

A Basic Study to Develop Shipboard and Airborne Gravimeter using a Force-Balanced-Type Accelerometer

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SUMMARY:

To know the ground structure is important for estimation of earthquake ground motions. Gravity survey is a useful technique for this purpose, and a spring-type relative gravimeter is usually used. Although this type of gravimeter can provide very accurate data, the gravimeter is very expensive and difficult to handle. Recently, to solve this kind of problems, shipboard and airborne gravimeter has been developed to cover large area. Gravimeter on a carrier, such as ship, airplane, vehicle, and so on, is huge and definitely expensive. We, thus, are developing a new gravimeter, which is compact and light weight, and can obtain gravity data on a carrier. We employ a new force-balanced-type (FB) accelerometer, which is not only inexpensive and easy operation, but also can provide high resolution data. To examine the performance of the FB sensor as a gravimeter, a prototype is developed and we carry out observations under different conditions.

Keywords: gravity survey, force-balanced-type accelerometer, blind signal separation

1. INTRODUCTION

To know the ground structure is important for estimation of earthquake ground motions. Gravity survey is a useful technique for this purpose (for example, Goto *et al.* (2005), Goto *et al.* (2009)), and a spring-type relative gravimeter is usually used. Although this type of gravimeter can provide very accurate data, whose resolution is about 1 micro Gal ($= 1 \times 10^{-6} \text{ cm/s}^2$), very long time is necessary to obtain data at a site. Furthermore, the gravimeter is very expensive and difficult to handle. Recently, to solve this kind of problems, shipboard and airborne gravimeter has been developed to cover large area. Present gravimeter on a carrier, such as ship, airplane, vehicle, and so on, is huge and definitely expensive. This means that large size of carrier is required and such large carrier cannot be used for some area: for example, shallow sea area is still blank area of gravity data.

We, thus, will develop a new gravimeter, which is compact, light, and can obtain gravity data on a carrier. For the estimation of earthquake ground motions, the required resolution of gravity survey is 100 micro Gal ($= 100 \times 10^{-6} \text{ cm/s}^2$), at least. For this purpose, we develop and employ a new force-balanced-type (FB) accelerometer, which is not only inexpensive and easy operation, but also can provide high resolution data.

To examine the performance of the FB sensor as a gravimeter, a prototype, which is named EZ-GRAV, is developed and we carry out observations under some different conditions: on an observation wheel, a ship, and a vehicle. The observation wheel has constant velocity and small vibration, the ship has various velocity and not large vibration with long period, and the vehicle has almost constant velocity and large vibration with short period. The observed data are compared with known or analytical values of gravity.

Table 2.1. Basic specification of accelerometers (Gal = cm/s²)

	VSE-156SG	JA-40GA02
Observable Range	±50 Gal	±2 × 980 Gal
Max. Output Level	±10 V	
Resolution	2 ~ 10 × 10 ⁻⁶ Gal	N/A

Table 2.2. Comparison between two types of prototypes EZ-GRAV

	EZ-GRAV I	EZ-GRAV II
Sensor(s) for gravimeter	VSE , JA40	VSE
Accelerometer	2 horizontal components	2 horizontal & 1 vertical components
Gradiometer	2 horizontal components	2 horizontal components
Recording interval	0.25 s	0.01 s
Max. Input Voltage	±2.04 V	±10 V
Constant temperature reservoir	Yes	No

2. PROTOTYPE OF GRAVIMETER

To apply the gravity anomaly to modelling a ground structure, which is used for the estimation of earthquake ground motions, the required information is a map with contour lines of one-milli-Gal interval. Thus, our target accuracy of the gravity survey is order with sub-milli-Gal, which is from 10×10^{-6} to 100×10^{-6} cm/s².

To obtain this accuracy, a sensor unit have to satisfy the resolution of 10×10^{-6} cm/s² at least, because the observed data is contaminated by various noise such as vibration of carrier, circuit noise, and so on. We find some candidates of sensor for a gravimeter and try two sensors: VSE-156SG (hereafter, VSE) by Tokyo Sokushin Co.Ltd. and JA-40GA02 (hereafter JA40) by Japan Aviation Electronics Industry, Ltd. (JAE). The basic specifications are listed in Table 2.1.

The prototype of gravimeter used in this study is called EZ-GRAV generally, however, there are some variations of system. In a case where the differences of each type are necessary explicitly, we call them EZ-GRAV I and EZ-GRAV II. The differences are summarized in Table 2.2.

2.1. EZ-GRAV I

EZ-GRAV I uses VSE and JA40 as its sensors. Furthermore, EZ-GRAV I includes gradiometers with two axes and accelerometer with two horizontal components. The observed data is recorded in digital format with 0.25-second interval after using analogue-to-digital converter with maximum input of ±2.04 volts.

The sensors are fixed on an aluminum thick plate and set inside of a constant temperature reservoir, because the devices are sensitive to temperature and its fluctuation is too larger than the variation of gravity. The temperature is controlled within ± 1 °C.

2.2. EZ-GRAV II

EZ-GRAV II uses only VSE as its sensor and includes gradiometers with two axes and accelerometer with three components, which are one vertical and two horizontal. The data is recorded in digital format with 24 bit and 0.01-second interval. All the sensors are also fixed on an aluminum plate.

3. OBSERVATIONS AND OBTAINED DATA

The sensor output under a static condition seems to respond to the Earth tide, whose amplitude is about 200 micro Gal in peak-to-peak at most. Thus, we carried out observations under dynamic conditions on a carrier.

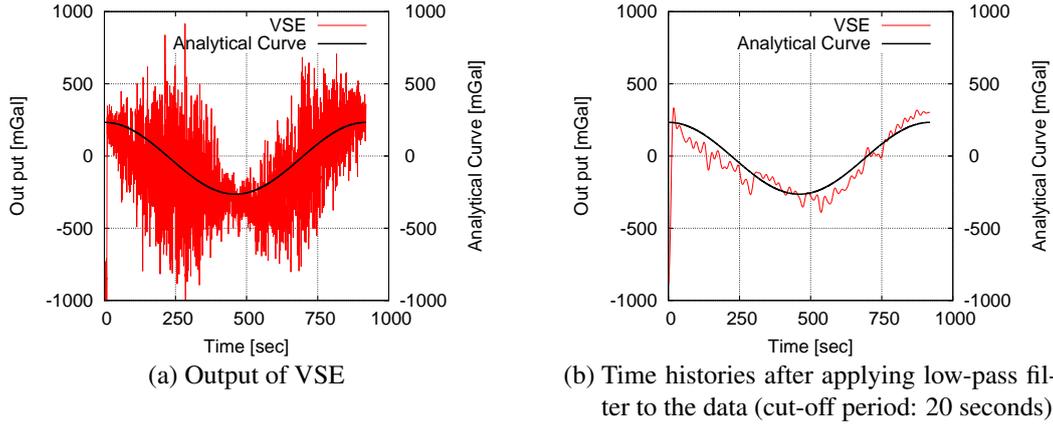


Figure 3.1. Output signal from VSE on an observation wheel with 100m diameter.

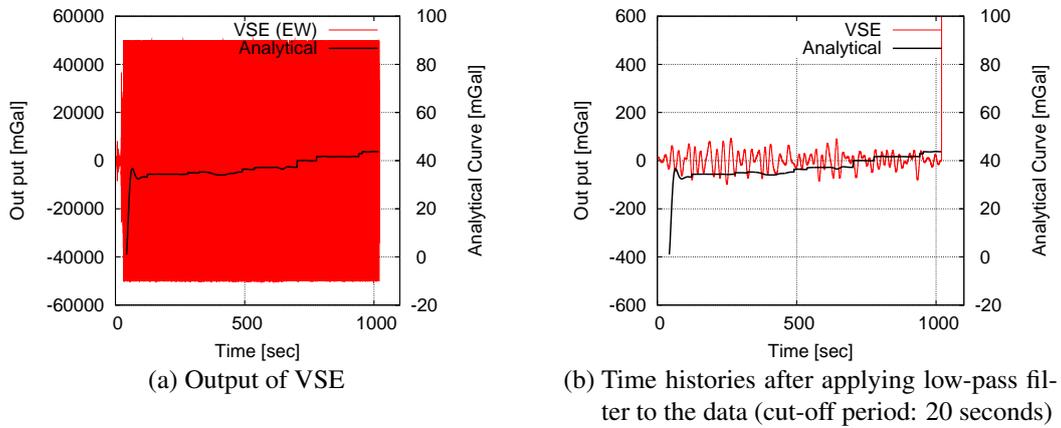


Figure 3.2. Output signal from VSE on a vehicle by about 3km travel.

3.1. Constant Velocity and Less Vibration

EZ-GRAV I is set on an observation wheel. The wheel moves with almost constant and small angular velocity with less vibration and provides very large difference of altitude. The wheel is located in Tokyo, Japan, and its diameter is 100 meters.

Fig.3.1 shows the output of VSE. In this figure, red and black colored lines show the observed data and analytically obtained values, respectively. The horizontal axis shows time from the beginning of record in second, and left and right vertical axes show the acceleration for observed data and analytical one in milli-Gal, respectively.

To obtain the analytical value, only centrifugal force and freeair anomaly are considered. The Eötvös's effect, the effects by Earth tide and atmosphere pressure are not included, because they are enough small.

The freeair anomaly and centrifugal force are obtained as follows:

$$F(t) = -0.003986[r\{1 - \cos(\frac{2\pi}{n}t)\}] \quad (3.1)$$

$$C(t) = r(\frac{2\pi}{n})^2 \cos(\frac{2\pi}{n}t) \times 1000, \quad (3.2)$$

where $F(t)$ and $C(t)$ are freeair anomaly and centrifugal force in mGal, respectively, and n time in second for making one period, r radius of wheel in meter, t is elapsed time from the bottom of the wheel in second. 0.003986 as shown in Eqn. 3.1 is freeair coefficient. The ideal observed gravity value $G(t)$ is obtained as

$$G(t) = C(t) + F(t). \quad (3.3)$$

The output of VSE corresponds to the analytical value as shown in Fig.3.1(b) except for small offset.

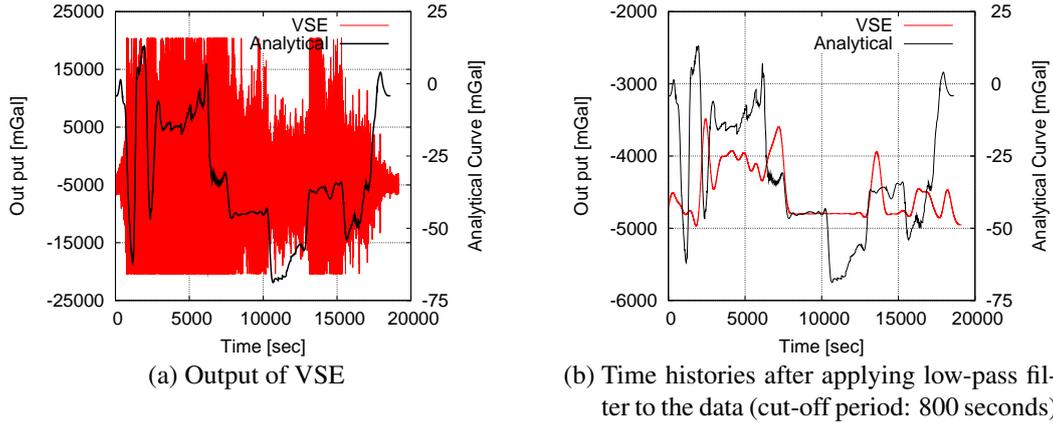


Figure 3.3. Output signal from VSE on a ship in Toyama Bay, Japan.

JA40 provided similar result as VSE, however, the result of filtering is worse than VSE, because JA40 is much more sensitive to vibrations in short period range than VSE.

3.2. Constant Velocity and Large Vibration with Short Period

To consider the condition with vibration of a carrier, we carried out the observation using EZ-GRAV II on a vehicle. The vehicle runs on a flat road with constant velocity for about 3.0 km. In this area, the gravity anomaly has been obtained using a spring-type relative gravimeter and the anomaly is changed linearly with distance. The vibration of vehicle is very large, because a part of the road is not paved.

Fig.3.2 shows the output of VSE with same legends as Fig.3.1. The analytical value of gravity is calculated from the relative gravity, which has been obtained by a spring-type relative gravimeter, and Eötvös's effect. The effects of freeair anomaly, Earth tide, and atmosphere pressure are not included for the analytical value, because there is no difference of altitude in the area and duration of observation is short.

The Eötvös's effect is an apparent gravity occurred by the inertial force from Earth's rotation. Position of the vehicle is observed by GPS (global positioning system). The velocity and heading of the vehicle are calculated using the GPS data and the Eötvös's effect is obtained as follows:

$$\delta_{gE} = 2\omega V \cos \phi \sin \alpha + V^2/R, \quad (3.4)$$

where ω is angular velocity of Earth's rotation, V velocity of the vehicle, ϕ latitude, α heading, R radius of the Earth.

From Fig.3.2(a), the amplitude is saturated. The variation of the analytical value is only 10 mGal, though, the output of the sensor is more than 5000 times of the analytical value. Fig.3.2(b) shows the filtered signal of output from VSE. The accuracy of the data must be not so good, because the signal is saturated. However, signal with long period can be remained in a case where some of local maxima is not saturated.

After filtering, the amplitude of the signal is reduced and closer to the analytical value. However, the observed data is too large and it is not found that variation of the gravity anomaly.

3.3. Variable Velocity and Large Vibration with Long Period

To introduce a general condition of the observation on a carrier, EZ-GRAV I is set on a mid-size ship, whose properties are 231 t of gross tonnage, 53.59 m of length and 15 knot of maximum speed. The ship navigates in the Toyama Bay, Japan for about 5 hours.

Fig.3.3 shows the output of VSE with same legends as Fig.3.1. The analytical value is obtained from the Eötvös's effect and freeair anomaly, which has been obtained already by a shipboard gravity survey. The Eötvös's effect is calculated from the position of the ship every second obtained from GPS.

From Fig.3.3(a), some parts of the signal is not saturated, however, some parts are saturated like the

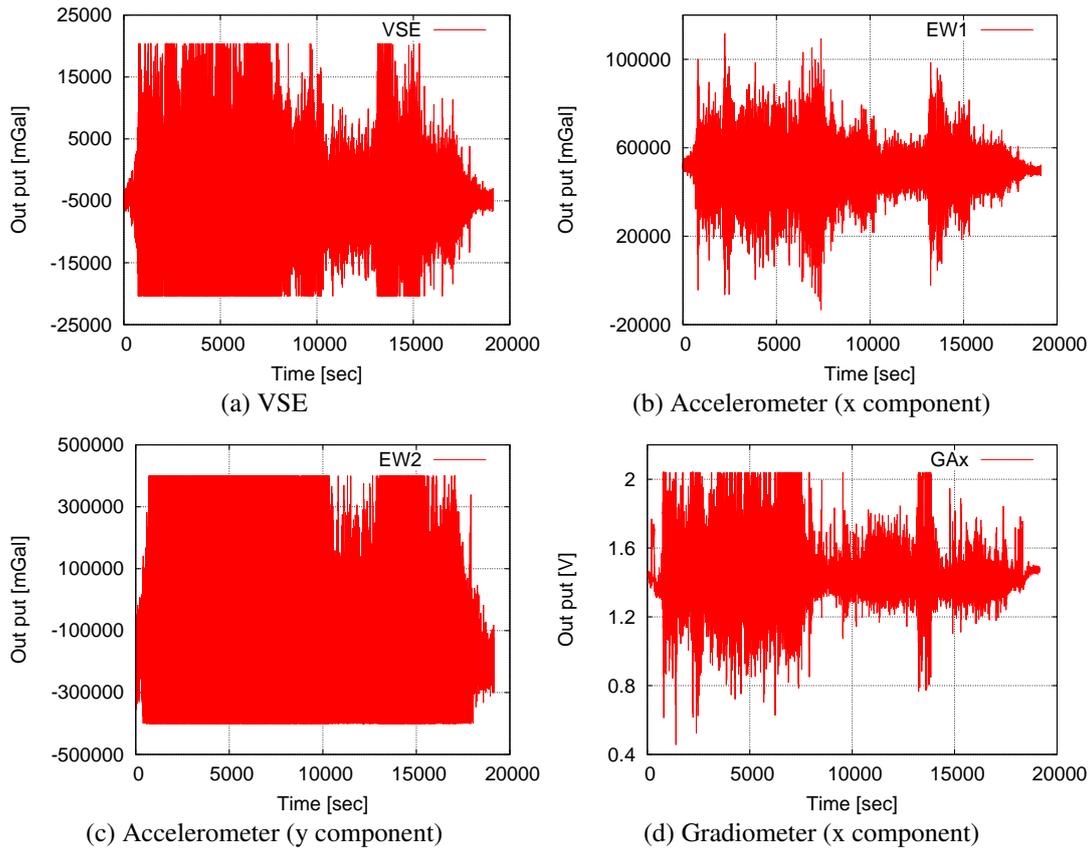


Figure 4.1. Outputs from VSE, two accelerometers, and one gradiometer on a ship in Toyama Bay, Japan.

data in the previous observation. It is observed that the filtered signal of Fig.3.3(b) is very different from the analytical value in amplitude and phase.

4. FINDING GRAVITY FROM VERY NOISY DATA

In the previous section, the low-pass filter is used to find the gravity from the noisy data. We can expect that the variation of gravity consists of components with long period, however the vibration of carrier with short period. If this expectation is satisfied, the low-pass filter should work well. Actually, analysis for the first observation on an observation wheel works well, though, not for the other two observations. The reason is the difference of the amplitude of the noise: it is very difficult to pick up the gravity data with very small amplitude from very large vibration of the carrier. This must be limitation of simple filtering technique.

To reduce the vibration of the carrier, we can choose two different approaches. One is introducing an active isolation system to remove the vibration of the carrier (for example, LaCoste, 1967), and the other is pick up signal of gravity from the noisy data using a technique of signal processing. For our objective, the complicated system cannot be introduced, because it bring on large size and heavy weight. Thus, we have no choice but to discuss the latter approach.

LaCoste (1973) have proposed a technique to find the signal of gravity from the data of shipboard survey. In the technique, he showed that gravity should be remaining signal after removing various correlated signals, such as outputs from horizontal accelerations, gyro etc. and their time derivatives.

This technique is a kind of a technique of blind signal separation (BSS) such as independent component analysis (Hyvärinen et al., 2001). Thus, we apply a technique of BSS to the observed data to find signal of gravity using other data such as acceleration of horizontal components and so on.

A technique of BSS, generally, separates some independent component considering the correlation matrix, and does not consider any kind of noise. BSS can provide the independent components, how-

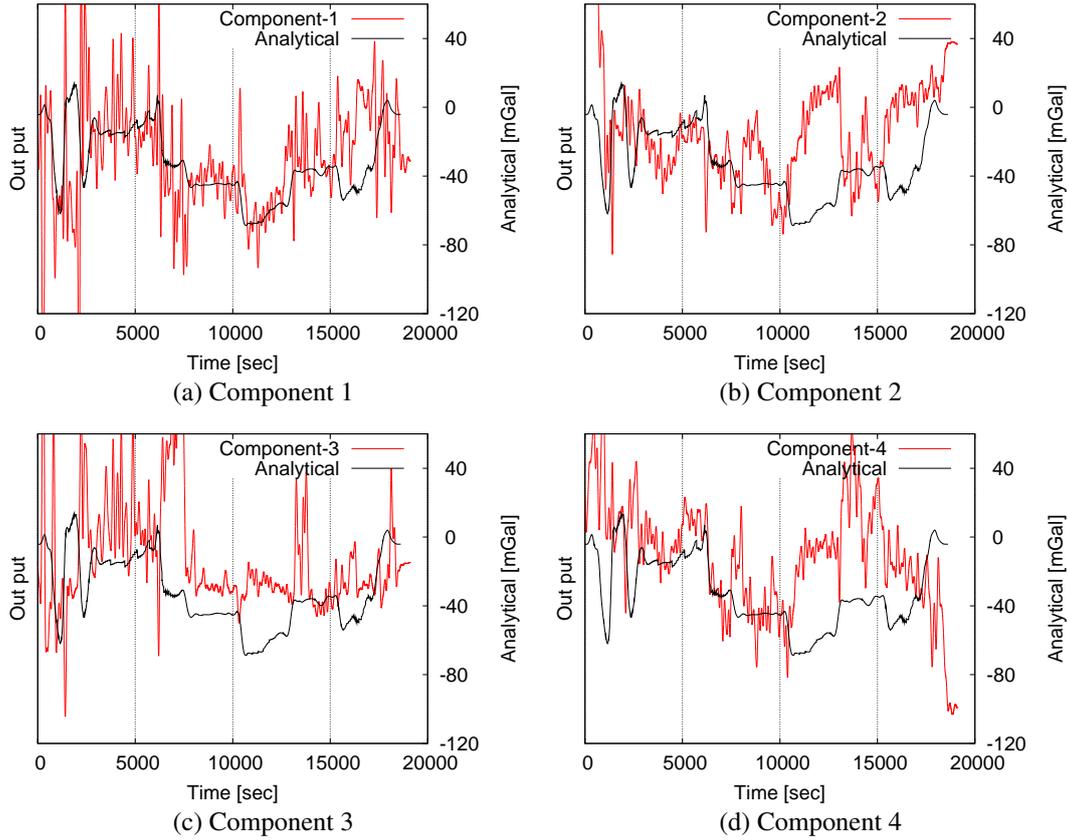


Figure 4.2. Independent components separated from data obtained on a ship using SOBI

ever, the absolute amplitude and order of the separated components are unknown from its mathematical properties.

We apply the second order blind identification (SOBI) technique (Belouchrani et al., 1997), which is a one of BSS technique, to the data obtained on a ship described in Section 3.3.

EZ-GRAV I includes VSE and JA40 as gravimeters, and accelerometers and gradiometers with two horizontal components. We choose the data from VSE, two components of accelerometers and one component of gradiometer for the analysis. The output of the sensors are shown in Fig.4.1. The horizontal axis is elapsed time in second from leaving a port and the vertical axes are output of the sensors in milli Gal for VSE and accelerometers and voltage for gradiometer.

Before applying SOBI, low-pass filter with 150 seconds of cut-off period is applied to the signals. The separated signals are shown in red lines of Fig.4.2. In this figure, analytical value is also shown in black, and horizontal axis is same as Fig.4.1. The right vertical axis is analytical value of gravity in milli Gal, which is obtained from Eötvös's effect and freeair anomaly in the area. The left vertical axes for the independent components are non-dimensional, because the BSS provide only relative value and does not absolute value. The amplitude and offset of the independent components are arranged to fit the analytical value.

From Fig.4.2, the component 1 seems to correspond to the analytical value. This figure suggests that the technique of BSS is useful tool to pick up signal of gravity. However, BSS provide no information about the absolute values and order of components. Furthermore, in a case where we apply BSS to output of sensors without any filtering, the signals are considered as mutually independent components and any separation cannot be obtained. This means that BSS requires some pre-processing of data such as filtering by low-pass filter to obtain appropriate results. There is no reasonable way to give the properties of filter, though the cut-off period of the filter can be determined arbitrarily and the results depend on the pre-processing. In the case of Fig.4.2, the parameters for the filter are determined by trial-and-error method.

The technique by BSS is remaining still some problems to apply, however, it is noted that the sensor

can record the variation of gravity and we can find an appropriate technique to pick up desirable signal.

5. CONCLUSIONS

We developed a prototype of sensor to measure gravity on a carrier, which is named EZ-GRAV, and discussed its basic performance: EZ-GRAV is set on an observation wheel, vehicle, and ship. As a result, it is observed that the sensor can respond to gravity of 100 milli Gal ($= 100 \times 10^{-3} \text{ cm/s}^2$) in a case where the vibration of a carrier is not so large. However, if the vibration of a carrier is relatively larger than the values of gravity, it is very difficult to obtain an appropriate values of gravity. We, thus, apply a technique of blind signal separation (BSS) to pick up gravity data from the data contaminated by the vibration of a carrier. BSS works well to separate the gravity signal from observed data, though we have still some problems how we can identify a component as gravity signal and how we can determine the absolute values.

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