Some Possible Causes of and Corrections for STS-1 Response Changes in the Global Seismographic Network

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INTRODUCTION

The Global Seismographic Network (GSN) (Figure 1) plays a key role in providing seismic data for global earthquake monitoring (*e.g.*, Benz *et al.* 2005), earthquake science (*e.g.*, Tsai *et al.* 2005), and studies of Earth structure (*e.g.*, Dalton *et al.* 2008). One of the key GSN design goals is to "provide high fidelity digital recordings of all teleseismic ground motions (adequate to resolve at or near ambient noise up to the largest teleseismic signals over the bandwidth from free oscillations (10^{-4} Hz) to teleseismic body waves (up to approximately 15 Hz))" (GSN ad hoc Design Goals Subcommittee 2002). To help meet this goal, Streckeisen STS-1 seismometers were deployed at 80 GSN stations.

Some of the GSN sensors have been deployed for more than 25 years. Several recent studies (Davis *et al.* 2005; Ekström *et al.* 2006; Davis and Berger 2007) have examined the question of overall calibration of the GSN. Ekström *et al.* (2006) indicated that a number of sites showed anomalous responses and suggested a gradual decay in the sensitivity.

We have investigated the anomalous responses at several GSN sites. At least some of the problems observed by Ekström *et al.* (2006) may be attributed to humid air leaking into the feedback electronics of the STS-1 seismometers, which produces lower than normal sensitivities near the long-period corner of the instrument (360 seconds period). It appears that even though the feedback electronics boxes are designed to be sealed, water vapor can penetrate their interior after they have been exposed to highly humid seismometer vault air for extended periods. Highly humid air was also found to be present inside some STS-1 bell-jars (especially horizontal instruments) after loss of vacuum, resulting in corrosion and leakage between electrical conductors in connectors. This also resulted in a lowered (over-damped) amplitude response near the 360-second corner. Yuki and Ishihara (2002) documented similar humidity and moisture effects for STS-1 seismometers that are operated as part of Japan's Ocean Hemisphere Network Project (OHP). All of the evidence points toward a simple solution: keep all critical components clean and dry.

STS-1

The STS-1 is the lowest noise (particularly in the long-period band) broadband seismometer operating at more than 200 observatories throughout the world (Ringler and Hutt 2010). The STS-1 seismometer is no longer in production and there is currently no observatory quality replacement to the STS-1, making it critical that the limited number of these instruments in operation be preserved (Laske 2004).

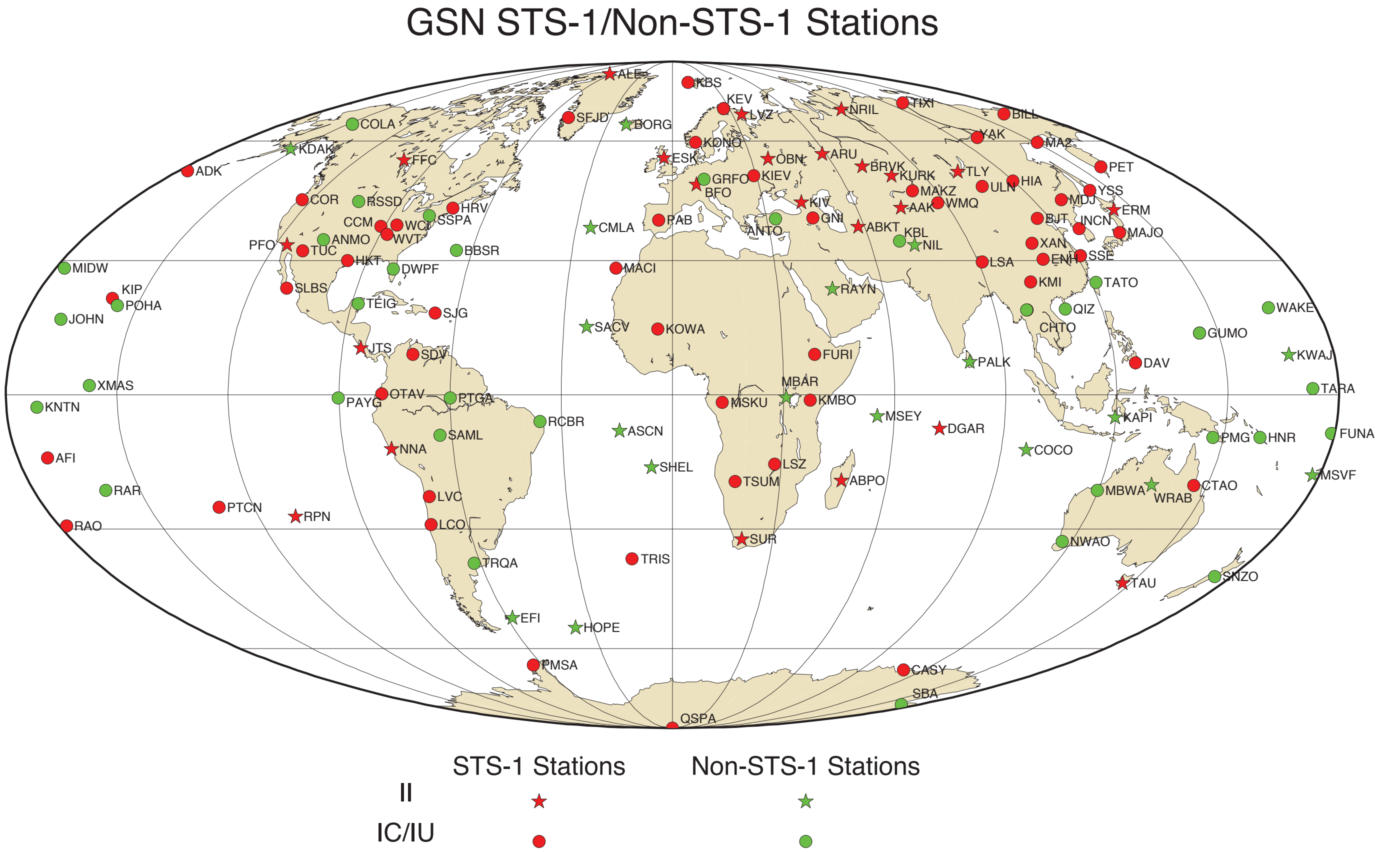
The use of feedback seismometers provides instrumentation that is highly linear as well as extremely stable as compared to previously deployed conventional (non-feedback) seismometers (Wielandt 2004). Since the STS-1 is a feedback instrument, most early users of STS-1 seismometers did not consider it necessary to calibrate the STS-1 very often. Calibrating seismometers interrupts normal operation and thus impacts data analysis during the calibration period (Woodward and Masters 1989).

GSN RESPONSE STABILITY INVESTIGATIONS

The Waveform Quality Center (WQC), located at Lamont-Doherty Earth Observatory (LDEO), routinely compares the amplitudes and polarizations of synthetic and observed earthquake waveforms recorded by the GSN and other networks to help verify the quality of seismic data from these networks. The WQC analysis focuses on long-period body and mantle waves, with a period range of 50 to 400 seconds. Ekström *et al.* (2006) identified a number of GSN stations with anomalous responses (Table 1). In some cases, the WQC analysis showed a gradual decay in the long-period response over time, particularly in the STS-1 sensor, raising the specter of aging instrumentation. For example, the WQC observed mantle wave amplitudes as much as a factor of two smaller than predicted at GSN station KIP (Kipapa, Hawaii) from 2004 through 2006 (Figure 2).

In contrast, a study modeling the Earth's tides (Davis and Berger 2007) did not see changes in response at the M2 tidal period of the same amplitude or during the same epochs as the WQC results. A study of synthetic and observed ${}_0S_0$ amplitudes from the Sumatra-Andaman earthquake of 26 December 2004

 doi: 10.1785/gssrl.82.4.560

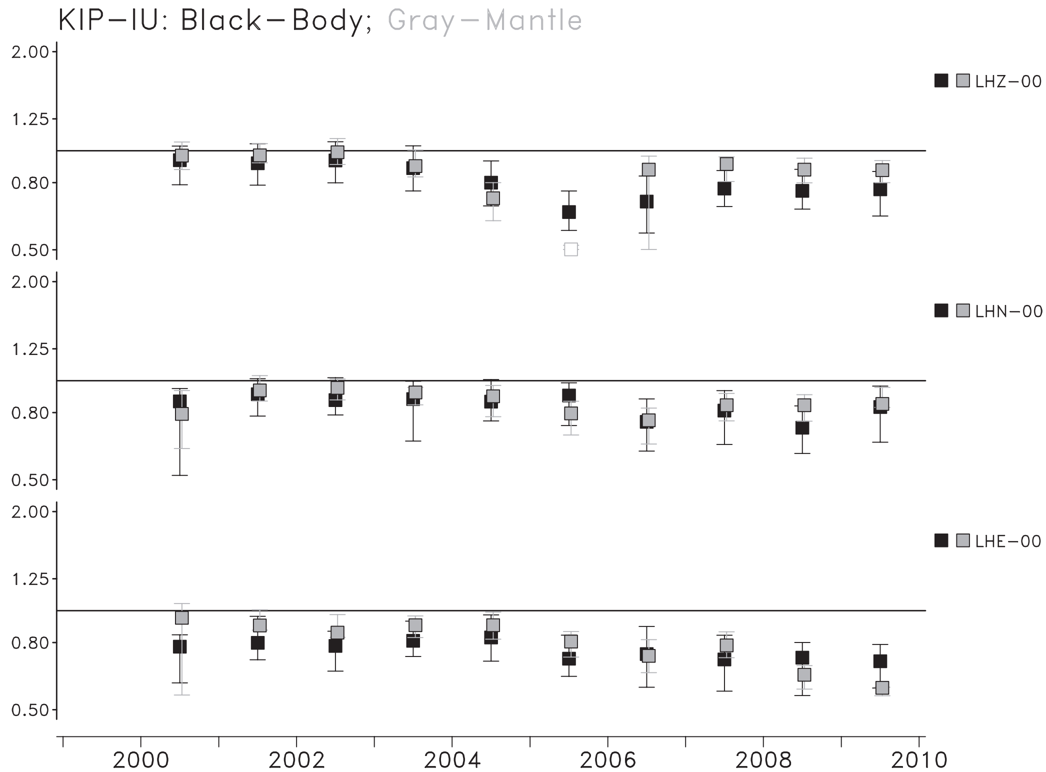


▲ **Figure 1.** The 132 stations of the Global Seismographic Network (GSN), consisting of 91 IU and IC stations operated by the USGS (circles) and 41 II stations operated by the University of California, San Diego IDA group (stars). This map does not include the Caribbean Network (network code CU) and the Global Telemetered Seismograph Network (network code GT). Stations operating Streckeisen STS-1 seismometers are depicted in red, others are in green.

TABLE 1
Some stations for which the WQC has identified a gradual change in the long-period response for the indicated component. This list includes some of the stations listed in Table 1 of Ekström *et al.* (2006) along with additional stations/components and later date ranges as identified by the WQC (Ekström, personal communication 2008).

Station	Network	Component	Start[a]	End[b]
ABKT	II	LHZ	1995	1997
BJT	IC	LHZ, LHN, LHE	1999	2006
BRVK	II	LHZ	2001	2005
HIA	IC	LHZ	2006	2007
HRV	IU	LHN, LHE	1996	2007
KIP	IU	LHZ	2004	2006
LVZ	II	LHZ	1995	2007
MA2	IU	LHE	1998	2007
OTAV	IU	LHZ	2005	2007
PAB	IU	LHE	1999	2006
PET	IU	LHN	2002	2007
SSE	IC	LHN	2000	2007
WCI	IU	LHZ, LHN, LHE	1997	2007
XAN	IC	LHZ, LHN, LHE	2003	2007

[a] Year in which change in response first clearly observed.
[b] Year in which change last observed (2007 is most recent year analyzed).



▲ **Figure 2.** Scaling factors observed at GSN station KIP by the WQC at LDEO for body waves in the 50–75 s period range and mantle waves in the 200–250 s period range. These plots represent the scaling factors needed to optimally fit synthetic long-period seismograms used in LDEO's centroid moment tensor (CMT) algorithm. The open gray square for LHZ in 2005 indicates a scaling factor of less than 0.50. Graphic provided by M. Nettles and G. Ekström, LDEO.

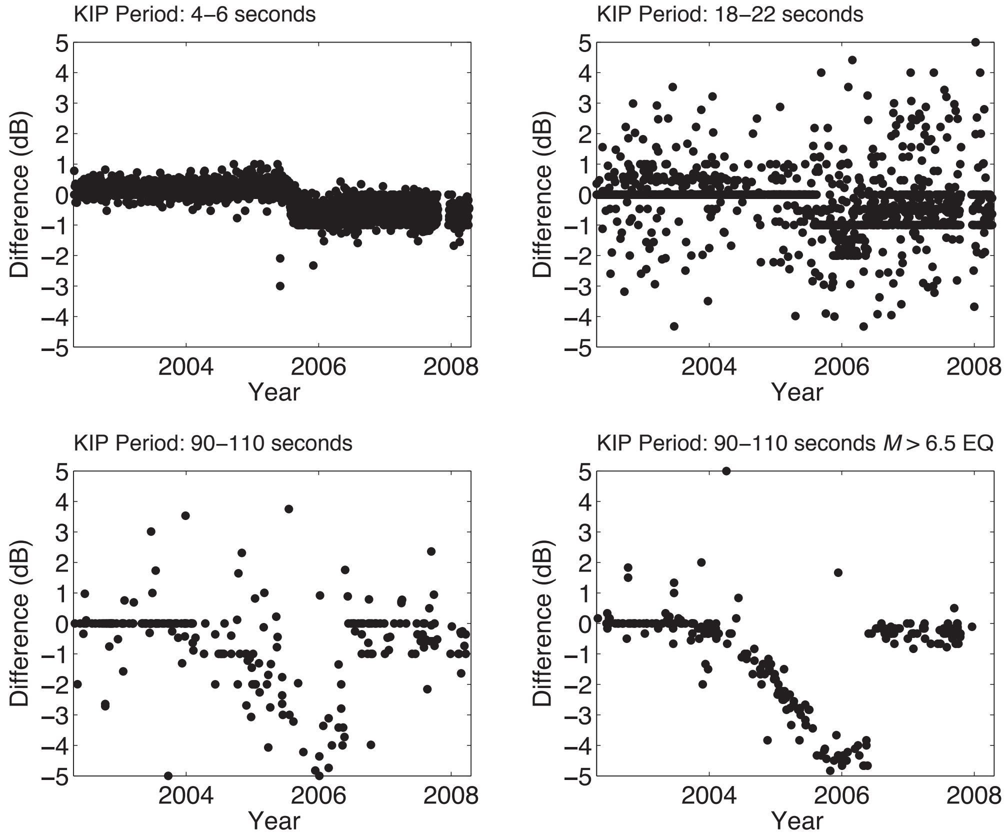
(Davis *et al.* 2005) showed lowered sensitivities at approximately 1,200 seconds period on some STS-1 vertical seismometers as well as some KS54000 vertical seismometers. However, this study is for a single point in time and therefore does not allow tracking changes in response over time. Analysis conducted by the authors in 2008 at the Albuquerque Seismological Laboratory (ASL) comparing collocated sensors in the microseism band confirmed the step offsets observed by the WQC at KIP and other sites, but also did not show the gradual decay observed by the WQC. These studies concentrate on very narrow period ranges (12 hours, 1,200 seconds, and six seconds period) and are therefore not suitable for identifying changes at other periods in the amplitude responses of the seismometers.

Initial investigations of the WQC observations by the ASL complicated the picture. A site visit to TUC (Tucson, Arizona) in 2007 revealed that the sensitivity problem on the vertical and east components was due to a non-standard digitizer gain. At HRV (Harvard, Massachusetts), a site visit in 2006 and subsequent analysis indicated that the STS-1 horizontal seismometers had severe over-damping of the 360-second corner. At the time, we suspected either that they had been set up with a mechanical free period that was too short during a maintenance trip in 1996 to install the warpless baseplates, or that the high vault humidity was possibly causing the problem.

Ringler *et al.* (2010) investigated time-dependent changes in the GSN using power spectral density (PSD) data. Investigations in the 90–110 second period band comparing the vertical components of the STS-1 and STS-2 seismometers at KIP following large events confirmed the WQC observations, suggesting that the observed response changes at some stations with STS-1 seismometers were frequency and time dependent (Figures 2 and 3). The difference in PSD values between the two vertical seismometers returned to approximately 0 dB when the STS-1 feedback electronics (FBE) box was replaced in May 2006 during a station maintenance visit, providing evidence for the problem being localized to the instrument's FBE in this case.

HUMIDITY EXPERIMENTS

In order to investigate the response changes at select GSN stations, we experimented with the FBEs recovered from KIP in 2006. We connected them to a set of test STS-1 seismometers in the ASL test vault and checked their responses by driving the seismometer calibration coils with random telegraph signals. The initial tests in the standard low-humidity environment of New Mexico showed a normal response. We then exposed the "sealed" FBEs to highly humid air (>90% relative humidity) for several days and their responses remained normal. We then removed the lid of one of the FBEs and exposed the interior to highly humid air, resulting in much lower than normal sensitivity near the 360-second corner (an over-damped response) while the mid-band response (near six seconds period) remained normal.



▲ **Figure 3.** Difference in PSD values between the KIP STS-1 vertical seismometer and STS-2 vertical seismometer in three different period bands and in the 90 to 110 second band just after **M** ≥ 6.5 earthquakes (reproduced from Ringler *et al.* 2010).

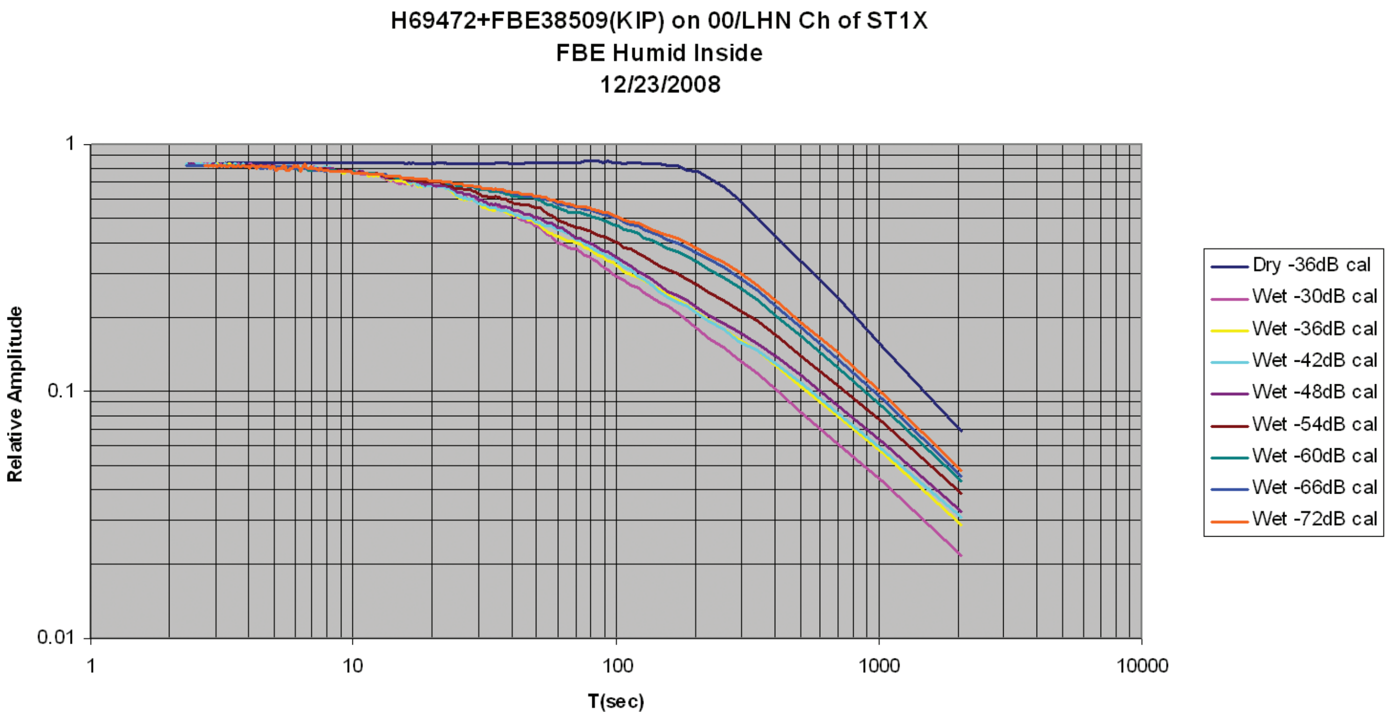
We performed a series of similar experiments with other FBEs. All FBEs associated with over-damped responses in the field showed similar behavior to the KIP FBEs when the interiors of the boxes were exposed to highly humid air. This was not the case when only the exteriors of the FBEs were exposed to air with high humidity. Many of the malfunctioning FBEs from the field showed evidence of corrosion and growth of oxides or mold on the printed circuit boards and components. In comparison, the clean, dry FBEs from ASL's stock of spares performed normally when their interiors were exposed to highly humid air. We did not experiment with moistening the seismometer baseplate connector, as Yuki and Ishihara (2002) did.

To investigate the linearity of the over-damped response, we conducted experiments using variable amplitude signals on some of the malfunctioning FBEs. Our tests indicate that the effect is non-linear, resulting in lower amplitude response at higher signal amplitudes (Figure 4). This result agrees with the observation that response changes are observed mostly when moderate-to-high levels of ground motion from fairly large earthquakes (**M** > 6.5) are recorded at GSN stations with STS-1 seismometers (Ekström *et al.* 2006).

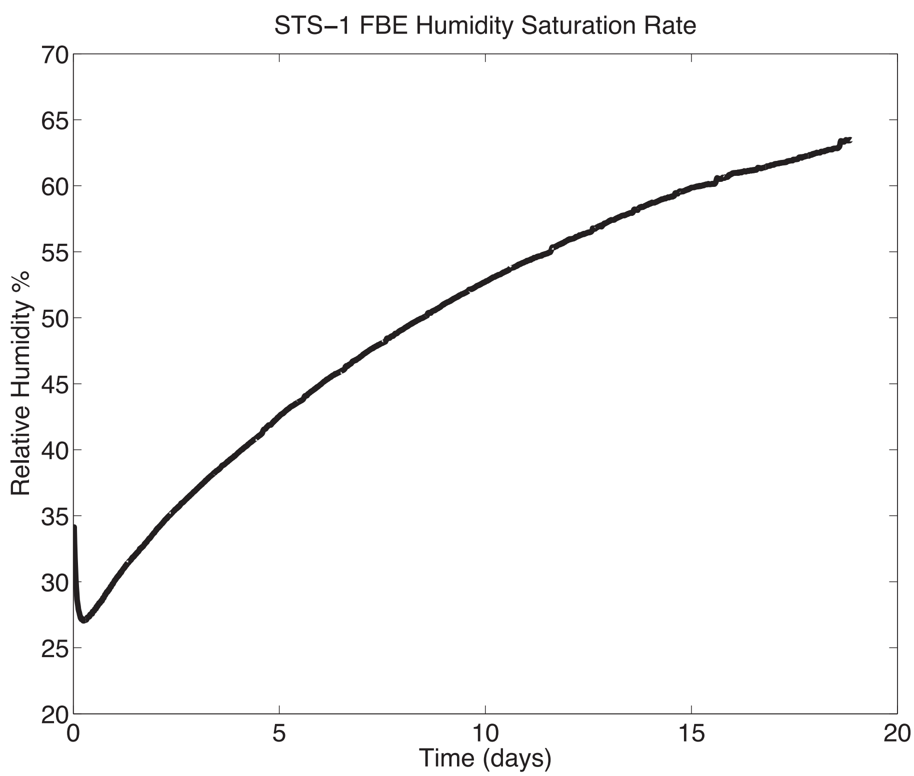
In at least some cases, the onset of the lowered response appears to be time-dependent (the response changes with time). In the case of KIP, the amplitude response in the 90–110 second band gradually became lower during a two-year period (Figure 3). It appears that, even though the original Streckeisen FBEs are designed to be sealed, water vapor can penetrate their interiors after they have been in humid vault environments for extended periods. Evidence that the FBEs are not always sealed is shown in Figures 5, 6, and 7. Figure 5 shows that humidity inside a "sealed" FBE gradually increases with time when it is placed in a high humidity environment. This is evidence that the FBE is leaking. Figure 6 further confirms this, showing that air pressure inside two different "sealed" FBEs closely tracks external atmospheric pressure. A final test is documented in Figure 7, in which a "sealed" FBE was placed in water and then a slight external vacuum (about 10 mm Hg) was applied. As seen in the photograph, air bubbles began escaping from the inside of the FBE, mostly from around the connectors, providing an air leakage path between the internal electronics and the outside atmosphere. These various tests indicate that the connector mounting method does not provide an air tight seal against the metal box. Gradual replacement of dry air inside a leaky FBE box with humid vault air, eventually overcoming the capacity of the dessicant inside to absorb water vapor, would explain the time-dependent nature of the lowered response.

EXAMPLES OF OVER-DAMPED RESPONSES AT SOME GSN STATIONS

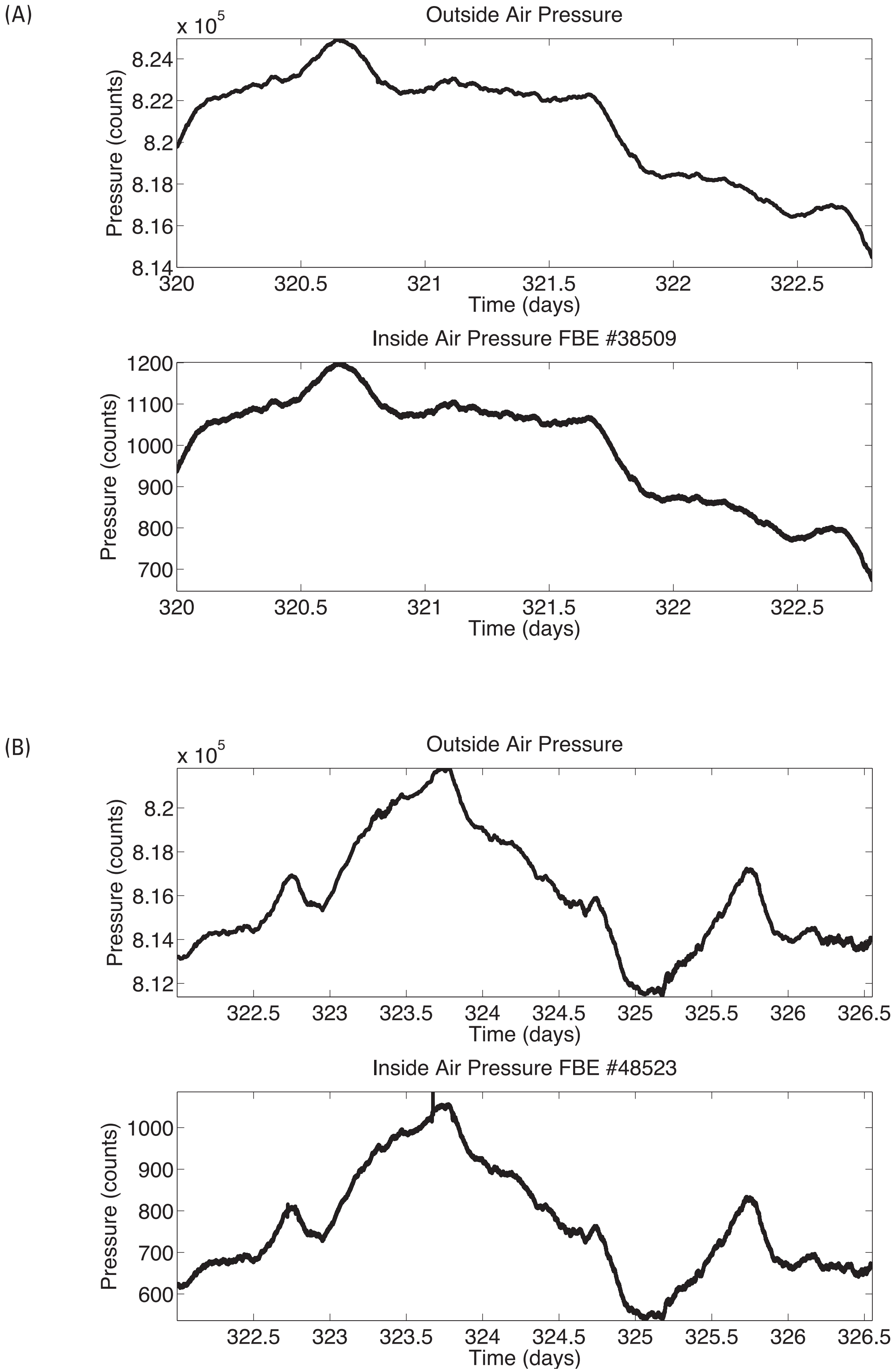
In some cases where STS-1 seismometers have been observed to have over-damped responses, multiple-amplitude calibrations indicate that the amplitude response does not depend on the input signal amplitude. Since the response-determining elec-



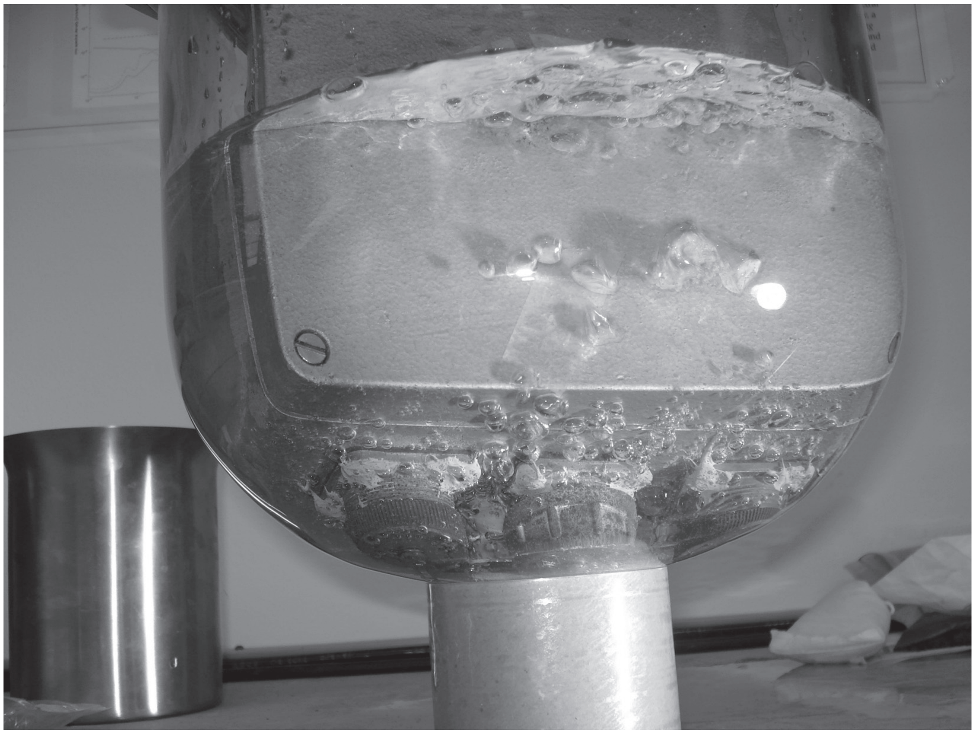
▲ **Figure 4.** Relative amplitude responses derived from calibrations using random telegraph signals for the vertical FBE #38509 that was installed at KIP until May 2006. The "Dry -36dB cal" (upper dark blue line) was done with dessicant inside the FBE. All other calibrations shown (the lower lines in the plot) were done with the interior of the FBE at about 90% relative humidity. Note the decrease in amplitude response with increasing calibration amplitude. The -30dB calibration results in driving the output to more than half of full scale; the -72dB calibration results in driving the output to about 1/200 of full scale. At very long periods (>40,000 seconds period, not shown on plot), the lowered responses are asymptotic to the "Dry -36dB cal" response.



▲ **Figure 5.** Relative humidity as a function of time inside a "sealed" FBE with insufficient dessicant inside. The FBE was exposed to an external 90% humidity environment.



▲ **Figure 6.** (A) Upper panel is ambient air pressure, lower panel is pressure inside "sealed" FBE #38509 (former KIP vertical FBE). (B) Upper panel is ambient air pressure, lower panel is pressure inside "sealed" FBE #48523 (former OTAV horizontal FBE).



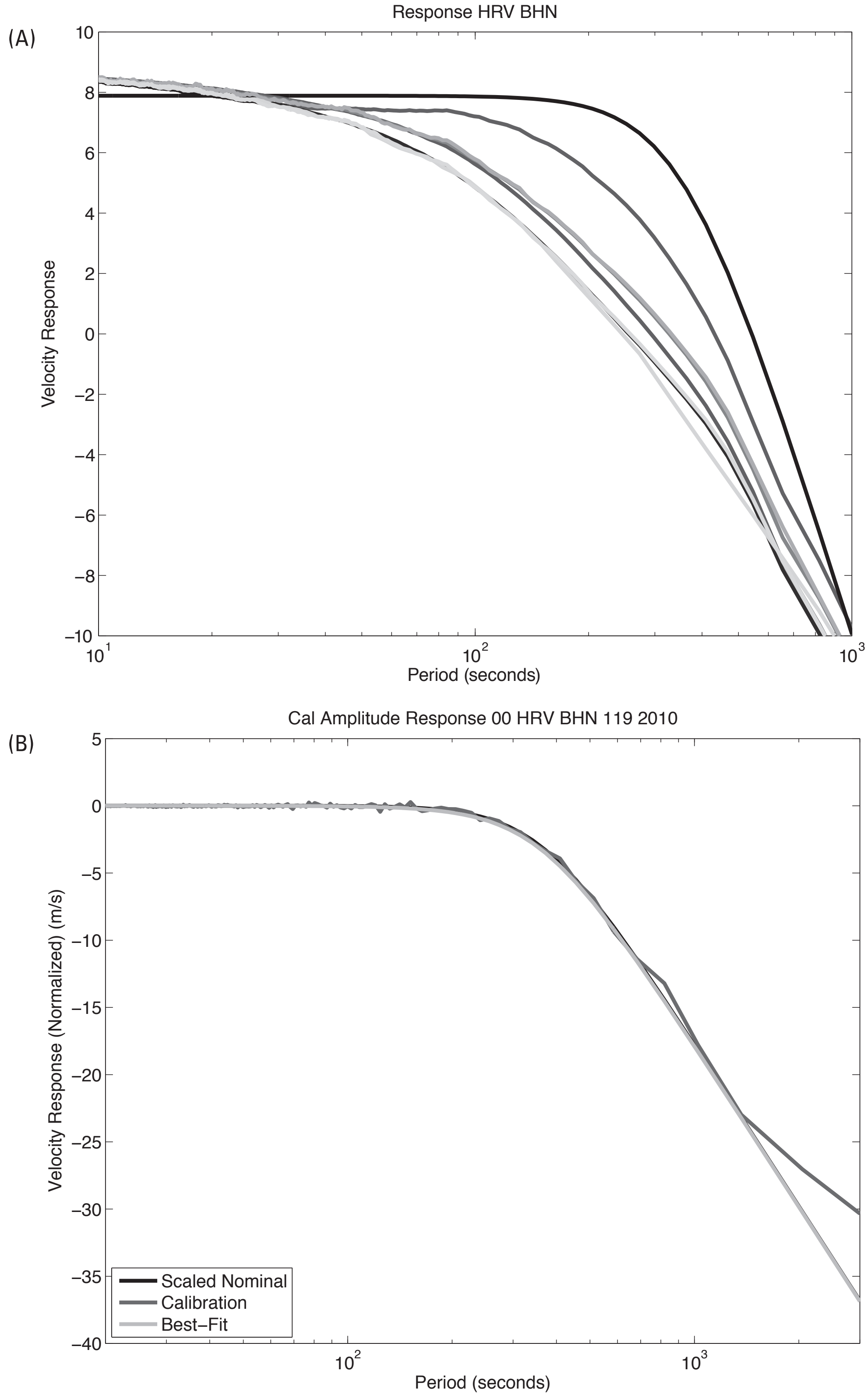
▲ **Figure 7.** FBE placed inside vacuum chamber (inverted STS-1 glass bell jar) with connector end under water. When a slight vacuum (~10 mm Hg) was applied, air inside the FBE bubbled out through connectors and connector screw holes. Air was also leaking past the lid gasket on the right side (not visible in photo).

tronics are all contained inside the FBE, this is a likely indication of purely resistive electrical leakage outside the FBE, such as in a connector or in the seismometer itself. (A pure resistor is a linear device and will not change its resistance with changes in voltage applied across it. On the other hand, the active response-determining elements inside the FBE may respond in a non-linear fashion to voltage changes because of multiple leakage paths.) One such example is the NS component at station HRV (Harvard, Massachusetts), which exhibited an increasingly over-damped response from 2008 to early 2010 (Figure 8). During a maintenance visit to HRV in April 2010, it was found that the bell jars of both horizontal instruments had lost vacuum, resulting in high humidity inside the bell jar and around the connector that routes signals from the FBE to the inside of the bell jar. In both cases, the connector and associated cable going to the seismometer were replaced. Upon removal, the original connector of the NS seismometer was found to have solder flux between some of the pins, resulting in leakage between feedback paths under high humidity conditions. Since there is little or no increase in noise levels when a horizontal seismometer's bell jar loses its vacuum (unlike the case for the vertical component), quality control personnel are unable to observe this change as it does not immediately compromise the quality of data. Of course, loss of vacuum means that potentially very humid vault air then enters the bell jar and can cause pin and solder joint corrosion or mold growth, resulting in electrical leakage between conductors in these very small connectors.

At station KMBO (Kilima Mbogo, Kenya), the result was excessive corrosion of the solder joints (Figure 9). In this case, replacement of these connectors and cables corrected the lowered long-period response problem.

There are other examples of lowered long-period responses (over-damped at the long-period corner). At station SDV (Santo Domingo, Venezuela), all three components had over-damped long-period corners in 2004. During a maintenance visit in January of 2010, SDV was upgraded, including replacing the Streckeisen FBEs with a hermetically sealed Metrozet E-300 FBE. The vertical seismometer was also replaced, and the baseplate for the NS component was rebuilt. After all of these steps were taken, the Z and EW components had amplitude responses that matched the manufacturer's nominal response closely. The NS component still exhibited an over-damped long-period corner, but the response was no longer found to be amplitude dependent. Electrical leakage between cable conductors or connector pins somewhere in the system is suspected to have been the cause of the change in response characteristics.

At station KIP, replacing the three original FBEs in mid-2006 with newer Streckeisen FBEs having fresh dessicant inside solved the problem temporarily. While the vertical component still appeared to be okay in early 2010, both horizontal components had gradually developed an over-damped response at the long-period corner (a time-dependent change in response). Replacing dessicant in the new FBEs did not solve the problem, and drying out the connectors also had no effect. Multiple-amplitude random calibrations indicated that the lowered response was not dependent on amplitude, meaning that the problem may not have been due to excessively humid air inside the FBEs, but instead may have been due to spurious electri-



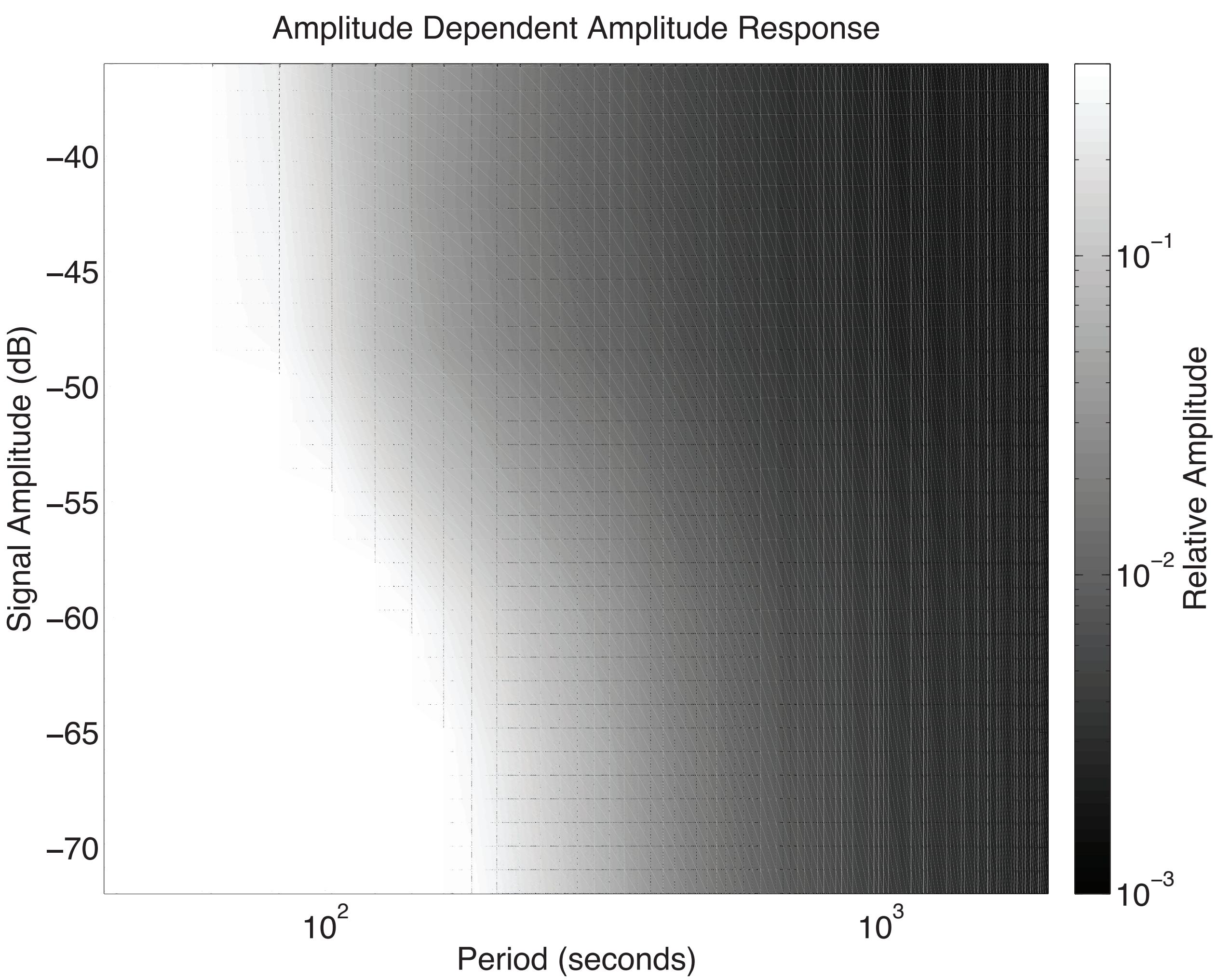
▲ **Figure 8.** (A) HRV NS amplitude responses over time, from 2008 to early 2010. Upper black curve is the manufacturer's nominal response. Below the nominal response, darker colors indicate older responses, while lighter colors indicate more recent responses. This shows that the response was gradually getting more over-damped with time. B) HRV NS amplitude response after replacing internal cable and connector and pumping down bell jar in April 2010. The black curve is the response to a random calibration signal, the gray curve is the best pole-zero fit. The nominal response is also plotted in black, but it is completely covered by the gray curve, showing that the best-fit calibration response matches the manufacturer's nominal response very closely.

▲ **Figure 9.** Magnified view of connector pins from one of the STS-1 seismometer baseplates at GSN station KMBO. This corrosion resulted in electrical leakage between conductors, which caused an over-damped long-period response.

cal leakage paths outside the FBEs (such as in connectors either inside or outside the bell jars). The problem was corrected during a maintenance visit in August 2010 by replacing cables, connectors, and the Streckeisen FBEs with a hermetically sealed Metrozet E-300 FBE. It was necessary to replace both horizontal STS-1 seismometers to completely solve the problem.

REPRESENTATION OF NON-LINEAR RESPONSES

In some cases, we found that the over-damped response at the long period is non-linear and time-dependent. In these cases, it is not possible to represent the response with a linear, time-invariant pole-zero model, the currently used method for publishing instrument metadata (Havskov and Alguacil 2004). ASL is investigating ways to properly represent the response of such a non-linear system. One possibility is to use a listing (tabulation) of amplitude and phase response as a function of frequency and amplitude (Figure 10). This could possibly be done in SEED (Ahern *et al.* 2007) as a variation of blockette 55 (Response List Blockette), with multiple lists for various ampli-



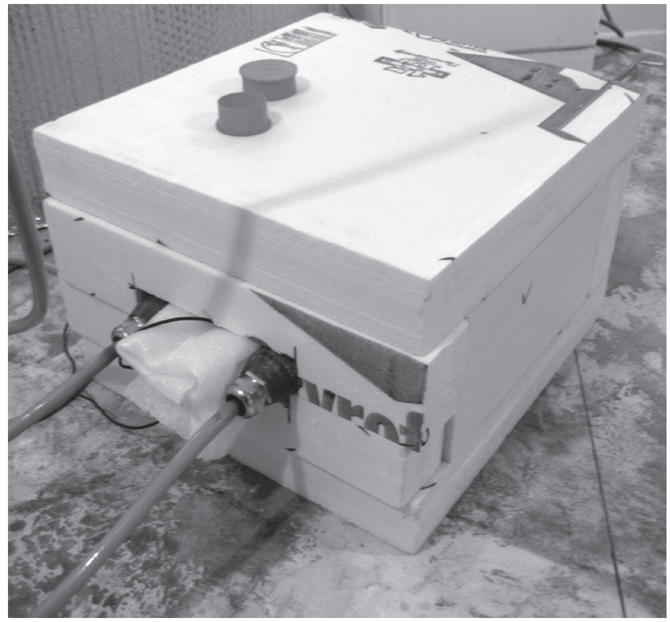
▲ **Figure 10.** Amplitude dependent amplitude response. This provides one way to describe the amplitude response when it is shown to be amplitude dependent. The vertical axis indicates the signal amplitude while the horizontal axis indicates the period of the signal. Finally, the gray scale indicates the relative amplitude response of the instrument.

tudes. However, since it is not possible to go back in time and calibrate affected components using multiple-amplitude calibrations, it may not be possible to characterize some of the older data in this way. The time-dependent effect further complicates the job of describing the instrument response. This can be dealt with by modifying metadata as often as is necessary to meet the GSN design goal of knowing the response to within 1% (GSN ad hoc Design Goals Subcommittee 2002). In order to prevent non-linear response issues from compromising future GSN data, the affected FBEs are being replaced as quickly as possible with Metrozet E-300 FBEs, which are hermetically sealed.

SOLUTIONS

As indicated by Yuki and Ishihara (2002), the main problem is moisture and high humidity in cables, connectors, and FBEs. Associated problems include loss of vacuum in the STS-1 protective bell jars, corrosion of connector pins, and incomplete cleaning of flux and debris from between the pins when cables are constructed. Solutions to these problems include:

1. Keeping connectors as dry as possible. For connectors external to the evacuated bell jars (those exposed to potentially very high humidity environments), this means thoroughly drying out the connectors and using special techniques to keep moisture away from the connector pins. These techniques include replacing connectors with special connectors designed for this purpose, using potting compound on the backs of connectors (where wires are soldered to connector pins) to keep moisture out, and using silicone grease on connector faces to prevent moisture intrusion.
2. When making up connectors, using good soldering and cleaning techniques to make sure that there is no flux or other debris left between connector pins. It is important to further verify the integrity of the cables and the absences of additional flux by looking at the connector pins under a magnifying glass. It is also important to check for very high (>100 Mohm) resistances between conductors.
3. Replacing the original FBEs with hermetically sealed FBEs. If the latter are not available, one can try better sealing the original FBEs by replacing lid seal gaskets and by placing gaskets under the connectors and screw heads holding them to the case (the most likely air leakage path is through the connector screw holes). Also replace dessicant in the FBEs annually. Another solution is to seal the entire FBE in another enclosure such as a heavy plastic bag containing a large amount of dessicant, taking care to seal around the cable entrances to this external enclosure. Additionally, one can place the FBEs in insulated boxes to keep them further isolated from environmental conditions (Figure 11).
4. Taking steps to ensure that a good vacuum is maintained on all seismometer bell jars. This includes routinely manually checking the vacuum (perhaps monthly) or by monitoring the vacuum electronically and transmitting that information (as state-of-health channels) to the network control center. The latter method can be achieved with an inexpensive vacuum monitor attached to the vacuum valve on the aluminum ring below the bell jar and recording its output on a datalogger auxiliary channel (Figure 12). Of course, when loss of vacuum is detected, it is important to evacuate the bell jar as soon as possible.
5. Replacing the seismometers themselves. This step may be necessary only in rare cases but should be left as a possibility when making maintenance visits to remote stations, where frequent visits are prohibitive.

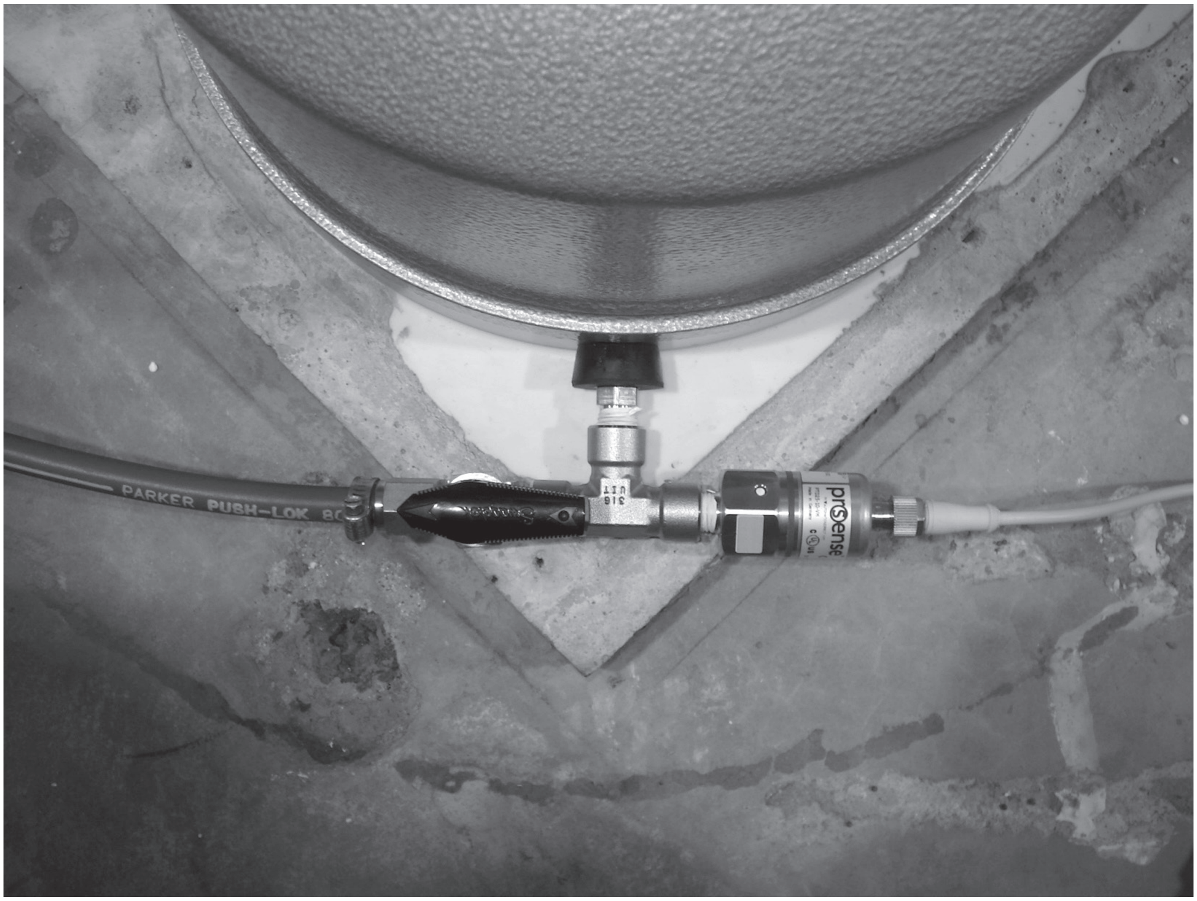


▲ **Figure 11.** Insulating box around FBE at GSN station HRV. The heat dissipated by the FBE (about 3.5 watts), along with this extra insulation, helps keep the FBE warmer, thus reducing relative humidity in and around the FBE and its connectors.

SUMMARY

Water vapor and moisture in the STS-1 feedback electronics boxes, cables, connectors, and seismometers appears to explain many of the response anomalies observed by the WQC. Our investigations indicate that high humidity conditions can modify the response of the STS-1, producing an over-damped corner at 360 seconds period. In particular, excessively humid air inside the FBEs can produce non-linear responses. The effect of the over-damping has the largest effect near the 360-second corner, but has very little effect on the response at periods far away from the corner, such as at microseismic periods (and shorter periods) and at tidal frequencies (Figure 8A).

We estimate that 35 of the 140 STS-1 channels (approx. 25% of STS-1 components) in the USGS portion (network codes IU and IC) of the GSN had over-damped long-period response corners in February 2010. In 17 of these cases, this lowered response may have been non-linear, probably due to excessively high humidity *inside* the FBEs. The cause of the lowered (but linear) response for the other 18 cases was likely due to electrical leakage in connectors and cables external to the FBEs, and in the seismometers.



▲ **Figure 12.** Stainless steel T-connection with *ProSense* PTD25-10-VH vacuum transmitter attached to the right branch of the T. Attached to the left branch of the T is a Teflon ball valve (controlled by the black handle) and vacuum hose, which is attached to a vacuum pump (only used during pump-down of the vacuum chamber). In this case, the STS-1 vacuum jar is a double-walled aluminum model instead of the usual glass bell jar. The USGS is currently installing vacuum monitoring equipment like this on all STS-1 vacuum chambers at all GSN stations in the IU and IC networks.

As part of the effort to ensure the correctness of the metadata, the GSN now performs annual calibrations of both the primary and secondary sensors. This effort is facilitated by the current effort to upgrade from older dataloggers to the Q330 HR system. As part of the upgrade process, the original STS-1 FBEs are being replaced with Metrozet E-300 FBEs (which are hermetically sealed) and all suspect cables and connectors are being replaced as well. In addition, we are installing secondary sensors at stations where only one broadband instrument is currently in operation.

At those problematic stations where upgrades are not imminent, we are replacing the dessicant in the original FBEs. As of January 6, 2011, the number of USGS GSN stations with STS-1 channels having observed lowered responses has been reduced from 35 to 15 channels. The vast majority of those that have not been repaired are located at stations having limited access for maintenance (*e.g.*, IC network stations and remote stations like CASY [Casey, Antarctica]).

Initial work has begun in developing methods for modeling amplitude dependent over-damped responses, using both linear and non-linear models (Figure 10). For stations with non-amplitude dependent over-damped corners we have begun modeling the response with a linear pole-zero model and updating the instrument's metadata to better describe the instrument's response parameters. For those stations for which we have identified amplitude dependent (non-linear) responses, we plan to propose possible ways of representing these non-standard responses in SEED format metadata. Finally, by deploying broadband co-located sensors at all GSN stations and calibrating all instruments routinely (perhaps annually or bi-annually), we hope to prevent the over-damped response problem from compromising the integrity of GSN data as well as prevent future response problems at GSN stations.

ACKNOWLEDGMENTS

We thank P. Davis, G. Ekström, L. S. Gee, and M. Nettles for many useful discussions that helped in identifying the observed response problems. We thank the ASL field engineers and QC staff for all of their hard work correcting these observed response problems. We thank L. D. Sandoval and D. Wilson for careful reviews of the manuscript. Finally, we thank J. Steim for useful discussions about the feedback electronics of STS-1s along with ideas on describing non-linear response metadata.

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