

## Earthquake monitoring with gravity meters

T.M. Niebauer, Jeff MacQueen, Daniel Aliod, and Olivier Francis

### Abstract

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. Gravity meters have traditionally been used to characterize the earth-tides that vary with diurnal and semidiurnal periods. Higher frequency 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 which are optimized to record higher frequencies (0.1-10Hz). In this paper, we compare the response of five nearly identical *gPhone* gravity meters to an earthquake in Japan recorded in Colorado. We found almost perfect correlation between the records. Next we compared the response of two different types of gravity meters with a standard seismometer to an earthquake of magnitude 8 in Japan recorded in Walferdange, Luxembourg. We found very good correlation between all three types of instruments indicating that they were all capable of providing a reliable measurement of the surface motions induced by the earthquakes. The gravity meter signals, however, appear to have some advantage over the seismometer for measuring traveling surface (Rayleigh) waves that reoccur on time scales of one to two hours. In particular, we could clearly see at least 11 separate arrivals for Rayleigh waves generated by a magnitude 8.2 earthquake in the gravity meter record and only one in the seismometer record. These data may yield new information that can be used to study and understand crustal seismic velocities, attenuation, and dispersion.

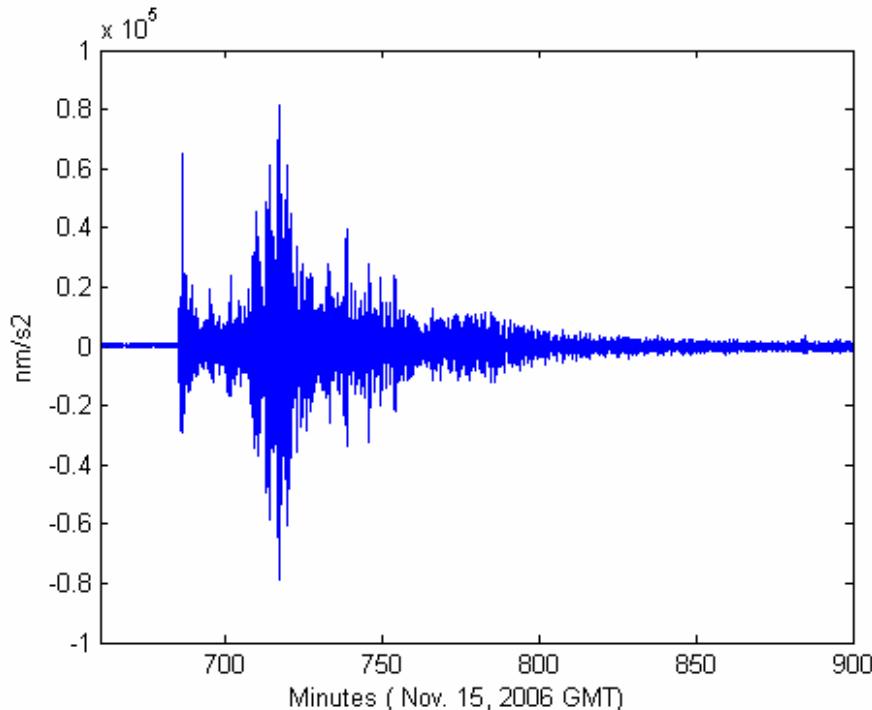
## Introduction

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 (milliHertz) gravest seismic modes excited by the 2004 ( $M > 9$ ) Sumatra-Andaman earthquake<sup>i</sup>. 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 a first arrival of an earthquake due to a limitation of dynamic range. Recently, these difficulties have been overcome with the introduction of a new type of gravity meter (gPhone) with large dynamic range and high sensitivity. The gPhone has a very large dynamic range that allows it to record the high amplitude first arrival signals from an earthquake and still have enough sensitivity to record normal background seismic activity that occurs at all times (in the absence of an earthquake signal).

In this paper we examine gPhone gravity records after two different earthquakes in order to investigate the efficacy of using gravity meters for more standard earthquake recording. First we compared the response of five nearly identical gravity meters to an earthquake in Japan (Nov. 15<sup>th</sup>, 2006) recorded in Colorado. We found almost perfect correlation between the records. We then compared and contrasted three types of instruments: a Streckeisen STS-2 long period seismometer, a GWR superconducting gravity meter (SG), and a Micro-g LaCoste(MGL) gPhone gravity meter by analyzing their response to a different earthquake (Jan 13, 2007) simultaneously recorded in Walferdange, Luxemburg. Again we found a very good correlation between all the instruments before, during, and after the earthquake. The gravity meter signals, however, appear to have some advantage over the seismometer for measuring traveling surface (Rayleigh) waves that reoccur on time scales of one to two hours. In particular, we could clearly see at least 11 separate arrivals for Rayleigh waves generated by a magnitude 8.2 earthquake in the gravity meter record and only one in the seismometer record. This compares favorably with the 7 arrivals reported from the magnitude 9.0 great Sumatra earthquake (Ferreira et. al, 2006<sup>ii</sup>). These data may yield new information that can be used to study and understand crustal seismic velocities, attenuation, and dispersion.

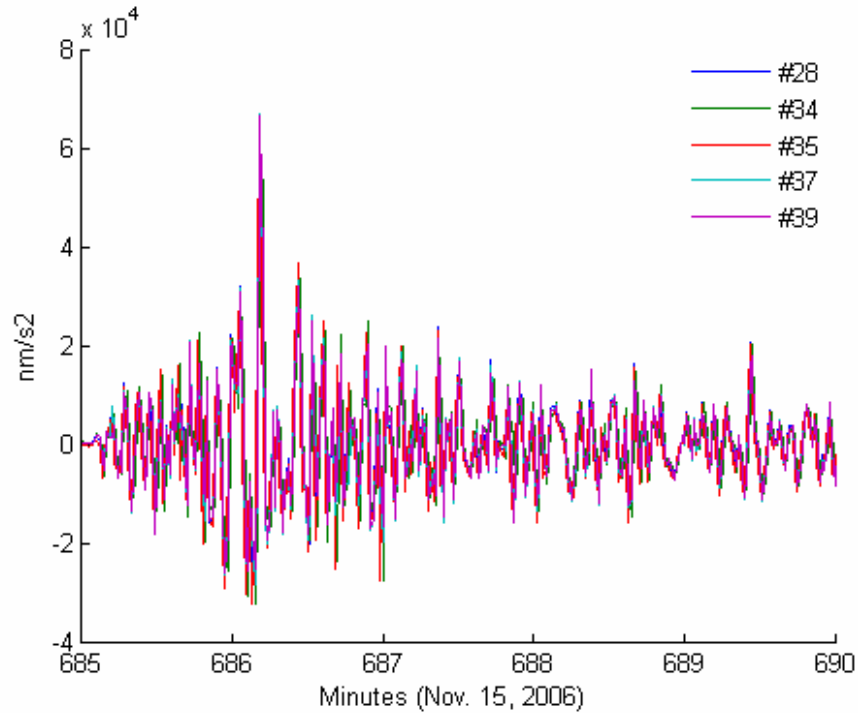
## November 15th, 2006 Earthquake (Kuril Islands)

First we studied the response of five different gPhone gravity meters (Serial numbers #28, #34, #35, #37 & #39) to a magnitude 8.3 earthquake that occurred in the Kuril Islands (Japan) on November 15<sup>th</sup>, 2006. These instruments were in various stages of the manufacturing process but were recording continuously at the Micro-g LaCoste facility in Lafayette, Colorado. In particular, several of the instruments had relatively large drifts associated with the fact they were newly built and only recently put on temperature control. While these instruments did not have a low enough drift to be used for conventional static gravity measurements, their high frequency noise level was near normal specifications. The record produced by gPhone #28 is given in Figure 1.



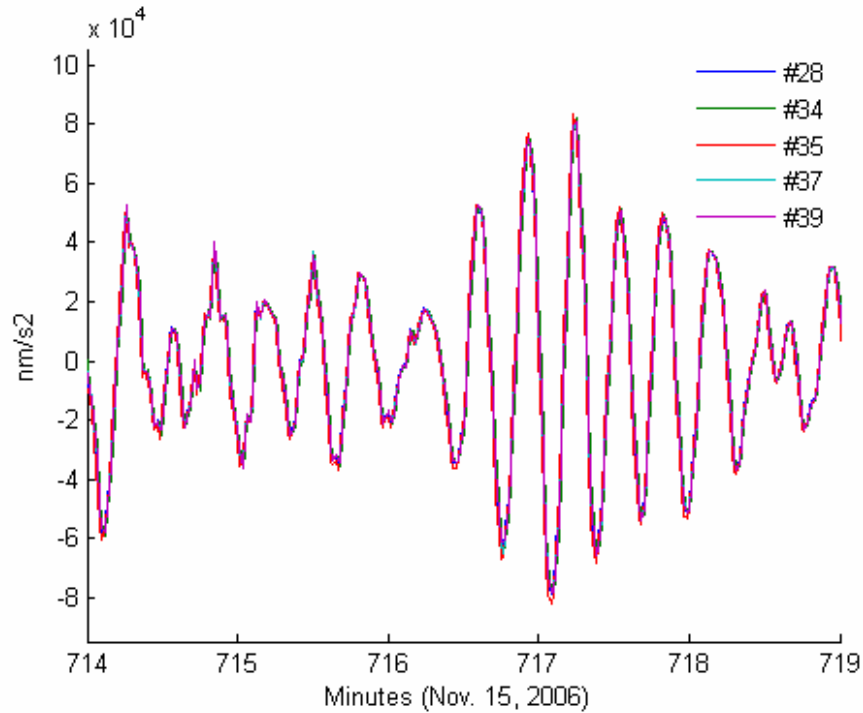
**Figure 1: Earthquake recorded with gPhone #28 (data sampled at 1s)**

The records for the other 4 instruments are nearly identical. The peak to peak amplitude of the earthquake response is about 200000 nm/s<sup>2</sup> ( $2 \times 10^{-4}$  m/s<sup>2</sup>). 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 ( $g \sim 10$  m/s<sup>2</sup>). A plot of five minutes of the gPhone data near the beginning of the earthquake P wave arrival is shown in Figure 2.



**Figure 2: Five minute record near the beginning of the earthquake with five different iPhones (data sampled at 1s)**

The 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 time perfectly synchronized before the recording. The plot shows that the first waves have a characteristic period of about 5-6 seconds, which centers in the usual frequency band for the peak in seismic records (even during quiet periods). The S wave arrival is shown in Figure 3

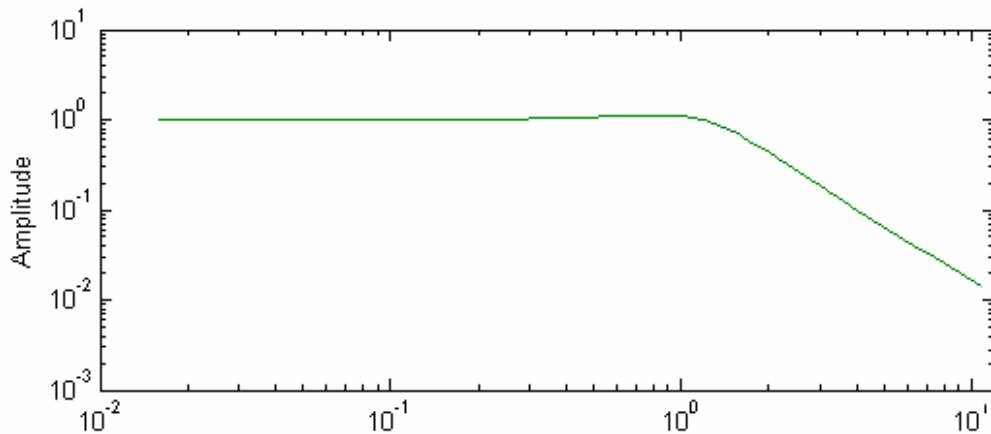


**Figure 3: S-wave arrivals (data sampled at 1s)**

The period of the S waves is about 20s or about 4 times longer than the P waves. Again one can see near perfect correlation between all of the gPhone records.

## Instrument frequency response

The five nearly identical records of the earthquake, while intriguing, still leaves open the question about the possibility that part of the observed signal could be due to some special characteristic (electrical or mechanical resonance) common to all of the gPhones. In order to better understand the gPhone, frequency response we subjected it to an artificial impulse and calculated the transfer function using the System Identification routines in MatLab. The transfer function of the gPhone is shown in Figure 4.

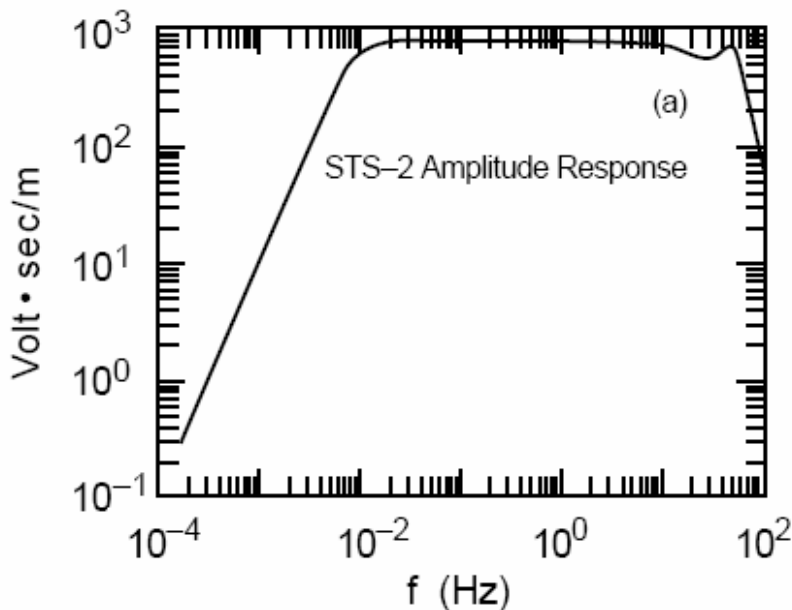


**Figure 4: Measured transfer function of gPhone**

We see that the gPhone gravity meter has an amplitude response that acts as a low pass filter with a cut off frequency of about 5Hz. The frequency response is very flat between DC and 1Hz. The data used in this study were sampled at 10Hz which means that the transfer function of the gravity meter can be ignored for the records presented here.

We note here that any type of gravity meter with a low drift (i.e. a superconducting relative gravity meter or absolute gravity meter) will similarly have a flat transfer function at low frequencies (until the frequency is low enough for drift to become visible). The low frequency gravity meter response provides low frequency information that is normally cut off by the response of a traditional seismometer.

Figure 5 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).



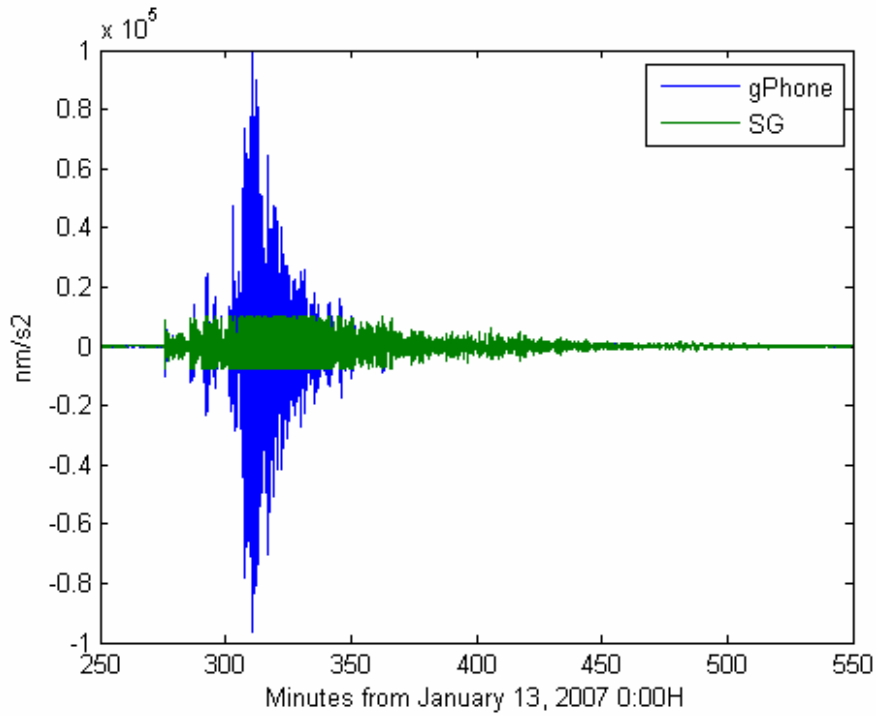
**Figure 5: Amplitude response of STS-2**

The discussion of the frequency response of an instrument should not be confused with the frequency-dependent instrument noise level. Since all three instruments exhibit good correlation both during the earthquake and during periods of calm (prior to the earthquake), we know that the signal to noise ratio is reasonably high for all instruments and we will therefore ignore differences in instrument noise levels.

## **January 13th, 2007 Earthquake (Kuril Islands)**

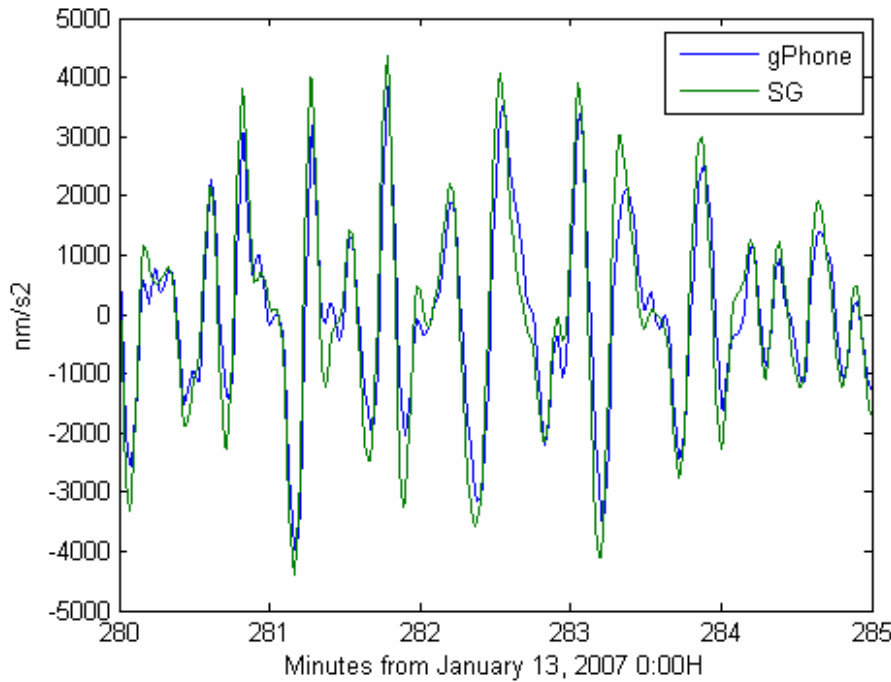
We next studied another earthquake recorded simultaneously at one site with three different types of instruments. This earthquake was also a magnitude 8.2 with its origin in the Kuril Islands (Japan) on January 13, 2007. It was recorded in the Walferdange Underground Laboratory for Geodynamics in Luxembourg with a gPhone gravity meter, a superconducting (SG) gravity meter, and an STS-2 long period seismometer. We found very good correlation between all three instruments.

First we compared the two different gravity meter responses. Figure 6 shows the record from the superconducting gravimeter (green trace) and the gPhone (blue trace). The correlation is nearly perfect, except where the earthquake exceeds the dynamic range of the superconducting gravity meter at about  $\pm 7500 \text{ nm/s}^2$ .



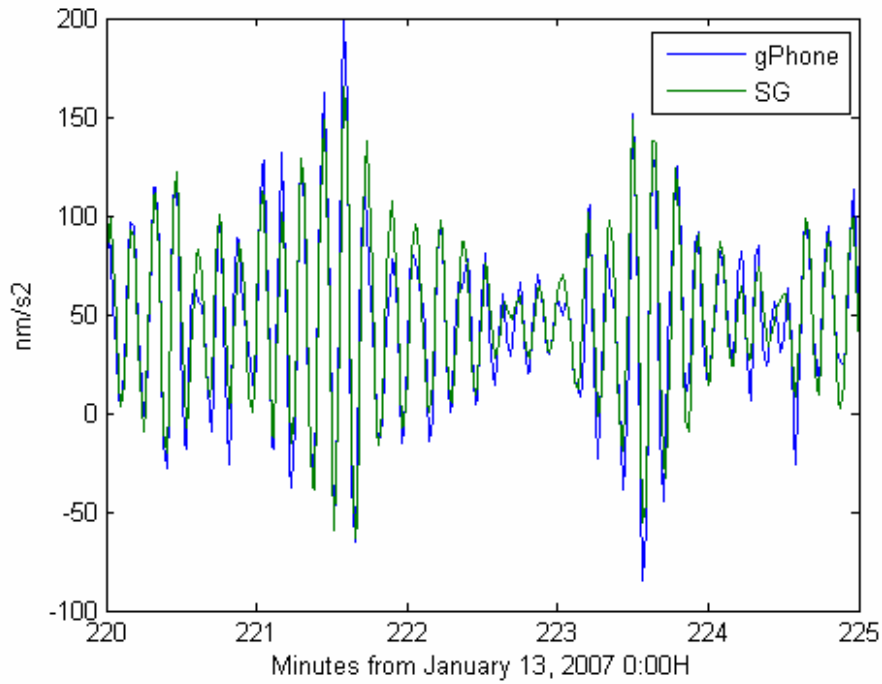
**Figure 6: Superconducting (green) and gPhone (blue) earthquake record (data sampled at 1s)**

There is good correlation near the beginning of the earthquake as shown in Figure 7. This correlation of two significantly different instruments is very 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.



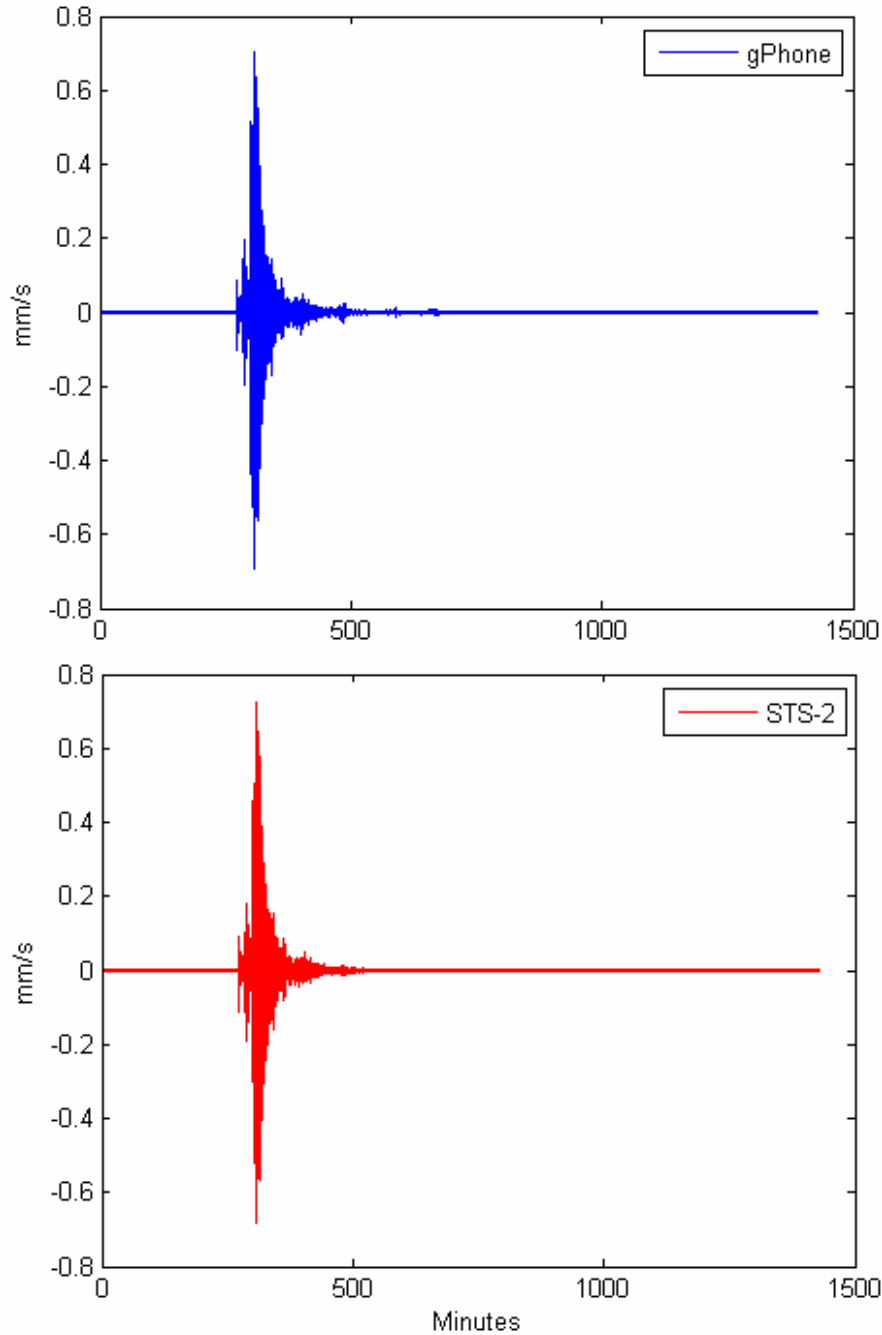
**Figure 7: Five minute record near the beginning of the earthquake (data sampled at 1s)**

Possibly the most interesting part of this record occurs long after the primary body and surface wave arrivals when the earth has returned to its “normal” quiescent state. Figure 8 shows a record of five minutes with a gPhone and a superconducting gravity meter (SG) during a quieter period about 3.5 hours after the earthquake. The gravity value is changing only about 10  $\mu\text{Gal}$  (peak-peak) yet the two instruments are still in very good agreement. This is very strong evidence that both instruments are measuring real seismic noise rather than some artifact of the gravity meters.



**Figure 8: Seismic noise during a quieter period a few hours after the earthquake (data sampled at 1s)**

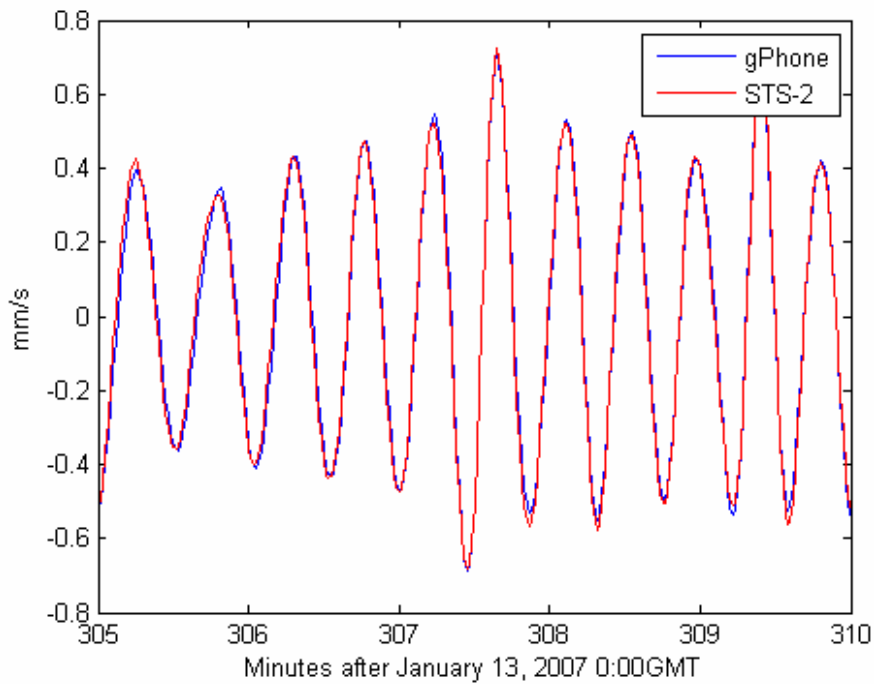
Figure 9 shows a one day record of the gPhone and STS-2 during the earthquake. In order to make the comparison, we integrated the gravity (.i.e. acceleration) from the gPhone to yield velocity, which we compared to the vertical velocity component of the STS-2. The scale of the STS-2 data was normalized 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 the dynamic range limitation.



**Figure 9: gPhone (blue) and STS-2 vertical velocity (data sampled at 1s)**

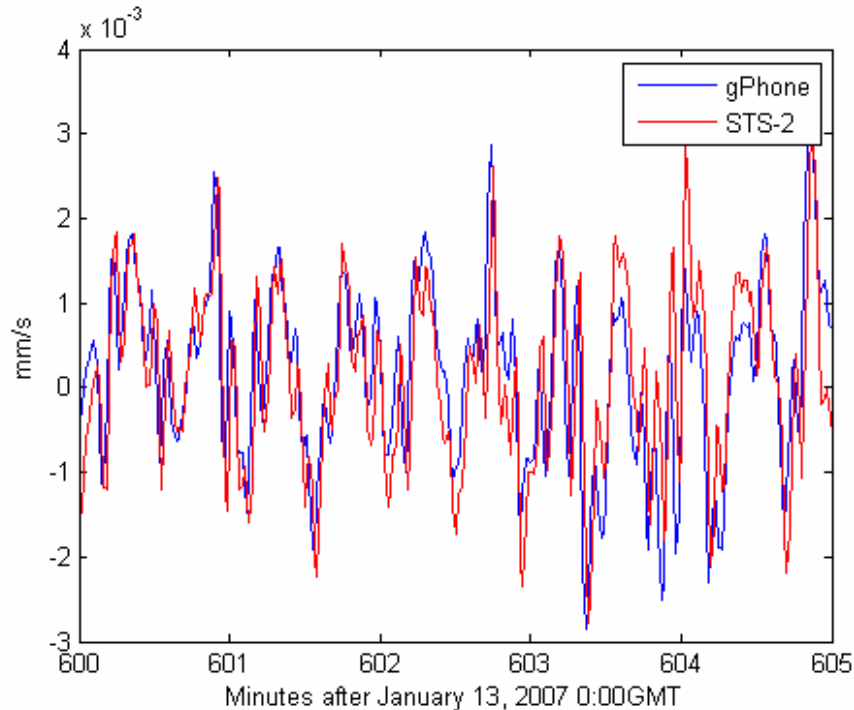
There was remarkable agreement of the two instruments during the main peak of the earthquake although the gPhone shows a more obvious train of multiple Rayleigh wave arrivals.

It is useful to compare the records more closely during the peak of the earthquake to verify that the two instruments are well correlated. Figure 10 shows a five minute record of both the gPhone and STS-2 velocity during a section of data with peak wave amplitude. A peak to peak velocity of about 1.6mm/s was clearly measured with both the STS-2 and gPhone.



**Figure 10: Five minute record with an STS-2 seismometer and gPhone gravity meter during the earthquake S-wave arrival (data sampled at 1s)**

There was also good agreement between the two instruments during quiet periods. Figure 11 shows a five minute record with a peak-peak amplitude of about  $6 \mu\text{m/s}$  during a quiet period 10 hours after the earthquake. The correlation between the instruments was not as good for longer period waves but that is understood because of the large attenuation and phase shift introduced in the STS-2 at frequencies of 100 s and longer (see Figure 5).

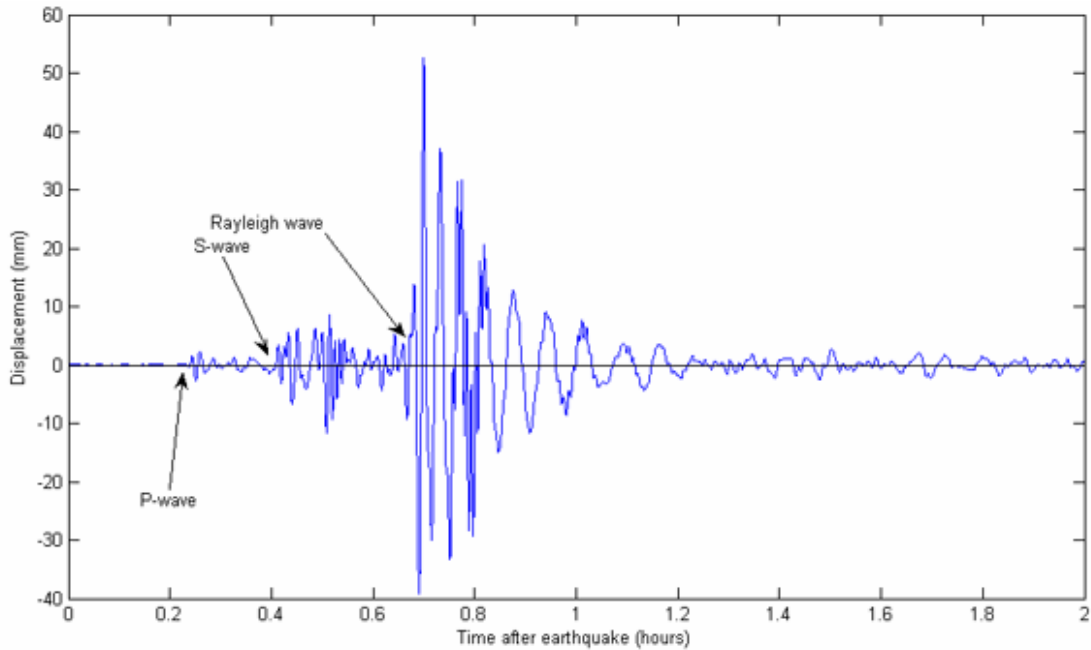


**Figure 11: Five minute record during a quieter period after the earthquake with STS-2 and gPhone (data sampled at 1s)**

For completeness, we then integrated the gPhone velocity to obtain a record of the 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 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.

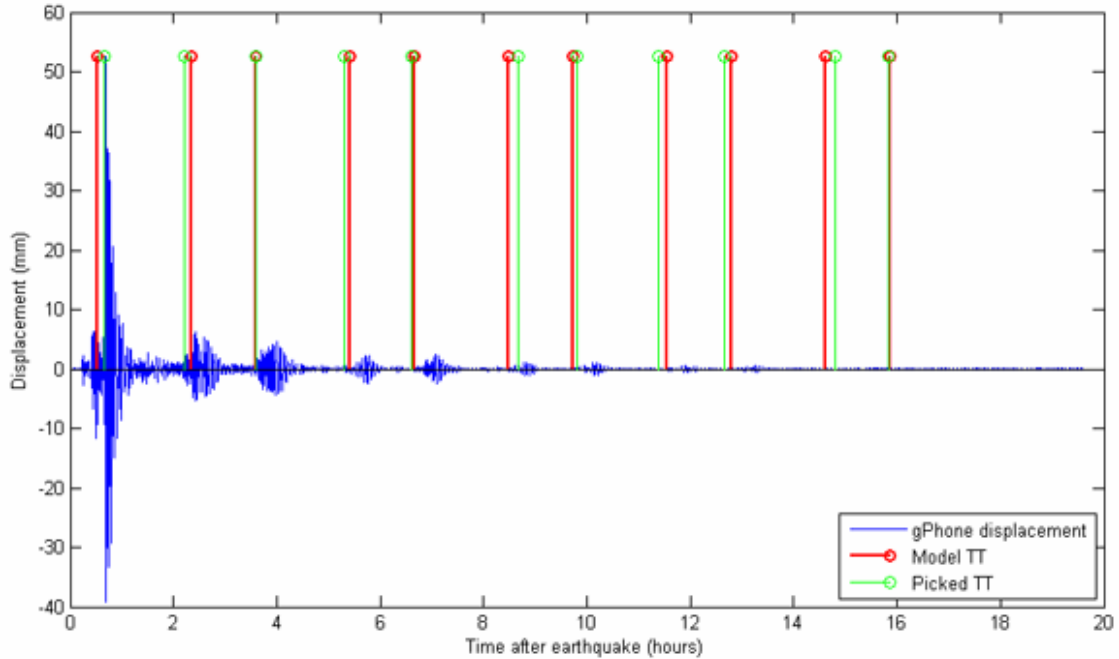
Figure 12 shows the displacement due to the P and S body waves and Rayleigh surface waves recorded with the gPhone. The primary or P wave is the fastest ( $\sim 5.5$  km/sec in granite) (Bolt, 1993<sup>iii</sup>) of the body waves and is the first wave usually recorded on a seismograph. The secondary or S wave travels more slowly ( $\sim 3.0$  km/sec in granite) (Bolt, 1993) than the P wave. The S wave travels only through solid material and its movement is similar to light waves in that it moves perpendicular to the direction of motion as it propagates. Love and Rayleigh waves are two types of surface waves. Surface waves travel more slowly than body waves (Bolt, 1993) and usually cause the most destruction in populated areas (Kulhanek, 1990<sup>iv</sup>). Love waves normally travel faster than Rayleigh waves with horizontal (shear) motion perpendicular to the direction of propagation while the motion of a Rayleigh wave is in a vertical plane parallel to the direction of wave propagation (Kulhanek, 1990). Since the gPhone is a vertical component instrument, we would not expect to see Love wave arrivals. The different arrival times for these waves are clearly visible in the record. We measured a maximum vertical displacement of almost 10cm. The good correlation with the STS-2 during this

period is a strong indication that the results are not dependent upon the type of instrument used to monitor the earthquake arrival.



**Figure 12: Displacement due to P, S, and Rayleigh waves recorded with gPhone (data sampled at 1s)**

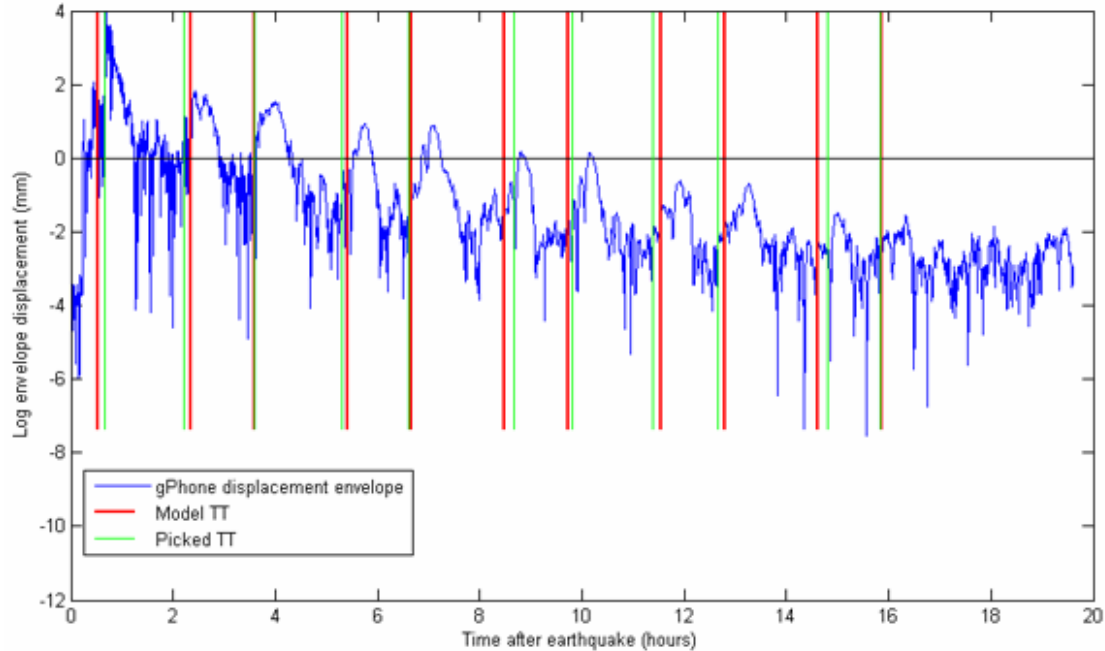
We would expect to see a reoccurrence of the Rayleigh waves as they traverse the globe in a great circle path through Luxembourg(49.6° N, 6.15 ° E) and Japan (46.272° N, 154.455° E) in both forward and reverse arcs from the source. Figure 13 shows a longer record from the gPhone where the waves can be seen making several orbits around the globe. The figure shows the position of the arrival of these 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.



**Figure 13: Rayleigh waves traveling around globe (using gPhone data)**

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 a magnitude 8.2 earthquake. This compares favorably with the seven arrivals from the magnitude 9.0 great Sumatra earthquake (Ferreira<sup>ii</sup> et. al, 2006). 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 long period seismometer data.

Figure 14 shows the amplitude envelope of the gPhone displacement plotted on a log scale. The Rayleigh wave amplitude decreased by a factor of about 10 on each round trip around the earth. This means that the energy in the wave disturbance decreases by a factor of about 100 on each round trip.



**Figure 14: Rayleigh waves on log scale (using gPhone data)**

## 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 (1-1Hz) 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 position 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.

<sup>i</sup> 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.

<sup>ii</sup> 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.

<sup>iii</sup> Bolt, B. A., 1993, Earthquakes: New York, New York, W. H. Freeman and Company, 331 p.

<sup>iv</sup> Kulhanek, Ota, 1990, Anatomy of Seismograms: Amsterdam, The Netherlands, Elsevier Science Publishers B. V.