Effects of Earthquake Ground Motion on Tracking Characteristics of New GNSS Hardware

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Strong motion near the epicenters of recent great earthquakes such Maule and Tohoku have resulted in tracking disruptions, hardware failures and data loss at GNSS stations. In order to optimize GNSS-based hazard monitoring and early warning systems the reasons for these failures must be understood and mitigation strategies developed. Controlled shake table experiments provide a means to evaluate various hardware components and identify failure mechanisms and shaking thresholds responsible for system failures.

Findings regarding the impacts of earthquake ground-motion on tracking characteristics of new GNSS hardware will be highlighted. Five receiver models from four manufactures were evaluated using an all-electric 3-axis shake table. Simulated ground motions from the February 2010 Chile earthquake were reproduced at three magnifications with maximum amplitudes of approximately 0.6g, 4g, and 7g. A high-pass filter was used to remove large low frequency ground motions due to limitations in the shake table's spatial range. Accelerations were measured at 100 samples per second using a Kinimetrics EpiSensor. GNSS observations were recorded at ≥10 sps by the test receiver and at two collocated base stations to allow for carrier-phase double-difference processing. To separate tracking performance degradation from shaking the receiver and from shaking the antenna, several tests were conducted with only the antenna fixed to the shake table.

Our results show that during the largest simulated shaking events (4g and 7g), the number of tracked satellites decreased to 4 (the minimum needed for a position solution) for several of the receiver models. One model lost acquisition of all satellites during the largest accelerations (>6g). Tracking performance improved when the receiver was removed from shake table and only the antenna was shaken. This suggests that mechanical stresses applied to the receiver's internal quartz oscillator during shaking increase clock dynamics and decrease phase tracking loop performance. If the acceleration of the receiver is constant, an offset in the oscillators frequency can occur. If the acceleration is a vibration, the phase noise of the oscillator may increase. Both frequency offsets and phase noise can decrease receiver-tracking performance. The g-sensitivity of the quartz oscillators used in GNSS receivers may vary between manufactures and could explain the difference in tracking performance between models. Differences in tracking loop methodologies between manufactures may also explain the variation in observed tracking performance. All receivers were set to use their default tracking loop parameters.

These results demonstrate the importance of properly securing receivers when they are used for long-term geodetic observations in earthquake prone areas. Accelerations experienced by a receiver during an earthquake may exceed the tested values if allowed to rattle freely, thereby causing data loss.

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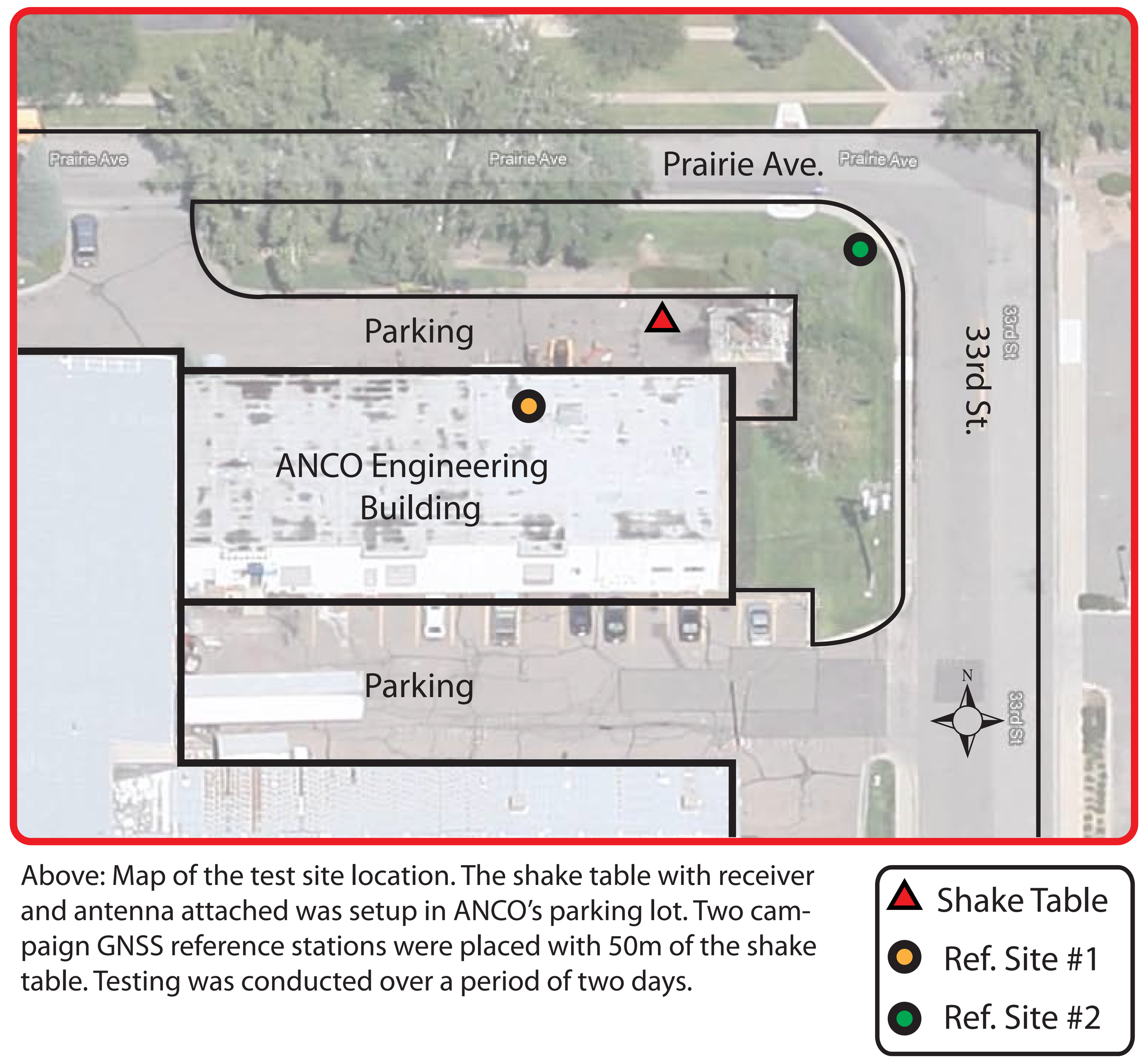


Above: Map of the test site location. The shake table with receiver and antenna attached was setup in ANCO's parking lot. Two campaign GNSS reference stations were placed with 50m of the shake table. Testing was conducted over a period of two days.

The testing locality provided a challenging environment for GNSS tracking. (Above) A photo of the test site looking to the NW. A large tree obstructs the sky view.

A close up of the shake table apparatus. Each receiver was fixed to the table using angle iron anchored with 1/4″ bolts. The table design consisted of three very large DC servos connected to a triangular table with carbon rods. The table's capacity was limited to 200 lbs. The the table's maximum acceleration was limited to 8g.

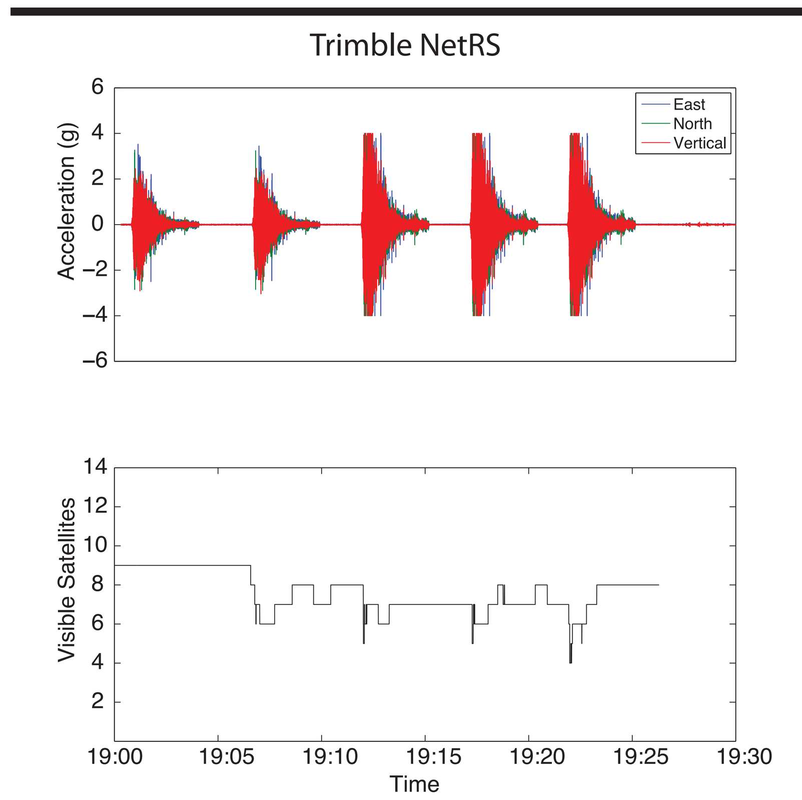
Introduction:
To determine the impacts of earthquake ground-motion on Global Navigation Satellite System (GNSS) receiver tracking performance, we shook five receiver models using an all-electric 3-axis shake table (lower left). Ground motions were simulated from the February 2012 Chile earthquake and reproduced at three levels of magnification with maximum accelerations of 0.6g, 4g, and 7g. Acceleration was measured at 100 samples per second (sps) using a Kinematrics EpiSensor (upper right). GNSS observations were recorded at 10 sps by the test receivers located on the shake table and by two additional collocated base stations. The majority of the tests were conducted with both the receiver and the antenna fixed to the shake table. However, one test was conducted with the receiver removed from the shake table while the antenna remained fixed to the table.

Questions:
(1) What magnitude of acceleration is required to force a receiver to track less than 4 satellites?
(2) If loss of lock occurs, was it caused by accelerating the receiver, or moving the antenna, or some combination of both?
(3) Do different GNSS receiver models have similar tracking performance during strong shaking?

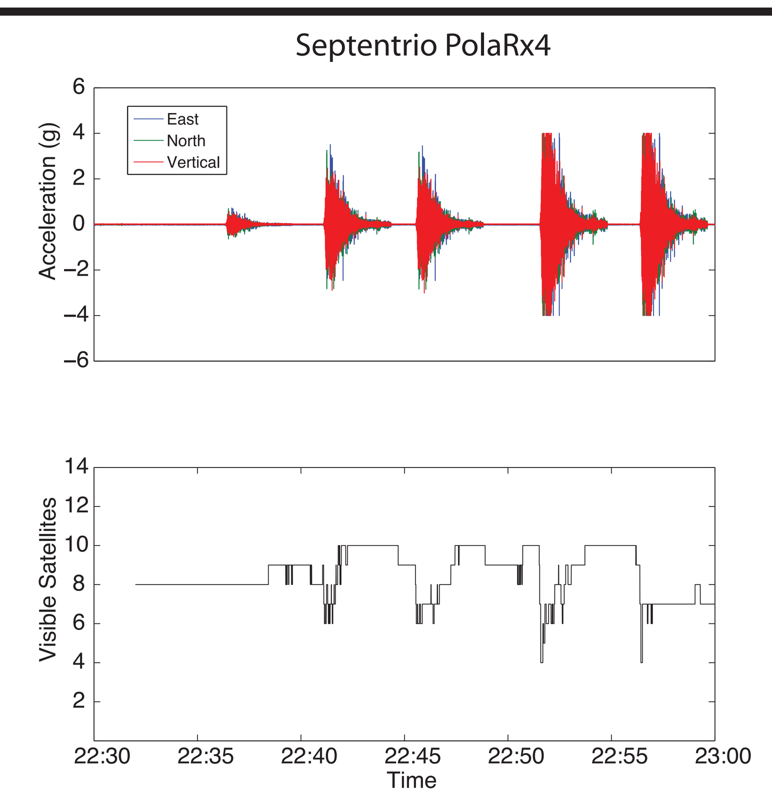
Results:
We plot the number of satellites tracked at each epoch along with the acceleration time-series from each test (shown below). During the largest simulated shaking events (4g and 7g), the number of tracked satellites decreased to 4 (the minimum needed for a position solution) for several of the receiver models. One model lost acquisition of all satellites during the largest accelerations (>6g). Tracking performance improved when that same receiver was removed from shake table and only the antenna was shaken.

A Kinemetrics EpiSensor ES-T was also affixed to the table allowing 100 sps measurements of acceleration in the X, Y and Z components. The measurement range of the ES-T was limited to ±4g. Clipping occurred during the experiment when accelerations exceeded 4g.

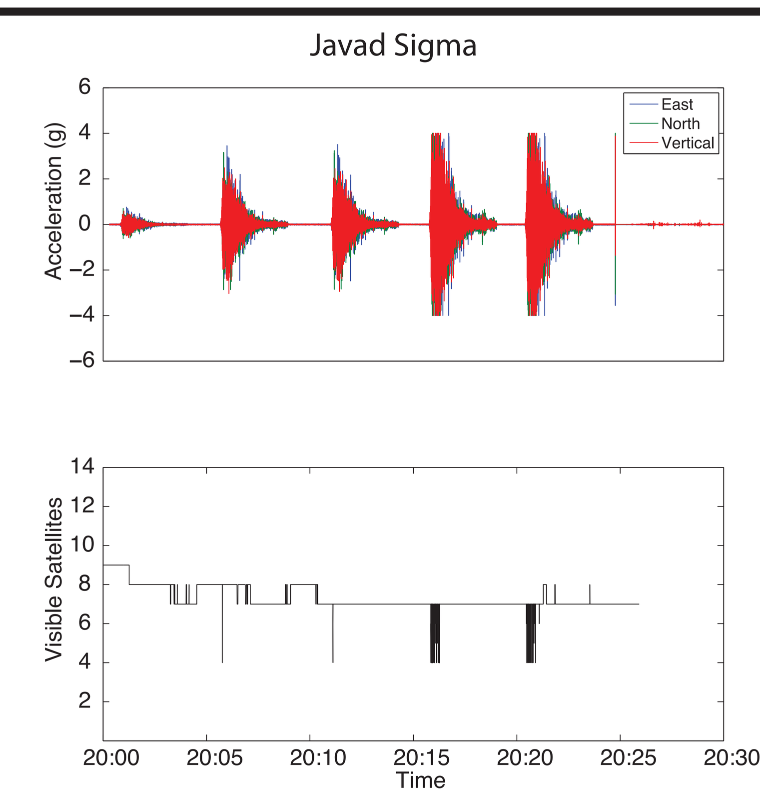
Each test antenna was fixed to the NE corner of the shake table using a 3/4″ to 5/8″ threaded stud. Locknuts were used to prevent the antenna from loosening during the test. The antenna ground plane was ~4″ above the surface of the table.



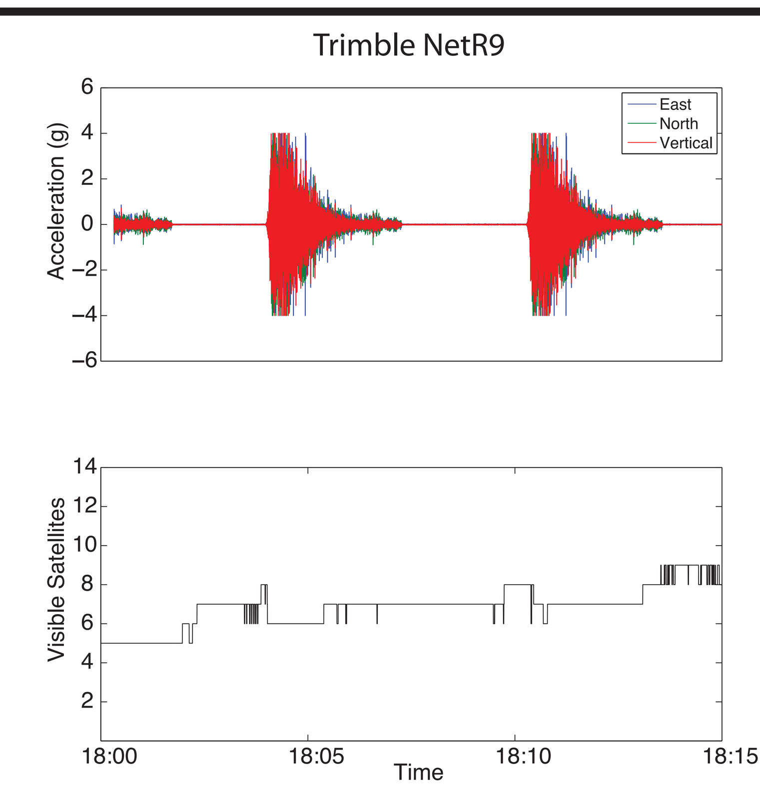
Top panel - shows 3-component acceleration data from five simulated earthquake events. Lower panel - shows the number of visible GPS satellites for the Trimble NetRS receiver.



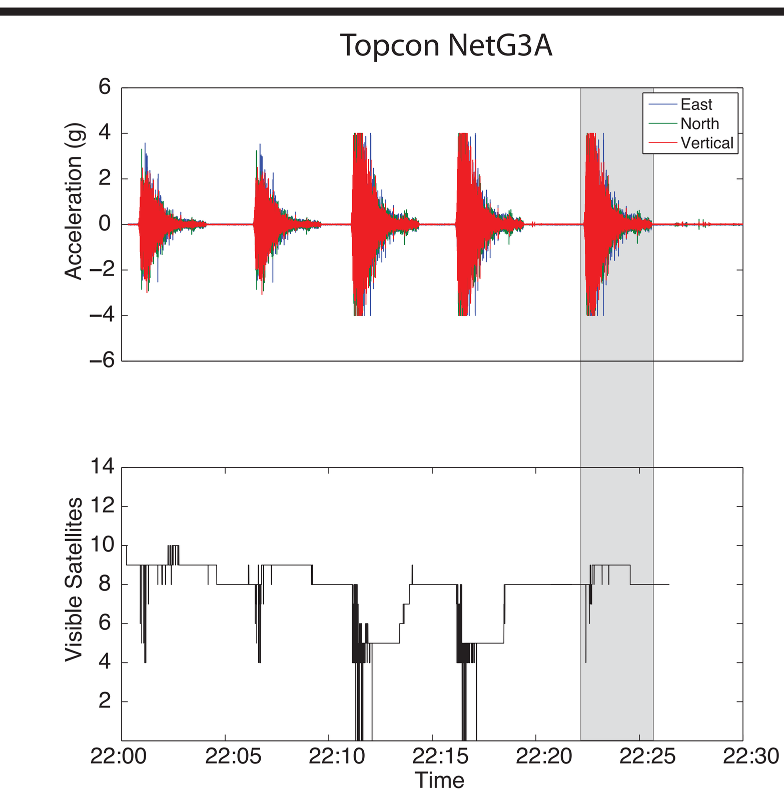
Top panel - shows 3-component acceleration data from five simulated earthquake events. Lower panel - shows the number of visible GPS satellites for the Septentrio receiver.



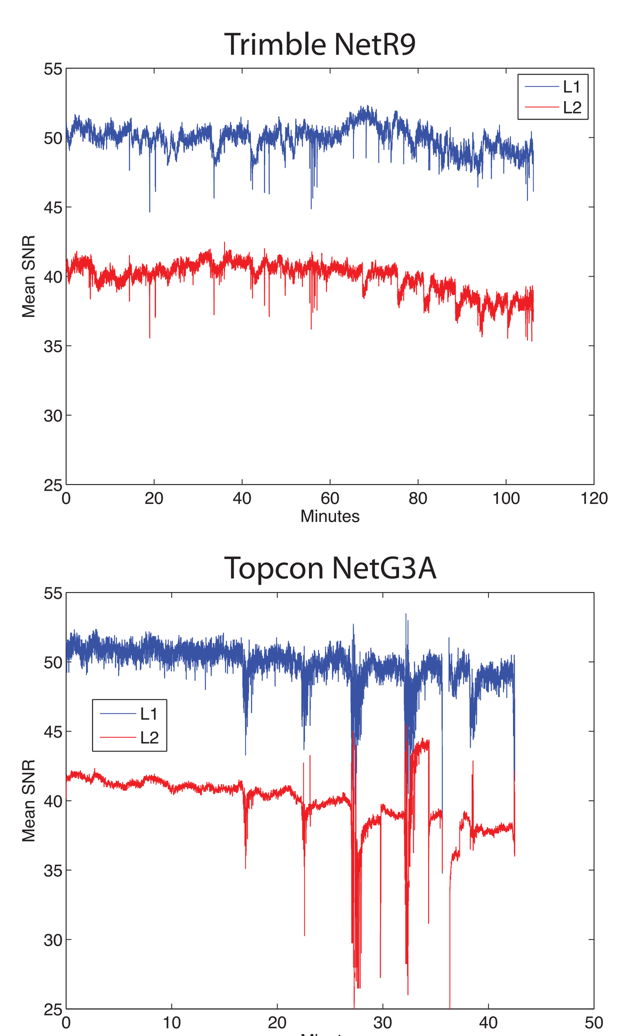
Top panel - shows 3-component acceleration data from five simulated earthquake events. Lower panel - shows the number of visible GPS satellites for the Javad Sigma receiver.

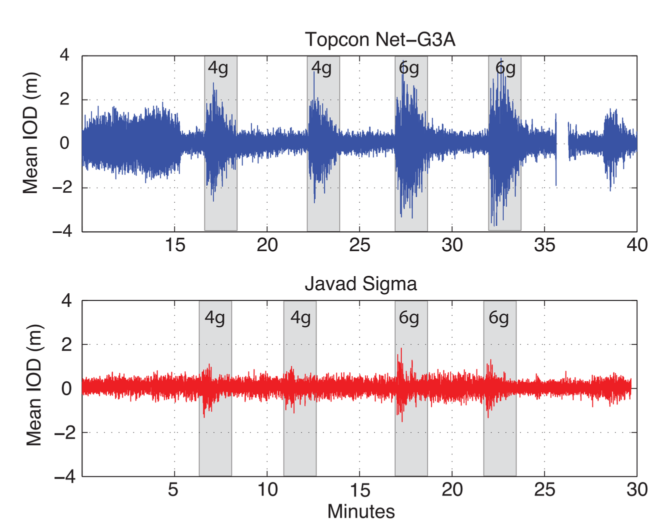


Top panel - shows 3-component acceleration data from two simulated earthquake events. Lower panel - shows the number of visible GPS satellites for the Trimble NetR9 receiver.



Top panel - shows 3-component acceleration data from five simulated earthquake events. Lower panel - shows the number of visible GPS satellites for the Topcon Net-G3A receiver. The lightly shaded region indicates when the receiver was removed from the shake table and only the antenna was shaken.



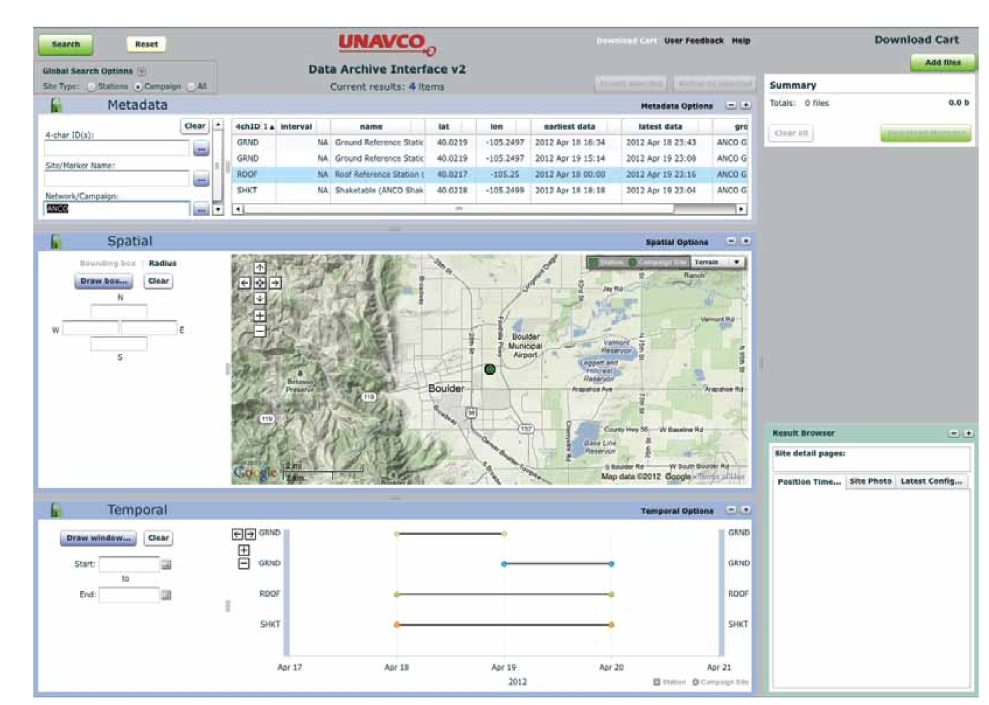


$$IOD = \frac{a}{a-1}[(L_1 - L_2)_j - (L_1 - L_2)_{j-1}]/(t_j - t_{j-1})$$

Upper Left: Mean Signal to Noise Ratio (SNR) recorded by a Trimble NetR9 receiver during five simulated earthquake events.
Lower Left: Mean Signal to Noise (SNR) recorded by a Topcon Net-G3A receiver during five simulated earthquake events.
Above: Mean time "derivative" of the ionospheric delay estimate from two receivers. The upper panel shows the results from a Topcon Net-G3A. The lower panel shows the results from a Javad Sigma receiver.

Conclusions:

(1) Our Results show that during the largest simulated earthquake events (max. amplitude of 4g and 7g), the number of tracked satellites decreased to 4 (the minimum needed for a position solution) for several of the tested receiver models.
(2) Tracking performance improved when the worst performing test receiver (Topcon Net-G3A) was removed from the shake table and only the attached antenna was shaken. This suggests that mechanical stresses applied to the receiver's internal quartz oscillator during the simulated shaking rather than increased dynamics from shaking the antenna were the primary cause of tracking performance degradation.
(3) The difference in observed tracking performance between the receiver models tested in this report could be explained by several mechanisms. Either we are observing a difference in oscillator g-sensitivity between receivers, or a difference in tracking loop performance in the presence of increased oscillator noise, or some combination of the two mechanisms.
(4) Due to ongoing changes in the satellite constellation throughout the experiment, these results are not a complete or fair comparison of receiver tracking performance during strong accelerations.
(5) Our methodology could be improved by conducting a simulated ground-motion experiment in an anechoic chamber using simulated GNSS signals. Signal simulation would allow accurate test repeatability with each test device.
(6) Our time using the shake table was limited by the manufacturer, who graciously provided access to the table while it was undergoing tests before being delivered to the customer.
(7) These results demonstrate the importance of securing receivers when they are used for long-term geodetic observations in earthquake prone areas. The g-forces of an unsecured receiver during an earthquake may exceed the tested values (6g) and thereby cause poor tracking performance and loss of data during an important event.



Where can I find all of the data from this experiment?
On the UNAVCO Data Archive Interface (DAI), shown above. (http://goo.gl/TJ18f)

For direct FTP access:
ftp://data-out.unavco.org/pub/pickup/campaigns/anonymous/3486