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THE INS PROSPECTS FOR IN FLIGHT GRAVITATION MEASUREMENTS

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Abstract

Currently airborne gravity results can be getted using either sea/air gravimeters on a stable platform gravimeter systems such as a LaCoste and Romberg (LCR) S-model marine gravimeter or a Inertial Navigation System (INS) mainly strapdown, showing comparable accuracies.

Receiving the precise flight parameters information about the flying vehicle velocities and location (e.g. available from Differential Global Position System), then by recording installed on an aircraft flying within the indicated range of altitudes and velocities, the accelerometers data it can be separated the inertial components so leave only the gravitational ones.

Airborne gravimetry is conducted using either sea/air gravimeters on a Schuler tuned stabilized platform for scalar gravimetry, or with an Inertial Navigation System mainly Strapdown INS for scalar or vector gravimetry. In both cases, the separation of the gravitational and kinematic accelerations from the systems is crutial in estimating the gravity field. Results of scalar airborne gravimetry survey using gravimeters, modified for high dinamics of the aircraft in Greenland and Switzerland show that the accuracy of 3 to 5 mGal and a resolution of 10 km wavelenght is achievable [1] . The main error source in this case is insufficient platform stabilization. Another test using inertial platform system ITC-2 showed that the accuracy of 1 mGal with resolution of 2-3 km is achievable [4] .

Unlike to the stabilized systems, there is no physical stabilizing platform in strapdown system. Instead the inertial sensors are physically bolted down to the vehicle so that the measured data in the body frame are transformed to the local level frame computationally. The advantage of the strapdown INS is its smaller size, lower cost and more operational flexibility. The performance of SINS is comparable to the airborne gravimeter. Among several problems to be solved such as increased GPS positioning accuracy, improved signal processing, also the alignment and calibration problem has to be developed, if possible, as in-flight procedure as part of the observation mission.

The important result of using INS gravitation measurements in flight is the separation of the gravitational acceleration from kinematic acceleration as well as the system errors. The kinematic acceleration can be separated from the sensed acceleration of INS by using a different sensor such as GPS. The separation between gravitational acceleration and system errors from INS can be achieved by introducing external information e.g. ZUPT (Zero velocity update). Thus bringing the aircraft to stop periodically so can be controlled the unknown systematic errors by feeding the zero velocity information back to the system. Although this method has been successfully used in many cases [4], it is still inefficient and expensive for for the exploration of large areas. It cannot be used in areas essentially inaccessible from land vehicles or helicopters such as seas, deserts or mountains. Obviously the other way of determining the kinematic position and velocity is by performing the the mobile especially airborne gravity surveys.

The main obstacle in integrated GPS/INS for gravitation measurements in flight is the low signal of noise ration of the system. Typically gravity disturbance vector does not exceed 100 mGal in each component over distance of about 100 km while the noise level of the system is much higher. Through applying a low pass filter on the signal can be reduced the system noises and receive the optimal gravity values in airborne GPS/INS. In some tests flight made in 1995 has been carried out to determine the feasibility and accuracy of airborne gravimetry [5]. SINS can be purchased off-the-shelf as a navigation system for between US$ 90,000 and 160,000 and requires no modification. It has been shown that 1 mGal accuracy in GPS acceleration and 2-3 mGal accuracy at a half-wavelength resolution of 5 km.in the vertical gravity compoment can be achieved. In 2000 the SINS approach yield an accuracy of 1.5 mGal at a half-wavelength of 2 km, therefore demonstrating its role in high-resolution applications.

Investigating the readings of accelerometers installed on a vehicle flying within the indicated range of altitudes and velocities (its flight of velocity in range from 100 to 300 km/h and height, ranging from 100 to 500 m above the earth surface) by separating the inertial components and leaving only gravitational field measurements is presented in [3] . If we have accurate data about the flying vehicle velocities and location (e.g. when using GPS under a differential operating mode), then by applying a mathematical model we can separate the inertial components from the accelerometer readings thus leaving only gravity field measurements. The technical system designed for solving the problem will be called Gravitation Measurement System (GMS). On board of the plane are installed: a receiver of signals from the ground correction station; two receivers of signals from GPS satellites capable of operating under a differential mode; a control display unit; inertial units consisting of three accelerometers and three gyroscopic angular rate sensors (RFOG for strapdown systems) with mutually perpendicular sensitive axes. Additional inertial units are installed along the same sensitive axes (the plane construction lines) but at a certain distance; a GMS controller for solving the gravitation measurements problem. A ground correction station operates in the area of geophysical measurements which has known geodetic coordinates.

The control display unit using the data from DGPS and the inertial unit installed in center of mass solves the navigation problem. Thus, on board the plane besides velocities and location of the mass center, we also have a navigation apparatus base, so it is possible to calculate the angles of roll, pitch, true heading and their derivatives.

The readings from the accelerometers in additional units are collected, processed and compared in the GMS controller with those from the navigation controller.

Investigations on a strapdown variant of using inertial sensors are more difficult to perform, because it is necessary to take out from the accelerometer readings the inertial components of the plane movement around its mass center. But this is also necessary to be done when the inertial platform is positioned beside the mass center.

In the local-level frame the model of airborne gravimetry can be expressed by Newton's equation of motion in the gravitational field of the earth. When considering scalar gravimetry, only the vertical component of this equation is required. The equation can be rearranged for gravity disturbance determination, and is of the form:

$$\delta g = f_u - \dot{v}_u + \left(\frac{v_e}{R_n + h} + 2\omega_e \cos\phi \right) v_e + \frac{v_n^2}{R_m + h} - \gamma \quad (1)$$

where f_u is the upward component of specific force (from INS), v_e, v_n, v_u are the east, north and up components of the vehicle velocity (from GPS), R_m, R_n are the meridian and prime vertical radii of curvature, φ, h are geodetic latitude and height, ω_e is the earth rotation rate, and γ is normal gravity. The sum of the third and fourth terms is often called the Eötvös correction. This approach has become known as SISG (Strapdown Inertial Scalar Gravimetry). A first-order error model for the SISG approach to airborne gravity can also be obtained.

$$d\delta g = f_e \varepsilon_N - f_n \varepsilon_E - \mathbf{A} d\mathbf{f}^b - d\dot{v}_u + (\dot{\mathbf{A}} \mathbf{f}^b + \mathbf{A} \dot{\mathbf{f}}^b) dT \quad (2)$$

where $\mathbf{A}$ and $\dot{\mathbf{A}}$ are row matrices of the form

$$\mathbf{A} = \begin{bmatrix} -\cos\theta \sin\phi & \sin\theta & \cos\theta \cos\phi \end{bmatrix} \qquad (3a)$$

$$\dot{\mathbf{A}} = \begin{bmatrix} \dot{\theta} \sin\theta \sin\phi - \dot{\phi} \cos\theta \cos\phi \\ \dot{\theta} \cos\theta \\ -\dot{\theta} \sin\theta \cos\phi - \dot{\phi} \cos\theta \sin\phi \end{bmatrix}^T \qquad (3b)$$

and ϕ, θ are the roll and pitch angles of the transformation from the body frame to the local-level frame, dT is a synchronization error between the INS and GPS data streams, f^b and df^b are the specific force vector and the error in the specific force vector respectively, $d\dot{v}_u$ is the error in vertical GPS acceleration, f_e, and f_n are the east and north specific force measurements and ε_N and ε_E represent misalignment in the north and east directions. The dot above a quantity denotes time differentiation.

In 1998 three flight tests were undertaken in the Disko Bay area [6] off the west coast of Greenland which tested a LCR S-model gravimeter, a strapdown INS Honeywell LRF III system side-by-side showing comparable accuracies and an orthogonal triad of QA-3000 accelerometers. Several of the flight lines have been partly flown along existing shipborne gravity profiles to allow for an independent source of comparison of the results. Two dual-frequency GPS antennas have been mounted on the fuselage of the aircraft-the front antenna attached to a Trimble 4000 SSI receiver and the rear to second Trimble 4000 SSI and an Ashtech Z-XII receiver to provide a synchronization for SINS. The observed acceleration is compared to kinematic accelerations derived from precise positioning, usually GPS. The difference provides the gravitation sought for. The station receivers are Trimble 4000 SSI and one Ashtech Z-Surveyor. The flights are performed off-the -shore, average flight heights are 300 m and average flight velocity is 70 m/s.

Data for the Q-flex triad is not been collected on the first day. For off-the-shelf inertial navigation systems within an airborne strapdown system Q-Flex accelerometers can be used. These sensors still have the best potential for gravity observations and are used as industry reference for acceleration measurements of all kinds. For some rugged environment the Q-Flex are more suitable by their wider temperature range and shock and vibration parameters, measuring 3D accelerations resulting from gravity and kinematics. The LRF and LCR gravity estimates have been low-pass filtered (to 200s). The results of the flight tests show that the gravity estimates from the two systems agree at the 2-3 mGal level, after the removal of a linear bias. This near the combined noise levels of the two systems. It appears that a combination of both systems would provide and ideal airborne gravity survey system; combining the excellent bias stability of the LCR gravimeter with the higher dynamic range and increased spatial resolution of the strapdown INS.

If the lowest elevation angle for satellite tracking is chosen to be 10° then can be induce the problem that during aircraft roll, low satellites emerging or submerging are “switched on and off” continuously during observations due to the roll of the aircraft. For future applications therefore it is suggested that the elevation mask angle be set between 10° and 0°.

It can be presented that the integration of a multi-antennae GPS attitude system and some low cost gyros provides a high accuracy for the rotation transformation between the sensor frame and the navigation frame – and hence any global reference frame. Another step will be the determination of calibration parameters also for the accelerometers by GPS observations. These in-flight calibration procedures are an important prerequisite for big operational advantages of strapdown airborne gravimetry. From former airborne gravimetry campaigns such as AGMASCO [2] is shown that receivers mixing types is not a good idea. Receivers in the air and on the ground should be as close to each other in observation technology as possible. In that way, systematic errors between receivers can be reduced dramatically.

Five Novatel OEM-4 receivers (24 channel on L1/L2)(three for ground reference coverage and two for aircraft installation) of a new generation are capable of precise kinematic measurements at high data rates (up to 20 Hz). These receivers will considerably enhance the crucial GPS quality for aerogravimetry system and will give a much better reduction control for more strap-down airborne gravimetry systems.

Conclusions

As a sophisticated system the gyrostabilized platform has a high price comparable to the price of a light-flying vehicle. It is mainly for this reason that it is not suitable for gravimetric measurements.

Strapdown INS has several significant advantages including the facts that an off-the-shelf SINS can be used that has been designed and sold for navigation purposes. These advantages lead to a much smaller size, lower cost, lower power consumption and lower failure rate than other alternatives, while providing considerable flexibility.

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