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Instrument Performance in M8.3 Tokachi-Oki Earthquake

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1. Introduction

The M8.3 Tokachi-Oki Earthquake occurred on 25 September 2003, $60km$ ESE of the South-Eastern tip of Hokkaido Island, Japan. Intense ground motions of long duration, with co-seismic offsets of many tens of centimeters, were widespread over Hokkaido island. Motions well above the signal-to-noise of 24-bit strong motion sensors were reported through-out the Japanese islands.

The ground motions were extremely well recorded by the various dense strong-motion nation-wide networks run by NIED (`www.bosai.go.jp`) and the nation-wide GPS network operated by GEONET (`mekira.gsi.go.jp`). Motions recorded during the earthquake provide a huge dataset for an investigation into modern broadband instrument performance.

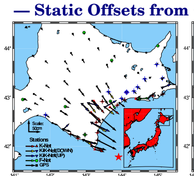
The NIED networks with strong motion sensors are :

- **K-Net** — 1000 station 24-bit surface accelerometer network, $25km$ spacing. $100sps$ triggered data only.
- **KiK-Net** — 650 station 24-bit borehole accelerometer network, with sensor both at surface and bottom of the borehole. Borehole depth: min 100m, max 2000m, modal 300m. $200sps$ triggered data only.
- **F-Net** — 80 station 24-bit vault 'full-range' network, with both low-gain strong-motion velocity instruments and high-gain broadband instruments, covering seismic motions from the station background noise to large earthquake strong ground motions. $100sps$ continuously recorded data.

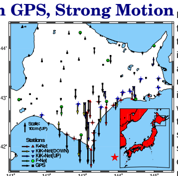
The F-Net strong motion instrument, Tokyo Sokushin VSE-355G2, was obtained and tested at Caltech. It essentially behaves like an STS-2 with $1/150$ the gain. Serious problems with its performance in strong motion were discovered, which were also observed during the M8.3 event. These problems have since been rectified in the new VSE-355G3, which could be an important component for broadband networks.

2. Displacements : GPS vs. Strong Motion

— Static Offsets from GPS, Strong Motion



Horizontal



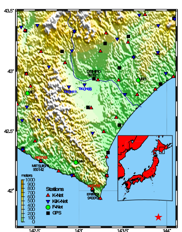
Vertical

Daily GPS variation is freely available from GEONET, from which we determine the co-seismic offset. For the seismic data, first the pre-event mean and then the instrument response (using a time domain integration) are removed. The static displacement from the strong motion is then estimated, as tilting and numerical instability cause trends and other long period motion which obscure the final displacements. The Figures show the horizontal and vertical static offsets from all GPS stations in the near-source, and some selected NIED stations. '+', '∘' over an NIED station indicates a static offset could not be reliably estimated. Accelerometers in K-Net, KiK-Net perform at least as well as F-Net strong motion velocity sensors, which had low clipping problems.

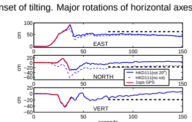
— 1sps GPS and Strong Motion

[*1sps GPS data provided by Kristine Larson*[1] *Shin'ichi Miyazaki*[2] and Atsushi Yamagiwa[3]]

1sps GPS data was recorded throughout the near-source region, though many of the near-source stations suffered power outages, and stopped recording after about $25s$ of strong motions. GPS Comparisons with almost co-located ($< 1km$) NIED accelerometer displacements show excellent correlation, allowing clear identification of onset of tilting. Major rotations of horizontal axes are required to optimally match seismic and GPS.

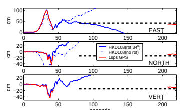


Station Location Map

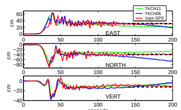


Erimo1 ($\Delta = 67km$, stas $1km$ apart)

Erimo1 has very little tilt at the site; GPS and seismic data almost identical after rotation of 20^o. **Mitsuishi** has significant tilt at the site; but GPS and seismic data are almost identical in E-W and Z after a rotation of 34^o. **Obihiro** seismic stations (both downhole KiK-Net) are located far from the GPS, but all are still very similar, with stable offsets. Note the basin wave in GPS, TKCH06, that is not present at foothill site TKCH11. [Black Line: 7day average GPS offset.]



Mitsuishi ($\Delta = 123km$, stas $260m$ apart)



Obihiro ($\Delta = 162km$, stas $25km$ apart)

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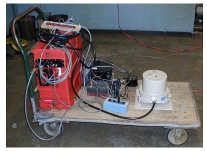
3. The Advantages of a Strong Motion Velocity Sensor? - Lab and Field Data

— Caltech Laboratory



Cart Test - Side View

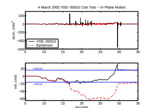
Front View

Clinton and Heaton (2002) discuss the potential advantages of recording strong motion velocity instead of acceleration. This sensor theoretically has greater long period sensitivity (recording more regional teleseismic events) and improved recovery of non-static displacements. The ability to recover strong motion is as good as with accelerometers. Tokyo Sokushin in Japan manufacture a range of these type of sensors, with the VSE-355G2 deployed in F-Net. This sensor was procured with IRIS funds in late 2001.

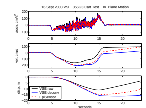
The VSE-355G2 was tested at Caltech in 2002, and the instrument was observed to clip whenever velocities reached $\sim 15cm/s$ (design clip is $200cm/s$). A Cart Test was performed to investigate broadband response to large motions. The cart was moved $\sim 15m$ along the floor at speeds from $1m/s - 2.5m/s$.

Instruments — VSE-355G2: large silver cylindrical instrument at front of cart; EpiSensor: small black cylindrical instrument behind VSE, middle of cart; Q4120 datalogger: orange, located at back of cart.

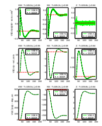
In late 2003, after numerous manufacturer visits and sensor overhauls, the new sensor, the VSE-355G3, was shown to perform well in the cart tests, with clipping near $250cm/s$. A time domain instrument deconvolution of the data shows static offsets can be stable and equivalent to actual test displacements. Noise tests indicate it is operating near 132dB dynamic range, and calibration tests show all three channels can be approximated as 60% damped, $105s$ SDOF oscillators. The sensor is much better long period seismometer than an FBA. This has acute importance for the measurement of massive earthquakes, such as a repeat of the M9.5 Chilean Earthquake, as strong motions as well as very long period motions can be recorded by this instrument.



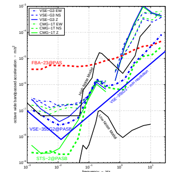
VSE-355G2 Cart Test



VSE-355G3 Cart Test

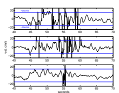


VSE-355G3 Calibration

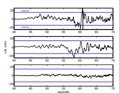


VSE-355G3 Noise at CRP

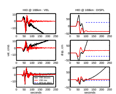
— Field - Tokachi-Oki Strong Motions



KMU - raw velocity

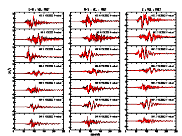


KSR - raw velocity

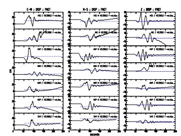


HID - raw, deconv. vel.

Four F-Net VSE-355G/G2 sensors were located within $170km$ of epicenter, and all record velocities greater than $10cm/s$. As F-Net sites are located in $30m$ deep vaults at hard rock sites, their velocities are not large (many surface K-Net and KiK-Net sites record velocities $> 100cm/s$). Nonetheless, spikes similar to those observed in the cart tests were observed at KSR and KMU (both VSE-355G2). URH (VSE355G) reached $22cm/s$ without any clip. HID (VSE-355G2) records $16.9cm/s$ without clip, though has unexpectedly large tilts which corrupt the data.



Other Hokkaido F-Net - Velocity

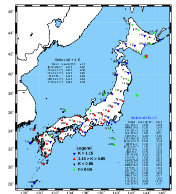


Other Hokkaido F-Net - Displ.

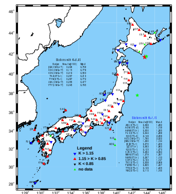
The other F-Net stations located around Hokkaido island all have velocities below the expected low clip level. The Figures show the raw velocity (red) as well as the deconvolved velocity and displacement from these stations. Displacements are compared with the 7day average offset from the nearest GPS stations (blue). In general, where no clipping occurs the VSE-355G/G2 ability to measure the static offset is similar to the accelerometer. Both are equally sensitive to small tilts, which appear to be present at many stations throughout the island. Without exact knowledge of the static offset, this tilt is difficult to remove.

4. F-Net : The Importance of a Strong Motion Sensor in a Broadband Network

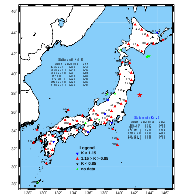
F-Net stations all consist of a VSE-355G/G2 strong motion velocity sensor and a CMG-1T, STS-1 or STS-2 broadband sensor. In 3 large recent earthquakes, for each station, the *min* and *max* for the 3 components of the ratio, K, of peak strong motion to peak broadband velocity is determined. If $K_{max} > 1.15$ or $K_{min} < 0.85$, on the following Figures, the station is flagged. $K_{max} > 1.15$ usually indicates broadband sensor at a station has clipped. Note for M8.3, all broadband sensors within $500km$ clip, some out to $1000km$.



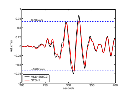
M8.1 Tokachi-Oki



M7.1 Tokachi-Oki Aftershock

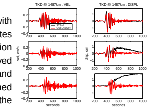


M6.8 10 Oct 2003

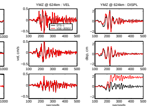


NAA E-W clip @ $924km$

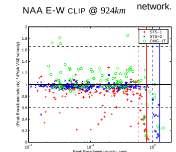
In the regions far from the epicenter, with no broadband clip, high or low K indicates a problem with the station (incorrect station gains or sensor malfunction). It is observed both the strong motion and the broadband sensors (except STS-2) have unexplained poor behaviour at various stations in the network.



Stn TKD - STS-1 error



Stn YMZ - VSE-355G2 error



BroadBand Instrument Performance Summary

In the Figure, $1/K$ is plotted against the broadband sensor velocity for each of the > 500 components of F-Net data recorded during the 3 events. Colors represent the type of broadband sensor each channel is recorded on. The STS-2 sensor is shown to have an average ratio very close to 1, with small variance. The STS-2 does not record velocities above the expected clip level of $1.3cm/s$, and all clipped values fall within 80% of this value. The STS-1 data is to have an average $1/K$ below 1, with a large variance, indicating either error in network gains, or in instrument repeatability. The instrument clip falls reliably within 80% of the expected $0.8cm/s$. The CMG-1T has average $1/K$ well above 1, with a large variance, as well as a widely varying clip level. It appears the sensor reliability is not as good for this instrument.

BroadBand Instrument Properties (BroadBand vel. $< 0.8cm/s$) [*Relative to VSE-355G/G2*]

	STS-2	STS-1	CMG-1T
# channels	252	141	96
mean	0.971	0.930	1.116
std. deviation	0.049	0.384	0.232

5. Conclusions

- The density of GPS and strong motion networks in the near-source region, which had widespread large displacement offsets, make this dataset invaluable in attempting to devise a method to produce exact displacement timeseries, from high frequency to DC.
- The strong motion velocity sensors used by F-Net are shown to have poor performance in strong motions both in the lab and in the field. The manufacturer has since produced a model we have tested in the lab that appears to record the strong motion without problem. Weak motion performance is excellent, with significantly enhanced long period sensitivity compared to FBA accelerometers, for both sensors.
- A strong motion velocity sensor is no improvement on accelerometers in terms of recording static offset, as both are inertial sensors, and thus equally sensitive to ground tilting. Tilts are a major feature of Tokachi-Oki ground motions. Co-location of high sample rate GPS with inertial sensors provides for accurate recovery of large motions, and would be an extremely valuable addition to existing seismic network stations.
- The motions from the mainshock saturate all F-Net broadband sensors within $500km$ of the epicenter, and some out to $1000km$. All strong motion sensors recorded signals above the background noise level over the entire Japanese islands.
- Comparing strong motion with broadband sensors at each F-Net station after a large event is an excellent indicator of network health. Comparisons from multiple events show the STS-2 is more reliable than the STS-1 and CMG-1T in terms of sensor gain and clip level.

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