Chapter 5 Modifications to the VSE-355G2 — The VSE-355G3

5.1 Introduction

In Chapter 3 the VSE-355G2 instrument was introduced, and the major problem with a low clipping level was exposed. In Chapter 4, this problem was observed by the same instrument in the field during the M8.3 Tokachi-Oki earthquake. This Chapter summarises the modifications made to the instrument by the manufacturer, and provides laboratory and station data which indicates that the instrument is now performing to original specifications.

During the modification and re-testing process, low clip levels were found in the vertical channel once the horizontal problem seemed to have been corrected. The cart test was run in a elevator in Japan, as the set-up at Caltech did not easily facilitate this type of test.

Cart test data now shows impressive strong motion performance from the VSE-355G3, with motions exceeding $200cm/s$ being recorded linearly by the instrument. The dynamic range of the instrument has not been compromised by the modifications, and retains similar performance to the VSE-355G2.

The equivalent SDOF determined from the calibration testing indicates the instrument has a different response from the VSE-355G2, with a longer equivalent free period of about $105s$ now observed. This is well in excess of the range specified by the manufacturer of only $80s$. Damping is slightly lower at 65% of critical. There much better correlation with the observed SDOF response and the expected theoretical Transfer Function response than is shown for the VSE-355G2.

The instrument is currently deployed within the CISN alongside a CMG-1T at CRP, the Caltech Robinson Pit.

5.2 Modifications

The instrument has been modified internally once, and fully overhauled twice. Both overhauls involved an engineer from Tokyo Sokushin visiting Caltech, and removing the existing suspension and feedback for all 3 components, replacing them with new sensors and feedback circuitry.

The first internal modification occurred in 18 June 2002, after Sokushin had identified the source of the low saturation velocities as a fault with the power regulator in the electronic feedback system which prevented the final stage amplifier from operating correctly. This attempt to increase the clip level to the expected level of $200cm/s$ only succeeding in moving the observed clip from $15cm/s$ to $40cm/s$ (see Figs 3.21 and 3.24).

A full overhaul took place on 11-12 November 2002. This was again in response to the low clipping levels. Cart tests subsequent to this showed the low clip level problem had been resolved for the two horizontal components, but not for the vertical component (Figure A.3(b)). Also, there was significant cross-coupling between all three components (Figure A.3(a)).

After investigation, Tokyo Sokushin reported that both problems were caused by a mechanical problem — the suspension spring in the Z-axis being unable to adequately resist the large velocities. This was fixed, as evidenced by elevator tests performed in Japan, where the vertical component was subjected to $\sim 1m/s$ velocities without any problems (Figure A.4).

On 15-16 Sept 2003, this same modification was incorporated into the Caltech sensor, which again involved replacing all 3 sensors. Cart tests subsequently confirmed the clip level was acceptable for the horizontal components, recording linearly beyond $2m/s$. Without the ability to perform an elevator test at Caltech, the vertical component could not be excited up to 2m/s. Velocities up to about $10cm/s$ were successfully recorded. Cross-axis sensitivity seemed to have been eliminated.

At this stage, with the apparent success of the instrument in strong motion, calibration tests were performed. These tests produced large permanent offsets in raw velocity output from simple step-function excitations that should not result in permanent offsets

(Figures A.7 and A.8, the expected response shown in Figure 3.5).

Once again the manufacturer visited Caltech, where it was discovered from careful analysis of the response of a similar VSE-355G3 instrument in Japan, that the errors were produced by incorrect pin connections between the sensor and the datalogger. When this was repaired, the instrument performed well in the calibration tests. At this stage, a full series of tests were repeated to confirm compliance with the sensor specifications. An in-depth chronological list of site visits by Sokushin, including results, and important milestones in the testing regime, are presented in Appendix A.

5.3 Test Analysis

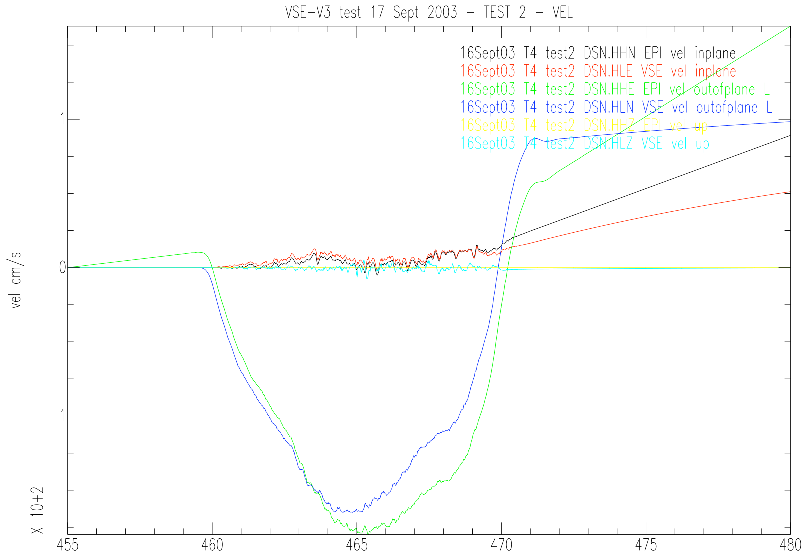
5.3.1 Instrument Clipping

After all the repairs had been completed, by September 2003, the VSE-355G3 was observed to perform well in the cart test. A typical result is seen in Figure 5.1(a). The 'raw' output only is plotted, with nominal station gains removed, and acceleration data integrated to velocity. All three channels, the in-plane motion in the direction of the cart displacement, the out-of-plane, and the vertical, have very similar timeseries for both sensors. Figure 5.1(b) presents the large in-plane motions only, in acceleration, velocity and displacement. Also included in this plot is the time-domain deconvolution solution for the VSE-355G3. The deconvolved motion maps the EpiSensor's motions extremely well. In the velocity time-series, the maximum recorded deconvolved velocity is $211cm/s$, which exceeds specifications. After the motion has ended, the deconvolved VSE-355G3 velocity records a near-zero velocity, reflecting the true physical position of the sensor, and indicates little tilting has occurred. The similarities in the displacement timeseries are also obvious, and the lack of tilt in the VSE-355G3 is reflected by a very steady final displacement of about $-16.4m$ being recorded. This is about the same distance traversed in the test (it was not precisely measured). This Figure can be compared to the theoretical solution of a similar cart test shown in Figure 3.10. This example has the least tilt of all the runs performed, in other tests, as seen in the subsequent plots, tilt seriously distorts both sensors' translational response.

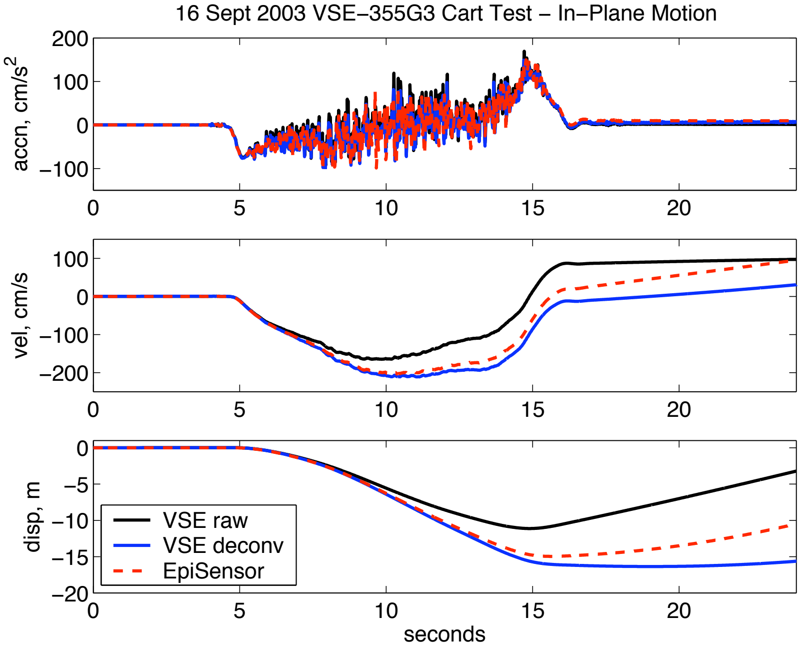
In the suite of tests which included the above data, clipping was observed only well beyond the $2m/s$ level, near $2.5m/s$. No cross coupling was observed, though some large offsets were observed in the 'zero' level for the horizontal channels. A plot of the entire suite of tests is in Figure A.6, showing a timeseries which consists of numerous cart tests, forwards and backwards along the hallway, and is interspersed with rotations of the VSE-355G3 sensor. The large offsets are caused by tilting of the instrument during both the translation and rotation — if tilts are large enough, they cannot be rectified by the sensor feedback. Figure A.11 shows a test subsequent to the discovery of the occurrence of the tilting, and the instrument's sensitivity to the problem. In this sequence of tests, whenever a tilt was observed after a displacement or rotation, the instrument was re-levelled. Re-levelling caused the background output level to return to zero.

In Figure 5.2, another example of a cart test is presented, from tests run in November, after all pin connection problems had been resolved. Again all three components are compared, also oriented to record in-plane motion, the out-of-plane and the vertical motion. All VSE-355G3 data has the instrument response removed using a time-domain deconvolution. Considering the rugged nature of the test, there is very good correlation of all components. Close correlation of large peak velocities over $175cm/s$ is recorded for the in-plane velocity. The effect of the tilt is severe, as seen by large linear trends in the out-of-plane velocity, which are similar for both sensors. Even so, the slope of the velocity is roughly $8cm/s^2$ for both sensors in the out-of-plane direction, which corresponds to a tilt of only 0.475^o (Equation 1.18), a small rotation. The effect of this tilt so strong it even affects the insensitive vertical components in both sensors. The permanent displacement is observed by the very similar in-plane displacement behaviour, with an offset of about -11m being recorded once the event is over, which correlates with the cessation of large accelerations and velocities. After this time, the large tilts cause immediate deviation of the displacement record. In the other components, displacements are expected to be small with little or no permanent offset. The large tilts, of the same order of magnitude as the in-plane tilts, cause large, non-physical displacements almost immediately after test begins.

The largest motions recorded in the correctly levelled sequence of cart tests are shown



(a) All 3 components, raw velocity



(b) In-plane components, EpiSensor: solid line, raw VSE: dotted, deconvolved VSE: dashed line

Figure 5.1: Typical Cart Test result for VSE-355G3, 16 September 2003. Very little tilting of VSE-355G3 over course of test, seen by relatively flat displacement after test is completed. An error in the pin connection led to the mis-labelling of in-plane/out-of plane components for both sensors.

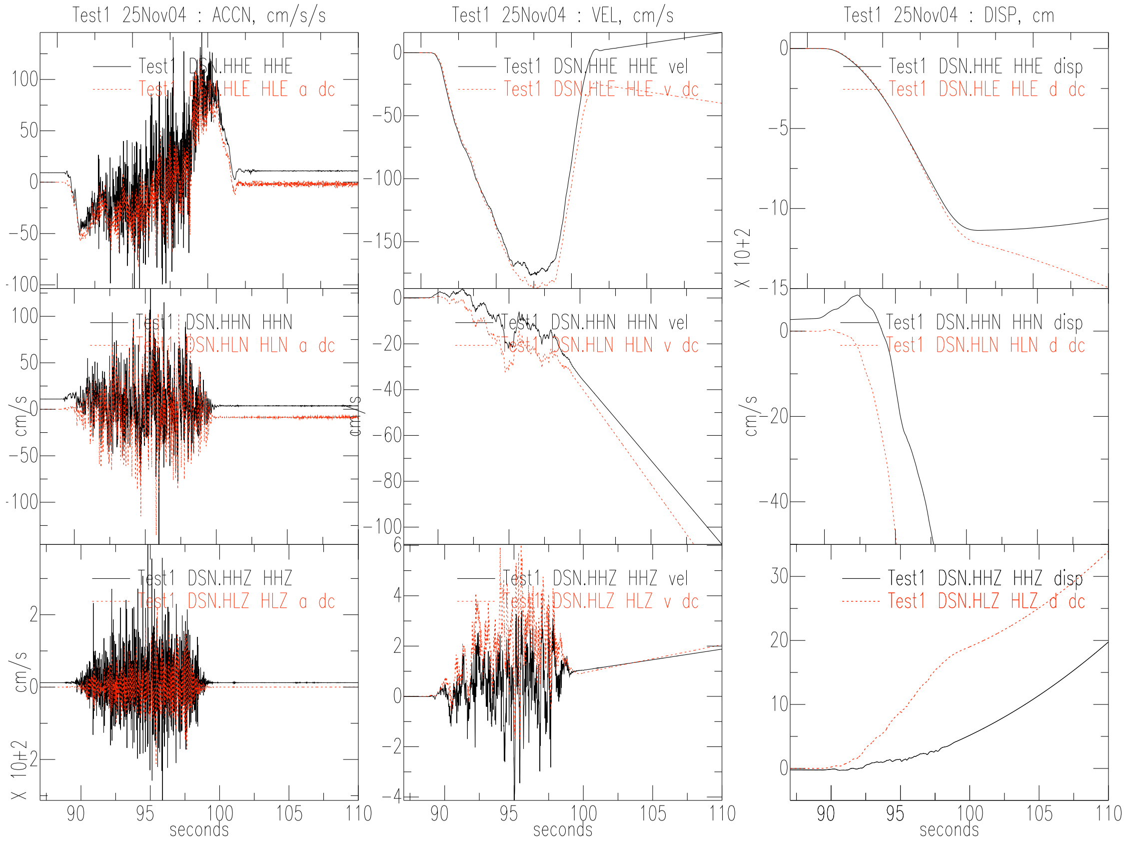


Figure 5.2: Typical Cart Test result for VSE-355G3, 25 November 2003. VSE-355G3 (dashed line) and the EpiSensor (solid) components are compared for in-plane motion (top), out-of-plane motion (middle) and vertical motion (bottom). Acceleration, velocity and displacement are all presented. VSE-355G3 data deconvolved using time domain integration. Large tilts observed in all components.

in Figure 5.3. The maximum 'raw' velocity in this case is $200 cm/s$, which, when deconvolved, reaches $256 cm/s$, well in excess of the minimum acceptable clipping velocity or $200 cm/s$. As the character of the deconvolved velocity is very similar to that of the EpiSensor (and EpiSensor accelerations are not near its clipping level), and $250 cm/s$ was the approximate speed estimated during the test, it is deduced that the VSE-355G3 is still recording linearly at this speed. Note tilts are also significant in this test, and are of a similar order as observed in Figure 5.2.

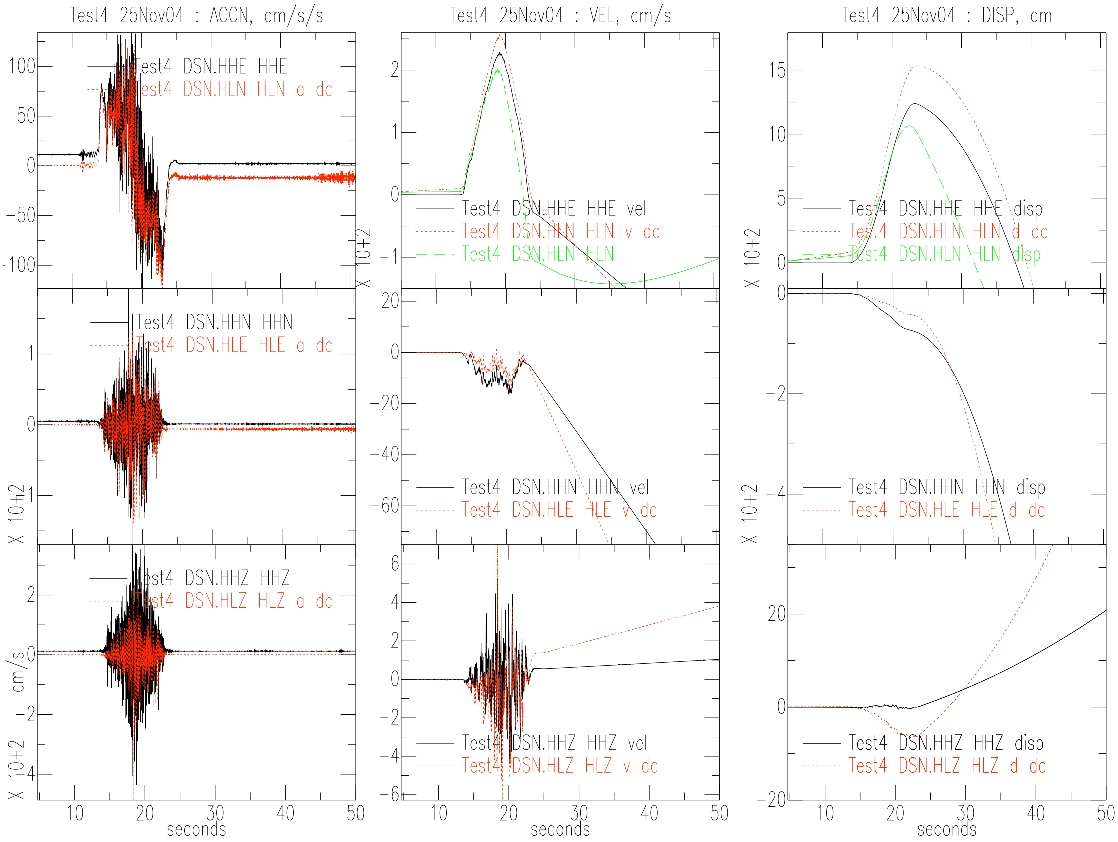


Figure 5.3: Typical Cart Test result for VSE-355G3, 25 November 2003. VSE-355G3 (dashed line) and the EpiSensor (solid) components are compared for in-plane motion (top), out-of-plane motion (middle) and vertical motion (bottom). Acceleration, velocity and displacement all presented. VSE-355G3 data deconvolved using time domain integration. Velocities in excess of $200 cm/s$ are recorded by both sensors.

Figure 5.3 provides a lower bound for the clipping level of the instrument. The tests where levelling was not closely monitored include data from cases where there were large pre-event velocity offsets. When in-plane motions increase the large offset velocities further, clipping can be observed even if the true velocity is low. Figures A.5 and A.6 show some data from these tests, where clipping is observed at $243cm/s$ for the N-S channel, and at $252cm/s$ for the E-W channel. Once these velocities are reached, the sensor output flatlines. Note these are not deconvolved velocities; for this character of motion, the deconvolved velocities would be larger. This is well in excess of the expected clip level of $200cm/s$.

5.3.2 Instrument Response

Once it had been determined that all the problems had been dealt with, calibration tilt tests were performed. [After the final overhaul, this included ensuring the clipping levels were satisfactory, no cross-coupling occurred during strong motions, and the pin connection problems were fixed.]

Figure 5.4 presents the output of the seismometer to a tilt produced by adjusting the levelling screw. The best fit SDOF solution is $T_0 = 105.5s, \zeta = 0.55$ E-W component, $T_0 = 105.2s, \zeta = 0.59$ N-S, and $T_0 = 105.8s, \zeta = 0.64$ Vertical. These SDOF's are significantly different from those of the VSE-355G2 (In Figure 3.12, all 3 components are shown to have a free period $\sim 93s$, and damping of 0.65).

The Transfer Function was supplied from the manufacturer in January 2004, given in the following form:

$$F(i\omega) = \frac{A1(i\omega)^3 + B1(i\omega)^2}{A2(i\omega)^4 + B2(i\omega)^3 + C2(i\omega)^2 + D2(i\omega) + E2} \tag{5.1}$$

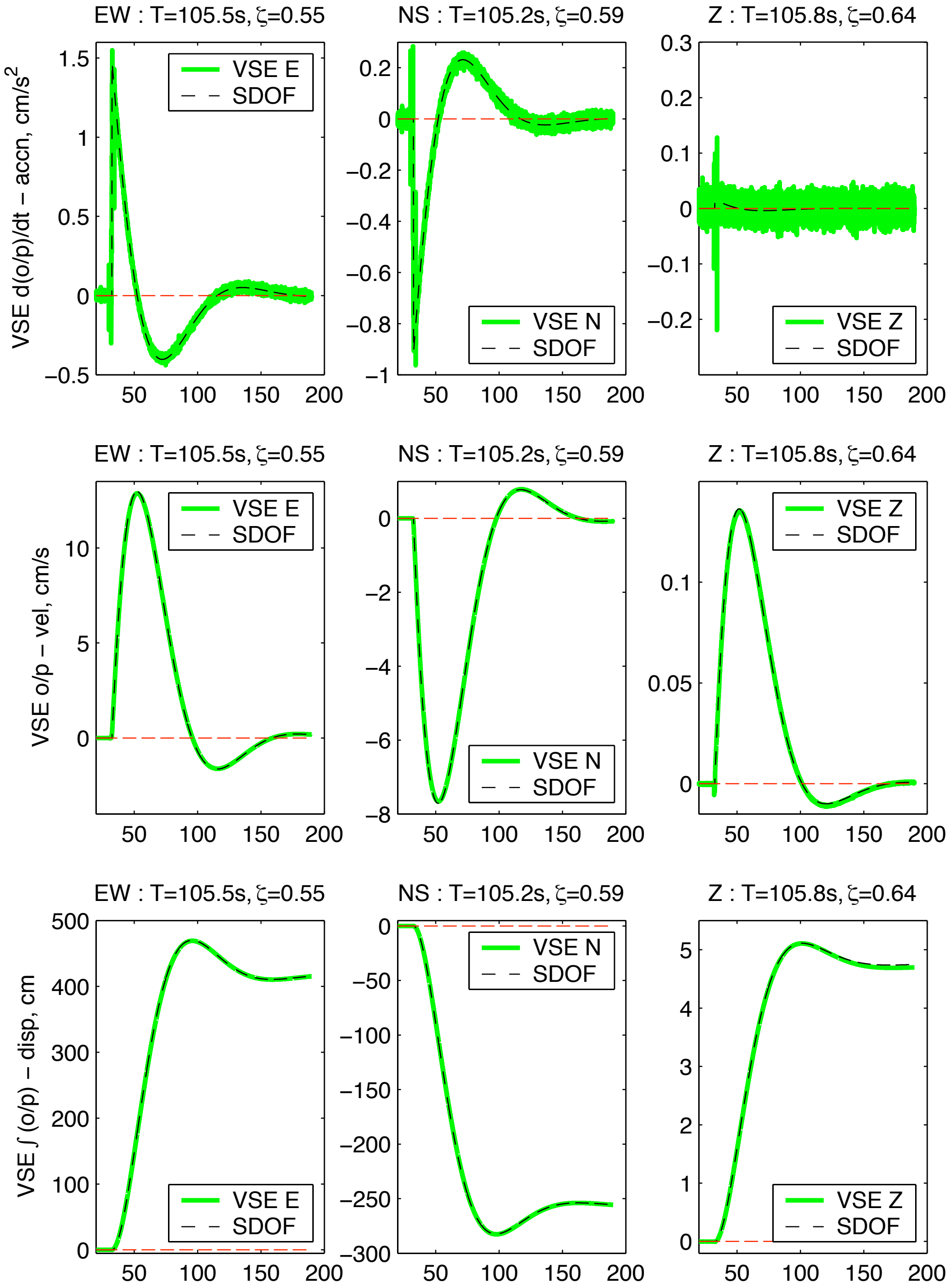


Figure 5.4: Response to a tilt, produced by adjusting the levelling screw, January 2004.

where each of these constants are defined as —

$$A1 = aA*Q*N \tag{5.2}$$

$$B1 = aA \tag{5.3}$$

$$A2 = Q*N \tag{5.4}$$

$$B2 = \left(1+\frac{aA*B*G*K*Q*(R+N)}{m*R}\right) \tag{5.5}$$

$$C2 = \left(\frac{aA*B*G*K}{m*R}+\frac{aA*G*K*Q*(R+N)}{m*E*R}\right) \tag{5.6}$$

$$D2 = \left(P+\frac{aA*G*K}{m*E*R}+\frac{aA*g*Q*N}{m*F*C*D}\right) \tag{5.7}$$

$$E2 = \left(\frac{aA*g}{m*F*C*D}\right) \tag{5.8}$$

and —

$$aA = 500000V/m \quad ; \quad B = .7\text{x}10^{-9}\mu F$$

$$C = 2.2\mu F \quad ; \quad D = 4.4M\Omega$$

$$E = 2.778M\Omega \quad ; \quad F = 200K\Omega$$

$$G = 200 \quad ; \quad g = 20$$

$$K = 1.3M\Omega \quad ; \quad m = .03kg$$

$$N = 51\Omega \quad ; \quad Q = 32\mu F$$

$$R = 500K\Omega \quad ; \quad P = 355$$

This theoretical solution, determined from the characteristics of the mechanical sensor and the feedback control system, is shown in Figure 5.5, alongside a representative VSE-355G3 SDOF ($T_0 = 105.5s$, $\zeta = 0.60$). Also shown are the Transfer Function and equivalent calibration coil SDOF for the VSE-355G2. The longer period response, and lighter damping, of the VSE-355G3 is apparent. This is more clearly seen in Figure 5.6, a close up of the $\sim 100s$ corner. Also obvious is the better fit of the VSE-355G3 theoretical and experimental result, compared to the VSE-355G2. The manufacturer claims the behaviour of the Transfer Functions at high frequency ($> 100Hz$) is not correct. In the specifications, linearity is only expected out to $70Hz$, and the behaviour above this frequency is not determined.

Figure 5.7 presents the SDOF for each individual channel of the VSE-355G3, as determined by the tilt test in Figure 5.4. All 3 components are shown to have a very similar response.

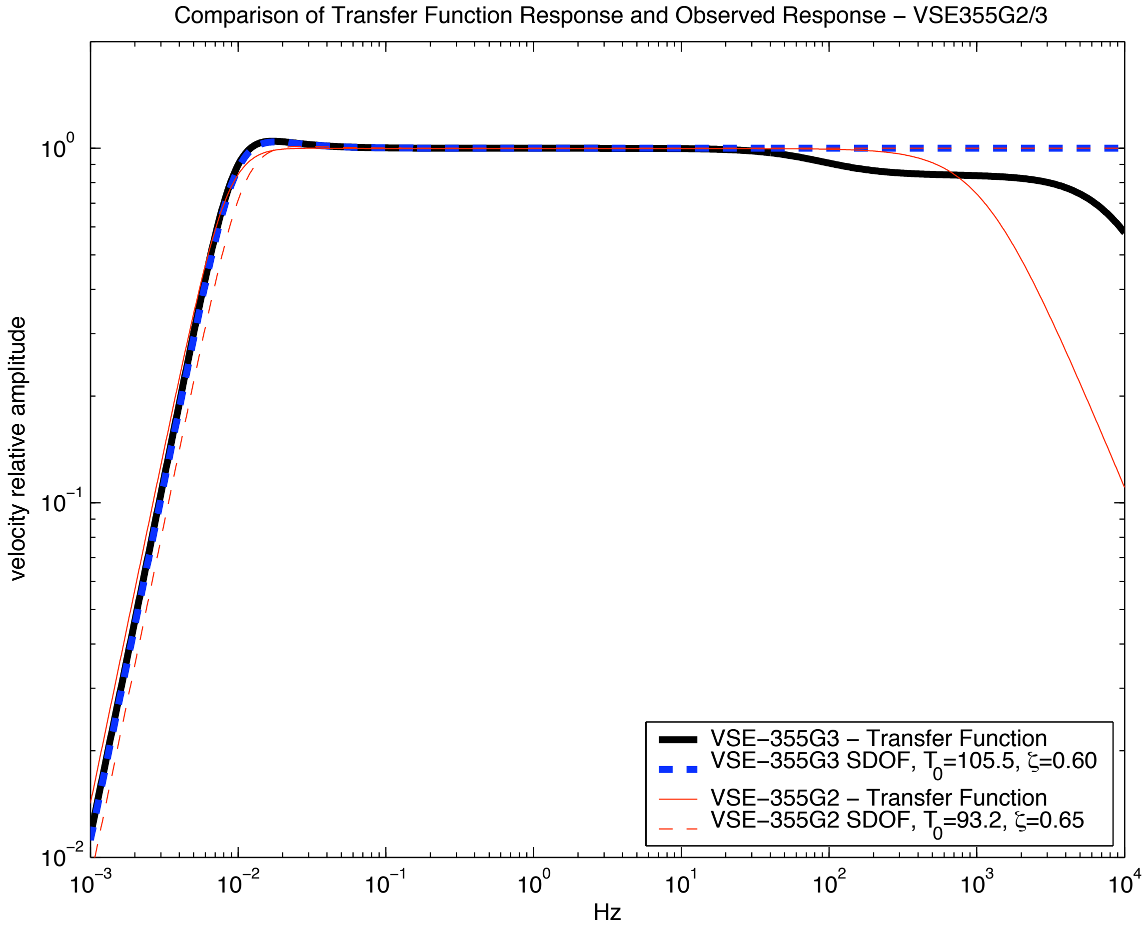


Figure 5.5: Comparison of the theoretical response from the Transfer Function and the observed calibration coil/tilt test results, for both the VSE-355G2 and VSE-355G3. Includes inaccurate high frequency response.

5.3.3 Instrument Sensitivity

For the VSE-355G3 sensitivity test, the instruments were located at the Robinson Pit, Caltech, recording onto a Q680 digitiser, operating as test station CRB. The instrument was

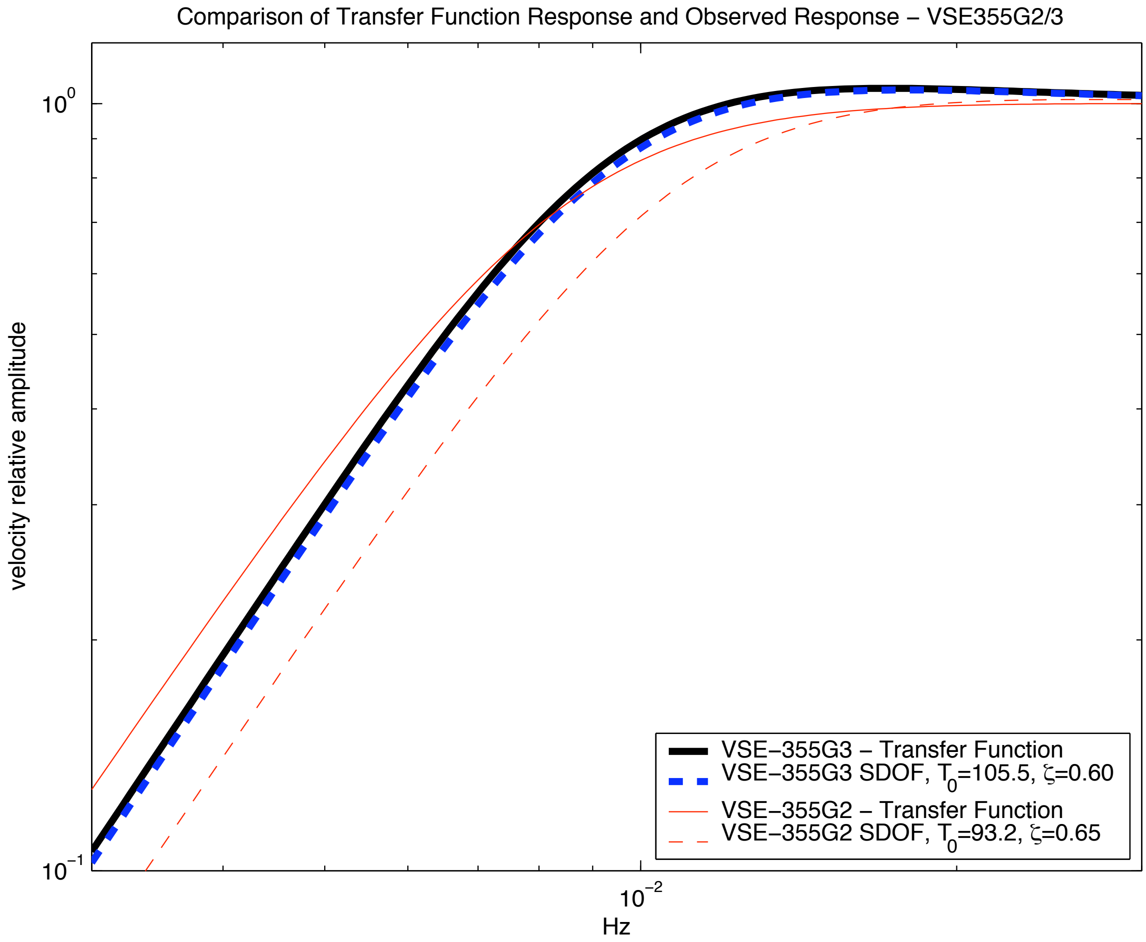


Figure 5.6: Comparison of the theoretical response from the Transfer Function and the observed calibration coil/tilt test results, for both the VSE-355G2 and VSE-355G3. Centred around the $\sim 100s$ corner frequency.

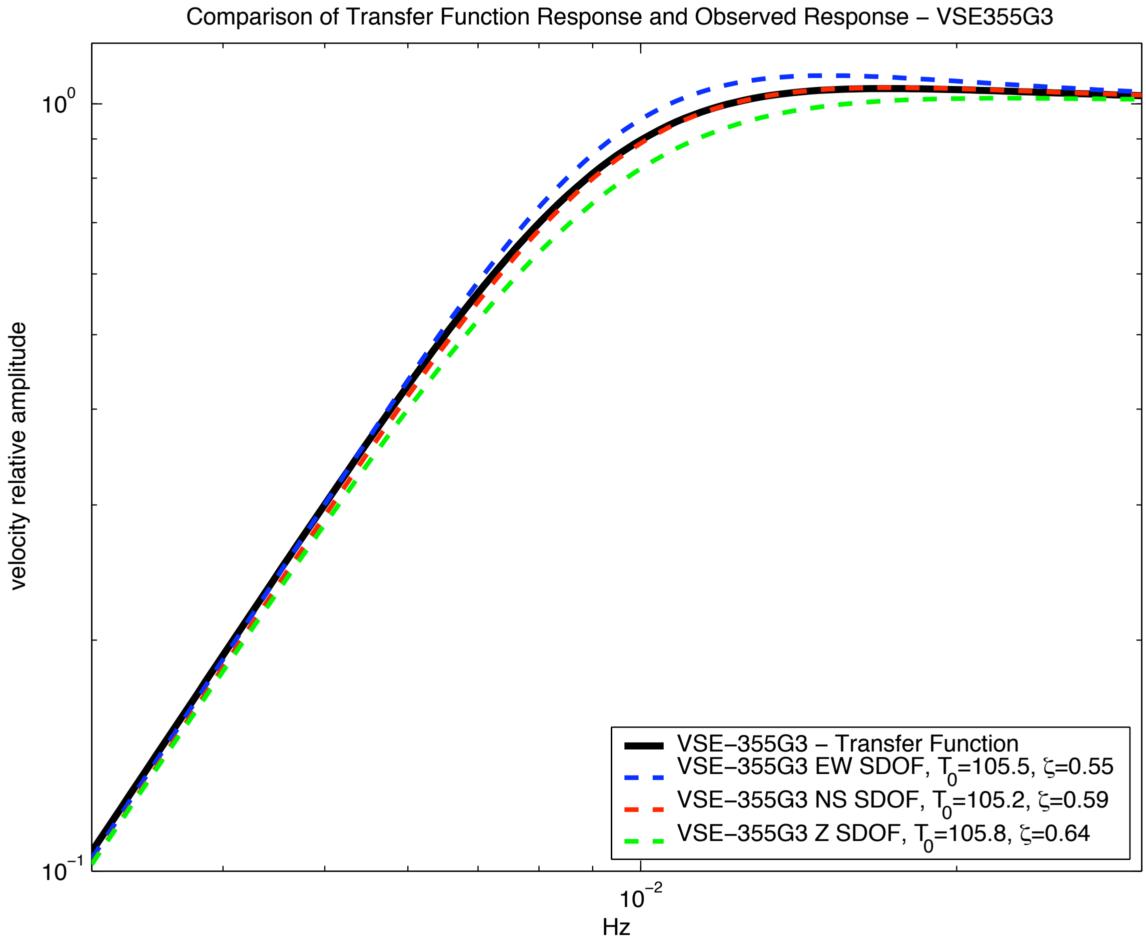


Figure 5.7: Comparison of the theoretical response from the Transfer Function and the observed calibration coil/tilt test results, including the individual responses for each VSE-355G3 channel.

initially deployed alongside an STS-2 on CRP, with an additional STS-2 and an FBA-23 on nearby test station CRPA (recording on a Q330). This setup was only deployed for a few days, as the STS-2's were required for use at other CISN stations. The STS-2 at CRP was replaced with a CMG-1T. CRPA was unreliable for comparisons as sensors and sensor position changed frequently.

Sensitivity versus STS-2

Unfortunately no small earthquakes with enough signal strength to record above the noise on all instruments occurred within the time-frame of this test, which was for ~ 2 weeks in mid-October 2003. However, upon examination of ambient noise, some peaks which appear to correspond to elevator use were observed. Time series around these peaks were bandpassed between $1-10Hz$, and scaled to get a best fit. The time-series (digital counts) were almost identical after multiplication of the VSE records by a scalar constant. This constant was found to be ~ 144 E-W, ~ 156 N-S and ~ 136.5 for the Z component.

As in the case of the VSE-355G2, the published STS-2 sensitivity of $15V/cm/s$ is assumed to be correct. The published VSE-355G2 sensitivity is $100mV/cm/s$, so our expected constant should be 150. For the 3 components there is 4% error E-W, 4% error N-S and 9% error in the Vertical component.

Figure 5.8 shows the timeseries for the 4 instruments during the larger elevator excitation, with the VSE scaled by the above values. The records are bandpassed between $1-10Hz$.

A comparison of noise levels can be seen in Figure 5.9, where the VSE is compared with the two co-located STS-2 instruments.

No parasitic resonances, including those observed for the VSE-355G2 (Figure 3.25), were observed out to $40Hz$, the limit of our digitising, for the VSE-355G3.

Calibration tests subsequent to these sensitivity tests were not satisfactory (see Figures A.7 and A.8) — the problem was found to be caused by poor pin connections. Thus, even though the data performs as expected, the observed signal at these tests may thus not be the true signal as recorded by a working VSE-355G3. After calibration tests were observed to be successful, a further sensitivity analysis was performed with the VSE-355G3

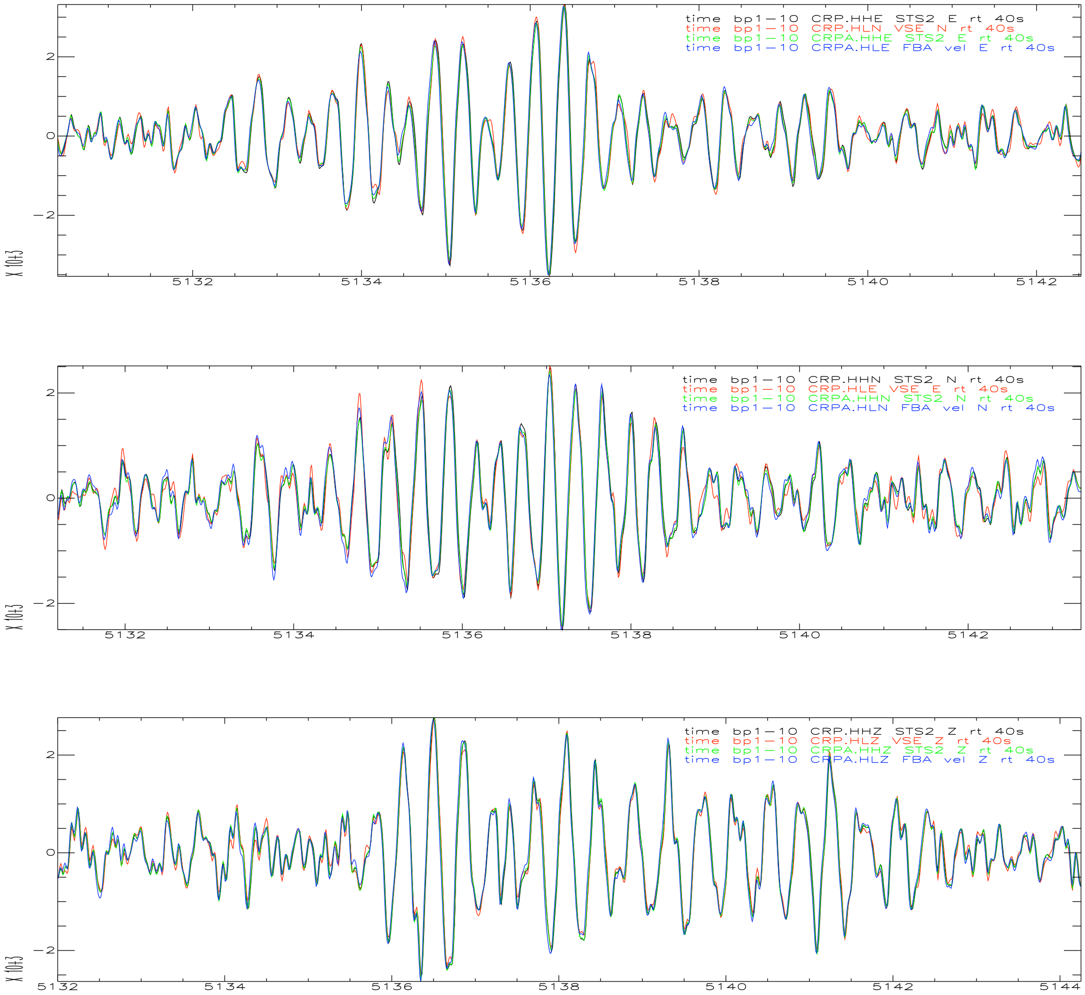


Figure 5.8: Sensitivity scaling: timeseries data for building noise recorded at CRP and CRPA, 18 October 2003, 18:25pm UTC. Bandpass from $1-10Hz$. Y-axis is raw counts, X-axis is seconds. STS-2 data is in raw counts, VSE is counts(VSE) x Sensitivity(VSE), FBA is counts(FBA) x Sensitivity(FBA). Top plot is E-W, middle is N-S, bottom is Z component.

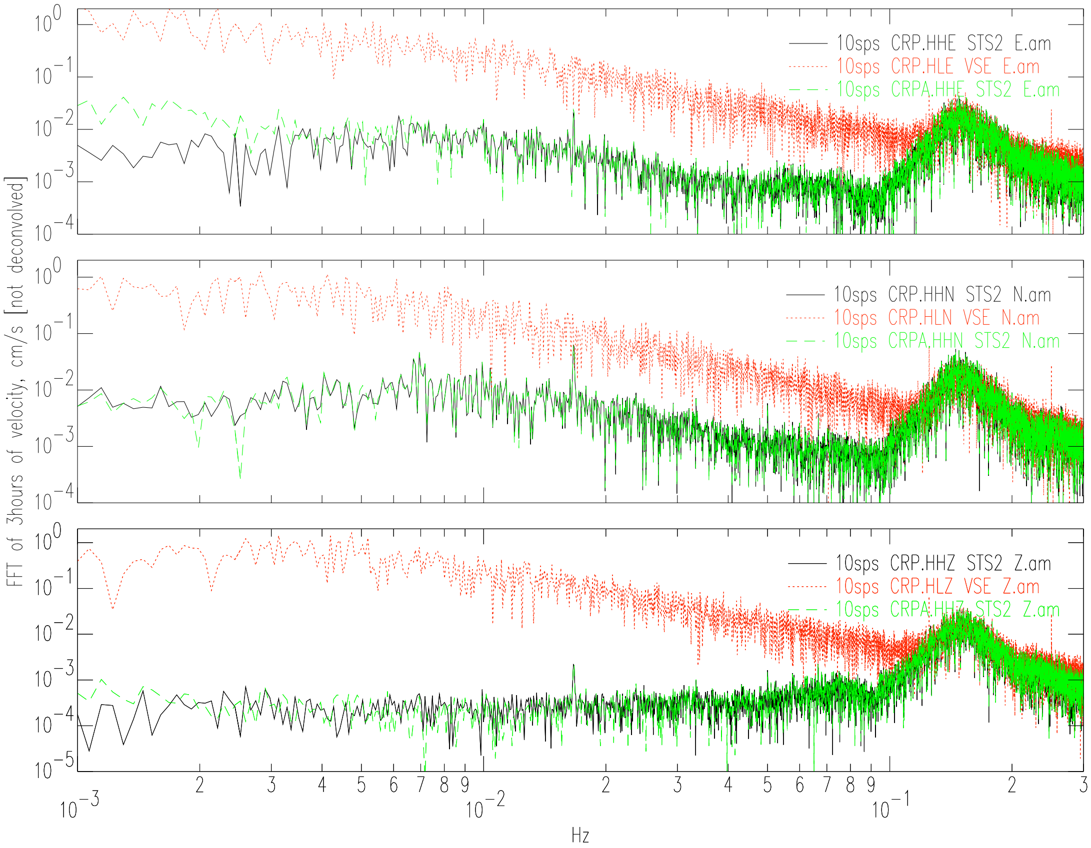


Figure 5.9: Noise: FFT of three hours of ambient data from VSE-355G3 and 2 STS-2's at CRP, CRPA. VSE-355G3 (dotted line) and the STS-2's have their instrument constants (gains) removed, but do not have the instrument response deconvolved.

alongside a CMG-1T.

Sensitivity versus CMG-1T

In late October 2003, the STS-2's at CRP and CRPA were replaced with CMG-1T's. Though this instrument has poorer reliability characteristics than the STS-2, as seen in Figure 4.61 for the Japanese F-Net network, the expected instrument gain of $150V/m/s$ will be assumed correct, which is the same gain as the STS-2. In Figure 5.10, bandpassed CRP data from the M6.5 San Simeon earthquake, $323km$ from the station, is compared for the 2 components. The scaling factors are 144.8 E-W; 162.4 N-S, and 131.0 Z. They are very similar to those determined in November 2003 using an STS-2, and correspond to a 3.5% error E-W, 8.2% error N-S (a little higher than the STS-2) and 12.6% error in the Vertical component (again a little higher than the STS-2). It is not known whether this reflects on a change in the VSE-355G3 sensitivity, or is due to sensitivity errors of the CMG-1T itself.

[The broadband San Simeon timeseries, and an FFT analysis for the VSE-355G3 E-W component of this same data is presented in Figure 3.4, showing the effect of different deconvolution schemes on data analysis.]

Figure 5.11(a) presents FFT data from a $3hr$ period of noise in February 2004. The noise level of the deconvolved VSE-355G3 response is just above the noise level of the station, as seen by the CMG-1T, for the horizontal channels for long periods from $8s$ out to $1000s$. Though the VSE-355G3 vertical channel noise is lower than the horizontal noise at long periods, it is significantly higher than the CMG-1T vertical channel noise at these same periods (up to 2.5 orders of magnitude more).

A comparison of the higher frequencies for a short period of 1 minute of noise, can be seen in Figure 5.11(b), which has good correlation for each channel for both sensors. This recording is not the noise floor of the instruments, and is due to cultural noise, as the noise level is far higher than that expected for either instrument, as shown in Figure 5.12.

Figure 5.12 is a similar plot to Figure 3.19. This presents the amplitude of the CRP noise seen in Figures 5.11(a) and 5.11(b), in octave-wide bandpasses of the acceleration timeseries. USGS High and Low Noise Models, and the PAS/PASB VSE-355G2 noise

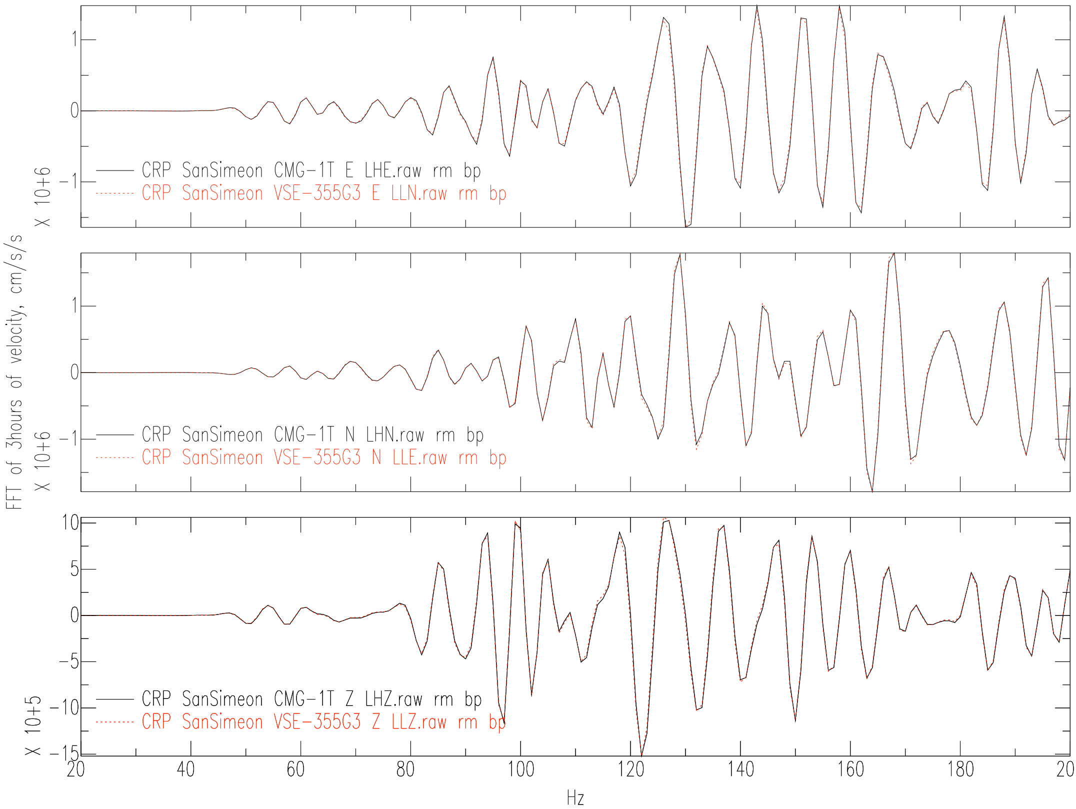
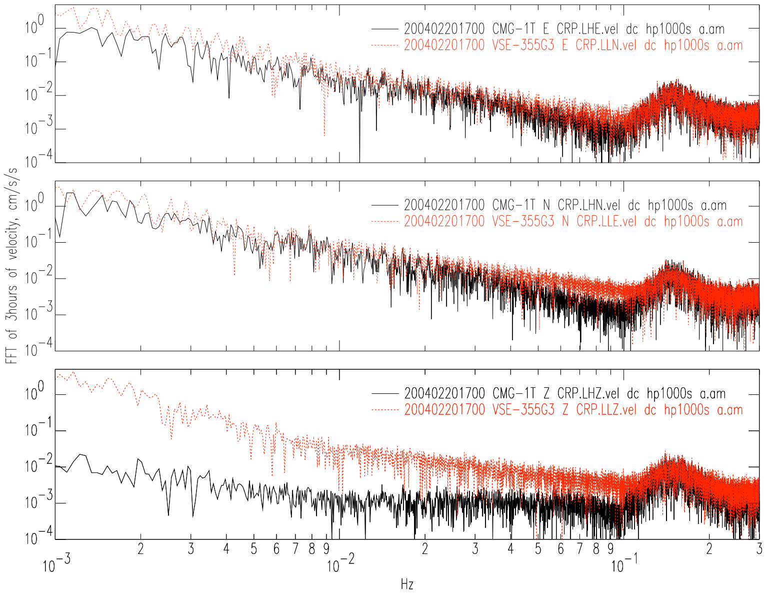
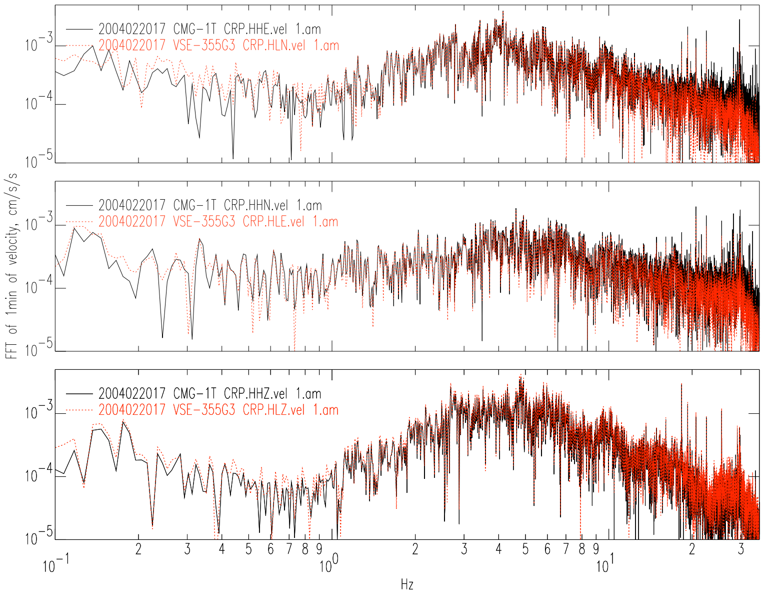


Figure 5.10: M6.5 San Simeon earthquake, 22 December 2003, at CRP, 323*km* distant. All 3 components from VSE-355G3 and CMG-1T (Top: E-W, Mid: N-S, Bottom: Z). Data is bandpassed from $5s - 20s$, and the VSE-355G3 is scaled so that it best fits the CMG-1T. Scaling factors: 144.8 E-W; 162.4 N-S, and 131.0 Z.



(a) Long period noise - 3*hrs* FFT (20 Feb 2004: 1AM-4AM PST)



(b) High frequency noise - 1*min* FFT (20 Feb 2004: 01:27:00AM PST)

Figure 5.11: Ambient noise resolution for VSE-355G3 vs. CMG-1T. Sensors have default station gains removed, and instrument response removed, and long period data has a bandpass at 1000*s* to stabilise the FFT

floor results (from Figure 3.18) are also included. CRP is seen to be a very noisy station, higher than the High Noise Model at periods greater than $10s$, and less than $1s$, for all the horizontal channels. The high frequency data is clearly recording only the noise of the station, which is well above the resolution of the instrument, and so this is not determined for the VSE-355G3, and it can only be assumed to be similar to the VSE-355G2. For the long periods, the vertical CMG-1T does record a low noise level, well below the High Noise Model, and below the minimum resolution of the VSE-355G2 at PASB. This is still above the CMG-1T minimum resolution, which should be below the Low Noise Model at all frequencies higher the $500s$ (`www.guralp.com`), and so likely records the true station vertical noise level. This provides a good test for the VSE-355G3. The noise of the vertical VSE-355G3 is above the VSE-355G2 for all the frequency range. The CMG-1T horizontal channels are noisier than the VSE-355G3 vertical, but as the VSE-355G3 horizontal channels are both noisier than the resolution of the CMG-1T horizontal motions beyond $100s$, this could be at the component resolution. As the vertical component is an order of magnitude more sensitive, this more likely due to tilting effects at these long periods, due to building straining. The vertical sensitivity is within an factor of 2 of the VSE-355G2 resolution, and consistently within a factor of 4 above the VSE-355G3 min resolution line, which is 7 orders of magnitude below the $2m/s$ expected clip level (assuming an operation of $140dB$). The instrument is thus operating at about $132dB$ dynamic range, and provides much improved longer period sensitivity to the typical 24-bit accelerometer, as represented by the PAS FBA-23 data. Note also that though the VSE-355G3 noise is about 2 times higher than the VSE-355G2 over a broad frequency range, the clip level has been raised by over a factor of 10.

5.4 Summary

The VSE-355G2 instrument as delivered to Caltech in 2001, has a performance generally similar to the manufacturer specifications, except for a significantly lower instrument velocity at clipping. This behaviour appears to have been confirmed from strong motions recorded in the M8.3 25 September 2003 Hokkaido earthquake.

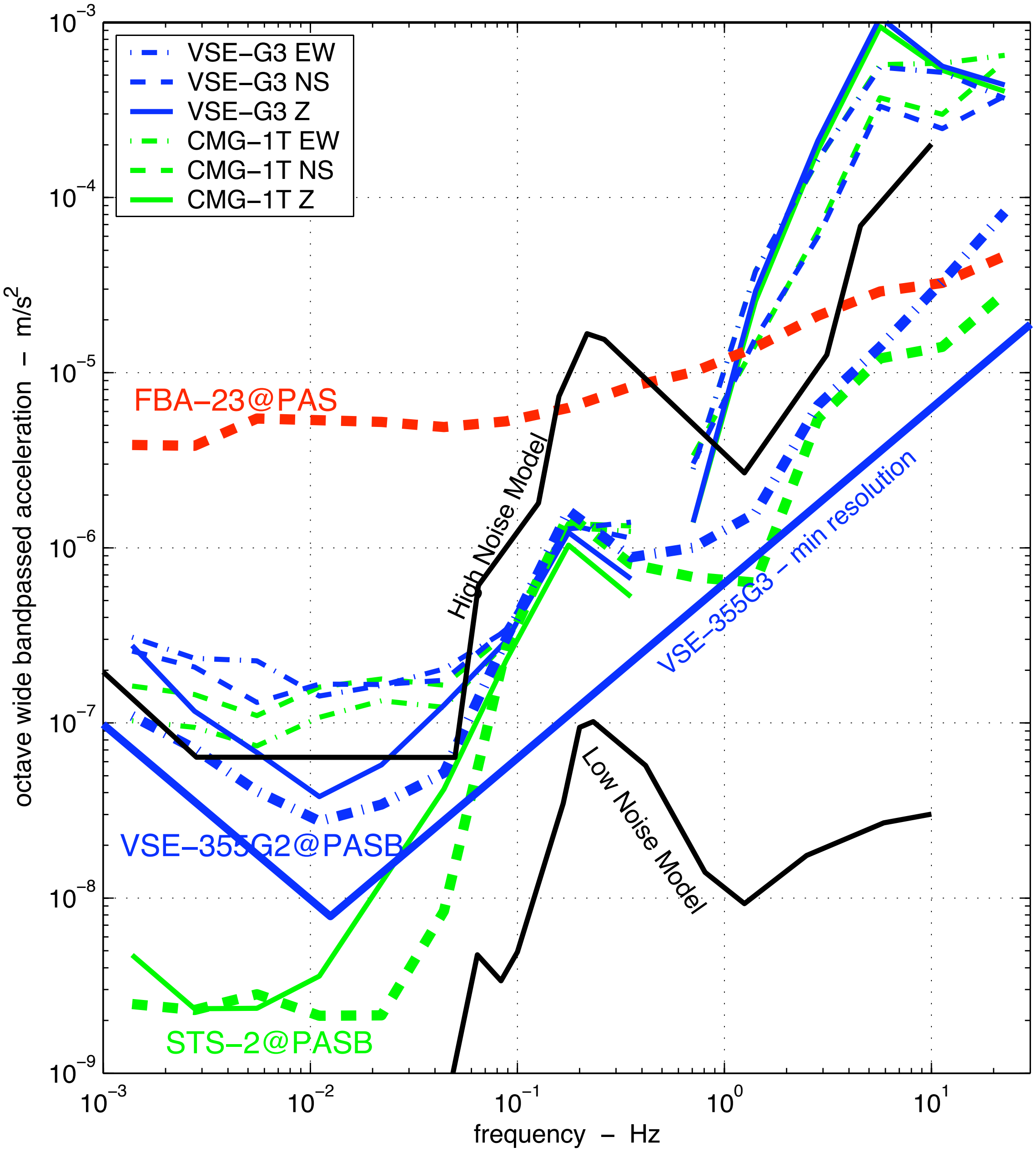


Figure 5.12: Station CRP channel sensitivity, February 2004, data from Figures 5.11(a) and 5.11(b). VSE-355G3 channels in blue, CMG-1T in green. Note both the vertical channels are significantly quieter than their horizontal counterparts. High and Low Noise USGS models included (Peterson, 1993). CRP is a very noisy site, with periods $> 20s$, $< 2s$ being slightly noisier than the High Noise model. Compare with data from PAS/PASB, with STS-1, FBA-23 and VSE-355G2, re-presented from Figure 3.19. PAS is a much quieter site. VSE-355G3 noise is about 2 times higher than the VSE-355G2 over a broad frequency range, though the clip level has been raised by over a factor of 10.

During the tests at Caltech, initially the clip velocity was observed at $15 cm/s$, only 7% of the $200 cm/s$ specified clip level. Clip level was estimated by translation of the instrument (alongside an accelerometer) along a laboratory floor. The manufacturer was informed, and after isolating the source of the low clipping to be a malfunctioning power regulator, a representative from Tokyo Sokushin visited Caltech to fix it. After the modifications, we repeated the cart test and observed clipping at about $40 cm/s$, still only 20% of the specified clip level of $200 cm/s$. After further tests in Japan, Tokyo Sokushin Engineers returned to Caltech and replaced mechanical and feedback systems for all 3 components. The strong motion cart tests then showed the horizontal components of the instrument did not clip until motions exceeded $200 cm/s$. The vertical channel was shown to clip at about $15 cm/s$, and there was serious cross-coupling between all channels. The manufacturer returned to Japan, and discovered the vertical suspension was insufficiently strong, and caused both problems. In Japan, the cart test was repeated in an elevator to demonstrate the ability of the vertical channels to recover strong motions. Sokushin returned to Caltech to replace all three sensor components with the redesigned seismometers. Tests then indicated satisfactory performance in strong motions from all three components. Further calibration tests indicated there was a problem with the pin connection from the sensor to the datalogger, with resultant very strange calibration test behaviour. Once the pin connections had been re-done, the calibration test output was consistent with expectation, and the general performance tests were repeated.

The VSE-355G3 instrument performance is now similar to, or in exceedance of, the manufacturer specifications. The ability to resolve long period ($> 30s$) motions is much better than that of a strong motion accelerometer, and the instrument has good response even at 100's of seconds. Instrument sensitivities, calibrated with an STS-2, are within 9% of manufacturer's specifications. Noise resolution was measured at the Caltech Robinson Pit, site of CISN Station PAS, and is found to track that of the CMG-1T and STS-2 out to $10s$, and remain at about an order of magnitude at $100s$. With the instrument clip at over $200 cm/s$, the instrument is operating near $132 dB$ dynamic range for a very broad band of frequency. All 3 components can be approximated as SDOF systems with $T_0 \sim 105s$ and $\zeta \sim 0.60$.

Compared to a typical accelerometer, the VSE-355G3 has been shown to have enhanced performance at long periods, and can produce very stable non-DC displacement timeseries. Once a signal with frequencies greater than 100*s* is produced, such as for some teleseismic waves, and for permanent displacement offsets, a deconvolution of the instrument response is required to reproduce the true ground motions. A time-domain integration of the time-series is shown to be an effective way to estimate the permanent offsets in strong ground motions. This method involves double integration of the time-series, which introduces the same sensitivity of the instrument to tilt, and small errors in baseline measurements as are observed with accelerometers.

From the viewpoint of event data retrieval in a seismological network, the VSE-355G3 is clearly an improvement to the existing accelerometers, though its extra weight and size are disadvantages. Within the CISN, which is not as constrained by these parameters as a typical strong motion network with sensors located throughout structures, it would ideally be used to replace the accelerometer sensors, particularly at stations with only a single (strong motion) sensor.

As with any inertial sensor, a strong motion velocity sensor cannot distinguish rotations from translations. This is a significant problem for any network which attempts to recover true ground displacement, as most ground displacements will be accompanied by some ground rotation involving the vertical direction. To determine the complete and correct translational and rotational movements at a site expected to experience strong motions requires the addition of a separate GPS sensor.