, Leuven, Belgium; a uBlox Antaris 4 from **u-blox Holding AG**, Thalwil, Switzerland; two MEMS IMUs from **iMAR GmbH** in St. Ingbert, Germany; and a Litef LLN-G1 IMU from **Northrop Grumman LITEF GmbH**, Freiburg, Germany. The equipment used for the high dynamic flight tests included an OEM V GPS receiver from **NovAtel, Inc.**, Calgary, Alberta, Canada; a **u-blox** Antaris 4 GPS receiver; a flight data recorder and flight data visualization software from **messWERK GmbH**, Braunschweig, Germany; an **iMAR** MEMS IMU; a Litef LLN-G1 IMU from **Northrop Grumman LITEF GmbH**,; digital-to-analog converter model ICS 572 from **General Electric**, Augsburg, Germany. The flight trials used the research aircraft DO 128-6 by **Dornier Fleugzeugbau GmbH**, Oberpfaffenhofen, Germany, and an aerobatic aircraft Laser 200, a kit plane from **York Enterprises**, Tacoma, Washington USA.

Additional Resources

[1] Minimum Aviation System Performance Standards for the Local Area Augmentation System (LAAS); RTCA Do-245A; RTCA, Inc., 2004

[2] *Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment*; RTCA Do-253C; RTCA Dec 2008

[3] Steen, M., and M. Becker, U. Bestmann, M. Kujawska, T. Feuerle, and P. Hecker, "Integrated GBAS/INS Navigation System – Continuity and Integrity Aspects," Symposium Gyro Technology 2009, Karlsruhe, ISSN 1439-4502, pp. 16.1-16.15

[4] Steen, M., and P. Hecker, "GBAS/INS Navigation System: Further Developments of On-Board Integrity Monitoring," *Proceedings of the 2010 International Technical Meeting of the Institute of Navigation*, San Diego, California USA, January 25–27, 2010, pp. 386 – 393

[5] M. V. T. Heckler, W. Elmarissi, L. A. Greda, M. Cuntz, and A. Dreher, "Narrow-band microstrip antenna array for a robust receiver for navigation applications", 3rd European Conference on Antennas and Propagation (EuCAP 2009), Berlin, Germany, Mar. 2009, pp. 1206-1210.

[6] M. Cuntz, L. A. Greda, M. Heckler, A. Konovaltsev, M. Meurer, L. Kurz, G. Kappen, and T. G. Noll, "Architecture of a real-time safety of life receiver", Proc. of the 2009 ION International Technical Meeting, Savannah GA, USA, Sep. 2009.

[7] A. Konovaltsev, F. Antreich, A. Hornbostel (2007), "Performance assessment of antenna array algorithms for multipath and interferers mitigation", Proc. of 2nd Workshop on GNSS Signals & Signal Processing (GNSS SIGNALS'2007), 24-25 April 2007, Noordwijk, the Netherlands.

[8] A. Konovaltsev, L.A. Greda, N. Basta, M. Cuntz, A. Dreher (2010), "Calibration of Adaptive Antennas in Satellite Navigation Receivers", Proceedings of European Conference on Antennas and Propagation 2010 (EuCAP2010), 12-16 April 2010, Barcelona, Spain.

Authors

"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by **PROF. DR.-ING. GÜNTER HEIN.** Prof. Hein is a member of the European Commission's Galileo Signal Task Force and organizer of the annual Munich Satellite Navigation Summit. He has been a full professor and director of the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich (University FAF Munich) since 1983. In 2002, he received the United States Institute of Navigation Johannes Kepler Award for sustained and significant contributions to the development of satellite navigation. Hein received his Dipl.-Ing and Dr.-Ing. degrees in geodesy from the University of Darmstadt, Germany. Contact Prof. Hein at <Guenter.Hein@unibw-muenchen.de>.

Ulf Bestmann received a Dipl.-Ing. in mechanical engineering from the Technische Universität Braunschweig. He is employed as a research engineer at the Institute of Flight Guidance of the Technische Universität Braunschweig, where he is head of the navigation department. He works in the areas of applied satellite and inertial navigation, GBAS, pseudolite testbeds, real-time measurement systems and visualization. Together with three colleagues, Ulf Bestmann established the company messWERK GmbH in 2004, which specializes in flight testing of small and medium aircraft and real-time measurement and recording techniques.

Meiko Steen holds a Dipl.-Ing. in aerospace engineering and since 2005 has been employed as a research engineer at the Technical University of Braunschweig, Institute of Flight Guidance where he works in the navigation department in the field of inertial, satellite, and integrated navigation. He is currently especially involved in the institute's GBAS activities.

Andriy Konovaltsev is a research associate at the Institute of Communications and Navigation of the German Aerospace Center (DLR). He received his engineer diploma and the Ph.D. degree in electrical engineering from Kharkov State Technical University of Radio Electronics, Ukraine. His research interests are in array processing for satellite navigation systems, signal processing algorithms for navigation receivers including synchronization, multipath ,and radio interference mitigation.

Marcos V. T. Heckler received his BSc. degree in electrical engineering from Universidade Federal de Santa Maria, Santa Maria, Brazil, and his MSc. degree in electronics engineering from Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil. Since 2003, he has been working towards his Ph.D. and on several research projects as a research associate at the Institute of Communications and Navigation of the German Aerospace Center (DLR). His research interests include the development of numerical methods for the analysis of microstrip antennas and the design of antennas and antenna arrays, especially in microstrip technology, for GNSS and communications systems.

Peter Hecker joined the Institute of Flight Guidance of the Technische Universität in 1989 as a research scientist. Initial focus of his scientific work was on the field of automated situation assessment for flight guidance, where he was responsible for several

Working Papers *continued on page 72*

Working Papers *continued from page 71*

research projects. From 2000 until 2005 Hecker was head of the DLR "Pilot Assistance" Department. Since April 2005 he has been director of the Institute of Flight Guidance of the Technische Universität Braunschweig. He is managing research activities in the areas of air/ground co-operative air traffic management, airborne measurement technologies and services, satellite navigation, human factors in aviation, and safety in air transport systems.

Felix Kneissl is a research associate at the Institute of Geodesy and Navigation (IGN) of the University of the Federal Armed Forces in Munich. He received his diploma in mathematics at the Technical University in Munich (TUM). Since then he has worked on projects related to GNSS integrity data processing, GNSS signal monitoring, and GNSS user and signal authentication. IG