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Reply

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Imanishi (this issue) commented that (1) the noise level at Matsushiro, Japan (MA) is much lower than at Syowa Station, Antarctica (SY), (2) oscillation signals are not observed at MA, and therefore (3) peaks below 3 mHz observed at SY are unlikely to be real signals of free oscillations. We point out that (1) he made a comparison between MA in the Japanese quiet month and SY in the Antarctic windy month, (2) the Matsushiro record does show up oscillation signals, and therefore (3) his assertion that peaks below 3 mHz observed at SY are unlikely to be real signals is not founded.

1. Introduction

Nawa *et al.* (1998a; abbreviated as N98) reported the first evidence for the continuous excitation of Earth's free oscillations from the analysis of superconducting gravimeter (SG) records at station SY. The reports on the evidence from other data have immediately followed (Suda *et al.*, 1998; Tanimoto *et al.*, 1998; Kobayashi and Nishida, 1998). Nawa *et al.* (1998b) reported the evidence from SG data at stations other than SY, for which they made an error analysis including the evaluation of the noise level at SY. Imanishi (this issue; abbreviated as IM98) commented to N98, based on his reconnaissance analysis of the one-month SG records at SY and MA, to conclude that (1) the noise level at MA is much lower than at SY, (2) seismic mode signals are not observed at MA, and therefore (3) peaks below 3 mHz observed at SY are unlikely to be real signals of the Earth's free oscillations. We examine each of these points in what follows.

2. Free Oscillation Signals at Matsushiro

An essential element in a study of this type is to remove the data in seismically active periods in order to use only those in quiet days. Imanishi (1998) personally communicated us that he identified seismic disturbances by visual inspection of the original record, which were then removed and linearly interpolated so that more than 3/4 of the original record was effectively retained for the spectral analysis. IM98 emphasized that the Matsushiro data after this (visual) removal of seismic disturbances do not show any clear signals of free oscillations. This emphasis is puzzling since the only less than 1/4 removal from the one-month record is not enough, in general, for the remaining data to be free from the effect of large earthquakes and therefore the resultant spectrum should show free oscillation signals of earthquake origin.

This question has motivated us to reanalyze the Matsushiro data by our own method. The computational method of spectrum is the same as in Suda *et al.* (1998). The whole record at each station is divided into 3 day-long records with a time lag of 1 day. Each record is Fourier-transformed to obtain its spectrum, to which corrections are made for tapering of the record. A seismically quiet period is defined, based on the Harvard CMT catalog, as the 3 day-long interval not containing the days and next days of earthquakes with moment magnitudes greater than a prescribed cutoff. The spectra for such periods are stacked to obtain an averaged spectrum, which is lastly moving-averaged over 11 points.

We impose a cutoff magnitude of 6.5 to remove 2/5 of the August record at MA (see Table 1 for the detailed parameters). Note that the total sampling length is much shorter than that in IM98 who used more than 3/4 of the whole record. Figure 1 shows the spectrum for the remaining 3/5 portion of the August record, from which the peak positions are read and listed in Table 2. As demonstrated in Fig. 1, and as quantified in Table 2, the spectrum at MA shows, among other peaks, a large number of fundamental spheroidal peaks not only at frequencies higher than 3 mHz but also at the lower frequencies. This feature is in marked contrast to the essentially featureless spectrum in IM98 over the whole frequency band. Unless Imanishi demonstrates that his spectrum above 3 mHz exhibits the signal peaks at least as clear as in Fig. 1, there remains a big possibility that the apparent absence of signal peaks in his spectrum below 3 mHz is simply due to the lack of resolution in the analysis.

IM98 claimed "the spectral intensities of Matsushiro are lower than those of Syowa by a factor of 3–10 over the whole frequency range in terms of power spectral density". IM98 obtained this conclusion by comparing the Matsushiro data in a quiet month (August) to the Syowa data in a windy month (August). In fact Syowa station in August, 1994, had 17

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Table 1. Parameters pertinent to Figs. 1 and 2.

Figure	Sta.	Period	Mo	Mw	QD	N	Mo (sum)
Fig. 1	SY	94/12	50.0	6.4	17	44	150
	MA	97/8	70.0	6.5	17	44	220
Fig. 2(a)	CB	97/1–7	2.5	5.5	7	33	31
	MA	97/7–9	5.0	5.7	7	29	42
Fig. 2(b)	CB	97/1–7	5.0	5.7	26	83	120
	MA	97/7–9	14.0	6.0	26	98	240

Mo: cutoff moment in unit of 10^{17} Nm, Mw: cutoff magnitude, QD: number of quiet days with cutoff moment Mo and cutoff magnitude Mw, N: number of available Harvard CMT solutions on the quiet days, Mo (sum): sum of the moments for N earthquakes.

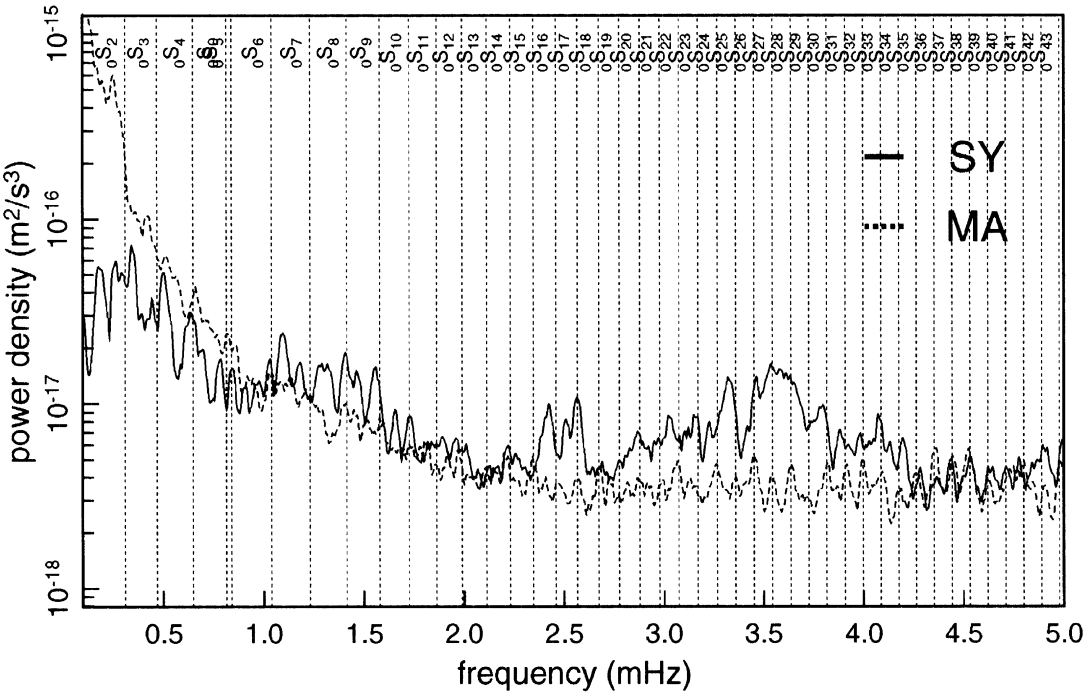

Fig. 1. Comparison of averaged power spectral densities between Syowa (December 1994) and Matsushiro (August 1997). The number of stacked spectra is 17, corresponding to a cutoff magnitude of 6.5 for Matsushiro and 6.4 for Syowa (see Tables 1 and 2 for detail).

blizzard days on which the 10 min-averaged wind speed at 12 o'clock exceeded 10 m/s. We present, in Fig. 1, the Syowa spectrum for the austral summer (December, 1994) after the 2/5 removal of the data (equivalent to a cutoff magnitude of 6.4; see Table 1). The intensity difference between SY and MA is now much less than one as claimed by IM98. (The intensity difference at frequencies less than about 1 mHz is due in part to the difference in filter response: MODE filter at SY and TIDE filter at MA.)

Figure 1 is thus the spectral comparison in a seismically quiet period between MA and SY. The spectrum at SY exhibits many peaks whose frequencies are coincident with those of the fundamental spheroidal modes observed at MA. We see such coincidence at frequencies not only above 3 mHz but below it. Table 2 lists the frequencies of these peaks in comparison with those reported in N98. As indicated in this table, the Matsushiro spectrum in Fig. 1 exhibits almost all the peaks corresponding to the fundamental spheroidal modes from ${}_0S_4$ to ${}_0S_{43}$ except for ${}_0S_7$, ${}_0S_{12}$, ${}_0S_{19}$, ${}_0S_{29}$. Similarly the Syowa spectrum shows up the peaks corresponding to the fundamental modes from ${}_0S_3$ to ${}_0S_{43}$ excluding ten missing modes. We note at the same time that apparent peaks other than those identified as the fundamental spheroidal modes increase with decreasing frequency, especially below 2 mHz, indicating a difficulty of signal identification at lower frequencies. However, the appearance of the identified peaks is so persistent over a wide frequency range from 0.5 to 5 mHz and so consistent between the two stations that we find no justification for the suggestion by IM98 that all the identified peaks below 3 mHz (${}_0S_3$–${}_0S_{21}$) are just noise. It would be more natural to consider that they are mostly signals. Among the total of 31 identified modes at SY, 26 modes have also been reported in N98. Among the total of 10 missing modes at SY, 7 have also been reported to be undetectable or unsep-

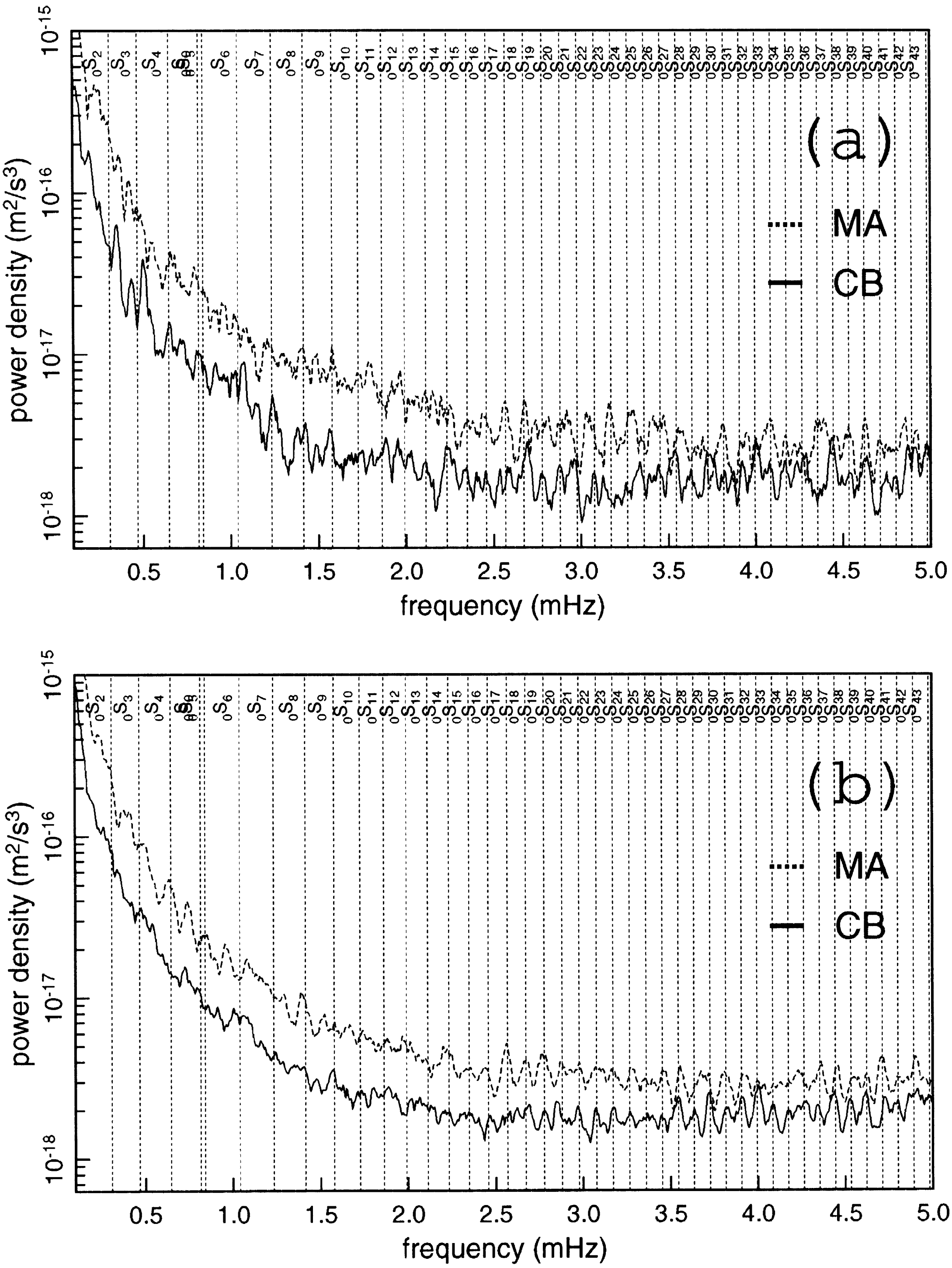

Fig. 2. Comparison of averaged power spectral densities between Canberra and Matsushiro. In (a) the number of stacked spectra is 7, corresponding to a cutoff magnitude of 5.7 for both the stations. In (b) the number of stacked spectra is 26, corresponding to a cutoff magnitude of 5.7 for Canberra but 6.0 for Matsushiro (see Tables 1 and 2 for detail).

arable in N98. Among the total of other 18 peaks (excluding 2 marginal peaks) at SY, 9 peaks have also been reported in N98. Thus, the result of N98 is quite consistent with the present result for SY. Although IM98 claimed to use a more tight criterion for mode identification by referring to the standard errors of ordinary eigenfrequency measurements of Earth's free oscillations, the accuracy required for the identification of weak mode signal should be different from the accuracy required for the eigenfrequency measurements.

At this stage we point out a difference in the absolute level of spectra between Fig. 1 and Fig. 1 in IM98. What are shown in IM98 are the two-sided spectra that were obtained by averaging the individual spectra in log scale (Imanishi, personal communication). Figure 1, on the other hand, represents the

Table 2. Observed frequencies at SY, MA and CB.

N98	Figure 1		Figure 2(b)		PREM	mode
	SY	MA	MA	CB		
0.25–0.26	0.27	0.25	0.23	0.26		
0.29			**0.29**		**0.3093**	**$_0S_2$**
0.35	0.34	0.36*				
	0.40*	0.42	0.41	0.42		
0.45	**0.44**		**0.47**	**0.48**	**0.4686**	**$_0S_3$**
0.50	0.50	0.51				
		0.57		0.60		
0.65	**0.64**	**0.66**	**0.64**		**0.6471**	**$_0S_4$**
		0.71*	0.74	0.73		
0.78	0.79	0.77		0.80	0.8143	$_0S_0$**
0.84–0.85	**0.85**	**0.82**	**0.85**	**0.86**	**0.8405**	**$_0S_5$**
	0.91	0.92		0.91	0.9399	$_1S_3$**
	0.98		0.96	1.00		
1.02–1.03	**1.03**	**1.04**	**1.02***		**1.0384**	**$_0S_6$**
1.09–1.10	1.10	1.14	1.08		1.1063	$_3S_2$**
1.17–1.18	1.18	1.21		1.16	1.1729	$_1S_4$**
				1.24	**1.2319**	**$_0S_7$**
			1.29			
1.32	1.32	1.34*				
1.40–1.41	**1.41**	**1.41**	**1.39**	**1.41**	**1.4136**	**$_0S_8$**
1.46–1.47	1.46			1.48		
			1.52		1.5221	$_1S_6$**
1.57–1.58	**1.56**	**1.58**	**1.58**	**1.57**	**1.5783**	**$_0S_9$**
	1.66		1.67		1.6555	$_1S_7$**
1.72–1.73	**1.73**	**1.72***	**1.74**	**1.73**	**1.7266**	**$_0S_{10}$**
		1.80			1.7993	$_1S_8$**
1.82–1.83						
		1.86*			**1.8625**	**$_0S_{11}$**
	1.89	1.92	1.88	1.89	1.8652	$_2S_7$**
	1.96	1.97	1.97		1.9638	$_1S_9$**
	2.01				**1.9905**	**$_0S_{12}$**
				2.07	2.0495	$_2S_8$**
		2.11			**2.1130**	**$_0S_{13}$**
		2.15			2.1485	$_1S_{10}$**
2.23	**2.22**	**2.20**	**2.20**	**2.21**	**2.2315**	**$_0S_{14}$**
2.29		2.26*			2.2797	$_4S_4$**
		2.34	**2.36**	**2.35**	**2.3464**	**$_0S_{15}$**
	2.42	2.41			2.4115	$_4S_5$**
2.43		**2.46**	**2.44**	**2.47**	**2.4583**	**$_0S_{16}$**

Table 2. (continued).

N98	Figure 1		Figure 2(b)		PREM	mode
	SY	MA	MA	CB		
2.57	**2.57**	**2.57**	**2.56**		**2.5672**	**$_0S_{17}$**
				2.62		
	2.69	**2.67**	**2.68**	**2.69**	**2.6734**	**$_0S_{18}$**
			2.76	**2.78**	**2.7771**	**$_0S_{19}$**
2.88	**2.87**	**2.87**	**2.87**	**2.85**	**2.8785**	**$_0S_{20}$**
				2.92		
	2.97	**3.00**	**2.98**	**2.97**	**2.9778**	**$_0S_{21}$**
	3.02					
3.08		**3.07**	**3.07**	**3.07**	**3.0754**	**$_0S_{22}$**
3.18	**3.15**	**3.13**	**3.16**	**3.17**	**3.1714**	**$_0S_{23}$**
3.22–	3.23					
		3.27	**3.27**	**3.27**	**3.2660**	**$_0S_{24}$**
	3.32					
–3.38		**3.36**	**3.35**	**3.37***	**3.3595**	**$_0S_{25}$**
3.45	**3.46**	**3.45**	**3.47**	**3.45***	**3.4520**	**$_0S_{26}$**
3.53–3.54	**3.54**	**3.54**	**3.55**	**3.54**	**3.5438**	**$_0S_{27}$**
3.64–3.65		**3.64**		**3.63**	**3.6349**	**$_0S_{28}$**
		3.69*	3.67			
	3.74			**3.72**	**3.7255**	**$_0S_{29}$**
3.82	**3.80**	**3.82**	**3.81**	**3.82**	**3.8157**	**$_0S_{30}$**
3.90–3.91	**3.88**	**3.92**	**3.91**	**3.91**	**3.9056**	**$_0S_{31}$**
4.00	**3.98**	**3.99**	**4.00**	**4.00**	**3.9952**	**$_0S_{32}$**
	4.03*	4.04*				
4.09	**4.07**	**4.09**		**4.09**	**4.0847**	**$_0S_{33}$**
	4.13		4.13			
4.18	**4.19**	**4.18**	**4.17**	**4.18**	**4.1741**	**$_0S_{34}$**
			4.23			
4.26	**4.28**	**4.27**		**4.28**	**4.2635**	**$_0S_{35}$**
4.35	**4.36**	**4.36**	**4.36**	**4.34**	**4.3528**	**$_0S_{36}$**
4.44–4.45	**4.43**	**4.44**	**4.46**	**4.44**	**4.4421**	**$_0S_{37}$**
4.53	**4.53**	**4.52**	**4.53**	**4.53**	**4.5315**	**$_0S_{38}$**
4.62	**4.64**	**4.62**	**4.62**	**4.62**	**4.6209**	**$_0S_{39}$**
4.72	**4.71**	**4.75**	**4.71**	**4.72**	**4.7104**	**$_0S_{40}$**
4.80	**4.78**	**4.80**	**4.80**	**4.80**	**4.8000**	**$_0S_{41}$**
4.89	**4.90**	**4.91**	**4.90**	**4.91**	**4.8897**	**$_0S_{42}$**
	5.00	**4.98**			**4.9795**	**$_0S_{43}$**

*Marginal peak, **tentatively assigned, speculative mode, thick letters: peaks identified as the fundamental spheroidal modes.

one-sided spectra obtained through the averaging procedure in linear scale. The log averaging causes a constant negative bias of −0.25 (Percival and Walden, 1993), equivalent to a factor of 1/1.8 in linear scale. The absolute level of spectra in IM98 is thus apparently 1/3.6 times as low as that in Fig. 1. Besides this apparent reduction of the spectral level, perhaps more importantly, the log averaging in IM98 might have caused a reduction of resolution in the resultant spectra. For a purely stochastic time series, the log averaging may be robust in the sense that it gives small weights to large values, i.e. outliers. However, for a time series containing periodic components, the log averaging tends to smooth them out since they appear as large values in spectra. We believe that the log averaging is not appropriate for detecting subtle periodic components in spectra.

3. Spectral Peaks of Seismically Inactive Days

The spectral peaks in Fig. 1 are due largely to earthquakes. We next show that although the Matsushiro data are available only for 3 months (July–September, 1997), they do contain a signature of free oscillation signals of non-earthquake origin. For the data selection we impose a cutoff magnitude of 5.7 to minimize the excitation effect by earthquakes (Suda *et al.*, 1998). This threshold leaves only 7 sets of spectrum for the analysis from the total of 89 sets (see Table 1 for the detail). The averaged spectrum of these 7 sets is shown in Fig. 2(a). For comparison we also show the average of the 7 spectra from the 6-month SG records at Camberra (CB), Australia, where the observation started in January, 1997 (Sato *et al.*, 1998).

Obviously a stack of only 7 spectra is not enough to suppress a highly oscillatory feature of the noise spectrum. However, it can already be seen both for MA and CB that the oscillatory peaks tend to locate near the expected positions of the fundamental spheroidal modes. This tendency suggests that further stack should average out the irregularly ragged background spectra to enhance the signal peaks. Such an expectation may be confirmed by a stack of the total of 26 spectra with the same cutoff magnitude of 5.7 selected from the 6 month observation at CB. Figure 2(b) shows the averaged spectrum of CB. Comparison of Fig. 2(b) with 2(a) clearly indicates that the stacking has unmasked a larger number of signal peaks from the background noise. Note that these signal peaks are observed not only above 3 mHz but below it, as detailed in Table 2.

The corresponding averaged spectrum cannot be obtained for MA because of the limited length of the available record. We instead create 26 spectra by changing the cutoff magnitude from 5.7 to 6.0. The resultant averaged spectrum (Fig. 2(b)) shows many mode signals that have evolved through the stacking process, although they may not be entirely free from the effect of earthquakes with Mw in a range 5.7–6.0. As quantified in Table 2, among the total of 46 (47) apparent peaks at MA (CB), 33 (34) are identified as the fundamental spheroidal modes. Especially, the peaks above 2.2 mHz are in almost one-to-one correspondence with the fundamental spheroidal modes. At the lower frequencies apparent peaks other than fundamental modes increase with decreasing frequency, thus degrading the reliability of mode identification.

In Fig. 2 we note that although the noise level at MA is higher than at CB, the signal intensities relative to the noise level seem to be unaffected by whether the noise level is higher or lower. We interpret this observation in terms of the mutual independence of the assigned signal and noise and the approximate coincidence in the signal level between the two stations, both of which are the required characteristics of the Earth's free oscillations. Figure 2, thus, represents evidence of the continuously excited modes of Earth's free oscillations at frequencies even below 3 mHz at least down to 2.2 mHz.

4. Discussion

We now summarize our reply to the three major comments by IM98.

(1) The noise level at MA is much lower than at SY.

This assertion is based on a comparison between the Matsushiro spectrum in a quiet month and the Syowa spectrum in the worst month. Such a comparison is biased, since the Syowa spectrum in a quiet month (Fig. 1) is rich in free oscillation signals with noise at a much lower level. IM98 should have observed real signals from the Syowa data if he choose a more appropriate month. In Fig. 1 relatively large noise in a frequency band around 3.5 mHz and those in other narrower bands at SY may be local phenomena near the station or inside the observation room or of instrumental origin, as Nawa *et al.* (1998b) and IM98 pointed out.

(2) Seismic mode signals below 3 mHz are not observed at MA.

IM98 claimed this without mentioning whether the mode signals above 3 mHz are observed or not. Although he did not mention explicitly, the Matsushiro spectrum in IM98 is apparently featureless not only below 3 mHz but above it. We suggest that this is due to the lack of resolution in his spectral analysis method for detecting weak signals of free oscillations. In fact the Matsushiro spectrum obtained by us has shown up almost all the fundamental mode peaks over a frequency range from 0.5 to 5.0 mHz, although the reliability of mode identification reduces below 2 mHz because of the existence of other peaks (Fig. 1 and Table 2). Even when a more stringent criterion is adopted to avoid the effect of earthquakes, the resultant spectrum still shows the persistent appearance of signal peaks at frequencies at least down to 2.2 mHz (Fig. 2(b) and Table 2). IM98 should have detected free oscillation signals from the Matsushiro data if he adopted a more appropriate analysis method.

(3) Peaks below 3 mHz at SY are unlikely to be real signals.

This is a natural consequence of the above two assertions, both of which, however, we have shown not to be founded. Accordingly we suggest that this third assertion is also not founded. We have rather shown that most of the peaks identified as the fundamental modes in N98 can be regarded as real signals. A caution is required, however, for the mode identification at frequencies less than 2.2 mHz, where other peaks are observed as well (see Table 2). Table 2 also compares the peak positions read from the Syowa spectrogram (N98) to those read from the averaged spectrum (Fig. 1), demonstrating the consistency between the two methods.

Admittedly, our analysis at frequencies less than 2 mHz may require elaboration, where the noise level could be reduced by removing the effects of atmospheric attraction and loading as done by IM98. The ocean effects can also be significant since SY is located near coast (e.g., Agnew and Berger, 1978). Nagata *et al.* (1993) reported a seasonal variation of the amplitudes of ocean tides near SY. Some of the peaks not identified as the fundamental modes at frequencies below 2 mHz (Table 2) may be due to such effects. Unless these local effects as well as the instrumental effects are assessed carefully, the discussion about the possible excitation source developed in N98 may not be justified on the observational ground.

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References

Agnew, D. C. and J. Berger, Vertical seismic noise at very low frequencies, *J. Geophys. Res.*, **83**, 5420–5424, 1978.

Imanishi, Y., Comment on "Incessant excitation of the Earth's free oscillations" by Nawa *et al.*, *Earth Planets Space*, **50**, this issue, 883–885, 1998.

Kobayashi, N. and K. Nishida, Continuous excitation of planetary free oscillations by atmospheric disturbances, *Nature*, **395**, 357–360, 1998.

Nagata, Y., M. Kawamiya, Y. Michida, and M. Odamaki, Seasonal variations of the sea level at Syowa Station, Antarctica, *Proc. NIPR Symp. Polar Meteorol. Glaciol.*, **7**, 60–72, 1993.

Nawa, K., N. Suda, Y. Fukao, T. Sato, Y. Aoyama, and K. Shibuya, Incessant excitation of the Earth's free oscillations, *Earth Planets Space*, **50**, 3–8, 1998a.

Nawa, K., N. Suda, Y. Fukao, T. Sato, Y. Tamura, K. Shibuya, H. McQueen, and H. Virtanen, Detection of Earth's background free oscillations using the Australian and Finnish superconducting gravimeter records (abstract), *Jpn. Earth Planet. Sci. Joint Meeting*, Sn-p003, 1998b.

Percival, D. B. and A. T. Walden, *Spectral Analysis for Physical Applications*, 583 pp., Cambridge University Press, Cambridge, 1993.

Sato, T., H. McQueen, B. Murphy, K. Lambeck, Y. Hamano, K. Asari, Y. Tamura, and M. Ooe, On the observations of gravity tides and Earth's free oscillations with superconducting gravimeter CT#031 at Mt. Stromlo, Australia, *Proc. 13th Int. Symp. Earth Tides*, Bruxelles, 1998 (in press).

Suda, N., K. Nawa, and Y. Fukao, Earth's background free oscillations, *Science*, **279**, 2089–2091, 1998.

Tanimoto, T., J. Um, K. Nishida, and N. Kobayashi, Earth's continuous oscillations observed on seismically quiet days, *Geophys. Res. Lett.*, **25**, 1553–1556, 1998.

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