A Testbed for Airborne Inertial Geodesy: Terrestrial Gravimetry Experiment by INS/GPS

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Abstract. Gravimetry from a combination of INS and GPS measurements is well known and investigated since several years. The main application is in the field of airborne gravimetry, where the results can be used to fill the spectral gap between spaceborne gravity field data (from satellite missions such as CHAMP, GRACE or GOCE) and terrestrial data available from regional or continental gravity networks. Our intention is to study in detail the behaviour of such an INS/GPS instrumentation, the applied signal processing techniques and the derived signal.

As a first step, a ground based INS/GPS survey was carried out, where the results can directly be compared to terrestrial data without any need of downward continuation. Also the spatial resolution of such a terrestrial experiment is higher, than for airborne gravimetry, due to a much smaller vehicle velocity. The experiment was carried out by car in a test area in the Bavarian Alps. This area was set up several years ago in order to investigate in detail the gravity field in mountainous regions. Since about 10 years a huge number of gravity values was determined, leading to a point density of about 2.5 points/km^2. Therefore the region was chosen as testbed for our inertial measurement campaign.

The first results presented in this paper show, that our navigation grade inertial measurement unit is well suited to derive gravity values with an accuracy of a few mGal. Still, problems with the GPS visibility and the accuracy of the kinematic accelerations are an obstacle for precise determination of gravity disturbances along the trajectory.

Keywords. Inertial measurement unit, gravity, INS/GPS, airborne gravimetry

1 Introduction

A combination of GPS measurements and data from an inertial measurement unit (IMU) is capable of gravity determination in kinematic mode. Thereby the kinematic accelerations derived from GPS positions are subtracted from the dynamic accelerations measured by the IMU (containing gravity and vehicle motion). This principle is investigated since several years by different groups, see e.g. Schwarz and Wei (1990), Kwon and Jekeli (2001) or Bastos et al. (2001). Our intention is to experiment with the methodology and test different algorithms in preparation for future airborne gravimetry missions. This paper shows results from the first gravimetry experiment conducted with our navigation grade IMU in a car mission.

The survey was carried out in the Estergebirge region (northern border of the Alps). In this area a dense gravity network was set up by the Institut of Astronomical and Physical Geodesy of Technische Universität München (Munich, Germany) for gravity field modelling in mountainous regions (see Flury, 2002). Figure 1 shows a digital terrain model of the test area and the location of gravity points as well as the trajectory of the present INS/GPS ex-

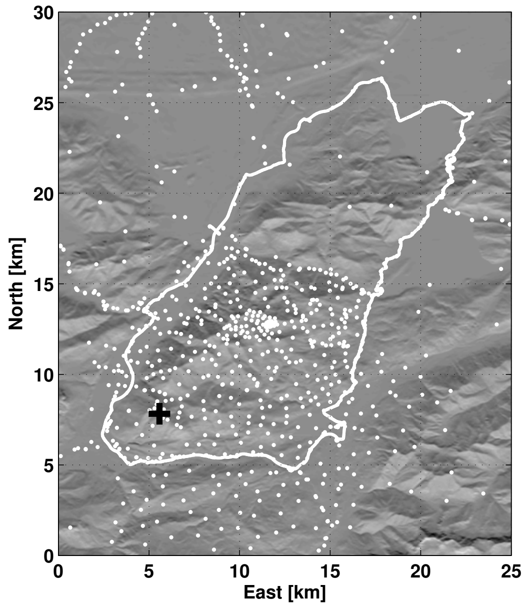

Fig. 1. Test area around Estergebirge mountains; trajectory (white solid line), gravity reference points (white dots) and SAPOS GPS base station (black cross).

periment. The density of gravity field information in Estergebirge is about 2.5 points/km^2. In addition there are about 40 stations with measured deflections of the vertical and about 200 km of leveling lines in and around Estergebirge. The Estergebirge covers an area of about 15×15 km^2, while the driven trajectory reaches further to the north and covers about 15×25 km^2. Due to the dense coverage with gravity field information the Estergebirge region is considered an adequate testbed for our inertial gravimetry experiments (both terrestrial as well as future airborne missions). The driven trajectory has a length of about 80 km showing altitude variations between 640–970 m and 80 mGal differences in gravity respectively 40 mGal in gravity disturbance. The maximum speed of the vehicle was about 15 m/s or 54 km/h. About every 5 minutes a stop was taken for use as zero velocity update (ZUPT), allowing to correct for the drifts inherent in the inertial sensors (accelerometers and gyros). After an initial alignment phase of about 30 minutes 55 ZUPTs were taken along the trajectory. For validation of the measured accelerations in static mode (see sections 3.3 and 3.4) the ZUPTs were either taken at existing gravity stations or gravity was measured next to the car using a Scintrex gravimeter. For validation of the measurements in kinematic mode, gravity disturbances were estimated along the whole trajectory using least-squares prediction.

In the following sections the instrumentation and computational methodology will be presented as well as the first results of the car mission.

2 Instrumentation

This section gives a short overview on the IMU and GPS instrumentation. Both sensors were mounted on top of the car. For the GPS antenna a ground plate was used to prevent from multipath effects. The IMU was enclosed in a plastic box to shield it from wind and rain. The box also acts as a thermal isolation.

2.1 IMU instrumentation

The IMU used in the experiment is a strapdown navigation grade unit of type iNAV-RQH. It contains three QA2000 accelerometers and three GG1320 ring laser gyroscopes (all manufactured by Honeywell). The maximum output rate of the IMU is 500 Hz, which actually was used in the present experiment. Table 1 gives the noise level and resolution of both sensor types. More details on the IMU sensor technology can be found in Dorobantu and Gerlach (2004). The unit is not temperature stabilized, but the temperature is measured and the data is corrected before output. In case of the accelerometers a polynomial of fourth order is used, where the polynomial coefficients were determined by the manufacturer. In an earlier static measurement deficiencies of these calibration parameters were found for the vertical accelerometer and a correction to the polynomial coefficient of first order was estimated. This additional correction was applied to the data of the present experiment as well.

Table 1. Sensor characteristics of GG1320 laser gyroscopes and QA2000 accelerometers.

	GG1320	QA2000
resolution	1.13 arcsec	0.2 μg
noise	0.0018 deg/$\sqrt{\mathrm{h}}$	8 μg/$\sqrt{\mathrm{Hz}}$

2.2 GPS instrumentation

The kinematic positions of the car are determined by differential GPS. The mobile receiver on top of the car was a Trimble 4000SSI dual frequency receiver. The SAPOS (national network of reference stations for differential SAtellite POSitioning) station at mount Wank (marked with a black cross in Figure 1; altitude 1830 m) was used as master station. A Leica SR520 receiver is mounted there. Both master and rover have a sampling rate of 1 Hz.

3 INS/GPS experiment

3.1 Computational methodology

Gravimetry by a combination of a strapdown IMU and GPS can be performed either in scalar or in vectorial mode, where either only the gravity value or the full gravity vector is derived. In this first experiment the computation is restricted to the scalar case (strapdown inertial scalar gravimetry, SISG). Then the gravity disturbance δg can be determined by (see, e.g., Salychev, 1998)

$$\begin{aligned} \delta g = a_u &- \dot{v}_u - \gamma \\ &+ \left(\frac{v_e}{R_N + h} + 2\omega_E \cos\varphi \right) v_e \\ &+ \frac{v_n^2}{R_M + h}, \end{aligned} \tag{1}$$

where a_u is the vertical dynamic acceleration (specific force) sensed by the IMU and $\dot{v}_u$ is the vertical kinematic acceleration derived from the GPS positions. Furthermore γ is normal gravity, v_e and v_n

are the horizontal components (East and North) of the vehicle velocity, ω_E is the rate of Earth rotation, h and φ are the ellipsoidal height and latitude and R_N and R_M are prime vertical and meridian curvature radii. The terms in the second and third row are usually called Eötvös correction.

3.2 Data processing

For the processing of the IMU data we used the dedicated Kingspad software of the University of Calgary (see Schwarz and El-Sheimy, 2000). This software allows to process both, a separate inertial navigation solution and kinematic GPS positions, as well as a combined INS/GPS trajectory. Due to frequent gaps in the GPS data it was not possible to process the data in a single run, but only short pieces of a combined INS/GPS solution. In order to compute a continuous specific force vector for the whole trajectory, an INS-only solution was derived. Therefore only ZUPTs and coordinate updates (CUPTs) at the ZUPT points could be used. This means an update frequency of some minutes (period between successive ZUPTs).

For validation of the positions a separate GPS-only solution was derived using the Bernese software (Rothacher et al., 2001). At this stage, kinematic accelerations have only been computed from the Bernese solution. Further computations will be done to compare with results achieved from the separate Kingspad-arcs. Figure 2 shows the processing chain of our computations.

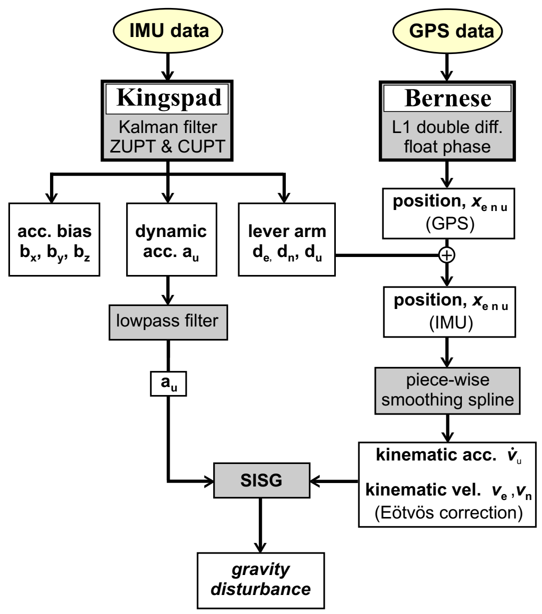

Fig. 2. Flowchart: processing chain of IMU and GPS data for strapdown inertial scalar gravimetry (SISG).

About 20% of the trajectory suffer from lack of GPS data (3 or less satellites) and only for about 55% both L1 and L2 are available. Therefore a L1-only double difference solution was computed. The length of the baseline is between 5 and 25 km, therefore ionospheric effects can be expected to be in the dm-range. Most of these atmospheric effects have long-wavelength characteristics (at least with respect to the computation of accelerations). Residual high frequent errors are expected to be below 10 cm. Periods with only 4 satellites might have larger errors. Unfortunately, the largest errors can be expected in the vertical component, which is the critical one for our SISG application. At the moment only a float solution was computed, which suffers from frequent cycle slips. Therefore the kinematic accelerations could only be computed piecewise along continuous arcs (see section 3.5).

3.3 Static IMU-gravimetry without Kalman filter

Evaluation of the IMU quality can be done easily at ZUPTs, in case a reference gravity value is known. As there are no kinematics involved (zero velocity!) the IMU acts like a gravimeter. In this case it holds

$$g_{\text{IMU}} = \sqrt{a_x^2 + a_y^2 + a_z^2}, \tag{2}$$

where a_x, a_y, a_z are the readings from the three accelerometers. Figure 3 shows the mean gravity measured at the ZUPTs compared to the reference values. The latter ones had been determined by gravimetry (accuracy well below 1 mGal). It is obvious that there are large differences at the beginning of the mission (first 1 to 2 hours up to ZUPT number 15). For the rest of the mission the error of the IMU-derived gravity has a standard deviation of 2 mGal. This indicates good performance of the IMU.

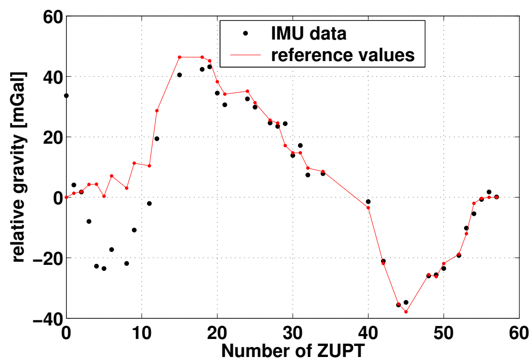

Fig. 3. Gravity from raw IMU-data at ZUPTs compared to known reference values.

3.4 Static IMU-gravimetry with Kalman filter

A similar comparison of IMU-only data at ZUPTs can also be performed with the output files of the Kingspad software, i.e. with Kalman filtered estimates. Kingspad uses a 15-states Kalman filter. Three of the states are bias values for the accelerometer. Assuming the actual instrument bias to be more or less constant during the mission, the bias variation at the ZUPTs shows the variation of the gravity disturbance. Figure 4 shows a comparison between the gravity disturbance and the bias of the z-accelerometer (z-axis of IMU body system; approximately vertical at the ZUPTs). Again the values fit quite well after about 2 hours (first 30 minutes are the initial alignment). From then on the standard deviation of the differences is 4 mGal. The same holds for the gravity disturbance computed from the vertical dynamic acceleration (Kingspad output) after additional lowpass filtering (butterworth filter of fourth order, cut off frequency 0.1 Hz). This corresponds to equation (1) in static mode, where both the kinematic accelerations $\dot{v}_u$ and the Eötvös correction are zero. The values are shown in Figure 5.

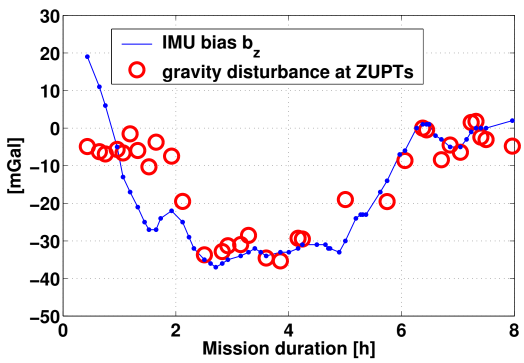

Fig. 4. Estimated accelerometer bias (z-component in IMU body frame) compared to gravity disturbance at ZUPTs.

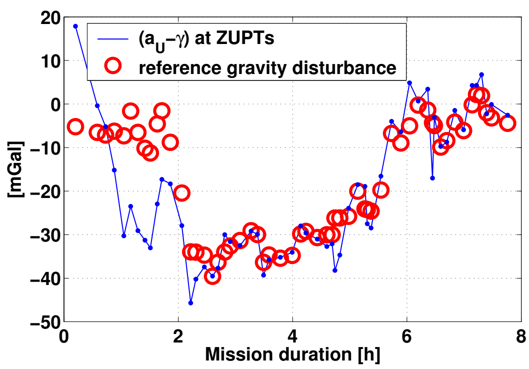

Fig. 5. Vertical dynamic acceleration a_u (minus normal gravity γ) compared to gravity disturbance at ZUPTs.

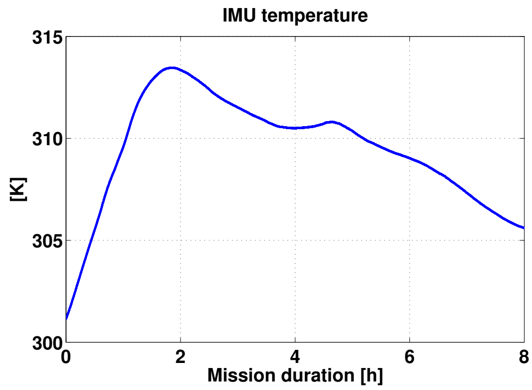

Fig. 6. Temperatur of the IMU during the INS/GPS experiment.

All of the above IMU-only tests match reasonably well with the reference values. Large deviations show up only in the first two hours. Figure 6 shows the temperature variation inside the IMU during the mission. The temperature is rising fast for about 12°C over the first two hours and declines slowly for about 7°C during the next 6 hours. Therefore residual temperature effects (connected to the temperature gradient) are possible candidates for the deviations in the first mission phase.

3.5 Kinematic gravimetry

For gravimetry in kinematic mode the dynamic acceleration a_u needs to be compared to the acceleration computed from the GPS kinematic positions. According to the flowchart in Figure 2 the kinematic coordinates were first reduced from the GPS phase center to the IMU reference point, using the lever arm components (in the local horizontal ENU-system) computed by Kingspad. Due to gaps and cycle slips in the GPS phase solution about 100 separate pieces of trajectory had to be processed, some of them lasting only about 10 epochs. In order to reduce the position noise a smoothing cubic spline function (see Reinsch, 1967) was fitted to each arc separately. Spline functions have the advantage, that the coefficients of the cubic spline function directly give position, velocity and the desired acceleration at every epoch. Figure 7 shows both the dynamic and the kinematic acceleration over an arbitrary period of 6 minutes. There is a ZUPT at the beginning and the end of this period and a gap in between. Even though the curves show strong correlation, the actual deviations are rather large. The differences have a standard deviation of about 150 mGal, which is much larger than the actual signal variation over the whole trajectory. Obviously the applied filtering (of dynamic

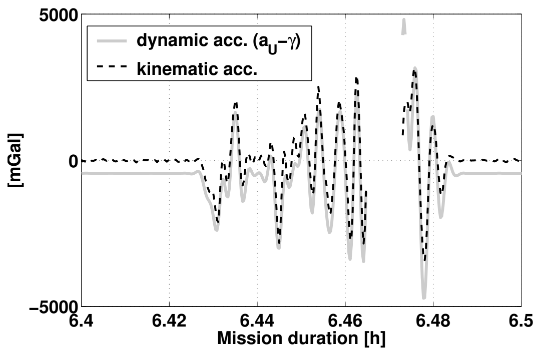

Fig. 7. Vertical dynamic acceleration a_u (minus normal gravity γ) compared to kinematic accelerations (from GPS) over a 6 minutes period.

and/or kinematic accelerations) leaves to much noise in the signal, or the smoothing spline does not only filter the high frequencies, but also harms the lower parts of the spectra. Further investigations have to be taken to clarify this point.

4 Summary and conclusions

The paper shows first results of a terrestrial INS/GPS campaign carried out by car in the Bavarian Alps. The location is considered very well suited for inertial gravimetry from the point of view of validation. The dense coverage of the region with gravity field information allows the derived signal to be validated easily. Also the variation of the signal is well above the expected SISG accuracy (80 mGal variation in gravity). The obstacle of such a mountainous region for terrestrial experiments, of course, is the visibility of GPS satellites. In our case the receiver was not capable to track the L2 signal over more than half of the mission, while L1 is present over nearly 80%. This is a drawback of our Trimble 4000SSI, which does not belong to the latest generation of receivers. New receivers would probably be able to track the signal faster, allowing a L1/L2 ionosphere-free solution over longer periods. Two more hardware aspects could improved the GPS part considerably. The first is the number of available satellites and the second one is the sampling rate. An adequate receiver should at least be able to track both GPS and GLONASS, increasing the number of satellites approximately by 2 or 3, and if possible give positions at a higher sampling rate than 1 Hz, allowing more accurate determination of kinematic accelerations.

While showing deficiencies in the GPS part, the IMU results are fully satisfying for a first experiment. Using the raw as well as the Kalman-filtered data one can evaluate the dynamic acceleration in static periods, where no kinematics show up. In those periods the derived values correspond to the reference gravity at the level of some few mGals. Only in the first period of the mission there are larger discrepancies. These might be due to residual temperature effects which are not taken care of by the calibration algorithm. Two strategies could be followed to eliminate this behaviour in future missions: first, a refined calibration model and a new estimation of the calibration parameters or, secondly, an additional temperature stabilization. Last but not least, refined algorithms and data processing strategies (,e.g., for filtering) should improve the results in the future.

References

Bastos, L., P. Tome, T. Cunha, S. Cunha, M.J. Fernandes (2001) Gravity anomalies from airborne measurements - experiments using a low cost IMU device. In: Sideris, M.G. (ed.) Gravity, Geoid and Geodynamics 2000, *IAG Symposia, Vol. 123*, 253–258, Springer Verlag.

Dorobantu, R., Ch. Gerlach (2004) Characterisation and Evaluation of a Navigation-Grade RLG SIMU. *European Journal of Navigation*, Vol. 2 (1), 63–78.

Flury, J. (2002) Schwerefeldfunktionale im Gebirge. *DGK Reihe C*, 557, Verlag der Bayerischen Akademie der Wissenschaften, München.

Kwon, J. H., C. Jekeli (2001) A new approach for airborne vector gravimetry using GPS/INS. *Journal of Geodesy*, 74, 690–700, doi: 10.1007/s001900000130.

Reinsch, C.H. (1967) Smoothing by Spline Functions. *Numerische Mathematik*, 10, 177–183.

Rothacher, M., G. Beutler, H. Bock, E. Brockmann, R. Dach, P. Fridez, W. Gurtner, U. Hugentobler, D. Ineichen, J. Johnson, M. Meindl, L. Mervart, S. Schaer, T. Springer, R. Weber (2001) Bernese GPS Software, Version 4.2., Astronomisches Institut Universität Bern.

Salychev, O.S. (1998) Inertial Systems in Navigation and Geophysics. Baumann MSTU Press, Moskau.

Schwarz, K., M. Wei, (1990) A Framework for Modeling Kinematic Measurements in Gravity Field Applications. *Bulletin Geodesique*, 64, 331–346.

Schwarz, K.P., N. El-Sheimy (2000) KINGSPAD User Manual. Department of Geomatics Engineering, University of Calgary.