Journal of Applied Geophysics 152 (2018) 221–235

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A novel approach to reduce environmental noise in microgravity measurements using a Scintrex CG5

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ARTICLE INFO

Article history:
Received 2 March 2017
Received in revised form 16 January 2018
Accepted 25 March 2018
Available online 29 March 2018

Keywords:
Microgravity
Signal processing
Noise reduction

ABSTRACT

The accuracy and repeatability of microgravity measurements for surveying purposes are affected by two main sources of noise; instrument noise from the sensor and electronics, and environmental sources of noise from anthropogenic activity, wind, microseismic activity and other sources of vibrational noise. There is little information in the literature on the quantitative values of these different noise sources and their significance for microgravity measurements. Experiments were conducted to quantify these sources of noise with multiple instruments, and to develop methodologies to reduce these unwanted signals thereby improving the accuracy or speed of microgravity measurements. External environmental sources of noise were found to be concentrated at higher frequencies (> 0.1 Hz), well within the instrument's bandwidth. In contrast, the internal instrumental noise was dominant at frequencies much lower than the reciprocal of the maximum integration time, and was identified as the limiting factor for current instruments. The optimum time for integration was found to be between 120 and 150 s for the instruments tested.

In order to reduce the effects of external environmental noise on microgravity measurements, a filtering and despiking technique was created using data from noisy environments next to a main road and outside on a windy day. The technique showed a significant improvement in the repeatability of measurements, with between 40% and 50% lower standard deviations being obtained over numerous different data sets.

The filtering technique was then tested in field conditions by using an anomaly of known size, and a comparison made between different filtering methods. Results showed improvements with the proposed method performing better than a conventional, or boxcar, averaging process. The proposed despiking process was generally found to be ineffective, with greater gains obtained when complete measurement records were discarded. Field survey results were worse than static measurement results, possibly due to the actions of moving the Scintrex during the survey which caused instability and elastic relaxation in the sensor, or the liquid tilt sensors, which generated additional low frequency instrument noise. However, the technique will result in significant improvements to accuracy and a reduction of measurement time, both for static measurements, for example at reference sites and observatories, and for field measurements using the next generation of instruments based on new technology, such as atom interferometry, resulting in time and cost savings.

1. Introduction

Microgravity measurements are a useful tool within the geophysicist's toolbox for locating subsurface voids, as the instrument responds to the physical property that defines a void as opposed to a proxy (i.e. density contrast). Furthermore, as a passive method, it measures a gravity field and thus has no theoretical limitations on penetration depth. These advantages give it a capability unparalleled by other geophysical techniques, especially for deeper features. Instruments such as the Scintrex CG5 (Scintrex, 2006) perform many corrections to the raw gravity signal for time-varying effects automatically (e.g. temperature, tilt, tide and drift), and standard data processing usually consists of data reduction of the acquired points to correct for variations in the topography and position of the gravity stations using well-understood techniques (Gabalda et al., 2003; Long and Kaufmann, 2013; Nabighian et al., 2005; Seigel, 1995; BlÍžKovskÝ, 1979). However, gravimeters are strongly affected during measurements by noise, defined as any unwanted signal manifesting itself in the measurements. Noise stems from both the instrument itself, and from vibrational environmental sources which greatly affect the accuracy and repeatability of estimated gravity values and must be accounted for by using long integration times (i.e. the time for a single measurement cycle should be at least 30 s) for each measurement. Whilst the majority of surveys are to assess regional gravity fields, setup gravity

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https://doi.org/10.1016/j.jappgeo.2018.03.022

networks (e.g. Martín et al., 2011; Charles and Hipkin, 1995; Camacho et al., 2009; Parseliunas et al., 2011) or locate large targets like ore bodies (e.g. Nabighian et al., 2005; Martinez et al., 2013), there is a growing demand for smaller scale surveys capable of finding smaller targets in advance of civil engineering development work (e.g. Tuckwell et al., 2008) such as low-density ground, sinkholes and solution features. However, as the signal from these targets is notably smaller, and the sampling density reasonably coarse in relation to their size, it is imperative that data is obtained and corrected with the highest possible accuracy to avoid the creation of correlated noise signals of a similar spatial wavelength to signals from potential targets, which may result in the signal being lost in the noise or false features being detected, especially as interpolation between points is used on the final gravity map. Whilst the acquisition of high accuracy data is important with any geophysical method, the long acquisition time for microgravity data leads to large costs involved in reacquisition of points and a lower spatial resolution than other geophysical methods making the acquisition of good quality measurements first time all the more important.

Several authors have taken long period measurements using multiple field gravimeters (CG3 and CG3M) to assess their long-term stability (e.g. Debeglia and Dupont, 2002; Bonvalot et al., 1998; Lederer, 2009) for monitoring purposes. Many of these studies were important for developing corrections for low frequency noise sources which affect measurement values between points including celestial and ocean tidal loading and atmospheric pressure changes. Extensive testing has been also been carried out on known instrumental effects such as tilt (Reudink et al., 2014; Liard et al., 1993) and temperature (Bonvalot et al., 1998), although quantification of sensor and instrument electronic effects on the final measurement has only been defined as a general residual once all other corrections have been implemented (Jiang et al., 2012).

Much less consideration has been given to higher frequency sources of noise such as wind, vibrations due to traffic and other anthropogenic activity and ambient microseism noise caused by pressure changes on the ocean floor due to the action of waves in the open ocean (Ardhuin et al., 2011). This is partially due to the high frequency nature of these noise sources and the resolution limitations of the CG3's 1 Hz sampling rate in comparison to the CG5 which samples at 6 Hz, although Debeglia and Dupoint (Debeglia and Dupont, 2002) did note the need for statistical despiking techniques to remove statistically outlying individual samples within the signal processing. These noise sources are often accounted for in large-scale surveys by positioning measurement points away from trouble spots, such as soft ground or near to roads (Seigel, 1995). However, this is rarely realistic on smaller scale sites and a more practical solution is increasing the instrument's integration time to allow the noise to be averaged out using a boxcar filtering approach (Debeglia and Dupont, 2002). However, as ambient microseism noise is formed from a superposition of primary and secondary microseisms (Essen et al., 2003) and other forms of vibrational noise such as road noise form unequal positive and negative contributions (Fig. 1), the integration method is imperfect as the partially deterministic signal causes a mean shift when not integrated over infinite time. Nevertheless, integration has been shown to give accuracies of up to 5 μGal with comparatively lengthy occupations of 15–20 min per point (Allis et al., 2000) which are commercially unviable due to financial and time constraints. Another approach taken by Sugihara (Sugihara, 2004) is to use visual inspection of the raw data to find periods of high microseismic and wind activity and remove them from the data. Two main problems exist with this method; first it is time consuming and not necessarily statistically rigorous on large datasets and secondly, the method does not provide a clear on-site assessment of when a suitable amount of data has been collected to give sufficient accuracy. Another method is to address the noise through the use of filtering techniques such as Scintrex's own seismic filter embedded in the CG5's software, which reduces noise from microseismic wave noise and rejects spikes (Scintrex, 2006), but the operation of this filter is unknown making replication impossible from the description in the manual, and no published assessment of the filter in controlled field conditions can be found to assess its effectiveness. It is therefore recognised that filtering of these higher frequency sources of noise may significantly reduce the integration times, saving time and money during a survey. This paper focuses on the quantification of these noise sources which affect the data quality of single-point measurements and some novel methods for improving data processing using the raw data from the instrument

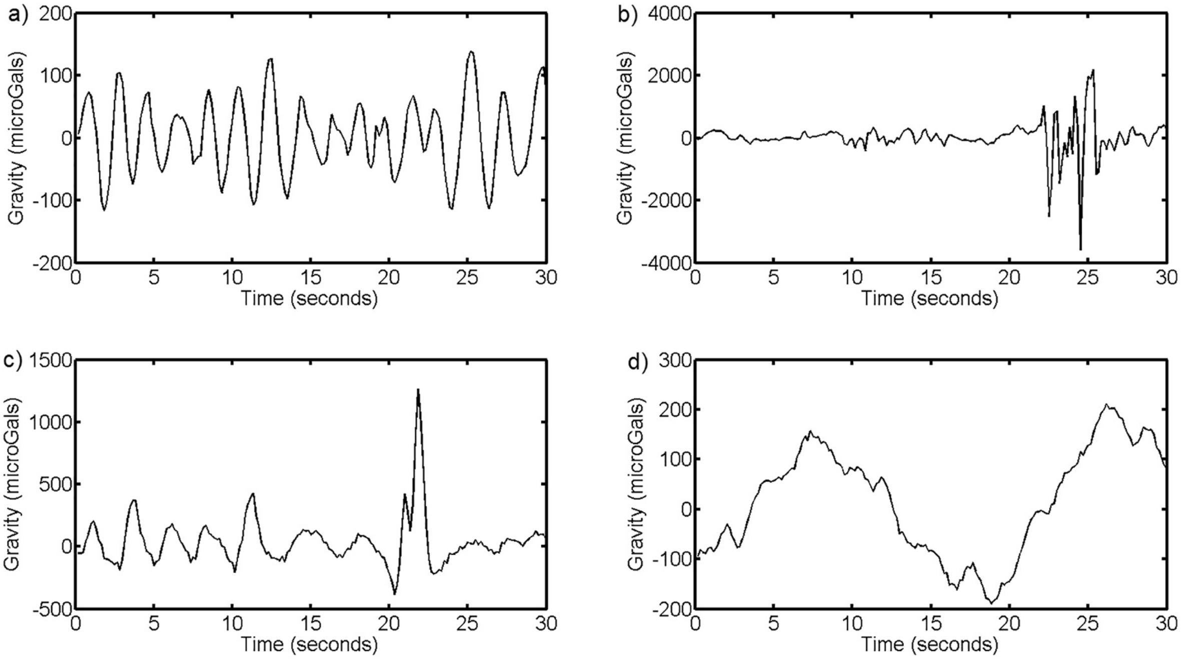

Fig. 1. 30 s sections of longer gravity measurements showing the effect of measurement high-frequency noise. Notice the imbalance in positive and negative fluctuations around the mean (defined as zero). a) Microseism noise only b) microseism and wind noise spikes with negative spikes c) microseism and road traffic noise with positive spikes d) microseism and earthquake noise introducing a low-frequency signal which dominates the microseism noise.