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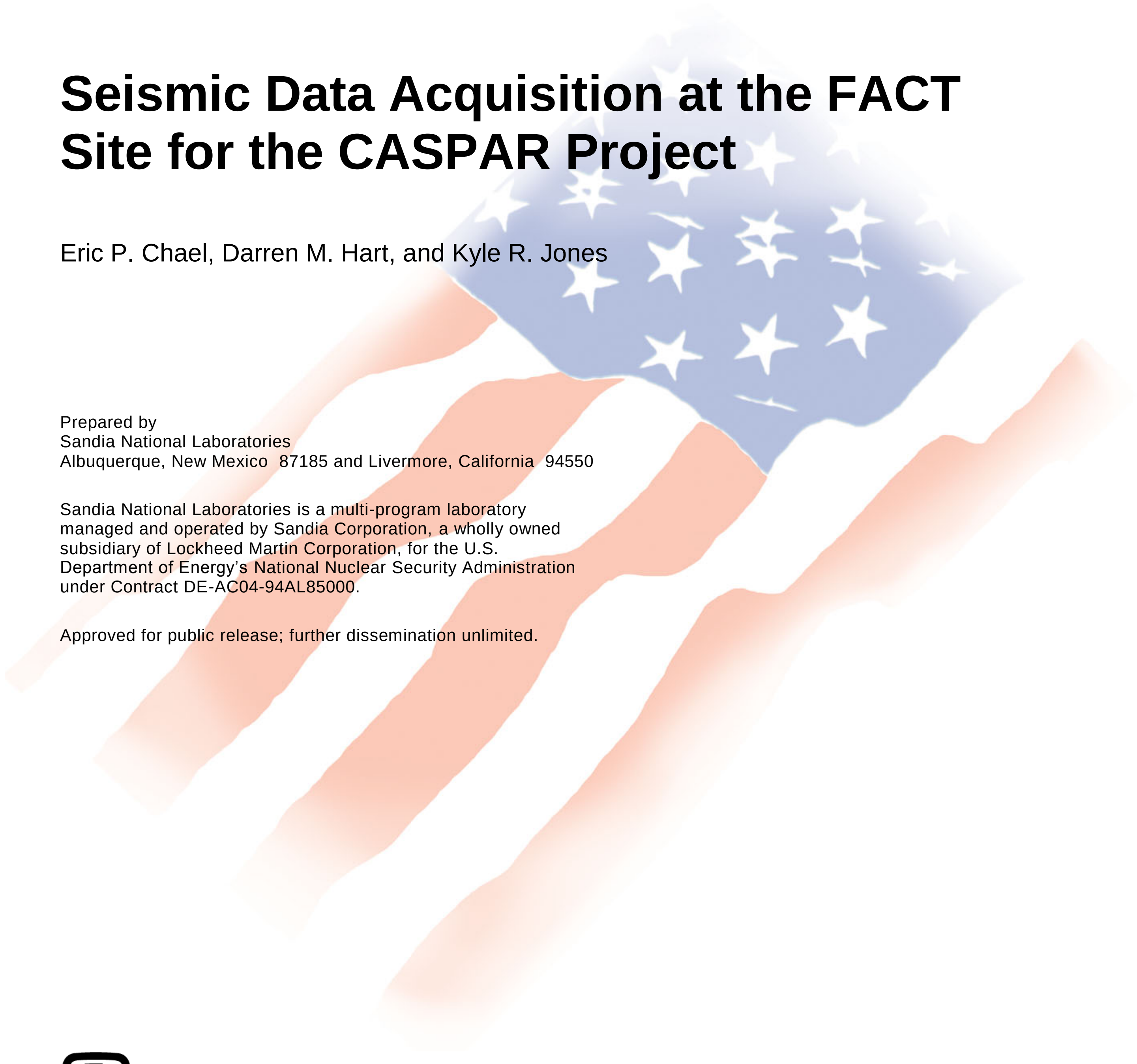

Seismic Data Acquisition at the FACT Site for the CASPAR Project

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Abstract

Since May 2010, we have been recording continuous seismic data at Sandia's FACT site. The collected signals provide us with a realistic archive for testing algorithms under development for local monitoring of explosive testing. Numerous small explosive tests are routinely conducted around Kirtland AFB by different organizations. Our goal is to identify effective methods for distinguishing these events from normal daily activity on and near the base, such as vehicles, aircraft, and storms. In this report, we describe the recording system, and present some observations of the varying ambient noise conditions at FACT. We present examples of various common, non-explosive, sources. Next we show signals from several small explosions, and discuss their characteristic features.

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FIGURES

NOMENCLATURE

CASPAR	Close Access Sensors, Planning, and Analysis Research
IMS	International Monitoring System
NLNM	New Low Noise Model
NNSA	National Nuclear Security Administration
rms	root mean square
SBIR	Small Business Innovation Research
SNR	signal-to-noise ratio
USGS	United States Geological Survey

1. INTRODUCTION

Sandia's Close Access Sensors, Planning, and Analysis Research (CASPAR) project was established to define and improve the capabilities of local seismic and acoustic monitoring of small explosions. Current global monitoring networks, such as the IMS, were designed to have stations within regional or teleseismic distances of most of the world's continental areas. With such station spacing, these networks can reliably detect seismic events with magnitudes above 3.0 to 3.5 worldwide, consistent with their design goals (Hafemeister, 2007). This level corresponds to well-coupled underground explosions equivalent to a few hundred tons of TNT or larger. To push monitoring levels significantly below magnitude 3 or so will require stations within local distances of particular sites, that is at ranges of 200 km or less. Local networks operate in many places around the world, primarily to address seismic hazards in active zones or areas that have suffered damaging earthquakes in the past. Local-network bulletins commonly report events with magnitudes well below 2. Much is known about the operational capabilities of local networks, but some questions remain for local monitoring of explosions. The CASPAR project is intended to identify and address such questions.

The CASPAR project plan defines three research areas that can help prepare the United States to be ready to conduct effective local monitoring at desired sites. The first topic, Sensors and Systems, focuses on the required hardware capabilities for local stations. Ideally, such stations would be small, low-power, and autonomous, yet offer advanced performance and high reliability. Under CASPAR we proposed to document required hardware specifications and identify commercially-available components (sensors, digitizers, processors, etc.) that meet those specs. Later, we could address system-architecture issues, which would cover all aspects of a deployable unit, including power and communications. The second research area for CASPAR is Signal Processing and Analysis. This task addresses effective methods for analyzing local seismic and acoustic signals in order to detect and characterize events of concern. The analysis routines should be suitable for implementation within the field system, to reduce data communication to a minimum. In FY09-10, we began this effort by exploring the range of amplitudes and frequencies to be expected from small local explosions. The third research area is Deployment Planning and Performance Estimation. We have developed software applications for modeling the performance of hypothetical deployments of local stations, similar to existing network simulation programs used for teleseismic and regional networks. For this, we need the best available information on source scaling of small explosions, and on signal propagation within 200 km of the epicenter.

This report describes our efforts to collect a substantial test set of local seismic data that will be useful for developing effective data analysis methods for local monitoring. For over a year, we have been recording continuous signals from seismometers at the FACT site, near the southern boundary of KAFB. During much of this time, we also have acoustic recordings available from the site, collected under a separate project for evaluating infrasound sensors. Over the course of the past year, we have recorded many small explosive tests from different locations on the base. These provide useful sources for refining detection and event classification routines. In addition, we observe a wide variety of other source types, including vehicles, airplanes and helicopters, mechanical equipment, etc. Such activity must be screened out during the detection and identification process for explosion monitoring. For other applications, however, learning to recognize and characterize these kinds of events may itself be of value. First we describe the seismic instrumentation system that we have used. Following this there is a section on the behavior of ambient seismic noise at FACT. Finally there are two sections that discuss various types of transient events that have been observed: the first section covers non-explosive sources such as traffic, aircraft, etc., while the second describes the signals collected from numerous small explosions that occur at different sites on the base.

2. SEISMIC RECORDING SYSTEM

We are recording signals from four Geotech GS-13 seismometers at FACT. A 3-component set of sensors was installed in a plastic tank sunk about 1 m into the surface in the open area between the buildings at the site. Nearby, we placed a single vertical sensor in FACT's underground vault, at a depth of about 4 m. The surface installation is arguably more representative of the typical installation that would be available in a real local monitoring situation. At such a shallow depth, it is susceptible to wind noise as well as vehicle or foot traffic in the vicinity. The vault sensor provides us with a somewhat quieter reference that is better isolated from above-ground disturbances. The seismometers have nominal sensitivities of 2000 V/m/s, and free periods of 1 sec. We tested all the sensors in order to document their true response characteristics; the test results have been reported by Hart and Chael (2010a). All four had responses very close to the manufacturer's nominal behavior.

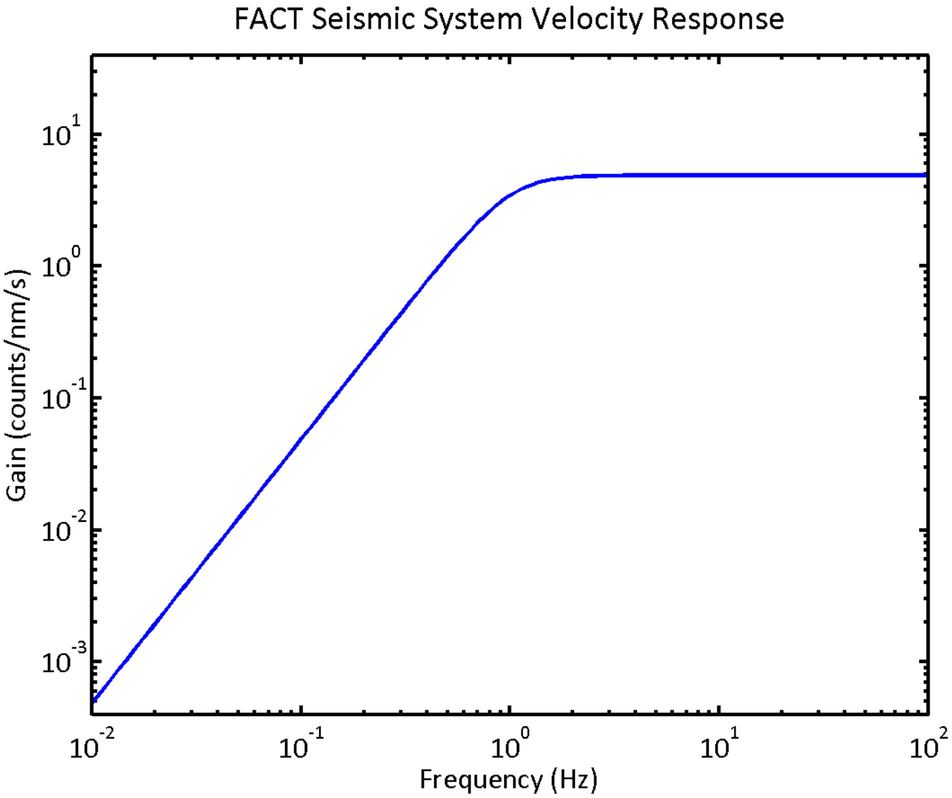

Figure 1. Seismic system velocity response.

Signals from the seismometers were digitized and recorded by Geotech Smart-24 data recorders. A single Smart-24 collected data from the three sensors in the surface tank, and another was connected to the vertical sensor in the vault. These acquisition boxes have a selectable input voltage range. We configured them for an input range of ±5 volts, with a nominal sensitivity of 2445663 counts/volt. Combined with the sensor gain value, this results in a system sensitivity of

4.891×10^9 counts/m/s in the flat portion of the velocity response above the 1-Hz corner frequency. Figure 1 plots the system's velocity response curve. Calibration tests of the Smart-24 units have been reported in Hart and Chael (2010b). Both recorders are powered by 12-volt batteries connected to solar panels. GPS receivers provide them with a UTC time reference. Radio links from the recorders to FACT's local area network allow us to automatically archive the continuous signals in the standard NNSA format on a common computer. Figure 2 shows a photo of the surface site, with the yellow sensor tank, white electronics box, antennas, and solar panels. Throughout the experiment, we have been digitizing the seismic signals at 100 samples per second.

Figure 2. Surface view of the seismic system installed at FACT.

These systems have now been operating at FACT for over a year. They have proven to be very reliable and have needed almost no maintenance. The solar panels keep the batteries charged sufficiently to power the recorders and radios through the coldest winter nights, and the communication links to the archiving computer rarely falter. Data gaps in our collection are infrequent and short in duration, mostly caused either by power outages affecting the computer or deliberate interruptions needed for other instrument testing activities at FACT.

3. AMBIENT NOISE AT FACT

Because the FACT site is situated near a metropolitan area, and on an active Air Force base, we do not expect it to match the quiet seismic noise levels of remote locations preferred for global network stations. FACT provides a reasonable analogue of the situations likely to be available for local monitoring of known or suspected test sites, the aim of the CASPAR project. We need to identify data analysis methods that work reliably in moderate to high noise environments. During several months of operation at FACT, we have recorded signals over a very wide range of noise conditions. As expected, the quietest and most stable conditions are typically observed during the overnight hours, when cultural noise from the city and base subside, and surface winds lessen or cease altogether. Figure 3 shows the power spectrum of the vertical-component seismic noise at the surface during one of the quieter times at FACT (6:00-8:00 UTC on 1 November 2010). The USGS' New Low-Noise Model (NLNM; Peterson, 1993), which represents a composite of the lowest attainable noise levels anywhere, appears on the plot for comparison. At its quietest, FACT approaches the NLNM over a narrow frequency range from about 0.5 to 1 Hz. At lower frequencies, the persistent microseismic peak usually remains well above the NLNM. This is consistent with data from the nearby ANMO station operated by the USGS (Peterson, 1993). Above 1 Hz, the NLNM shows a steadily decreasing velocity spectrum, while the spectrum for FACT first flattens and then rises for frequencies of 10 Hz and higher. The short-period to high-frequency noise at FACT is likely due to a combination of factors, including mechanical and electronic equipment in the buildings there, and reduced but persistent levels of nearby cultural activity, all exacerbated by the soft near-surface sediments that host the sensors. Also seen on the plot are some sharp spectral lines, in particular near 19 and 30 Hz. These are ubiquitous at FACT, caused by fans on some of the equipment there. Eventually we plan to add some sensors at a surface site away from the fenced area at FACT, to see if we can avoid some noise sources in the immediate vicinity.

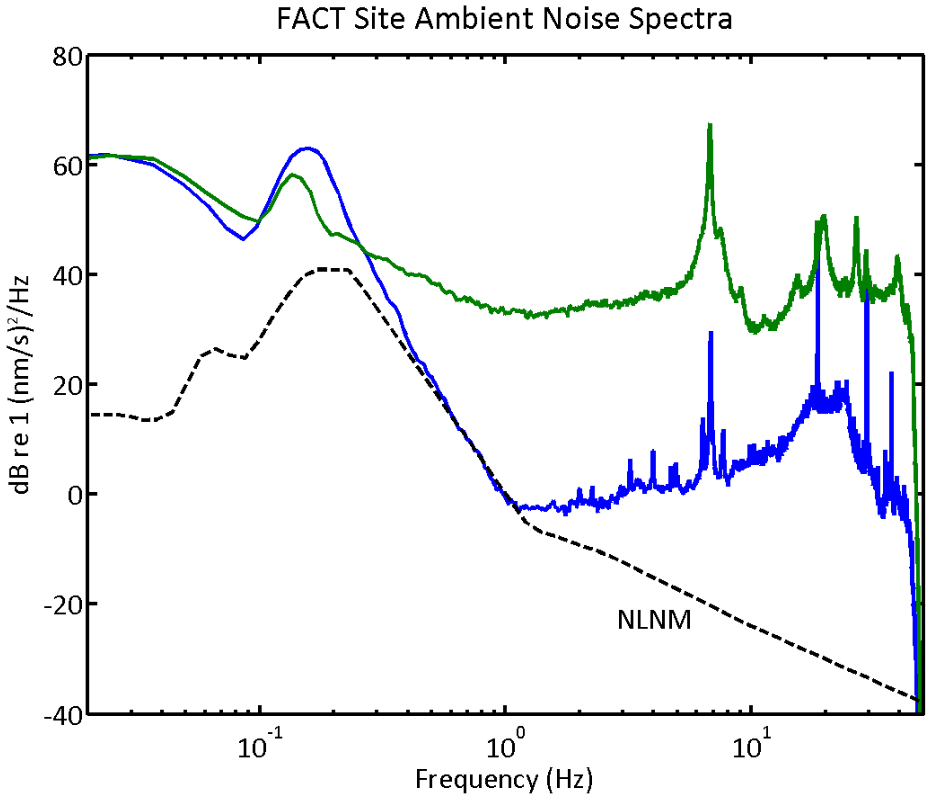

Figure 3. Noise spectra at FACT. Power spectra of the ambient noise during quiet (blue) and noisy (green) time intervals at FACT. For reference, the black curve shows the New Low Noise Model (Peterson, 1993)

During daylight hours, noise levels at FACT generally increase. Particularly high levels are observed when strong winds are blowing. The noise spectrum for a representative high-noise time period is displayed as the green line in Figure 3 (8:00-10:00 UTC on 30 September 2010). At such times, the noise increases dramatically, and small events that are clearly recorded at other times can be impossible to see in the signals. Across the band from 1 to 40 Hz, the noise now exceeds the NLNM by 30 dB or more. For operational local monitoring, it will be desirable to isolate the sensors from wind noise to the greatest extent that is feasible, even if the 100-m boreholes preferred for global-network stations are impractical.

4. SIGNALS FROM VEHICLES, AIRCRAFT, AND STORMS

In this section, we present some typical examples of events other than explosions that are routinely recorded by the system at FACT.

Several vehicles pass by FACT every day on the paved access road. On most days, these are the most frequent and noticeable short-duration events seen on day-long plots of the signals. Figure 4 shows an example of a typical signal from a vehicle. Such events display a characteristic rise and decay as the car or truck passes, without the sharp phase arrivals expected in seismic signals from more distant impulsive events. Another distinguishing feature is their frequency range – they are typically broadband, with energy above noise up to the anti-aliasing cutoff for our systems above 40 Hz. They tend to be relatively weak at lower frequencies below 5-10 Hz, and this can provide a reliable means to quickly distinguish signals due to vehicles from those produced by small explosions or earthquakes.

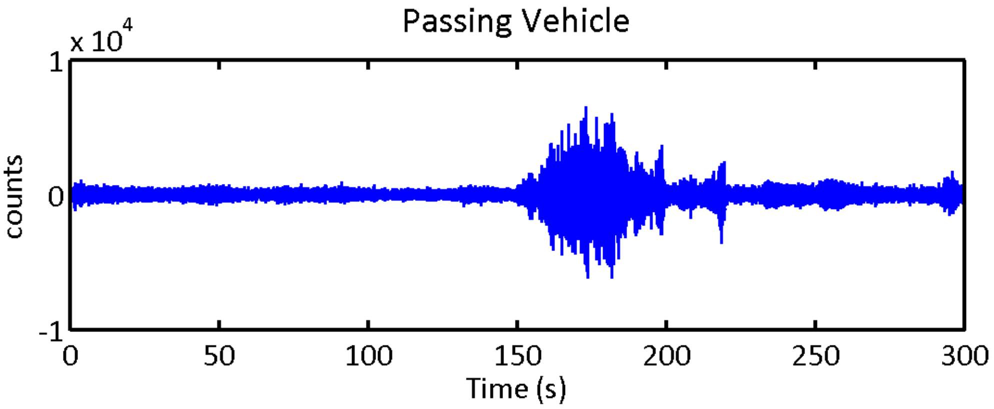

Figure 4. Vehicle passing by the FACT site. 16:40:50 UTC on 1 August 2010.

The FACT site is located about ten miles southeast of the Albuquerque Sunport. Numerous civilian and military aircraft take off and land at this airport throughout the day, and quite often they pass over or close to FACT. In addition, KAFB conducts frequent helicopter training flights which can also pass nearby. All of these produce prominent acoustic signals, which can couple enough energy into the ground to be apparent in the seismic data. Such signals can be observed most readily on spectrograms, or time-frequency plots of the recordings. An example is shown in Figure 5. In this spectrogram, one can readily see the aircraft fly-over. The characteristic feature of these signals is a power increase at narrow spectral peaks, with the frequencies decreasing as the aircraft flies past, due to the varying Doppler shift from approach to retreat. The resulting sloping lines across the spectrogram are easily recognizable.

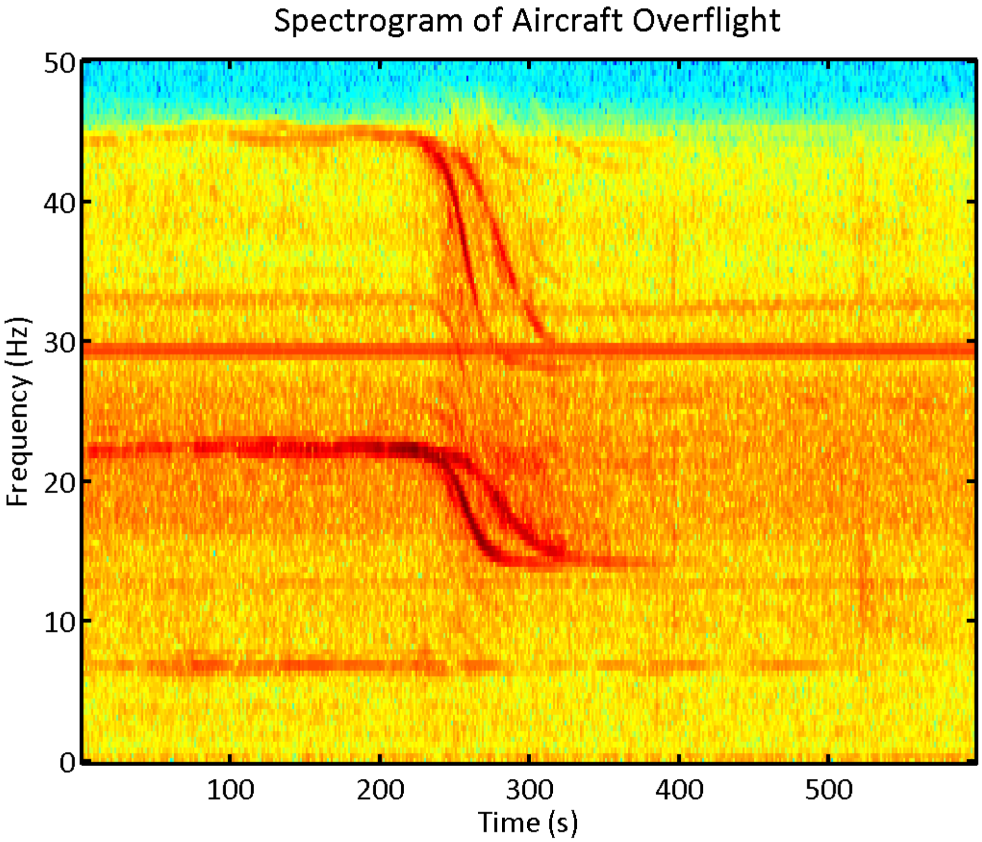

Figure 5. Time-frequency plot of signal from passing aircraft. 14:55 UTC on 7 June 2010.

Because the 3-component set of GS-13s is installed at the ground surface, it is much more susceptible to weather effects than sensors in underground vaults or boreholes. Both wind and rain can increase the background noise levels on all three axes dramatically. We placed these sensors in a plastic tank to protect the cabling from animals, while still allowing ready access for maintenance or reconfiguration. The tank, however, acts something like a drum during high winds or rain, producing strong reverberations and overwhelming the signals from any seismic events of interest. An impressive example appears in Figure 6, which shows the vertical signal recorded during rainfall at the site (2:00-2:30 UTC on 1 August 2010). This is an acceptable trade-off for our purposes, since we can simply wait for other events during quieter times. In an operational situation, better isolation from weather effects would be essential. Burying the sensors without the tank would likely reduce the sensitivity to wind and rain, but they would need to be protected from moisture.

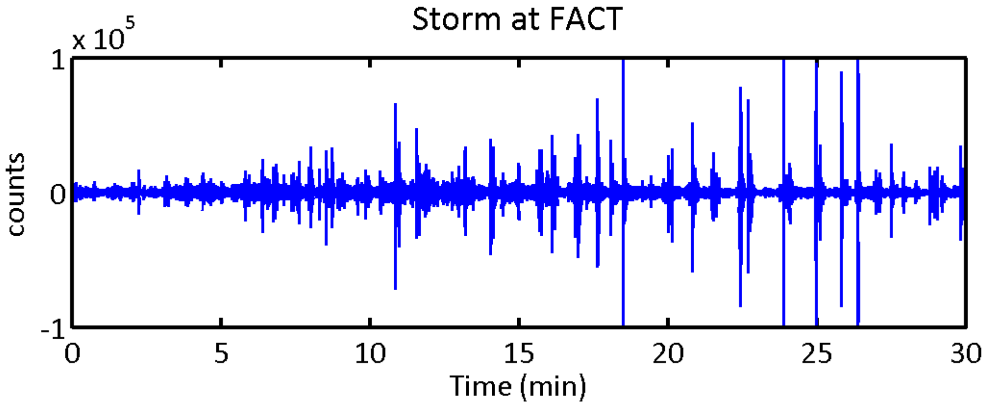

Figure 6. Rainfall (including some hail?) recorded at FACT. 02:00 UTC on 1 August 2010.

For the CASPAR project, our primary interest is in recording small local explosions. Because the FACT site is located on a military base adjacent to a city, we cannot avoid this wide variety of seismic and acoustic sources. In a realistic local monitoring situation, one would likely be confronted with similar routine but uninteresting activity, unless the monitored site was both far from urban centers and used exclusively for explosive testing. This is a key difference between the local monitoring situation and traditional regional/teleseismic monitoring. For the latter, the stations can be installed in boreholes or vaults in very quiet, remote locations. Natural seismicity is then the main source of ‘nuisance’ events. For local monitoring, a wider assortment of event types will need to be screened. The archive of continuous signals from FACT includes a large collection of these, so it provides a valuable data set for evaluating signal analysis methods for local monitoring of active test sites.

5. LOCAL EXPLOSIONS OBSERVED AT FACT

Different agencies detonate small explosions at various sites around KAFB, either for ordnance disposal, explosion effects testing, or research on the behavior of explosives. Some active sites are marked on the overhead image in Figure 7. These sites are located at distances between 3 and 7 km from FACT, in the northwest quadrant. Some are used frequently, with small shots fired almost every week, while others can have extended intervals between short durations of activity.

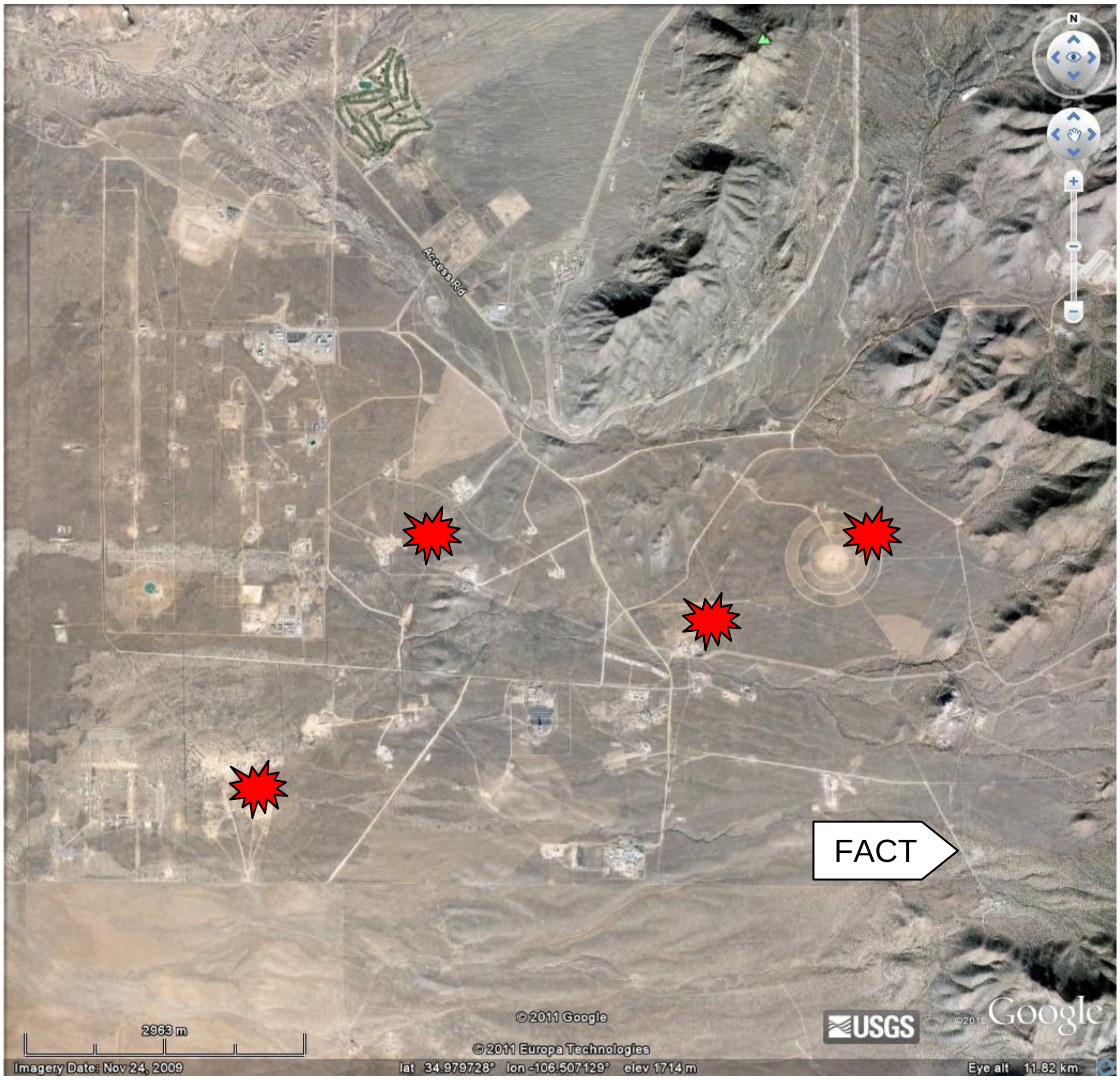

Figure 7. Overhead view of the area surrounding the FACT site. Red stars mark sites used for detonating small explosions.

Most shots are conducted on the ground surface, with at most a small amount of overburden. Nearly all blow out into the air, and so they generate prominent acoustic waves but are only weakly coupled to the ground as seismic sources. Though small and relatively close, they still serve as useful events for developing local-monitoring analysis methods. Several dozen explosion recordings are already available in the data archive we are assembling. An example displaying high signal to noise on all three components is shown in Figure 8.

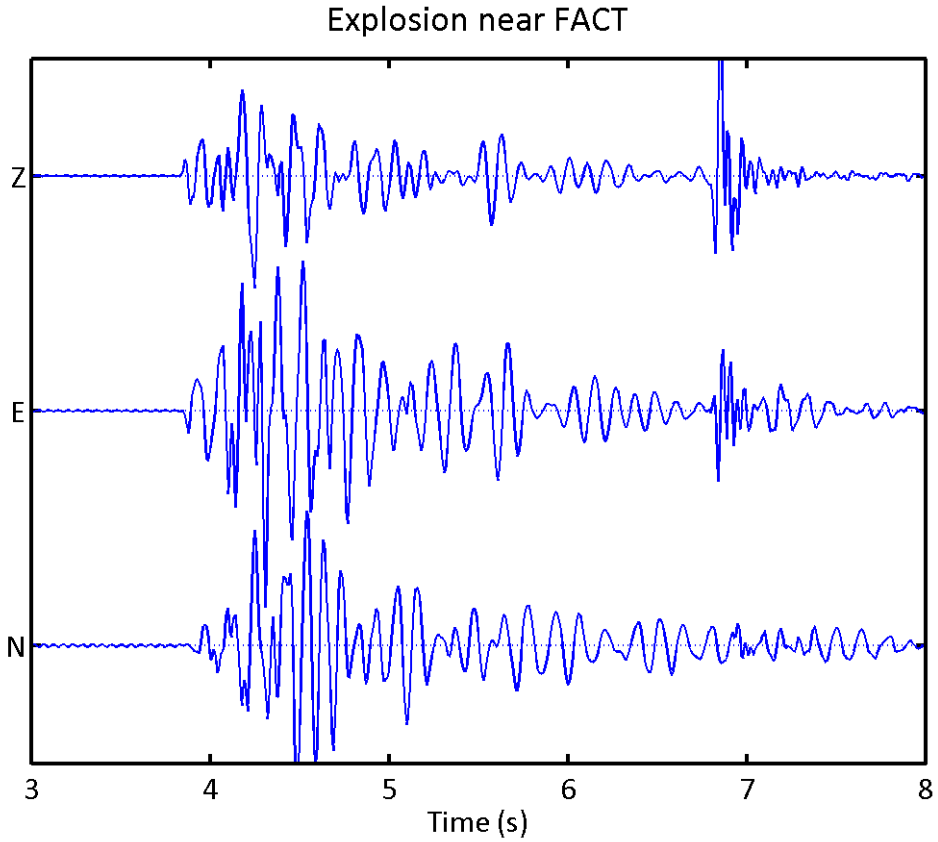

Figure 8. Three-component recording of a small explosion near the FACT site.
Traces start at 18:15:43 UTC on 15 September 2010.

Seismic waves through the ground arrive near 4 secs on the time axis; at this close distance the P, S, and surface arrivals are not readily distinguished. The strong secondary arrival on this seismogram, the higher-frequency pulse appearing just prior to 7 secs, is actually the air or acoustic wave. This pressure wave is sufficiently strong to deflect the soft surface sediments at FACT and register clearly on the seismic trace. The comparable amplitudes of the seismic and acoustic arrivals in this record indicate that the shot occurred at or above the surface, somewhat decoupled as a seismic source. Had it been fully tamped underground, the air wave would have been much weaker. The 3-sec separation of the seismic and acoustic arrivals implies a source-to-receiver range of about 1 km in this case.

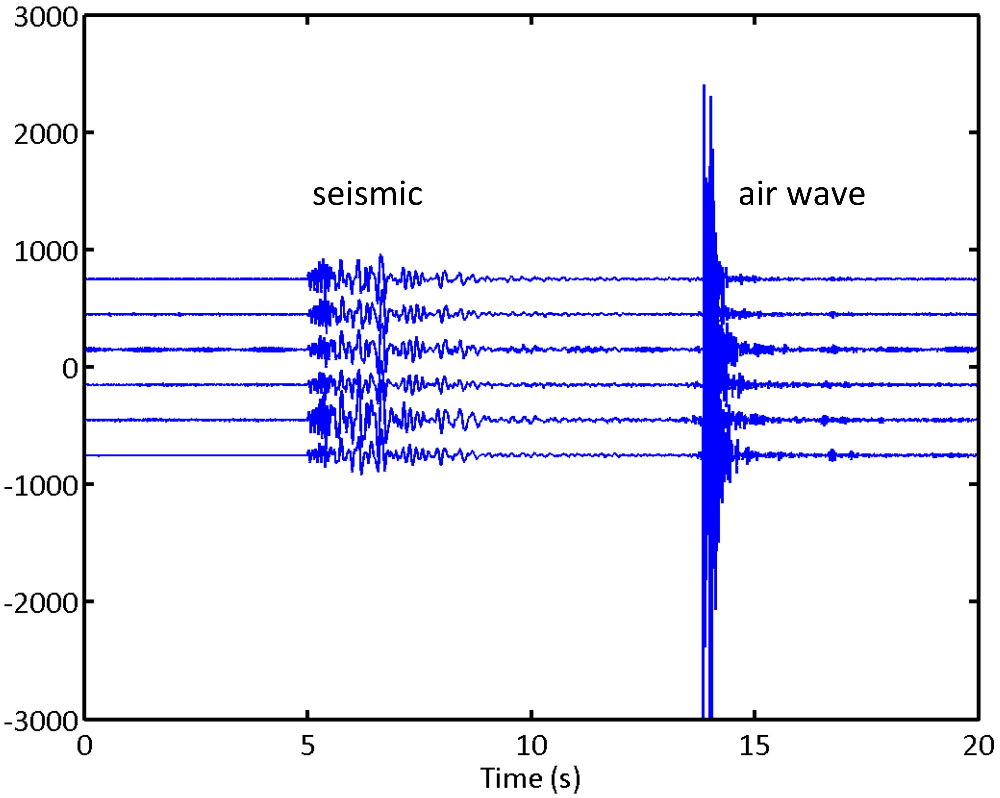

Figure 9. Repeating explosions. Vertical signals for six similar explosions fired at the same location. Note the high degree of correlation of both the seismic and acoustic arrivals. Though not apparent in the figure, there is some variation in the time interval between the ground and air waves, caused by winds or changes in sound speed with temperature.

Figure 9 shows the vertical seismic signals from six different explosions fired at a site further from FACT. The events occurred on six different days during the summer of 2010; the traces have been time-aligned on the seismic arrival. For these shots, the air wave arrives about 8 sec after the start of the seismic one, indicating a distance of about 3 km. This figure reveals an impressive degree of waveform similarity, or signal correlation, between all six of the events. The similarity proves that these blasts all occurred at nearly the same place, so that propagation effects along the path to the sensor are the same. In this case, the amplitudes are very consistent as well, so the source yields must have been almost identical. Any of these signals can serve as a fingerprint for recognizing subsequent events at the same test facility. Because most explosive testing around KAFB is restricted to a small number of discrete sites, one could use a limited number of template signals to efficiently characterize most of the routine explosive events. An unusual signal which did not match any of the common patterns would then be of particular interest, and merit extra attention. We are currently implementing signal analysis routines to measure a number of features for these events; eventually we would like to include a correlation detector algorithm (Resor et al., 2009).

6. CONCLUSIONS

In May 2010 we began recording continuous, three-component seismic signals at the FACT site near the southern boundary of Kirtland AFB. We now have an archive with over 12 months of recordings. During much of the time, acoustic signals have been collected as well. The resulting data set includes a wide variety of discrete events, observed under differing noise conditions.

Recently, we have been implementing software to allow consistent analysis of any recorded events. The routines measure arrival times and directions, as well as amplitudes of the background noise, the seismic arrivals, and the acoustic waves. Then they prepare a brief standard report on the features of each event. Of particular interest are the relative amplitudes of the ground and air waves, because these should indicate whether an explosion was detonated above or below ground. In a future report, we will document the results of these measurements for a large number of shots.

The archive will be useful for developing and testing automated algorithms for detecting and characterizing small explosive tests. Such methods could be implemented in future ‘smart’ field stations to enable them to recognize and report only events of interest. This would minimize data transmission and power requirements for the deployed systems. DOE has funded some Small Business Innovation Research (SBIR) projects to develop prototypes of such next-generation monitoring stations.

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