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Result of the tests conducted by a newly developed helicopter borne gravimeter system

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Abstract: Airborne gravity measurement has long been a desirable goal for exploration geophysicists. Success of the air-borne gravity surveys mainly depends on determining the three-dimensional (3-D) position of the moving platform (*i.e.* airplane/helicopter). Recent advances in technology, especially in Global Positioning System (GPS) have made it possible to determine the velocity and 3-D position of the moving platform with greater accuracy. Taking these advantages of the GPS technology and using a gravimeter system newly developed, helicopter-borne gravity measurements were successfully carried out over the Kanto district of Japan during May, August and December 1999. This new gravimeter system is composed of a servo accelerometer sensor, a stabilized platform, an optical-fiber gyroscope to control the stabilized platform, a data processor & controller, onboard GPS receivers and a land-based GPS receiver. Gravity acceleration and GPS positioning data were collected at intervals of 0.1 sec and 1 sec respectively. The GPS positioning data were used to compute helicopter vertical acceleration, Eötvös, altitude and latitude corrections, which were applied to the measured gravity acceleration. The gravity acceleration data collected were processed and necessary corrections were applied. Numerical filtering was carried out to remove high frequency noises present in the data. The observed free-air gravity anomalies were quite comparable with the upward continuation of the anomalies observed on the ground. Thus the preliminary analysis of the test data demonstrates the feasibility of helicopter-borne gravity measurements.

1. Introduction

Methods capable of measuring the acceleration due to the Earth's gravitational field are amongst the earliest applications of the geophysical sciences. Gravity surveying is one of the important techniques in modern exploration for nearly all minerals and petroleum commodities. Significance of this method has increased in recent times with major advances in satellite positioning technology, which provides cost effective access to surveys over much larger regions than previously possible. The need for acquisition of large gravity data sets at high speed over highly prospective areas is renewing demands for airborne gravity measurement system. There are many noted advantages for this method. Primarily, airborne measurements have unlimited accessibility. For example, swampy jungles as well as mountainous terrain, which are extremely difficult to be surveyed, can be easily covered. For line data such as gravity, magnetic, seismic etc, a minimum line spacing is important (Agocs, 1955). This minimum line spacing can be achieved by airborne gravity survey, which may also be used for interpolation between widely spaced reconnaissance seismic surveys (Hammer 1983). Rapid coverage and report considerably improve overall effectiveness of geophysical exploration, which is possible by the airborne gravity survey. Moreover this can be used simultaneously with other airborne

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geophysical methods such as total field magnetic measurements. Airborne gravity measurements can also be used for geodetic and tectonic studies. The airborne gravity measurements were first reportedly made for the US Navy in late 1950s (Thompson and LaCoste, 1960). But the navigational accuracy was the limiting factor.

Success of the airborne gravity measurements mainly depends on determining the three dimensional (3-D) position of the moving platform (*i.e. airplane, helicopter etc.*). Advancement of Global Positioning System (GPS) has made it possible to determine the velocity and 3-D position of the moving platform with greater accuracy. So far very few groups have successfully conducted such experiments (e.g. LaCoste, 1967; Gumert and Cobb, 1970; Brozena, 1984; Halpeny and Darbha, 1995; Schwarz and Li, 1996; Forsberg and Brozena, 1996). Most of these airborne gravity measurements were conducted on fixed-wing airplanes. These experiments reported that the short wave length gravity anomalies are attenuated mainly due to high altitude of the airplanes. One way of alleviating this problem is by making measurements aboard a helicopter, which can fly at low altitude and slow speed. Development of such a helicopter borne gravimeter system has been a desirable goal for exploration geophysicists, which is the primary objective of the on-going project entitled "Development of helicopter borne gravimeter system" funded by New Energy and Industrial Technology Development Organization (NEDO) Japan. The gravimeter system was built at TOKIMEC Inc, Japan and tested during the airborne experiments conducted in the year 1999.

2. The measurement system

The helicopter borne gravimeter system is composed of gravity sensor, stabilized platform, optical fiber gyroscope and data processor & controller. The gravity sensor (TGA-109) is basically a magnetic-servo accelerometer, which is mounted on a gimbal mechanism. It has sensitivity of 0.01 mGal, measurement range of ±500 Gal and sampling interval of 0.01 sec. The gravity sensor recording was monitored continuously for a period of one month in a room where the temperature is kept constant and it was found that the drift is of the order of 0.26 mGal/day. Gravity tides were also observed during this process. The optical fiber gyro-multi-sensor (FMS-1) controls the stabilized platform (SP-120) with an accuracy of 0.05° and provides the pitch & roll, which also are recorded along with gravity acceleration. A GPS receiver (Ashtec-BR2G) is attached to the system for obtaining real-time Differential GPS (DGPS) positioning. This system receives signals from both the GPS satellites as well as DGPS ground network stations. Maritime Safety Agency of Japan maintains these ground transmitters. The real-time DGPS data are used to control the optical fiber gyro-multi-sensor. The whole system weighs about 250 kg. Figure 1 shows the sketch of this gravimeter system. Details of this newly developed system can be found in Segawa *et al.* (2000).

During the airborne survey, the 3-D position of the helicopter was accurately determined every second by interferometric GPS method. A GPS receiver unit consists of two parts, a GPS receiver and a GPS antenna. We used two sets of Ashtec Z-12 GPS receiver units for this purpose. One of these GPS receivers was installed on the helicopter with the GPS antenna mounted just beneath the transparent plastic roof along with DGPS antenna (Ashtec-BR2G) and the other unit served as a temporary base station at the heliport. The base station was erected one day prior to the helicopter survey and collected data for a period of 12-15 hours with a sampling interval of 30 sec, minimum number of satellites (SVS) as 4 and elevation mask of 15°. This data along with corresponding data from permanent IGS (International GPS Service for Geodynamics) station at Tsukuba were used for precisely determining the base station position.

3. Experiment

Helicopter borne gravity measurements were conducted in three phases during May, August and December 1999. Figure 2 shows the helicopter flight tracks during these operations. The test flight during 13-14 May was carried out mainly to determine the flight speed and altitude at which the noises due to the helicopter rotor propulsion are minimum. Each flight was for a period of less than an hour. We used Bell-412 type helicopter belonging to Aero Asahi Corporation, Japan and test flights were operated from the heliport at Kawagoe, Saitama Prefecture, Japan. Gravimeter system was installed inside and fixed to the base of the helicopter. For conducting interferometric GPS positioning along with the gravity acceleration measurements, Ashtec Z-12 receivers were installed as explained in the previous section. Data were stored into a laptop computer connected to the receiver through a data logger. Data reception was displayed on the receiver monitor.

The test flights during 25-27 August and 15-17 December 1999 were conducted by changing sensor installation inside the helicopter. Rest of the initial procedures was followed as in the case of previous test flights. Apart from monitoring the system by changing the gravity sensor installation mode, we also tested the repeatability of the measurements. For this purpose the flight tracks were kept constant (approximately) for both onward and return flights. Due to some logistic reasons we could not operate for more than two hours during one flight.

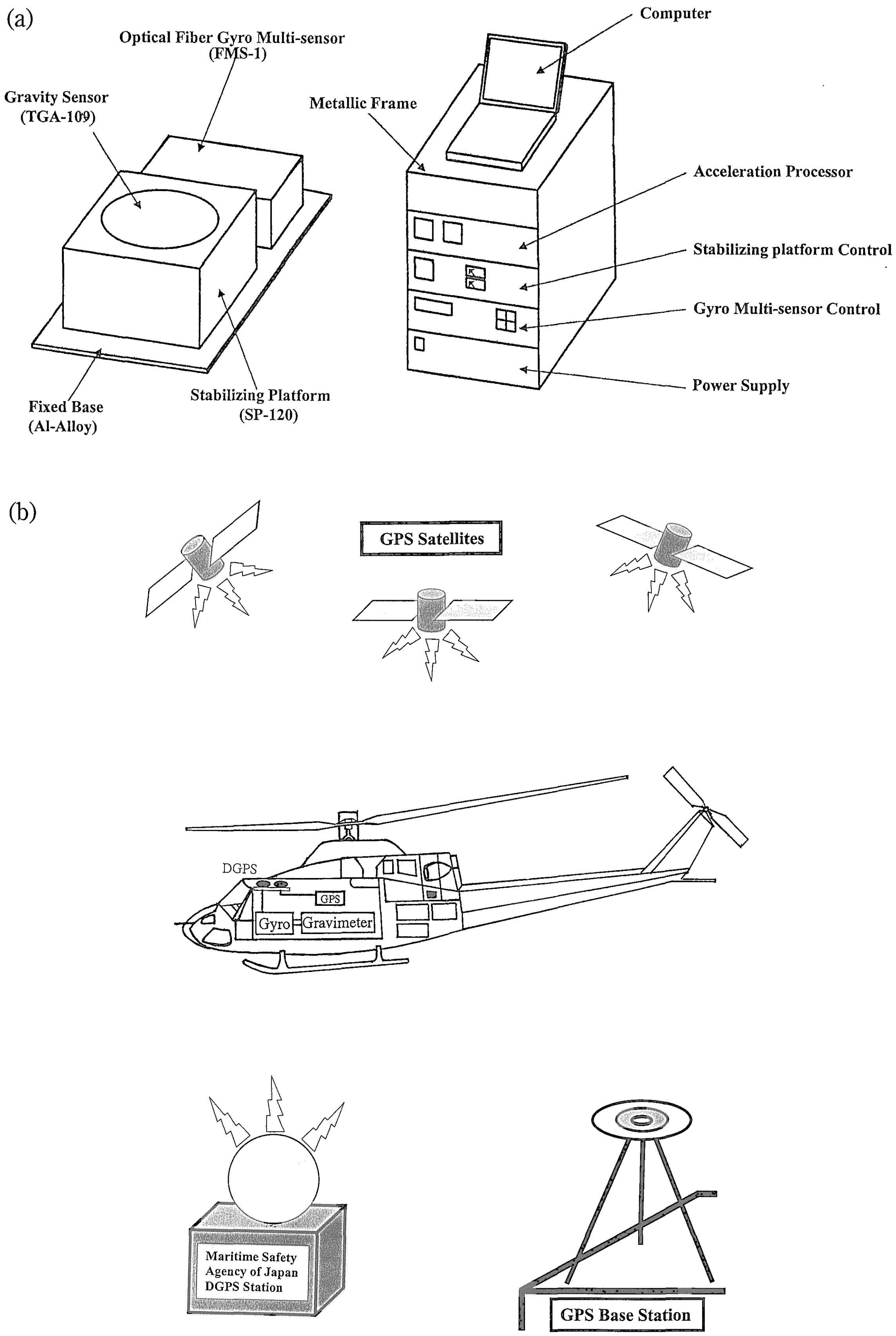

Fig. 1 A schematic view of helicopter borne gravimeter system. (a) The gravimeter assembly, (b) the GPS units, GPS satellites and helicopter.

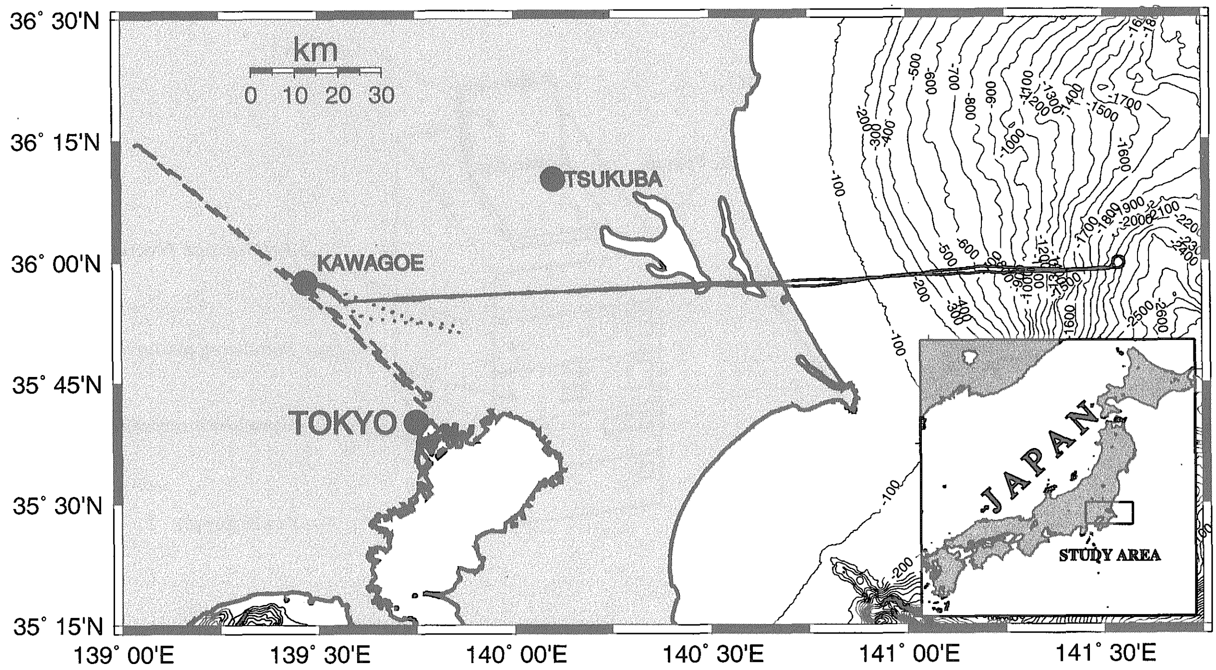

Fig. 2 Flight tracks of the helicopter borne gravimeter experiments conducted during year 1999. Dotted, dashed and solid lines correspond to tests conducted on 14th May, 27th August and 16-17 December 1999 respectively. Contour lines shows the bathymetry (m) in the survey region (Kisimoto, 2000).

4. Data processing

Gravity acceleration data collected at a sampling interval of 0.1 sec were averaged at every 10 points to get a data set (*X(t)*) with 1 sec interval. The pitch and roll of the stabilized platform as well as the real-time DGPS positioning data are also recorded along with the gravity acceleration data. Precise Differential GPS Navigation and Surveying post-processing software was used for interferometric GPS positioning. This software is designed to carry out high accuracy (centimeter level) carrier phase processing with dual frequency, full wavelength (P-Code) data. Here in these present experiments we used P-Code and Carrier Phase data with fixed ambiguities. By this process we obtained flight altitude (h), height above the ellipsoid (h_e), latitude (ϕ), longitude (λ), horizontal velocities (V_e and V_n) and other parameters related to the accuracy of the results such as position *rms* errors, average post-fit residual and χ^2 goodness of fit indicator.

We need to apply various corrections to the measured gravity acceleration (*X(t)*) such as vertical acceleration (*Y(t)*) correction of the helicopter (moving platform), Eötvös correction (e), latitudinal correction (l_{corr}), altitude correction (h_{corr}) and base line correction (b_{corr}). Following equations are used for computing these correction parameters.

$$\text{Helicopter vertical acceleration } (Y(t)) = \frac{d^2h}{dt^2} \qquad (1)$$

Eötvös correction (e)

$$= \frac{V_n^2}{a}\left[1 + \frac{h_e}{a} + f(2 - 3\sin^2\phi)\right] + \frac{V_e^2}{a}\left[1 + \frac{h_e}{a} - f\sin^2\phi)\right] + 2V_e\Omega\cos\phi\left[1 + \frac{h_e}{a}\right] \qquad (2)$$

where f is the flattening of the Earth, a is the semi-major axis of the Earth, h_e is the height above the ellipsoid, and Ω is Earth's rotation rate (Harlan, 1968).

$$\text{Altitude correction } (h_{corr}) = h \times 0.3086 \qquad (3)$$

Latitude correction (l_{corr}) were computed according to normal gravity formula 978,032.67715 (1+0.0052790414 $\sin^2\phi$ +0.0000232718$\sin^4\phi$ +0.0000001262$\sin^6\phi$).

Figure 3 shows an example of gravity acceleration and helicopter vertical acceleration corresponding to one of the test flight. During flight, both accelerations are observed in the range of ±70,000 *mGal*. Time-domain Gaussian Filter was applied to all the time series *X(t)*, *Y(t)*, *e(t)*, $h_{corr}(t)$ and $l_{corr}(t)$ by convolution of time series with a weight function *w(t)* as shown below:

$$G(\tau) = \int_{-\infty}^{\infty} x(\tau - t)\, w(t)\, dt \qquad (4)$$

where $w(t) = \frac{1}{\sqrt{2\pi}\sigma}\exp^{\left(\frac{-t^2}{2\cdot\sigma^2}\right)}$ and σ is taken as 1/3 of the half window width ($\pm 3\sigma$ is close to where

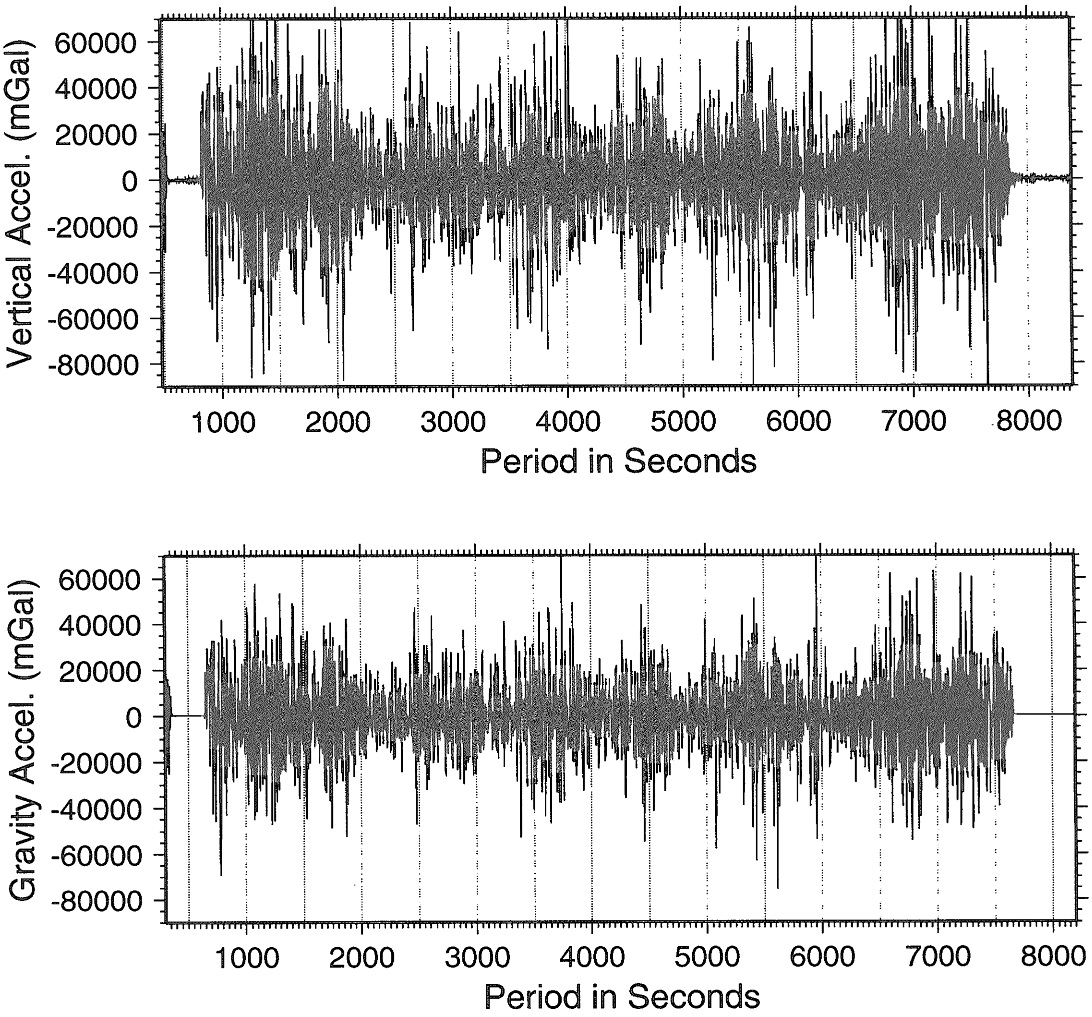

Fig. 3 Gravity acceleration (lower) and helicopter vertical acceleration (upper) observed during the test flight on 27th August 1999.

the filter drops very close to zero). Then the free-air gravity (FAG) anomalies were computed as:

FAG anomaly

$$= X(t) - Y(t) \pm e(t) + h_{corr}(t) - l_{corr}(t) \pm b_{corr} \qquad (5)$$

For convenience we retain the same notations for the filtered time series. Figure 4 shows various parameters and the free air gravity anomaly obtained using equation (5) for the airborne observation on 27th August 1999. Here the half width is taken as 200s ($\sigma = 66.67$). It shows FAG anomaly ranging from -10 mGal to about 85 mGal along the flight track. But the very high frequency noises still persist even after applying the gaussian filter.

To overcome this high frequency noises we made an attempt by adopting another digital filter called cosine filter. The time-domain cosine filter (*Hanning Window or raised cosine window*) was applied to all the time series, *i.e.* gravity acceleration (*X(t)*), altitude (*h(t)*), Helicopter Vertical Acceleration (*Y(t)*), Eötvös correction (*e(t)*), Altitude Effect ($h_{corr}(t)$) and Latitude Effect ($l_{corr}(t)$) by convolution of time series with a weight function *w(t)* as shown below:

$$G(\tau) = \int_{-\infty}^{\infty} x(t)\, w(\tau - t)\, dt = \int_{-\infty}^{\infty} x(\tau - t)\, w(t)\, dt \qquad (6)$$

where $\tau = k\Delta t$ and $w(t) = 0.5\left(1 + \cos\left(\frac{\pi t}{M}\right)\right)$ when $|k| < M$; $w(t) = 0$ when $|k| > M$. $k = 0, \ldots\ldots M$ and M is the chosen number of filter coefficients. $\frac{\pi t}{M}$ varies between $-\pi$ and $+\pi$ as the window runs from left edge to right edge. Filter width was taken similarly (half width=200s) with the case of gaussian filter. Then FAG anomalies were computed using equation (5). Figure 5 shows the observed FAG anomaly after applying cosine filter. The very high frequency noises observed previously are no more present but the gravity anomaly features are retained.

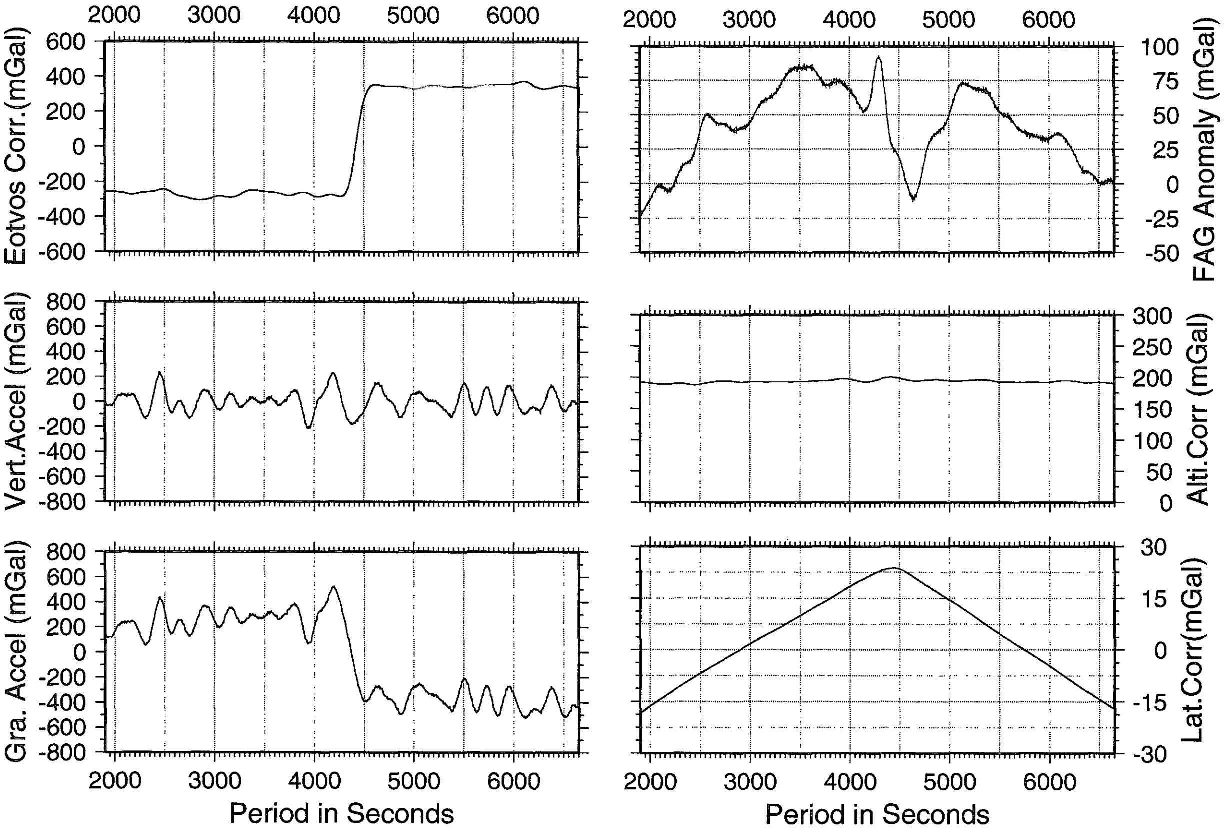

Fig. 4 Gravity acceleration, helicopter vertical acceleration, Eötvös, altitude and latitude correction parameters after applying gaussian filter. Observed FAG anomaly is also shown.

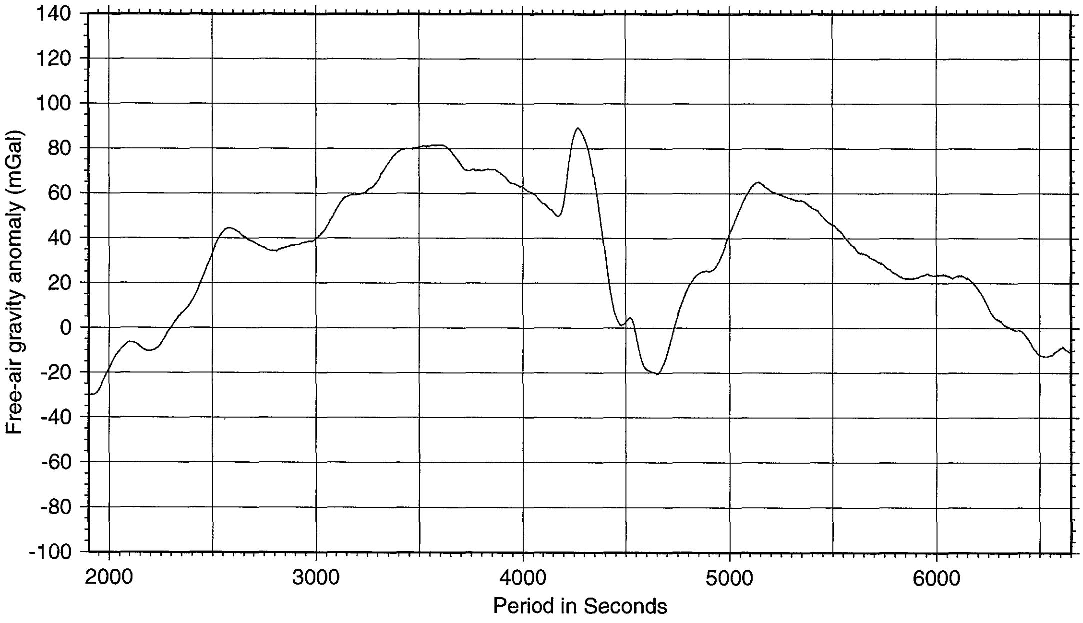

Fig. 5 Observed FAG anomaly after applying cosine filter.

5. Result and discussions

Airborne gravity results are evaluated in several ways such as (a) comparison with gravity contour map, (b) repeating observations over almost the same line, (c) comparison of flight intersection (cross-over), (d) comparison with values calculated from known gravity stations and (e) comparison with upward continuation of the ground measurements to the flight altitude. The present airborne tests were conducted in a region where on-shore and off-shore gravity surveys were already carried out by Geological Survey of Japan (GSJ) and ground-based gridded data (herein after called as ground truth) are available. For comparison we computed the upward continuation of the ground truth. Upward continuation is a method that transforms anomalies measured at one surface into those that would have been measured on some higher surface. The upward-continued anomalies do not provide direct information about the source, nonetheless they can be instructive. This transformation attenuates anomalies with respect to wavelength. It is sometimes necessary to compare or merge aerial surveys conducted at various altitudes, and upward continuation provides a way to transform individual surveys onto a consistent surface.

A level-to-level continuation of the potential field can be achieved by Fourier transforming the measured data, and multiplying it by the exponential term $e^{-\Delta z|k|}$ (where $\Delta z > 0$ is the altitude to which the upward continuation is calculated and k is the wave number) and inverse Fourier transforming the product (Blakely, 1995). We made an attempt to compute the 2-dimensional upward continuation of the ground truth to the flight altitude (~2000 ft) and compare with observed values of the test flights. Figure 6 shows the observed free-air gravity anomalies and the upward continuation of the ground truth along the flight track. Onward and return flight observations for 16th December 1999 and onward flight observations of 17th December are shown. Flight on 17th December followed the same track as that of 16th December. Due to some logistic reason we could not continue measurements during the return flight on 17th December. The test result clearly shows that short wavelength anomalies observed on the ground level have been partially suppressed due to the attenuation of gravity anomaly. Since the onward and return flights followed the same track, we compared the anomalies observed during the onward and return flights (see Figure 6.a) and found them comparable with a standard deviation of 2.4 mGal. Similarly the observed anomalies corresponding to the onward flights on 16th December and 17th December are also quite comparable (see Figure 6.b) with a standard deviation of 2.7 mGal. This clearly shows the repeatability of the gravimeter system used. Figure 6.c shows the comparison between the observed anomaly during the flight on 17th December and the upward continuation of the ground truth. It may be noted that there is a slight deviation between these two from the transect point corresponding 140.7°E longitude to further East. The above mentioned location corresponds to the coast line (land-sea transition point) and there may be some discrepancies in the interpolation of the land and marine data since the marine data along the continental margin may not be available. Moreover the marine measurements were made more than a decade back when the precision of the shipboard measurements may not be as good as the present technology. Secondly one should account for the horizontal acceleration especially at the point where the flight course changes drastically. In future operations measurements of horizontal acceleration may also be incorporated to improve the performance of the gravimeter system. Thus the result obtained from these airborne tests using helicopter borne gravimeter system are regarded as encouraging.

6. Conclusions

Helicopter-borne gravity measurements were successfully conducted over the Kanto region, Japan. These test surveys were conducted in three phases during May, August and December 1999. Since this was the first helicopter-borne gravimeter system tested in Japan, we had to use trial and error method for the mode of system installation. During these tests we found that the suspension mode similar to that of ship-board marine gravimeter sensor proved to be a better choice. Simultaneous positioning by interferometric GPS method proved to be an integral part of the airborne measuring system. To fulfill this, we have carried out interferometric GPS measurements using two sets of Ashtec Z-12 type GPS receivers and antenna. One of these units was installed on the helicopter and the other served as base station at the heliport.

The gravimeter system recorded the vertical gravity acceleration and pitch & roll of the stabilized platform whereas the interferometric GPS system recorded signals received from GPS satellites which were used for computing the 3-D position of the helicopter every second. Post-processing of the GPS data provided precise flight altitude, latitude, longitude, horizontal velocities, height from ellipsoid etc. It also provided the parameters related to the accuracy of the interferometric GPS measurements such as position *rms* errors, χ^2 goodness of fit indicator etc. Helicopter vertical acceleration, Eötvös correction, latitude and altitude correction factors were then computed using the parameters obtained from GPS data processing and applied to the gravity acceleration recorded by the gravity sensor to obtain the free air gravity

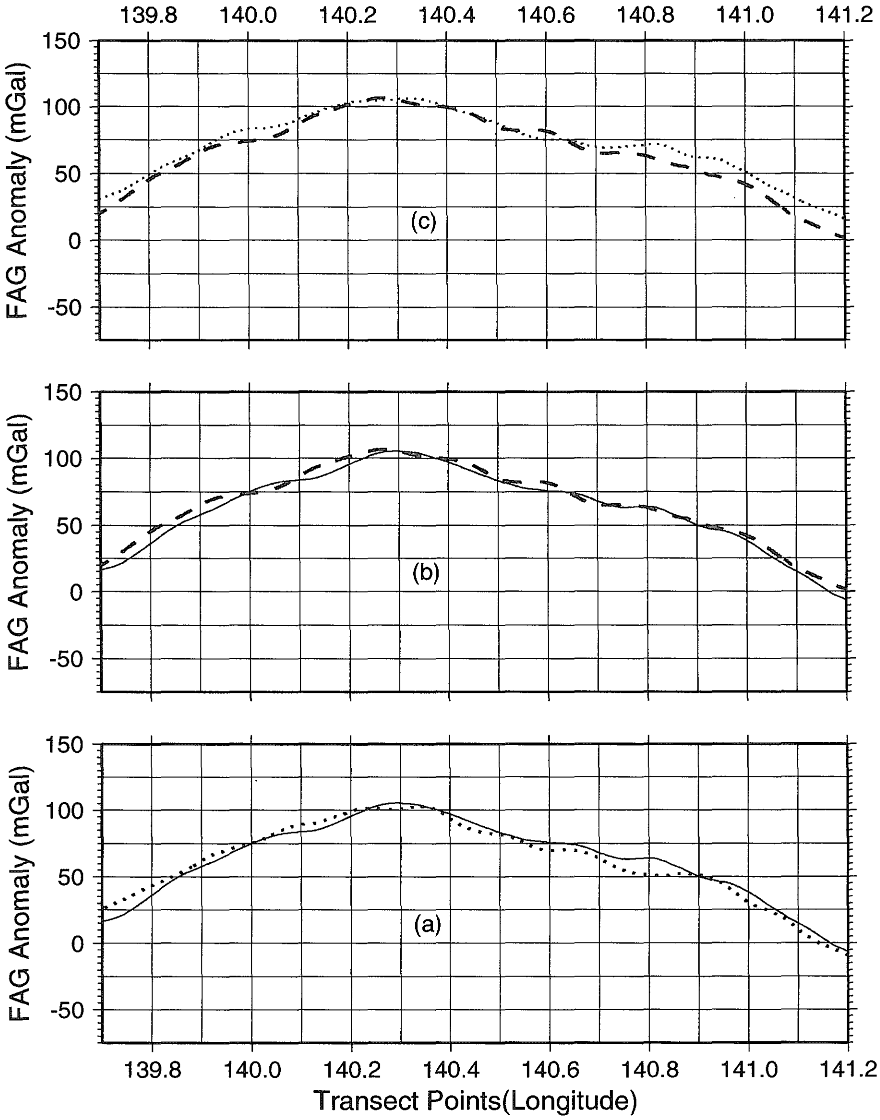

Fig. 6 Free air gravity anomaly observed during the test flights on 16th and 17th December, 1999 and the upward continuation of the ground truth. (a) Comparison of anomalies observed during onward flight (solid line) and return flight (dotted line) of 16th December. (b) Comparison of anomalies observed during the onward flights on 16th December (solid line) and 17th December (dashed line). (c) Comparison of the anomalies observed during the flight on 17th December (dashed line) and the upward continuation of the ground truth (dotted line). The values are projected along the corresponding longitudes.

(FAG) anomaly. Numerical filters were applied to the recorded gravity acceleration as well as the computed correction factors prior to this calculation. FAG anomaly thus calculated are then compared with the upward continuation of the ground truth. Repeatability of the measurements were tested by conducting the surveys along the same track and found that they agree quite well. Comparison was also carried out between the observed anomalies and the upward continuation of the ground truth up to the flight altitude and found encouraging. Improvements can be made by incorporating the measurements of horizontal acceleration. Thus the preliminary results obtained from these experiments show the success of helicopter borne gravity surveys.

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新たに開発されたヘリコプター搭載重力測定システムによる試験測定結果

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要　旨

物理的資源探査を目指す分野においては，航空重力測定は，長きにわたってその実現が望まれていた手法の一つであった．航空重力測定の成否は，移動プラットフォーム（例えば飛行機やヘリコプター）の３次元精密測位如何によっていた．最近における宇宙技術の進歩，特に汎地球測位システム（GPS）は，移動体の３次元位置および速度を高精度で測定することを可能にした．GPS測位技術と新たに開発した重力測定システムを使用することにより，1999年５月，８月および12月に我々は本州，関東地域において重力測定試験を実施し，測定に成功した．新しい重力測定システムは次のものよりなる：サーボ加速度計型重力センサー，水平安定化プラットフォーム，プラットフォームを制御する光ファイバージャイロスコープ，データ処理制御装置，機上に設置されたGPS受信機とヘリポートに設置されたGPS受信機（精度３～５cm），および光ファイバージャイロスコープ制御のためリアルタイムでヘリコプターの３次元位置（精度１～２m）と速度を提供するDGPS受信機．

重力加速度とGPS測位データはそれぞれ0.1および１秒間隔で読み取られる，GPS測位データはヘリコプターの鉛直加速度，エトベス補正および高度と緯度補正を計算するために使われ，重力センサーが出力する重力加速度を補正する．また，測定値に含まれる高周波の加速度は数値式フィルターによって取り除かれる．上空で測定された結果は地上で測定された重力を上方接続した値と矛盾なく調和し，本重力測定システムの有用性を証明した．