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# Performance of the Barry Controls, Inc. STACIS active isolation system

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# 1 ABSTRACT

The performance of a commercial active seismic isolation system is described. The active system serves as a first stage of isolation, providing suppression of ground motion in the 1-200Hz frequency band while supporting a passive isolation stack. The behavior of the active system in the presence of stationary and non-stationary ground noise is studied. The response to stationary noise shows a maximum ground noise suppression of about 40 dB at 10 Hz. The system also suppresses typical impulsive events by a factor of 20-30.

# 2 INTRODUCTION

This technical note describes the performance of an active seismic isolation system (product name STACIS) recently developed by Barry Controls, Inc. In March 1994 we tested an alpha version, which provided active control of three degrees of freedom. We have recently tested the beta version of the system, which provides control of six degrees of freedom, and this report refers to the performance of the beta version. Some differences between the beta version and the production version are described later.

At MIT, the STACIS isolators will be used as a first stage of seismic isolation in the Phase Noise Interferometer project. They are mounted on the ground, outside the vacuum system, and support the passive isolation stacks, with bellows providing the seal to the vacuum enclosure.

# 3 DESCRIPTION OF STACIS

The STACIS system consists of three isolation feet and a control unit (which, in the beta version, only provides power to the feet). The three feet are independent from each other; there is no mixing of sensing or control signals among them. Each foot senses and corrects for velocities in three mutually perpendicular directions. By controlling three degrees of freedom at three separated points, the system provides six degree-of-freedom isolation for the payload.

Each foot contains an inner block in which three velocity sensors (geophones) are mounted; two of them sense velocities parallel to the ground and the third senses in the vertical direction. The geophone signals are amplified and filtered with analog electronics, all of which is located on a board in the foot. The control signals are then amplified by a HV amplifier (0-900 V) and sent to the actuators, which are PZT stacks.

The inner block sits on three vertically-oriented PZT stacks; these stacks provide the actuation in the vertical direction. The roughly cylindrical inner block sits inside a cylindrical housing. Two horizontally oriented PZT stacks are mounted on the housing and contact the inner block; these provide the actuation in the horizontal directions. The HV amplifiers are normally mounted underneath the housing, in a U-shaped structural base. In our case, the amplifier box and U-base have been removed, and the amplifiers mounted to the side of the foot; this was done to decrease the height of the isolator, necessary because of height constraints.

The connection of the inner block to the payload is made through a passive (rubber) isolator. The cylindrical passive isolator sits in a cylindrical recess in the inner block; it is a Barry Controls model 512 mount.

The range of the PZT actuators is approximately 40 μm for the full range of the HV amplifier. The load bearing capacity is 2500 lbs/foot, or 7500 lbs for the system. This is limited by a depoling of the vertical PZTs under high pressure.

The sensors are 4.5 Hz resonant frequency geophones manufactured by Geospace, Inc. (model HS-1). A Barry Controls engineer has measured the noise floor of the geophone and its preamplifier. From 10-100 Hz, the equivalent displacement noise is roughly $x(f) = 3\times10^{-12}(10\text{ Hz}/f)^{3/2}\ \text{m}/\sqrt{\text{Hz}}$ . If one extrapolates this down to 1 Hz, taking into account the 4.5 Hz resonant frequency, the equivalent displacement noise would be $x(1\text{ Hz}) = 5\times10^{-10}\ \text{m}/\sqrt{\text{Hz}}$ .

In the production version of STACIS, the control unit mentioned above will provide access to the amplified geophone signals in the feet; all three geophone signals will be available from each foot, and the control unit will allow one to select between the three feet. In addition the control unit will display some system fault error codes.

# 4 IMPLEMENTATION OF STACIS AT MIT

The STACIS system is used underneath the passive isolation stack in the large chamber of the MIT 5m vacuum system, as a mounting platform for the stack. The three STACIS feet sit on a common concrete slab, which is decoupled from the floor and from the concrete columns that support the chamber. The legs of the stack's support plate can be supported either by the STACIS feet, or directly on the ground by lowering three jack-stands (see Fig. 1). In this way the STACIS system can be installed and removed without disassembling the stack.

The vacuum seal is made with a vertically oriented bellows at each foot. They are stainless steel formed bellows, made by HPS. One concern has been the coupling of ground motion through these bellows to the stack's support plate. The axial compliance of the bellows is 100 lbs/in.; they are stiffer in the horizontal (shear) direction, but this compliance has not been measured. The bellows connection is a possible flanking path for ground noise, of which more will be said later.

The weight of the stack's support structure (bottom plate, three vertical posts, three jack stands) is 965 lbs. The stack leg elements weigh 1800 lbs total, and the stack top plate weighs 720 lbs.

When the STACIS system was first installed underneath the MIT stack, the horizontal servo

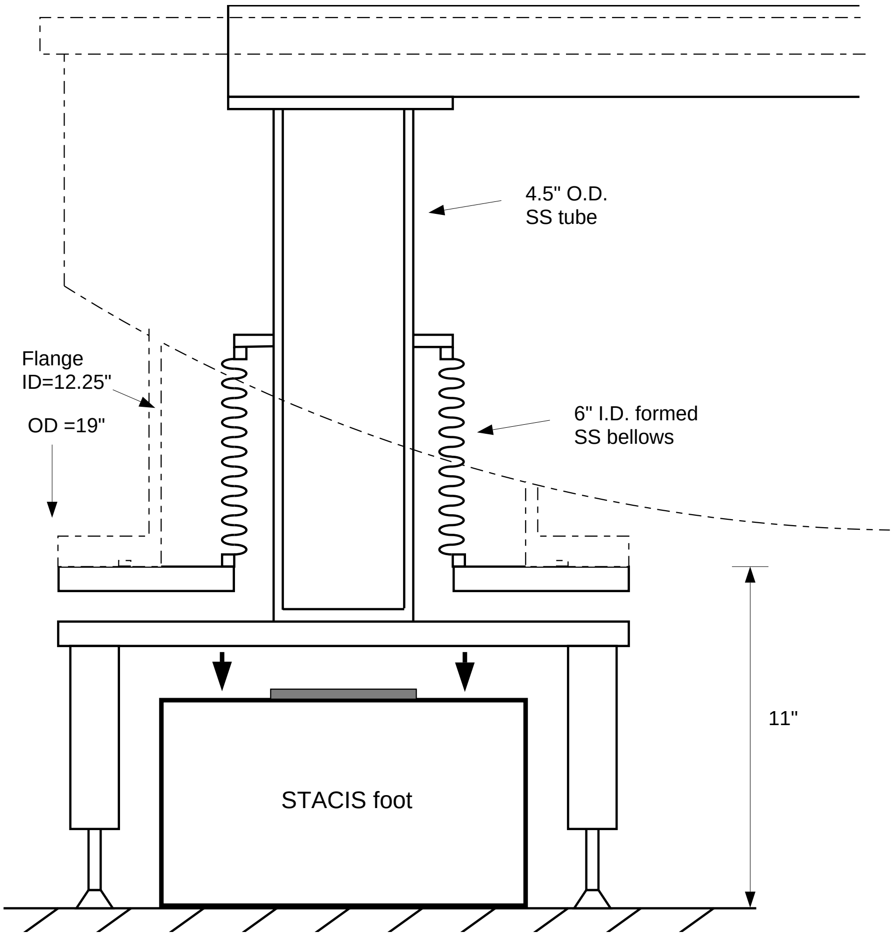


Figure 1: Tank foot

loops were not stable, though the vertical loops were. Open loop transfer function measurements seemed to show that the passive isolator was not performing as expected. A horizontal transfer function between motion of the inner block and motion of the payload showed an unusual resonance behavior at 90 Hz, with 180° of phase lead and 10 dB dip in amplitude. The vertical transfer function showed the resonant response expected of the passive isolator, with a resonant frequency of 80 Hz.

A piece of compliant material (a 3” x 3” x 1/4” thick piece of EAR Isodamp C-1002) was added between the STACIS foot and the payload. This changed the character of the preceding open loop measurement, so that it was similar to the vertical response. It was then verified that in fact this change led to stable closed loop performance in all degrees of freedom. This behavior is not understood, but it is believed that there was either some rocking motion in the STACIS-payload interface, or that the STACIS passive isolator was acting very stiff (or mechanically shorted).

All three feet were modified in this way. Following that, the loop gains for the nine loops were adjusted for maximum gain (consistent with a given phase margin at the unity gain points).

# 5 MEASUREMENTS ON THE STACIS SYSTEM

## 5.1. Measurements by Barry Controls

Open loop measurements and ground-inner block transfer functions were measured by Barry Controls personnel at MIT, taking the signals from the circuit boards in the feet. These transfer function were very similar in all three feet. They showed that the servo bandwidth (frequencies where open-loop-gain ≥ 1) is 1-250 Hz for the horizontal loops, and 0.5-300 Hz for the vertical loops, with the gain peaking at 40 dB at 10 Hz. The ground-inner block transfer functions with the loops closed, (Figure 2), are consistent with the open loop measurements, though the data is poor at high frequencies (the measurements were made with seismic noise excitation, which falls very steeply with frequency).

## 5.2. Measurements by MIT: stationary noise

We installed 3-axis geophones (velocity sensors) on the ground and on the stack support table, and measured transfer functions with seismic noise excitation. Vertical and horizontal transfer functions are shown in Fig. 3, with information about where the coherence is larger than 0.5 and 0.75. Note that in theory these measurements include not only ground noise suppression due to the servo loop gain, but also ground noise filtering at high frequencies due to the passive isolator (though in practice the measurements at high frequencies do not have good coherence).

The vertical transfer function is consistent with the open loop and ground-inner block measurements, achieving a maximum isolation of 40 dB between 10 and 20 Hz. The horizontal transfer function, however, levels off at -20 dB from 3-10 Hz, and then falls another 10-15 dB, achieving a maximum isolation of 35 dB from 30-40 Hz. This is not consistent with the open loop gain or ground-inner block measurements, which do not level off in the 3-10 Hz region. The reason for this is not well understood, but some possible explanations are:

- Seismic noise is leaking through the bellows. Neglecting the internal resonance of the bellows, this should be in the ratio of the bellows spring constant to the spring constant of the passive isolator.
- There are mechanical resonances in the system in the 3-10 Hz band. We don’t know the horizontal compliances of either the passive mount or the added piece of elastomer.
- There is some cross-coupling between the feet or between vertical and horizontal degrees of freedom that is compromising the horizontal performance.

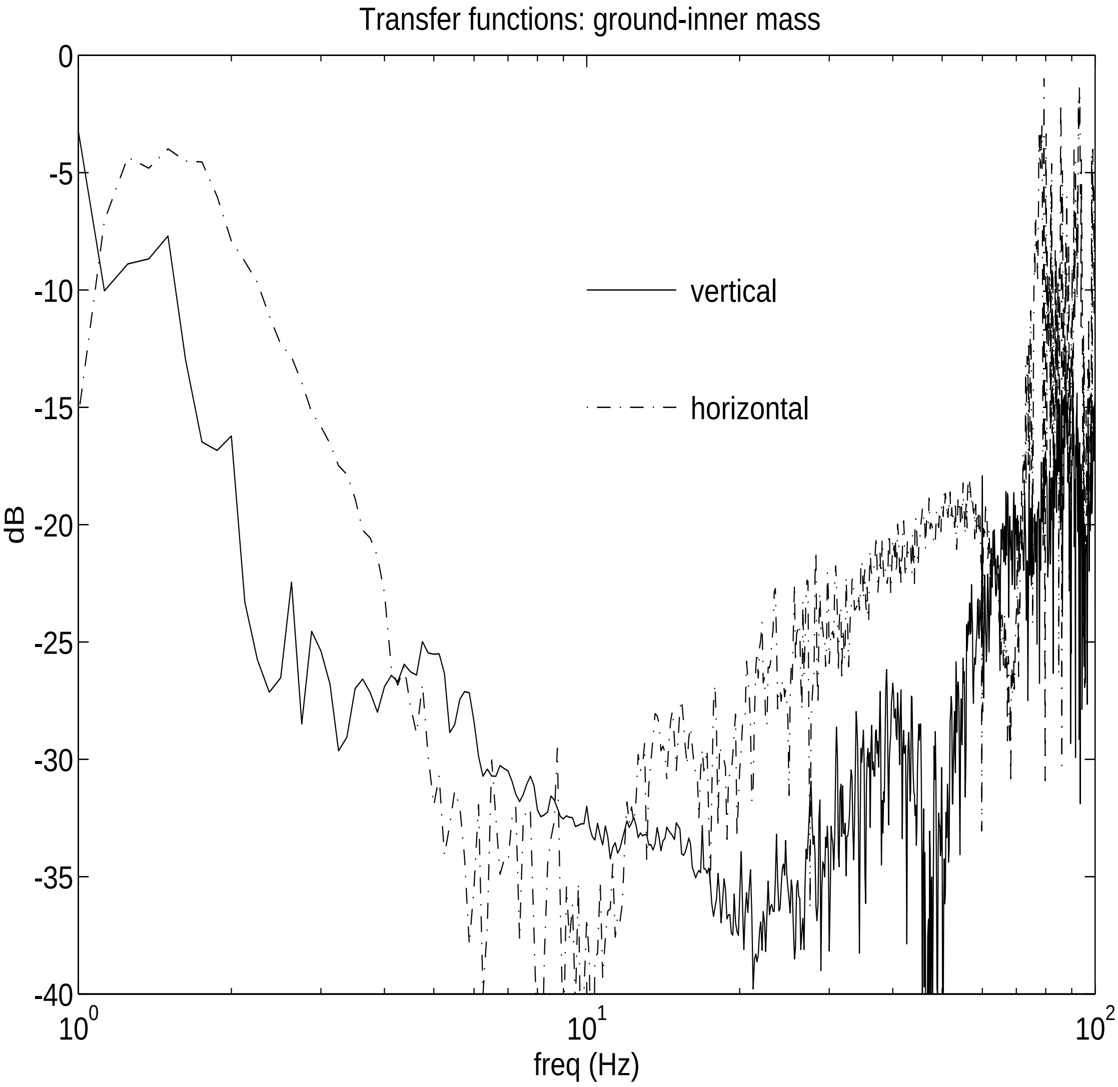


**Figure 2: Transfer functions ground-inner mass in active isolators.**

We would like to be able to decouple the bellows to determine their effect, but this is not possible without disassembling the stack. We looked for a sign of the first two hypotheses by increasing the area of the added piece of elastomer (from 6 in. sq. to 16 in. sq.) The assumption was that the horizontal spring constant should have changed noticeably (the larger area making it stiffer); the ratio of bellows compliance to rubber compliance therefore should have changed, as well as any resonance associated with the piece of elastomer. However, no significant change in the horizontal transfer function was seen. This seems to indicate that the compliance of the passive mount (in the STACIS foot) is smaller than the compliance of the added piece of elastomer.

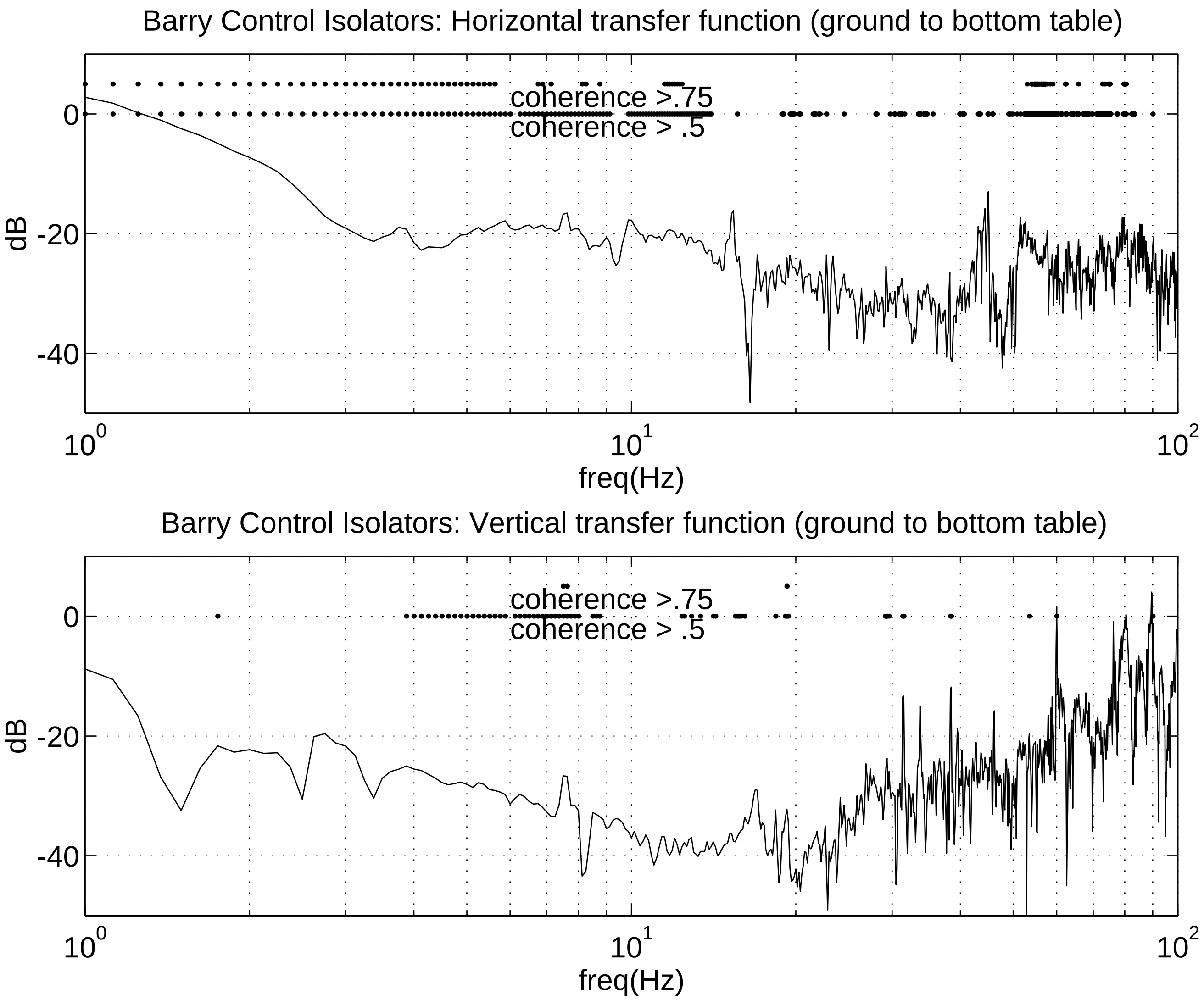
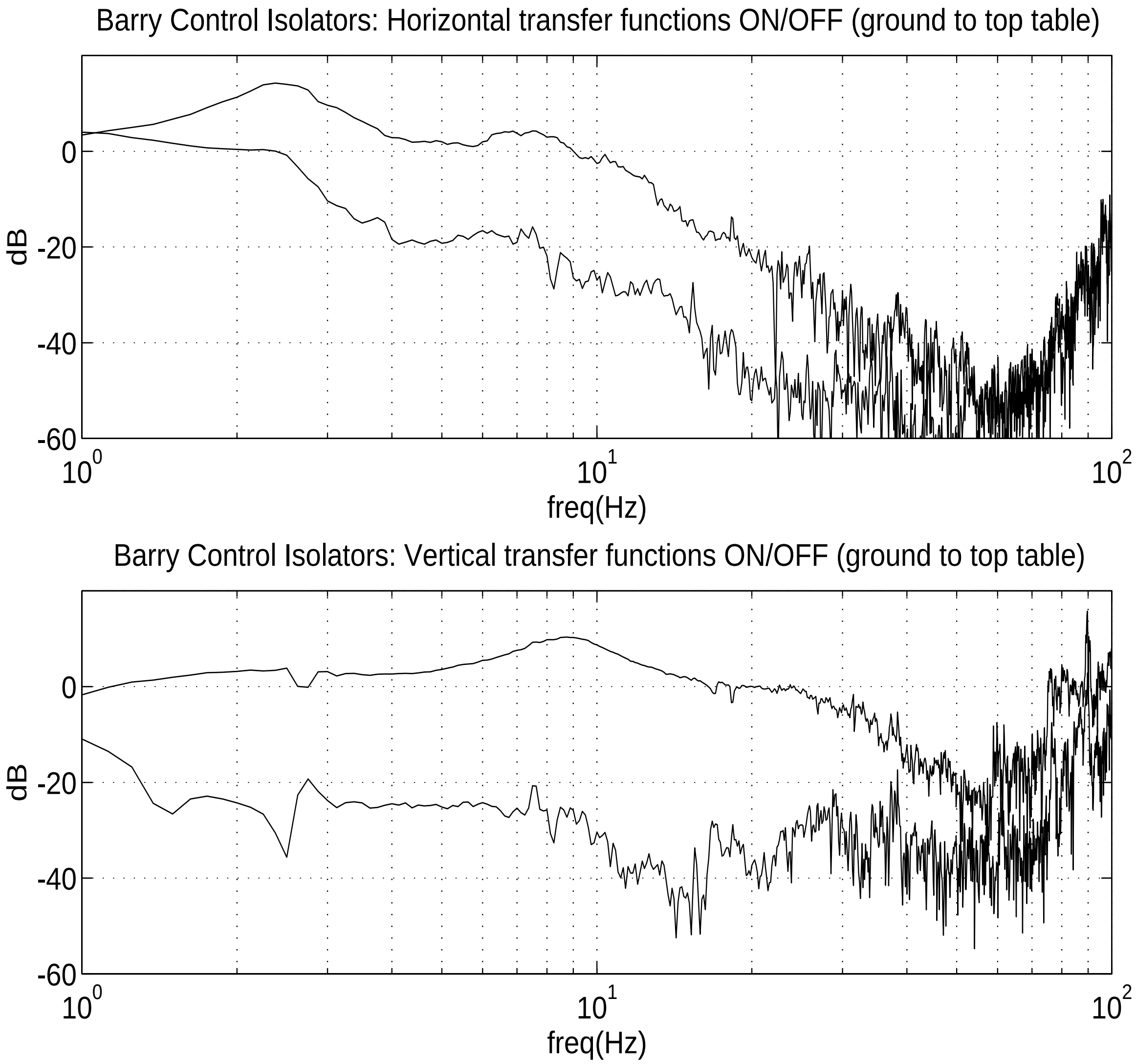


**Figure 3: Transfer functions**

Figure 4 shows the transfer functions from ground motion to optical table motion (the top plate of the stack), with STACIS turned on and off. Stack resonances can be identified at 2.5 Hz and 9 Hz. In the servo band, active isolation provides 20 to 40 dB of ground noise suppression in addition to the suppression provided by the passive isolation. The horizontal active isolation is again not as good as the vertical. The rise in the transfer function above 60 Hz does not represent decreased isolation - it is due to measurement noise and lack of coherence at those frequencies. Figure 4 shows one of the main benefits of the active isolation: suppression of motion at the stack resonant frequencies. With the active and passive isolation together, the optical table motion is never larger than the ground motion.


Barry Control Isolators: Horizontal transfer functions ON/OFF (ground to top table)

Barry Control Isolators: Vertical transfer functions ON/OFF (ground to top table)

**Figure 4: Transfer functions ground-optical table with STACIS on/off.**

For reference, Figure 5 shows the calibrated power spectrum of horizontal seismic noise on the optical table and support table, and on the ground, with active isolation active and inactive.

## 5.3. Measurements by MIT: Non-stationary noise

The feature of seismic noise that is not captured by the transfer function measurements is non-stationary noise. These are impulsive events, of short duration and large amplitude, which may or may not have a characteristic frequency. To investigate the rate and amplitude of these events, and the response of the active isolators to them, we implemented a threshold detection on the geophone signals. The vertical and one horizontal signal from the ground and support table

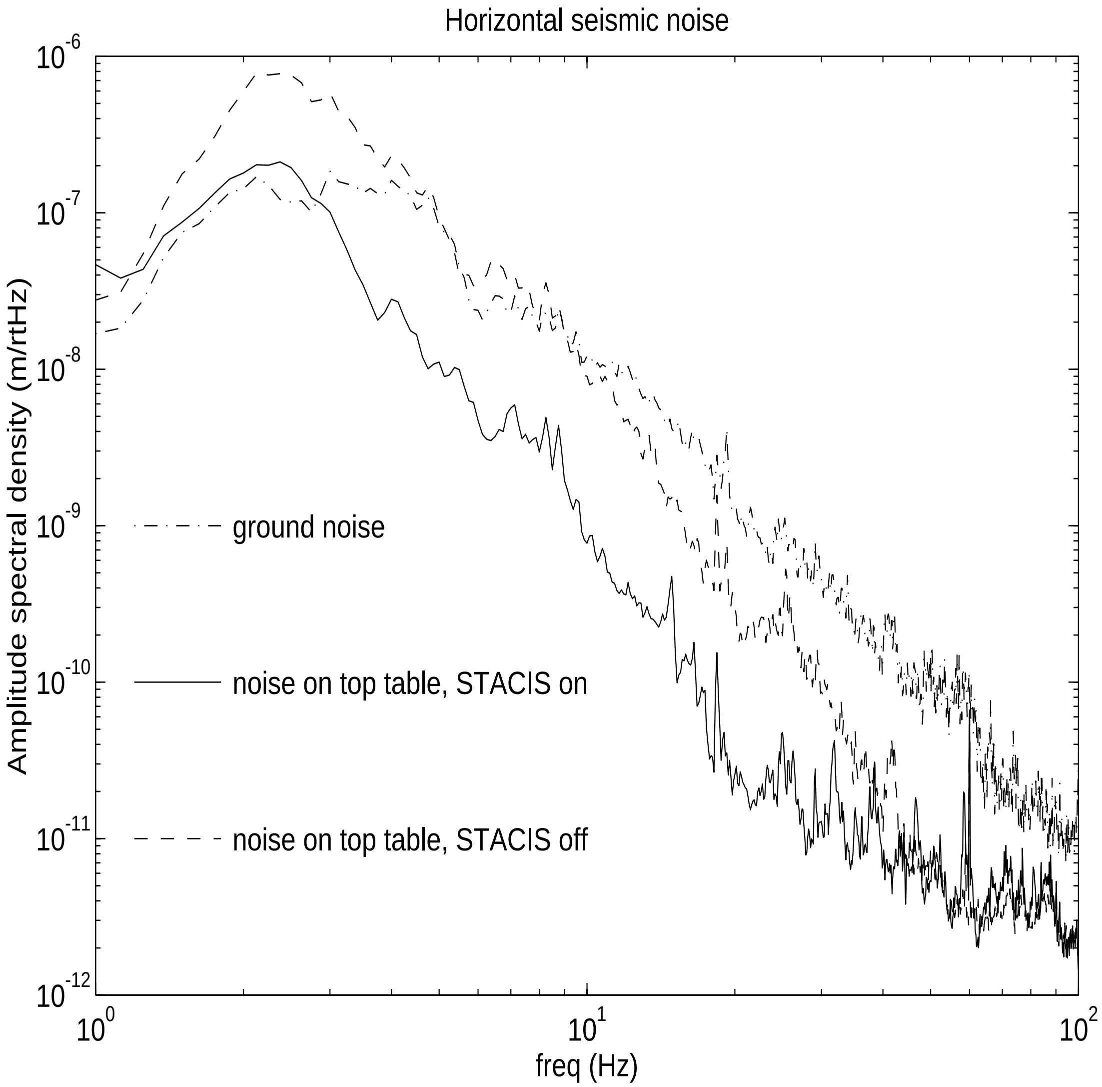


**Figure 5: Seismic power spectra**

were passed through a 1 second integrator (to make a signal proportional to displacement), and sent to a computer, sampling at 100 Hz. Signals that crossed a threshold of 6 microns in any of the four channels were captured in a 0.5 second long data block. This program was run for 36 hours on May 16 and 17, 1995. Figure 6 shows histograms of the maximum peak value in each recorded event (signals that span more than one consecutive block are considered as one event).

Over 24 hours, about 2000 events crossed a 10 micron threshold in both the horizontal and vertical ground signals. In the same period of time, less than 20 events crossed the same threshold in the support table signals - a suppression of more than 100 in the number of events above this threshold. The reduction in amplitude of these events is typically a factor of 20-30. Larger events exceeded the threshold on the support table more frequently: of 16 events in the horizontal and 94

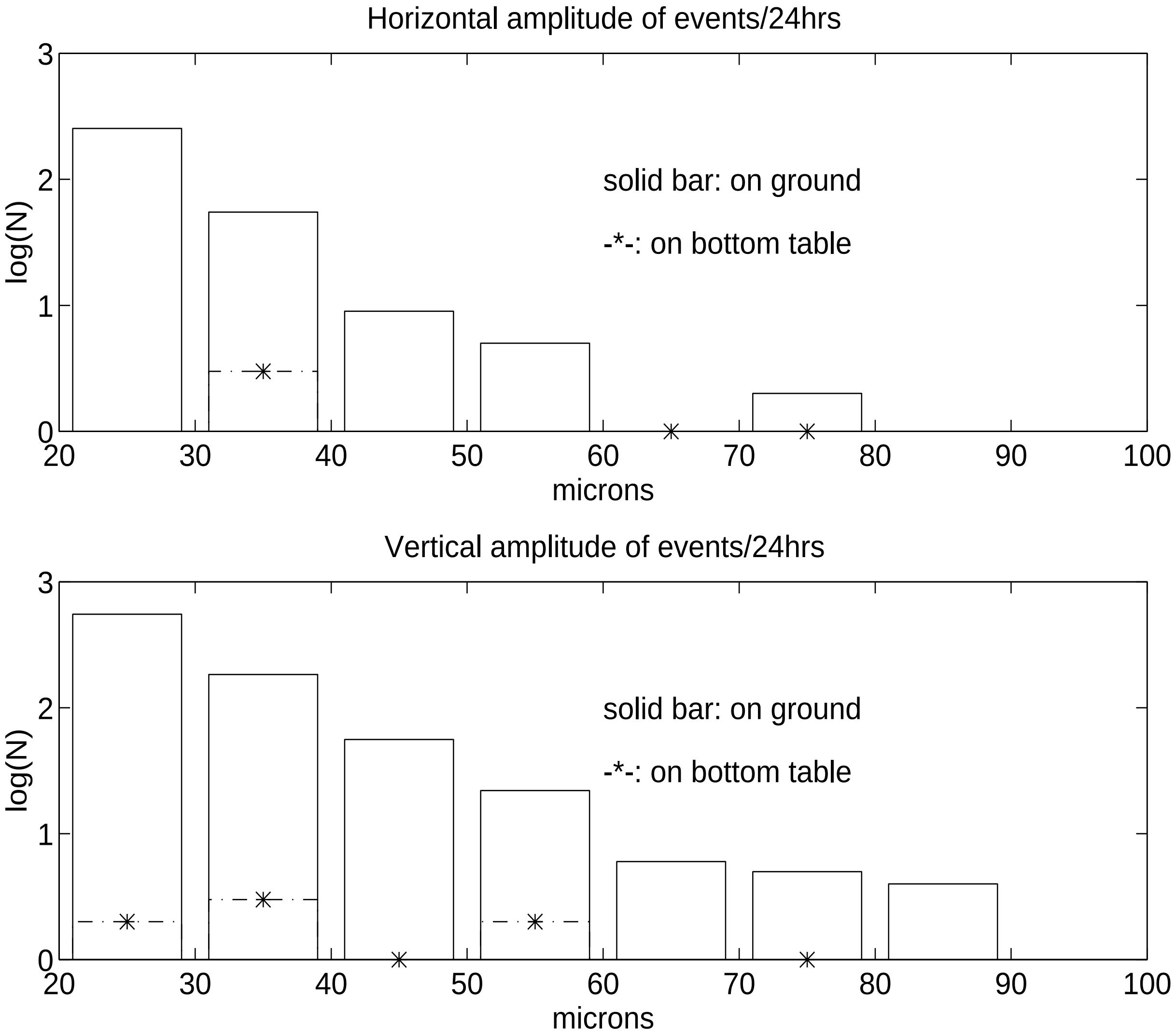


**Figure 6: Histograms of peak values on the ground and on the bottom table.**

events in the vertical ground signals crossing a 40 micron threshold, 2 horizontal and 4 vertical support table signals were larger than 40 microns.

A “large” event (40 microns pk-pk or larger) that was well suppressed by the active isolators is shown in Figure 7. (Notice the different scales in the vertical scales.) This behavior is typical for impulses smaller than ~ 30 microns in the vertical ground signal, and the one showed here is about the largest handled without saturation.

For larger ground noise signals, the isolators would exhibit an overload behavior, with a relaxation time of a few seconds. The overloading behavior was mostly observed in the vertical direction. Figure 8 shows one of these events, which also seems to show some cross-coupling,

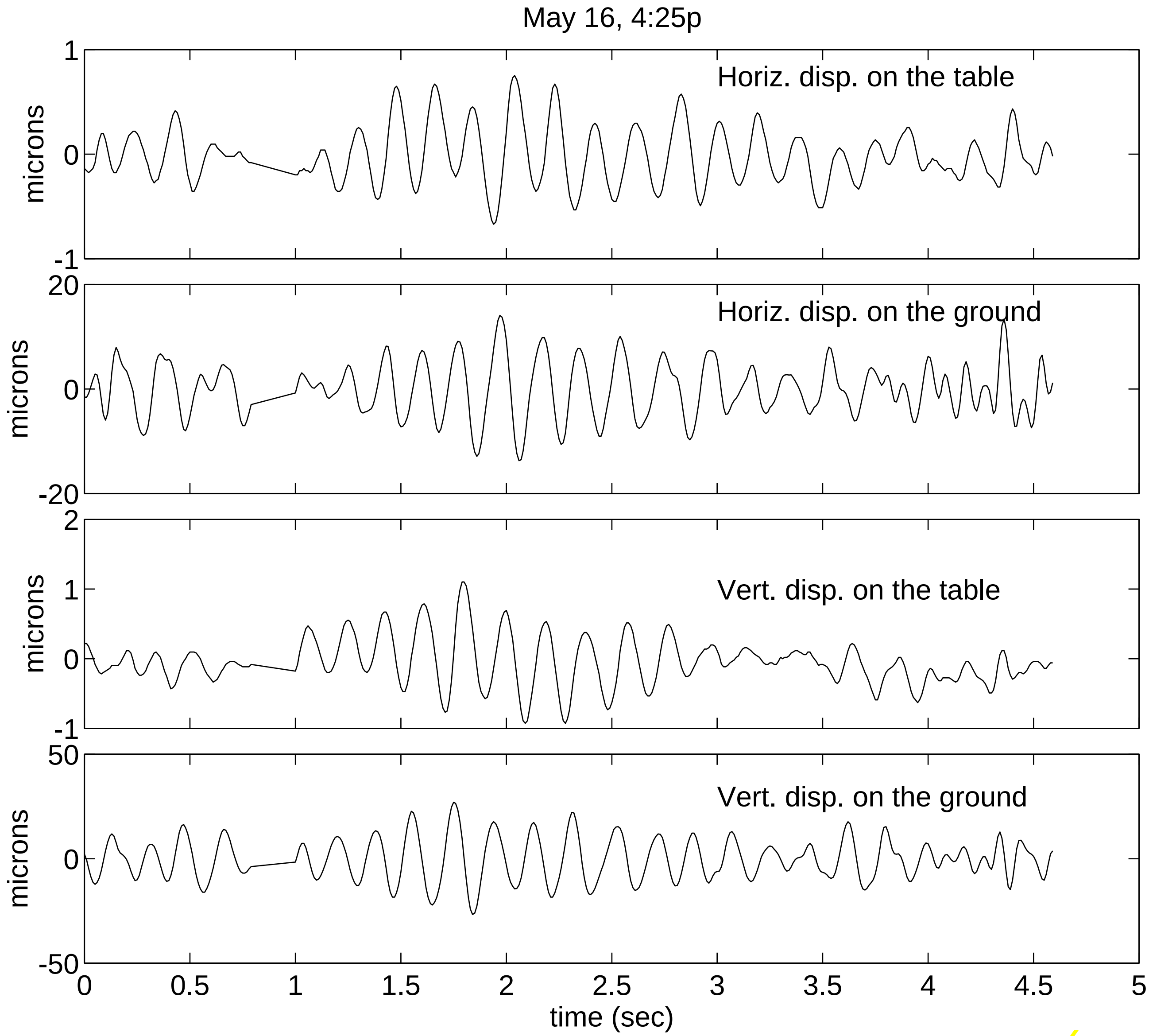


**Figure 7: A “large” event suppressed by active isolation.**

since the non-saturated horizontal support table signal appears correlated with the saturated vertical signal.

The impulsive events on the ground show characteristic frequencies around 5 Hz and 10 Hz. Impulses larger than 40 microns on the ground typically saturated the vertical isolation loops, but events smaller than that, with frequency close to 10 Hz also sometimes saturated these loops (in fact it is not known how many of the three vertical loops were saturated, since the individual loops were not monitored). This behavior is possibly due to a stack resonance at 10 Hz, creating a large motion of the inner block through its back-reaction.

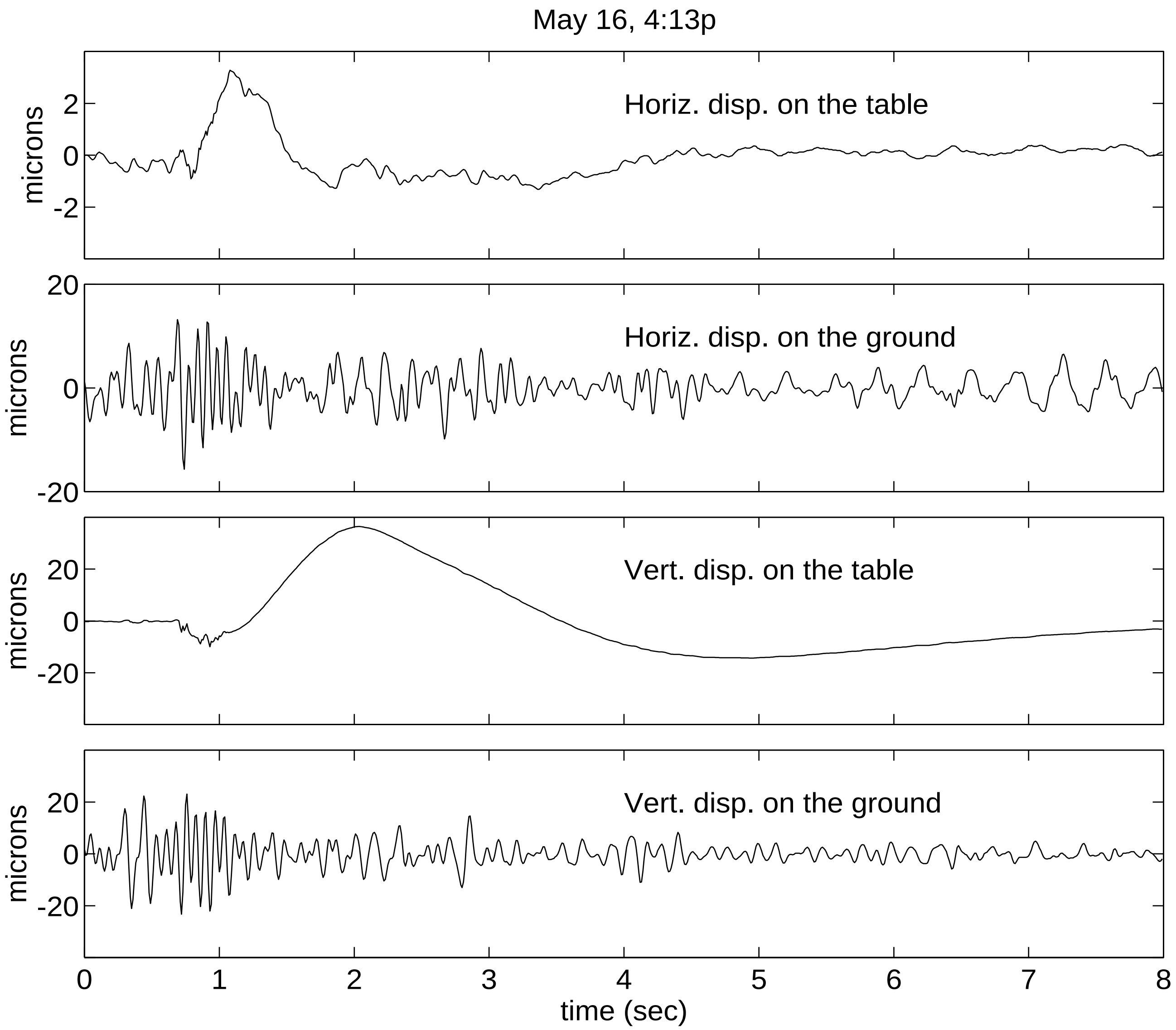


**Figure 8: An event that shows saturation of active isolators.**

In summary, the performance of the active isolators in the presence of impulsive events is quite good: events larger than 10 microns are suppressed by a factor of 20-30 in amplitude and a factor of 100 in number. The vertical loops are seen to be overloaded a few times a day, but they recovered in less than 10 seconds. The horizontal loops were only seen to overload twice.

We also took data with a geophone on the top table, during 24 hours on May 18. The results were qualitatively the same described before, namely, suppression in number and amplitude of impulsive events and few overloading impulses. The suppression factors were slightly different due to the effect of the stacks' resonances at 2 Hz: the reduction in number of events was around 30 in the horizontal and 60 in the vertical, and typical events were reduced in amplitude by a factor of 15 to 20.

# 6 CONCLUSIONS

The performance of the active isolators is satisfactory and reliable. The actuators did not produce any excessively large motion on the table, even when saturated.

The reason for the decrease in performance with respect to measurements of the inner mass motion is not understood, but the isolators do provide 20 to 40 dBs of isolation over a decade in frequency around 10 Hz. In particular, this helps to reduce the amplification of noise at the passive isolation resonances (~2.5Hz), so that the transfer function from ground to top table is never above unity.

The impulsive events were also reduced by factors of 20-30 in amplitude and 100 in number, a fact that helps considerably to reduce non-Gaussian noise on experiments.