Galileo and the Earth's Gravity Field
Using GNSS for Airborne Gravimetry — An Overview

Measuring variations in the Earth's gravity field has practical implications for commercial exploration for natural resources as well as advancing geophysical knowledge. The value of gravimetric methodology relates directly to the precision of spatial resolution derived from the measurement instruments. For years, researchers have used the complementary technologies of GNSS positioning and inertial sensors to refine their methods. Today, new data-processing algorithms and the advent of Europe's Galileo system promise new advances in these techniques.

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Most readers will certainly associate the new European global navigation satellite system Galileo with the name of the famous Italian physicist, astronomer and philosopher Galileo Galilei. Undoubtedly the name of the program has been well chosen if we consider the achievements of the historic Galileo in astronomy and physics alone.

During his lifetime, however, Galileo dealt not only with astronomy but also founded modern kinematics by studying the motion of bodies, and, most importantly in the context of this article, examined the laws of gravity, or to speak more precisely, of gravitational acceleration. To honor his achievements the unit of gravity in the centimeter-gram-second (cgs) system is called "Gal," defined as one centimeter per second squared.

Today this relationship is more present than ever when it comes to the subject of determining the gravity field of the Earth using moving platforms. This is especially true whenever GNSS is used to determine the (inertial) vehicle accelerations. If in a few years the Galileo system is used in addition to GPS for making gravimetric measurements, the circle will be closed back to the founder of kinematics.

The detailed structure of the Earth's gravity field and its temporal and local variations are important for many scientific and economic applications (for example, exploration, geophysics, and geoid determination). Whenever dealing with height systems, the shape, the structure, or the interior of the Earth, the gravity field is of major interest. While the determination of the geoid — an equipotential surface representing the idealized average oceans' level extended under the land mass — remains one of the main challenges for geodesy, the ever more thorough evaluation of the structure and the interior of the Earth continues to be a major objective of geophysics.

Therefore, the determination of the gravity field and its derivatives has been a challenge for many years, and, to help them meet that challenge, researchers have developed a variety of instruments. Although at first only static instruments were used, for decades ships have served as mobile platforms to determine gravity disturbances at sea. Nowadays, however, flying platforms such as airplanes, helicopters, and satellites are also used for gravimetry and offer significant economical advantages in comparison to stationary or shipborne methods.
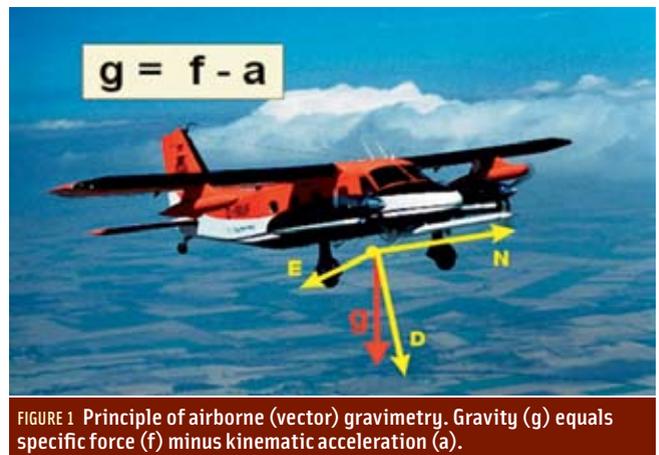

FIGURE 1 Principle of airborne (vector) gravimetry. Gravity (g) equals specific force (f) minus kinematic acceleration (a).

This column will deal especially with airborne GPS gravimetry, which means determination of the Earth's gravity field using aeroplanes as moving platform carrying different sensors (gravimeters). We will first consider some of

the principal technical challenges, tools, and techniques associated with airborne gravimetry. Then, to illustrate these elements, our discussion will introduce and present results from airborne systems and gravimetric programs conducted by three separate organizations.

The "Bayerische Komission für die internationale Erdmessung" (BEK) of the Bavarian Academy of Sciences and Humanities (BAdW) will present their gravimetry system based on the custom-designed SAGS4 inertial measurement unit; the Institute of Flight Guidance (IFF) of the Technical University of Braunschweig, their system based on a modified Russian sensor system, and the University of the Federal Armed Forces Munich (UniBwM), their system based on a commercial, high precision ring laser gyro inertial navigation system (INS).

Gravimetry from the Ground Up

Unlike static gravimetry, in airborne gravimetry the "gravity sensitive device" (gravimeter) is carried by a moving platform and, therefore, is tied to its accelerations. Additionally we must note that "gravity" is only a short form of "gravitational acceleration," and hence a gravimeter is an accelerometer.

The acceleration measured by statically mounted gravimeters always results from the sum of the gravitational forces and the centrifugal forces caused by rotation of the Earth. In addition to these forces, gravimeters on mobile platforms also experience the platform accelerations with respect to the inertial reference frame.

Accelerations caused by platform motion can be much stronger than the gravity accelerations to be observed, by a factor of up to 10^4 to 10^5. Therefore, the platform accelerations have to be determined very precisely by other means. Nowadays, researchers frequently accomplish these precise measurements using satellite navigation systems (GNSS) such as GPS, GLONASS, or, in the future, Galileo.

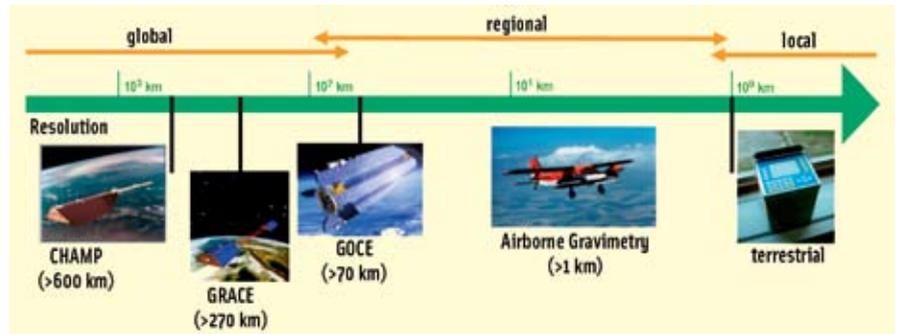The basic equation of airborne gravimetry reads, therefore, $g = f - a$, where

FIGURE 2 Resolution and application of different gravimetric systems

g denotes the gravity vector, f the total acceleration vector including inertial acceleration plus gravitation to be observed by the spring-mass system of an airborne "gravity meter" and a is the inertial acceleration vector. (See **Figure 1**.) Consequently, the task of airborne gravimetry can be described by three steps: 1) observe f, 2) observe a, 3) Relate f and a to an identical reference frame and take the difference. An important ancillary task is filtering.

A variety of instruments have been developed to measure the various components of the gravimetric equation. These can be divided into *vector gravimeters* and *scalar gravimeters*. (Gradiometers will not be covered in this article due to their special properties, which make them more suitable as satellite payload.)

Scalar gravimeters can only determine the vertical component of the gravity field without determining the directional components with respect to the local horizon. In contrast, vector gravimeters are capable of evaluating the full three-dimensional gravity vector, which also enables them to measure the *deflection of the vertical*.

Static single point measurements of local gravity using, for example, a LaCoste-Romberg gravimeter are still often carried out as a standard methodology of geodesists. However, the construction of dense measurement nets with many measurement points requires very labor-intensive efforts. The resulting resolution and achievable accuracy of the measurements are mainly a function of the time, resources, and experience of the geodesists involved in the campaign.

To improve the efficiency of gravimetric projects, researchers began equipping moving platforms with gravimeters. The first such platforms were ships from which to make measurements on the oceans. But airplanes and satellites are also used today as gravimetry platforms. In accordance with Einstein's equivalence principle, the measurements of moving platforms contain not only the gravity, but also the accelerations of the moving platforms. These accelerations have to be determined and subtracted from the measurements to receive the gravity signal.

Among leading examples of satellite-based gravimetry programs are CHAMP (CHAllenging Minisatellite Payload), a German small satellite mission for geoscientific and atmospheric research managed by the GeoForschungs Zentrum Potsdam; the Gravity Recovery and Climate Experiment (GRACE) satellite, launched by the U.S. National Aeronautics and Space Administration, in partnership with the German Space Agency; and the European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) program.

Airborne Platforms: A Happy Medium

Because of their speed and altitude, satellites are able to cover the largest areas in the shortest time all the possible gravimetric platforms. However, with increasing altitude above the Earth's surface, the resolution of gravimetric data decreases due to the radial field progression.

Local gravity anomalies interfere with the environment and, despite new

and modern algorithms, the separation of the different influences on satellite gravimetric data still cannot be solved sufficiently and may never be. Therefore, the choice of the appropriate platform is also a trade-off between the achievable resolution and the efficiency of the data collection.

Due to their nearly constant and well-observed mass, satellites are without a doubt the best platforms for gradiometers and for global observations. On the other hand, as **Figure 2** shows, airborne gravimetry on low-flying platforms can provide a much higher resolution and is capable of providing high quality regional data up to the level needed for exploration or geodesy.

In order to assure as wide a field of use as possible, a measurement system for the determination of gravity data on the one hand should be accurate, reliable, and with a high resolution, while on the other hand also being efficient and independent of the geographic area of operation. In comparison and combination with satellite-based and terrestrial methods, the principle of airborne (vector-) gravimetry seems to be an optimal solution to determine significant regional gravity changes.

Overview: Airborne Gravimetry

As mentioned earlier, acceleration-sensitive sensors are unable to distinguish between the specific forces resulting from accelerations between the sensor platform and the inertial frame and the accelerations resulting from gravity. Therefore, gravity sensors mounted on moving platforms measure the vector sum of both influences. To determine the actual gravity acceleration, we must determine the accelerations of the platform with respect to the inertial system as well as the actual attitude with respect to the Earth and then compensate the sensor output for these.

Today, GNSS systems such as GPS are used to challenge the goal of determining the point mass movement. Platform attitude is usually determined by inertial instruments — gyroscopes and accelerometers. In evaluating existing

systems we must consider the gravity sensor and GPS equipment used and also, even more important, GPS processing technique employed.

Several types of gravity sensors are used today in experimental and commercial systems. The most common approach is to adapt classical gravimeters or sea gravimeters to an airborne

> **The choice of the appropriate gravimetry platform is a trade-off between the achievable resolution and the efficiency of the data collection.**

application. This approach has been followed intensively and is even offered as commercial products and services.

Investigations into the use of inertial navigation systems (INS) as gravity sensors have resulted in approaches using different kinds of INS designs, including former military submarine INS, commercial strap-down INS, and custom-designed sensor constellations operated in a strap-down INS manner. These systems have in common the use of inertial sensors integrated in inertial measurement units, although their shape, dimensions, technology, and former application may differ significantly.

During the program "Entwicklung der Fluggravimetrie unter Nutzung von GNSS Satellitenbeobachtungen" (Development of airborne gravimetry using GNSS satellite observations), several airborne gravimetry systems were discussed, developed, and tested by German institutes. This program was sponsored by the Bundesministerium für Bildung und Forschung (BMBF, Federal Ministry of Education and Research, Germany) and the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under the program "Geotechnologien."

In a final measurement campaign the various systems showed their capabilities on the same platform, a Dornier Do-128, operated by the Technical University of Braunschweig. Each system operated on test flights over an interesting gravity anomaly between the German cities of Braunschweig and Magdeburg. Three of the developed systems and their process-

ing algorithms will be presented in the following sections.

University FAF Munich

As mentioned earlier, the observation of gravity anomalies using airborne gravimetry principle is already offered by some companies. These operational systems mostly use modified sea-gravimeters mounted on a stabilized platform to detect the specific forces.

In order to derive the required gravity value, the kinematic accelerations of the airplane, especially in height, must be determined additionally. This is currently done in some cases using GPS combined with other instruments, for example, barometric sensors. So far, operational airborne gravimetry is able to achieve spatial resolutions of about 5 kilometers with an accuracy of 2 mGal ($1mGal = 10^{-5}m/s^2$). The spatial resolution is limited mainly by the integration times of the filters used and, therefore, corresponds to a distance along the flight path.

Using such an approach, the computation of kinematical accelerations by GNSS phase observations and the stabilization of the gravity sensors are the most important limitations. Moreover, to fulfil the requirements for most exploration applications, which are very important as potential customers especially in the economical aspect, the accuracy and spatial resolution of such systems must be increased.

Other common disadvantages of the current systems include size, weight, and cost. Furthermore, such systems are limited to observing only the absolute gravity value. Information about its direction is only available by employing the vector gravimetry principle.

Against this background, the UniBwM Institute of Geodesy and Navigation (UniBwM) has developed an airborne vector gravimetry system that is being further improved by incorporat-

ing a commercial high precision strapdown INS and a geodetic GNSS receiver combined with a multi-antenna GNSS receiver system. Relying particularly on improved data processing methods, the institute is aiming for an accuracy of 0.5 mGal over 0.5 km. Accuracies of 2-3 mGal over 1 km have already been realized and demonstrated with the actual system.

UniBwM's main focus lies on the development of powerful algorithms and filters for processing the data. Therefore, only high precision commercial-of-the-shelf (COTS) components have been chosen; no dedicated gravimetry sensor hardware was developed for the system. The results of the performed measurement flights, however, show the great accuracy and capabilities of these components.

System hardware components. The heart of the system is an aviation grade

FIGURE 3 **Hardware overview of the airborne gravimetry system of the University FAF Munich**

FIGURE 4 **GNSS/ Strap–down INS airborne gravimetry system and general data processing**

INS, equipped with ring-laser gyros (drift <0.003°/h, resolution 0.006μrad/s) and very sensitive accelerometers (resolution 0.023 μm/s²). The INS delivers the inertial measurements (rotation rates and accelerations) at a frequency of 100 Hz.

The main GNSS sensor is a dual-frequency (L1, L2) 12-channel GPS receiver that delivers code, Doppler measurements, and carrier phase observations at a frequency of 10 Hz. In addition, two 16-channel GPS L1 receivers with multi-antenna systems were flown in the demonstration campaigns to support the attitude determination and assist in carrier phase ambiguity fixing by the known baseline between the antennas. All onboard sensors are controlled and synchronized by a flight computer system. For differential processing, several GPS reference ground stations are needed. Demonstrations have been performed with different receivers.

The entire system components are shown in **Figure 3**. The INS pictured on the left-hand side of the figure measures inertial specific forces and the rotation rates in the instrument frame, represented by the symbols f and ω. An L1/L2 receiver, shown on the right-hand side of the figure in a 19-inch rack slide, measures the kinematic acceleration. The symbols ρ and θ represent the measured quantities for pseudoranges and carrier phases, respectively. The figure also shows the multi-antenna system and its receivers (center).

Data processing algorithms and filters. In the case of airborne gravimetry, the primarily long- term INS errors and the short-term acceleration errors caused by the noise of the GNSS observations are combined in the error behavior of the gravity signal. Long-term INS errors are the result of sensor errors, alignment errors, Schuler-oscillation, and many more. If the INS were running free without external aiding, these errors could reach large values. The INS error dynamics are in any case slow with high-quality sensors.

The GNSS acceleration determination has different error behavior. A steady error growth is not to be expected with GNSS, while the phase noise produces short-term or high frequency errors at the acceleration determination. The gravity signal, dependent of the platform speed and the dimensions of possible anomalies, usually has a frequency between the described errors.

Consequently, when filtering the GNSS derived kinematic accelerations and the measured specific forces to reduce these error influences, there is, unlike the typical navigation application GNSS/INS integrations, only a small frequency window within which an accurate gravity determination is possible.

Therefore, the goal of the data processing is to increase this spectral window to fulfill user requirements. **Figure 4** demonstrates the most important steps of this procedure. Unlike traditional approaches in airborne gravimetry the inputs for the designed integration filter are not position data but rather on the acceleration level. So, the sensor data must be processed separately to extract the specific forces (denoted in the figure as f^b) from the INS as well as the kinematic accelerations in the inertial frame
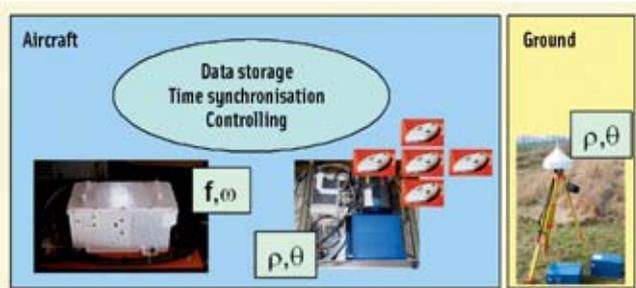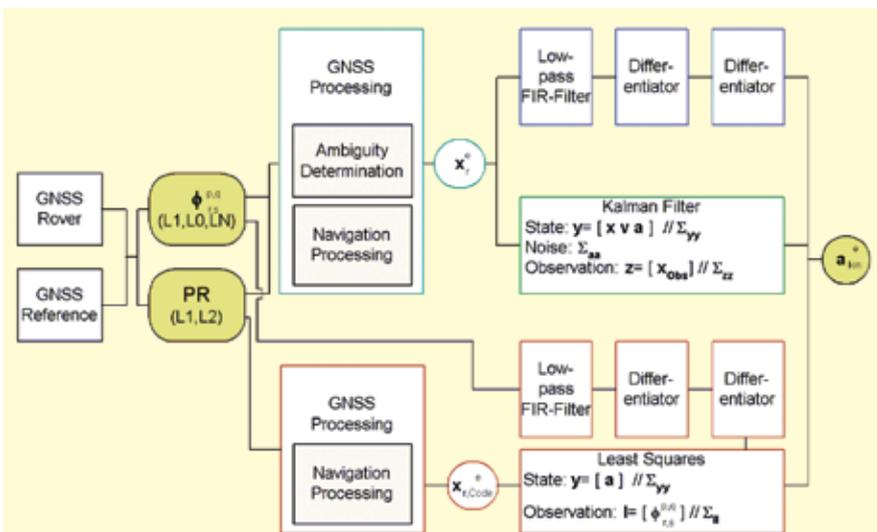
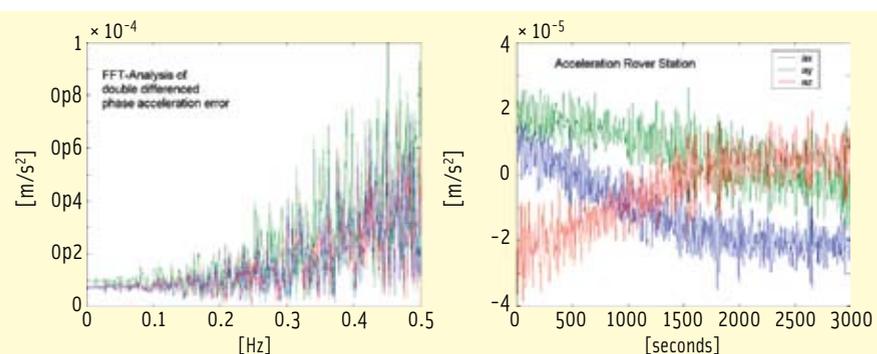**FIGURE 5** Algorithms of kinematical acceleration determination out of GNSS measurements

FIGURE 6 Spectral Analysis of phase accelerations/Calculated acceleration using least squares approach (legend applies to both figures)

$(a_{kin}^{\ i})$ from the GPS measurements (ρ, θ). In the case of INS data that mainly means transformation into a common inertial reference frame and correction of systematic errors estimated at the beginning or during the flight.

The measured inertial rotation rates (ω^b) are used to calculate the actual attitude and the transformation matrices in a strap-down algorithm. Customized filtering is applied to the inertial measurements to compensate for sensor noise and the induced vibrations by the platform.

Emphasis must be placed on the synchronism of filters and data processing algorithms in both data streams to maintain the relationships between the measurements. Even small diversions can result in large processing errors. As mentioned previously, the derivation of kinematical accelerations out of GNSS observations is an important — maybe the most important — limiting factor of airborne gravimetry.

The central Kalman filter should divide gravity signal and sensor errors as much as possible. Use of special filter models integrating additional gravity field information can support this error-separation process. Postprocessing algorithms like waveform correlation filters can improve the system performance using redundant gravity information derived from end point conditions, crossing points in the flight path, or forward and backward processing.

Role of GNSS. The determination of an object's absolute or relative position is the standard application of GNSS systems in which the influences of system errors are well known. As the GNSS raw data is on the position level, such applications do not require integration or differentiation of errors. Moreover, the derivation of precise velocities using mostly a combination of phase and Doppler measurements can be characterized as a standard processing technique.

Airborne gravimetry is nearly the only application in which GNSS measurements need to provide accurate mGal-level acceleration data. Consequently, the error influences must be evaluated in a completely different way than positioning or navigation applications of GNSS. First, we must consider that the process of differentiation amplifies these errors as a function of increasing frequency, causing them to be larger as the upper edge of the bandwidth is increased. For instance, long-term errors such as ionospheric influences have only small direct effects on the acceleration solution, whereas the receiver noise is the most dominant influence, and even a small cycle slip leads to immense errors.

The spectral analysis of double-differenced GNSS phase data using different observation conditions demonstrates the particular influence of GNSS errors on the acceleration determination. As an example, the left side of **Figure 6** shows a typical frequency spectrum for the errors in 3D kinematic acceleration derived from double-differenced GNSS phase observations using a baseline length of 300 meters. Note that typical cut-off frequencies for airborne gravimetry are up to 0.05 Hz.

The acceleration accuracy level of airborne gravimetry is only achievable if low-pass filters are applied. But to guarantee a sufficient spatial resolution their cut-off region must be restricted. Aside from various data differentiation methods (polynomial approximation, Taylor-approximation, differentiating numerical filters), with respect to the low-pass filtering only finite-impulse-response (FIR) filters are suitable for this application. Their important property of constant group delay is a valuable quality for the time synchronization of both sensor data streams.

Concerning the complete calculation of kinematic acceleration out of GNSS measurements, essentially three algorithms are possible. The traditional method is presented in the upper part of **Figure 5** and will be referred to as

the *position* approach. In the first step, this approach uses standard software packages to calculate the differential GPS (DGPS) phase solution. This step includes the ambiguity fixing and the navigation processing itself, which leads to a high precision position solution. Then the position is filtered according to the required spatial resolution of the data set. The process of double-differencing finally leads to the kinematic acceleration.

A second data processing technique involves Kalman filtering of the position data (the green box in Figure 5). Using a simple second-order dynamic model, the GNSS positions can be used to derive the actual acceleration state. Here, the definition of the acceleration noise affects the spectral properties and the time delay of this filtering process. An advantage of this method is that additional information, such as the fixed baseline between two antennas, can easily be integrated. However, in this case the ambiguity terms also have to be fixed.

The disadvantage of the position approach lies in the fact that, with increasing baselines to the reference stations, ambiguity determination with only single-frequency observations can become impossible due to ionospheric disturbances. An ionosphere-free linear combination L1-L2 has to be used then, which increases the signal noise level and therefore the noise level of the results.

The lower portion of Figure 5 marked with red boxes shows another approach. Here the processing algorithm is based on a least squares approach and requires as input values only the low-pass filtered phase accelerations of rover and reference receivers and the GNSS code solutions. Using the reference coordinates and the approximate rover position, a functional model can be designed to allow direct estimation of airplane accelerations. Satellite geometry is considered in an accompanying stochastic model.

This method, which we'll call the *acceleration approach*, is very interesting for airborne gravimetry because it does not require resolution of integer phase ambiguities. Therefore, this method

should allow substitution of L1 phase measurements with a lower noise level for the ionosphere-free linear combination normally used.

As an example for the data processing using the least squares approach, the right-hand graph in Figure 6 displays the calculated acceleration of a static antenna ("Rover") (0.02 Hz cut-off frequency low-pass filter, 300 m baseline) with respect to a base station ("Station"). As can be seen, the least-square the accuracy level of airborne gravimetry is nearly achieved.

UniBwM Flight Tests

Tectonic activities in former times in the area between the German cities of Braunschweig and Magdeburg have created significant gravity anomalies — already well mapped by previous gravimetric surveys — which provide a useful ground truth for flight tests conducted by all three airborne gravimetric systems described in this column. Prior to the UniBwM system's flight, the INS was aligned in several filter steps using GPS updates: first a coarse alignment by levelling and gyro compassing, then several steps of fine alignment.

The aim of the calibration process is to align the strap-down INS to the navigation frame and to determine as accurately as possible sensor errors such as biases or scale factor errors. In flight a number of calibration maneuvers are performed to increase the Kalman filter states' observability. During these maneuvers sensor error states can be readily detected and mapped. Sensor data gathered later can then be corrected accordingly.
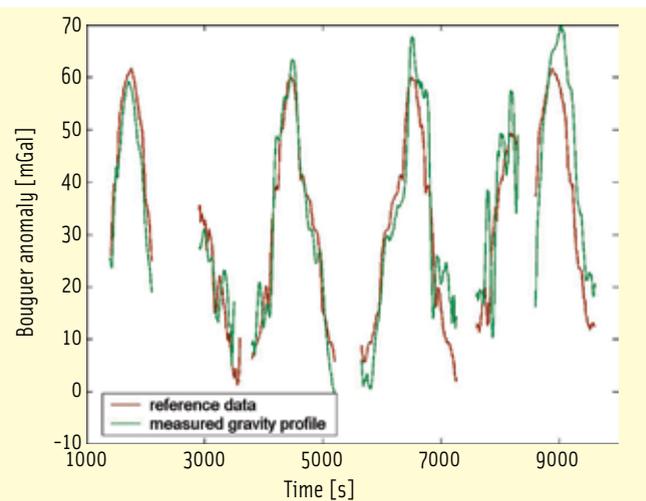
The flight trajectory crossed the test area two times per flight to allow crossing point corrections. In the corners the increased

observability of the Kalman filter states allowed new estimations of the sensor errors; this procedure prevented the steady increase of INS errors. During the gravity measurement profiles the aircraft was flown as smoothly as possible.

Data from the flight test campaign have been processed using the different types of processing described earlier. Of these, the acceleration approach seems to provide slightly better performance. **Figure 7** shows some results of the data processing using this method in which the convergence to reference data gained by static single-point measurements can easily be recognized.

The airborne gravimetry approach using a high-precision commercial strap-down INS proved itself to be reliable and efficient. The strategy of using COTS hardware and UniBwM's focus on the processing algorithms worked well, demonstrating the potential of the hardware as well as the algorithms with achievable accuracy being in the region of 2-3 mGal at a resolution of 1 km.

The main challenge has been obtaining accurate inertial kinematic acceleration determination using the GPS data. Especially the phase noise showed the actual limitations. The Institute of Geodesy and Navigation therefore is pursuing a program of innovations to improve the GNSS acceleration determination, in which the Galileo GNSS system will play an important role.

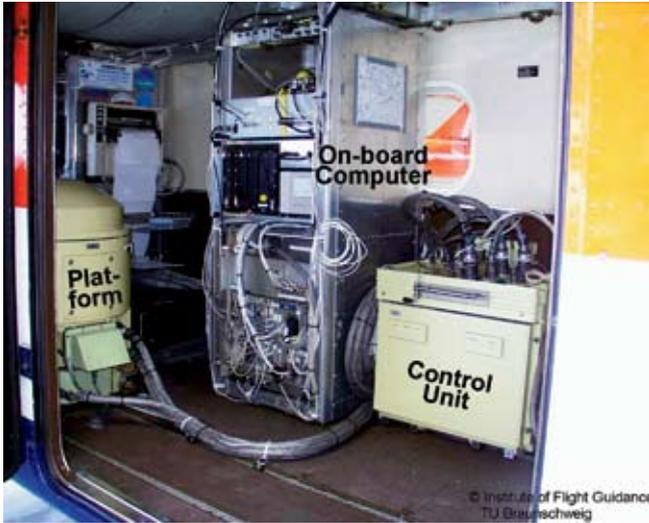FIGURE 7 Comparison of reference data and measured gravity profile using acceleration approach to data processing
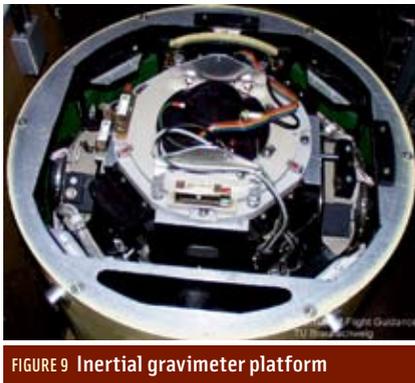
In particular, UniBwM researchers expect to obtain low noise carrier phase solutions. With these innovations an increase in performance to 0.5 mGal accuracy at a resolution of 0.5km seems realistic and recommends the flight gravimetry for efficient exploration as well as for high-value scientific research.

Technical University of Braunschweig

The Institute of Flight Guidance (IFF) of the Technical University of Braunschweig (TU BS) has been involved in the development of airborne gravimetry since 1985. Until 1997 fundamental theoretical examinations of airborne gravimetry were carried out. Since then the IFF has possessed a highly precise Russian navigation platform, which serves as a carrier system for a Russian gravimetric sensor. The assembly of both devices constitutes the main component of the airborne gravimeter system.

In addition to the sensors for altitude measurement, the inertial platform represents the decisive item of the sensor package necessary for airborne gravimetry. The gravimeter system supplies both the acceleration signal necessary for the determination of gravity anomalies and data needed for various corrections.

The measuring system supplied from a Russian manufacturer consists of two main parts: a control unit and a gyro-stabilized platform. **Figure 8** shows the two main components mounted in the TU BS IFF experimental aircraft.

The inertial platform ensures the stabilization of the gravity sensor's sensitivity axis in the vertical direction and incorporates a two-axis gyro stabilizer with a two-degree-of-freedom gyro and a gearless servo drive. Outer and inner rotating gimbals are supported by precise bearings, and their axes are aligned parallel to the longitudinal and lateral vehicle axis.

A set of sensors is installed on the platform. A highly sensitive accelerometer (gravity sensor, **Figure 9**) located in the center of the unit measures the vertical acceleration. Two further accelerometers are mounted in the horizontal level and provide data for platform levelling.

A gas-bearing gyro stabilizes the gravimetric platform. In order to compensate for the Earth's rotation rate Ω_E and the relatively large drift $(D=3°/h)$ of the gyroscope, the platform was originally controlled with an analog Schuler-control. This design, however, is not suitable for airborne gravimetry; so, the analog controller was replaced with a digital one, which creates a further degree of freedom (yaw) around the vertical axis for the two-frame platform.

The two-frame platform is upgraded to a three-frame platform through use of GNSS data and an azimuth gyro by an additionally installed ring laser gyro. The third frame is based on a strap down calculation. Compensation for the influence of the Earth's rotation rate and the Eötvös acceleration is generated from the azimuth gyro data and GNSS information.

System Development

In the course of its investigations the IFF developed the concept of a re-fed complementary airborne gravimeter (patent number 40 13 570, announced April 27, 1990, filed at the German Patent and Trade Mark Office, Munich), which it examined systematically in extensive simulations and, more recently, on various platforms. In the DFG project Scha 334/6-1 this new concept of a gravimeter was simulated in combination with a real airplane model (5-point model), as well as air-turbulence and simple analytic gravitation models. During the SFB 420, subproject B4 "Fluggravimeter," the highly exact, platform-based gravimeter was procured, installed, and tested in the IFF's experimental aircraft Do 128-6.

Figure 10 depicts the IFF approach to separate variations in gravitational force. Gravitational anomalies are determined differently from usual procedures. The elimination of the normal gravity portion and the Eötvös correction are analogous to marine gravimetry. The accuracy of the positioning sensors employed in the gravimetry system therefore directly affects the accuracy of determination of normal gravity and the Eötvös terms.

The characteristic supplement of airborne gravimetry is the integration of the measured flight altitude in a separate branch of sensor/data. From this the free air correction is derived among others. In order to minimize phase shifts between the two measurement chains, each sensor has a model of the different sensor downstream. Ideal sensors or at least similar time constants are usually assumed in other products and therefore this suppression of errors is not done normally. The data streams are merged in the estimator, which separates the disturbing signal (platform accelerations) from the desired signal (gravitational force).

Modeling of the Gravimeter. The central element within the system is the gravity sensor (**Figure 11**). The sensing element consists of two identical torsion frames with pre-stressed quartz filaments. On each filament a pendulum with a mass and a reflector are mounted. The pendulums are inversely arranged to minimize cross coupling effects.

Under normal gravity conditions the pendulums are horizontally aligned. To enhance attenuation of the vibratory pendulum system, the entire construction is installed in a case filled with a viscous fluid.

The pendulum system has been mathematically modelled, and the model shows significant correlation in comparison to real measurements (**Figure 12**).

Acquisition of the reference trajectory. For airborne gravimetry high-precision positioning is crucial. Most important is the determination of true flight altitude, which can be considered the bottleneck for development of airborne gravimetry at this moment. State-of-the-art sensors for measuring gravitational force provide the ability to improve the achievable resolution in determining gravitational anomalies by at least an order of magnitude. Therefore, IFF is treating the positioning challenge with a combination of high precision GNSS positioning and barometric height determination. In the following paragraphs, the processing of GNSS data is described.

IFF On-Board System

In principle a gyro-stabilized gravimeter platform is levelled automatically. Nevertheless, due to the drift of the gyros, stabilization is supported through GNSS positioning in real time. IFF hopes to achieve centimeter-level positioning accuracy. This is based on GPS measurements and network real-time kinematic (RTK) processing with an area correction parameter (in German, "Flächen-Korrektur-Parameter" or FKP).

In this mode FKP information transmitted from a network of reference stations is received by a rover. The FKP transmission provides information about the distance-dependent error
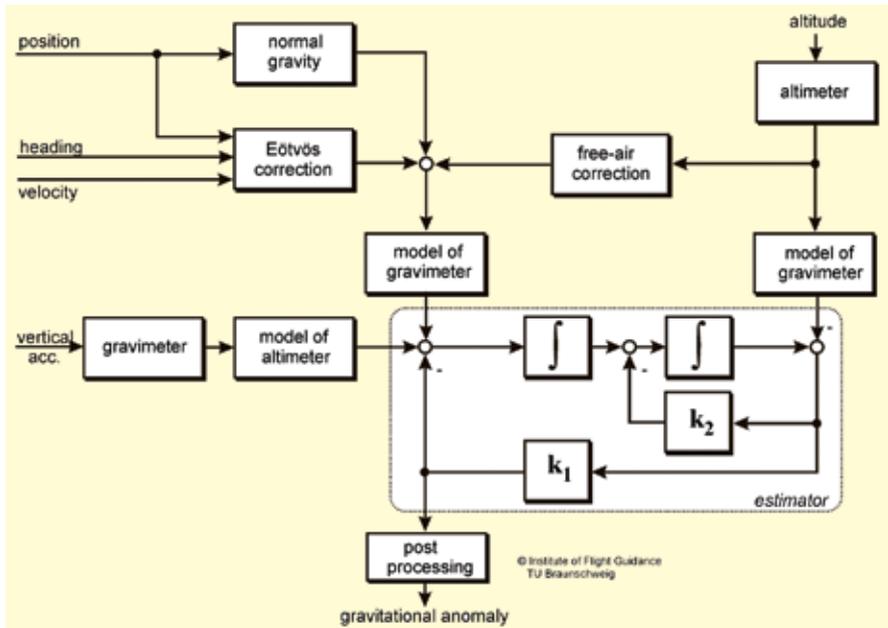

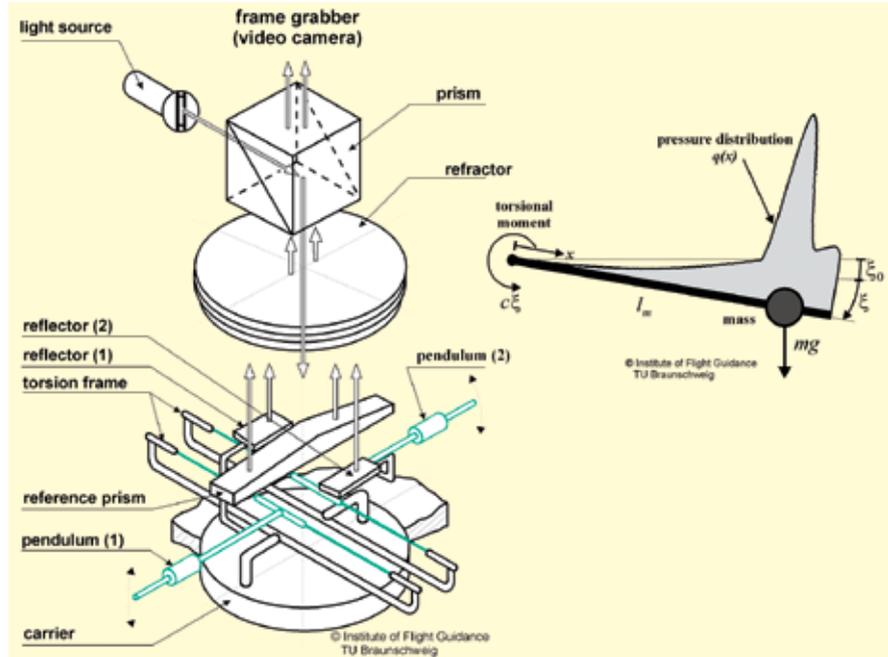FIGURE 10 Simplified overview of the IFF data processing

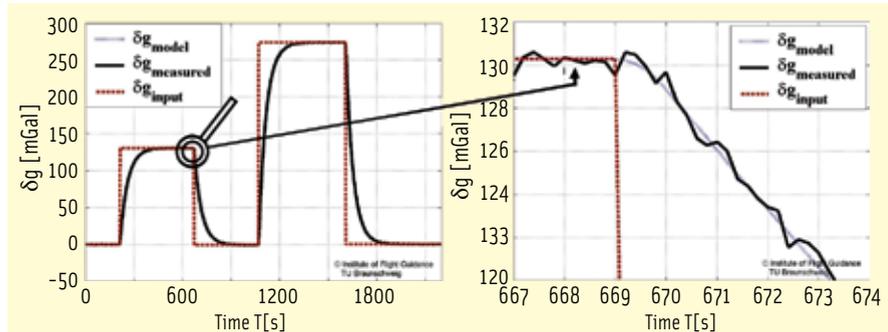FIGURE 11 Schematic of the gravity sensor components

FIGURE 12 Comparison of mathematical model and performance of gravity sensor pendulums
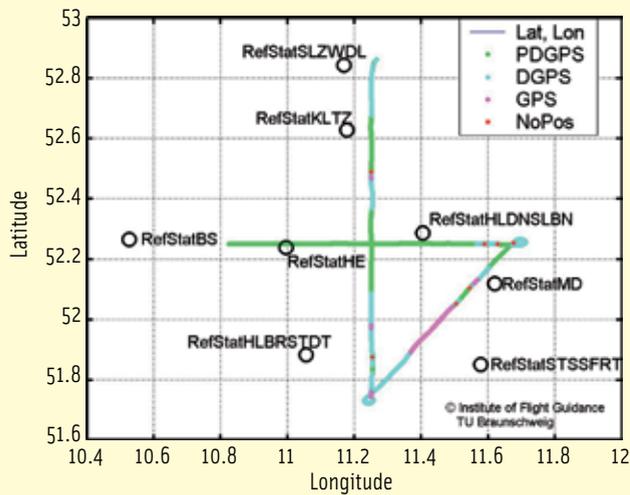
components in the network RTK. The FKP mode uses a polynomial parameterization to describe the influence of distance-dependent errors for any rover position in the network area.

Use of the FKP mode requires the approximate rover coordinates and information about satellite geometry. A major advantage of FKP is that the data can be distributed in RTCM-format by broadcast media, which in Germany are operated by the service providers SAPOS and ASCOS.

A dedicated candidate for transmitting these large amounts of data is the mobile telephone standard GSM. However, the operation of GSM in aircraft is still not allowed by technical safety regulations. With the aid of a special compression method, the RTCM-AdV format (developed by Geo++), the RTCM with FKP can be transmitted via two-meter band radio. Precise DGPS with FKP mode is possible because the decoder (SAPOS box) obtains its approximate position information and the geometric satellite constellation from the rover GPS receiver.

The complete aircraft rover system for network RTK consists of a dual-frequency GPS receiver, a SAPOS box, and a two-meter band radio receiver with aircraft radio antenna. The GPS receiver uses RTK techniques to achieve centimeter-level positioning accuracy. The initialization of the receiver is very reliable; nevertheless, incorrect initializations can occur, resulting in errors of one to three meters. Successful initialization

requires between 10 seconds and a few minutes, depending on baseline length, multipath, and prevailing atmospheric errors. The influence of baseline length and atmospheric errors is enormously reduced in network RTK.

Due to low power of the two-meter band radio transmitter, approximately 40 percent of the GNSS data from IFF gravimetric missions to date have been usable for PDGPS (Precise DGPS) processing. A further 50 percent were adequate for standard DGPS, and the remaining 10 percent were stand-alone GPS solutions. For its next gravimetric missions, IFF intends to receive the RTCM data in the research aircraft by means of, for instance, GSM, which should improve the reliability of RTCM data reception.

Figure 13 shows an example of the quality of in-flight correction data.

Another concept to consider corrections for distance dependent errors in GNSS processing is referred to as RTK Network – VRS (Virtual Reference Station) mode. A prerequisite of the real-time VRS is a bi-directional communication link (for example, GSM) between a node of the reference station network and the rover. The rover has to transmit its approximate coordinates to the network, which then interpolates a reference data stream for the transmitted position information. This concept of VRS is treated in the following section.

Postprocessing of Aircraft Trajectories

IFF uses the standard postprocessing software available from the GPS receiver manufacturer in combination with a third-part software for postprocessing VRS data in semi-kinematic mode.

In postprocessing as well as real-time applications a static VRS can easily be

computed from FKP. Using the static VRS mode in real time, all relevant information is included in the transmitted data stream to apply the individual corrections for each given rover position. Today most rover systems and even the postprocessing software cannot handle a reference station that changes its position. Unfortunately this is indispensable for increasing baseline lengths. Therefore, static VRS methods are especially suitable for small-scale kinematic and static applications, whereas FKP can also be used for kinematic applications over a larger area.

The main advantage of the VRS software is the semi-kinematic option for postprocessed applications. Until now baseline processing software have not incorporated moving reference stations. If new or changing coordinates are assigned to a reference station, traditional software has assumed the moved reference station to be a new one and ambiguity resolution is restarted.

The VRS semi-kinematic software was developed for large-scale kinematic applications in order to overcome these difficulties. A semi-kinematic VRS still refers to a fixed position, whereas the correction parameters are applied according to the trajectory of the aircraft or other rovers. In effect, a semi-kinematic VRS partly behaves like a static reference station and partly like a moving receiver. Post processing with semi-kinematic VRS has shown significant improvements in determination of flight trajectories.

IFF Results and Future Work

During the research work at the IFF, very high accuracies and high spatial resolutions of gravity anomalies have been achieved along with reliable reproducibility of results. The momentarily attainable resolution for determination of gravitational anomalies lies in the range of 5-6 kilometer wavelength (spatial resolution) with a standard deviation of 1 mGal. **Figure 14** compares measured data gathered during flight trials with measured stationary reference data.
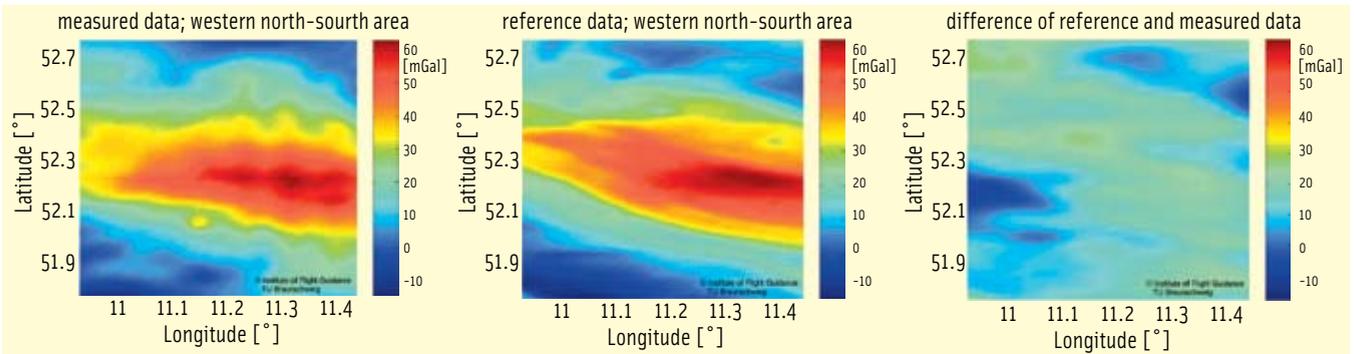
FIGURE 14 **Comparison of determined anomalies with stationary measured values**

The present airborne gravimetry system at the IFF has proven its ability to detect small scale anomalies in the gravitational field of the Earth. Consequently, IFF evolved plans to establish a commercial airborne gravimetry system in a spin-off enterprise. To enhance the chances of the spin-off company, a new version of the Russian gravimeter was acquired and will be brought into operation shortly.

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BADW/BEK is working on a strapdown airborne gravimetry system (SAGS). The current prototype is number 4; hence, the present system discussed here is designated "SAGS4.

Currently, the operational airborne gravimeters are scalar instruments observing the dominant vertical component only on gyro-stabilized platforms. For more than 20 years, efforts have been made to use (strapdown) inertial navigation instruments for vector gravimetry because of their inherent operational advantages and higher data output.

Despite this long history, however, no such system is actually in service yet with a commercial company. From BAdW/BEK's perspective, this situation calls for a custom-designed instrument to blend the benefits of classical gravimetry traditions with the advantages of advanced inertial navigation hardware — such things as thermal control, enhanced vibration isolation, lightweight and compact size, and tuning of major components for gravimetry rather than navigation.

SAGS4 System Characteristics

The SAGS4 accelerometer triad includes four accelerometers capable of a resolution of better than 10^{-5} ms^{-2} – two anti-parallel in the vertical channel. The analog signal is Bessel-filtered and 23-bit analog/digital converted at 100/s. Special dampers isolate the device from the aircraft engines' vibrations.

The inertial acceleration is observed by GPS receivers. SAGS4 employs one 50-channel L1 GPS/GLONASS receiver and a 24-channel L1/L2 GPS receiver, both operating with a 50 Hz position update rate, connected to a single L1/L2 antenna using a power splitter. Observation data are logged to a computer for postprocessing. **Figure 15** depicts the cluster of the GPS receivers on the left side of a common base plate, the accelerometer and gyro assembly with ADC on top at right, and computers in the middle.

The total acceleration vector is provided by a combination of fiber optical gyros (FOGs) in the accelerometer assembly and a multi-antenna (MA) GPS receiver providing attitude. In the near future, BAdW/BEK plans to acquire a new higher-performance system.

The combination of the two different sensor types enables long-range reference frame stability and high value and time resolution, elimination of relative fuselage deformations, and cost reduction compared to laser gyros. The analysis of the two rotation sensor data streams permits recovery of mutual transformation parameters and, therefore, referencing of the accelerometers to a global frame.
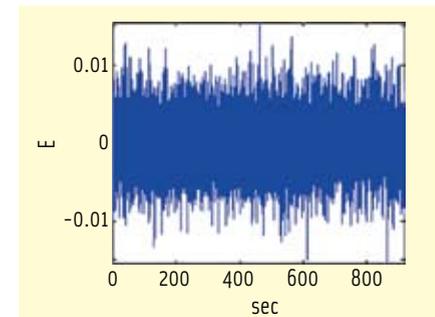

FIGURE 15 **General view on SAGS4**

FIGURE 16 **Inter-receiver height scatter**

High-Speed GPS positioning

BADW/BEK has flown the two different GPS receiver systems (using a single antenna) in various aircraft. **Figure 16** shows the differences between the two GPS systems in height calculations from more than 800 seconds of logged flight data (50 Hz sampling rate) after independent processing and removal of offsets. The RMS inter-receiver difference amounts to 3 millimeters. Of course, this is not the height accuracy, because both receivers are prone to ionospheric and tropospheric effects, but it gives an idea of the receiver performance.

In order to provide ground truth for testing the receiver characteristics, BAdW/BEK constructed a manually driven lift for moving the antenna in the vertical by about 0.6 meter, simulat-

FIGURE 17 **Lift for GPS receiver tests to simulate aircraft motion**

FIGURE 18 **Sample GPS heights at 20/s compared to ground truth**

FIGURE 19 **Sample relative ionosphere effect on P1 code (blue), L1 phase (green), and L2 phase (red)**

FIGURE 20 **Data fusion of 24-channel multi-antenna GPS and fiber optic gyro attitudes**

ing the motions of a light aircraft. See **Figure 17**.

The lift heights are provided by a scale with a resolution of 0.01 mm at sampling rates of 200/second or more. The differences between the ground truth heights and the GPS heights, of course, depend on the receiver parameters such as loop order and bandwidth. **Figure 18** depicts a test sample for one particular receiver parameter setting. From the deviations we can assess the system's performance. (More precise characterization of receiver system behavior could be obtained using line-of-sight observations to individual satellites.)

In order to cope with the tropospheric and even more important ionospheric effects on GPS positioning, two different approaches were explored: the reference station network approach (for both tropo and iono effects) and the L1/L2 combination approach (for ionosphere only). The reference station network approach uses a network of GPS reference stations at a spacing under 30 kilometers. Using the Wanninger approach, ionospheric corrections along the flight trajectory were predicted. Comparison of various variants on the processing and the set of reference stations indicated that the kinematic positioning accuracy which initially varied up to 40 centimeters with respect to a regional reference network, were reduced to very few centimeters.

However, the intended BAdW/BEK scenario for airborne gravimetry assumes operations beyond well-surveyed regions with a good ground infrastructure, such as a dense GPS reference network. Also, the sampling rate of reference receivers may not be commensurate with ionospheric scintillations, BAdW/BEK researchers started to look into the L1/L2 combination approach.

Unlike other researchers, BAdW/BEK did not begin with the differenced observations; rather, its approach took the raw code observations P and phase observations L of the 24-channel L1/L2 GPS receiver to model ranges ρ, ambiguities n and total electron count-variables q , as follows:

$$P_{i,k} = \rho_k \quad\quad + \frac{q_k}{f_i^2} \quad + \frac{s_k}{f_i^3} + ...$$

$$L_{i,k} = \rho_k + n_{i,s}\lambda_i - \frac{q_k}{f_i^2} - 0.5\frac{s_k}{f_i^3} - ...$$

Indices: $i = 1, 2$ wavecount, $s =$ series, $k = 1...l$ epoch

The L2 code data were not used because special properties in the receiver loop aiding. Therefore, it is not possible to resolve for the higher-order terms s. **Figure 19** shows a sample of least-squares-adjusted, relative epoch ionosphere effects for P1 code and L1 and L2 phases of one satellite.

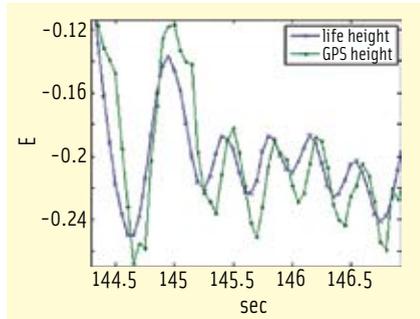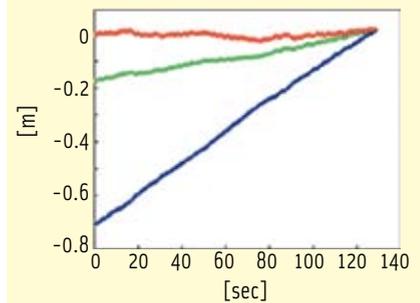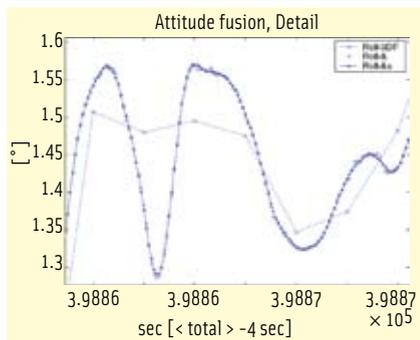From such work, stochastic models will be improved further.

Multi–Antenna GPS Attitude Receiver

As mentioned earlier, the attitude of the strapdown accelerometers are determined from a combination of a multi-antenna (MA) GPS system and FOG gyros inside the sensor assembly. **Figure 20** illustrates the data fusion for the roll axis: At low sampling rates the 24-channel MA GPS receiver provides great uncertainty per epoch but long term stability; the FOG gyros provide high precision and time resolution.

Because of the low sampling rate of this MA GPS receiver, BAdW/BEK acquired a 16-channel L1 code/carrier
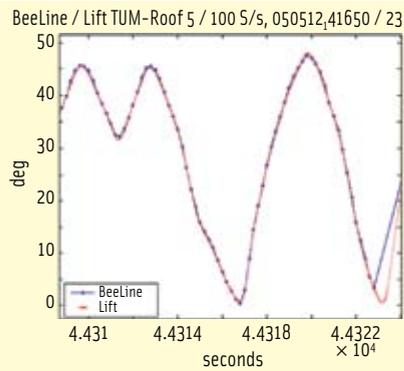
FIGURE 21 **One-axis tilt ground truth compari-son with 16-channel GPS receiver**

MA GPS receiver for which research-ers tried to provide ground truth for the GPS-derived attitude angles. With a lever arm modification of the lift, researchers were also able to provide tilt ground truth for one axis. **Figure 21** shows ground truth angles (red) derived from the test table's scale at a 100 Hz sampling rate and the angles provided by the 16-channel MA GPS receiver with a baseline length of 0.8 meters at a sam-pling rate of 5 Hz.

A large error source for MA GPS attitude is multipath. Static tests were conducted with the 16-channel MA GPS receiver on the roof of a building with obvious structures creating mul-tipath: first with ground planes under the antennas, the next day during an identical satellite configuration without the ground planes.

The results are shown in **Figure 22**. On the first day (with ground planes, green line) relatively short-period mul-tipath effects are visible but only small amplitude longer period effects. On the other day (without ground planes, blue line), the same short-period multipath signature appears, but additionally higher amplitude, longer period effects can also be seen.

In any case, such multipath effects are not acceptable for gravimetric appli-cations, and it would require sophisticat-ed measures to mitigate multipath using ground planes, absorbent materials, or similar methods. Multipath observed in the aircraft was less significant, but tests cited in the literature and BAdW/BEK's own experiments led to a deci-
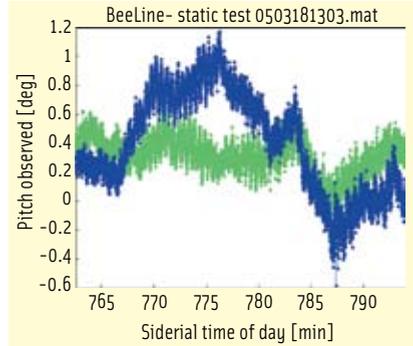

FIGURE 22 **Sample multipath effects on pitch angle**

sion to acquire a MA system with more antennae (about 9) and a modelling of multipath effects.

In conclusion, returning to our fun-damental gravimetric equation, $g = f - a$, the components of the total acceleration f can be observed with an accuracy of a few parts of 10^{-5} ms^{-2} (mGal) within a second. This should support a spatial resolution of 100 meters or so at the level of 10-5 ms-2. The discrepancy between this high precision and the much lower performance of the resulting gravity measurements achieved so far obvious-ly lies in the lower performance of the inertial acceleration determination by GNSS and in subsystem mismatches. Consequently, further detailed studies on topics presented here are needed.

Conclusions

As has been shown in our foregoing dis-cussion, airborne GNSS gravimetry is still an evolving scientific field. Although some scalar instruments are already offered commercially, several institutes are still working on various instruments including scalar and vector gravimeters with very sensitive measuring units and customized systems, as well as dedicated algorithms and software.

Despite their differences, these efforts have in common the usage of GNSS as a sensor for the determination of the kine-matic acceleration acting on the gravity instruments. Despite the various inertial sensors, the development and improve-ment of data fusion algorithms and the derivation of precise acceleration information by GNSS observations still seem to offer the greatest potential for

the improvement of the overall system performance.

Good efforts have been achieved so far but a lot of work still remains to be done. In particular, the added new Galileo observations and performance levels could be a major step of improve-ment in airborne gravimetry in future. The subject keeps on challenging us in many ways.

Manufacturers

The University FAF Munich Institute for Geodesy and Navigation gravi-metric system incorporates a **Sigma 30** ring-laser gyro inertial navigation system, from **Sagem Défense Sécurité**, Paris, France; an Ashtech Z-Xtreme from **Magellan Navigation, Inc.**, San Dimas, California; and two Beeline L1/L1 multi-antenna GPS receivers from **Novatel, Inc.**, Calgary, Alberta, Canada, for attitude determination. The Techni-cal University of Braunschweig Institute for Flight Guidance system uses a 5700 GPS receiver from **Trimble Navigation**, Sunnyvale, California USA; Trimble Total Control postprocessing software in combination with WaSoft/Virtuell SK from **Ingenieurbüro Wanninger**, Radebeul, Germany. TU BS has also acquired a CHEKAN-AM mobile gra-vimeter from **Elektropribor**, St. Peters-burg, Russia. The BAdW/BEK system uses four Q-Flex QA-3000 accelerom-eters from **Honeywell Inernational Inc., Defense and Space Redmond** division, Redmond, Washington, USA; a JNS 100 GPS/GLONASS receiver from **Javad Navigation Systems**, San Jose, California, USA, and Moscow, Russia; an OEM4-G2 receiver from NovAtel, Inc., and an Ashtech3DF and NovAtel BeeLine receiver for attitude determina-tion.

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