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Scientific and Technological Enterprise
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LOMONOSOV MOSCOW STATE UNIVERSITY
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GT-1A Inertial Gravimeter System
Results of Flight Tests

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Moscow 2002

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GT-1A inertial gravimeter system. Results of flight tests.

A brief description of the functional scheme, system organization and software operation of the GT-1A inertial gravimeter, developed by ZAO NTP Gravimetric Technologies, is given. The software system for post-processing of airborne gravimetry data, developed by MSU Laboratory of Control and Navigation, is described. The results of laboratory and flight tests are discussed.

For graduate students and researchers interested in applied problems of gravimetry.

Reviewer: Dr. Tech. Sci. S.I. Gubarenko

Contents

Introduction

During 2000 and 2001 the closed stock scientific and technological company ZAO NTP Gravimetric Technologies (GT) developed, under a government contract with the Ministry of Science, Industry and Technology, a high precision, compact inertial gravimeter system with a broad range of applications (airborne, marine and surface-based). FGUP Delphin manufactured the prototype version of this system.

The development of the GT-1A airborne gravity survey system was based on the broad experience of GT in the design and manufacture of gravity meters. An inertial gravimeter developed by GT specialists has been in successful operation on a Navy ship continuously since 1990. This work was honoured in 1994 by a State Premium of the Russian Federation. In 1995, exceptional results were obtained in Norwegian Sea tests of a compact, marine gravimeter [9]. In 2000 a mobile surface gravimeter [10], which measures the gravitational force from a geodetic survey support vehicle operating with brief stops for measurement, was completed and field tests were performed, again with outstanding results.

The software for off-line data processing was developed by Lomonosov MSU Laboratory of Control and Navigation. The Laboratory started its work in the field of airborne gravimetry in 1994 in close collaboration with two developers of gravimeters: the Moscow Institute of Electromechanics and Automation (MIEA) and VNII Geophysics. Two tasks were undertaken: theoretical consideration of the airborne gravimetry problem and the development of software for off-line processing of airborne gravity data. This software was developed and used during several flight tests carried out in Russia and the Czech Republic over the past six years. A detailed description of the software is contained in an earlier report [5].

Cooperation between the MSU Laboratory and GT began in 2000. In 2000 and 2001 the MSU software was substantially modified to allow efficient operation with the GT-1A gravimeter.

During the period July to September 2001, the GT-1A airborne system was subjected to extended laboratory and flight tests. The tests were prepared and performed with the financial and technical support of Fugro Airborne Surveys under D. P. Olson, Project Manager for gravity research. Preparation for and execution of the flight tests was coordinated and supervised by A. V. Shabanov.

This paper contains a brief description of the GT-1A inertial gravimeter plus the results of laboratory and flight tests.

The participants in the project included:

At Gravimetric Technologies: M. A. Varvarichev, V. A. Zajtzev, V. P. Nikitin, V. L. Ride, N. P. Ruban, E. B. Savelyev, N. N. Stepanov, A. G. Chernyshuk.

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1 Problem Description

In airborne gravity measurement, an Inertial Gravimetry System (IGS) is used to obtain the anomaly of gravitational force along the flight lines of the aircraft. The data thus collected forms the basis for the generation of gravity anomaly maps, which are useful in hydrocarbon and mineral exploration.

Let us outline the main principles of airborne gravimetry (a survey of different approaches can be found in [12]). We restrict our consideration to the class of gyro-stabilized platform based systems with a single vertical component gravity sensing unit (GSU). Systems of vector gravimetry as well as strap-down systems are very sensitive to errors in vertical axis orientation.

In the mathematical description of the airborne gravimetry problem, we assume that the IGS includes a gyro-stabilized platform, an indicator of the vertical specific force (GSU) rigidly mounted on the platform in such a way that its sensitive axis coincides with the platform vertical, a rover GPS receiver located on the aircraft, and at least one base station GPS receiver located on the surface of the Earth within the survey area.

The main stages of the airborne gravity evaluation are as follows [5].

1.1 On-board algorithms

a) Control of platform levelling using information from the accelerometers, with gyroscope moment sensors and possibly data from the on-board GPS receiver.
b) Recording of the information delivered by the IGS and the rover GPS receiver. This information includes: GSU and accelerometer readings; information required to estimate the platform misalignment; Cardano angles; and raw readings from the GPS receiver including phase measurements.

1.2 Off-line processing

a) Differential phase solution of GPS navigation problem
b) Determination of platform misalignment
c) Calculation of the forces of inertia (Eötvös correction)
d) Determination of the gravity force along the flight line
e) Construction of anomalous gravity maps

Let us consider here the principal ideas for platform levelling and determination of the gravity force along the flight line. We use definitions introduced in [11] (in descriptions of the on-board software we use somewhat different definitions). We restrict our overview to the ideal formulation, not taking into account measurement errors.

We take a homogeneous ellipsoid of rotation, whose axis coincides with the Earth's axis of rotation, as the navigation model of the Earth. Let *a, b* be the principal axes of the ellipsoid, *e* be its eccentricity.

Let us introduce the trihedron $O\eta = O\eta_1\eta_2\eta_3$ (*O* is the centre of the Earth), rigidly coupled with the Earth, where the $O\eta_3$ axis is directed along the axis of rotation of the Earth. The axis $O\eta_1$ lies in the plane of zero meridian. Also, we introduce the local right trihedron $Mx = Mx_1x_2x_3$, rigidly coupled with the geographical coordinate mesh at the point *M.* Here *M* is the point identified with the unit sensitive mass of the GSU, Mx_3 is the direction of the outer normal to the ellipsoid surface (the direction of geographical vertical), Mx_2x_3 is the plane of the current meridian. The axis Mx_2 is directed toward the north pole.

Let us define the location of the point *M* by the eastern longitude λ, the northern latitude φ and the height *h* above the ellipsoid surface. Denote by **u** the value of the angular rate of the Earth's rotation.

1.3 Gyro-platform levelling

The mathematical foundation for construction of the on-board algorithms of gyro-platform levelling are the equations of motion of the point *M* projected onto the axes My_1, My_2 of the so-called "ideal" trihedron $My = My_1y_2y_3$ and the equations describing the change of orientation of this trihedron in inertial space. The trihedron *My* is rotated by some known angle $\varepsilon(t)$ around the axis Mx_3 with respect to the trihedron *Mx*.

Let us denote by

V_1, V_2 the projections of relative linear velocity of the point *M* on the axes My_1, My_2,

$\boldsymbol{\Omega} = (\Omega_1, \Omega_2, \Omega_3)$ the angular rate of the trihedron *My* relative to the Earth in projections on its axes,

$B = b_{ij},\ i, j = 1,2,3$ the orientation matrix of the trihedron *My* with respect to $M\eta$,

$\mathbf{f} = (f_1, f_2, f_3)$ the projections of the specific force **f** applied at the point *M* on the axes of the trihedron *My*.

The following relationships hold [11]:

$$\dot{V}_1 = 2ub_{33}V_2 - (\Omega_2 + 2ub_{23})\dot{h} + f_1$$
$$\dot{V}_2 = -2ub_{33}V_1 + (\Omega_1 + 2ub_{13})\dot{h} + f_2$$
$$\Omega_1 = -\frac{V_2}{a}\left(1 - \frac{e^2}{2}b_{33}^2 + e^2 b_{23}^2 - \frac{h}{a}\right) - \frac{V_1}{a}e^2 b_{13}b_{23}$$
$$\Omega_2 = \frac{V_1}{a}\left(1 - \frac{e^2}{2}b_{33}^2 + e^2 b_{13}^2 - \frac{h}{a}\right) + \frac{V_2}{a}e^2 b_{13}b_{23}$$
$$\dot{B} = \Omega \times B$$

Using these equations, it is possible, for arbitrary motion of the point *M*, to determine the angular rates of the gyro-platform that deliver its horizontal orientation and, therefore, the vertical orientation of the sensitive axis of the GSU.

The actual algorithm of levelling is connected with the choice of azimuthal orientation of the ideal trihedron and depends on the set of navigation sensors present and their accuracies. For the GT-1A inertial gravimeter, the information is delivered by two horizontal accelerometers, an on-board GPS receiver, a high-precision sensor of the horizontal components of angular rate (dynamically tuned gyro), and a low-precision azimuthal angular rate sensor (fibre-optic gyro, or FOG). The so-called absolutely azimuth-free trihedron *My*, for which $\Omega_3 = -u_3$, is selected as the ideal trihedron.

The possibility to estimate the misalignment errors during off-line processing is stipulated by the presence of additional information from the GPS base station receiver and the opportunity to use smoothing operations.

1.4 Gravitational anomaly determination

The principal equation of airborne gravimetry is the equation of motion of the material point M of unit mass in the gravity field of the Earth under the action of an external force **f** projected onto the vertical axis $Mx_3 = My_3$.

The equation can be written as [4]:

$$\ddot{h} = f_3 + f_E + g_0 + \Delta g$$

Here f_3 is the vertical component of specific force acting on the point M, $g_0 = g_0(\varphi, h)$ is the regular component of the gravitational force. The Gelmert formula is commonly used:

$$g_0(\varphi, h) = 9.7803(1 + 0.005302 \sin^2 \varphi - 0.000007 \sin^2 2\varphi) - 0.00014 - 2\omega_0^2 h$$

where $\omega_0 = 1.2383 \cdot 10^{-3}$ sec^{-1} is the Schuler frequency.

The value f_E, which includes inertial terms, is called in gravimetry the Eötvös correction term:

$$f_E = \frac{V_E^2}{R_E} + \frac{V_N^2}{R_N} + 2uV_E \cos\varphi$$

Here R_N, R_E are the curvature radii of the ellipsoid in the north and east directions, V_E, V_N are the eastern and northern components of relative linear velocity of the point M.

The value $\Delta g(\varphi, \lambda, h)$ is the anomalous value of the gravitational force, which is to be determined. To solve the principal gravimetric equation is to extract the value of Δg from it.

The main difficulty of the airborne gravimetry problem, as opposed to, for example, marine gravimetry, is the fact that the spectrum of anomalies coincides with the spectrum of perturbing vertical accelerations. Hence, high-precision external measurements of the aircraft altitude are required. The value of h is derived from GPS measurements, which are also used for calculation of the Eötvös correction. Residual errors, after the elimination of $\ddot{h}$ and f_E, are filtered out using optimal methods of filtering and smoothing [5].

2 Description of inertial gravimeter system

2.1 Functional scheme and structure

The functional scheme of the GT-1A inertial gravimeter system (IGS) is shown in Fig. 1. The IGS consists of:

a) central inertial gravimeter device mounted on a shock absorbing base
b) control, display and data acquisition unit (CDU) using an industrial-grade Asmet 08-12-PC 14 computer

c) on-board Ashtech Z-12 GPS receiver
d) power supply system
e) one or more surface-based GPS receivers supporting differential mode operation

The IGS central device contains a gyro-stabilized platform which is non-perturbed by motion and stabilized in an azimuth-free coordinate frame. The following parts are mounted on the platform: a gravimetrical sensing unit (GSU); two horizontal accelerometers (HA), a dynamically tuned gyro (DTG) with vertical orientation of the kinematic moment; a fibre-optic gyro (FOG) with a vertical sensitive axis; and two gravimeter calibration devices (GCD).

The GSU has an axial structure with a proof mass on an elastic suspension, a photoelectric position sensor and magneto-electric sensors of the feedback force and the compensation force. A current, proportional to the vertical apparent acceleration, originates in the coil of the feedback force sensor and runs through a series reference resistor. The output signal (W_z) is the voltage on the reference resistor which passes through an integrating analogue-to-digital converter (ADC) into an Octagon Systems' MicroPC central processing unit (CPU). The stabilized reference current runs though the coil of the compensation force sensor which compensates the fixed value of the gravitational force. The integrating ADC of the GSU consists of serially connected converters: voltage-to-frequency and frequency-to-code. The ADC has two channels: one narrow-band with a range of $\pm 0.25g$ and one wide-band with a range of $\pm 0.5g$ [1], which allows, through selective operation, achieving the accuracy of the narrow-band converter together with the large dynamic range of the wide-band converter.

The GSU in conjunction with the ADC has a bandwidth of approximately 100 Hz and a random noise error of 0.1 to 0.2 mGals (1 σ) with an averaging time of 60 secs. The scale factor instability of the GSU is 10^{-4}. The GB-23 dynamically tuned gyro has a random noise error of 0.01° per hour (3 σ) for an averaging time of 10 minutes. The VG910FOA FOG has a random noise error of 0.5° per hour (1 σ) for an averaging time of 60 secs and a scale factor instability of approximately 10^{-3}. The AK-10 quartz accelerometers have a random noise error of $2 \cdot 10^{-6}$g (1 σ) over 60 secs, a long-period systematic error with correlation interval of the order of 20 hrs of $5 \cdot 10^{-5}g$ (3 σ), and a scale factor instability of $6 \cdot 10^{-4}$.

The gravimeter calibration device is based on AK-10 accelerometers. The DGC performs highly accurate measurement of the gyro-platform tilt about its horizontal axes, which allows calibration of the GSU by inclination without removing it from the instrument. During calibration, the GSU scale factor, the scale factors of the accelerometers and the misalignment of the GSU sensitive axis from the platform vertical are determined.

The gyro-stabilized platform is mounted on a triaxial Cardano gimbal with external azimuthal axis located outside of the device case [3]. This gimbal scheme, compared with a biaxial arrangement, allows the virtual elimination of errors due to instability of the FOG scale factor and the non-orthogonality of the DTG kinematic moment to the platform plane. Compared with a traditional triaxial scheme, it eliminates the so-called "bearing" error, induced by varying orientation of the platform with respect to spurious sources of magnetic and thermal fields caused by the gimbal axes and the device case.

The model PO-20 angle sensors and motors for the servo stabilization systems (SS) are mounted on the axes of the Cardano gimbal (in Fig. 1 the azimuthal SS motor is not shown). The angle sensors are used to measure the roll, pitch and course angles of the aircraft.

To ensure constant operating temperature of the sensitive units and the principal components of the gravimeter, three thermal control systems (TCS) are used:

a) Double-circuit TCS of the GSU and the reference voltage source
b) Single-circuit TCS of the DTG controller DAC
c) Single-circuit TCS of the DTG, AC and DGC

Control of the functional elements of each TCS, consisting of heating coils and fans, is performed by the CPU according to signals received from the thermo-sensors via the ADC. Information exchange with the CDU and the on-board GPS receiver is through the serial COM-ports of the CPU.

All processes in the IGS, including start-up, GSU calibration and monitoring of the system state, are fully automated. The CDU displays all necessary information to the operator grouped by function: start-up, warm-up, operating mode, reference measurements, system monitoring, GSU calibration, and maintenance. The monitoring mode indicates monitoring results and the isolation of failures to the operator. The CDU allows the operator to enter control commands plus various constants, and also shows moving plots of many selectable system variables in real time. During gravimetric surveys, files of gravimetric and navigation data are stored on the CDU hard disk. Operation of the IGS during surveys does not require manual intervention.

The small power consumption of the IGS (150 W from 27 Vdc) allows the use of a rechargeable battery as a power source in the aircraft, which assures full independence from the aircraft electrical system.

2.2 On-board software

A flowchart of the main on-board IGS algorithms is shown in Fig. 2. Sensor sampling is performed at a rate of 300 Hz. The output of the GSU is corrected with respect to the joint influence of horizontal accelerations and platform tilts (Harrison correction) [7], non-orthogonality of the GSU sensitive axis to the platform plane, and influence of the square acceleration. The platform tilt correction is incorporated into the accelerometer measurements [8].

With the FOG data sampled at 300 Hz, a coordinate frame free in azimuth is constructed and accelerometer data is projected onto this coordinate system. Integration of the dynamic equations of inertial navigation is carried out at a rate of 18 Hz in this azimuth-free coordinate system.

External information on aircraft velocity and latitude, delivered by the on-board GPS receiver, is used for correction. The values of absolute angular rates Ω_{xa}, Ω_{ya}, generated at a rate of 300 Hz, are projected onto the platform coordinate frame and control the sensors of DTG moments. The value of platform course angle thus obtained is passed to the input of the servo system for azimuthal stabilization. The servo system for horizontal stabilization operates at a frequency of 300 Hz, and azimuthal stabilization occurs at a frequency of 18 Hz. The algorithms for both horizontal orientation control and for the stabilizing servo systems are built around stationary Kalman filters.

Calibration of the GSU and accelerometers is fully automated. The calibration process takes 3 hours and can be performed while the aircraft is parked on the ground and oriented in any direction.

The monitoring algorithms perform logical control of all sub-systems of the inertial gravimetric device. The results of monitoring are passed to the CDU for display to the operator.

3 Software for off-line processing

In this section the software for off-line processing of gravimetric information is briefly described. The software takes into account peculiarities of operation and error models of the GT-1A.

The flowchart of information processing is shown in Fig. 3. The three main stages of processing are: determination of coordinates with GPS data; gyro-platform correction with the GPS data (determination of platform misalignment in particular); and solution of the principal gravimetric equation.

Software for processing GPS phase measurements uses algorithms developed by the Laboratory of Control and Navigation for applications in gravimetry. It differs from most commercial GPS data processing packages in its approach to the problem of cycle slips [6]. The software allows the incorporation of information from an arbitrary number of GPS base stations.

To solve the gyro-platform correction problem with GPS data, the gyro-horizon control signal is used. The problem is solved using sub-optimal Kalman smoothing. The algorithms allow the estimation of platform misalignment with high accuracy.

The design of the shock mount results in tilting of the gravimeter due to the action of horizontal accelerations. This lead to the requirement to model the compliance of the shock mount during the calculation of relative motion of the GPS antenna and GSU using Cardano angle measurements of the IGS. The compliance parameters were determined on a swinging Scorsby table (Fig. 10) using special identification software.

Solution of the principal gravimetric equation is performed using non-stationary adaptive Kalman filtering and smoothing. This approach allows more flexibility in reaction to possible data corruption, provides for non-stationary correlations of various kinds and minimizes the influence of boundary effects at the beginning and end of survey lines and during aircraft turns.

4 Results of laboratory tests

The IGS was put through a vast amount of laboratory tests over the past two years: on a stationary bench; on a vibration table; on a rotating Scorsby table; and in motion over the ground. The results of stationary tests on the ground are given in Figs. 4 and 5. Here as well as in the rest of the laboratory tests, a filter with a bandwidth of 0.017 Hz was used.

The results of the vibration table tests with and without the shock mount are presented in Figs. 6 and 7 respectively. These results illustrate the high efficiency of the shock mount in damping frequencies above 10 Hz.

Fig. 8 shows the results of system tests with large horizontal accelerations.

The results from the Scorsby table are given in Fig. 9 and a photo of the gravimeter mounted on the table is shown in Fig. 10. The IGS was located 1.4 m from the centre of motion and the parameters of motion were:

a) Yaw amplitude 6°, period 10 secs
b) Roll amplitude 6°, period 6 secs
c) Pitch amplitude 6°, period 8 secs

The operational integrity of the complete IGS system and the validity of data obtained were verified in motion over the ground, where the GPS base and rover receivers were used. For this test, the system was installed in a small cart which was pulled over a horizontal asphalted surface outdoors (Fig. 11).

5 Results of test flights

5.1 Flight conditions

In order to test the gravimeter in the air, four flights were made near Vologda on an An-30 aircraft (Fig. 11b). The aircraft was based at the Cherepovets airfield for the duration of the test flights. Due to internal RAM memory limitations of the GPS base station receivers, the length of each record was limited to 2.5 hours per flight. The flight plan is shown in Fig. 13. A short flight was undertaken on 2001.09.04 to test the operational integrity of the entire system and also to test the means of communications with the GPS base stations. The three production flights are described below:

Wednesday, 5th September, 2001
Flight time: 14:15 to 16:45 GMT (17:15 to 19:45 Moscow time)
Flight duration: 2 hours 30 minutes
Mean speed on flight lines: 90 m/sec
Flight altitude (over WGS84 ellipsoid): 1,000 m
Weather: clear skies

Thursday, 6th September, 2001
Flight time: 02:15 to 05:15 GMT (05:50 to 08:15 Moscow time)
Flight duration: 2 hours 30 minutes
Mean speed on flight lines: 90 m/sec
Mean flight altitude: 1,000 m
Weather: clear skies

Saturday, 8th September, 2001
Flight time: 07:50 to 10:10 GMT (09:50 to 13:10 Moscow time)
Flight duration: 3 hours 20 minutes
Mean speed on flight lines: 90 m/sec
Mean flight altitude: 1,200 m
Weather: cloudy

The spectral density of the vertical acceleration on all three production flights is shown in Fig. 14. The vertical acceleration during flights of 2001.09.05 and 2001.09.06 was up to 150 Gals. The vertical acceleration on 2001.09.08 was up to 300 Gals, which required the data from the wide-band channel of the gravimeter. The altitude was maintained to within ±10 m by the aircraft's autopilot linked to a barometric altimeter.

During turns, the value of the roll angle was kept to within ±5° due to the ±12° limits for roll angles on the prototype instrument being tested. The commercial GT-1A gravimeters have both roll and pitch limits of ±45°.

The location of the GPS antenna relative to the gravimeter GSU in terms of the aircraft axes was: X = -0.80 m, Y = 1.57 m, and Z = 0.17 m. A photo of the IGS mounted inside the aircraft is shown in Fig. 12.

5.2 Navigation conditions

Ashtech Z-12 GPS receivers were used as the rover and as base station number 2. A Z-Xtreme GPS receiver from Ashtech (Magellan) was used as base station number 1. The measured data was recorded in the built-in RAM memory of the receivers and was transferred after each flight to a PC. The recording rate of all GPS data was 2 Hz.

Figs. 16, 17 and 18 present graphs of navigation data for each of the three production flights. They show: the number of visible satellites (SVs); the geometric factor (PDOP); the error of the differential mode phase solution for base station number 1 in Kirilov (RMS); the length of the baselines for both of the base stations; and estimates of the platform levelling errors (misalignment).

This information presents a view of the satellite navigation conditions during the flights and the accuracy of the vertical orientation of the GSU. The adequate numbers of visible satellites (typically 8 or 9) combined with the acceptable range of the geometric factor (PDOP < 2.5) provided good navigation solutions from differential processing despite baseline lengths exceeding 100 kms at times. The RMS deviations of the phase measurement based positioning were typical for navigation solutions under similar satellite visibility conditions.

Typical values of platform misalignment obtained were approximately ±1´. The accuracy of misalignment estimates carried out off-line was 1 to 2 arc-seconds, acceptable for integrated processing of the gravimetric data.

5.3 Anomaly estimation

To estimate the gravity anomaly, a filter with a cut-off frequency of 0.01 Hz was used. The resolution of such a filter in space, defined as half wavelength at half amplitude (FWHM), equals approximately 4.5 kms at an aircraft speed of 90 m/sec. This corresponds to a map of anomalies at a scale of 1:450 000. The gravity anomaly was calculated as the free air anomaly at the survey altitude.

The anomaly was evaluated along two repeated lines: Line 1 (direction E-W) and Line 2 (direction NW – SE). The results of flights on 2001.09.05, 2001.09.06, and 2001.09.08 are shown in Figs. 19 and 20. There were 9 passes along Line1 and 9 passes along Line 2, described in the following table:

Lin	***Name***	***Direction***	***Comments***
1	F010905-010	East	
1	F010905-040	West	
1	F010905-040	East	
1	F010906-010	East	
1	F010906-040	West	rejected due to GPS
1	F010906-050	East	
1	F010908-010	East	rejected due to GPS
1	F010908-040	West	
1	F010908-050	East	
2	F010905-020	South-east	
2	F010905-030	North-west	
2	F010905-060	South-east	
2	F010906-020	South-east	
2	F010906-030	North-west	
2	F010906-060	South-east	
2	F010908-020	South-east	
2	F010908-030	North-west	
2	F010908-060	South-east	

Passes F010906-040 and F010908-010 were rejected because of the low quality of the GPS data. On pass F010906-060 the angular rate sensor (ARS) offset exceeded acceptable limits. As a consequence, the error of platform misalignment increased to 8′. The excess ARS error was readily detected by the IGS control system. Once the platform levelling errors were eliminated, off-line processing gave satisfactory results for this pass.

The degree of thermal stabilization is shown in Figs. 15(a) to 15 (c). The gravimeter offset caused by the thermal changes was not greater than 0.5 mGals for any line.

The accuracy of the gravity anomaly estimation was determined in the following way. First, the systematic error, which did not exceed 1 mGal, was removed for each pass individually. It should be noted that it is possible to reduce the systematic error by increasing the time of reference measurements before and after each flight up to 1.5 hours. Then the average anomaly for all passes was evaluated along the line and the error of anomaly estimation was evaluated for each pass as the RMS deviation of the anomaly from the average value. The average error is approximately 0.53 mGal (1 σ). The RMS errors for each pass are given in the following table.

Line 1	*RMS error*	*Line 2*	*RMS error*
F010905-010	0.70	F010905-020	0.36
F010905-040	0.37	F010905-030	0.53
F010905-050	0.66	F010905-060	0.35
F010906-010	0.80	F010906-020	0.50
F010906-050	0.61	F010906-030	0.56
F010908-040	0.75	F010906-060	0.83
F010908-050	0.37	F010908-020	0.31
		F010908-030	0.40
		F010908-060	0.32
Mean RMS error	***0.61 mGals***		***0.46 mGals***

Figs. 19 and 20 show the gravity anomalies along Lines 1 and 2 for all accepted passes. The mean value of the anomaly is indicated by a heavy dotted line on each graph.

In the authors' opinion, the main contribution to the error of gravity anomaly estimation in these tests was the GPS measurement error. This conclusion was made on the bases of indirect evidence: by comparing the GPS solutions for different base stations, combinations of carriers L1 and L2, and baseline lengths.

Conclusions

Versatile laboratory and flight tests of the GT-1A airborne inertial gravimetry system have demonstrated its efficiency, ease of installation and use, high performance, low noise levels and high spatial resolution.

In the presence of vertical accelerations as high as 150 to 300 Gals, the error of gravity force estimation (1 σ) was 0.53 mGals with a bandwidth of 0.01 Hz and 1.0 mGals with a bandwidth of 0.0125 Hz.

We expect that the accuracy of anomaly estimation can be enhanced one and a half to two times by using more precise GPS receivers and by decreasing baseline length by increasing the number of GPS base stations deployed.

Specifications of the GT-1A Gravimeter

Range of gravitational acceleration measurement m/sec^2	9.76 to 9.84
Dynamic range of disturbing accelerations	
a) fine range	± 0.25 g
b) coarse range	± 0.5 g
Error in gravity anomaly estimation (1 σ) without altitude estimation errors:	
a) For autonomous operation of up to 2 months for marine version	0.3 to 0.5 mGals
b) For autonomous operation of up to 12 hours for ground and airborne versions	0.2 to 0.3 mGals
Error in gravity anomaly estimation (1 σ) including GPS-derived altitude estimation errors:	
a) With 0.01 Hz cut-off	0.5 mGals
b) With 0.0125 Hz cut-off	1.0 mGal
Spatial resolution at vehicle velocity V m/sec	
a) With 0.01 Hz cut-off	$0.05 \cdot V$ km
b) With 0.0125 Hz cut-off	$0.04 \cdot V$ km
Drift per 24 hours	0.2 ± 0.02 mGals
Accuracy of scale factor determination	$5 \cdot 10^{-4}$
Attitude limits for both roll and pitch	± 45º
Attitude measurement error (1 σ)	
a) heading	10′
b) roll & pitch	3′
Operating temperature	-10 ºC to +50 ºC
Vibration tolerance between 5 and 35 Hz	0.2 g
Power consumption	150 W @ 27 Vdc
Weight including rotation table and shock mount	75 kg
Dimensions excluding rotation table and shock mount mm	400 x 400 x 595
Service life	30,000 hours

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