Geophys. J. Int. (1999) **139,** 87–97

Noise levels of superconducting gravimeters at seismic frequencies

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Accepted 1999 May 10. Received 1999 April 30; in original form 1998 May 27

SUMMARY

Until recently superconducting gravimeters (SGs) have been used principally in tidal studies (periods 6–24 hr) due to their high sensitivity and low drift rates. This paper considers the performance of these instruments as long-period seismometers, particularly in the normal mode band (periods 1–54 min). To judge their suitability in providing useful information to seismology, it is important to determine their noise characteristics compared to other established instruments such as spring gravimeters.

We compare several continuously recording instruments: the SGs in Esashi (Japan), Wuhan (China), Strasbourg (France) and Cantley (Canada) and the spring gravimeter ET-19 and seismometer STS-1 at the Black Forest Observatory (BFO, Germany). We also include non-permanent instruments, the SG102 at BFO as well as the ET-18 in Metsähovi (Finland). The five quietest days out of the available records are stacked to obtain the power spectral density of the noise in the frequency band 0.05–20 mHz (50 s to 6 hr). Our reference is the New Low Noise Model designed for seismometers. Only at the BFO site were there several instruments that could be compared; even so, in order to obtain the best individual data for each instrument the records selected were not simultaneous.

The noise characteristics of the different instrument–site combinations are compared, leading to conclusions about site selection, instrument modifications and the recent potential of SGs to contribute to seismic normal mode studies. We refer to our previous work on the seismic noise magnitude, a summary statistic derived from the power spectral density which has been used to rank the performance of instrument–site combinations.

Key words: normal modes, seismic noise, superconducting gravimeter.

INTRODUCTION

Studies of the free oscillations of the Earth are based mainly on seismometers and classical spring gravimeters, which are connected in large networks such as IRIS (Smith 1987), GEOSCOPE (Romanowicz *et al.* 1984), IDA (Agnew *et al.* 1986) and DWWSSN (Peterson & Hutt 1982). Due to the activity of the Global Geodynamics Project (GGP; Crossley & Hinderer 1995), there is now a network of more than 15 superconducting gravimeters (SGs), some of which have been recording for more than a decade. Despite the slow growth in SG installations over the last decade, it is unlikely that this network will reach the density of the established networks due to limited financial and technical resources.

Several studies have shown that SGs, as acceleration sensors, can clearly record normal modes, e.g. Zürn *et al.* (1991), Kamal & Mansinha (1992), Richter *et al.* (1995a,b) and Banka & Crossley (1995). It is therefore worthwhile to investigate their characteristics in this frequency band in comparison with established instruments such as spring gravimeters.

Initially the SG was developed for investigations in the low-frequency (tidal) band (Prothero & Goodkind 1972). The low drift and high sensitivity of their design is due to the extreme stability of the superconducting currents supplying the 'magnetic' spring, compared to the metal alloy spring of a classical gravimeter. The idea is now to use this sensitivity also to record the seismic normal modes and to contribute data to the established networks. Zürn *et al.* (1991) and Richter *et al.* (1995a,b) have claimed that SGs have a higher noise level than LaCoste–Romberg spring gravimeters with electrostatic feedback in this frequency range. In these studies, as well as our own, there are legitimate concerns about whether the noise levels reflect differences between sites or differences between instruments. Naturally, our study is limited by having to accept the instruments sited where they were installed. Even within a particular category of instrument (e.g. a single model of SG) there are significant mechanical and electrical differences that will affect the noise levels we are trying to define.

In the present study, the ambient site noise and the New Low Noise Model (NLNM; Peterson 1993) are used as a reference signal to give an estimation of the quality of the site–sensor combination. With a single instrument at a site, it is not possible to separate site noise from instrument noise; from only one site (BFO) did we have several instruments to compare. Our procedure was to choose data based on the lowest individual noise spectra for single days, and it turned out that there were no common days when the data from two (or more) instruments were used. At other sites we made no attempt to choose similar days; nevertheless, we are confident in reaching several conclusions about the performance of the instruments and the contributions of site noise.

Our study is complementary to the other aspects of SG measurements; for example, it has been demonstrated repeatedly (e.g. Goodkind *et al.* 1991; Hinderer *et al.* 1994) that SGs have a very stable calibration, they have very small drift compared to spring gravimeters, and they are very sensitive (high precision). Compared to most other spring gravimeters, except installations such as the ET-19 at BFO, which Richter *et al.* (1995a) showed to be of very high quality, and certainly compared to seismometers, SGs yield the most accurate tidal amplitudes and phases. They are clearly the only type of gravimeter that can compare over intervals of years with absolute gravimeters (e.g. Lambert *et al.* 1995).

PROCESSING PROCEDURE

The processing procedure is fully described and evaluated in Banka *et al.* (1998); here it will be only briefly summarized. Compared to the older seismic data, gravimeter data are usually continuous, often for many years, and have to be processed to reduce the influence of long-period effects (e.g. tides). Seismometers attenuate low frequencies by design, and the recent IRIS broad-band data sets are also much more continuous than a few years ago. We apply the following processing steps to the various data sets where possible.

(1) Amplitude calibration with a calibration factor extrapolated from the tidal band, usually obtained by comparison with absolute gravimeters or an indirect equivalent absolute measure.

(2) Subtraction of the tides computed using an elastic reference earth model.

(3) Reduction of the influence of the air pressure with an admittance factor extrapolated from the tidal band.

(4) Subtraction of a best-fitting ninth-degree polynomial to eliminate the instrument drift and any residual tidal signal.

(5) Windowing with a 10 per cent cosine bell window, and padding by a factor of at least two before taking a fast Fourier transform (FFT). A correction is made for the data taper, assuming a white noise spectrum, and the power spectral densities are multiplied by a factor 2 to include the complex FFT at negative frequencies.

(6) The amplitude spectrum is then smoothed by an 11-point Parzen frequency window; this does not change the power spectral density (PSD) estimates.

These steps provide an objective comparison between the different instruments.

DATA ANALYSIS

Collection

At the beginning of 1995 we contacted several groups involved with instruments and requested low-noise data for the current study. One condition was that each data set should have a length of at least 1 day. We requested several days of data, with particularly low noise, from the last four years. Details of the data sets can be found in Banka (1997). SG station information is given in Crossley & Hinderer (1995) and in Wenzel *et al.* (1991), Zürn *et al* (1991) and Widmer *et al.* (1992) for the very quiet multipurpose Black Forest Observatory (BFO). All SGs are manufactured by GWR Instruments (San Diego).

Selection

The aim was to select data which have the lowest noise level for each instrument, as indicated above. From the database supplied by the operators (representing by no means all the SG sites available), those records were chosen with the least number of steps, spikes, gaps, earthquakes and other obvious noise sources such as atmospheric or oceanic noise.

Steps can in principle be removed, but there is no reliable way to estimate visually the amplitude of a step and it is dangerous to rely on automatic methods to remove steps completely (Crossley *et al.* 1993). As far as possible records with steps (and spikes) were therefore excluded.

For most spectral analyses gaps have to be replaced by simple mathematical functions or synthetic tides without noise. Because in our study the noise is the main component, it makes no sense to fill a gap with synthetic noise.

Earthquakes bring two problems. First, they can saturate the sensor and this adds artificial noise to the spectrum; second, the frequency content of seismic signals cannot always be distinguished from site or instrument noise. However, as was noted in Banka (1997), a small earthquake adds insignificant noise to an otherwise quiet record.

We very quickly established that the winter months are not suitable for our study due to high atmospheric and oceanic noise. This was one of the reasons we did not ask for specific records, but for quiet records chosen by the operator. A quiet time interval at one site can be unacceptable due to atmospheric or oceanic noise at another. Also, small local earthquakes and instrument disturbances have to be avoided on an individual site or instrument basis.

To achieve comparable conditions in terms of padding, frequency sampling, etc., a fixed record length was chosen, which also makes it possible to stack the spectra to smooth individual records. For convenience a 1 day record length was chosen.

To summarize, our selection procedure was based partly on operator expertise, since we asked for five quiet days for some of the stations, and partly on an objective measure where we had access to sufficient data ourselves. The latter circumstance enabled us to reject days with obvious visual problems and then to compute the PSD of the remaining records. The five days with the lowest overall PSD were selected for each station (see Table 1), this number (5) being the largest given to us for one of the stations, for the final stack.

Table 1. Recording periods of different stations (the length of each record is 1 day).

Site	Julian day and time (UTC) of the start of each record				
	Day 1	Day 2	Day 3	Day 4	Day 5
Superconducting gravimeters					
Cantley SG-T012	90223 00 : 00	93184 00 : 00	90219 00 : 00	90218 00 : 00	90210 00 : 00
BFO-SG102	94193 00 : 00	94219 00 : 00	94216 00 : 00	94208 00 : 00	94200 00 : 00
Strasbourg SG-T005	91173 21 : 13	92144 17 : 04	92138 23 : 04	92142 22 : 04	91176 06 : 13
Esashi SG-T007	94218 17 : 30	94223 07 : 29	94221 07 : 29	94219 17 : 30	94224 07 : 29
Wuhan SG-T004	91258 00 : 00	91257 00 : 00	91242 00 : 00	91259 00 : 00	91255 00 : 00
Earth tide (spring) gravimeters					
Metsähovi ET18	91243 00 : 00	90292 00 : 00	90300 00 : 00	91011 00 : 00	90332 00 : 00
BFO-ET19	94179 00 : 00	94174 00 : 00	94158 00 : 00	94175 00 : 00	94165 00 : 00
Seismometer					
BFO-STS-1	94215 00 : 00	94208 00 : 00	94192 00 : 00	94227 00 : 00	94224 00 : 00

Processing

Our attempt to treat the data equally failed because the sampling rates were different; therefore, the number of values in each record was different and thus also the padding. For most stations we had the tidal record of the instrument, but for two stations (Strasbourg and Esashi) only the mode output was available. This meant that there was an additional amplification factor with a non-uniform frequency response that had to be taken into account when computing and subtracting the synthetic tides.

Ideally, one should correct for the instrument response first, before performing the tidal subtraction and the atmospheric correction, which most people assume is similar at seismic frequencies to tidal frequencies. Because the mode output response is somewhat uncertain, we could not correct for it accurately enough to permit a pressure correction.

The STS-1 seismometer has a frequency-dependent transfer function that should be subtracted before doing any processing such as tidal subtraction and atmospheric pressure subtraction. We did not apply this correction before processing and so did not subtract tides or correct for air pressure. Even though Zürn & Widmer (1995) have noted that air pressure corrections were not as significant for the STS-1 as for the ET-19 (the same instruments that we were using at BFO), an air pressure correction would reduce even more the noise for the STS-1. Note that the STS-1 transfer function was corrected for in the spectral domain before we computed the final noise spectrum (Fig. 1). The effect of different processing steps was tested for an SG using 1 day of data from Cantley (Banka *et al.* 1998).

Air pressure data from a gravimeter station is often included as an extra channel of information in tidal analysis where the tidal amplitudes and phases have to be determined from the data. Once a tidal model for a site is known, the tides can to a good approximation be subtracted, although time variations in ocean loading and air pressure effects usually leave small residual tidal signals, and the air pressure effect can be treated separately. For seismic normal mode studies, atmospheric pressure can either be removed as for tidal studies or considered as broad-band site noise, although we have shown that neglecting the air pressure correction does not significantly change our noise estimates (Banka *et al.* 1998).

A study by Beauduin *et al.* (1996) showed that a pressure correction reduced part of the noise in the normal mode band of two GEOSCOPE seismic stations. For seismometers and spring gravimeters in particular, the effectiveness of this correction depends critically on the quality of the site and instrument; not every situation will show a clear improvement.

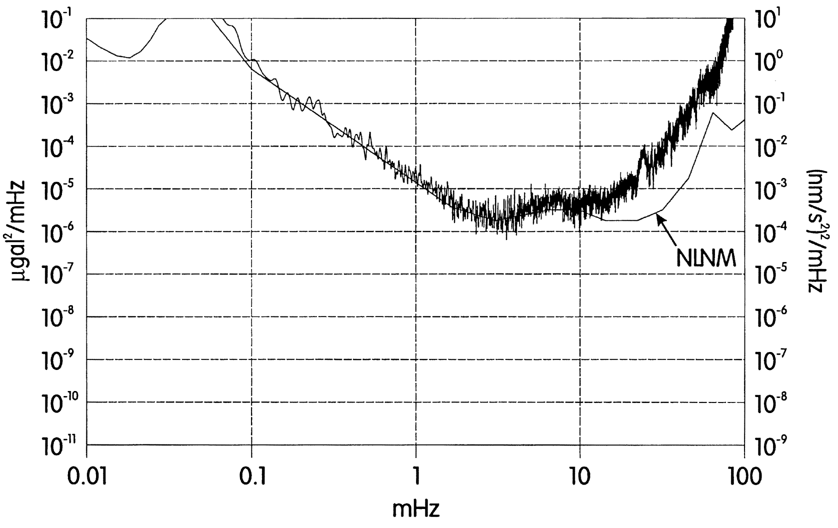

Figure 1. PSD of five quiet days at the Black Forest Observatory, Germany, recorded with a Streckeisen STS-1 seismometer.

Calibration

Gravimeter calibration factors were originally determined by comparisons with either raw data from absolute gravimeters (Hinderer *et al.* 1991; Bower *et al.* 1991) or tidal analysis of data from relative gravimeters (Sato *et al.* 1994). The disadvantage of both methods is the dominance of the M_2 tide (≈ 12 hr period) that determines the single calibration factor.

We assume that at seismic frequencies the calibration factor can be extrapolated from the appropriate filter functions supplied by the manufacturer (GWR-Manual 1985). Richter (1995) showed that the calibration of spring gravimeter LCR-D009 was within 1 per cent from 200 to 900 s, but no direct extension to tidal frequencies has yet been carried out for any gravimeter. The transfer functions of the STS-1 seismometers are similar, as they are for the SGs, so it is unlikely that assumptions about this extrapolation will affect our conclusions.

The additional amplification of the mode output requires an adjustment of the calibration factor, and the high-pass filter used in Strasbourg and Esashi means that frequencies lower than 0.833 mHz are not reliable.

The output of the Wielandt STS-1 seismometer is essentially a velocity, but with a non-constant transfer function, given in the frequency domain; the output can be converted to acceleration. In this case the calibration was the last step.

Subtraction of synthetic tides

As mentioned, we subtracted synthetic tides for an elastic reference earth model using the program GTIDE (Merriam 1992), including the free core nutation correction, using 3070 waves, but without local or ocean tides. The residuals had amplitudes of 1–2 μgal (10–20 nm s^{-2}). For mode data, the synthetic tides were subtracted and reduced by a factor of 1/213 to take into account the high-pass mode filter. As indicated earlier, for the STS-1, due to the frequency-dependent transfer function that rolls off the tidal frequencies, we did not subtract a model synthetic tide; tidal residuals were present only at the 1–2 μgal level.

Air pressure correction

For tidal analysis the air pressure correction is important. Hourly atmospheric pressure typically has a standard deviation of ~ 10 mbar, which leads (see below) to gravity variations of ~ 3 μgal. These are significant in high-precision tidal analysis when looking for small waves. In gravimetry, pressure is often recorded at a much lower sampling rate than the gravity signal and occasionally it may not be recorded at all (although this is less and less common). We (see Banka 1997) confirm the experience of other groups (e.g. Zürn & Widmer 1995) that the air pressure can influence noise in the normal mode band. Obviously, this correction will be more important where the site and instrument quality are high. Only where the data were available, the correlation with gravity was high and the admittance was reasonable did we perform an air pressure correction.

For Esashi, Sato *et al.* (1994) gave an admittance of -0.373 μgal mbar^{-1} (-3.73 nm s^{-2} hPa^{-1}); for Cantley it is -0.322 μgal mbar^{-1} (Hinderer *et al.* 1994), and Richter *et al.* (1995a) obtained -0.328 μgal mbar^{-1} for the SG102 and -0.337 μgal mbar^{-1} for the ET-19. Although at BFO the instruments are at the same site, they seem to have a slightly different admittance factor, even though this should not depend on the type of instrument used. For most data sets a nominal admittance of -0.3 μgal mbar^{-1} should be suitable for the air pressure correction in the seismic band.

Residual tides and instrumental drift

A ninth-degree polynomial is used to remove the remaining low frequencies due to tides and instrument drift. Experiments were made using lower-degree polynomials, but undesirable large amplitudes were left at the beginning and end of the residual series. With a ninth-degree polynomial four oscillations can be modelled, which corresponds to an oscillation with a 6 hr period—at the limit of the frequency range for this study.

Spectral analysis

We took the FFTs, as discussed previously, of the five quietest days for each station (Table 1). These were than averaged before computing the smoothed PSD.

RESULTS

We discuss the mean PSD of all the instrument–site combinations in three period ranges.

Short periods: 2 s–5 min (3.3–500 mHz)

This part of the spectrum includes the two minima of the NLNM, the increasing noise at high frequencies and in some cases the roll-off of the anti-aliasing filter.

The NLNM and the spectrum of the STS-1 (Fig. 1) agree very well; even the small maximum around 8 mHz is visible. At higher frequencies the anti-aliasing filter begins around 45 mHz but this is not apparent for either the seismometer or the NLNM as they are compensated by their transfer functions. The small maximum is also visible in the record of the spring gravimeter ET-19 at BFO (Fig. 2).

All the other sites are too noisy to show the small maximum between 5 and 10 mHz and the PSDs are more or less flat in this frequency range. The standard, original GWR tidal filter has a corner frequency at ~ 12.5 mHz (80 s), so there is no advantage in recording at a sampling interval shorter than 16 s.

The Esashi record (Fig. 3) shows a strong peak at ~ 10 mHz, and a similar peak can be seen in the Cantley record (Fig. 4). These peaks are undoubtedly the sphere resonance of SGs (Zürn *et al.* 1995), this mode being excited by horizontal artificial disturbances such as helium refills. Nevertheless, we chose to include one of these days for Cantley because its noise level is otherwise very low. At Esashi this resonant mode is present in all our records and, according to R. Reinemann at GWR (personal communication, 1995), is continuously excited by an interaction between the refrigeration tubes and the gravimeter.

In Cantley only the tide output is sampled, but with a modified analogue filter (with a corner period of 6.2 s) to permit full use of the 1 s data sampling. These data are filtered

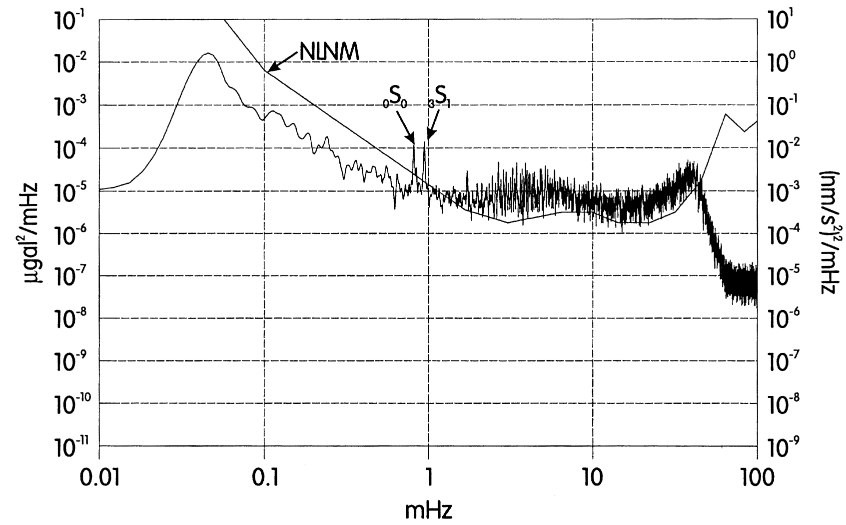

Figure 2. PSD of five quiet days at the Black Forest Observatory, Germany, recorded with the LaCoste–Romberg Earth tide gravimeter ET-19.

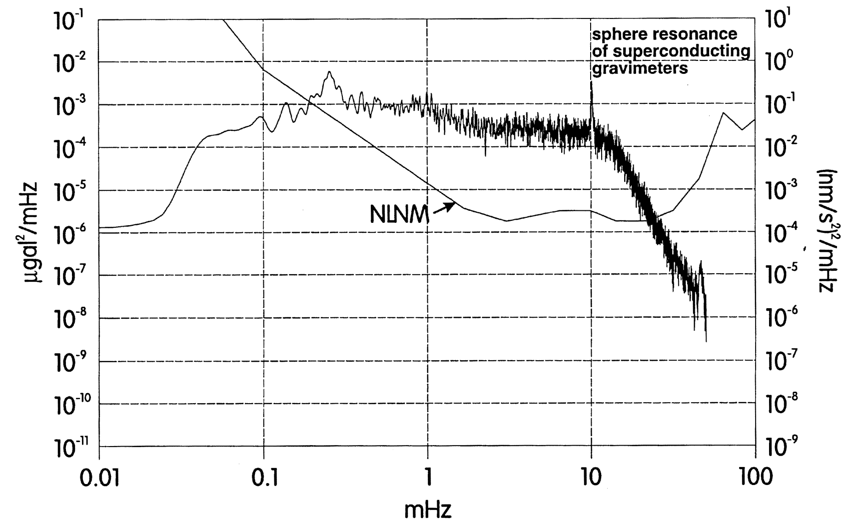

Figure 3. PSD of five quiet days at Esashi, Japan, recorded with SG-T007.

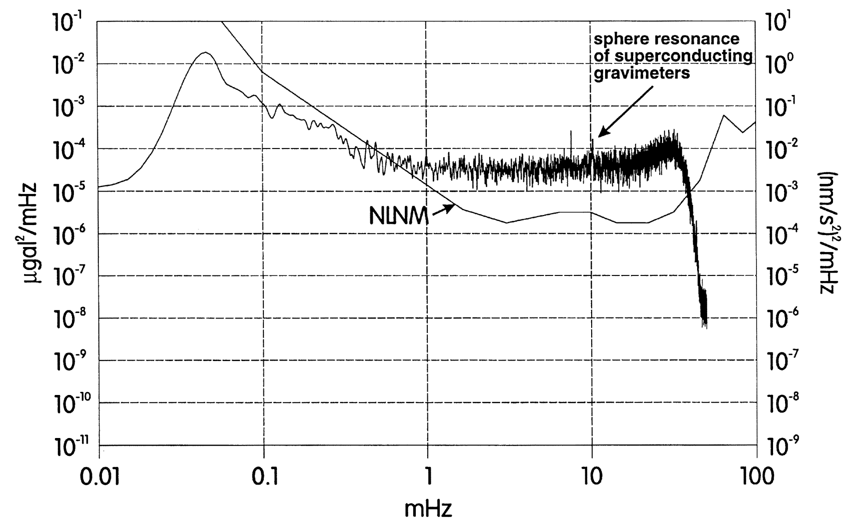

Figure 4. PSD of five quiet days at Cantley, Canada, recorded with SG-T012.

with a Chebyshev filter (with a cut-off period of 40 s) and decimated to 10 s. The effect of the Chebyshev filter with a corner frequency of 25 MHz can be seen in Fig. 4.

In Wuhan (Fig. 5) and Metsähovi (Fig. 6) different data acquisition systems were used. The A/D conversion performed an integration directly on the raw analogue data, without any filter. Subsequently, the data were filtered with a digital low-pass filter with a cut-off period of 30 s and stored at 20 s samples (Asch 1988). Because there is no analogue anti-aliasing filter, phase shifts are avoided. The feedback system of the ET-18 has a time constant of ~10 s, so that there are only minor problems to be expected. There are, however, a number of problems with 10 s integration that can be shown to cause aliasing and increased noise levels in our processing. For details we refer to Banka (1997).

Intermediate periods: 5–24 min (0.69–3.3 mHz)

It is obvious that Wuhan, China, is the noisiest site (Fig. 7), which confirms the work of Jentzsch & Melzer (1991). The data for a typical day shows a dramatic difference between the day and night hours (Banka 1997). At night the noise level is comparable to the SG record at BFO, whereas during the day large one-sided spikes dominate the record. This noise is of cultural origin and is the reason this instrument has now been relocated to a new site outside the city (Hsu, personal communication, 1997).

In the records of Esashi, Metsähovi and Strasbourg such clues are not visible and one must assume that these noise levels (Figs 3, 6 and 8) are due to their locations. For example, in comparing Strasbourg (Fig. 8) with Metsähovi (Fig. 6), one can see that they have similar medium noise levels, but one is an SG and the other a spring gravimeter. It needs to be stated that the full-sized SG instrument at Strasbourg used in this study has now been replaced by a newer compact SG with much improved noise characteristics. A new analysis for this site should be performed, and we anticipate that Strasbourg would probably now be included with BFO and Cantley (below) as a low-noise site.

The last group, BFO and Cantley, can be called the low noise sites (Fig. 9). If several instruments are recording at the same site, one assumes the noise differences are generated

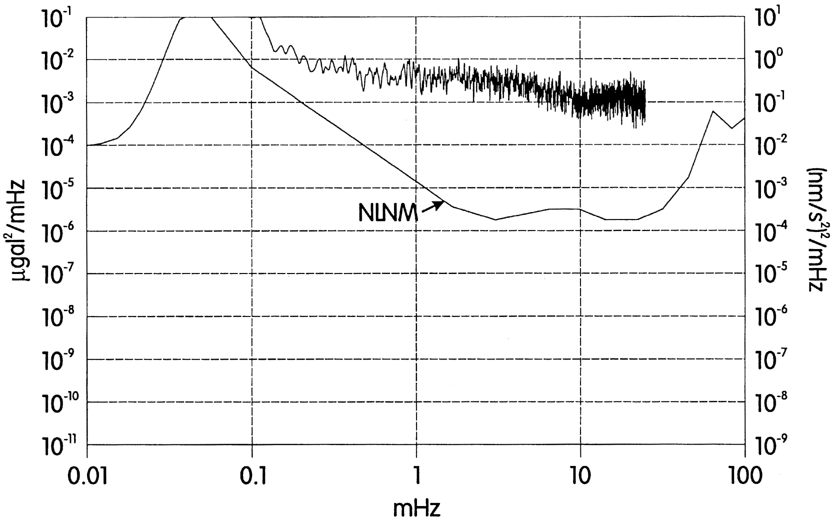

Figure 5. PSD of 5 quiet days at Wuhan, China, recorded with SG-T004.

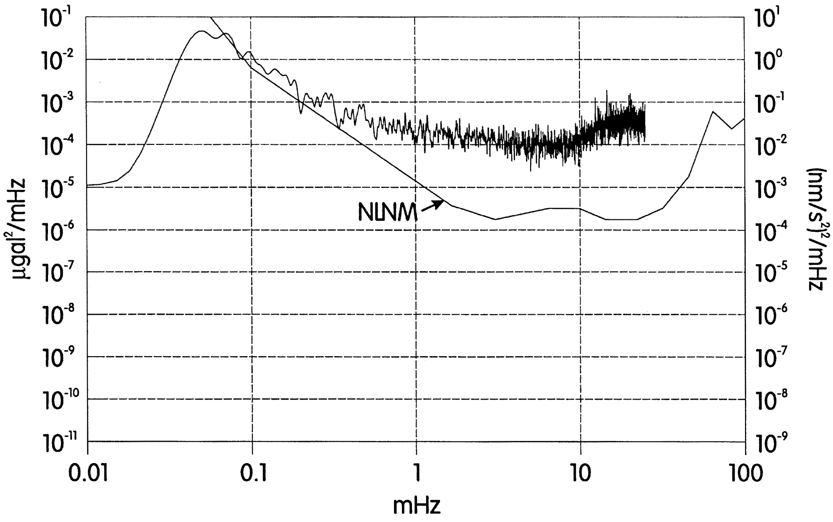

Figure 6. PSD of five quiet days at Metsähovi, Finland, recorded with Lacoste–Romberg Earth tide gravimeter ET-18.

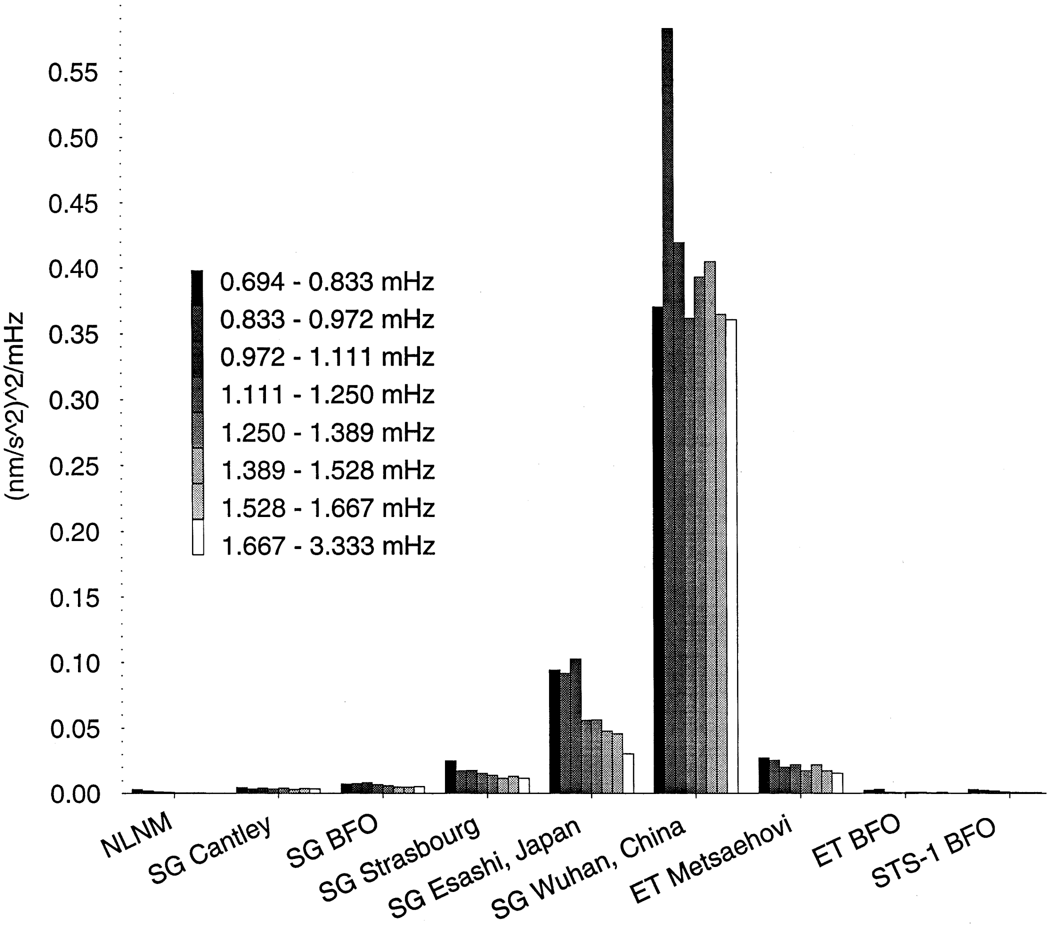

Figure 7. Comparison of mean PSD in various frequency bands from a stack of five quiet days, all noise levels.

by instrumental effects, as should be the case for the SG and spring gravimeters at BFO. The SG102 was added to the installation at BFO for only a short time period. This SG has a half-sized sensor with a 50 l dewar (the standard instruments have 200 l dewars), but without a refrigeration system, and is supposed to meet the same specifications for sensitivity, stability and drift as the large instruments. This was a prototype instrument, at that time still under evaluation (Richter *et al.* 1995a,b), and was manufactured with a smaller sensor in a set of only three (SG101, 102 and 103). The next generation of compact instruments (e.g. designated C024, van Dam & Francis 1998) all have a full-size (original) one inch sphere.

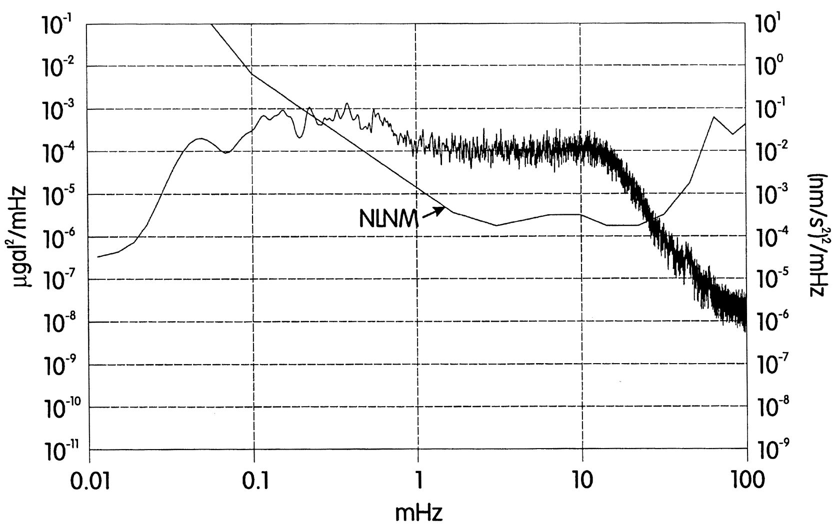

Figure 8. PSD of five quiet days at Strasbourg, France, recorded by SG-T005.

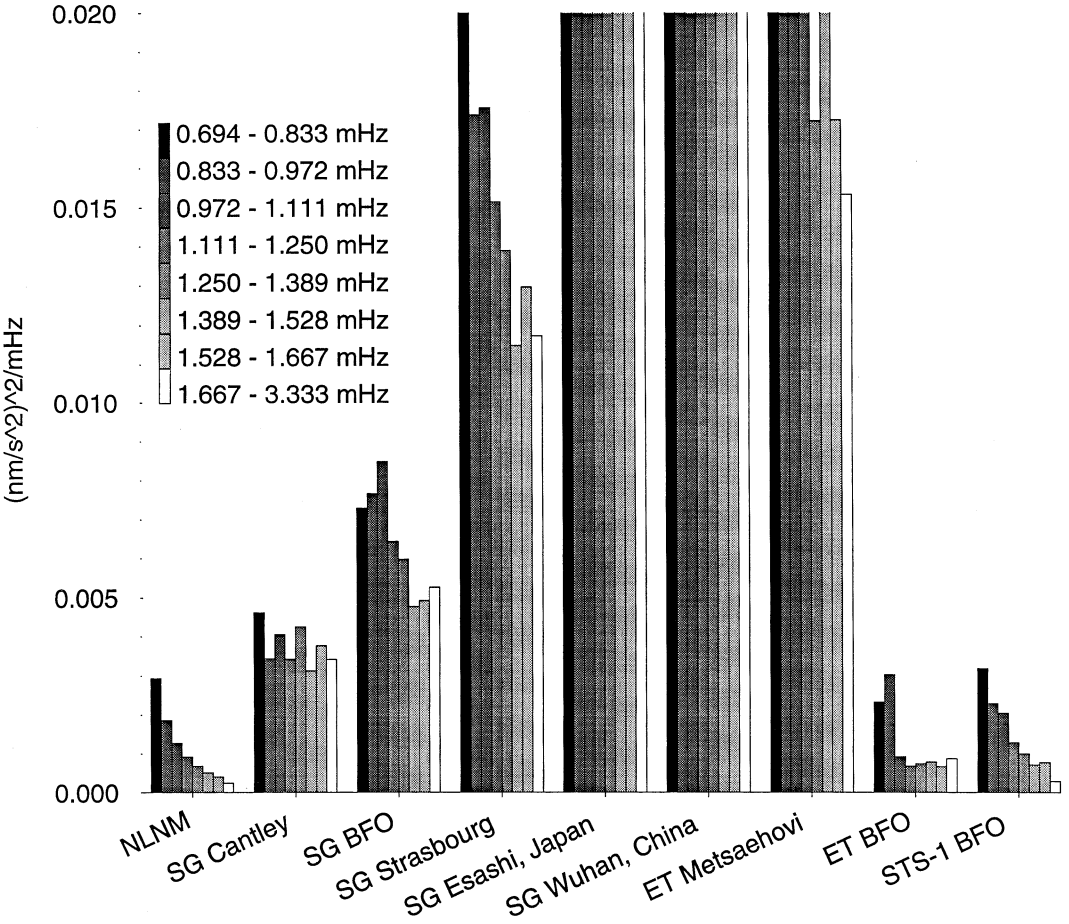

Figure 9. Comparison of mean PSD in various frequency bands from a stack of five quiet days, low noise levels.

Assuming the same NLNM (shown in Figs 1–10) at both Cantley and BFO, one might conclude that the SG at BFO has a higher instrument noise than that at Cantley, probably due to the fact that the sensor sizes are different. If so, this would indicate that the larger sensor is less noisy than SG102. Nevertheless, the Cantley instrument still has a higher noise level than the spring instruments at BFO, as can be seen by comparing the stacked spectra shown in Figs 1 and 4 (plotted to the same scale). The average PSD level in the selected band is obviously different from instrument to instrument. As an example, comparing the BFO and Metsähovi spring gravimeters, small signals, clearly visible at BFO around 1 mHz, would be below the noise level at Metsähovi.

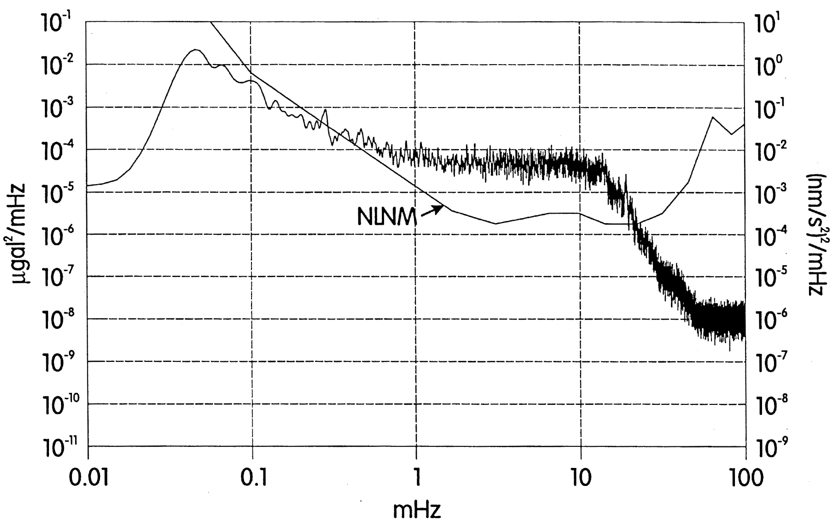

Figure 10. PSD of five quiet days at the Black Forest Observatory, Germany, recorded with GWR superconducting gravimeter SG-102.

The spectrum of ET-19 shows peaks at 0.943 and 0.813 mHz (21 and 17 min respectively) that come from one of the five selected days following the deep Bolivian earthquake (6.9 mb). This earthquake occurred 5 days previously (94160, see Table 1). These are the high-Q modes ${}_3S_1$ and ${}_0S_0$ respectively that were strongly excited due to the depth of the event. The other modes had already decayed into the residual signal, which shows that the tail of a large deep earthquake does not necessarily contribute to a high broad-band noise level. This day was still one of the quietest available by our PSD criterion.

Long periods: 24 min–5.5 hr (0.05–0.69 mHz)

In this frequency band between the tides and the middle of the normal mode band, the high-pass filter of the mode output comes into effect, so not all stations can be used for a comparison in this frequency band; in particular, Esashi (Fig. 3) and Strasbourg (Fig. 10) have to be excluded.

The NLNM shows an increasing noise level at lower frequencies, which is true of all stations and is generally attributed to atmospheric pressure fluctuations (Jensen *et al.* 1995). Naturally, the STS-1 fits the model very well because it is a seismometer, and the NLNM is based on seismometer data. At the other stations the noise levels are lower than the NLNM because they are based on gravimeters which perform better in this frequency range. Furthermore, it is possible to subtract the tides and atmospheric pressure from the gravimeter records, whereas they are included within the NLNM.

Instrument–site noise comparison

For high signal-to-noise ratios in the normal mode band it is obviously important to have quiet sites. The example of Wuhan shows the necessity of locating instruments far from cultural interference. The SG at Cantley is located 20 km outside Ottawa, the nearest large city, and this distance should be valid for most GGP sites, depending on the main industry (a heavy industrial area will need a greater distance). Also, a distance of a few kilometres from major transportation routes (main highways, railroads and runways) is necessary.

Strasbourg shows the problem of a site located on the sediments of the Rhine valley, at the boundary of a forest. At tidal periods the site noise is comparable to Cantley (Hinderer *et al.* 1994), but at high frequencies it is noisier. Clearly, bedrock would be a better solution. In Esashi there is a strong resonant mode excitation caused by the gravimeter frame, in addition to strong disturbances by local earthquakes and oceanic noise. Of course, it is not possible to avoid all noise sources without reducing the coverage of gravimeter sites that have convenient access from scientific support institutions. As indicated previously, some of the problems with the Strasbourg noise levels were undoubtedly due to the instrument, because data from the newer SG installed there shows some improvement (see Hinderer *et al.* 1998).

One reason why the SG at BFO was installed only temporarily was the problem of helium refills. Because of the airlock in the chamber, refills were found to generate disturbances of the other instruments in the observatory; additionally, the outgassing helium forces the breathable air out of the mine. Therefore, one should operate the SGs only in chambers which are large enough, and reduce the time between refills, as is the case for the more recent designs. One advantage of BFO is the integration of the SG with other instruments for data acquisition, including high sample rate pressure data.

The seismic noise magnitude

Elsewhere (Banka 1997; Banka *et al.* 1998; Crossley & Xu 1998) we have introduced a summary statistic that can be derived from the PSD. This we called the seismic noise magnitude (SNM), a quantity that is based on a narrow window of the normal mode band between 200 and 600 s. By taking the log of the PSD and normalizing it so the NLNM is zero, we are able to use a single figure that acts as a quality factor for site–instrument noise.

Such a measure clearly contains much less information than the spectra presented in Figs 1–6, but in some cases it might be useful in quickly comparing the high-frequency performance of accelerometers. We refer the reader to the papers quoted above for more details.

CONCLUSIONS

Stacked spectra of quiet days at different sites were compared. It can be seen that BFO is a very low-noise site and that the small SG (Fig. 10) has a significantly higher noise level than the spring instruments. Comparing the noise spectra (Figs 1 and 4) of Cantley and BFO demonstrates that the full-size T012 at Cantley has a lower noise level than the small sensor prototype SG102 at BFO.

Looking at the noise levels of the other instruments and sites, it can be seen that at most SG sites the instrument potential is not fully exploited, because of the following:

(1) problems in the data acquisition systems, e.g. aliasing, insufficient resolution;
(2) site location, including cultural and tectonic noise (earthquakes);
(3) site noise, e.g. location on sediments rather than bedrock, or the presence of trees;
(4) signal treatment (filtering, etc.).

In Strasbourg and Esashi we might speculate that using the mode output and its additional amplifier is detrimental to this study. For the ET-18 in Metsähovi and especially for the Wuhan SG there are clearly doubts about the data acquisition systems. According to G. Jentzsch (personal communication, 1995) these data acquisition systems have subsequently been changed (for the ET-18) and for Wuhan with the installation at a new site. We anticipate that with the new installation of the Wuhan SG, the cultural noise will disappear.

Two further remarks should be made concerning the processing. In this study a constant calibration function for all the gravimeters was assumed. Richter *et al.* (1995c) have shown, by accelerating an SG artificially with different frequencies in this band, that the calibration factor decreases towards higher frequencies, that is, the instrument becomes less sensitive due to the anti-aliasing filter. Only if we assume that this effect is similar for all SGs would the results of our intercomparison remain unchanged.

What does the present study say about the performance of these instruments in the Slichter mode (subseismic) band? Assuming PREM values of the inner core–outer core density jump, the Slichter periods should be about 5.4 hr, i.e. ~0.04 mHz, as computed by Crossley *et al.* (1992). As can be seen from the spectra (Figs 1–6), the NLNM increases significantly at such periods compared to the normal mode band, and so do the apparent noise levels of seismometers and spring gravimeters, due probably to atmospheric pressure effects. Using our restricted data length (1 day) it is not possible to determine with confidence the noise level at such periods; rather, one should use quiet records of several days or weeks—these are of course difficult to find. Pillet *et al.* (1994) examined the performance of STS-1 seismometers, demonstrating that they can be used for tidal studies, albeit with some reservations. More recently, Freybourger *et al.* (1997) concluded that seismometers do not perform as well as gravimeters at subseismic periods because they have poorer temperature regulation.

Our study has confirmed that of Zürn *et al.* (1991) and shows that a well-sited and well-maintained seismometer or spring gravimeter is still superior to the best SG examined to date in the long-period seismic normal mode band. Bearing in mind their other strengths, however (mentioned in the Introduction), we still claim that the overall performance of SGs at periods from minutes to years is unmatched by any other instrument.

ACKNOWLEDGMENTS

We acknowledge the support of the Canadian Superconducting Gravimeter Installation by the National Science and Engineering Research Council of Canada. DB was supported by the Government of Canada Awards and by grant JE 107/26-1 from the German Research Society (DFG) and DC supported through the NSF.

We would like to thank all the operating groups for making the data available to us: Y. Tamura for the Esashi data, C. Kroner and G. Jentzsch, who also provided helpful unpublished background information about their sites and instruments, for the Metsähovi and Wuhan data (for the Wuhan data, we also thank H. Hsu), J. Hinderer for the Strasbourg data, and for the BFO data, R. Widmer and W. Zürn, to whom we are also grateful for several interesting discussions.

Finally, our paper was subject to careful reviews by three referees, one of whom we know to be Walter Zürn, that enabled us to improve the paper significantly.

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