Earthquake Monitoring with Gravity Meters:
Case studies from the November 2006 and January 2007 Kuril Islands Earthquakes

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Introduction

Relative gravity meters are sensitive instruments capable of detecting small changes of the earth's gravity field with a precision of a few parts per billion (10^9) over time scales of one second. They are often used to characterize earth-tides that vary with diurnal and semidiurnal periods. Recently, a superconducting gravity meter was successfully used to record low frequency gravest seismic modes (< 1 mHz) excited by the 2004 (M> 9) Sumatra-Andaman earthquake (Rosat et al., 2005; Ferreira et al., 2006). High frequency and high amplitude signals such as the S and P body waves and the Rayleigh and Love surface waves associated with earthquakes have traditionally been the purvey of seismometers. Seismometers are usually optimized to record seismic frequencies (0.1-10Hz) and are designed not to saturate during large amplitude signals. Gravity meters, on the other hand, are usually optimized to filter out seismic noise and often are too sensitive to faithfully record the high amplitude waves associated with the first arrival of an earthquake. Recently, these difficulties have been overcome with the introduction of a new type of gravity meter (gPhone) with both large dynamic range and high sensitivity.

In this paper we examine records from two earthquakes: the November 15, 2006, magnitude 8.3 Kuril Islands (Japan) earthquake, and the January 13, 2007, magnitude 8.2 Kuril Islands earthquake. In order to determine the efficacy of using gravity meters for earthquake monitoring, we compared and contrasted data from three types of instruments: a Streckeisen STS-2 long period seismometer, a GWR superconducting gravity meter (SG), and six Micro-g LaCoste (MGL) gPhone gravity meters. Our results are encouraging. While still limited to vertical component waves, time-series records from improved gravity instruments may yield new information that can be used to study and understand crustal seismic velocities, attenuation, and dispersion, as well as the 1D density model of the earth. Their low frequency content augments traditional seismic data providing enhanced interpretation and inversion capabilities as well.

Earthquake Data

The signal from the November 2006 Kuril Islands earthquake recorded on a gPhone gravity meter in Lafayette, Colorado is shown in Figure 1. All data used in this study were sampled at 1 Hz (1s). Note that gravity signals (vertical acceleration) can be integrated to obtain calibrated vertical velocity and displacement signals. Figures 2-3 show some comparisons between the gPhone, SG superconducting gravity meter, and the STS-2 seismometer signals recorded simultaneously in Walferdange, Luxembourg during the January 2007 Kuril Islands earthquake.

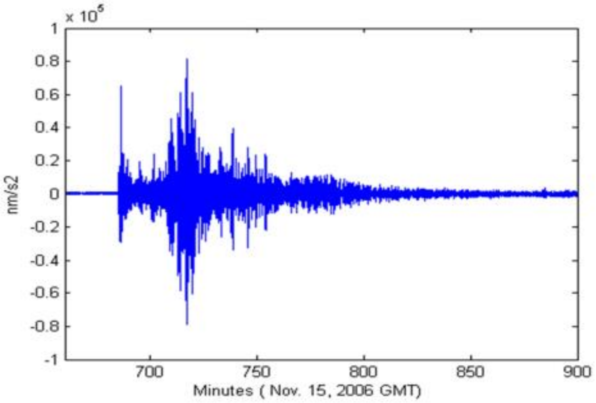


Figure 1. November 2006 Kuril Islands earthquake recorded with gPhone #28 in Colorado, USA.

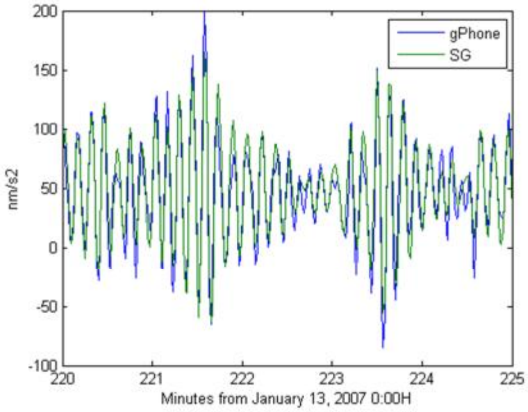
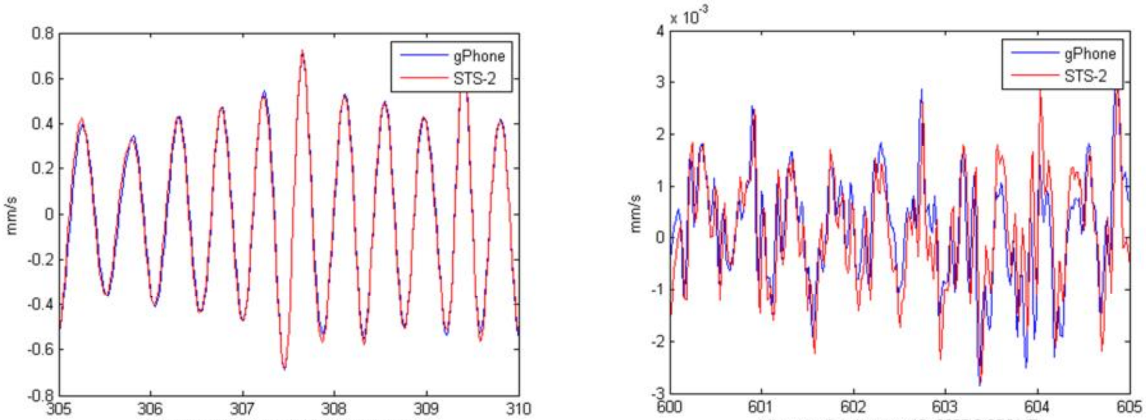


Figure 2. Seismic noise recorded simultaneously with the gPhone and SG gravity meters in Luxembourg during a quiet period a few hours after the January 2007 Kuril Islands earthquake. Note the amplitude envelope is about 100 nm/s^2, or about 10 microGals.



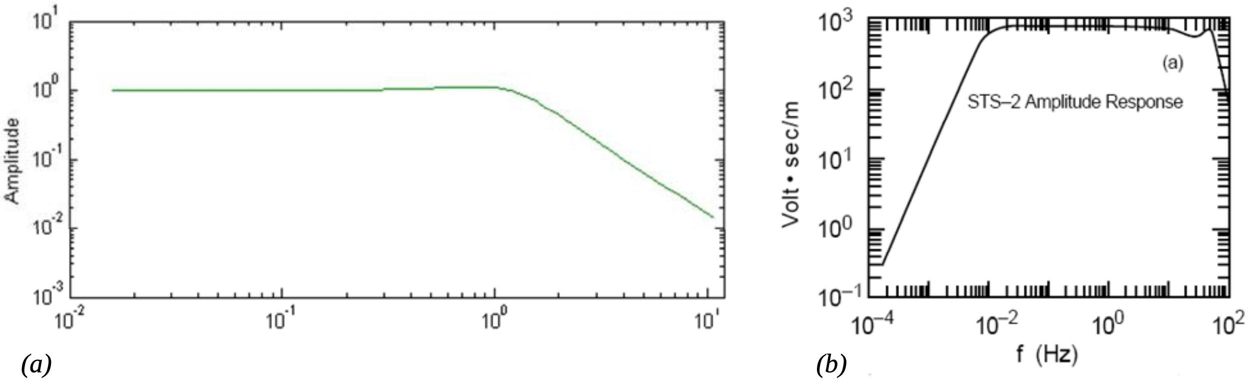
(a) *(b)*

Figure 3. Five minute records comparing vertical velocity data (mm/s) from the gPhone gravity meter and STS-2 seismometer during the 2007 Kuril earthquake. (a) The S-wave arrival. (b) A quieter time period 5 hours later.

Results and Discussion

We first studied the response of five different gPhone gravity meters to the magnitude 8.3, Kuril Islands earthquake on November 15th, 2006. These instruments were in various stages of the manufacturing process but were recording continuously at the Micro-g LaCoste facility in Lafayette, Colorado. The record produced by gPhone #28 is nearly identical to the other four gPhone records. The computed correlation between all five instruments over the entire earthquake was better than 90% and in fact was limited by sub second differences due to the fact that they were not perfectly synchronized before the event. The peak to peak amplitude of the earthquake response is about 200000 nm/s2 (2 x 10-4 m/s2). The vertical acceleration in Colorado caused by a magnitude 8 earthquake in Japan is a small but easily measurable 20 parts per million of the earth's gravity field (1 g ~ 9.8 m/s2, or about 980 Gals).

Note that the frequency response of a gPhone is very flat between DC and 1Hz (Figure 4(a)). The data in this study were sampled at 1Hz (1s) which means that the transfer function of the gravity meter can be ignored for the records presented here and the correlation of gPhone signals from the earthquake is not due to some special characteristic (electrical or mechanical resonance) common to all of the instruments. Figure 4(b) shows the amplitude response of an STS-2 long period seismometer with a low frequency cut off at 0.01Hz (120s) and an upper cutoff frequency at 100Hz (0.01s). The gravity meter response provides low frequency information that is normally cut off by the response of a traditional seismometer.



(a)

(b)

Figure 4. (a) Measured transfer function of the gPhone gravity meter. (b) Amplitude response of STS-2 seismometer.

We next studied the January 13th, 2007 Kuril Islands earthquake recorded on three different instruments (gPhone, SG, and STS-2) at the Walferdange Underground Laboratory for Geodynamics in Luxembourg. We found very good correlation between all three instruments.

The two gravity meters showed nearly perfect correlation except where the earthquake exceeds the dynamic range of the superconducting gravity meter at about +/-7500 nm/s^2 in the high amplitude early arrival waves. Figure 2 shows the two instrument signals during a quieter time about 3.5 hours after the earthquake. Note that the gravity value is changing only about 100 nm/s2 (about 10 microGals) yet the records are still in very good agreement. This correlation of two significantly different instruments is good evidence that the signals are indeed real and not an artifact of either instrument. The gPhone has a zero-length metal spring that balances a proof mass on a hinged beam, whereas the superconducting gravity meter employs a niobium sphere suspended by a superconducting magnetic field. It is therefore unlikely that these instruments would have similar mechanical resonances.In order to compare the gPhone and STS-2 seismometer responses, we integrated the gravity (vertical acceleration) to yield velocity and compared it to the vertical component of the STS-2. The scale of the STS-2 data was normalized to the velocity obtained by integrating the gravity meter data because the scale factor of the STS-2 was not well known, whereas the gravity meter is well calibrated. There was remarkable agreement of the two instruments during the main peak of the earthquake to about 10 hours or more after the earthquake (e.g., Figure 3). The differences in the overall records from the two instruments included 1) a more obvious train of multiple Rayleigh wave arrivals on the gPhone record, and 2) less correlated signal for longer period waves due to the attenuation and phase shift introduced by the STS-2 for frequencies of 100 s and longer (Figure 4).

Figure 5 shows the amplitude envelope of the gPhone displacement (integrated from velocity) plotted on a log scale. The peak displacement is about 10 cm. The displacements for the SG agree very well with the gPhone when the SG is within its dynamic range. Likewise, the derived displacements from the STS-2 agree well with the gPhone when sections of data are used that are not attenuated by frequency response of the STS-2.

We would expect to see a reoccurrence of Rayleigh waves as they traverse the globe in a great circle path through Luxembourg and Japan in both forward and reverse arcs from source to receiver (e.g., Kulhanek, 1990; Bolt, 1993). Figure 5 shows modeled and picked Rayleigh wave arrivals in the gPhone data. The figure shows the position of the wave arrivals using a green vertical bar. The red bars indicate theoretical (modeled) arrival times, using best-fit velocities of 3.97 km/s and 3.54 km/s for the forward and reverse arcs, respectively. The higher velocity for the forward arc is consistent with a higher velocity across the cold, fast Eurasian craton compared to the reverse arc containing considerable slow, hot oceanic crust. The modeled arrival times (in hours) for the forward arc occur at 0.70, 3.83, 6.96, and 10.10 hrs and the modeled arrival times for the reverse arc occur at 2.43, 5.56, 8.70, and 11.83 hrs. We could identify six forward arc arrivals and five reverse arc arrivals from the gPhone data, for total of eleven arrivals from this magnitude 8.2 earthquake. This compares favorably with the seven arrivals from the magnitude 9.0 great Sumatra earthquake (Ferreira et al., 2006). Our data show the waves decreasing by a factor of about 10 in amplitude (100 in energy) for each round trip around the earth. The waves clearly lose energy as they travel around the globe making it more and more difficult to see later arrivals. We could identify only one round trip using the STS-2 seismometer data.

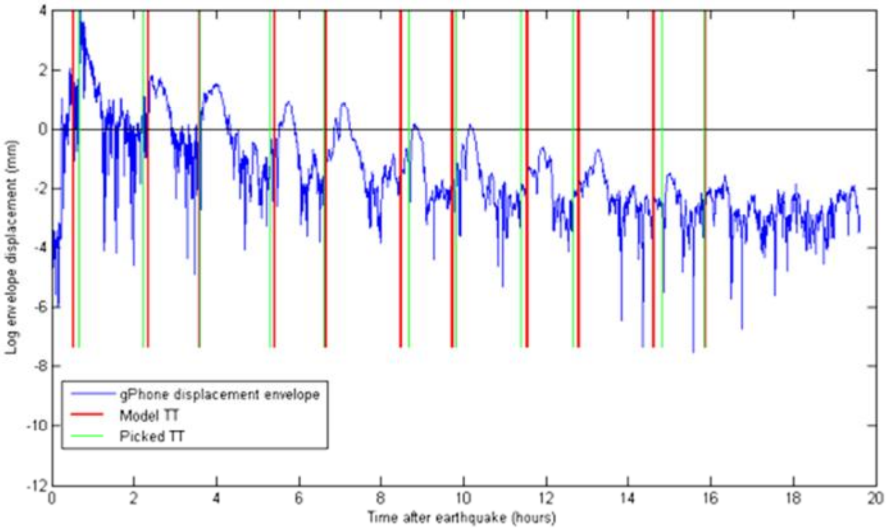


Figure 5. Rayleigh waves recorded on the Luxembourg gPhone from the 2007 Kuril Islands earthquake. Arrivals up to 16 hours after the earthquake are clearly detected. Modeled and picked arrival times are shown in red and green.

Conclusions

We have shown that gravity meters can be used to provide a complementary data set to seismometers for analyzing earthquakes. They have very good sensitivity in the normal seismic band (1 to 0.1Hz) and this sensitivity extends to much lower frequencies than can be interrogated with a seismometer. The gravity meter signals can be integrated to obtain valid calibrated velocity and displacement signals even during quiet periods when there is no earthquake signal. The velocity signal obtained from the gravimeter has been directly compared to the usual velocity signal from a standard seismometer and found to have good agreement.

Gravity meters seem particularly well suited to gather information about the velocity, attenuation, and dispersion of surface waves in the earth’s crust. We could clearly see at least 11 separate arrivals for Rayleigh waves generated by a magnitude 8.2 earthquake, with a reduction in energy of about 100 on each round trip. We also note that gravity meters appear to be very useful as a calibrated measurement of seismic noise at very low frequencies.

References

Rosat, S., T. Sato, Y. Imanishi, J. Hinderer, Y. Tamura, H. McQueen, and M. Ohashi, 2005, High-resolution analysis of the gravest seismic normal modes after the 2004 $M_w = 9$ Sumatra earthquake using superconducting gravimeter data, *Geophys. Res. Lett.*, 32, L13304, doi:10.1029/2005GL023128.

Ferreira, A. M. G., N. F. d'Oreye, J. H. Woodhouse, and W. Zürn, 2006, Comparison of fluid tiltmeter data with long-period seismograms: Surface waves and Earth's free oscillations, *J. Geophys. Res.*, 111, B11307, doi:10.1029/2006JB004311.

Bolt, B. A., 1993, Earthquakes: New York, New York, W. H. Freeman and Company, 331 p.

Kulhanek, Ota, 1990, Anatomy of Seismograms: Amsterdam, The Netherlands, Elsevier Science Publishers B. V.