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Remote monitoring of repository integrity using passive seismic arrays

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Remote Monitoring of Repository Integrity using Passive Seismic Arrays

Report of a one-year feasibility study

presented to the U. S. Department of Energy Yucca Mountain Program

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Introduction

Once radioactive waste is emplaced in the repository, the challenge of monitoring the continued integrity of the excavated openings (e.g., emplacement drifts) escalates tremendously. We envision a seismic monitoring array installed on the surface at Yucca Mountain, which operates automatically to monitor repository opening stability in the long term. The objective is to monitor and validate the structural integrity of the emplacement drifts through identifying and localizing rock falls that could compromise drift access, hinder waste retrievability, and potentially reduce the effective life of waste canisters. Collateral benefits of the system include the ability to address some outstanding uncertainties regarding seismic wave attenuation in the vicinity of the repository, and provision of a tool for security monitoring of the repository in guarding against unauthorized access and entry.

The data collected with the array would be processed using an empirically calibrated matched-field processing (MFP) technique. Matched-field processing was pioneered by underwater acousticians for the purpose of tracking submarines. Recently, our collaborators/advisors at Lawrence Livermore National Laboratory (LLNL) used the technique successfully to track motion of a vehicle on the ground surface. Considering those successes and other factors we anticipate that the method should work well for our purposes – to identify and locate rockfall events. However, a key difference between the prior and proposed use of the matched-field processing technology is shifted focus from surface to body wave energy. The feasibility of such a transition must be determined experimentally.

This report documents a first-year feasibility study of the envisioned system. Two questions that we targeted are: 1.) Is a credible rockfall signal observable?; and 2.) Does empirical MFP appear to be suitable for locating an event?

Report Format and Supporting Materials

The main body of this report contains a brief overview of the project, a cataloguing of data collected on-site, discussion of preliminary data analysis, conclusions, and recommendations for follow-on activities.

The final report of the Computer Science group (Evangelos Yfantis, Ramzi El-Khater and John Istle) is a standalone subset of this report. Although it is included as a separate appendix (A), it should be taken as a key component of this report.

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In the course of the project we produced three publications, which are included in this report as appendices and should also be taken as key components of this report.

- Appendix B: "Seismic monitoring for rockfall at Yucca Mountain: Concept tests" (Luke et al. 2003). This paper provides an overview of the overall project, the three-year research plan, and the one-year feasibility study, and discusses early shakedown testing.

- Appendix C: "Deployment of a passive seismic array to remotely monitor for rockfall in underground excavations" (Twilley et al. 2003). This paper details the installation and operation of the three-component sub-array.
- Appendix D: "An intelligent system for seismic source localization" (El-Khater et al. 2003). This paper introduces computational methods for source localization.

We were also tasked with researching credible rockfall scenarios. During the course of the project we attended a presentation by Mark Board (YMP; to the NRC, Aug. 8, 2002) in which we learned that the maximum credible rock block size is quite large, greater than five tons, and the mean and median expected block sizes are 0.91 and 0.23 tons, respectively. We also met with Bill Boyle (YMP) who expressed the view that opening stability failures could occur through gradual raveling of small blocks. We met with researchers working on separate but complementary projects for the YMP and learned that rock fall scenarios might be different for different parts of the repository horizon, depending on lithophysal content, and that block theory (Goodman and Shi, 1985) might be used to determine credible block sizes, given opening geometry and jointing patterns (App. E). Given this broad sampling of views, we decided that for our first year feasibility study, it was reasonable to start by modeling the fall of a half-ton block. We were to learn that our system could readily capture this signal, and that much lower-energy signals, equivalent to the energy a strong person could generate by swinging a sledgehammer, could be detected on the surface as well.

A summary of all data that were collected and tests that were conducted is included as Appendix F.

Overall System Strategy

A preliminary view of the envisioned system is as follows: A set of seismic sub-arrays is deployed on the ground surface over the repository. Each sub-array consists of several vertically oriented seismometers. The system is networked to a data acquisition system and monitoring is continuous. Data are continuously combined, filtered, and compared automatically against pre-established thresholds for frequency content, amplitude, and duration. When thresholds are exceeded, the seismic response undergoes preliminary analysis. This process should remove from consideration responses to distant earthquakes and expected routine seismic activity such as might be caused by moving equipment on the surface and underground. If the event is found not to fit criteria for expected but unrelated activity, the data are evaluated using matched field processing to determine location. They would also be scrutinized to assess whether the event indeed appears to be rockfall, as opposed to another unexpected event such as human intrusion, and its level of significance.

A key component of this scenario is the matched field processing. We envision an empirical approach whereby an artificial source simulating as closely as possible a simple delta function is applied at regular intervals underground, to create a calibration catalog. Then responses from unexplained events are compared to the catalog. The location of the

event is determined to be in the vicinity of the location of the calibration signal with the closest match.

First-Year Study

During the one-year feasibility study described in this report, we deployed a single three-component array on the ground surface, close to Alcove 5 of the Exploratory Studies Facility, and set up continuous monitoring capability. Through preliminary testing we determined that seismic signals with energy approximating a rockfall of consequence could be readily observed on the ground surface. We studied whether rockfall signals could be distinguished from other expected events. We performed calibration testing, albeit with a low-energy source, to explore array separation criteria and correlation distances. We performed a simulated rockfall test in order to compare seismic signatures against calibration energy. We explored superposition of data from multiple sensors to enhance results.

Research using the experimental data is continuing beyond the end of our contract period. We anticipate that the culmination of this work will appear in Ms. Kristi Twilley's M.S. thesis, which is in preparation and planned for completion in December, 2003. Thus, this report summarizes research completed to date and presents sample data that illustrate key observations.

Field Studies

Locations of test components are shown in Fig. 1.

Array Design, Equipment Acquisition, and Array Installation A three-component trial seismic sub-array was deployed and tested on the ground surface, near well UZ SD-9, above and slightly to the northwest of the ESF at Alcove 5 (Twilley et al. 2003). The array center is approximately 300 meters above the ESF and approximately 80 meters west of the closest point to the ESF, slightly north of Alcove 5.

Three sensors labeled S1, S2, and S3, were placed up to 100 m apart (Fig. 1). Geotech S-13J short-period seismometers with reasonably high gain and low self-noise were used. The S-13J is a moving-coil type sensor with electromagnetic damping. It has a resonant frequency of 1 Hz.

The sensors were deployed in shallow holes or alcoves dug to competent rock. Sensors were placed in sand-filled PVC tubes anchored into flat concrete pads. The PVC tubes were capped, and each entire system was further isolated from wind and other elements with stacked sandbags.

For data acquisition, a Refraction Technology RT130-01 broadband recorder was used. One gigabyte of information can be stored on the data micro disk. This meant that at a

sampling rate of 100 sps, the disk would fill in approximately 5 weeks. The unit's dual disk drive became operational in late July, 2003, thereby doubling the storage capacity.

The data acquisition system (DAS) was housed in a weather-resistant metal box mounted on a pole, and powered by a solar panel. Global positioning systems technology is used to update the time stamp. A handheld computer, the Palm P105, was used to program the DAS, to observe data in the field in near real time, and to retrieve data.

During preliminary tests, the DAS collected data at the rate of 200 sps. Later, the rate was reduced to 100 sps. Unfortunately, this rate turned out to be too slow to characterize the sledgehammer strikes on rock bolts. We found that the rock bolt strikes produce a signal that is rich in energy in the range of 60 Hz. For a sampling rate of 100 Hz, this is higher than the Nyquist frequency, the maximum possible that can be resolved with the sampling rate used, of 50 Hz. This turned out to be a very important issue for our testing since planned follow-on testing with a higher-energy source did not occur. Fortunately, we have found that by upsampling prior to calculating spectra we can derive valuable results from the rock bolt strike tests.

During each test, a second DAS, identical to the one on the surface, was taken underground and used to record data from an S-13J seismometer and/or a 40-Hz geophone, very close to the events. The DAS units should be time-synchronized using Global Positioning Systems technology. The one used underground can not update constantly of course, but the drift while underground is expected to be small. Unfortunately, a bug in the DAS hardware caused a time discrepancy of approximately six seconds between underground and surface sensors. This denied us the ability to time-sync underground data with surface data.

Shakedown Test The initial test of the surface array confirmed proper working order of the equipment and provided insight as to whether seismic events of amplitude similar to what might be expected from a rockfall event in the ESF could be detected by the surface array (Luke et al. 2003). This was accomplished successfully through a shakedown test in which sledgehammer strikes on rockbolts in Alcoves 5 and 6 and train operation signals were detected and recorded by the surface array. The signatures of these signals were clearly distinguishable from one another and from distant microtremors.

Dropped Weight Test To better simulate the fall of rocks underground, with the help of Chris Hermes (YMP) we conducted a dropped weight test whereby a 55-gallon drum filled with concrete was dropped from a height of almost 2 m using a mucker. This test was conducted in each of Alcoves 5, 6, and 7.

Rockbolt Strike Test To explore development of calibration datasets for matched field processing, a test was conducted in whereby sledgehammer blows were applied at intervals over a long distance, in the main tunnel of the ESF, between Alcoves 5 and 7.

Interpretation of field test data

As presented in Appendix A, the Computer Science team created software for data manipulation. They used supersampling and cross-correlation to explore the time lag between sensors. They studied and documented what they learned about classical beamforming theory for source localization, using illustrations from the three sensors in our sub-array. Even with these very closely spaced sensors and low sampling rate, they were able to localize source energy to within 60 degrees. This accuracy would of course improve greatly in the event that multiple, distant sub-arrays are installed. Installation of a second, three-component sub-array was a planned part of the first-year investigation but did not occur due to site access restrictions. In their report, the Computer Science team also describes classical matched field processing in which calibrations are developed analytically (e.g., Schmidt et al., 1990; Baggeroer et al., 1993).

Distinguish simulated rockfall from other seismic events Near-field data such as train travel are clearly differentiated from distant earthquake data by frequency content, duration, and onset (App. B, Fig. 1). Both are differentiated from rock bolt strikes (Figs 2 through 4) and barrel drops (Figs. 5 and 6) by similar means.

Filter rock bolt strike signals Without filtering, even the closest rock bolt strikes (in Alcove 5) appeared faint on the surface (Figs. 2 and 3). Considering the frequency spectrum of a quiet signal on the ground surface (Fig. 7), we see that in addition to significant long-period energy, a spike appears at 30 Hz. The spectrum for the rock bolt hits (Fig. 6) contains the same 30-Hz spike but also contains another at about 60 Hz. Thus, a 40-Hz high-pass filter greatly enhanced results (Figs. 2 through 4).

Compare source-to-site distance Weight drop tests were conducted in Alcoves 5, 6, and 7. Representative results are shown in Figs. 5 and 6. The weight drop in Alcove 5 is clearly seen at the surface array, but the drop in Alcove 6 is obscured. Unfortunately, the frequency content of the weight drop energy is similar to that of the background noise, so filtering does not appear to be helpful. These data were collected at the lower sampling rate of 100 sps. It is possible that sampling at a higher rate might improve resolution. These results confirm that, as anticipated, surface array separation will have to be considerably shorter than the distance between Alcove 5 and Alcove 6.

Interpretation yet to be done Still in progress is work to improve signal quality by shifting and then summing data from the three sensors. Data from the final sledgehammer strike test will be analyzed to explore calibration distances. This information should help determine the resolution of the method. Since sampling rates for that test were too low for the source used, upsampling of data will be required.

Empirical Matched Field Processing
An introduction to the basic concepts of matched field processing is presented here. More detail of classical MFP is found in the Computer Science report (Appendix A) and in the published literature (e.g., Baggeroer et al., 1993; Schmidt et al., 1990). Classical MFP is a generalized form of beamforming, which uses knowledge of the wave propagation characteristics of the physical surroundings to locate an acoustic or seismic source. In MFP, the stress field at a sensor array due to some input motion is predicted empirically or using a physical model of the medium through which the mechanical energy will travel. Here, we emphasize the empirical approach to MFP. Through *in situ* calibrations, we collect a matrix of weight vectors corresponding to particular source locations. The wave field recorded at the sensor array as a result of application of a seismic source (in our case, rockfall) is then cross-correlated with each of the components of the calibrated weight vector. Source location is determined to be that which corresponds to the weight vector with the strongest correlation to the target signal.

The empirically calibrated model requires a dense sampling throughout the underground facility of delta functions in the range of amplitude and frequency expected for credible significant rockfall events. The calibration signals would then be cross-correlated with the actual target seismic signal, and the source would be considered to be located at the position of the calibration signal with the strongest correlation. Accuracy and reliability is strongly enhanced through the use of multiple sensor arrays. Compared to the undersea application for which this method was originally developed, our application is more challenging in that the physical environment can transmit shear as well as compression and is much more heterogeneous. We are also hampered by effects of tube waves in the underground and surface waves near our sensors. On the other hand, an advantage of our application is that the target events will be confined more or less to a single plane.

A trial application of empirical matched field processing, using the sledgehammer strikes for calibration and the dropped weight test in Alcove 5 as the target event, is a planned component of Ms. Twilley's M.S. thesis.

Conclusions and Recommendations

Detecting the direction of arrival of a seismic signal can be done relatively simply and in a robust manner without much knowledge of the environmental parameters by empirical matched field processing. Despite unexpected setbacks with the feasibility study that impacted schedule, precluded key testing, resulted in heavy turnovers of staff, and produced funding uncertainties, we were able to make good progress toward the eventual goal of continuous, automated, remote monitoring of underground opening stability. To date, we have found nothing to disprove our hypothesis, that rockfalls and other unexpected seismic events in the underground facilities can be identified and localized through empirical matched field processing of seismic signals collected on the ground surface.

Future work to develop the monitoring technology is envisioned as follows: A second sub-array is installed near the first, but on the opposite side of the ESF main tunnel. This will permit more reliable beam-forming. Sub-arrays are doubled in size to increase ability to discern low-amplitude events. Calibration data are collected with the surface arrays by generating and recording repeatable, strong seismic impulses from a large, accelerated weight-drop device applied at regular intervals, much smaller than half the designed emplacement drift separation distance, down the main tunnel of the ESF. Weight-drop tests using different masses are conducted at several locations within the calibration zone of the ESF. Matched-field processing is applied to establish the location of the events. This process will reveal accuracy, resolution, and range of the method. Once this work is completed successfully, additional sub-arrays can be installed to improve and extend coverage, to test for site-specificity of the system. It should be an eventual goal that the data from the sensors be transmitted automatically so that automated processing systems can be used for ongoing monitoring. Thus, processes for automation of data collection, transmission, processing, and interpretation will be developed simultaneously.

We also recommend that stability monitoring in the deep mines of southern Ontario, Canada, be investigated for commonalities. We learned about this opportunity too late in the project to be able to incorporate it in our work.

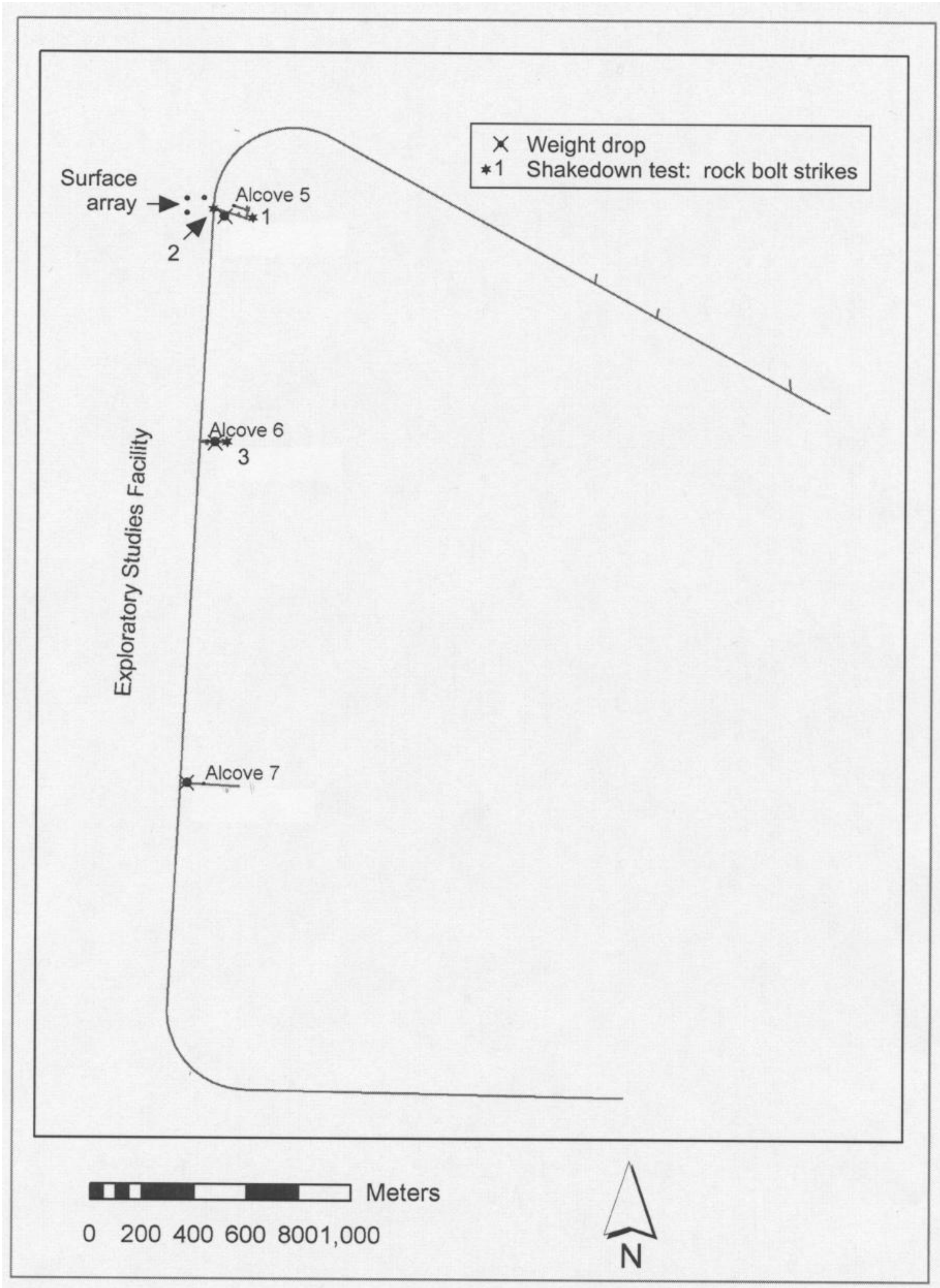

Figure 1a. Three-sensor surface array (just to the west of Alcove 5) shown in relation to the main tunnel and alcoves of the Exploratory Studies Facility. Approximate locations of three weight-drop tests and three rock bolt hammer strikes made during the shakedown test are also shown.

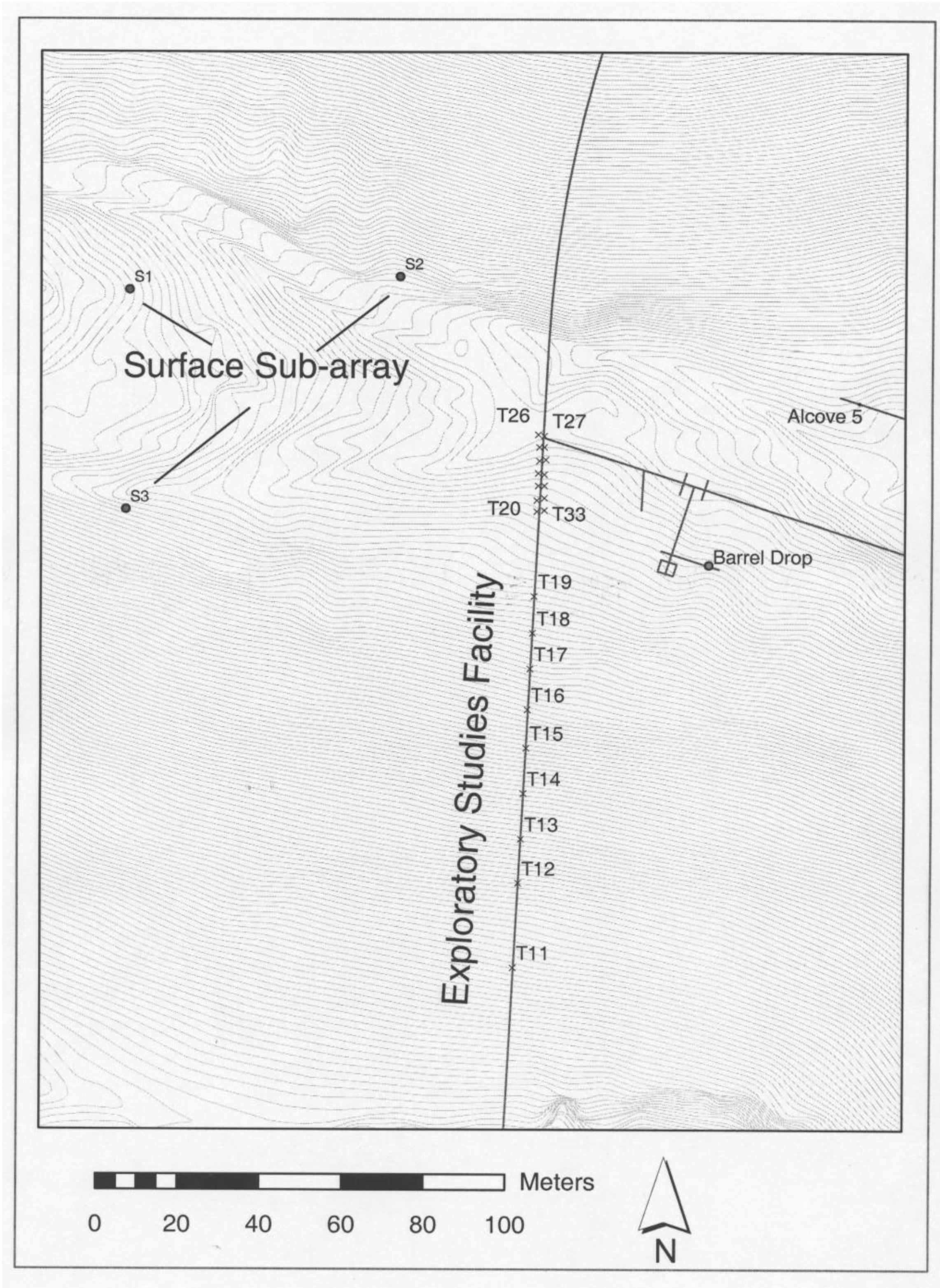

Figure 1b. Detail map showing surface sub-array and locations of rock bolt strike tests (third test set) near Alcove 5

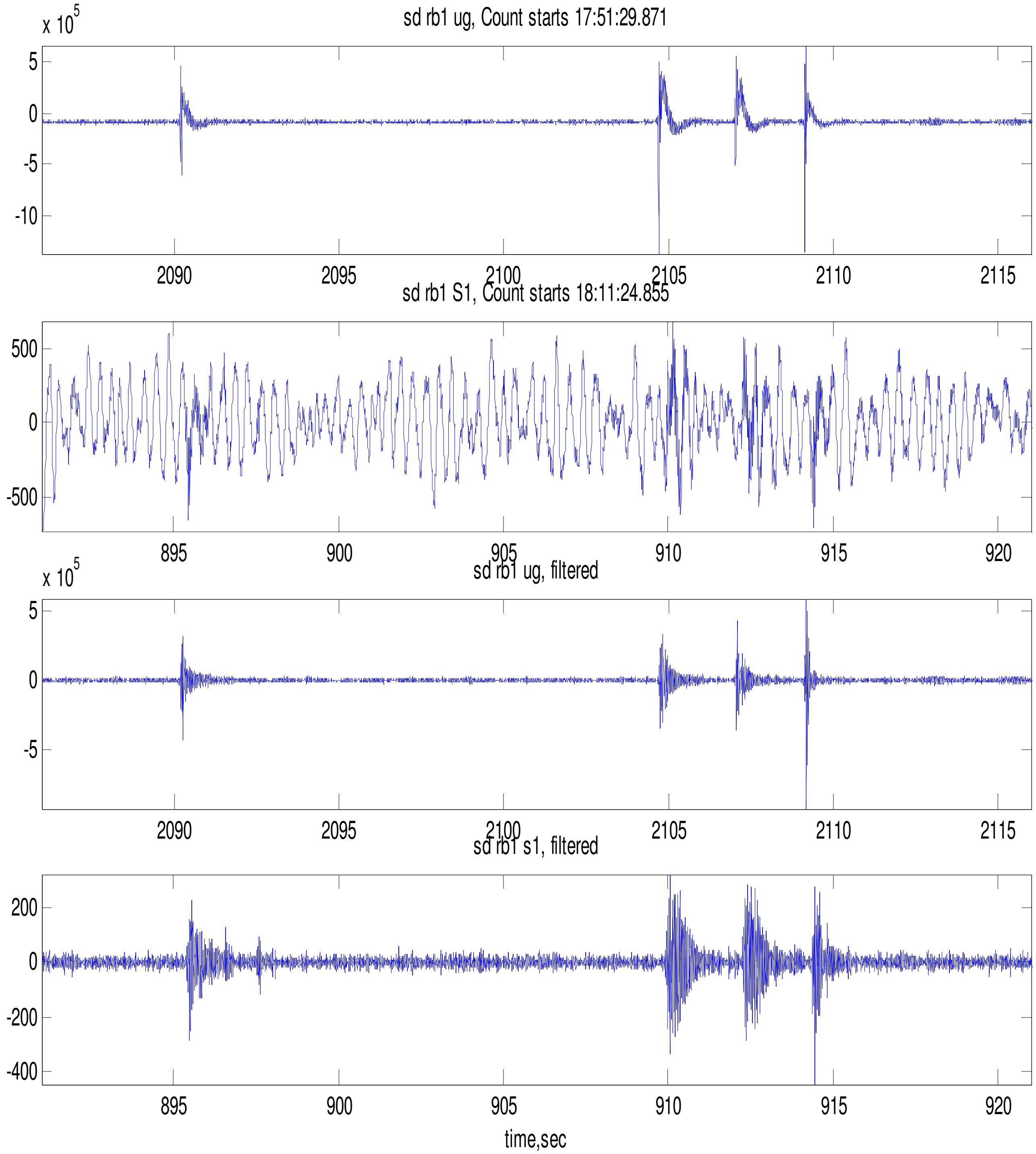

Figure 2. First set of four rock bolt hits in Alcove 5 during shakedown test, 9/26/03: a) underground sensor, unfiltered; b) surface sensor S1, unfiltered; c) underground, filtered; d) S1, filtered. Start times for underground and surface sensors are not synchronized.

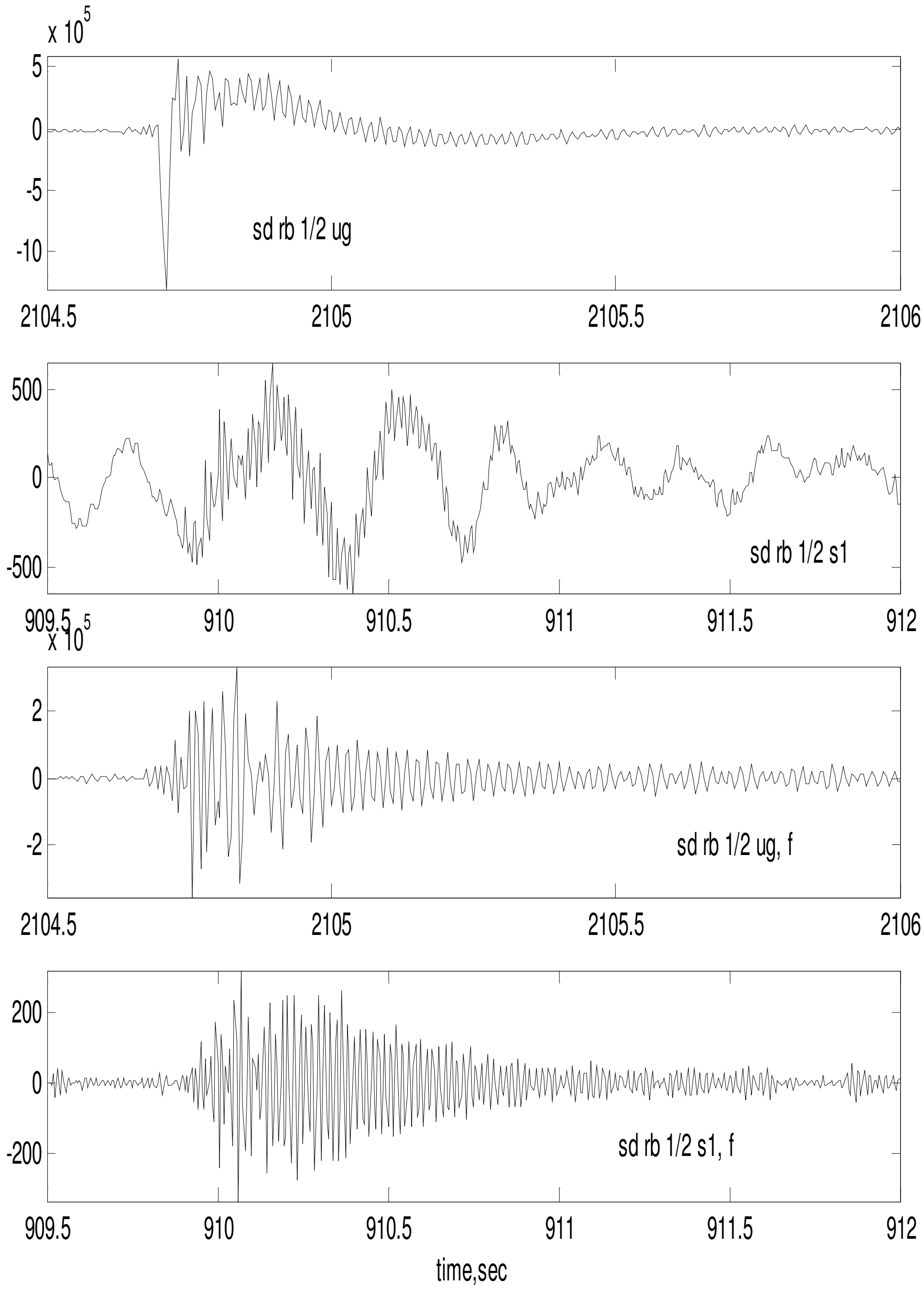

Figure 3. Second of first set of four rock bolt hits in Alcove 5 during shakedown test, 9/26/03: a) underground sensor, unfiltered; b) surface sensor S1, unfiltered; c) underground, filtered; d) S1, filtered. Start times for underground and surface sensors are not synchronized.

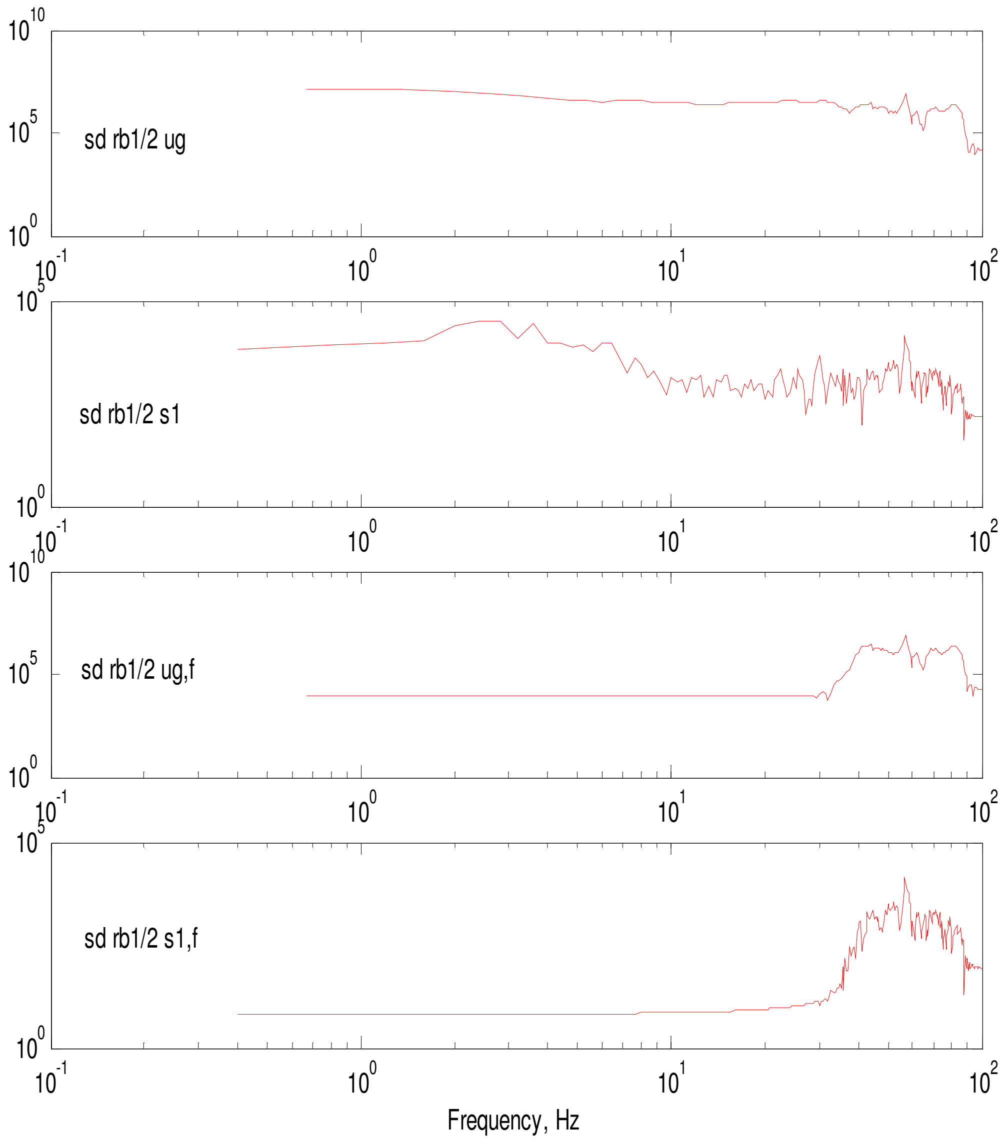

Figure 4. Frequency spectra for second of first set of four rock bolt hits in Alcove 5 during shakedown test, 9/26/03 (pictured in Fig. 3): a) underground sensor, unfiltered; b) surface sensor S1, unfiltered; c) underground, filtered; d) S1, filtered.

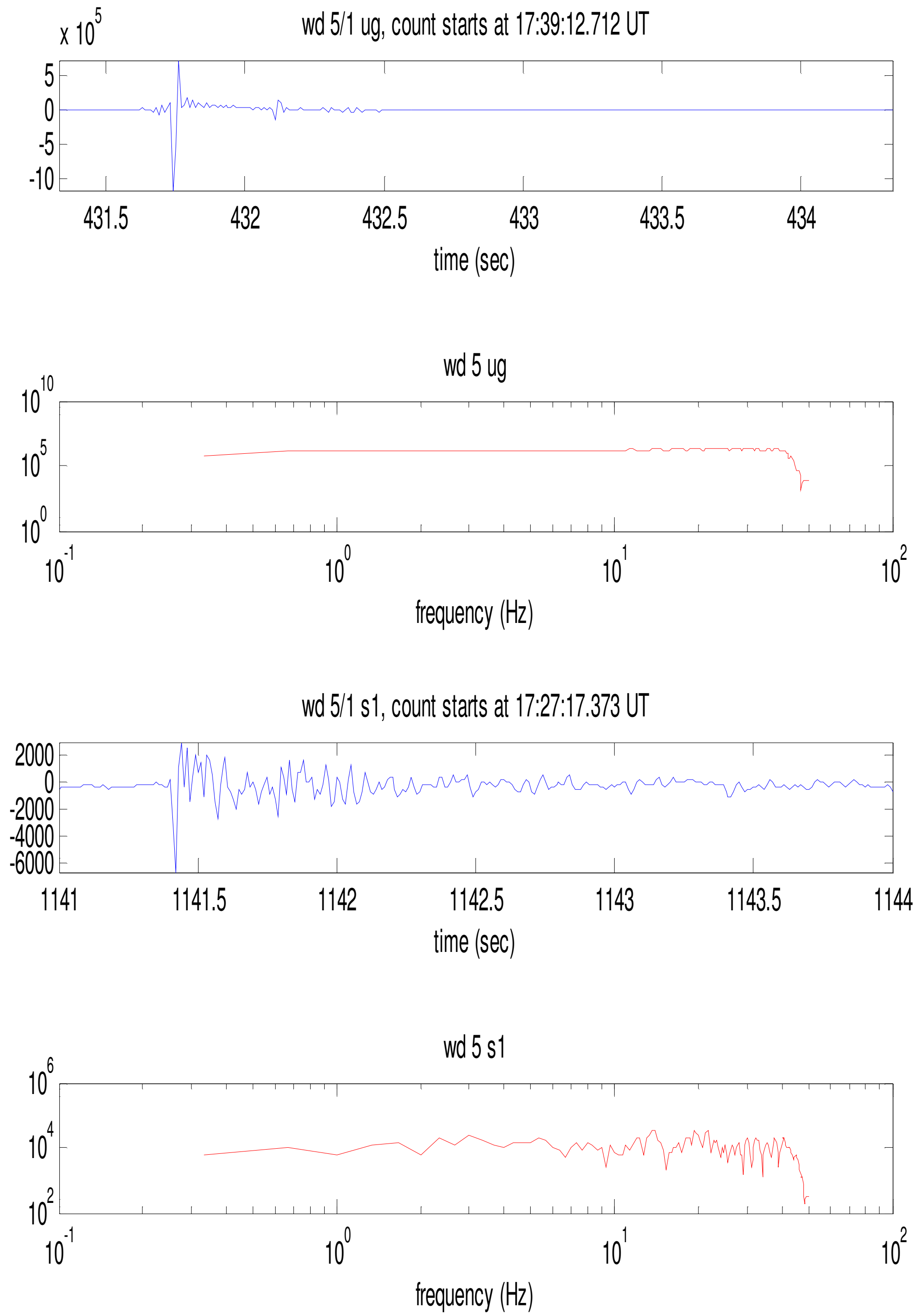

Figure 5. Weight drop data for first test in Alcove 5; observed underground and on surface at sensor S1, respectively. Start times for underground and surface sensors are not synchronized.

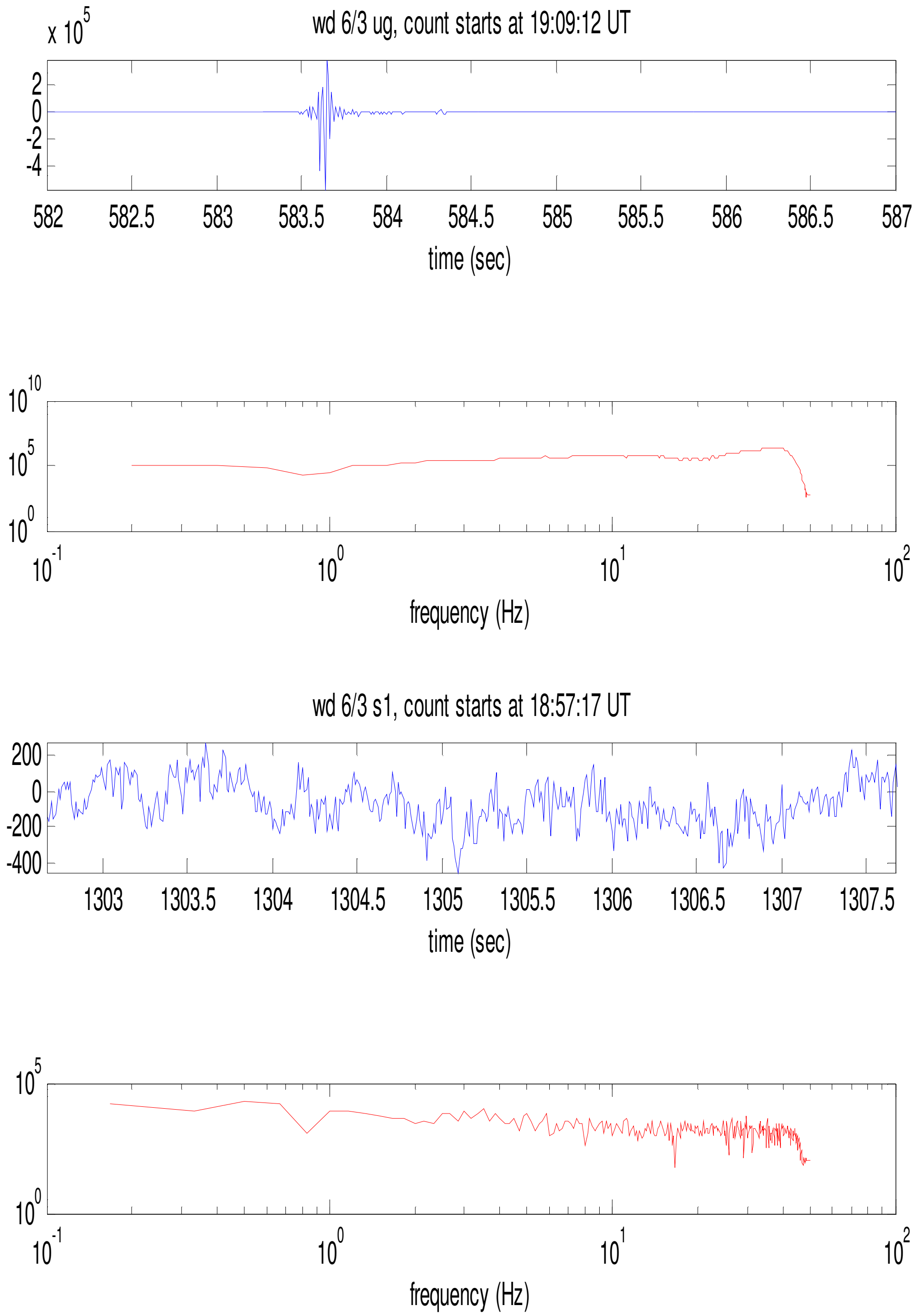

Figure 6. Weight drop data for third test in Alcove 6; observed underground and on surface at sensor S1, respectively. Start times for underground and surface sensors are not synchronized.

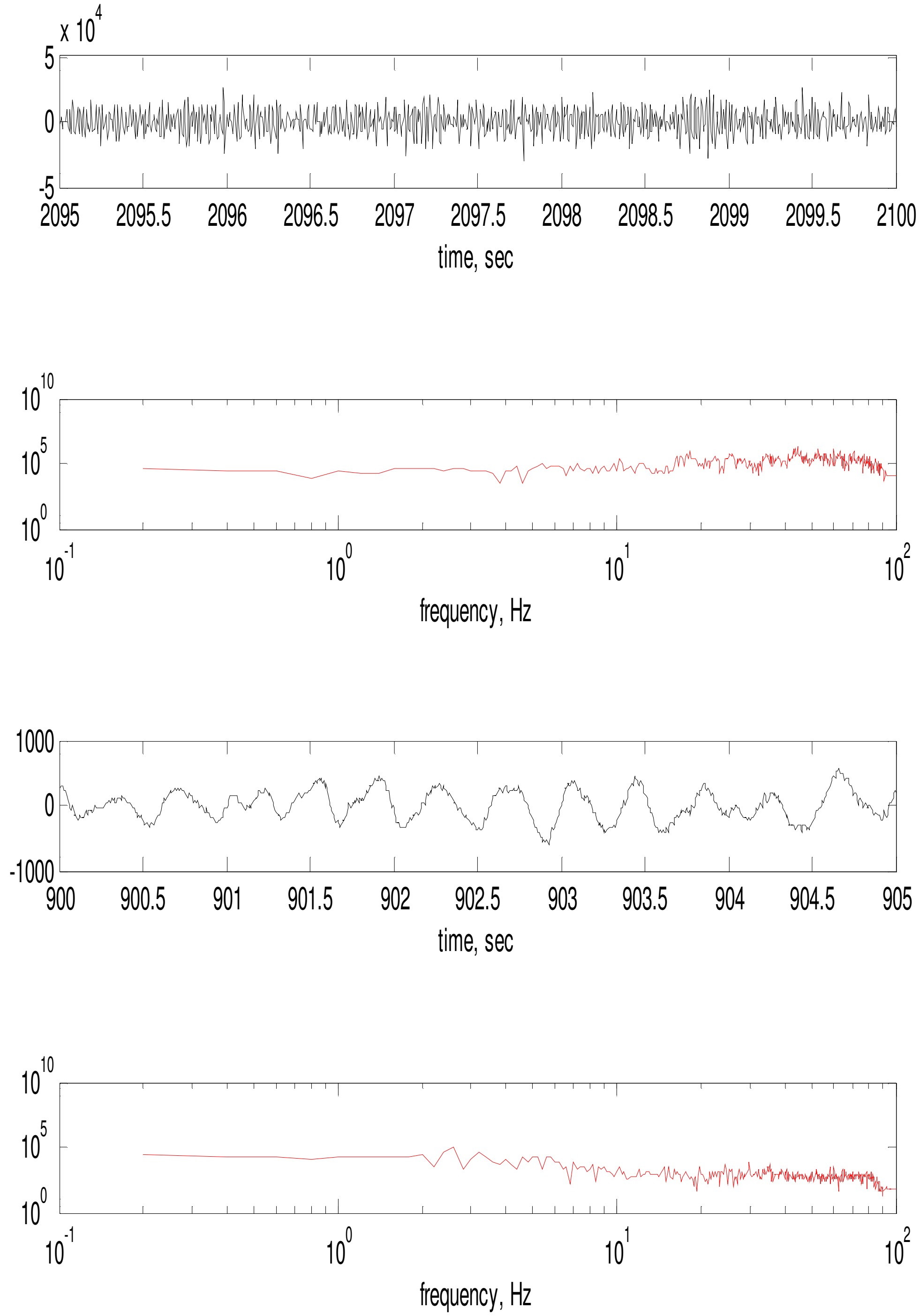

Figure 7. Unfiltered time histories and frequency spectra for background signal measured underground and on the surface, respectively during shakedown test

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Appendices

A. "Mathematical Modeling, Algorithms and Application of Seismic Data"; final report of the Computer Science group

B. Luke, B., K. Twilley, H. Murvosh, R. El-Khater, J. Cheng, E. Yfantis, and D. Harris, 2003. "Seismic monitoring for rockfall at Yucca Mountain: Concept tests." *Proceedings,* 38th Annual Symposium on Engineering Geology and Geotechnical Engineering. Idaho State University, Pocatello, 281-288.

C. Twilley, K., H. Murvosh, J. Cheng, B. A. Luke, D. Rock, and Y. Tu,, 2003. "Deployment of a passive seismic array to remotely monitor for rockfall in underground excavations." *Proceedings,* 38th Annual Symposium on Engineering Geology and Geotechnical Engineering. Idaho State University, Pocatello, 289-298.

D. El-Khater, R., J. Istle, P. Mandelbalum, E. Yfantis, and B. Luke, 2003. "An intelligent system for seismic source localization." Proceedings, 12th International Conference on Intelligent and Adaptive Systems and Software Engineering (IASSE-2003). International Society for Computers and their Applications (ISCA), 136-139.

E. Relationship of the subject work to other contemporaneous projects being conducted under the YMP – UCCSN Cooperative Agreement

F. Catalog describing data collected