ELSEVIER

Physics of the Earth and Planetary Interiors 101 (1997) 203–217

PHYSICS
OF THE EARTH
AND PLANETARY
INTERIORS

Comparative study of superconducting gravimeters and broadband seismometers STS-1/Z in seismic and subseismic frequency bands

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Received 5 June 1996; accepted 2 January 1997

Abstract

Superconducting gravimeters and broadband seismometers (vertical component) both measure gravity, but whereas the former are most sensitive to very long period signals (gravity tides with periods longer than 6 h), the latter are designed for recording the seismic band (elastic normal modes with periods shorter than 1 h). We investigate here the behaviour of each type of instrument in the spectral band where it is not generally used. More precisely, we compare the French superconducting gravimeter, located at Station J9 near Strasbourg, and the vertical component of an STS-1 seismometer located in a mine at Echery (ECH) in the Vosges, about 70 km away. Two different frequency bands are considered: the seismic band (frequencies between 0.2 and 1.667 mHz), for the study of normal modes after the Bolivian earthquake of 9 June 1994, and the subseismic band (frequencies lower than 0.2 mHz), including the study of gravity tides. The analysis of Fourier amplitude spectra and power spectral densities shows the obvious result that the broadband seismometer is more sensitive than the superconducting gravimeter in the seismic band because of a lower noise level, whereas the reverse is true in the subseismic band. The poorer quality of the gravimeter record in the seismic band is probably due to site effects (sediments vs. bedrock) rather than of instrumental origin. In contrast, the higher noise level of the seismometer in the subseismic band is probably due to the temperature response of the instrument. It is expected that operating the STS-1 isothermally, or recording on-site temperature changes for correction will considerably improve its signal-to-noise ratio in the subseismic band. In comparison with recent mean models of high and low seismic background noise levels, both instruments nevertheless indicate low noise levels at all frequencies. © 1997 Elsevier Science B.V.

1. Introduction

Cryogenic gravimeters have a rather large spectral domain of investigation ranging from the seismic band (say 1 Hz) to frequencies lower than 1 cycle year^{-1} (annual and Chandlerian terms in polar motion) and are therefore an excellent tool for the study of global dynamic problems of various origin, such as inner and outer core oscillations, and tides, including atmospheric, oceanic and rotational contributions (see Crossley and Hinderer (1995) for a review). On the other hand, STS-1 broadband seismometers (Wielandt and Streckeisen, 1982; Wielandt

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PII S0031-9201(97)00003-4

and Steim, 1986) are most sensitive to the elastic normal mode spectrum for periods shorter than 54 min, the period of the fundamental spheroidal degree 2 mode ($_0S_2$). Recently, much effort has been invested in the detection of core modes in the subseismic band with periods between 1 and 6 h (Hinderer and Crossley, 1993; Smylie et al., 1993; Hinderer et al., 1995; Jensen et al., 1995). The geodynamic implications of the detection of the Slichter mode (translational mode of the inner core) would be considerable. Unfortunately, its expected amplitude is very low (less than 1 ngal) and should be found at periods of several hours. Despite an initial claim of detection in a stack of four records from European superconducting gravimeters (Smylie, 1992), no clear observation has been made to date (Hinderer et al., 1995; Jensen et al., 1995). The quarter-diurnal tidal observations are a good sensitivity test for the various instruments. The amplitude (less than 5 ngal) and period (around 6 h) are well known, and long records (several years) from the French and Canadian superconducting gravimeters allow us to observe it (Florsch et al., 1995a). An alternative to long time series are stacking techniques which exploit the spatial coherency to improve the signal-to-noise ratio (SNR). Cummins et al. (1991) showed that the stacking of 11 IDA LaCoste and Romberg gravimeters achieved the noise level of one superconducting gravimeter. Stacking techniques are widely used in seismology as well; for instance, for the search of global seismic discontinuities (Shearer, 1991). Compared with superconducting gravimeters (at present, there are 18 of these in the world; see Crossley and Hinderer (1995)), the world-wide density of broadband seismometers is very high (more than 150). If seismometers had sufficient detection capability in subseismic bands, stacking of numerous records (of gravimeters and seismometers) might exhibit very low amplitude subseismic signals.

A first attempt to use broadband seismometers outside their traditional spectral range was made by Pillet et al. (1994), and they showed that the STS-1 is able to retrieve strong tidal signals around diurnal frequencies. An attempt to use superconducting gravimeters in the seismic band was recently made by Richter et al. (1995), who compared the SNR of records of the Bolivian earthquake of 9 June 1994 on various instruments including an STS-1 and a (prototype) cryogenic gravimeter. Another comparative study between cryogenic and spring gravimeters was done by Zürn et al. (1991) and led those workers to the conclusion that the cryogenic gravimeters are superior to spring gravimeters for retrieving long-period phenomena only because of their lower instrumental drift. The previous comparative studies between cryogenic gravimeters and broadband vertical seismometers did not focus on the subseismic band. This is why we propose here to further investigate the respective performances of a cryogenic gravimeter and a broadband STS-1 seismometer (vertical component) over a wide spectral range (from the seismic band to long-period phenomena). Section 2 is devoted to the description of the instruments and the data sets used in the comparison. Section 3 shows the results in the seismic frequency band, and Section 4 deals with the results of the comparison in the subseismic band for periods longer than 1 h. The power spectral densities of the noise content of both instruments are given in Section 5. We evaluate the frequency limit up to which a local pressure correction is efficient in reducing the noise on the superconducting gravimeter, and speculate that a temperature correction will be most effective to reduce the long-period noise on the broadband vertical component seismometer.

2. Instruments and data

In this comparative study, we consider data from two instruments of completely different types: on one hand, a superconducting gravimeter built by GWR Instruments (San Diego, CA, USA, Model TT70) and, on the other hand, the vertical component (Z) of an STS-1 seismometer built by G. Streckeisen AG (Pfungen, Switzerland). Although both instruments measure an electrical signal to generate a feedback force which opposes changes acting on an inertial mass, they are different in several aspects. Superconducting gravimeters use an electrostatic capacitive device to detect the vertical position changes of a superconducting sphere levitating in a highly stable magnetic field. A magnetic feedback force maintains the sphere in a fixed position. The transfer function for the superconducting gravimeter is proportional to acceleration from d.c. to 10 Hz. The feedback voltage is converted to gravity by a scale factor obtained from an in situ calibration experiment with an absolute gravimeter (Hinderer et al., 1991). The voltage passes through an anti-aliasing analogue filter with a cut-off period of 50 s and a slope of 36 dB per octave before digitisation at 2 s (TIDE channel).

The STS-1/Z sensor is a vertical leaf spring pendulum in which the mass is always kept close to its neutral position by an electrically generated restoring force. As electromagnetic transducers have a very large dynamic range, the same applies to the output signal. Practically, the dynamic range is only limited by the ability to measure the feedback current. We use the VBB (very broadband) version of the STS-1, whose response is proportional to velocity following a modification by Wielandt and Steim (1986) of the original BRB (broadband) version, whose response was proportional to acceleration. As shown in Fig. 1, there is a difference in gain between HGLP (high gain long-period) and VLP (very long period) channels.

The two instruments are located at two sites sufficiently close so that the gravity signals we are interested in are comparable in waveforms and amplitudes: the superconducting gravimeter is located at Station J9 (about 10 km from Strasbourg, France), and the broadband seismometer is located at Station ECH (Echery, France), in a mine less than 70 km away from J9. Considering the wavelengths of the signals (e.g. about 20 000 km for the fundamental mode ${}_0S_2$), the ground displacement at the two stations is indeed very similar.

Each record of the STS-1/Z is corrected for the instrumental response to recover ground acceleration in μgal (1 μgal = 10^{-8} m s^{-2}). The sampling rate of the gravity data is 5 min (after on-site numerical decimation from the raw 2 s sampling) and the seismic record is decimated from its original sampling rate (1 s for HGLP channel, 10 s for VLP channel) to the same rate using appropriate anti-aliasing filtering.

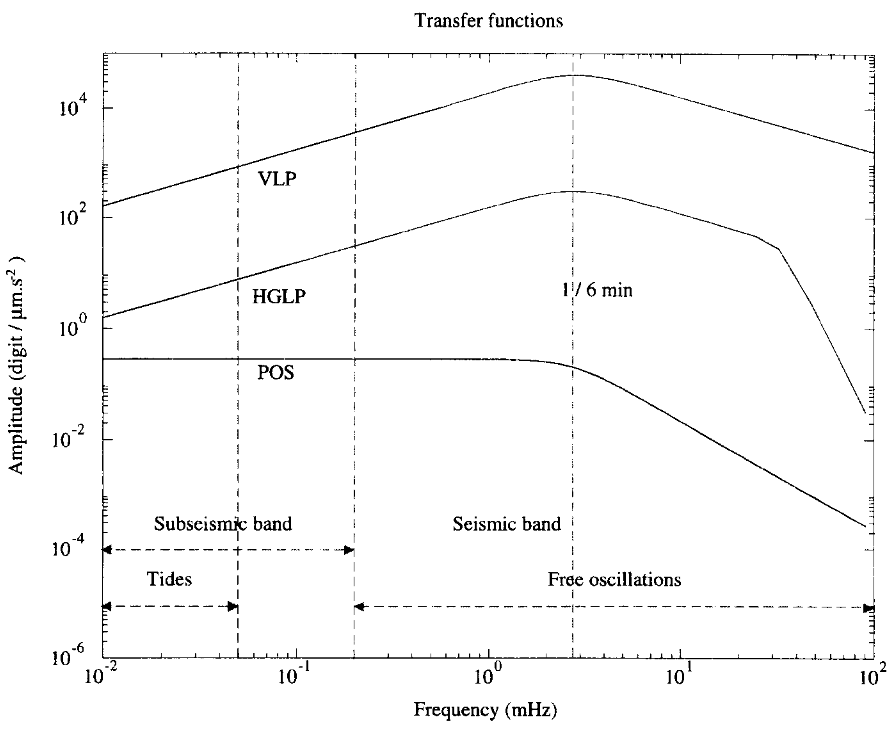


Fig. 1. Transfer functions in acceleration of the different channels of the ECH broadband seismometer STS-1/Z: HGLP, VLP and POS channels. In the bands of interest (frequencies lower than 1.667 mHz, or periods longer than 10 min), the transfer functions of HGLP and VLP channels are linear in frequency, with a unit slope (even up to 2.777 mHz, i.e. from d.c. to 6 min period).

3. Comparison in the seismic frequency band

We compare the performances of the superconducting gravimeter (TIDE channel) at J9 and the broadband seismometer STS-1/Z (HGLP channel) at ECH in the seismic frequency band (between 0.2 and 1.667 mHz, i.e. 1/83 min and 1/10 min). One of the goals is to evaluate the SNR of the two instruments for the free oscillations of the Earth generated by the Bolivian earthquake of 9 June 1994. This part of the study is very close to that of Richter et al. (1995), who compared various instruments (including a prototype cryogenic gravimeter and a STS-1/Z) at the Black Forest Observatory (BFO). We have chosen to take the BFO data as a reference to evaluate the J9 and ECH data, because of the well-known low level of background noise at BFO. The proximity of the three stations, which are less than 70 km apart, justifies such a comparison. We compare the records of the two gravimeters (at J9 and BFO), and the two seismometers (at ECH and BFO). Similarly to Richter et al. (1995), we use an 80 h common time interval which begins 5 h after the earthquake. The data of J9 and ECH are shown in Fig. 2. A theoretical tidal signal is computed for each station site, for the time interval considered and with the sampling rate of the data from the tidal potential development of Tamura (1987) with 1200 waves. These theoretical tides are subtracted from the original data. The residuals are discrete Fourier transformed, after multiplication by a Hanning window.

Fig. 3 shows the four amplitude spectra (in μgal).

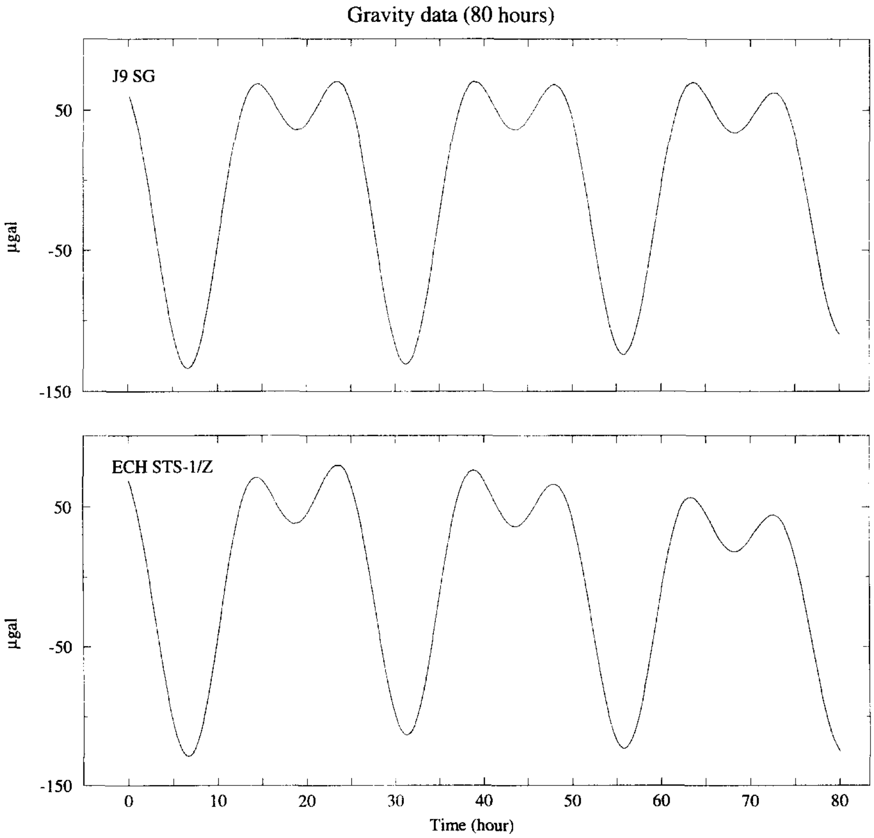


Fig. 2. Time fluctuations of gravity signals (in μgal) (80 h records starting about 5 h after the Bolivian earthquake of 9 June 1994) recorded by the J9 superconducting gravimeter (SG) and the ECH broadband seismometer STS-1/Z. For the gravimeter we show the raw gravity signal; for the seismometer we show the signal after deconvolution of the output by the instrument response in acceleration. We see that the very energetic diurnal and semi-diurnal gravity tides that have sufficiently long wavelengths (about 20000 km) are very similar at Stations J9 and ECH, which are only about 70 km apart.

The theoretical eigenfrequencies of the observed modes calculated for Earth Model 1066A (Gilbert and Dziewonski, 1975) are shown by vertical dotted lines. The amplitudes cannot be directly compared with each other, because the effects of the different anti-aliasing filters applied to the various records have not been removed, and thus only the SNR are significant. As expected, there are strong similarities in the four spectra; for instance, the peak corresponding to the modes ${}_1S_3$, ${}_3S_1$, ${}_2S_2$ has the largest amplitude in this frequency band for this time window and this seismic event; the mode ${}_1S_4$ is clearly split by rotation and ellipticity effects, and the radial mode ${}_0S_0$ is hardly excited above the average noise level.

The SNR are smaller for all peaks in the seismic band for the record of the J9 gravimeter. For instance, if we consider the peak related to the mode

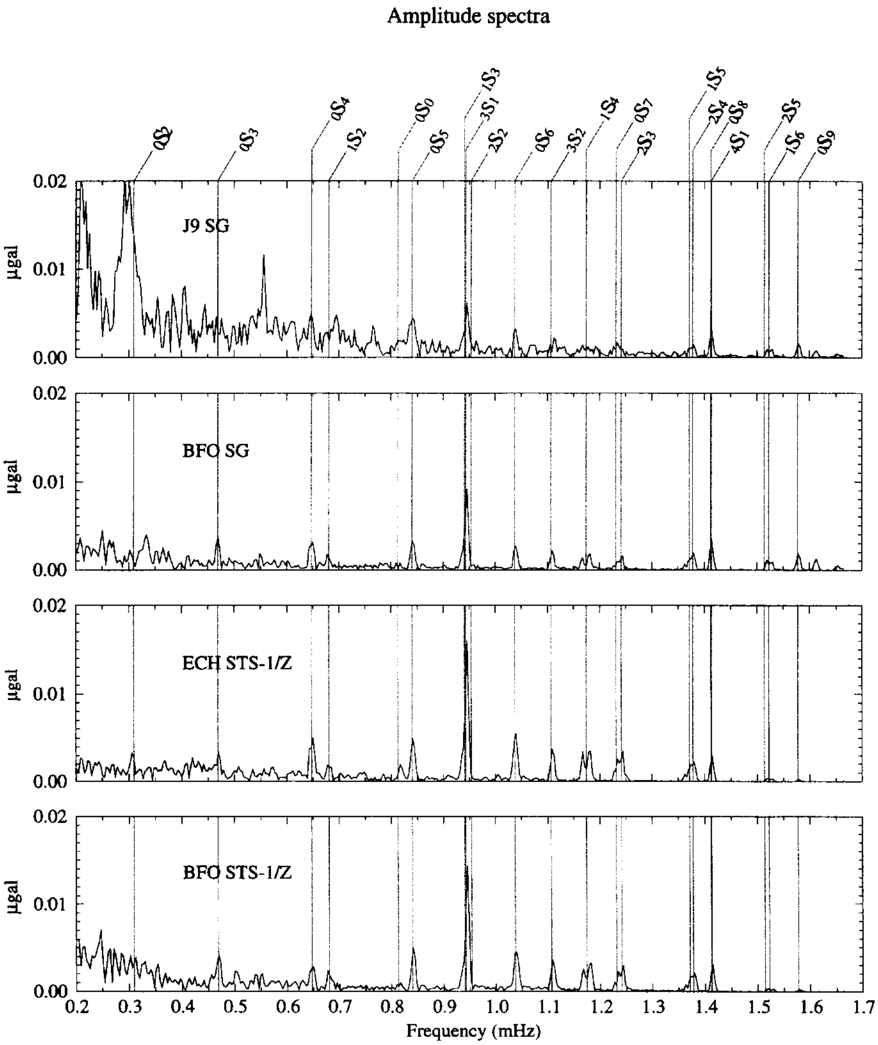


Fig. 3. Amplitude spectra of the 80 h records after the Bolivian earthquake from the J9 and BFO superconducting gravimeters (SG), and the ECH and BFO broadband seismometers STS-1/Z. BFO spectra (from Richter et al. (1995)) are used as references to evaluate J9 and ECH spectra. Vertical dotted lines indicate theoretical eigenfrequencies for some modes from Earth Model 1066A (Gilbert and Dziewonski, 1975).

$_3S_1$, the SNR at J9 is about five times smaller than in the other three spectra. The gravity spectra of the BFO station show that the seismometer STS-1/Z and the superconducting gravimeter are almost equivalent (see also Richter et al. (1995)). Therefore we believe that the high noise level shown by the superconducting gravimeter in Strasbourg is most probably due to site effects rather than to the instrument itself: a possible reason is that Station J9 is located on a thick layer of sediments (about 3000 m) in the Rhine Graben which amplifies noise at long periods. Additional problems for the J9 records in the seismic band could be pointed out by this study.

First, the very high amplitude peaks found near 0.3 and 0.55 mHz cannot be free oscillations and probably have a thermal origin related to the site; they have already been observed in other spectra from J9 superconducting gravimeter data (Florsch et al., 1991). Second, the on-site anti-aliasing filter used for sampling at a rate of 5 min is not efficient enough (with an attenuation factor of 0.96 at the 10 min Nyquist period) to avoid aliasing of seismic modes; as a consequence, we could verify that the peaks at 1.615 and 1.65 mHz are simply aliased peaks owing to higher frequency and larger amplitude modes $_4S_2$ and $_2S_6$. Similarly, we generate aliasing in the BFO superconducting gravimeter spectrum because the anti-aliasing filter we applied before decimating the data to 5 min has characteristics very close to the J9 filter to provide similar conditions for the comparison of the two superconducting gravimeter spectra. Fortunately, previous studies using the J9 superconducting gravimeter data are not seriously affected by this aliasing problem simply because major earthquakes (and the related sequence of excited normal modes) were taken out in the pre-processing step.

Paying more attention now to the spectrum of the ECH seismic data, we note that the SNR are equivalent to or even larger than those found for the BFO data, at least for this particular record. The breathing mode $_0S_0$ is a good example to show this. Similarly, the fundamental mode $_0S_2$ can be identified with a SNR of approximately three, whereas it has been hardly identified on any other individual spectrum after this particular earthquake (R. Widmer, personal communication, 1995). This clearly indicates the good quality of Station ECH for studies in the seismic frequency band. An obvious reason is the bedrock installation in an old silver mine, which shelters from most meteorological effects.

4. Comparison in the tidal frequency bands

Pillet et al. (1994) have already analysed several STS-1/Z records (including one ECH record) in the tidal domain and compared them with the J9 data. They used the STS-1/Z POS channel, which is directly proportional to acceleration (Fig. 1) and mainly studied the diurnal and semi-diurnal bands. As for the seismic band, we use the HGLP channel (Fig. 1) for the seismic record, mainly because of a higher sensitivity than that of POS, and the TIDE channel of the superconducting gravimeter. To study the SNR in the tidal frequency bands (below 0.05 mHz, periods longer than 5 h), we have to use a longer record than for the seismic band, to obtain sufficient resolution at low frequencies. We consider a 1 month signal (precisely 29 days, 22 h and 55 min in September 1994), chosen for its quietness from both the meteorological and seismic activity points of view. Both records are corrected for spikes and gaps by replacing the abnormal or missing values by a theoretical tidal signal (computed as explained previously in Section 3), a standard pre-processing technique of gravity signals (see e.g. Hinderer et al., 1994). As the total length of those perturbations represents less than 0.25% of each record, the corrections do not affect significantly the results of the tidal analysis. Both records exhibit similar tidal signals (Fig. 4), but we can already note a very long period signal perturbing the seismometer data compared with the gravimeter data.

The records are then multiplied by Hanning tapers and discrete Fourier transformed. Fig. 5 shows the spectra in four different tidal bands (1–4 cycles day^{-1}) for the two instruments as well as the theoretical spectra for the corresponding site. The theoretical spectra are obtained with a discrete Fourier transform of the theoretical tide signals and are taken here as references (rather than only theoretical frequencies of tides) because they show exactly the spectral shape obtained from a pure (noise-free) tide signal of the same length and experiencing exactly the same processing steps as the observed signals.

There is a good agreement between the observed spectra and the theoretical ones, at least for the large-amplitude diurnal and semi-diurnal waves. The noise level is higher for the ECH seismometer record in these bands and consequently its observed spectrum does not fit the theoretical one as well as the spectrum of the J9 gravimeter record does. The observed ter-diurnal tide at J9, with an amplitude about ten times lower, still correctly fits the theoretical peak. We can also identify the ter-diurnal peak in the spectrum of the ECH seismometer record, but the fit of the theoretical spectrum is poor because of the high noise level (about ten times higher than for the gravimeter in this band). The amplitude of the quarter-diurnal tides is too low (typically a few ngal) to be identified on both spectra and is totally submerged by noise; again, the higher SNR (roughly by a factor of ten) of the gravimeter data with respect to the seismometer data is evident. As the level of random noise decreases as $1/\sqrt{N}$ (N being the number of samples in time) with respect to harmonic signals such as tides (see, e.g. Florsch et al., 1995b), the 1 month time interval is clearly not long enough to allow the identification of the quarter-diurnal waves, which have been identified in a J9 gravimeter record that is more than 5 years long (Florsch et al., 1995a).

In addition to spectral analysis, we also perform a tidal analysis of the records to obtain more quantitative results in the tidal bands. We use the ETERNA

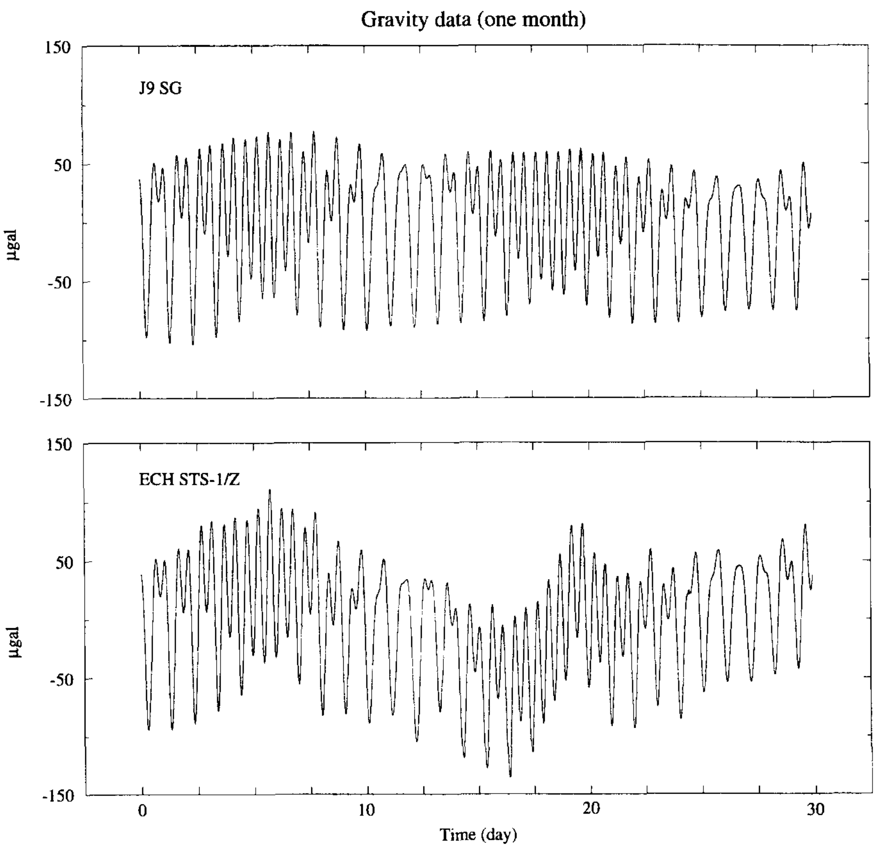
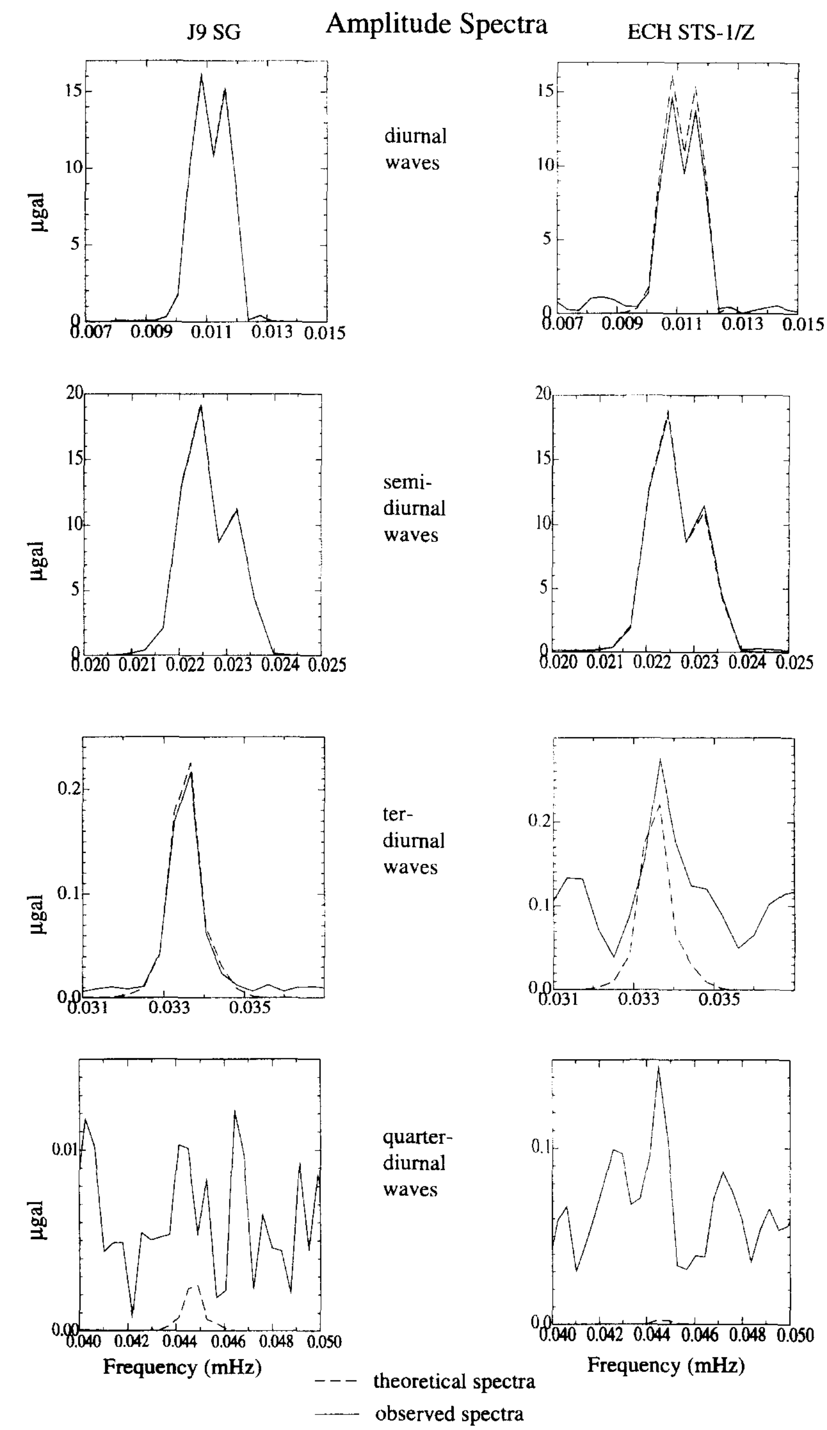


Fig. 4. Time fluctuations of gravity signals (in μgal) (29 days, 22 h and 55 min of records in September 1994) recorded by the J9 superconducting gravimeter (SG) and the ECH broadband seismometer STS-1/Z. For the gravimeter we show the raw gravity signal; for the seismometer we show the signal after deconvolution of the output by the instrument response in acceleration. Diurnal and semi-diurnal gravity tides are very similar on both records, but an important long-period component is superimposed on the seismometer signal with respect to the gravimeter signal.


J9 SG
Amplitude Spectra
ECH STS-1/Z
diurnal waves
semi-diurnal waves
ter-diurnal waves
quarter-diurnal waves
μgal
Frequency (mHz)
theoretical spectra
observed spectra

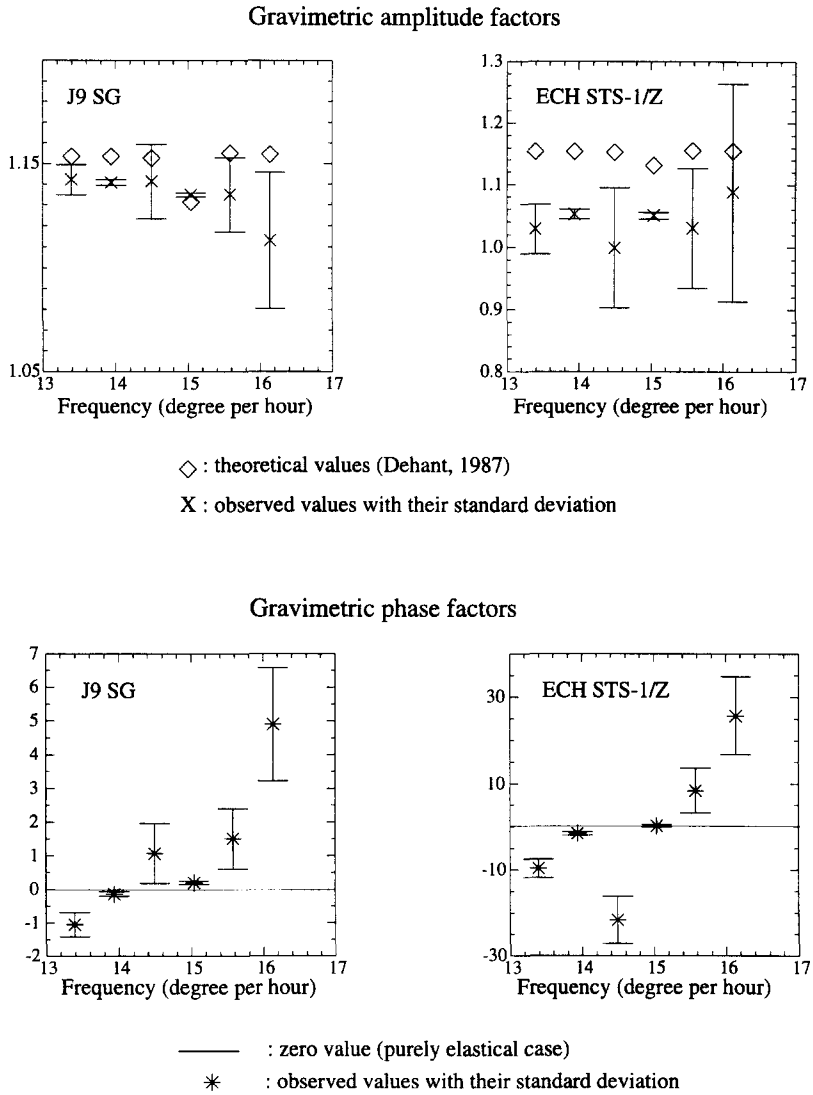


Fig. 6. Amplitude and phase gravimetric factors (delta and kappa factors, respectively) obtained by tidal analysis of the J9 superconducting gravimeter (SG) record and the ECH broadband seismometer STS-1/Z record (September 1994). We show here only the amplitude and phase gravimetric factors fitted by the ETERNA tidal analysis program (Wenzel, 1994) for the diurnal tidal wave groups. As frequency increases, we have the gravimetric factors for groups Q1, O1, M1, K1, J1 and OO1. The standard deviation obtained for each value is also given, as well as the theoretical value obtained by Dehant (1987) for an elliptical, uniformly rotating, oceanless Earth model, with an elastic inner core, a liquid outer core and an inelastic mantle.

Fig. 5. Amplitude spectra (September 1994) from the J9 superconducting gravimeter (SG) and the ECH broadband seismometer STS-1/Z. We show four tidal frequency bands: diurnal waves (about 1 cycle day^{-1}), semi-diurnal waves (about 2 cycles day^{-1}), ter-diurnal waves (about 3 cycles day^{-1}) and quarter-diurnal waves (about 4 cycles day^{-1}). Also presented as references are the theoretical spectra obtained by Fourier transform of theoretical tides computed from the Tamura (1987) tidal potential development for the same time interval and site locations.

code (Wenzel, 1994), which consists in a least-squares fitting of the amplitudes and phases of a given number of tidal groups (according to the available length of the record); the code also allows us to incorporate a polynomial function to account for instrumental drift, as well as an influence factor (admittance) for local meteorological or environmental parameters. The reference model is the Tamura (1987) tidal potential development. In our case, the program gives the amplitude gravimetric factor and the phase gravimetric factor (phase difference in degree), respectively called delta and kappa factors (Melchior, 1983) for 16 tidal groups, including monthly, semi-monthly and ter-monthly waves, diurnal, semi-diurnal, ter-diurnal and quarter-diurnal waves. We use a linear term for drift, and noise levels in four frequency bands (0.1, 1, 2 and 3 cycles day^{-1}) are estimated taking into account the frequency dependence of the average spectral noise level. We do not estimate the correlation factor between gravity and pressure, because no atmospheric pressure recordings are available at ECH. However, we have to mention here that the computed noise levels could be significantly lowered in the tidal and non-tidal bands after pressure correction (e.g. Crossley et al., 1995) and, as a consequence, the fitting of the gravimetric amplitude and phase factors could be better.

The delta and kappa factors for the diurnal frequency band are shown in Fig. 6. The gravimetric factors are in good agreement with theoretical values (Dehant, 1987) for both stations, and most of the discrepancies are caused by atmospheric and ocean effects which have not been taken into account. The standard deviations on the observed parameters are always smaller for the superconducting gravimeter record, and this is a consequence of smaller residual noise levels (Table 1). Indeed, the noise levels estimated are clearly higher for the seismometer residuals, from about five times higher in the diurnal band, up to about 20 times higher in the semi-diurnal band.

To check if the noise level would decrease significantly with a greater number of samples, we take 2 years of ECH STS-1/Z data (VLP channel, Fig. 1)

Table 1
Noise levels estimated from the Fourier spectral analysis of the J9 superconducting gravimeter and the ECH broadband seismometer STS-1/Z residual records (September 1994) after tidal analysis with the ETERNA code (Wenzel, 1994)

Frequency band (cycles day^{-1})	Noise level of J9 record (μgal)	Noise level of ECH record (μgal)
0.1	0.649	5.832
1	0.043	0.231
2	0.011	0.204
3	0.014	0.156
4	0.012	0.093

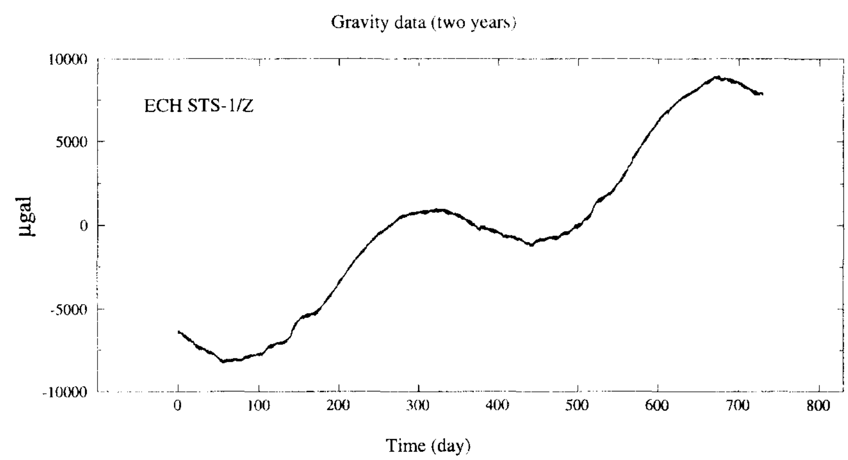


Fig. 7. Time fluctuations of the gravity (in μgal) recorded by the ECH broadband seismometer STS-1/Z during the years 1994 and 1995 (2 years, 20 min). The signal is presented after deconvolution of the output by the instrument response in acceleration. It shows a very important drift and large-amplitude annual variations that are probably a result of temperature changes.

and apply the same process as for the 1 month data. We choose the years 1994 and 1995 (precisely 2 years and 20 min of record). The data are presented in Fig. 7. We emphasise the fact that it is, to our knowledge, the first time that such a long STS-1 record of the VLP channel has been processed. Two very important phenomena can be noticed in this figure. First of all, we can estimate the linear drift of the instrument, owing to the mechanical creep of the spring. This drift is dramatic, at about 0.08 μgal per 5 min, which is approximately 16.6 mgal in 2 years (or around 23 μgal day^{-1}). In comparison, the superconducting gravimeter at J9 is known to show a linear drift of about 10 μgal $year^{-1}$ (Hinderer et al., 1994). The second striking phenomenon is a very large annual variation (approximately 6 mgal peak to peak). Clearly, this variation is linked to the annual temperature change. We essentially see this effect because the seasonal temperature changes are the largest.

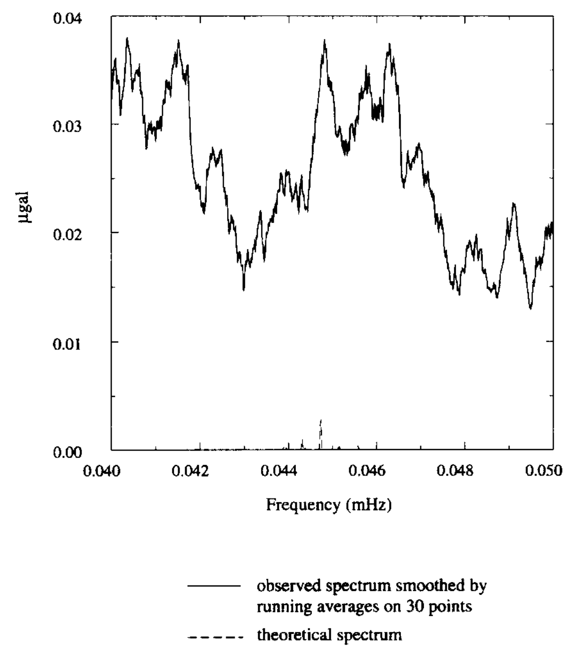


Fig. 8. Amplitude spectrum of the 2 year record of the ECH broadband seismometer STS-1/Z in the frequency band of the quarter-diurnal tides. The spectrum is smoothed by running averages on 30 points. Also presented as reference is the theoretical spectrum obtained by Fourier transform of theoretical tide signal computed from the Tamura (1987) tidal potential development for the same time interval and site location. In comparison with Fig. 5, the noise level has decreased by a factor of approximately four.

Table 2
Noise levels estimated from the Fourier spectral analysis of the ECH broadband seismometer STS-1/Z residual record (years 1994 and 1995) after tidal analysis with the ETERNA code (Wenzel, 1994)

Frequency band (cycles day^{-1})	Noise level of ECH record (μgal)
0.1	7.011
1	0.270
2	0.085
3	0.041
4	0.025

Similar effects probably exist at other frequencies but are smaller if one assumes a coloured type spectrum for the temperature and a simple (linear) instrumental temperature admittance. Unfortunately, it is not possible to investigate further this relationship with temperature, as no recording of this parameter was made at ECH.

The influence of temperature on the STS-1/Z signal is well known, and is generally observed on the POS channel, which is directly proportional to acceleration (Fig. 1). POS records are nevertheless complex to use, because they always have to be corrected for numerous 'steps' owing to the periodic recentring of the boom (D. Rouland, personal communication, 1996).

We apply to this data set the same process as for the monthly records. We also calculate a theoretical spectrum from the theoretical tide signals. We show in Fig. 8 these two spectra, in the quarter-diurnal tidal band in which we are particularly interested. Obviously, the noise is still too high to allow the identification of these very low amplitude tidal waves, but it has significantly decreased (by about a factor of four) in comparison with the noise shown in this band by the 1 month data (Fig. 5).

To obtain more quantitative results, we perform again a tidal analysis with the ETERNA code (Wenzel, 1994) described previously in Section 4, taking Tamura (1987) tidal potential development as the reference model and a linear term for the drift. Estimates of noise levels in the 0.1, 1, 2, 3 and 4 cycles day^{-1} frequency bands obtained by ETERNA are given in Table 2. In comparison with those obtained by the tidal analysis of the September

1994 seismometer data (Table 1), the noise levels are of the same order in the longer period bands (0.1 and 1 cycle day^{-1}), but they are significantly reduced in the shorter period bands (2, 3 and 4 cycles day^{-1}). In the quarter-diurnal band (4 cycles day^{-1}), the noise level is reduced by a factor close to four, when a factor of approximately five should be expected if the noise level is proportional to $1/\sqrt{N}$ (N being the number of samples). We would need at least 16 times more samples (more than 30 years) to reduce a 20 ngal noise level, as shown by the 2 year data, to a noise level of less than 5 ngal, which is the amplitude of the quarter-diurnal tide.

The delta and kappa factors fitting using the 2 year record is good, but it is still inferior to the quality of the fitting obtained with the J9 gravimeter 1 month record.

5. Noise levels in the seismic and subseismic frequency bands

We investigate here the noise levels of the J9 and ECH instruments' 1 month records. The power spectral density (PSD) values (expressed in $\mu gal^2\ Hz^{-1}$) are shown in Fig. 9 with respect to the average seismic background noise model of Peterson (1993) taken as reference. The NLNM (New Low Noise Model) and the NHNM (New High Noise Model) are respectively the low and the high limit of the

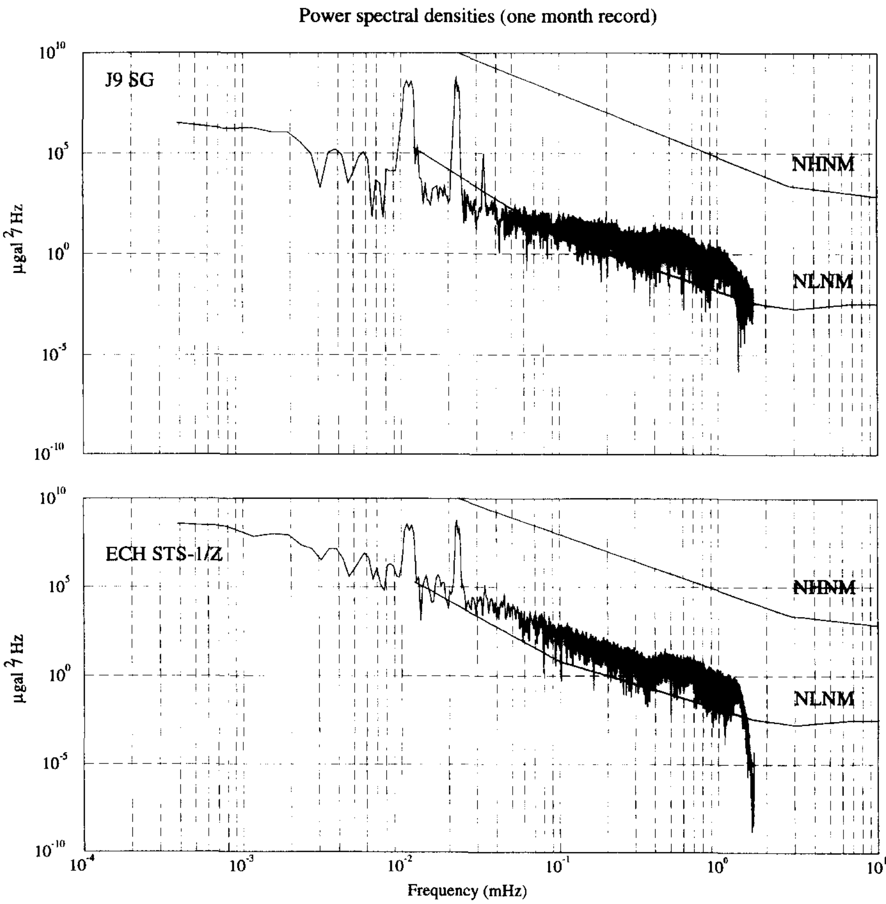


Fig. 9. Power spectral density (PSD) values of the 1 month records (September 1994) from the J9 superconducting gravimeter and the ECH broadband seismometer STS-1/Z. The New Low Noise Model (NLNM) and New High Noise Model (NHNM) of Peterson (1993) are indicated on this figure as references to evaluate noise levels of the J9 gravimeter and ECH seismometer during this time interval.

envelope of the average noise Peterson obtained from the analysis of a set of seismic data from 75 stations distributed world-wide. The PSD noise levels for both instruments and observing periods are close to the NLNM, indicating low noise levels for Stations J9 and ECH (and the instruments we are studying here) in comparison with the current global seismic network. The highest PSD peaks are, of course, the diurnal, semi-diurnal and ter-diurnal tides, which are clearly visible. Also clear is the coloured frequency dependence of the PSD close to f^{-2} (where f is the frequency) already seen elsewhere on gravity spectra (e.g. Jensen et al., 1995). In the tidal bands, the noise level shown by the superconducting gravimeter is much lower than that of the broadband seismometer (by a factor of approximately 50), and is even lower than the NLNM. Actually, the ECH STS-1/Z noise level is higher for frequencies lower than 0.3 mHz (periods longer than 50 min), whereas for higher frequencies both instruments show similar noise levels. A clear separation in the PSD levels around this 0.3 mHz frequency can be seen in Fig. 10, where the superimposed raw values have been smoothed by running averages over 50 points.

We also try to analyse the effect of (local) atmospheric pressure on the J9 gravimeter noise level and, in particular, to which frequency the correction using a barometric admittance works. Actually, the atmospheric pressure effect on gravity signals is very well known in tidal bands (e.g. Crossley et al., 1995), and attempts have recently been made to reduce this effect at higher frequencies (below 2 mHz) on spring gravimeters (Zürn and Widmer, 1995) as well as on broadband seismometers (Beauduin et al.,

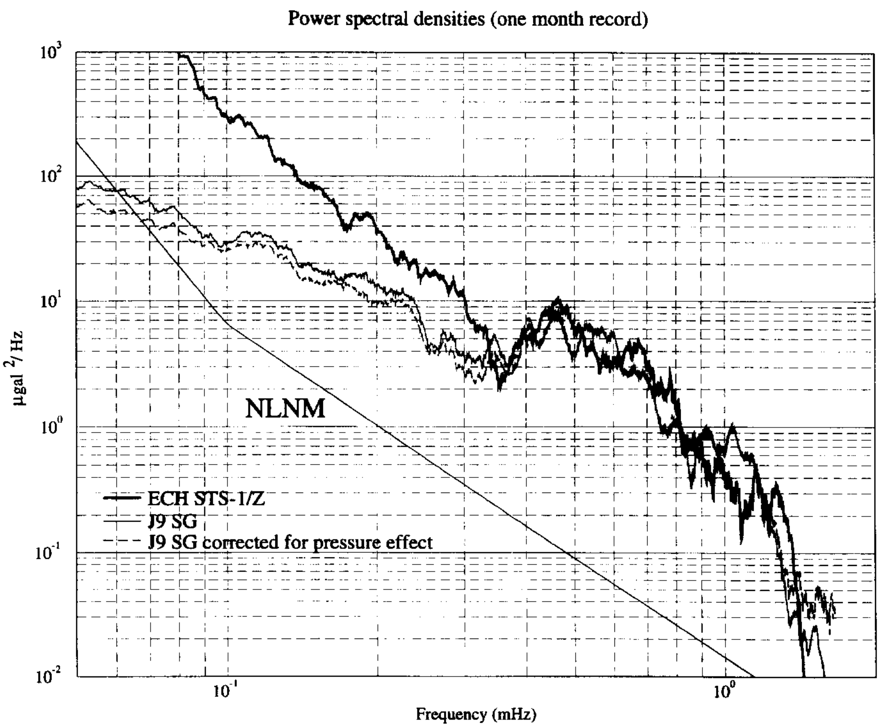


Fig. 10. Power spectral density (PSD) values of the 1 month records (smoothed version of Fig. 9 by running averages on 50 points). (Note the intersection of the curves indicating the highest frequency to which the ECH seismometer noise level is significantly higher than the J9 gravimeter noise level: 0.34 mHz, i.e. 50 min.) Also presented are the PSD values (also smoothed by running averages on 50 points) of the record from the J9 superconducting gravimeter corrected for atmospheric pressure effects with the local barometric admittance value of $-0.27\ \mu$gal mbar^{-1}. We compute $g(t)+0.27p(t)$, where $g(t)$ and $p(t)$ are respectively gravity and pressure time fluctuations at J9, and calculate the PSD of this pressure-corrected signal. (Note the intersection of the curves indicating the highest frequency to which the pressure-corrected record noise level is significantly lower than the raw gravity signal noise level: 0.41 mHz, i.e. 40 min.)

1996). We try to find the frequency limit to which a simple linear influence coefficient (in μgal mbar^{-1}) is efficient. We multiply the 1 month J9 pressure signal by the scale factor obtained by the ETERNA analysis (−0.27 μgal mbar^{-1}) and correct the gravity signal. We then compute the PSD values of the pressure-corrected gravity data and compare them with those of the raw gravity signal. Fig. 10 (smoothed curves by running averages over 50 points) shows that the correction is efficient mostly in the subseismic band, where the PSD noise level decreases significantly. Such a decrease in noise level actually holds for frequencies up to approximately 0.4 mHz (periods longer than 40 min). Our study is therefore in full agreement with the conclusion by Zürn and Widmer (1995), who pointed out that the NLNM could be lowered by appropriate pressure correction. We emphasise this point, which is important in the search for small-amplitude geodynamic signals such as the Slichter mode.

At frequencies higher than the 0.4 mHz limit, no difference is visible between PSD values of records with or without pressure correction. It would be interesting to investigate this point further in the future and find a physical explanation in terms of a time–space modelling of atmospheric pressure effects.

Finally, we would like to mention that we use a simple linear admittance factor to correct for pressure effects. It is nevertheless known that a more complex pressure correction (time-dependent phase shift and amplitude coefficients) can be efficient in the seismic frequency band (see, e.g. Beauduin et al., 1996).

6. Conclusion

The main purpose of this study was to investigate the detection capability of the STS-1 broadband seismometer (vertical component, Z) in the subseismic frequency bands (periods longer than 1 h), to check if it would be worthwhile to use the great number and the world-wide distribution of these seismometers for the detection of the very low amplitude subseismic modes by stacking techniques.

We compared the behaviour of a superconducting gravimeter and an STS-1/Z broadband seismometer located at two close sites (respectively J9 near Strasbourg and ECH, Echery, less than 70 km distant). In a first step, we analysed the response of the instruments to the normal modes generated by the Bolivian earthquake of 9 June 1994. In this analysis, we evaluated the quality of the two sites J9 and ECH with respect to the Black Forest Observatory, well known for its very low background noise. We found a relatively poor quality for J9 in this frequency band, whereas ECH is a good site, presenting SNR values comparable with or even higher than those for BFO. The site ECH should thus not be a limiting factor in our analysis of the subseismic frequency bands. The second step of our study was devoted to the comparison of the two instruments in the subseismic band (including tides) with 1-month-long records. A Fourier spectral analysis and a tidal analysis have shown the obvious result of a better capacity of the superconducting gravimeter to retrieve tidal waves. However, a further analysis of a 2-year-long record of the STS-1/Z has suggested its high dependence on temperature variations, which is probably at the origin of its high noise level in the subseismic band.

A power spectral density analysis of the 1 month records allowed us to compare the noise levels of the two instruments at all frequencies, showing two different frequency bands limited by a period of 50 min approximately. At the highest frequencies, the two instruments present comparable noise levels whereas at the lowest frequencies, the STS-1/Z clearly shows higher noise levels, which is probably due to temperature effects.

We also investigated the classical atmospheric pressure correction on J9 gravity data. We have observed that this simple linear correction is effective for frequencies lower than 0.4 mHz (periods longer than 40 min).

The important conclusion of this study is to emphasise that the on-site recording of meteorological parameters (temperature, atmospheric pressure or even hygrometry, as is usually done in gravimetric observatories) should be routinely done in seismological observatories. In particular, accurate temperature recordings (up to mK) should balance the suspected large influence of this parameter on the STS-1/Z records and improve the noise levels. We are currently checking the feasibility of these corrections by recording simultaneously temperature and barometric pressure at ECH. The corrections for temperature and pressure effects on broadband seismometers could then lead to significantly improved detection capabilities in the subseismic band.

Acknowledgements

We thank O. Jensen, W. Zürn, R. Widmer and D. Rouland for numerous interesting discussions, and W. Zürn also for kindly giving us the BFO data. We also thank B. Romanowicz and an anonymous reviewer for providing helpful comments and criticism.

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