Aviation Applications

Hybrid Navigation Techniques and Safety-of-Life Requirements Part 2

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In this conclusion to a two-part series describing key results from the UniTaS IV project, the authors focus on the role of signal authentication in life-critical applications such as civil aviation. They also discuss the design of the aviationGATE test range established near Braunschweig, Germany, and describe the results of initial flight trials there that demonstrate the performance of its pseudolite-based design.

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Evolution of GNSS into a global system of multiple systems opens up a new world of aviation applications, improving such factors as integrity, accuracy, and availability of positioning.

The first article in this two-part series presented techniques that are being evaluated during flight trials as part of Germany's UniTaS IV project, a cooperative endeavor bringing together academic and industrial researchers. This second part of the series concentrates on the question of signal authentication for safety-of-life applications, as well as ground-based activities and theoretical investigations concerning aspects of the new Galileo signals and multi-constellation GNSS. As part of this discussion, we will also present a short overview of the aviationGATE test infrastructure, built as part of the UniTaS IV project.

Signal Authentication for Aviation

The threat of GNSS spoofing — the transmission of false signals — has grown more acute in recent years. Accordingly, a variety of signal authentication schemes have been proposed as a response to GNSS spoofers, including server-based authentication and multi-antenna systems.

As part of the UniTaS IV project, and in the context of aviation services, we studied spoofing and signal authentication, particularly authentication schemes for ground-based and space-based augmentation systems (GBAS and SBAS).

For GBAS systems, users of VHF data links are not interested in authentic signals per se, but rather in authentic correction and integrity data. Thus, the VHF data link is canonically applicable for digital signature systems. The project defined a new message type for

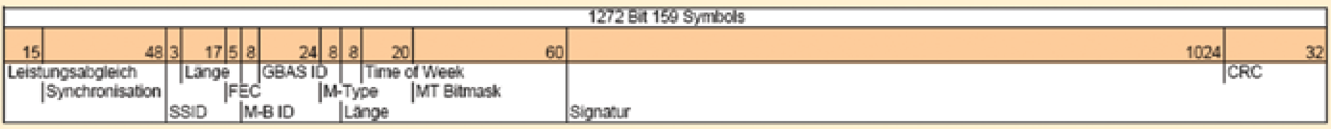

FIGURE 1 Message type definition for GBAS navigation message authentication

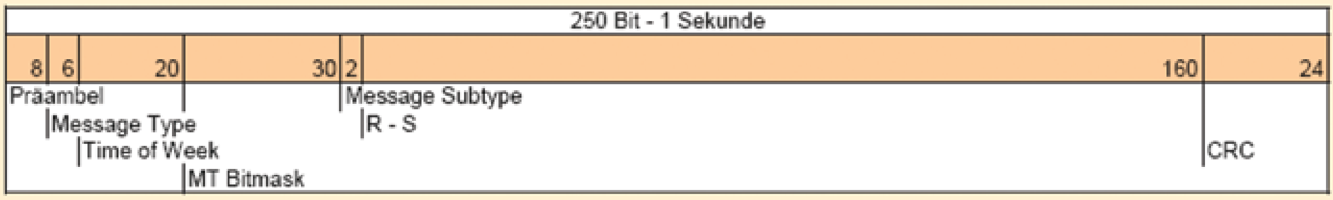

FIGURE 2 Message type definition for SBAS navigation message authentication

navigation message authentication (NMA) — shown in Figure 1 — together with a signing and verifying procedure based on the Rivest-Shamir-Adleman public-key algorithm in the Digital Signal Standard (RSA-DSS).

For SBAS systems, we propose to secure correction and integrity data using digital signature systems in a similar manner as GBAS systems. Due to the lower data bandwidth and the smaller frame size, new message types (Figure 2) and new signing and verifying procedures were defined based on the Digital Signal Algorithm (DSA) promulgated by the U.S. National Institute of Standards and Technology.

Because SBAS satellites are using signal relay techniques, SBAS would be an interesting platform for testing new authenticable signals. Newly designed NMA schemes with additional asymmetric or symmetric spreading code authentication have been developed. Even the use of only one comparatively strongly authenticable signal could assist other NMA-protected signals due to its capability of securely estimating the receiver clock bias at the roughly known user position.

One important assumption for spoofing detection algorithms in aviation is that potential attackers do not have physical access to the RF input of the receiver's front end. As a direct consequence, the authentic signal remains present in the captured signal, even if the spoofer was able to take over the tracking loops.

The visibility of the authentic signal during a spoofing attack mainly depends on the amount of additional noise induced by the attack. The noise level at the input of the analog-to-digital converter (ADC) of a GNSS receiver will be kept constant by the automated gain control (AGC), resulting in a lower amplification or in higher attenuation with a fixed amplifier, respectively.

We can use the control voltage of the AGC to monitor the jamming component (additional noise used to mask the authentic signal) of a suspected spoofing attack. However, this monitoring alone cannot distinguish among unintentional interference, intentional jamming, or an actual spoofing attack. We can accomplish this by searching the received signal for multiple appearances of the monitored signal.

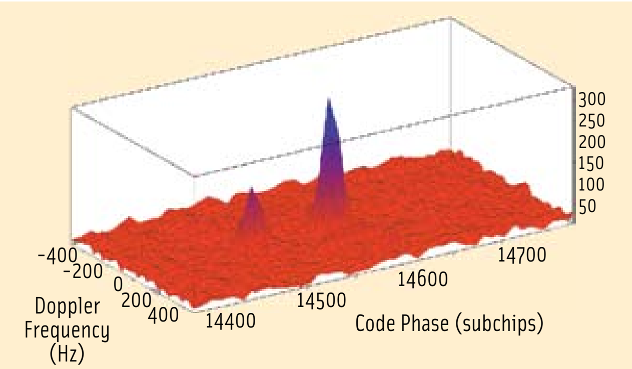

FIGURE 3 Monitoring for multiple signal occurrences in a jamming/interference environment using an FFT-based block acquisition technique

A coarse search for multiple signals can be carried out using acquisition techniques, for example, by using a fast Fourier transform– or FFT-based block acquisition as show in Figure 3. This figure shows two correlation peaks, were the higher peak represents the spoofing signal and the lower one the authentic signal.

With reasonable computational effort, the resolution in the Doppler and time dimension is comparatively low. The resolution of the acquisition/signal detection module is configurable, but the computational effort grows both with higher time resolution and with higher Doppler resolution of the signal detector. This allows efficient detection of multiple signal occurrences for time-separated signals but introduces problems for multiple signal occurrences with small separations in time.

In this situation, a complementary method — in terms of search space and computational burden — provides a method for addressing the latter problem using multi-correlators in a software receiver. Figure 4 shows results from tests performed using this method, which is described and evaluated in the paper by C. Stöber et alia cited in Additional Resources.

Combining the use of NMA schemes with monitoring of both the receiver clock error and the received signal for multiple signal occurrences provides authentic signal reception without showing any authentication delay.

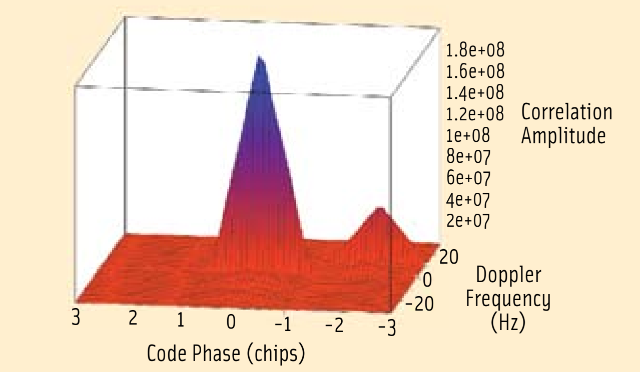

FIGURE 4 Monitoring for multiple signal occurrences using multi-correlators

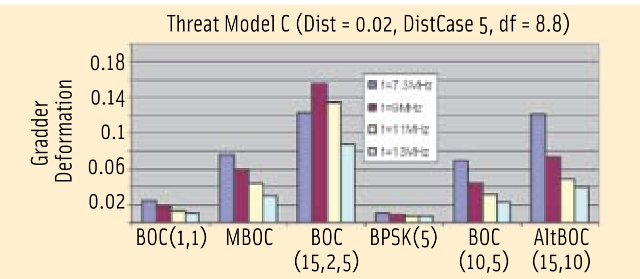

FIGURE 5 Influence of signal generation failures on different modulation types.

Delta	$\frac{(I_{-X} - I_{+X}) - (I_{-Y} - I_{+Y})}{I_Z}$
Symmetric Ratio	$\frac{(I_{-X} - I_{+X})}{I_Y}$
Simple Ratio	$\frac{I_X}{I_Y}$
Differential Ratio	$\frac{(I_X - I_Y)}{I_Z}$

TABLE 1. Commonly used test metrics

Monitoring Galileo

Erroneous signal generation induces errors on range measurements and thus signals must be monitored to ensure precise and secure applications. Erroneous signal generation is commonly described as a combination of errors in the digital and analog parts of the signal. Digital errors result in a lead/lag at falling/rising chip transitions, and analog errors are characterized by some second-order ringing of the generated signal.

Digital errors are referred as threat model A (TMA), where the model parameter denotes the lead or lag of the chip transition. Analog errors are referred as threat model B (TMB), where the model parameters are given in the damped natural frequency and the damping factor of the second order filter. A combination of digital and analog errors is denoted as threat model C (TMC).

Within the UniTaS IV project, the applicability of the threat models was assessed for the Galileo signals. For all binary offset carrier (BOC) modulations, both possibilities of digital errors occurring on chip- and subchip transitions were assessed.

Figure 5 shows the degradation of Galileo signals for TMC type of distorted signals with digital errors at all subchip transitions for different ringing frequencies. The figure clearly shows that an increasing subchip rate results in more severe signal distortions. As a result, signal quality monitoring gets more and more important for the new signal modulations.

A promising method for detecting evil waveforms can be found in the monitoring of the shape of the autocorrelation function using multi-correlator measurements. We therefore composed and monitored test metrics, which are linear combinations of the correlator outputs. Some examples are given in **Table 1**.

In order for the test metric to be sensitive to distortions of the correlation function coming from evil waveforms, the distortion dependency of the metric must exceed its noise level. The noise level of each test metric can easily be determined by the noise level of each correlator using the law of error propagation.

Therefore, the performance of the test metric can be defined as *detectability*, using the ratio of the deterministic influence of an evil waveform on the test metric to the test metric's noise (EW/N). In equation (1), *P* denotes the parameter space, and *p* represents one combination of threat model parameters. The definition of the EW/N ratio according to this formula results in high EW/N value for test metrics being capable of detecting specific signal distortions.

$$\frac{EW}{N} := \frac{\max_{\{p \in P\}}\left(M_p - M_0\right)}{std\left(M_0\right)} \qquad (1)$$

The definition of the EW/N ratio according to equation (2) valuates the capability of a test metric to detect any kind of signal distortion.

$$\frac{EW}{N} := \frac{\min_{\{p \in P\}}\left(M_p - M_0\right)}{std\left(M_0\right)} \qquad (2)$$

Whereas the use of EW/N definition 1 would result in choosing specialized test metrics at a high detection rate and the use of EW/N definition 2 would result in choosing test metrics with a broad but lower detection capability, some intermediate weighting yields to a broader detection capability on a higher detection rate.

$$\frac{EW}{N} := \frac{\sqrt{\frac{1}{|P|-1}\sum_{p \in P}\left(M_p - M_0\right)^2}}{std\left(M_0\right)} \qquad (3)$$

Our selection process computes the specified EW/N ranking for all possible test metrics, while accounting for band-limited signal processing and control loop effects. The best-ranked test metric is chosen, and all highly correlated metrics are disregarded in the second stage of the selection process. This process may yield up to five different test metrics for signal quality monitoring.

To achieve good monitoring results, we calculate the mean value of the test metrics calibrated for each monitoring station. Semi-automated procedures for the calculation of these test metrics have been developed with good initial results.

This concept of monitoring erroneous signals is similar to modern multipath-detection algorithms, because the effect of signal-generation failure is similar to multipath. Consequently, the signal quality monitor cannot distinguish between the two phenomena. So, we developed a methodology for monitoring networks based on the fact that multipath can be modeled as a local phenomenon and evil waveforms are seen as a global phenomenon that consequently affects all monitoring stations simultaneously. On the other hand, the probability of the coincidental occurrence of multipath at several monitoring stations decreases rapidly with the number of occurrences as shown in **Figure 6**.

Even for small monitoring networks and intermediate probabilities of multipath, evil waveforms can be detected at a high level of trust using as our detection criterion the simultaneous occurrence of correlation function distortions detected at different monitoring sites. Within the UniTaS IV project we successfully tested our detection methodology with real signals generated using distorted digital baseband signals converted to HF via a digital-to-analog converter combined with a laboratory upconverter.

Dual-Constellation RAIM

In the current GNSS scenario with new services and systems coming on line, the possibilities for optimizing the navigation solution in terms of availability, continuity, integrity and accuracy are steadily increasing.

Accordingly, the interest in using Receiver Autonomous Integrity Monitoring (RAIM) techniques is also growing, especially because different navigation systems can be combined to provide the user with a powerful integrity service. Within the UniTaS IV Project GPS/Galileo RAIM techniques for detecting multiple satellite failures have been developed.

The UniTaS IV Project's main goal was both to analyze the performance of current RAIM techniques and to propose new integrity techniques for combined GPS/ Galileo observations in a scenario with multiple simultaneous satellite failures. Our analysis focused on a combination of a weighted least squares method (LSQ) using range measurements from two different satellite systems, as well as on the assurance of integrity by an observation of the remaining error vector of the least squares adjustment. The use of space projections and satellite motion helps to formulate a model for detecting for multiple simultaneous satellite errors.

Snapshot schemes are common to most RAIM techniques and consist of monitoring, independently at each instant of time, the projection of the error vector with the help of the LSQ algorithm (see **Figure 7**). The LSQ method is widely used in statistics and shows good results for detection and identification of data outliers.

The observable discriminator, the sum-of-squares error (SSE), is used to judge if measurements are affected by biases or not. Depending on the particular RAIM application there is a fault-free limit for the SSE that will only rarely be exceeded by the observed test statistic when there are no faulty measure-

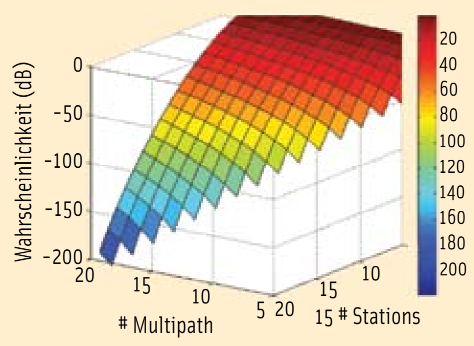

FIGURE 6 **Probability of simultaneous appearance of multipath at different monitoring stations**

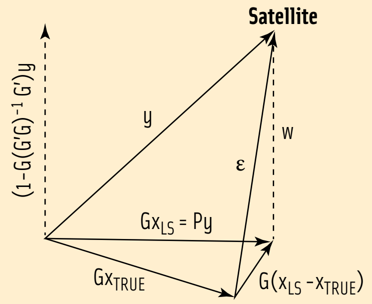

FIGURE 7 **Illustration of the least squares algorithm**

ments. This limit is called the *detection threshold* and depends on the specified false alarm and missed detection probability.

The test statistics use least squares projections, and consequently can prove inadequate for some failure combinations. Mostly in multiple-failure scenarios this may result in missed error detections. So, to address this situation we carefully assessed the integrity monitoring technique proposed by Ilaria Martini (see Additional Resources).

The objective of this approach is to reconstruct the error vector from its least squares projection. The idea used to overcome the limitations of LSQ algorithms is to extend the observation over different epochs to be able to reconstruct the error vector as a function of its projected components.

By using well-known geometry matrices for each epoch, we can describe the system rotation and accordingly reconstruct the true error vector. There is no limitation on the number of assumed faulty range measurements. For the true error vector determination, the residual estimations at two subsequent epochs need to be given as input. Furthermore, we assumed that the error vector keeps almost constant during the observation interval.

For simulation purposes a GPS/Galileo measurement simulator was developed in order to judge the performance of the proposed methods. The simulation assumes a 27 + 3 satellite Galileo constellation and a 24 satellite GPS constellation affected by all major error sources, including ionosphere and orbit/clock errors.

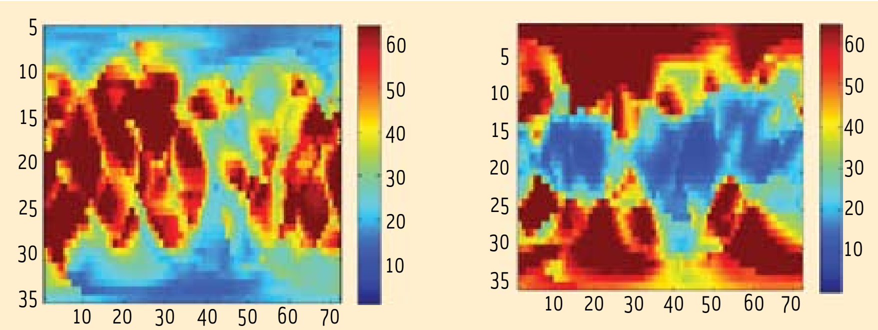

FIGURE 8 HPL and VPL values with an assumed triple-failure hypothesis

FIGURE 9 aviationGATE pseudolite positions, inner ring

The results have shown that the sequential algorithm is not robust with respect to matrix operations and has poor fault detection ability. One explanation is that geometry changes imperceptibly, resulting in a near rank deficient linear system. Furthermore, the assumption of timely constant error vectors seems not to be realistic. Additionally, the algorithm causes certain alarm latency. For these reasons we strongly recommend least squares RAIM techniques for both single and multiple failure hypothesis.

The assumption of multiple faults may reduce the least squares residuals in the presence of multiple erroneous measurements, making the fault detection and identification more difficult. Weighting of LSQ algorithm can be used to optimize the detectability of measurement errors, resulting in a more robust integer navigation solution.

The outcome of the proposed monitoring scheme is the extent of integrity, usually specified in terms of the *horizontal protection limit* (HPL) and *vertical protection limit* (VPL), respectively defining the largest horizontal and vertical position errors that can occur undetected at the specified system assumptions.

Within the proposed monitoring scheme, the user can choose how many satellites can be affected simultaneously by a fault. If two GNSS constellations are being used to provide integrity, we recommend a scenario that assumes simultaneous failures of two to three satellites (see **Figure 8**).

The proposed integrity algorithm for GPS/Galileo with multiple simultaneous range error failures, based on single frequency code measurements, provides integer positioning. The average protection level is around 30 meters when three simultaneous failures are allowed. The simulations have shown a good performance of proposed multi-constellation RAIM. The resulting extent of integrity mostly depends on the assumed satellite error rate and assumed failure hypothesis.

Building a Testbed: aviationGATE

The current status of Galileo having only two satellites (Giove A, Giove B) is not sufficient to test applications for aviation based on the European GNSS system alone. However, the full implementation of Galileo promises progress in safety-critical applications and technologies as developed within UniTaS IV. To be able to verify the these before the system is completed, a test range called aviationGATE is being set up at the research airport in Braunschweig.

The mode of operation for aviationGATE is based on pseudolite principles. Satellites are rebuilt as ground based stations to send out real satellite signals equivalent to those of the future Galileo system. With these signals, a user receiver can determine its distance to each of the pseudolites and, consequently, the position solution. The pseudolites will transmit on three Galileo frequencies, namely E1, E5a and E5b, making precise positioning available with the aviationGATE air space.

Measuring 5,500 square kilometers in extent and up to 100 kilometers across, aviationGATE enables planes to receive "genuine" Galileo signals during their entire approach to the Braunschweig airport. The variable topography of the environment permits the enacting a variety of test scenarios. A total of nine pseudolites provide the complete testbed with signals.

In the vicinity of Braunschweig, four pseudolites are mounted on elevations including the Deister ridge, and the Harz and Elm mountain peaks (illustrated in **Figure 9**). Within this perimeter, another four pseudolites surround the airport itself. Mounted in a central location, the ninth pseudolite covers both of these regions. This subdivision into an inner and an outer ring ensures that signals can be received in the entire area.

Of particular concern for safe opera-

The assumption of multiple faults may reduce the least squares residuals in the presence of multiple erroneous measurements, making the fault detection and identification more difficult. Weighting of LSQ algorithm can be used to optimize the detectability of measurement errors

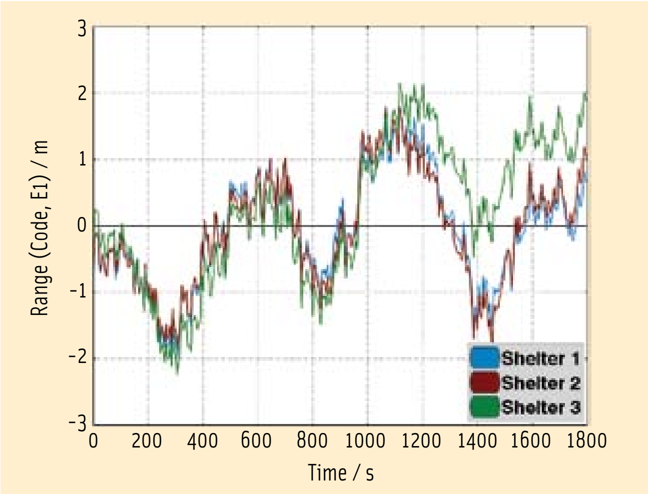

FIGURE 10 Correlated range measurements at the aviationGATE reference station

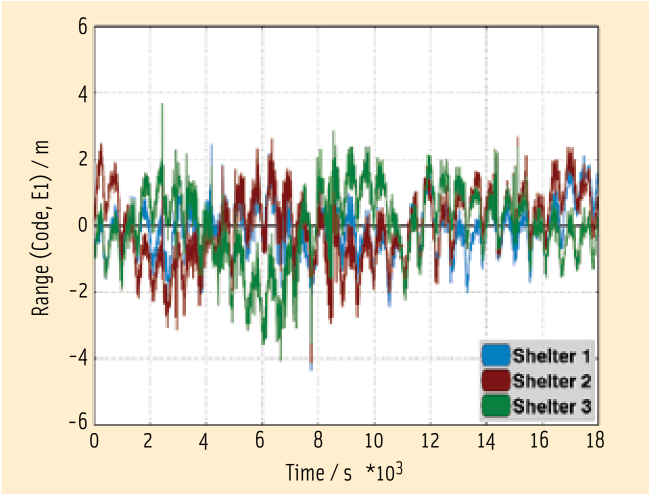

FIGURE 11 Receiver time-corrected ranges.

FIGURE 12 aviationGATE first positioning results

tions, the takeoff and landing section is covered by both pseudolite rings, which enhances the fail-safe quality of the facility. Conversely, positioning and navigation on the apron is served only by the inner pseudolite ring. Even distribution of the pseudolites around the aviationGATE site ensures that geometry-related imprecision is kept to a minimum.

Currently, the inner ring of the aviationGATE is fully operational, while the outer ring is under construction. As positioning in the area of the airport is possible using the signals of the inner ring, evaluation of the signals and achievable accuracies has just begun.

The pseudolites are synchronized in time by using a GPS timing receiver in each of the pseudolite shelters. These use oven controlled crystal oscillators (OCXOs) and can provide a drift-free 10-megahertz timing reference. The emitted signals are synchronized to this reference and, through it, to GPS system time.

Due to imprecision in the received GPS signal, each pseudolite's time, if not corrected by steering of each pseudolite by using measurement from the reference station, can have a timing offset at a maximum of five nanoseconds. These measurements can be used as well, if fed to the user, to eliminate these time offsets. In this case no direct need exists to provide additional steering to the pseudolite for initial positioning results.

Figure 10 shows correlated range measurements in millimeters at the reference station for three pseudolite signals over a period of 30 minutes. The maximum offset due to the receiver clock error is four meters. In relation to each of the other received signals (GPS or aviationGATE), it shows the attainable code precision of below one meter.

Figure 11 displays the same pseudolite ranges, only over a 12-hour period and with a corrected receiver clock. The maximum error per signal is still at about one meter but is correctable by steering the pseudolites. The noise in each measurement has a standard deviation below 0.4 meters.

These measurements already allow stand-alone positioning via aviationGATE and its Galileo signals limited to these precision of each pseudolite's timing. **Figure 12** shows the first positioning results using a single frequency, E1. The shown test trajectory is on taxiway Charly at the research airport in Braunschweig. All measurement have been taken by a ground vehicle using a Galileo L1/l5 antenna on top of the roof.

Part of the actual development in aviationGATE is to improve the steering of the pseudolites. In order to do so, a model of the pseudolite is developed to distinguish between pseudolite clock errors and signal disturbances. The result is a stable, synchronized signal with constant ranges at each receiver as well as correct absolute ranges. A strict and fast control of the pseudolite clocks allows reduction of the absolute range errors to a minimum that is basically a function of the receiver measurement noise.

Conclusion

In this two-part series, we have presented an overview of topics covered by the UniTaS IV Project, stemming from a successful cooperation between academia and industry to demonstrate the use of future GNSS and complementary navigation technologies. Beyond pure scientific research, the project results demonstrate the relevance of the developed algorithms and methods for future applications. For further information, please contact the authors.

Acknowledgement

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Manufacturers

The work described in this article used Galileo E1 and E5 signal generators from **Spirent Communications**; LL3760 GPS timing receivers from **Lange Electronic**, Gernlinden, Germany; Galileo receiver model Europak 15ab from **Novatel**, Calgary, Canada; digital-to-analog converter model ICS 572 from **General Electric**, Augsburg, Germany; research aircraft DO 128-6 by **Dornier Fleugzeugbau GmbH**, Oberpfaffenhofen, Germany; ipexSR software receiver, **University FAF Munich**, Germany.

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