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THE TOKACHI OKI EARTHQUAKE: EVALUATION OF GPS AS A STRONG MOTION INSTRUMENT

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ABSTRACT

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The goal of this work was to assess how well GPS can serve as a strong-motion instrument. Although GPS receivers do not have the dynamic range of seismic instrumentation, they do not clip and are intrinsically sensitive to position. GPS is not a replacement for seismic instrumentation, but in this study we have shown that high-rate GPS measurements can be used as seismometers. Furthermore, it is possible to combine seismic and geodetic observations to improve the utility of seismic measurements in the near-field of large earthquakes. We analyzed 1-Hz GPS data recorded during the 2003 Tokachi-Oki earthquake by the Geodetic Survey Institute GPS network in Japan. Many of these GPS observations could be combined with strong motion records, thus providing a very broadband displacement time history that can be used by a) geophysicists who model the rupture and b) earthquake engineers who need to understand ground shaking to build safer structures. Agreement between GPS and seismic records is very good as long as seismic orientation errors are taken into account. GPS networks currently installed in the United States are thus able to simultaneously measure long-term tectonic rates and strong motions during earthquakes.

Introduction

The goal of strong-motion networks is to measure ground motions during large earthquakes over a broad frequency band [*Clinton and Heaton*, 2002]. In the United States and Japan, strong-motion networks are dominated by triggered instruments that measure ground acceleration. To recover ground motions, such measurements must be integrated twice, a challenging task in the presence of noisy observations. Strong-motion instruments are inertial sensors and thus also limited by tilting effects.

The goal of this proposal was to assess how well GPS could serve as a strong-motion instrument. Although GPS receivers do not have the dynamic range of seismic instrumentation, they have two advantages over seismic instrumentation: they do not clip and they are intrinsically sensitive to position and thus require no integration.

An additional advantage of a GPS strong motion instrument is that it can do so while simultaneously measuring long-term tectonic deformation rates, which also contribute to earthquake hazard assessments. GPS networks are being installed all over the United States, most notably the Plate Boundary Observatory (http://www.earthscope.org). It is possible that many of these sites could be operated at high sampling rates, thus providing information at both seismic and tectonic frequencies. The high-rate GPS data could be buffered rather than archived, acting in the way many seismometers currently work.

GPS seismology, as a idea, has been discussed for many years. *Nikolaidis et al.* [2001] tried to measure seismic waves from the Hector Mines (1999) earthquake, but her evaluation was severely limited by the sampling rate traditionally used in GPS receivers at that time: 30 seconds. GPS was subsequently evaluated as a seismometer in the surveying community [*Ge et al*., 2000], but these results cannot be easily extended to a GPS-strong motion network because they are based on having a stationary receiver within ~10 meters of the shaking instrument (for geodesists, this is termed a short-baseline experiment, where relative orbit and atmospheric errors are essentially zero).

In the past 5 years, more GPS receivers installed for crustal deformation studies have been set to operate at higher sampling rates, with some at 1-Hz. This has allowed more convincing tests of GPS seismology. 1-Hz GPS recordings made ~150 km from the Denali Fault rupture measured dynamic displacements of up to 7 cm [*Larson et al*., 2003]. Unfortunately there were no high-rate GPS receivers closer to the epicenter and rupture.

Description of the Tokachi-Oki Earthquake and Dataset

The Tokachi-Oki earthquake on 2003 September 25 19:50:06 UTC was located approximately 40 km offshore Hokkaido and at a depth of approximately 30 km. This magnitude 8 earthquake was followed ~80 minutes later by a M7.4 aftershock. Horizontal co-seismic deformations of nearly a meter were observed with static GPS measurements. Intense ground motions with long duration were felt over large areas of Hokkaido, and landslides, liquefaction and lateral spreading were widely reported. Though civil

infrastructure was affected, since Hokkaido is sparsely populated and most buildings were well designed, there was little loss of life.

Hokkaido is well instrumented with seismic instruments in multiple networks operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). Data from four separate nation-wide seismic networks are available [*Okada et al*., 2003]. Three of these, K-Net, KiK-Net and F-Net, have strong motion sensors at all stations. K-Net is a very dense surface accelerometer network, with station spacing of 25 km. KiK-Net is a borehole network with 650 stations, each comprising of an uphole and downhole accelerometer. The depth of the boreholes range ranges from a 100-2000 meters. Both these networks operate as triggered sensors.

Japan also operates a state-of-the-art GPS network, GEONET, which is operated by the Geodetic Survey Institute (GSI). There are over 1200 GPS receivers continuously recording at 30 second sampling in Japan. The 30 second GEONET data are available to the public. These are the data that were used to produce static offset determinations for the Tokachi-Oki earthquake, e.g. *Miura et al*. [2004]. Many of these same receivers track the GPS constellation at 1-Hz and transmit those observations in real-time. The 1-Hz GPS data from Hokkaido were provided to our research group as a collaborative effort with Dr. Shin'ichi Miyazaki (Earthquake Research Institute) and Dr. Atsushi Yamagiwa (GSI).

Data Analysis

We analyzed the Tokachi-Oki data using the GIPSY software [*Lichten and Borders*, 1987] and IGS orbits [*Beutler et al*., 1994]. Positions are referenced to ITRF2000 [*Altamimi et al.*, 2002]. With orbits held fixed, the estimated parameters are receiver and satellite clocks, the zenith troposphere delay, and 1-Hz white noise receiver positions (100 meter *a priori* standard deviation) for all sites except reference sites outside Japan. A fuller description of data analysis is given by *Choi* [2007].

Results

We identified four tasks for this research grant.

I. Estimate static seismic offsets for the Tokachi-Oki earthquake and the M7.4 aftershock. While the M7.4 aftershock is barely observable in the western portion of Hokkaido, its static offset is important for combining the seismic and GPS records for sites that lost telemetry of the 1-Hz data during the mainshock and did not come online until after the aftershock. Static offsets have been computed for both the mainshock and aftershock and are available in Table 1. They will also be published in a refereed journal and archived at IRIS.

II. *Estimate 1-Hz GPS positions for all available sites in Hokkaido*

These solutions have been computed. They were used as input for *Miyazaki et al*. [2004] and *Larson etal.* [2006]. Individual time series, i.e. seismic waveforms, will be archived at IRIS.

III. *Retrieve strong-motion records. Compare GPS and strong motion records.*

Strong motion data were initially analyzed by John Clinton [*Clinton*, 2004]. He was instrumental in determining that some of the Japanese strong motion sensors had significant orientation errors. Note the comparisons given below, before and after rotation of the seismic sensor.

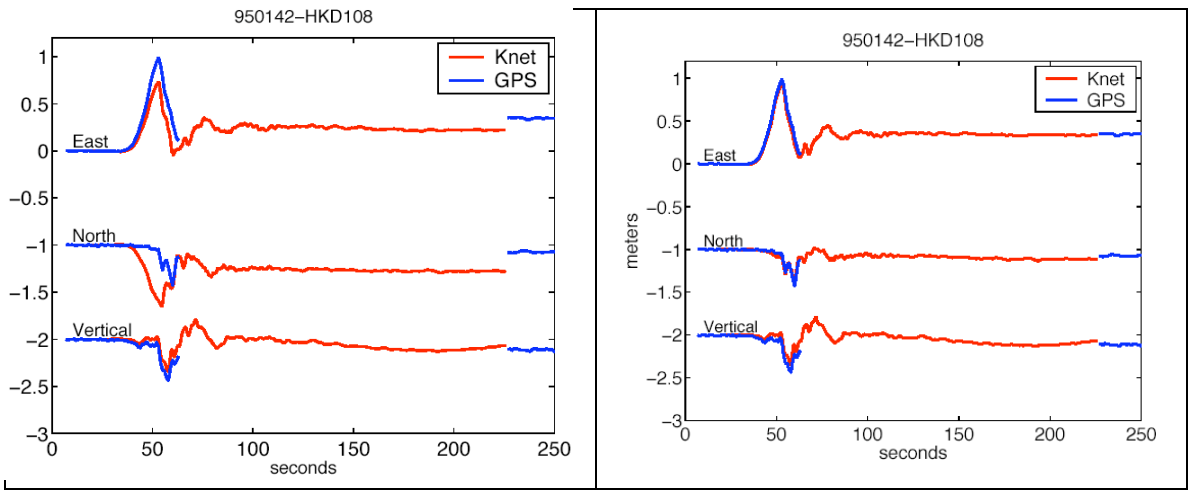

Figure 1. Time series of collocated GPS and strong motion sensors on Hokkaido. Seismic data shown on the right have been rotated. There was a ~200 second power outage at the GPS site. Seismic data shown in this figure were provided by John Clinton.

IV. *Develop software to integrate seismic records with GPS constraints*.

Although we believe the GPS records have important strengths, the data are still very noisy compared with seismic instrumentation. They are also limited by the 1-Hz sampling. The strong motion instruments are more precise but limited by integration errors and tilting. Ideally, one would wish to combine the two kinds of instruments by a fully constrained integration rather than imposing only the final (static) displacement on the double integration. Combining the two data streams (and removing timing and orientation errors) will produce a far more valuable data set for seismic source and hazard studies.

Some of the sites closest to the epicenter lost their real-time telemetry stream, and thus lost 1-Hz measurements ~25 seconds into the event. Although this might imply we could not further use GPS as an integration constraint, in fact the 30-second GPS data analyzed in Task I have no power related gaps.

Collaborating with our group, Gordon Emore, a graduate student at Purdue University, has developed software to combine the seismic and GPS records. His results are summarized in *Emore et al.* [2007]. Figure 2 shows the strength of using high-rate GPS as a constraint for integrating strong motion records. In this example, it is shown that even 30-sec sampled GPS data would provide sufficient constraints. An additional example of collocated GPS-seismic data is shown in Figure 3.

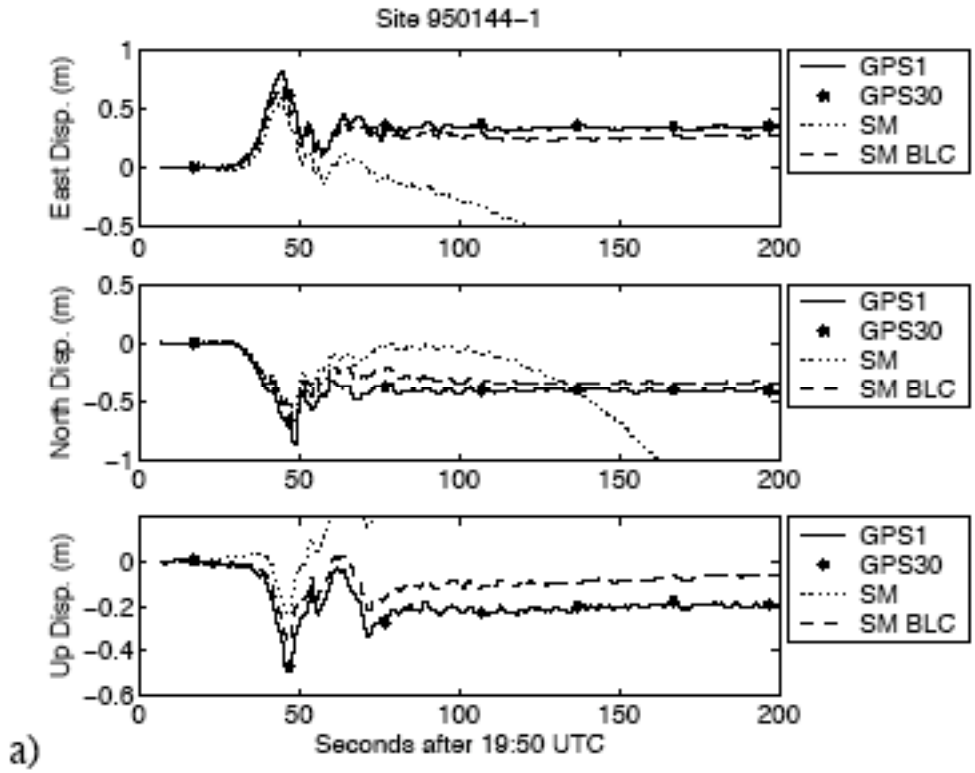

Figure 2. 1 Hz GPS displacement for site 950144 (solid line), GPS 30 second solution for displacement (stars), uncorrected integrated strong motion for Knet site HKD110 (dotted line) and baseline corrected integrated strong motion record (dashed line).

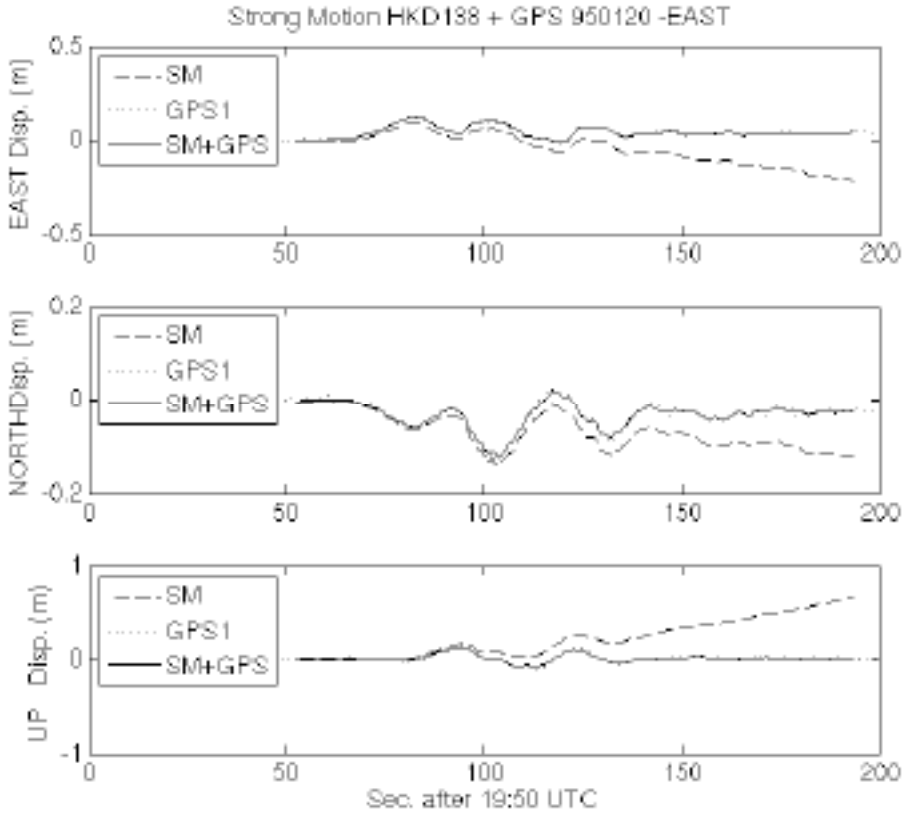

Figure 3. SM: seismic record, GPS1: 1-Hz GPS; SM+GPS, seismic record integrated to agree with 1-Hz GPS.

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Table 1.
Static Displacements for the Tokachi-Oki Earthquake

	Mainshock			Aftershock		
Site	East (cm)	North (cm)	Vertical (cm)	East (cm)	North (cm)	Vertical (cm)
0001	2.2 ±0.8	−1.9±0.9	−6.4±2.2	0.5±0.4	−0.5±0.5	−3.0±1.5
0002	2.2 ±0.5	−4.7±0.9	0.1±1.4	0.4±0.5	−0.3±0.7	−1.5±1.6
0003	3.9 ±0.8	−4.2±1.4	−0.3±1.8	0.2±0.5	0.6±0.7	−0.8±1.4
0004	1.4 ±0.7	−0.2±0.9	−1.5±1.7	0.2±0.4	0.1±0.7	−0.6±1.5
0005	3.4 ±0.7	−1.0±0.9	−2.2±1.6	0.3±0.4	0.0±0.7	−3.1±2.2
0007	9.8 ±0.6	−12.7±0.7	−1.6±1.4	0.3±0.5	−0.3±0.6	−1.1±1.7
0008	6.3 ±0.6	−4.5±1.0	−0.8±1.6	0.1±0.5	0.3±0.6	−1.2±1.5
0009	10.7±0.7	9.9±0.7	3.0±1.3	0.4±0.4	0.3±0.6	−1.8±1.6
0010	15.2±0.8	9.1±1.1	3.6±1.9	−	0.0±0.5	0.8±0.6	−1.1±1.2
0011	21.4±0.6	−31.4±0.8	−10.3±1.8	0.0±0.5	0.3±0.8	−1.8±2.5
0012	23.8±0.7	−18.7±0.9	−3.5±1.5	0.7±0.5	−1.1±0.6	−2.1±1.8
0014	11.8±0.6	−6.2±1.0	0.2±1.8	0.5±0.4	−0.2±0.6	−1.8±1.8
0015	76.5±0.7	−46.9±1.0	−24.6±1.5	1.6±0.5	−1.1±0.6	−1.5±2.0
0016	29.0±0.7	−7.4±1.0	−6.6±1.6	2.4±0.4	−2.1±0.6	−0.7±2.0
0017	2.9±0.7	0.2±0.7	−0.6±2.0	0.1±0.4	0.2±0.6	−1.2±1.8
0018	5.9±0.8	−0.2±0.9	−1.2±1.6	0.6±0.6	0.4±0.7	−0.4±1.7
0019	51.0±0.7	−8.5±0.7	−18.0±1.4	7.4±0.4	−3.3±0.5	−0.7±1.5
0022	2.8±0.8	0.0±0.8	−1.3±1.6	0.5±0.5	−0.2±0.8	−0.1±1.7
0101	0.8±0.7	−1.7±1.0	−2.4±1.9	0.4±0.3	0.4±0.5	−2.3±1.4
0102	2.0±0.4	−0.9±0.9	1.5±1.5	0.0±0.4	0.2±0.5	−1.5±1.3
0103	1.9±0.6	−3.7±0.8	3.9±2.0	−0.1±0.4	0.7±0.6	−2.9±1.6
0104	1.5±1.0	−1.8±0.9	0.3±1.8	0.1±0.4	0.2±0.8	−1.5±1.9
0105	2.7±0.6	−2.7±0.9	−0.4±1.5	−0.0±0.4	0.4±0.4	−2.0±1.9
0107	3.3±0.7	−4.9±1.0	−0.1±1.7	−0.1±0.3	0.5±0.5	−3.4±1.4
0109	2.7±0.9	1.9±1.1	−0.9±2.1	0.0±0.8	0.1±1.0	−2.3±2.9
0110	5.8±0.6	−6.0±0.9	0.2±1.3	−0.1±0.4	0.2±0.6	−0.9±1.7
0111	3.7±0.7	−6.9±0.8	−0.5±1.6	−	0.0±0.4	−0.2±0.5	−2.4±1.3
0112	21.9±0.8	−13.7±0.8	−5.9±1.5	0.2±0.4	0.2±0.6	−1.9±1.4
0114	3.2±0.6	−6.6±0.8	−0.6±1.7	0.0±0.4	0.4±0.6	−1.0±1.5
0115	3.4±0.9	3.2±0.9	0.2±1.6	0.3±0.5	0.3±0.8	−0.0±1.6
0116	4.4±0.8	3.8±1.0	−0.7±2.2	−0.1±0.5	0.6±0.6	−1.2±2.2
0117	6.8±0.7	−4.2±1.2	8.1±2.1	0.4±0.4	0.2±0.9	−2.7±2.3
0119	3.8±0.7	3.8±1.1	−0.6±2.4	0.0±0.4	0.4±0.7	−0.4±1.5
0120	5.2±0.6	−1.1±1.1	−0.5±2.2	0.3±0.5	0.2±0.5	−1.6±2.1
0121	10.5±0.6	−18.8±0.7	−5.4±1.4	−0.0±0.6	−0.1±0.6	−1.9±1.8
0122	7.3±0.8	−1.6±1.0	−1.3±2.1	−0.2±0.5	−0.2±0.8	−1.5±2.1
0124	10.9±0.9	−7.3±0.9	−2.4±1.5	−0.3±0.4	0.9±0.7	−1.7±1.6
0125	12.0±0.7	12.2±0.8	3.6±1.8	−0.0±0.5	0.7±0.8	−2.3±1.7
0126	4.4±0.7	−1.1±0.8	−0.3±1.4	−0.0±0.5	0.5±0.5	−2.1±1.4
0128	8.9±1.0	−2.2±1.1	1.9±2.5	0.2±0.6	−0.0±0.7	−3.4±2.3
0129	5.2±0.9	0.5±1.3	0.8±2.0	0.7±0.5	−0.4±0.9	−0.0±2.5

0130	4.6±0.5	0.1±0.9	1.0±1.7	0.3±0.5	0.5±0.8	−3.0±2.4
0132	14.8±0.9	−5.6±1.0	−1.4±1.8	0.8±0.7	−0.7±0.8	−3.3±1.8
0133	27.2±0.8	−14.8±0.8	−4.7±1.5	0.7±0.5	−1.1±0.7	−2.3±1.5
0134	48.5±0.6	−42.1±0.8	−20.9±2.0	0.3±0.5	−0.8±0.6	−2.1±1.9
0135	7.5±0.8	0.2±1.1	1.2±2.0	0.3±0.5	0.6±0.7	−1.7±2.5
0136	10.6±0.7	−1.8±1.3	−0.3±2.1	0.9±0.5	−0.9±0.8	−2.4±2.6
0138	56.9±0.7	−43.2±0.9	−16.8±1.6	0.3±0.4	0.3±0.6	−2.0±1.6
0139	7.3±1.1	−1.0±1.1	0.5±2.3	3.5±0.5	−0.6±0.6	−7.7±1.9
0140	3.2±0.8	0.1±0.8	−0.7±2.2	0.2±0.4	−0.3±0.8	−3.2±1.8
0141	18.3±0.8	−5.6±0.9	−4.3±1.3	1.7±0.6	−1.3±0.7	−1.4±1.2
0142	36.6±0.6	−6.8±0.9	−11.3±1.8	3.3±0.5	−2.7±0.6	−4.2±2.0
0143	2.6±0.7	−0.1±0.7	0.9±1.4	0.8±0.5	0.4±0.5	−3.1±2.3
0144	51.8±0.6	−9.4±1.0	−18.5±2.4	6.3±0.6	−4.2±0.9	−2.4±1.5
0147	3.1±0.7	−0.1±1.1	1.5±1.6	1.0±0.5	1.0±0.7	−0.6±1.3
0148	3.3±0.7	1.6±0.9	0.2±2.0	0.4±0.5	0.5±0.6	−3.0±1.8
0149	2.1±0.8	0.8±0.9	2.7±1.4	0.3±0.6	0.7±0.5	−2.1±1.9
0150	1.4±0.7	0.9±0.7	−0.8±1.2	0.8±0.4	−0.3±0.7	−1.8±1.3
0502	2.1±0.8	−2.4±1.4	−2.7±2.3	−0.1±0.8	0.1±1.1	−1.4±2.5
0503	2.5±0.7	−4.0±1.1	−0.3±2.0	0.1±0.6	0.4±0.8	−2.4±2.3
0504	3.7±0.9	−5.9±0.9	1.0±1.8	0.3±0.6	0.4±0.9	−2.0±2.9
0505	1.6±0.6	−1.8±1.0	−0.9±1.7	0.1±0.4	0.5±0.6	−1.0±1.8
0509	7.2±0.7	−6.2±0.7	0.4±1.5	0.7±0.4	−0.5±0.7	−1.6±1.7
0510	6.6±0.7	−9.8±1.1	−0.7±1.7	0.4±0.6	0.0±0.8	−1.9±2.1
0511	4.4±0.7	−11.1±1.0	−1.6±1.9	0.1±0.5	−0.3±0.7	−1.2±1.8
0512	6.8±0.7	7.2±0.9	−0.4±1.8	0.6±0.4	−0.4±0.7	−1.4±1.3
0513	4.9±0.7	−6.9±0.7	−1.6±1.4	−0.1±0.4	0.6±0.7	−1.0±1.5
0514	14.1±0.7	−14.8±1.0	−3.1±1.8	−0.0±0.5	−0.3±0.6	−1.3±1.7
0516	11.4±0.6	−6.1±0.9	1.0±1.9	0.1±0.5	−0.5±0.8	−4.0±1.5
0521	30.6±0.6	−36.2±1.0	−11.8±2.0	0.2±0.5	−0.1±0.7	−2.5±1.5
0525	2.7±1.6	3.0±2.6	7.0±5.7	0.5±0.4	−0.0±0.7	−4.6±2.0
0530	2.3±0.8	1.9±0.9	1.9±2.2	0.2±0.6	0.6±0.8	−5.5±2.3
0532	75.1±0.6	−33.1±0.7	−21.2±1.9	3.8±0.4	−0.7±0.6	−1.1±2.0
0533	1.5±0.9	1.2±1.2	−1.9±2.7	1.7±0.8	−1.2±1.0	−3.0±2.1
0534	1.5±0.6	1.0±1.1	1.3±1.9	0.3±0.6	0.6±0.9	−0.4±1.8
0782	3.8±0.5	−4.1±0.8	−0.2±1.4	0.1±0.4	−0.0±0.7	−1.5±1.4
0783	4.8±0.8	−3.3±1.2	0.4±1.7	0.1±0.4	0.2±0.6	−2.8±1.9
0784	1.3±0.6	−1.5±0.7	2.6±1.4	0.3±0.6	0.3±0.7	−1.0±2.1
0786	14.1±1.0	−20.6±1.4	−2.7±2.3	0.6±0.5	−0.2±0.8	−1.0±1.8
0789	27.0±0.8	−27.9±1.1	−7.6±1.9	−0.7±0.6	−1.0±1.0	3.0±1.5
0791	34.5±1.2	−39.8±1.6	−14.8±3.1	0.5±0.5	−0.1±0.7	−1.6±2.5
0793	64.4±0.8	−43.4±1.3	−25.2±1.7	0.8±0.4	−1.3±0.9	1.7±1.8
K011	27.8±0.8	−34.8±1.1	−9.6±2.1	0.4±0.4	−0.5±0.6	−0.5±1.5
K026	27.2±0.5	−35.2±0.8	−11.3±1.5	0.5±0.4	−0.4±0.5	−0.5±1.6
K027	29.9 ±0.7	−31.8±0.7	−11.5±1.7	0.0±0.4	−0.1±0.7	−1.1±1.5

Data Availability

Because the high-rate Tokachi-Oki GPS solutions are of greatest interest to seismologists rather than geodesists, we are archiving them at IRIS. High-rate solutions for the Denali event have already been archived and are available via the GD network (http://www.iris.edu/mda/GD).

Our colleagues at Purdue, Professor Jennifer Haase and Gordon Emore, have produced a combined geodetic-seismic product for many of the Tokachi-Oki GPS sites that had power outages. This significantly improves the resolution of these data in both time and space. These data will also be archived at IRIS. Discussion of the combination technique used is found in *Emore et al.* [2007].

Publications resulting from this grant:

Bilich, A., J. Cassidy, and K. Larson, GPS as a Strong-Motion Seismometer: Application to the 2002 Denali Fault Event, in preparation for submission to *BSSA*.

Emore, G., J. Haase, K. Choi, K. M. Larson, and A. Yamagiwa, Recovering absolute seismic displacements through combined use of 1-Hz GPS and strong motion accelerometers, *BSSA*, in press.

Larson, K., A. Bilich, and P. Axelrad, Improving the precision of high-rate GPS, *J. Geophys. Res*., in press.