Nuclear Test Illuminates USArray Data Quality

The seismographic stations deployed as part of USArray are one component of the U.S. National Science Foundation-funded major research equipment facility EarthScope. When fully operational, USArray will include 400 broadband stations in a Transportable Array (TA) that will be deployed over a regular grid of sites with approximately 70 kilometer spacing. The TA will migrate across the United States over the next decade, ultimately occupying about 2000 sites in the conterminous United States and Alaska.

While USArray’s primary objective is to record seismic signals for research applications addressing the structure, evolution, and seismicity of North America, the high-quality seismic recording capabilities of the TA installations allow data from small, distant events to be acquired and analyzed for other purposes, such as deep mantle studies, earthquake rupture investigations, and analysis of unusual seismic sources, such as underground nuclear explosions. The TA currently is undergoing its initial deployment in the western United States, and about 240 stations were operational at the time of the North Korean test site.

This article demonstrates the TA’s small-event detection capabilities through the extraction of high-fidelity signals produced by the North Korean explosion. Although simple teleseismic P waveforms are expected for an underground explosion, a magnitude 4.2 event is expected to produce only about a 2-nanometer displacement in this distance range; typically, only exceptionally quiet sites or seismic arrays specially designed to reduce seismic background noise [e.g., Douglas, 1998] can make robust detections of such small signals. The Comprehensive Test Ban Treaty Organization International Monitoring System (http://www.seismo.ethz.ch/bsv/cbto/ims.html) routinely uses small-aperture seismic arrays, which are also now being integrated into the National Earthquake Information Center monitoring operations (H. Benz personal communication, 2006).

The TA, in contrast, is designed to record a broad spectrum of ground motions at isolated sensors with an emphasis on uniform spatial coverage appropriate for seismic imaging of Earth’s interior rather than on multiple sensor stacking. However, the quality of the TA installations allows some applications to seismological problems other than the primary design goals which involve studying North America.

Casual inspection of the broadband TA recordings (openly available, along with all other TA data, from the Incorporated Research Institutions for Seismology (IRIS) data management system, http://www.iris.edu) reveals no discernible signal. However,

Detecting Explosion

The U.S. Geological Survey (USGS) estimated the hypocenter and magnitude of the North Korean event: 41.294°N, 129.094°E (Figure 1), 9 October 2006 at 0135:28 (UTC), m, 4.2 (http://earthquake.usgs.gov). Given independent calibration of the seismic magnitude versus known explosive yield for a particular geologic environment, the measured seismic magnitude can be used to estimate the explosion energy. Several yield estimates of less than 1 kiloton for the North Korean event have been announced in the popular media, based on various seismic magnitude estimates.

USArray TA stations operating in the western United States (Figure 1) are at epicentral distances of 66°–95° from the North Korean test site. Although simple teleseismic P waveforms are expected for an underground explosion, a magnitude 4.2 event is expected to produce only about a 2-nanometer displacement in this distance range; typically, only exceptionally quiet sites or seismic

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**Fig. 1.** (top left) Event and station map locations. (bottom left) Locations of the North Korean nuclear test and a deep event beneath the Sea of Japan. (right) Locations of unavailable Transportable Array (TA) station signals (light open circles), stations with usable but low signal-to-noise records (bold open circles), and stations with clear P wave arrivals for the North Korean test (solid circles).
when the data are band-pass filtered between 1 and 4 hertz, 45 of the currently operating stations show a coherent P wave signal a few seconds later than the arrival time predicted for a standard Earth model. The stations recording clear P wave arrivals are identified in Figure 1. These stations tend to be far from the noisy Pacific coast, but otherwise they are fairly uniformly dispersed throughout the current TA footprint.

**Enhancing the Signal**

The TA can be treated as a large-aperture array because of its relatively regular station grid and uniform instrumentation. We considered a subset of the data that recorded both the North Korean underground test and a magnitude 5.9 deep earthquake that occurred on 16 September 2006, 366 kilometers below the Sea of Japan (NEIC: 0222:50:59 UTC, 41.36°N, 135.70°E) (Figure 1).

The impulsive P arrivals for the deep event calibrate site effects that help extract the short-period signals produced by the North Korean test. Requiring each station to record at the time of the North Korean explosion and to record the deep event with a high signal-to-noise ratio yields a 172-waveform subset that includes 36 of the 45 clear signals from the North Korean explosion, which are shown in Figure 2. These traces were picked manually and aligned on the largest pulse in the filtered P waveforms. Individual station signal-to-noise ratios are in the range of 2–4 at these exceptionally quiet (in this passband) stations.

Four different sums of subsets of the 172 waveforms were considered in this study. For many stations, it was not possible to pick the P wave arrival reliably. Simply aligning all 172 signals on theoretical P wave arrival times predicted by the Jeffreys-Bullen (JB) travel time tables, weighting each signal by the inverse of its root-mean-square amplitude, and summing yielded the top trace in Figure 3, which lacked any clear detection of the explosion. The explosion signal was incoherent as a result of its short duration and arrival time fluctuations caused by crust and upper mantle heterogeneity and by station elevation variations across the large-aperture array.

By determining standard travel time corrections, based on impulsive P wave arrivals for the much larger Sea of Japan event, it is possible to improve the signal coherence. The corrections have about a 2-second scatter around a systematic delay relative to the JB tables. The weighted sum of all 172 traces aligned with these corrections is shown in the second row of Figure 3. A clear arrival near the expected time is now apparent.

If only the 36 high signal-to-noise ratio TA observations in Figure 2 are considered, simple unweighted stacks corrected for the Sea of Japan event station terms give the third trace in Figure 3, which has a clear P wave detection. The traces in Figure 2, aligned on the individual P arrivals, sum to give an even cleaner stack, as shown in the bottom trace of Figure 3, with the peak-to-peak amplitude being about 2 nanometers, as expected. The overall effect of improved signal alignment is an increase in signal coherency reflected by increasing signal amplitude. The noise level is insensitive to the time shifts and is below 0.25 nanometers, a remarkably low level that reflects the low noise levels of many of the TA stations and the effective suppression of incoherent noise. Secondary arrivals are observed in the stack within the first 6 seconds of the signal; these are most likely crustal reverberations generated near the source since they stack coherently across widely separated receivers.

**Implications of USArray Sensitivity**

The station corrections described here are the type of information that will accumulate from seismic events distributed at a variety of distances and directions from the TA. When thousands of such observations are available, they will contribute to imaging the lateral seismic wave speed variations in Earth’s interior.

Uniform installation procedures, which have evolved from extensive community experience with portable broadband seismic instrument deployments, are being followed for all TA stations (http://www.earthscope.org/usarray/site_char/trans_array_sites.php). The variations in TA noise properties thus are attributable largely to local seismic noise characteristics and site properties (detailed station information, including time-varying power density function data that quantify the noise levels for each station, is available from the USArray Network Facility site: http://anf.ucsd.edu/). While some sites intrinsically are noisier than others, the quality of many TA stations is comparable to that of the high-quality permanent sites within seismic monitoring networks.

The general quality and capabilities of the TA data are illustrated in this example through the clear detection of very small, 2-nanometer ground displacement signals for the North Korean nuclear test. It is unusual for portable seismometer installations to have background noise low enough that such signals can be observed, but many of the USArray stations are proving to be very quiet sites. This will allow vast amounts of useful data from many small events to be gathered during the TA rolling deployment across the United States.

TA data are not part of any routine global earthquake location/catalog operations, but the data are available to augment monitoring efforts (routine use is complicated by the scheduled migration of the TA). As the EarthScope project progresses, there will be many opportunities to use USArray for unexpected applications complementing the planned investigations of North America [e.g., Moschetti et al., 2005], including imaging earthquakes as well as deep and distant Earth structure [e.g., Lay et al., 2006].

More information about EarthScope is available at the Web site: http://www.earthscope.org. An animation of the planned deployment...
of the USArray Transportable Array is available at http://www.earthscope.org/usarray/array_design/transportable.php

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References


Satellite Observations of New Volcanic Island in Tonga

A rising volcanic plume from an unknown source was observed on 9–11 August 2006 in the Vava’u Island group in the northernmost islands of Tonga [Matangi News Online, 2006]. On 12 August, the crew on board the yacht Maiken, sailing west from Vava’u to Fiji, encountered “a vast, many miles wide, belt of densely packed pumice” floating on the water (F. Fransson personal communication, 2006). Later, the crew sailed south and discovered that the source of the pumice was a newly erupting submarine volcano near Home Reef (18.991°S, 171.787°W) (Figure 1a). The submarine Home Reef volcano last erupted in 1984, creating a small, temporary island, 1500 meters long × 500 meters wide [Smithsonian Institution, 1984]. The 1984 eruption also produced large amounts of pumice that rafted away with the currents, and over the following year the floating pumice traveled to beaches as far away as Fiji and Australia [Smithsonian Institution, 1985; Bryan et al., 2004]. With time, these ocean-reflecting marine organisms [Bryan et al., 2004].

The characteristics of the current eruption are similar to those of the 1984 eruption: a volcanic plume breaching the sea surface, extensive pumice rafts, and the formation of a new island [Smithsonian Institution, 2006]. In addition, satellite observations of Home Reef indicate water discoloration and increased sea surface temperatures. Discolored seawater caused by the precipitation of silicon dioxide, aluminum oxide, and iron oxide particles often is present around active volcanic islands and seamounts where hydrothermal fluids mix with cooler seawater [Urai and Machida, 2005].


Home Reef Observations

The first local observations of the new island were recorded on the Web log of the Maiken crew on 12 August 2006, who noted that the new island was “…one mile in diameter and with four peaks and a central crater smoking with steam and once in a while an outburst high in the sky with lava and ashes” (Figure 2b). After these initial observations were reported, data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite and MODIS onboard the Aqua satellite were used to pinpoint the timing of the eruption, locate and measure the new island at Home Reef, measure temperature and color changes in the water around the island, and measure the extent of the floating pumice rafts.

ASTER data were acquired before August 2006 to 4 October 2006. ASTER scenes acquired on 12 and 14 November show the island had decreased in size, based on a smaller thermal feature, and daytime images from 12 and 14 November showed the island had decreased in size to 0.16 square kilometers (Figure 1e). There was a visible discoloration of the water around the island in the daytime ASTER scenes. On 4 October, the discolored area was much wider and more intense, and was drifting away from the island with the currents toward the north and east (Figure 1a). The brightest area of the discolored water plume extended about 1 kilometer off the northeastern shore. The eastern limb of the drifting discolored island could be detected approximately 14 kilometers away.

On 12 and 14 November, the discolored water could be detected only adjacent to the island; however, partly cloudy conditions may have concealed the discolored plume drifting with the currents. The blue/green discolored areas in the water were interpreted to be volcanic materials (ash and/or mineral precipitates) suspended in shallow (<10 meter) water because (1) the texture of surface waves was superimposed on the discolored areas and (2) ASTER channel 3 (0.807 microns) radiance does not penetrate the water surface, which is why the ASTER false-color image using channels 3-2-1 as R-G-B produces the colors observed in Figure 1a. The brightest areas were presumably where this material was more concentrated and shallower; the discolored fades to darker blue as it drifts away from the source. Similar to studies by Urai and Machida [2005], the observed blue/green discoloration adjacent to the new island could be indicative of iron and aluminium oxides precipitating from the mixing of hydrothermal waters with cooler seawater.

Interpreting the Satellite Data

ASTER data acquired before August 2006 show no evidence of an island at Home Reef, confirming that any volcanic island that had formed there previously—from the 1984 Home Reef eruption [Smithsonian Institution, 1984]—had been eroded away. The first ASTER image of the new island was acquired on 4 October 2006, about 8 weeks after the recent eruption (Figure 1a). By this time, the new island at Home Reef was 900 × 400 meters (~0.28 square kilometers), elongated in a northeast-southwest direction, and about 90 kilometers southwest of the Vava’u Islands. Nighttime TIR ASTER data from 28 October suggest that the island was smaller in size, based on a smaller thermal feature, and daytime images from 12 and 14 November showed the island had decreased in size to 0.16 square kilometers (Figure 1e).

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On 4 October, ASTER TIR temperature data identified an anomalous thermal plume associated with the visibly discolored water (Figure 1c). The maximum temperature...