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# Monitoring earthquakes with gravity meters

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**Abstract**: Seismic waves from a magnitude 8.3 earthquake in Japan were consistently recorded by five nearly identical gPhone gravity meters in Colorado. Good correlation was also found in the response of two different types of gravity meters and a standard seismometer in Walferdange, Luxembourg to an earthquake of magnitude 8.2 in Japan, indicating that all of them were capable of measuring the surface waves reliably. The gravity meters, however, recorded 11 separate arrivals of Raleigh waves, while the seismometer only one. Thus the gravity meters may be useful for obtaining new information in the study of seismic velocities, attenuation and dispersion.

**Key words**: gPhone grarity meter; superconducting gravity meter(SG); monitoring eavtguake

## 1 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 ($10^9$) in a period 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 large low-frequency (milli Hertz) seismic waves excited by the 2004 ($M>9$) Sumatra-Andaman earthquake[1]. High-frequency signals such as the S and P body waves and the Rayleigh and Love surface waves of earthquakes have traditionally been recorded with seismometers, which are usually optimized for seismic frequencies (0.1 - 10 Hz) and designed not to saturate during large amplitudes. Gravity meters, on the other hand, are usually designed to filter out seismic "noise", and they are often too sensitive to record large seismic waves faithfullydue to limited dynamic range. Recently, these difficulties have been overcome with the introduction of a new type of gravity meter (gPhone), which has a very large dynamic range and a high sensitivity that it can record both large-amplitude seismic first-arrivals and normal background noise in the absence of any earthquake.

In this study we examined several gPhone records of two earthquakes in order to investigate the usefulness of gravity meters for standard earthquake recording. First, we compared the responses of five nearly identical gravity meters to a magnitude-8.3 earthquake in the Kuril Islands, Japan (Nov. 15th, 2006) recorded in Colorado. Then we compared three types of instruments (a Streckeisen STS-2 long period seismometer, a GWR superconducting gravity meter (SG), and a Micro-g LaCoste (MGL) gPhone, all in Walferdange, Luxemburg), by analyzing their responses to a magnitude-8.2 earthquake also in the Kuril Islands (Jan. 13, 2007).

## 2 November 15th, 2006 earthquake (Kuril Islands)

Five different gPhones (Serial numbers #28, #34, #35, #37 & #39) were used to study their responses to the magnitude-8.3 earthquake. These instruments were at various stages of the manufacturing process but were all recording continuously at the Micro-g LaCoste facility in Lafayette, Colorado. Some of the instruments had

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relatively large drifts, because they were recently built and put under temperature control. While these instruments did not have a low enough drift to be useful for conventional static-gravity measurements, their high-frequency noise levels were nearly identical and close to normal specifications. The record of gPhone #28 is given in figure 1, as an example.

The peak-to-peak amplitude in the figure is about 200000 $nm/s^2$ ($2\times10^{-4}$ $m/s^2$), and the vertical acceleration is small but easily measurable, at 20 parts per million of the earth's gravity field ($g=10$ $m/s^2$). A plot of five minutes of the gPhone data near the beginning of the earthquake's P-wave arrival is shown in figure 2.

The correlation between all the five instruments over the entire earthquake recording was better than 90%; there were only sub-second differences due to the fact that they were not perfectly synchronized in time before the recording. The plot shows that the P waves had a characteristic period of about 5 – 6 seconds. The 20 s-period S-waves were perfectly correlated also, as shown in figure 3.

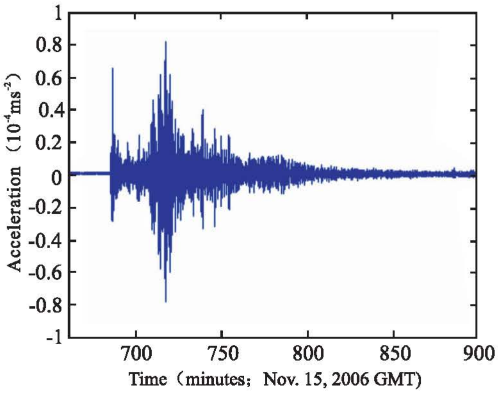


Figure 1 The 2006 magnitude-8.3 Japanese earthquake recorded with gPhone #28 in Lafayette, Colorado, USA (sample interval is 1s for all the data figures in this paper)

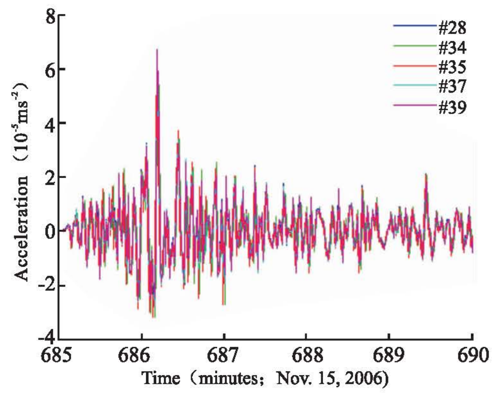


Figure 2 A set of five-minute records near the beginning of the earthquake with five different gPhones

## 3 Frequency response of gPhone

Although the records of the gPhones are nearly identical, still it is possible that parts of the observed signals were due to some special characteristic (electrical or mechanical resonance) common to them all. In order to better understand a gPhone's frequency response, we subjected it to an artificial impulse and calculated the transfer function using the System Identification routines in MatLab.

As shown in figure 4, the gPhone has a flat frequency response between DC and 1 Hz with a cut off frequency at about 5 Hz, like a low-pass filter. Since the data used in this study were sampled at 1 Hz, the transfer function of the gravity meter can be ignored for the records presented here.

We note that any type of gravity meter with a low drift (superconducting relative-gravity meter or absolute-gravity meter) has a similarly flat transfer function at low frequencies (until the frequency is low enough

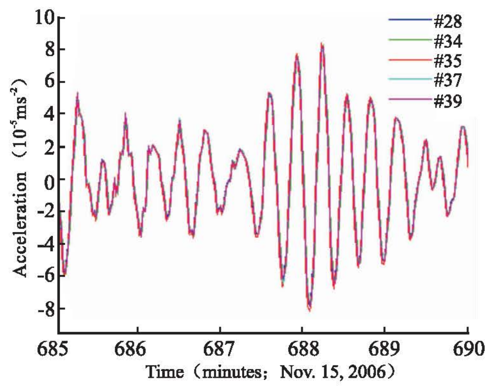


Figure 3 A set of S-wave arrivals recorded with five different gPhones

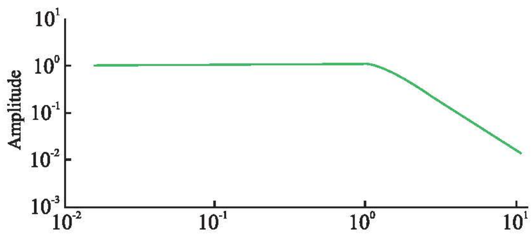


Figure 4 Measured transfer function of the gPhone

for drift to become visible). This low-frequency response provides low-frequency information that is normally cut off by traditional seismometers. For comparison, we show in figure 5 the amplitude response of an STS-2 long-period seismometer with cutoffs at 0.01 Hz (120 s) and 100 Hz (0.01 s).

The frequency response of an instrument should not be confused with the frequency-dependent noise level of the instrument. Since all the three instruments exhibited good correlation both during the earthquake and during calm periods prior to the earthquake, we knew that the signal-to-noise ratio was reasonably high for all the instruments, and therefore ignored the differences in the instruments' noise levels.

## 4 January 13th, 2007 earthquake (Kuril Islands)

We next studied the data of the magnitude-8.2 earthquake recorded simultaneously with three different types of instruments installed at the Walferdange Underground Laboratory for Geodynamics in Luxembourg: a gPhone gravity meter, a superconducting (SG) gravity meter and an STS-2 long-period seismometer.

First we compared the responses of the two gravity meters. As shown in figure 6, the correlation was nearly perfect, except where the earthquake amplitude exceeded the dynamic range of the gravity meter at about $+/-7500\ nm/s^2$.

There was good correlation near the beginning of the earthquake (Fig. 7), indicating that the signals were real and not an artifact of either instrument. Since the gPhone has a zero-length metal spring that balances a proof mass on a hinged beam and the superconducting gravity meter employs a niobium sphere suspended by a superconducting magnetic field, it is therefore unlikely that they would have similar mechanical resonances.

Figure 8 shows a record of five minutes with the two instruments during a quieter period about 3.5 hours after the earthquake. The gravity value changed only about 10 μGal (peak-peak) yet the two instruments were still in very good agreement.

Figure 9 shows a one-day record of the gPhone and STS-2 during the earthquake. We integrated the gPhone gravity (i.e. acceleration) data to yield velocity,

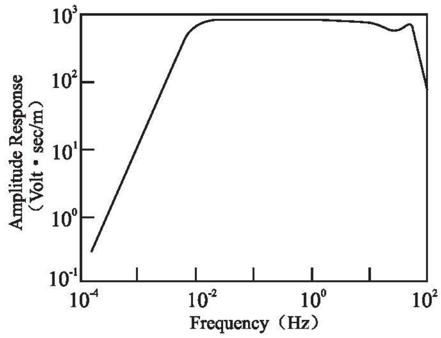


Figure 5 Amplitude response of the STS-2 seismometer

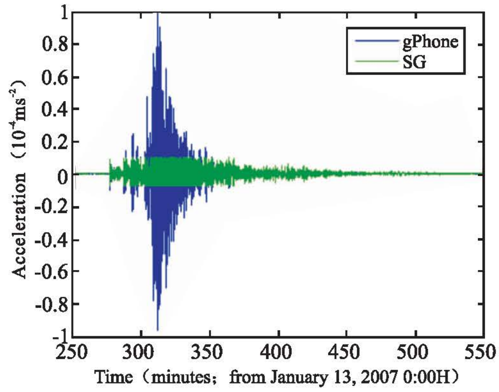


Figure 6 Earthquake records by a superconducting gravity meter (green) and a gPhone (blue)

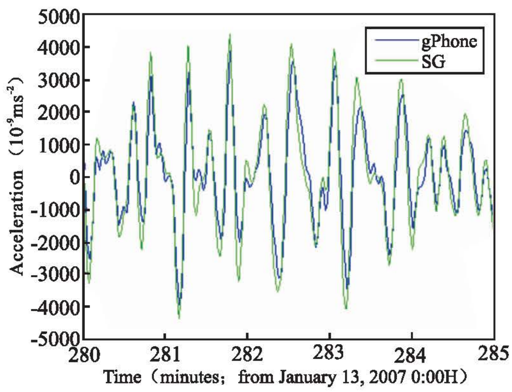


Figure 7 A set of five-minute records by the two meters near the beginning of the earthquake

and compared it with the vertical velocity 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 very well calibrated by measuring known gravity changes on the Rocky Mountain Calibration Range. The superconducting gravity meter was not used for the comparison because of its limited dynamic-range.

The agreement between the two instruments during

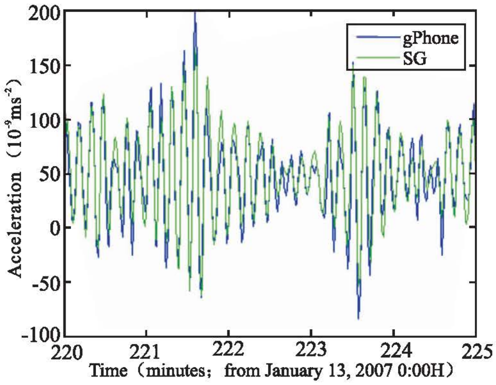


Figure 8 Seismic noise during a quieter period a few hours after the earthquake

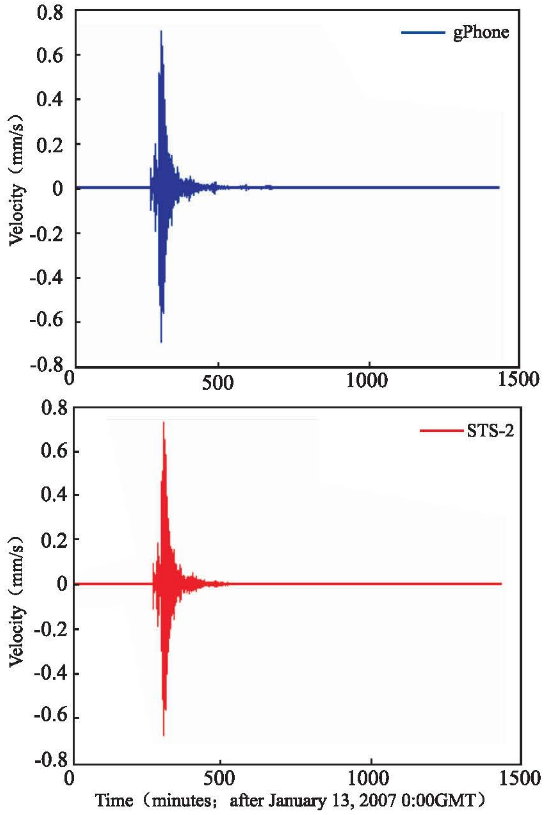


Figure 9 Seismic records by a gPhone (blue) and a STS-2 seismometer

the peak values was remarkable, but the gPhone showed more Rayleigh wave arrivals.

To examine the instrumental correlation more closely, we show in figure 10 a five-minute record of both the gPhone and STS-2 velocity in a section of data that had peak wave amplitudes. A peak-to-peak velocity of about 1.6 mm/s was clearly measured with both the STS-2 and gPhone.

There was also good agreement between the two instruments during quiet periods. Figure 11 shows a five-minute record with a peak-to-peak amplitude of about 6 μm/s during a quiet period 10 hours after the earthquake. The correlation between the instruments was

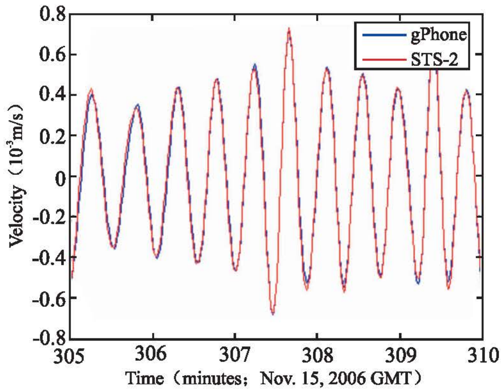


Figure 10 A set of five-minute S-wave records with an STS-2 seismometer and a gPhone

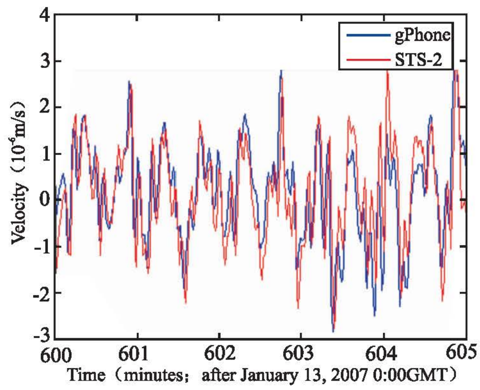


Figure 11 A set of five-minute records of background variation with an STS-2 seismometer and a gPhone

not as good for longer-periods, but this is understandable in view of the large attenuation and phase shift introduced in the STS-2 at periods of 100 s and longer (see Fig. 5).

For completeness, we then integrated the gPhone velocity to obtain a record of vertical displacement. We used the gPhone record because it had a larger dynamic range than the SG and a lower frequency response than the STS-2, but we note that similar plots can be made with the other two instruments as well. The displacements derived from the SG and gPhone agreed very well, when the SG was within its dynamic range. Likewise, the displacements from the STS-2 and gPhone agreed well, when the sections used were not attenuated by the frequency response of the STS-2.

Figure 12 shows the displacement (with maximum amplitude of almost 10 cm) of P, S, and Rayleigh waves recorded with the gPhone (Love-wave arrivals were not recorded, because gPhone is a vertical-component instrument). The different arrivals of these waves are clearly visible in the record. The good correlation of this instrument with the STS-2 during this period is a strong indication that the results are not instrument dependent.

Figure 13 shows a longer record from the gPhone, where the waves made several orbits around the globe in both forward and reverse directions. (The green bars indicate the arrivals; the red bars indicate theoretical arrival times, using best-fit velocities of 3.97 km/s and 3.54 km/s for the forward and reverse directions across the cold Eurasian craton and the hot oceanic crust, respectively.)

We could identify six forward-moving and five backward-moving, or a total of eleven, arrivals in the gPhone data for the magnitude 8.2 earthquake. This compares favorably with the seven arrivals identified previously for the magnitude 9.0 Great Sumatra Earthquake[2-4]. As shown in the gPhone displacement plot on a log scale (Fig. 14), the Rayleigh-wave amplitude decreased by a factor of about 10, and the energy by a factor of about 100, after each trip around the earth.

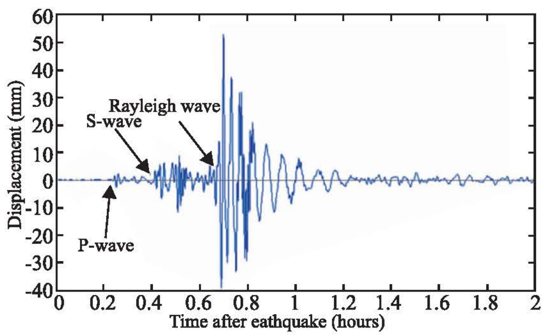


Figure 12 Displacement due to P, S, and Rayleigh waves recorded with a gPhone

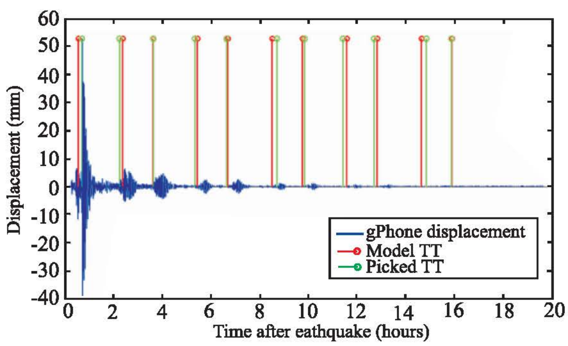


Figure 13 Multiple arrivals of Rayleigh waves of the magnitude 8.2 earthquake recorded with a gPhone.

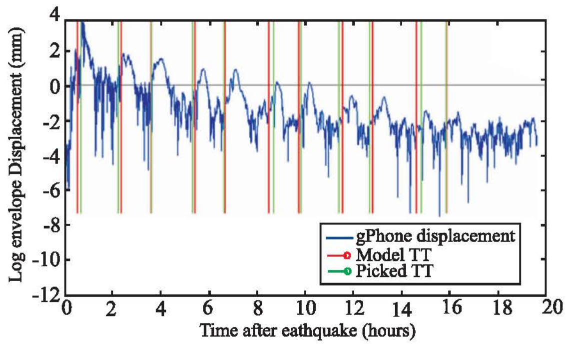


Figure 14 Rayleigh waves (data in Fig. 13) on log scale

## 5 Conclusions

We have shown that gravity meters could be used to provide complementary data to seismometers for earthquake studies. They had very good sensitivity not only in the normal seismic-frequency band (1 – 0.1 Hz), but also at much lower frequencies not detectable by ordinary seismometers. The gravity-meter signals could be integrated to obtain valid velocity and displacement signals even when there was no earthquake. The velocity signals from the gravimeters and a standard seismometer were found to be in good agreement.

Gravity meters seem particularly well suited for gathering information about the velocity, attenuation, and dispersion of surface waves in the earth's crust. We could clearly see at least 11 separate arrivals of Rayleigh waves generated by a magnitude 8.2 earthquake, with a reduction in energy of about 100 after each round-the-earth trip. Gravity meters appeared to be very useful for measuring seismic noise at very low frequencies also.

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