THE UPGRADE OF THE INTERNATIONAL MONITORING SYSTEM PRIMARY STATION AT SONSECA, SPAIN, (PS-40): A BEFORE AND AFTER COMPARISON OF THE SHORT-PERIOD ARRAY

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ABSTRACT

In early November 2001 the PS-40 Array, located at Sonseca, Spain, underwent a major upgrade of the short-period array elements by the station operators, the Instituto Geografico Nacional (IGN), under contract to the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). This upgrade was required to bring the PS-40 array into compliance with the Treaty specifications and for certification of the Station, which was accomplished on 21 December 2001. As part of this upgrade, the older passive Geotech 23900 sensors were replaced with new Güralp CMG-3ESPV sensors, which are themselves broadband sensors with a passband of 0.02 Hz to 50 Hz. These new sensors are flat to acceleration instead of being flat to velocity, like the 23900 sensors, which provides the array with higher sensitivity to short-period data while still being able to record the long-period data and have a sensitivity of 750 v/m/s^2. The 16-bit Remote Terminal (RT) digitizers were replaced with new Nanometrics Inc. Callisto-Europa 24-bit authenticating digitizers with a sensitivity of 2539 nv/count. This combination gives the overall system sensitivity, "NCALIB", of 0.0858 nm/count. Each digitizer is configured with 13 MB of internal data storage that gives a re-request capability at each element of between 16 and 24 hours, depending on compression.

The sample rate for each element was increased from 20 to 40 samples per second, and the 1200-baud private wire modems used by the old system were replaced with 9600-baud modems to handle the increase in data rate and packet size. Three new Sun Spark-5 work station computers were added, each configured the same, having over 20 days of data storage with one designated as the primary data acquisition computer, one the back-up and one the Network Operator Terminal. Each computer is configured with a CD1 sender and AutoDRM, and, at present, they are sending CD1 data to the International Data Centre (IDC) in Vienna, Austria, to IGN and to the Air Force Technical Applications Center (AFTAC). A new broadband element was also added to the array using a Güralp CMG-3T sensor, which has a sensitivity of 1500 v/m/s (flat to velocity) and which is located in a vault near the long-period array element and is designated as ESBB.

Initial data from the new configuration looks good with data availability at 100% for the past several months as measured by the IDC. At first glance, the waveforms look much noisier due to the higher sensitivity to the short-period cultural noise in the local area. This short-period noise was present before the upgrade but, due to the old configuration, was not detected. Because of this noise, several elements are problematic at present and are not being used for beam forming. IGN has also reported a marked increase in the number of false event triggers by their data acquisition system in Madrid used for regional event detection. To resolve this noise issue, the IMS staff is looking into several alternatives that are suitable to all parties, while still keeping the station within compliance of the Treaty.

INTRODUCTION

Location

The primary seismic array PS40 (the Station) is located in central Spain, in and around the town of Sonseca, with a reference location of 39.6744°N, 3.9630°W and an elevation of 752 m. Sonseca is a small town of about 10,000 people and is within the aperture of the array. Due to the size of the SP Array, over 8 km in aperture, it takes in residential and industrial areas, as well as some surrounding agricultural areas (Figure 1). Located about 24 km north of the Station is the city of Toledo with a population of about 75,000. Madrid, the capital of Spain, is located about 120 km north of the Station. The terrain around the Station is rocky, with small hills and farming areas spreading throughout the array. Several manufacturing facilities in and around Sonseca are the cause of much of the high-frequency noise seen in the data above 1 Hz. A highway running through the array also causes a great deal of noise in the data. The official station operator is the Instituto Geográfico Nacional (IGN) located in Madrid, Spain. Technical staff of IGN maintains the Station with five onsite IGN personnel and three contractors.

Brief History of the Station

The Station was installed, and originally operated, under the United States Air Force (USAF) nuclear test monitoring programs and has been in operation for more than 40 years. Over the past few decades, the Station had been modified and upgraded by the USAF to a final configuration of 19 short-period (SP) elements using Geotech 23900A seismometers and 7 long-period (LP) elements using Geotech KS54000 seismometers. All elements at the Station used 16-bit "Remote Terminal" (RT) to digitize the analog signals from the seismometers. The SP elements and the central LP element, LPA, were sampled at 20 samples per second (sps) while the remaining 6 LP elements were sampled at 1sps, with the LPA element also providing 1sps data stream.

In 1991 six LP elements were added to form an LP array using Geotech KS36000 seismometers in 60-m boreholes, with an array radius of 25 km centered on the SP array. These LP elements underwent a further upgrade in 1998 when the KS36000 were replaced with KS54000. Also in 1991 AFTAC upgraded the intra-array power and communications distribution systems by replacing over 600 power poles and installing new power and communication wiring.

A basic topology Global Communication Infrastructure (GCI) satellite link was installed at the Station by CTBTO International Monitoring System (IMS) in 1999 to integrate the Station into the International Data Centre (IDC) Operations (Figure 2). The IMS installed a new computer that was configured to send continuous data to both the IGN at the National Data Center (NDC) in Madrid and to the IDC in Vienna.

In January 2001, at the request of the Spanish Mission to CTBTO, the IMS initiated the upgrade process to bring the Station into compliance with the Treaty requirements for certification. The Provisional Technical Secretariat (PTS) purchased from Nanometrics Inc. three data acquisitions computers (DAC), 22 authenticating digitizers, and intra-array communications hardware and support equipment. A second contract was awarded to Güralp Systems Limited for the procurement of 22 CMG-3ESPV seismometers to replace the Geotech 23900 SP seismometers. A new CMG-3T seismometer was also ordered for a new broadband element ESBB that was installed as part of the upgrade to meet IMS requirements.

The new equipment was delivered mid October 2001 and the upgrade of the Station's SP elements commenced at the end of October. All 19 SP elements were upgraded, the new broadband element installed, and systems were fully operational sending CD1 data to the IMS Lab, AFTAC and IGN, in early November under the new configuration. After review of the Station performance and configuration, PS40 was officially certified on 21 December 2001 by the PTS under the new configuration.

Overview of new hardware and configuration

This system configuration described below provides a data acquisition and storage capability that meets the 98% timely data availability requirement under the Treaty for data availability at the IDC.

Basic Overview of the Station

Under the IMS configuration the SP array has 20 elements with a total of 22 channels, sampled at 40 sps. The aperture of the SP array is just over 8 km and is of a spiral design (Figures 1 and 3). The array consists of 19 vertical SP elements and one three-channel broadband element. Both the digitizers and communications modems are located in new Wellhead Termination Units (WTU) affixed to the top of the borehole casing, which provides protection from weather, as well as security, for the hardware (Figure 4). Each WTU has a tamper detection switch attached to the door that is connected to one of the External State of Health (SoH) channels of the new digitizer. Because of the geographic location of the array, and since the digitizer and communication modems are located in the WTU, a thermostatically controlled exhaust fan was added that would turn on if the inside WTU temperature reaches +40°C. A shade cover was also installed around each WTU to help provide additional protection from the sun and thus reduce the internal heat of the WTU, and help protect the equipment (Figure 5). All cables running to the WTU are housed in flexible or solid metal conduit to provide both security and weather protection.

The SP sensors are installed in the original 4.5-in. steel-cased boreholes at a nominal depth of 30 m below surface. Each SP seismometers is coupled to the borehole casing using a motor-driven three-jaw hole-lock attached to the bottom of the seismometer (Figure 6). The broadband element is a surface-mounted seismometer installed in a vault approximately 4 m below the surface and placed on a concrete pier. The digitizer and modem are also located within the vault. To help dampen the affects of acoustic sound waves in the vault produced by wind blowing across the door, and to provide additional thermal stability, the broadband seismometer has been buried in a box filled with sand.

Seismometer

The Güralp GMG-3ESPV borehole seismometer, with a bandpass of 0.02 to 50Hz and configured to 750 V/m/s^2 sensitivity, was chosen for the SP vertical-component elements due to their force feedback design, size, bandwidth, dynamic range, sensitivity and ease of importation within the European Union (Figure 6). Due to the background noise at the Station and the overall design requirements of the IMS, it was determined that using sensors flat to acceleration would be preferable as they would be more sensitive at higher frequency. The three-component broadband element uses a high-sensitivity Güralp CMG-3T triaxial seismometer that is flat to velocity, has a bandpass of 0.0083 to 50Hz, and is normalized to 20,000 V/m/s. It was chosen primarily for its compatibility with the CMG-3ESPV sensors, the dynamic range, sensitivity and ease of importation. It had been verified before that these two sensors meet the minimum self-noise requirements of the IMS.

Digitizer

The Nanometrics HRD Europa remote digital acquisition system, in a Callisto housing, provides 24-bit digitization, digital signal processing and data frame authentication (Figure 4). Each digitizer has two RS-232 outputs, one for the internal non-authenticated data and one for external authenticated data, as well as having one 10-base-T LAN port for both data output and programming. The output of the digitizer is compressed NMX-X format data and uses a UDP/IP communications protocol, instead of TCP/IP, to reduce communication overhead. Each data package is assigned a unique identification (ID) and also contains information on the oldest data package still in the digitizer's memory.

The HRD digitizer uses a 24-bit delta-sigma processor and, as measured at Sandia National Laboratory, has a "Noise Power Ratio" dynamic range of 125 db (131 db for shorted inputs). Input channel noise levels are generally less than two counts rms at 1.9 uV/bit & 100-sps and a cross-talk of less than –80db. Authentication of data is handled via a PCMCIA hardware token utility attached to the "Communications Controller Board" located inside the digitizer housing. Authentication hardware is protected with an internal tamper indication switch mapped to a SoH channel and incorporated into the data stream.

The digitizers in the array were each configured with a sensitivity of 2539 nV/count giving a nominal overall system sensitivity, "NCALIB", of 0.0858 nm/count for the SP elements and 0.0202 nm/count for the broadband elements. All data channels are sampled at 40 sps, per the IMS requirement, and data are sent over the intra-array communications network to the Central Recording Facility (CRF) using private wire modems and the authenticated RS-232 output of the digitizer. Independent timing for each element is provided by means of a Trimble GPS receiver incorporated into each digitizer and an external antenna mounted on the outside of the new WTU (Figure 5). Each digitizer has 13MB of RAM, which, depending on compression, can store over 20-hr of data in an internal "Ringbuffer". This data can be re-requested by any or all of the DAC in the event of missing data packages, or an interruption in communications between the CRF and the digitizer.

Each digitizer has three "fast" State of Health (SoH) channels and three slow SoH channels. The fast SoH channels sample at 10 Hz and monitor the vault door and internal authenticator tamper detectors and the calibration-enabled channel. These SoH channels are mapped in the data acquisition software to the appropriate CD1 status bits and forwarded to the IDC in the CD1 "Data Frame". The slow SoH channels are sampled at 0.1 Hz with two of the channels used to measure the internal digitizer temperature and input voltage, the third channel-free. Figure 7 shows the basic data flow within the digitizer.

Central Recording Facility Hardware

The CRF Data Acquisition Computers (DAC) consist of three Sun Microsystems Sparc Ultra-5 Workstations running the Solaris 8 (Unix) operating system. One of these computers is designated as the "Primary" IMS DAC and a second as the "Back-up" IMS DAC. Both are configured to send continuous data (CD1) to the IDC via the basic topology GCI. The station operators use the third computer as the Network Operator Terminal (NoT) for routine screening of waveform and SoH data. The NoT is also configured to send CD1 data to IGN in Madrid, Spain, and AFTAC in Florida, USA, via their respective independent sub-networks. The NoT is also capable of sending CD1 data to the IDC via the GCI if needed.

Data flow from each element via the Intra Array Communications equipment to one of four RM-4 Bridge-multiplexers. The RM-4 converts the RS-232 serial data to Internet Protocol (IP) and then multicasts the data over the LAN to the various DAC computers connected to the LAN. For reference, Figures 8, 9 and 10 show the interconnection to all hardware located at the CRF and the data flow for the new hardware and software installed as part of the upgrade. The RM-4 also provides full duplex communication with each digitizer for data recovery and issuing of various commands from the DAC, such as mass centering

and calibration. The data are received by each of the DAC and are stored in independent ringbuffers. Each ringbuffer is set to hold about 14 days of data assuming no compression of the data. Recovery of missing data packages is handled through the data acquisition software, NAQSServer.

The computers, and RM-4s, are each attached to one of two standard 3-Com LAN Hubs. These hubs also provide the physical link to the GCI, IGN, and AFTAC communications equipment for forwarding of data to their respective destinations. The computers, RM-4s, LAN Hubs, and communications equipment are installed in an equipment rack with intrusion detection switches that indicate when either of the doors to the rack has been opened (Figure 11). The switches are mapped into one of the SoH channels of one of the RM-4 and will set a "rack open" bit in the CD1.1 protocol when implemented. This rack also houses two Chrysalis authenticators for signing AutoDRM requests and the intra-array communications equipment.

The CRF itself is a brick building with office space, storage rooms, work rooms, and a separate room for the DAC and other central array equipment (Figure12). The CRF has three additional buildings used for equipment storage, maintenance facility, and the backup generator.

Central Recording Facility Software

Data are sent to the all three data acquisition computers over the Intra-Array Communication system in compressed NMX-X format where they are recorded, stored, converted to CD1 and forwarded on to the respective destination by the data acquisition software. Figures 9 and 10 show an overview of data flow from the seismometer through the DAC to the CD1 receivers. The data acquisition software running on the DAC is the Nanometrics NAQSServer software, which is a Java-based program that can also be run on PC-based computers with minor modifications to the set-up files. The primary role of the NAQSServer software is to acquire continuous error-free data sets for real-time and off-line processing by Nanometrics and third party client software modules. It also serves as the primary interface for receiving real-time seismic data from Nanometrics' remote field digitizers through the RM4 Bridge Multiplexers. Since the digitizers send data using a UDP/IP protocol, the NAQSServer performs all error correction by re-requesting missing data packages. Since each data package is assigned a unique ID, and each data package contains the ID of the oldest package still in the digitizer's memory, NAQSServer can recover most missing data packages, as bandwidth permits, in the event of communication outages.

To provide CD1 data, all three DACs are configured with multiple instances of NMXTOCD1 software. This program is also a Java-based program that connects to the NAQSServer program as a client and builds real-time CD1 data frames and then forwards them on to the appropriate CD1 Receiver. All three computers are configured to send CD1 data to both the IDC and IGN in the event that their respective primary computers should fail. Only the back-up computer and NoT are configured to send CD1 data to AFTAC due to firewall constraints. Both the primary and back-up computers are configured with AutoDRM to provide additional data via e-mail request to the IDC. AutoDRM messages are signed by one of the Chrysalis authenticator tokens installed in the rack and any incoming AutoDRM request must meet appropriate security requirements or the system will not respond.

Additional software is provided for monitoring real-time waveforms and for viewing the various SoH parameters. Calibration and Mass-Centering commands can be issued from any one of the DAC at the CRF using the NAQSView program. All programs can be used over the GCI from work stations and PCs located at the IMS in Vienna to help provide support to the station operator. Various playback programs are also available to the station operator for extracting additional SoH information as well as extracting and converting time-series event data.

Since the software provided under the contract with the equipment supplier, Nanometrics, does not have the capability to look at older waveform data, the IMS has installed additional software for the station operator to use. This software converts the NMX-X data to CSS-formatted data and stores about 5 days of continuous time-series data online. The IMS also installed various other programs developed by the IMS so that the station operator can view the data and perform routine analysis for data quality.

Intra-Array Communications

The intra-array communications between the digitizer and DAC is handled using private wire modems over the existing copper wire network (Figures 3 and 4). The array has over 50 km of cabling with the longest run between element and CRF of just over 8 km and uses the same transmission poles as the A/C power distribution system. Each element within the array has 4 pairs of wire between the CRF and the element: two for data, one for power monitoring, and one spare. Cables were recently checked as part of the IMS upgrade requirements and several bad sections were replaced under the site upgrade contract. New splice connections were made at each end and a new terminal board installed at the CRF during the upgrade.

The private wire modems are connected to each of the digitizers inside the WTU via a short, 1-m, communications cable (Figure 4). The modems are then connected to the private wire network for communications back to the CRF. The wires are attached to the corresponding modem at the CRF and terminate inside the equipment rack and attached to the appropriate RM-4. Each

digitizer/modem pair is configured to send data to the CRF at 9.6-kbaud, which provides ample bandwidth for data recovery and communications requirements between the DAC and digitizer.

Power Systems

The array elements use DC power provided by 24 VDC batteries with over 200 hours of autonomous run-time capability. They are charged by both a solar charging system and 440 VAC to 24 VDC, and are the primary source of power at each element. Power is converted within the modems to 12 VDC using an internal DC/DC converter. The DC/DC converter supplies power to the seismometer and digitizer at the site as well as meeting the modems power requirements.

A private above-ground power transmission network provides commercial 440 VAC power from the CRF and each element within the array (Figure 3). Both a UPS and a back-up generator are located at the CRF and provide back-up power for the 440 VAC power lines. At the CRF commercial power feeds into a new double conversion UPS that conditions power and provides back-up power to the DAC and associated equipment in the event of a power outage until the back-up generator comes on line.

Review of Array Testing

Component Testing

The Nanometrics digitizer underwent formalized testing in May 2000 at Sandia National Laboratories, under the supervision of the IMS Seismic Monitoring Section (IMS/SM), to validate the manufacturer's specifications, and to confirm that it meets IMS requirements. These tests demonstrated that the digitizer met or exceeded all IMS requirements for noise, dynamic range, timing and functionality. Additionally, each system provided to the IMS undergoes a formal "acceptance" testing at the manufacturer's facility before shipment. The acceptance tests are designed to test all aspects of the systems and to ensure that they meet the IMS requirements before shipping and that they are properly configured. They also provide a baseline for each system under a controlled environment.

After the upgrade of the first 10 SP elements and the installation of the new BB element, the CD1 data stream was started to the IMS Lab in Vienna via the Basic Topology GCI. CD1 data frames were checked to see that they met IMS requirements. As additional elements were upgraded throughout the array, they were added to the data flow to the IMS Lab and tested until all elements were functional. As each element was installed, the tamper switches were tested to ensure proper functioning. Calibration and mass centering commands were tested, as well as the GPS timing. Both CD1 sender and receiver logs were checked to ensure that the system was setting the proper status bits in the CD1 data stream. Evaluation of the receiver logs from the IMS Lab confirmed that the station met all IMS requirements for characteristics such as sampling rate, data frame length, proper implementation of the CD1 data format, and authentication signature for each element. After this initial checking by the IMS, data were transferred to the IDC test bed on 26 November 2001 for further analysis by the IDC.

Data Latency and Timely Data Availability

Data from the station under the old configuration were received by the IDC from August 1999 until the upgrade in October 2001 via the basic topology GCI. Data Availability (DA) statistics under the old configuration showed the station routinely performed above the 98% monthly DA requirement of the IMS, but missing data was never refilled. Under the new configuration, results taken from the "stacap" program while in the IDC test bed showed that DA for the station is now above 99.9% with most channels reporting 100% monthly DA. It should be noted that the ES10 element has been having major communication problems due to a faulty and intermittent problem with the intra-array wiring.

Data Latency

An indication of data latency for the station is shown in Figure 13. This figure shows a plot for CD1 data frames received in the IDC test bed over a 24-hour period. The y-axis represents the time that the data acquisition computer recorded the data and the x-axis the time the frames were received by the IDC DLMan program. The difference in these times is a good representation of the overall data latency between the station and the IDC. Frame latencies >300 seconds typically represent periods in which "catch up" occurred from the disk buffer. The mean latency for data sent by the NmxToCD1 software, as recorded in the IMS, from November 26 – December 10 was about 26 seconds.

Timely Data Availability

The IMS requirement for Timely Data Availability (TDA) is that data frames must be received by the IDC within 300 seconds (5 Minutes) of the actual recording time. As an example, an estimate of total TDA from 30 November to 2 December 2001 was made from the frame logs in the IDC. During this period, a total of 26214 CD1 data frames were received by the IDC of which 206 took longer than 300 seconds, giving a TDA of 99.22% of the total data received with 100% DA. Of the 206 frames, 170

were "second pass" frames where only missing data were retransmitted after 12 hours. Due to the way the stacap program reports TDA, these second-pass frames were weighed the same as a first-pass frame. If we correct for this, we see that the true TDA is around 99.98% for this period.

Review of Waveform Data[1]

Perceived Noise

Initial review of waveform data indicates that the station appears much noisier than it was before the upgrade. It should be pointed out that while the data *appear* to be much noisier, in fact it has been this way for many years as the array is centred on the town of Sonseca. There are several factories in the area, some of which are within 100 m of the elements, which produce high-frequency noise. Also a highway running through the middle of the array, and in some cases less than 100 m from the elements, is the source of much of the transient noise and causes many of the false triggers seen by IGN and the IDC. A new bypass highway is currently under construction that will pass within a few hundred meters of four more stations, (ES02, ES07, ES17 and ES18), which will increase the noise problem in the near future.

Because the new station configuration has an increase in gain, dynamic range, sampling rate, a higher sensitivity and sensor response is flat to acceleration, we see what is perceived as an increase in noise within the array. If we look at data from the array under the old configuration, i.e. using the older 16-bit RT and Geotech 23900 sensor, and simply differentiate the data from velocity to acceleration (Figure 14), we now see that the noise was there before the upgrade of the Station. Because we were looking at data relative to velocity, we did not see this noise as easily. Conversely, if we decimate the new data to 20 sps and then integrate it, it looks like the old data. Since the new seismometers and digitizer are more sensitive at higher frequencies, the amplitudes of the high frequency noise in the raw data are much larger. If we integrate the acceleration data to velocity, we can produce a trace that looks very similar to the old data. Decimation of the acceleration data from 40 sps back to 20 sps alone does little to remove the high-frequency noise in the data as much of it is still below 10 Hz.

Looking at just background data for ES01 before and after the upgrade, along with ESLA and ESBB vertical channels, and doing a simple FT analysis of the data, we see that in the raw data, the old data look quieter (Figures 15A and B). However, if we remove the instrument response, we can see that for data above 1Hz, the trace for ES01/BHZ, ESBB and ESLA track nicely (Figures 15C-D). If we first apply a simple Butterworth Low Pass (LP), 1-Hz, causal, first order, filter to the ES01/BHZ data, we now see an improvement in ES01/BHZ. Now the new configuration tracks the older ES01/sz data up to about 5 Hz, where it rolls over, possibly due to anti-alias filtering at the digitizer (Figures 16A-D). In either case it has been shown that the new sensor is performing nicely above 1 Hz and, even without filtering, is as good as the KS54000.

If we apply the simple LP filter described above, we can remove much of the high-frequency background noise while retaining much of the waveform information (Figure 17). With this simple filter we can produce a trace from the ES01/BHZ acceleration data that correlates very well with the new broadband velocity element, ESBB/BHZ. Further this filtered trace also correlates nicely with the integrated data.

Comparison of Event Data

Comparisons of waveforms were made for two sets of events under the old and new array configuration. Data for two each regional and teleseismic events were picked at random based on available data from the IDC database, location and magnitudes. These events are not meant as conclusive evidence as to the overall performance of the array but only given as examples. Comparisons were made using data from ES01, ESBB and ESLA, which are located near the center of town and are very noisy elements within the array. The regional events that occurred on 9 August 2001 and 4 April 2002 with magnitude ML 3.7 and 3.0, respectively, were located 1.3 and 0.8 degrees NNE of the array, depth at about 8 km for both. The teleseismic events occurred in northern Chile near the Bolivian border on 24 July 2001 and 28 March 2002 and were magnitude MW 6.3 and 6.5, respectively. The epicentral distances for these two events to Sonseca were about 85 degrees. The first teleseismic event had a reported hypocentral depth of 33 km while the second event was much deeper (about 125 km).

Regional Events

Comparisons of arrivals were made for old data (ES01/sz), new acceleration data (ES01/BHZ), integrated acceleration data (ES01i/BHZ), LP-filtered acceleration data (ES1lp/BHZ) and the ESBB/BHZ element. The data show that the first motion is very clear for the regional event using just the raw acceleration data and that secondary arrival in the initial part of the trace is clearly present (Figures 18A-D). The raw velocity data for the first event under the old configuration is still good, but does not

[1] *For the purpose of the following sections, ES01/sz and ESLA/bz are from the old configuration, ES01/BHZ is the new acceleration data and ES01i/BHZ is the integrated data of ES01/BHZ, and ES1lp/BHZ is LP data for ES01/BHZ.*

show as clear a first motion or the details for secondary arrivals (Figures 18A-C). It should be noted that these are different events, in a different area and at a different time, and as such a direct comparison is not possible as variation should be expected.

A basic integration of the acceleration data using the SAC software for this event provides significant first and secondary arrival information but is notably smoothed and has lower amplitudes as compared to the raw acceleration data. Applying a very simple LP filter to the acceleration data gives almost an exact match to the integrated data but provides greater amplitude information. The filtered, or integrated, data can be directly compared to the velocity data provided by the CMG-3T vault seismometer at ESBB. Adjusting for the station offset, again a good correlation can be made between the various waveforms, even without integration or filtering (Figure 18D).

Teleseismic Events

For the teleseismic events, we again looked at ES01, ESBB, and added ESLA for comparison. For the two events we can see that for the velocity data, i.e. ES01/sz, ESLA/bz, ES01i/BHZ and ESBB/BHZ, the first arrival is clearly present in the raw waveform data without any processing (Figure 19A). For ES01/BHZ, the first motion is present in the raw acceleration data but because of local noise, i.e. a vehicle driving by, it is hard to pick out if one does not know where to look (Figure 19B). Again, applying LP filtering enhances the first arrival and removes much of the noise in the trace, making it much easier to see (Figures 19A-F). For the second event you can clearly see a pP phase arrival, even in the raw acceleration data (Figure 19D).
Using a 3rd order LP filter at 0.1 Hz on both events, we can see that under either configuration, later arrivals are present in all traces (Figures 19C-D). LP filtering of the data at 0.01Hz shows that for the two broadband sensors, ESLA and ESBB, ESLA performs much better and has greater detail in later phase arrivals (Figures 19E-F). This would be expected, as ESLA is located in a borehole at a depth of about 100 m while ESBB is located at the surface. Also, the KS54000 performs much better at longer periods than the CMG-3T but this is well below the design criteria for the IMS.

It should be noted that the performance of the new short-period sensors, the CMG-3ESPV, is very good and these sensors provide additional information on later arrivals (Figures 19E-F). Due to their installation in boreholes, these SP sensors perform, in some respects, even better than the broadband ESBB sensor installed at the surface. When applying the LP filter at 0.01 Hz, the waveform for ES01/sz falls apart under this filtering, and no real useful data are provided, though this is well below the passband of the sensor (Figures 19E-F). This shows that the new SP sensors are indeed broadband sensors, as well as short period, and should provide additional information about seismic waveforms not seen by the array in the past. It has yet to be determined how useful this information will be for verification purposes.

Solutions to Reducing Noise

Various techniques have been looked at by the IMS staff to reduce the high-frequency noise at the site in post-processing and in the hardware itself. The software solutions include decimating the acceleration data from 40 sps to 20 sps after receiving it at the IDC, integration of the data at 40 sps or 20 sps, and applications of various low-pass filters before triggering and beam forming. The most promising is simply applying the 1-Hz, LP, first order, filter to the raw acceleration data. This filter essentially converts the data from acceleration to velocity and removes much of the high frequency noise seen in the data, but still retains all the information in the waveform provided by the sensor.

Several hardware solutions, and combinations, have been looked at. The first alternative would be to reduce the sample rate of the digitizer from 40 sps to 20 sps, like the old system. The second alternative would be to add an integrator into each of the seismometers converting them to be flat to velocity. The third alternative is to move the problem stations away from the noise source. Alternative 1 does little to reduce the actual noise in the traces, as much of the noise is still present after decimating the data and false trigging will still be present. Alternative 2 is possible, but the IMS feels that valuable data will be lost as these elements are providing useful data at the higher frequency. The third alternative may need to be implemented, as the new road construction will further reduce the capability of the array, and it may become necessary in the near future to move elements.

CONCLUSIONS

The station has been shown to meet all requirements for a primary IMS seismic station and as such has been certified by CTBTO. Authentication devices and GCI infrastructure are in place and have been demonstrated to work properly. The station underwent a complete upgrade in Oct and Nov 2001 with equipment purchased by the IMS. New software and hardware have proven to be stable with little or no trouble. The station has been sending CD1 data to the IDC, AFTAC and the NDC via basic topology GCI and independent sub-networks since 10 Nov 2001. Under the upgraded configuration, DA has been well above the Treaty's 98% requirement.

Event data clearly show that the new configuration is more sensitive and is able to record high-quality data for both regional and teleseismic events. With or without filtering, it is the PTS's feeling that the new SP elements are performing better than the old sensors and are capable of providing additional waveform information below 0.05Hz and above 5Hz. Comparisons of spectral noise plots show that the new SP elements are performing within specification and a simple low-pass filter is very effective in

removing high-frequency noise. Utilization of instrument corrections shows that the new SP elements respond better above the microseismic background noise as compared to the broadband element and the old equipment. This holds true with or without first using LP filtering. Comparisons of background data show that the array "appears" to be noisier under the new configuration. However, it has been shown that even under the old configuration the same types of noise sources were present and can be clearly seen when differentiated to acceleration. The new data can be decimated by a factor of two and then integrated to arrive at what looks like the old array.

The new configuration has greater sensitivity to high-frequency signals, which one would expect to see for a "Treaty Relevant Event". It is the PTS's feeling that this type of array configuration is acceptable for new and upgraded arrays as it should provide a better ability to detect small events at greater distances in the future. As such, analysts working with the new data will need to become accustomed to processing acceleration data, as several of the new IMS arrays will be configured the same as PS40, i.e. with sensor response flat to acceleration. While the new configuration is currently causing many false triggers at the IDC and NDC, it is the PTS's view that additional work must be done on software improvements to handle the use acceleration data and not to degrade the new performance of the station. Proper pre-filtering of the data should greatly reduce the number of false triggers.

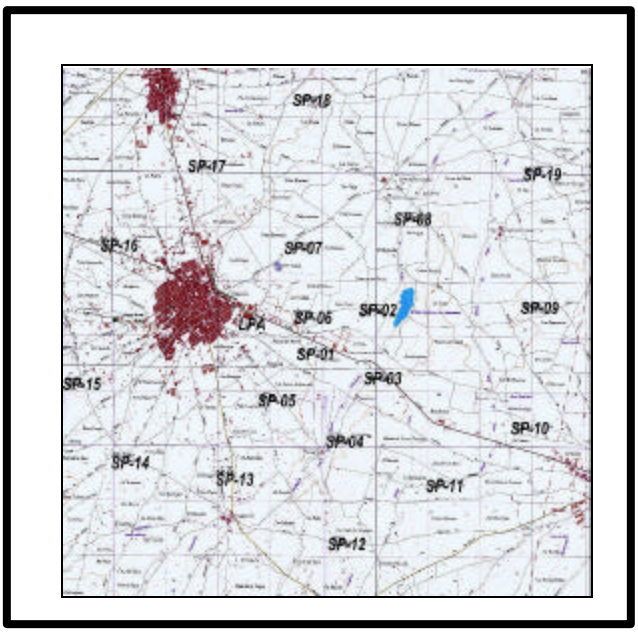


Figure 1. Map of PS40 Array showing the location of array elements and proximity of Sonseca, SP01=ES01.

Figure 2. GCI Dish installed on side of CRF.

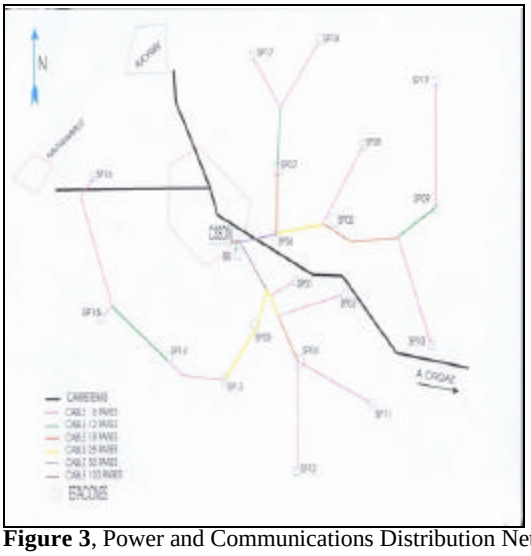


Figure 3, Power and Communications Distribution Network.

Figure 4. New Callisto Digitizer (L) and Modem (R).

Figure 5. New WTU with shade cover, external GPS antenna shown in upper right of picture.

Figure 6. New CMG-3ESPV seismometer with 3-jaw holelock.

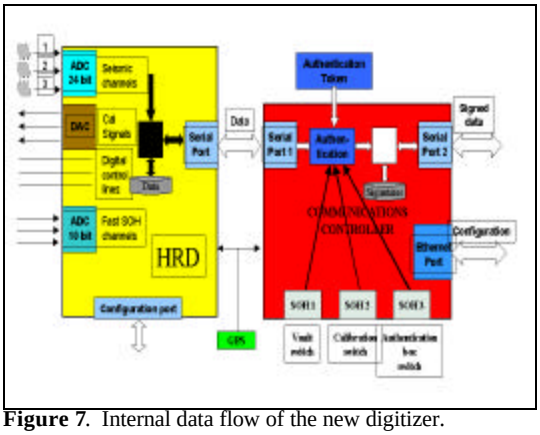


Figure 7. Internal data flow of the new digitizer.

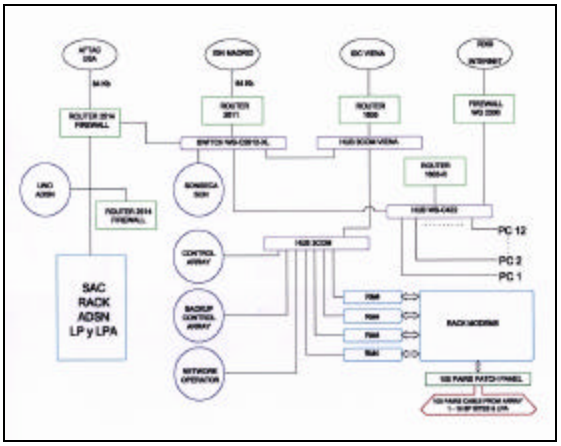


Figure 8. CRF equipment inter-connection showing new equipment configuration and physical connections. Flow to AFTAC still has LP elements going to them.

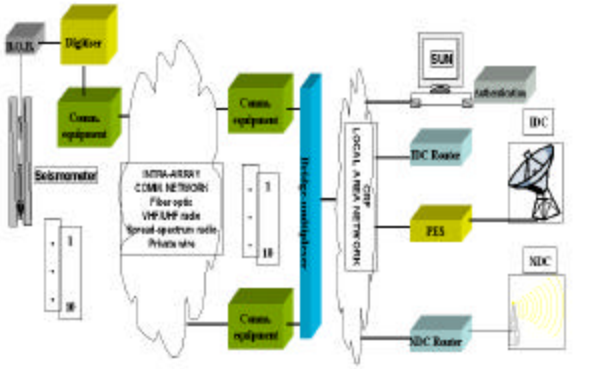


Figure 9. Block diagram of major components of the array.

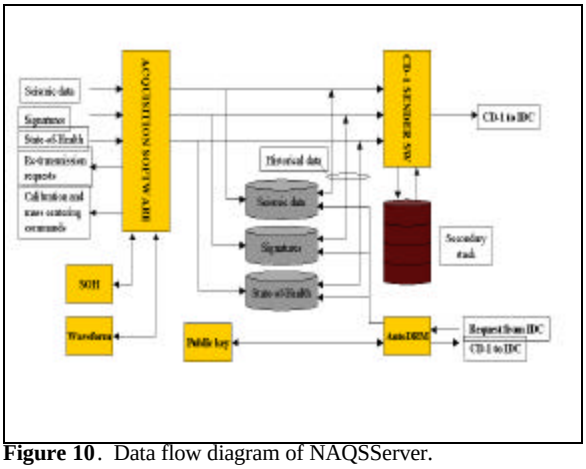


Figure 10. Data flow diagram of NAQSServer.

Figure 11. Front of new equipment rack at CRF, primary and back-up DAC on top, two each authenticators below DAC, 4 each RM-4s below authenticators, CRF communications modems below RM-4s. Older AFTAC rack to the right.

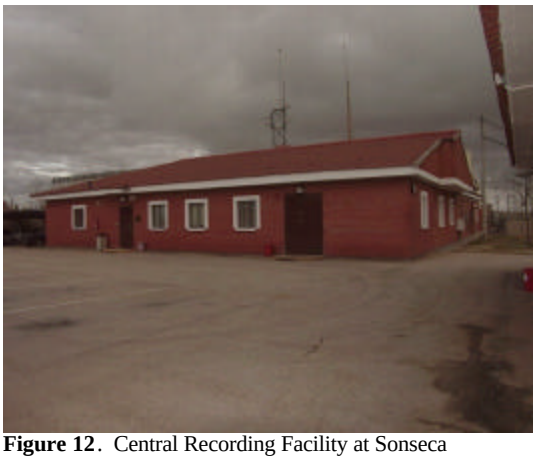


Figure 12. Central Recording Facility at Sonseca

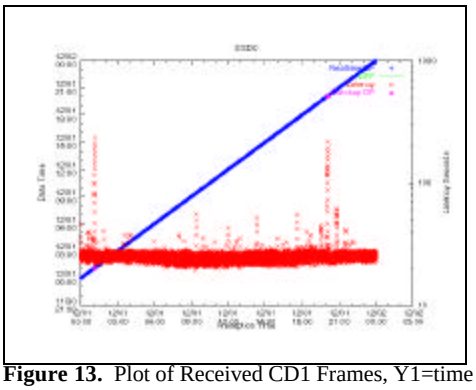
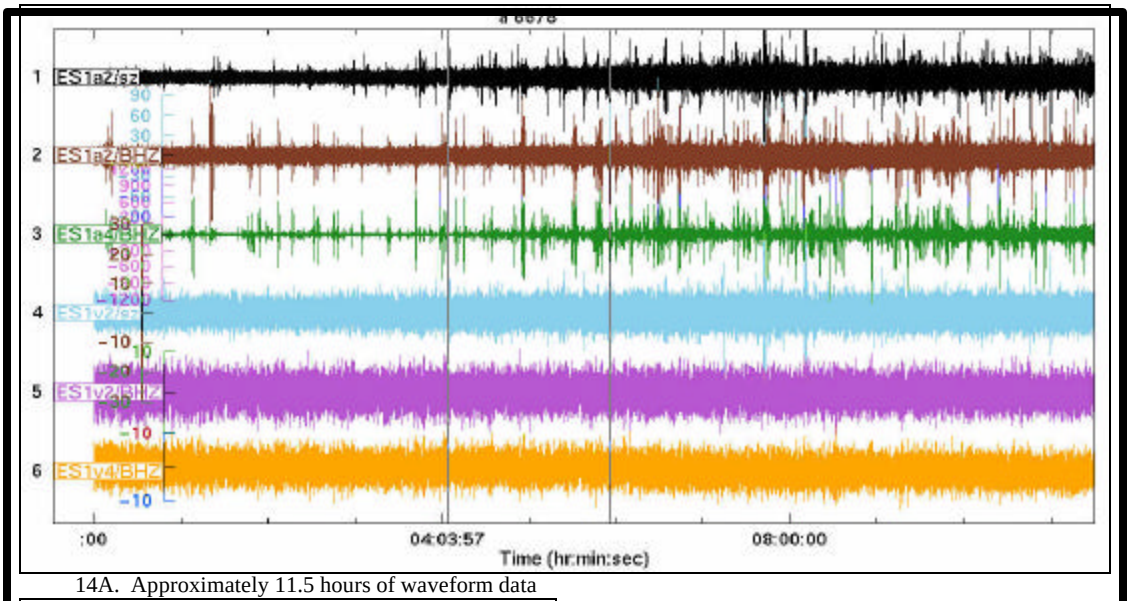
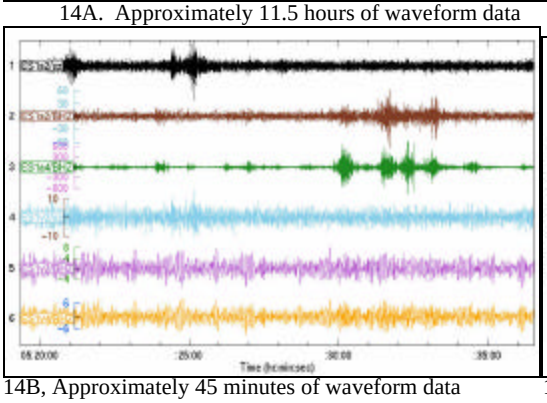


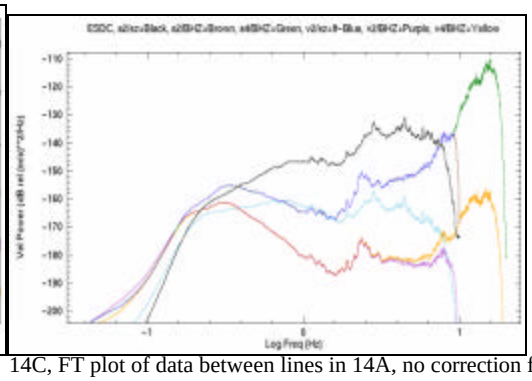
Figure 13. Plot of Received CD1 Frames, Y1=time that the data was recorded, X=time frame was received by IDC, Y2=log of latency time. Blue line plots the "Realtime" frames, red X is the difference of the X-Y1 times.



14A. Approximately 11.5 hours of waveform data



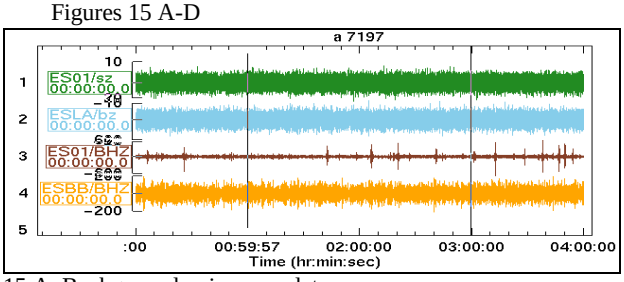
14B, Approximately 45 minutes of waveform data



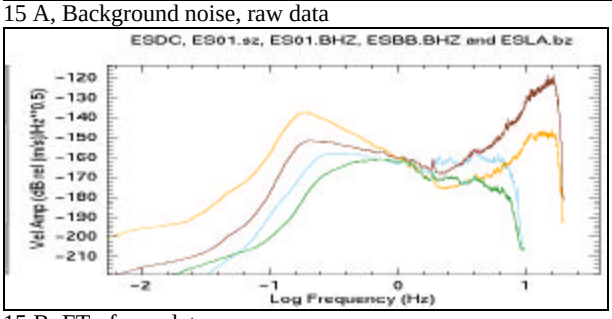
14C, FT plot of data between lines in 14A, no correction for instrument response.

Figure 14 A-C. Old and new ES01 data. Black=ES01/sz (ES1a2) differentiated to acc, brown=ES01/BHZ (ES1a2) decimated to 20 sps, green=ES01/BHZ (ES1a4) raw data (40sps Acc), light-blue= ES01/sz raw data (20sps Vel), purple=ES01/BHZ (ES1v2) integrated acc data decimated to 20 sps, yellow=ES01/BHZ (ES1v4) integrated acc data at 40 sps. 14A, note similarity between traces 1&2 (20 sps acceleration data). 14C-raw FT plot for each trace without instrument correction, only for comparison.

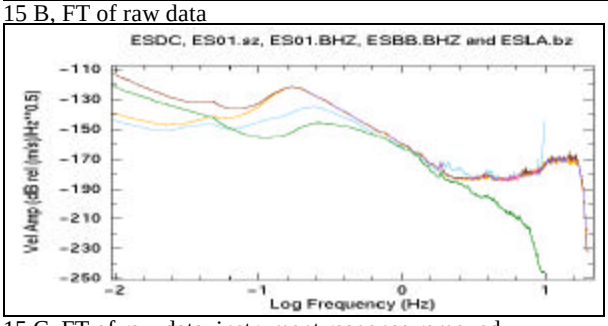
Figures 15 A-D



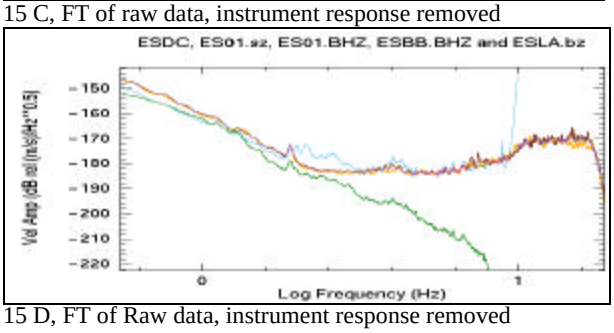
15 A, Background noise, raw data



15 B, FT of raw data

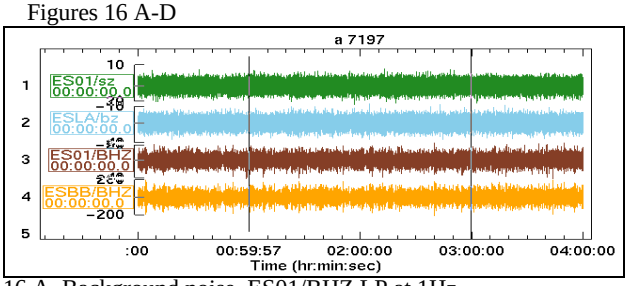


15 C, FT of raw data, instrument response removed

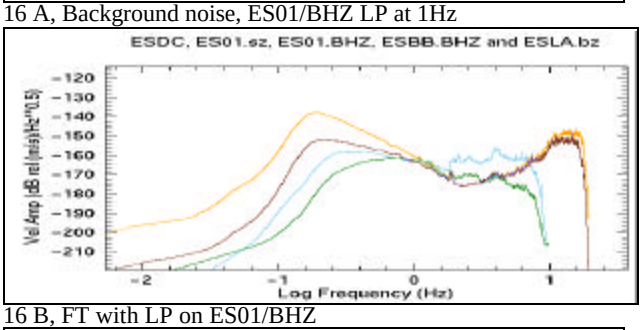


15 D, FT of Raw data, instrument response removed

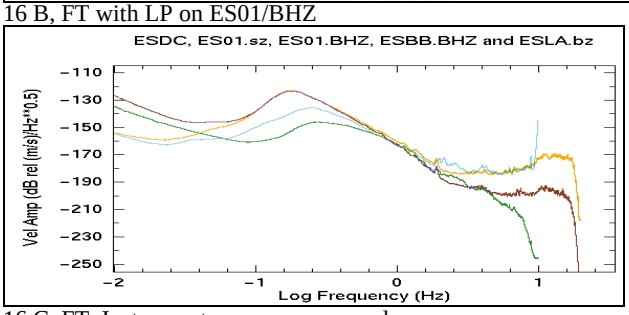
Figures 16 A-D



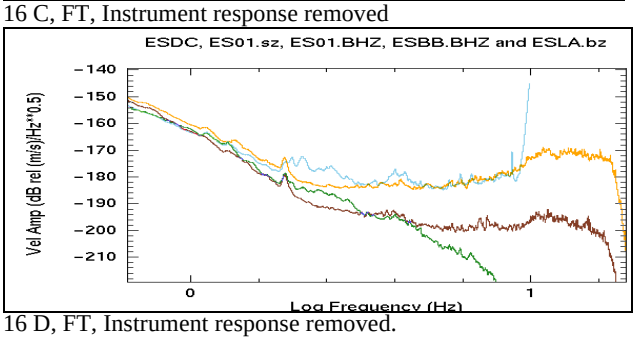
16 A, Background noise, ES01/BHZ LP at 1Hz



16 B, FT with LP on ES01/BHZ



16 C, FT, Instrument response removed



16 D, FT, Instrument response removed.

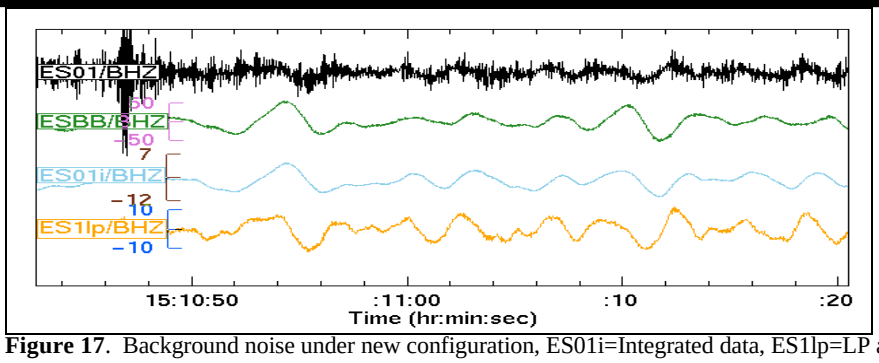
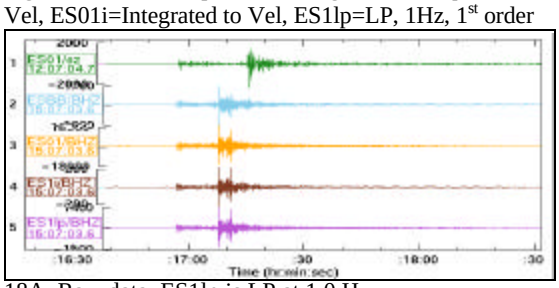
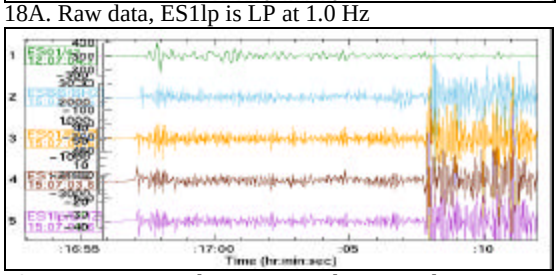


Figure 17. Background noise under new configuration, ES01i=Integrated data, ES1lp=LP at 1Hz

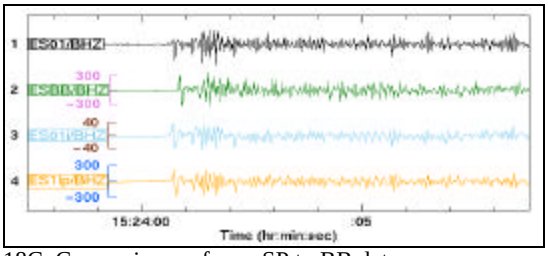
Figure 18 A-D, Comparison of Regional Earthquakes, ES01/sz=Old Vel, ES01/BHZ=New Acc, ESBB=Broadband Vel, ES01i=Integrated to Vel, ES1lp=LP, 1Hz, 1st order



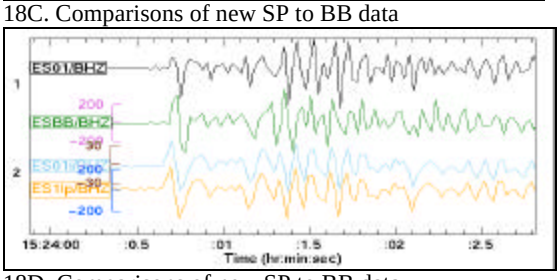
18A. Raw data, ES1lp is LP at 1.0 Hz



18B. First 15 seconds, note secondary arrivals.

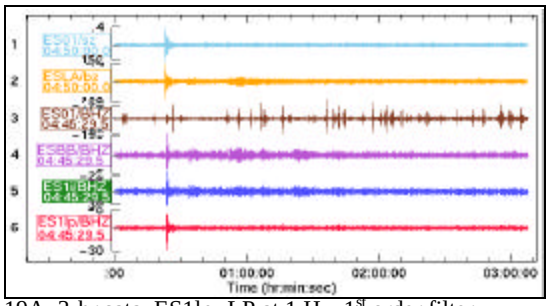


18C. Comparisons of new SP to BB data

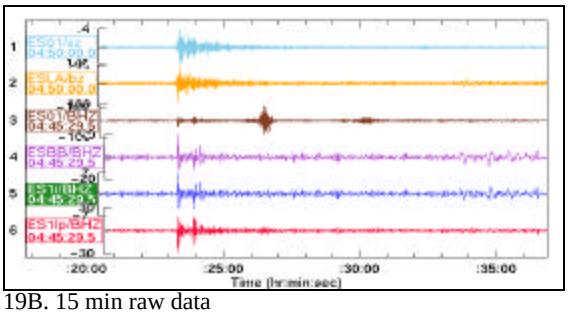


18D. Comparisons of new SP to BB data

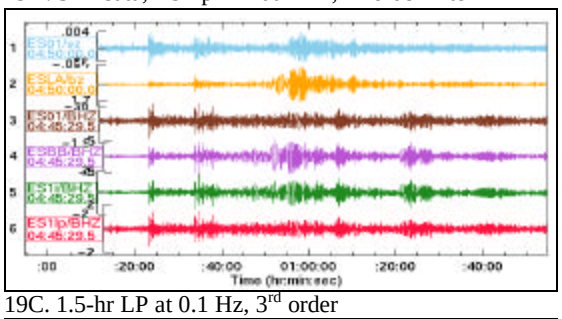
Figure 19 A-E, Comparison of Chile earthquakes, ES01/sz=old vel, ESLA/bz=KS54000 vel, ES01/BHZ=new acc,



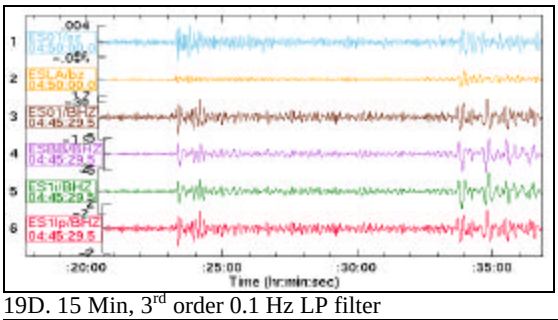
19A. 3-hr sata, ES1lp=LP at 1 Hz, 1st order filter



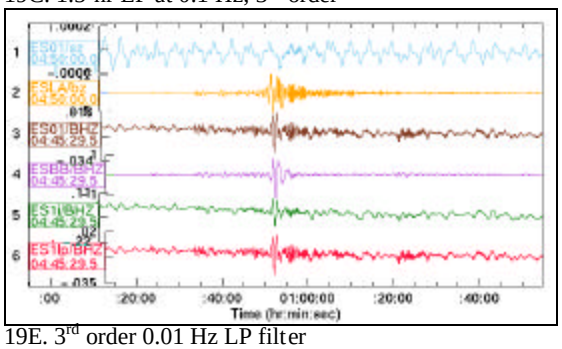
19B. 15 min raw data



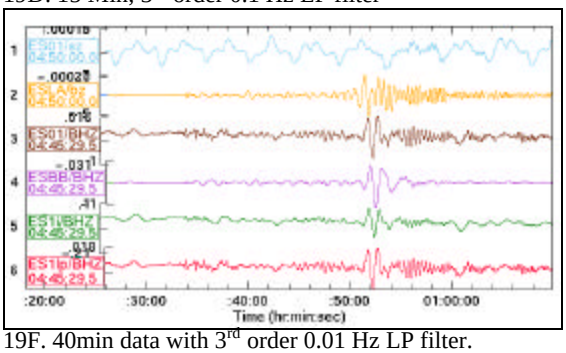
19C. 1.5-hr LP at 0.1 Hz, 3rd order



19D. 15 Min, 3rd order 0.1 Hz LP filter



19E. 3rd order 0.01 Hz LP filter



19F. 40min data with 3rd order 0.01 Hz LP filter.

LOCAL SITE EFFECTS AT THE NEVADA SEISMIC ARRAY (NVAR)

Eugene T. Herrin, Petru T. Negraru, Paul Golden, Carl Mulcahy

Southern Methodist University

Sponsored by Defense Threat Reduction Agency

Contract No. DTRA01-00-C-0093

ABSTRACT

In most cases array processing techniques are based on homogeneous structure assumptions, which is not always true. The output of a frequency-wave number analysis, based on the Fourier Transform, which is often used in processing raw data, will be strongly biased if all the stations do not have the same frequency content. In spite of the evidence that individual station corrections must be applied, corrections are not widely used. Often a simple relief correction is believed to account for all the local site effects.

The goal of this study is to present and, if possible, to explain the anomalous amplitude variations that are recorded at the Nevada Seismic Array (NVAR). Narrow-band frequency-dependent amplitudes were measured for both regional and teleseismic phases. Differences in source function (corner frequency) and attenuation account for the frequency content of different phases. Typically regional events allow observation from 0.5 to 16 Hz (0.5-1 Hz, 2-4 Hz, 4-8 Hz and 8-16 Hz) and teleseismic from 0.12 to 4 Hz (0.12-0.25 Hz, 0.25-0.5 Hz, 0.5-1 Hz, 1-2 Hz and 2-4 Hz). Although there are differences, particularly at high frequency, similar patterns are recognized for all phases. The most striking feature is the much larger amplitude exhibited by NV04 at frequencies 1-2 Hz and 2-4 Hz. Across the whole array, the variation in this frequency band can be higher than a factor of 8. The amplitude variation between NV04 and NV01, stations located only 500 meters apart can reach a factor of six. At higher frequency, 4-8 Hz and 8-16 Hz, NV09 dominates, its amplitude being occasionally more than one order of magnitude larger than the rest of the stations. No azimuth and distance dependence was found for these effects, which implies the absence of any organized dipping structure.

Taking advantage of the co-located seismic and experimental infrasound arrays, the seismic responses for propagating pressure waves were analyzed. The effects are larger, possibly because of the higher frequency (shorter wavelength) of the infrasound signals. The presence of the same amplitude effects leads to the conclusion that the structure responsible for these effects is shallow, being up to a few tens of meters.

To better understand the shallow structure, refraction profiles will be carried out in the field. Considering the depth of seismometer emplacement, true velocities can be obtained for the upper 12 meters using the short-period seismometer as a stationary receiver and moving the source further away from it, in a “walk-away” technique. In this way the presence of a low-velocity layer in the first 12 meters that may exist near site NV04 can be determined. It is desired to investigate the structure to a depth of 30 meters, the standard depth used by engineers to classify site characteristics.

OBJECTIVE

The objective of this study is to present and explain the effects that occur at the Nevada Seismic Array (NVAR) due to variations in the local geology. Common array processing techniques are based on homogeneous geological structure assumptions, which is clearly a simplification of the problem. In processing raw data the time-space domain is transformed in frequency-wave number domain by computing two-dimensional Fourier Transforms. The azimuth and phase velocity for the desired time window at the desired frequency are found by looking for the peak in power. Such an approach yields satisfactory results when the input time functions do not exhibit large spectral variations. This is usually the case in areas with uniform geological structure. Therefore, if an array exhibits large spectral variations, the outcome of f-k processing will be biased, and even the detection capability of the array could be lowered. At areas with large topographic variations, sometimes a simple relief correction is applied before processing, to account for the local site effects, but such an approach takes into account the topography rather than the geology.

RESEARCH ACCOMPLISHED

Berteussen (1974) was the first to observe and discuss amplitude variations at a seismic array. Explaining the travel-time anomalies recorded beneath several seismic arrays (NORSAR, LASA) in terms of scattering waves due to lower crust – upper mantle heterogeneities was the focus at the time. Additional papers were published discussing this subject (Aki, 1973; Capon 1974, Berteussen *et al* 1975; Berteussen 1975). More recently, the array calibration work has shifted toward experimental calibration (Tibuleac *et al*, 2001). A set of station corrections is developed empirically, to improve the location capabilities of the array. This approach yields better results, but it won't improve the detection capability for the whole array. Experience gained from the NORSAR array led to the installation of the small aperture NORESS array, which has a detection capability higher than NORSAR, for sources located close to the Semipalatinsk Test Site, although it was built at the location of one of the NORSAR subarrays.

The Nevada Seismic Array (NVAR) was installed in December 1998 by Southern Methodist University. The location of the array was chosen following negotiations between a team of experts from the USA and Russia. It was decided that one of the three-component stations would be located in the Black Butte mine, on the former setting of the station MNV (Mina, Nevada) for which historically recorded nuclear explosions exist (Figure 1). Although the array fulfills its mission very well, to provide coverage for the Nevada Test Site (NTS), the final location in a very

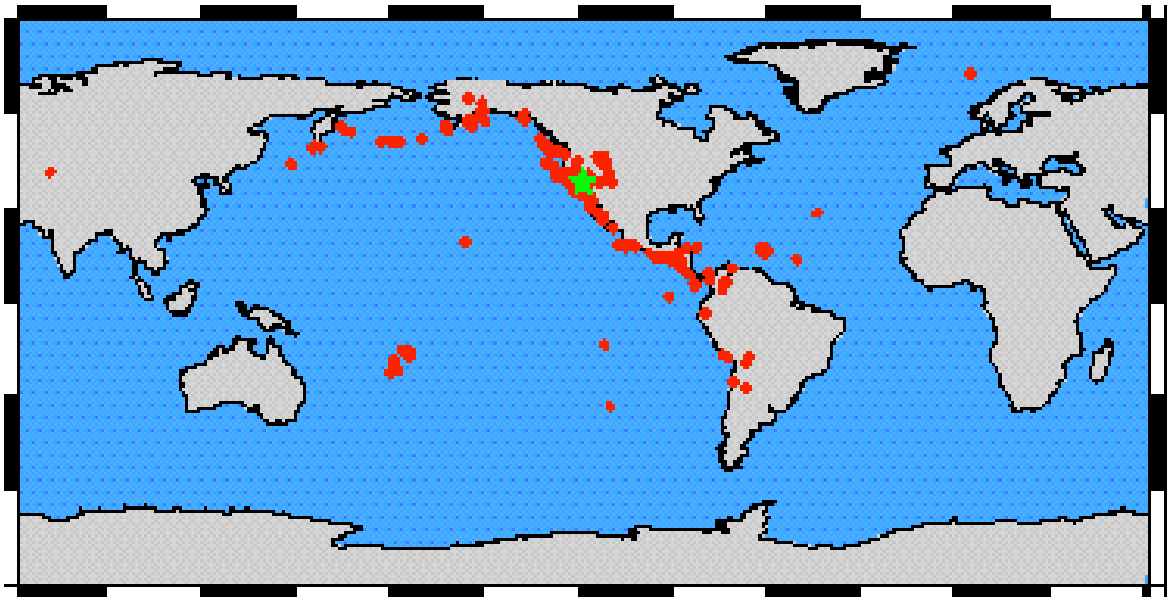


Figure 1. Position of earthquakes used in this study. The green star represents the location of the Nevada Seismic Array (NVAR)

complex geology led to unusual site effects, which raised the problem of determining an optimum array processing technique. The array consists of three broadband, three-component stations and ten short-period vertical stations. A weather station monitoring temperature, wind speed, wind direction, atmospheric pressure and relative humidity is located within the array. The present study is restricted only to the short-period stations, with the main focus on the inner ring of the array whose stations are co-located with an experimental infrasound array. More than half of the stations (stations NV01, NV02, NV03, NV05, NV06 and NV10) are located in the steeply dipping limestone of the Luning formation (Figure 2). These rocks were deposited during the late Triassic Period and can reach a thickness greater than 2 km close to the array. Site NV04 is located in lithified terrace gravels of Tertiary age. Site NV07 is located in the Dunlop formation, which comprises a very fine-grained sandstone, but the formation is variable within the region and can include shale and volcanic assemblages. Site NV09 is located in a Tertiary basalt flow, whereas site NV08 is sited in a Cretaceous granitic intrusive body.

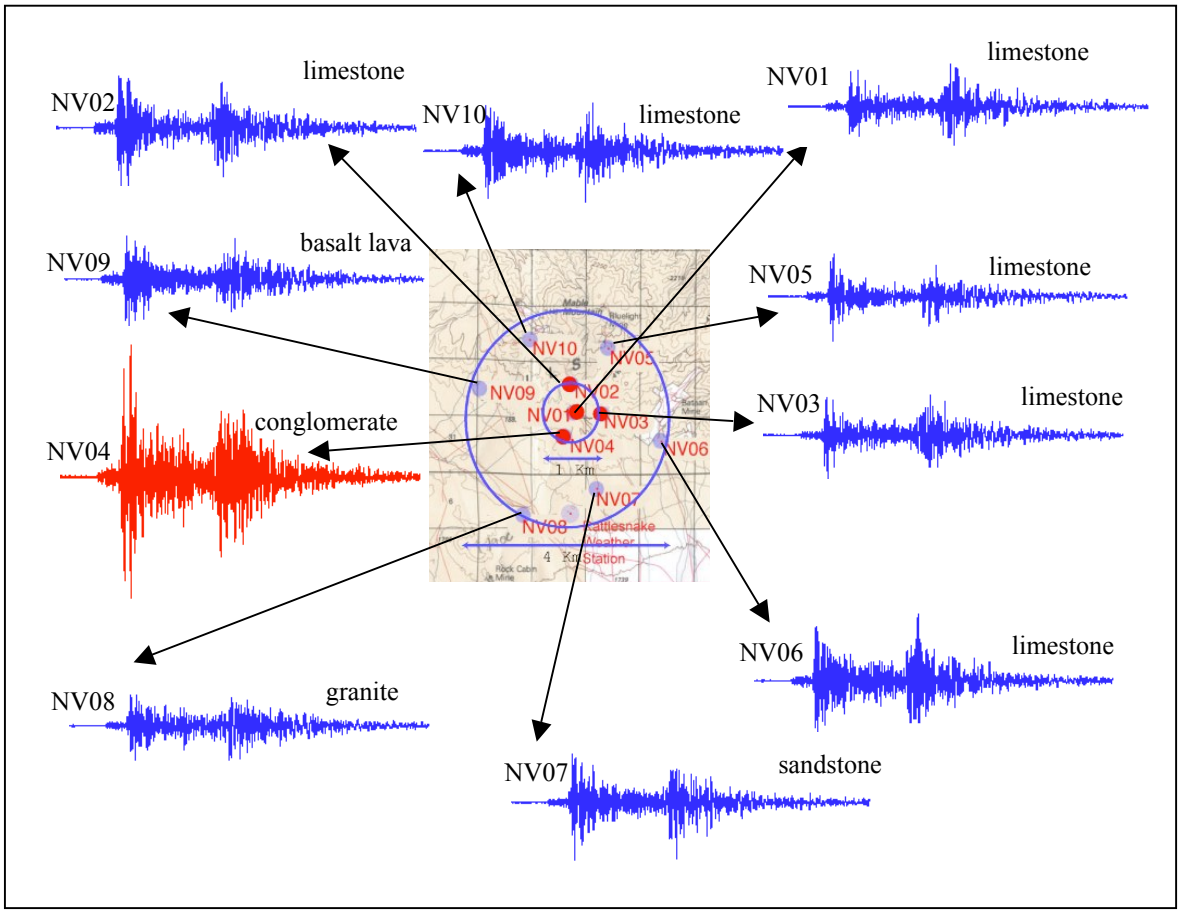


Figure 2. Detailed map of the NVAR array. The waveforms represent raw data recorded at NVAR at each of the short-period stations. The magnitude 5.7 earthquake occurred in California at a distance of 478 km. All the traces shown here are at the same scale. The red trace is channel NV04, located in Tertiary conglomerate, which exhibits the largest amplitude by a factor of three in this particular case.

To illustrate the local site effects encountered at NVAR, narrow-band frequency-peak accelerations were measured for both regional and teleseismic phases (Pn, Pg, Lg and teleseismic P). Although we desired observations in the same frequency band, variations in source functions and attenuation did not always allow this. In order to have a good signal-to-noise (SNR) ratio, most of the teleseismic earthquakes must have a magnitude higher than 5. Because the larger the earthquake, the lower the corner frequency, there is not too much energy above 4 Hz and secondly the high-frequency attenuation is much greater than at lower frequencies. Typically, teleseismic earthquakes, located at distances ranging from 24 to 90 degrees, allow observations from 0.12 to 4 Hz (0.12-0.25, 0.25-0.5, 0.5-1, 1-2 Hz) and regional events from 0.5 to 16 Hz (0.5-1, 1-2, 2-4, 4-8, 8-16 Hz).

In order to have a good azimuthal coverage, some earthquakes with lower magnitudes were included. The data consist of 75 teleseismic events and 213 regional earthquakes with magnitude between 3.5 and 7 (Figure 1). A fourth-order recursive Butterworth filter was applied for each frequency band, and the peak acceleration was measured from the envelope functions computed using Hilbert Transforms. In general the final results are relative to a particular channel, and thus most of the results will be equivalent for displacement, velocity and acceleration.

Taking advantage of the co-located seismic and experimental infrasound arrays, the seismic responses to propagating pressure waves were analyzed. The seismo-acoustic signals were detected by estimating the correlation coefficients at zero lag between seismic and acoustic envelope functions for a sliding 10-s window. Because the shorter the window, the higher the correlation coefficients for seismic and infrasound noise, a trade-off between window length and correlation threshold was achieved. The time length of most signals, which in general do not exceed a few seconds, was also taken into account. Empirically, the 10-s window and a detection threshold of 0.5 gave good results. Typically the noise for such a window length will have correlation coefficients below 0.3. Signals with good SNR have correlation coefficients above 0.5. The maximum correlation coefficient was 0.99, for a signal recorded on channel NV04. A detection was declared if there were correlation coefficients above 0.5 for at least three stations. Although this method works well for NVAR, it is not expected to work in the same way for all stations in the western US, but a similar approach can be used to make a detector at each particular array (or site). From 07/18/2001 to 08/30/2001 there were over 100 signals detected in this manner. Afterwards the amplitude was measured in the same way as the seismic signals, except that instead of peak acceleration, we calculated the root mean square value for the first three seconds of the signal. The bandpass filters used were similar to the filters used for regional events.

Background noise studies were also conducted. Ten-minute-long noise samples were chosen for different wind velocities. The sample was chosen so that the wind velocity had small variation during the time of interest. From every four-hour block, one time frame was chosen. The Welch Block Averaging method (Welch, 1967) was then applied to yield power spectral density estimates. The length of each data block was 512 points to constrain the individual estimates to frequencies greater than 0.1 Hertz. The individual blocks in each sample record were overlapped by 50 % and a Hanning window was used to reduce the variance of the power spectral density estimate.

CONCLUSIONS AND RECOMMENDATIONS

Figure 3 represents the spatial variations in ground motion peak acceleration for teleseismic P, Pn, Pg and Lg phases. Although there are differences, most notably at high frequencies, the patterns are very similar. The common feature for all analyzed phases is the much larger amplitude recorded at channel NV04 for frequency bands 1-2 Hz and 2-4 Hz. For stations NV01 and NV04, located only 500 m apart, the difference in peak acceleration can be as large as a factor of six. The largest difference across the whole array occurs usually for stations NV04 (largest amplitude) and NV05 (smallest amplitude), and could be higher than a factor of eight. At longer periods (0.12 – 0.25 Hz and 0.25 – 0.5 Hz), the signal is very similar, the variations being less than a factor of two. At higher frequencies (4 – 8 Hz and 8 –16 Hz), NV09 exhibits the largest amplitude, its peak acceleration being sometimes more than one order of magnitude larger than NV07.

No significant azimuthal or distance pattern has been found for this effect (Figure 4), which suggests the lack of any organized dipping structure. This conclusion is also supported by a previous calibration study (Tibuleac *et al*, 2001). This would suggest that the anomalous structure is flat to the first order.

The effects are larger for the pressure waves (Figure 5), possibly because of the higher frequency (shorter wavelength) of the infrasound signals. For approximately the same pressure levels, the variations in amplitude can be larger than a factor of 20. In general the amplitude recorded on the seismic channels for NV01 and NV03 are similar, which suggests the presence of the same physical properties beneath these two stations. NV04 always exhibits the largest amplitude and NV02, although located in the same geology as NV01 and NV03 can exhibit amplitudes larger than a factor of 10 when compared with NV02 and NV03.

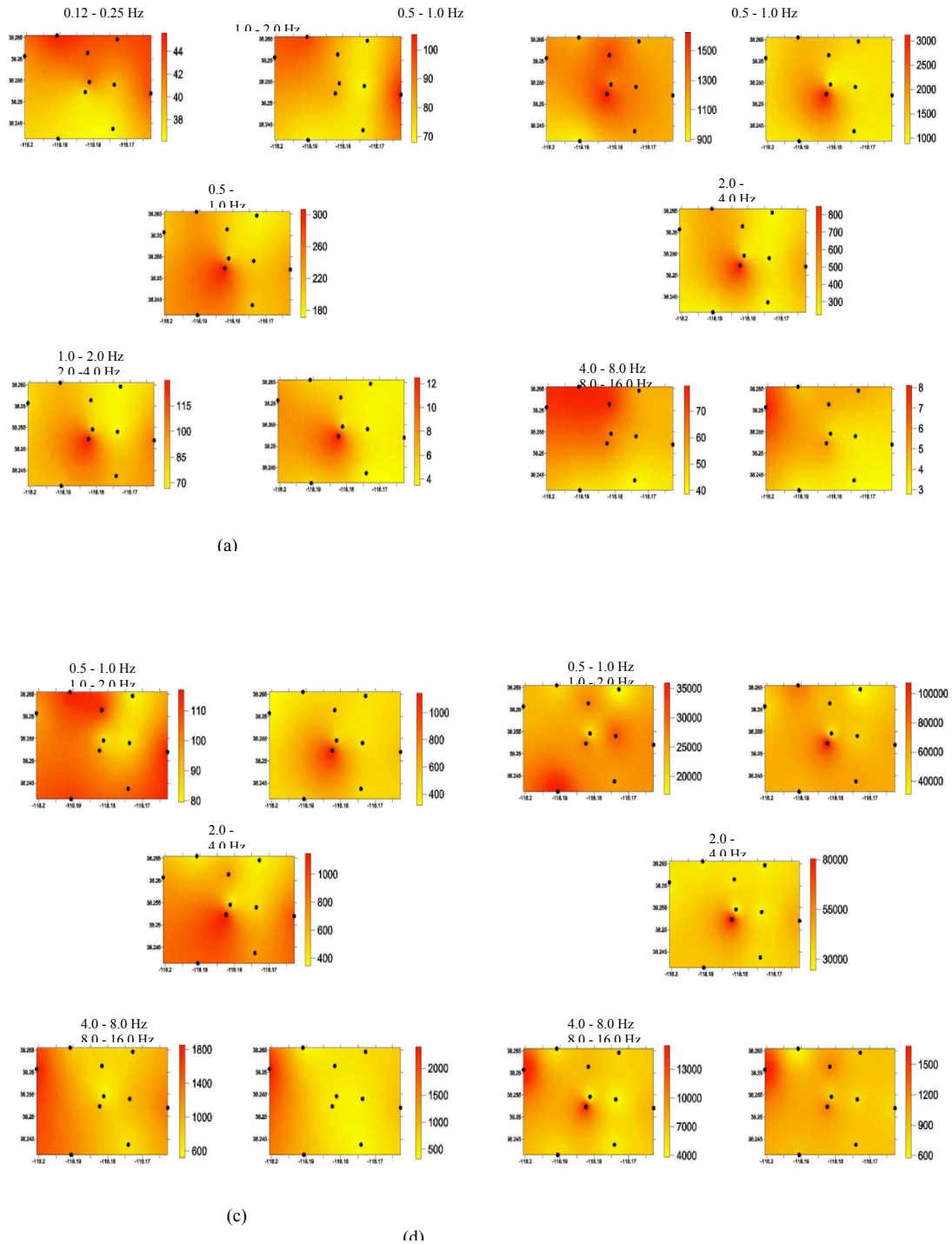


Figure 3. Spatial variations in ground motion peak acceleration of teleseismic P (a), Pn (b), Pg(c) and Lg (d). The black dots represent the position of each individual station. The units of the map are nm/s^2.

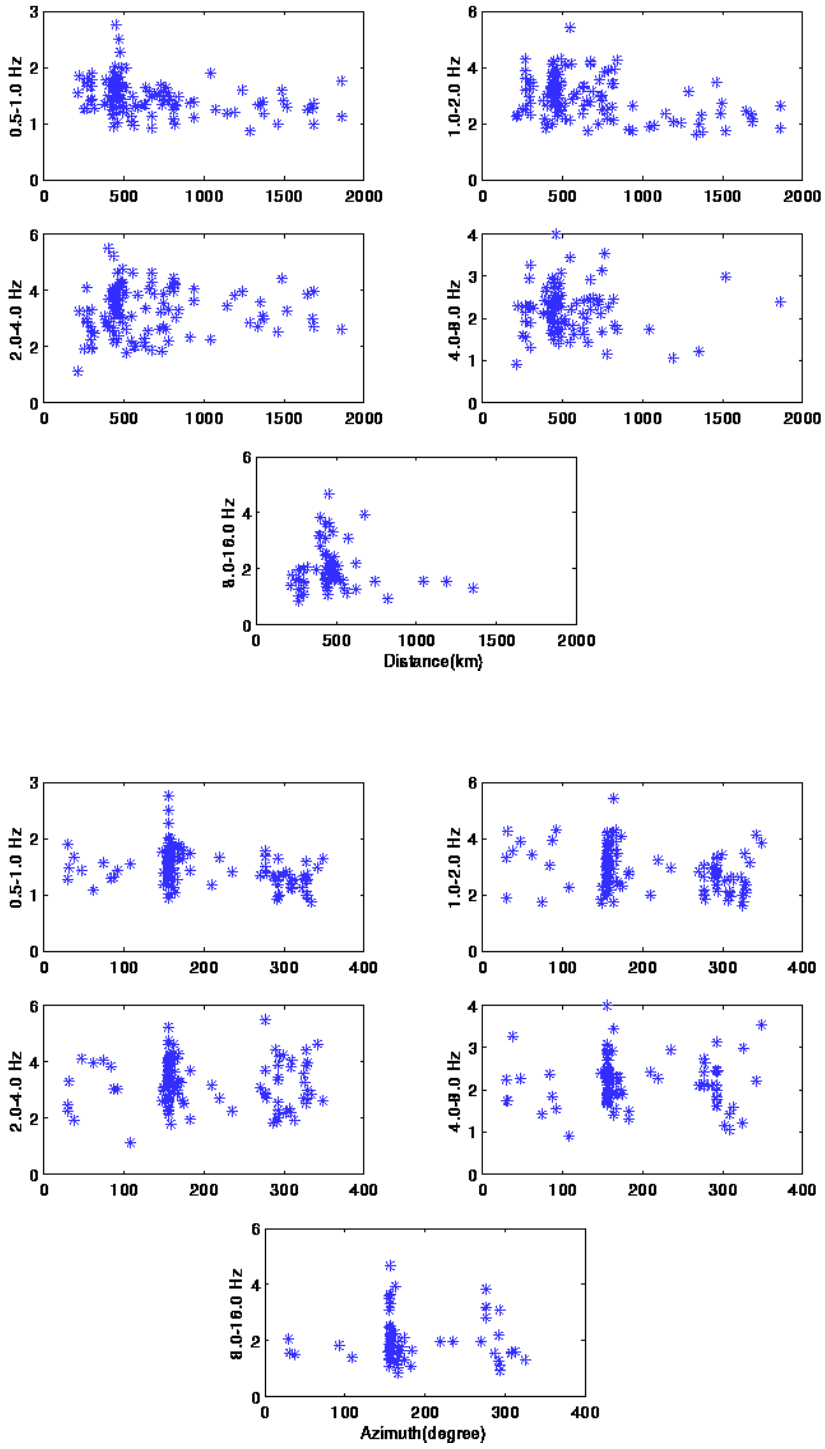


Figure 4. NV04/NV01 peak acceleration ratio for regional events. No pattern has been found as a function of distance (upper plot) or azimuth (lower plot). These two stations situated only 500 m apart exhibit variations as big as a factor of six in peak acceleration. The largest variation across the whole array for this set of events occurred for NV04 (largest acceleration) and NV05 (lowest acceleration) and was more than a factor of eight.

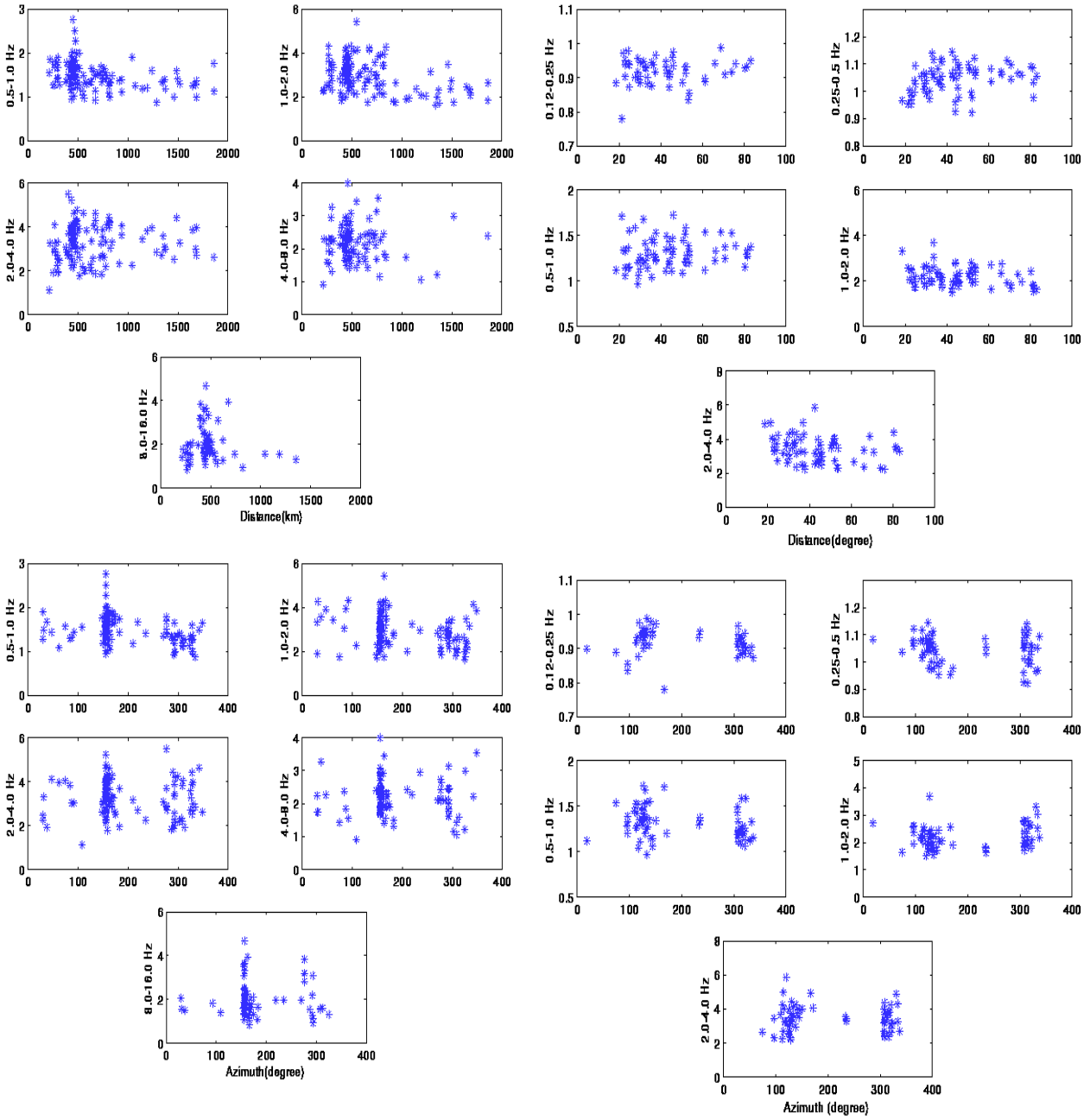
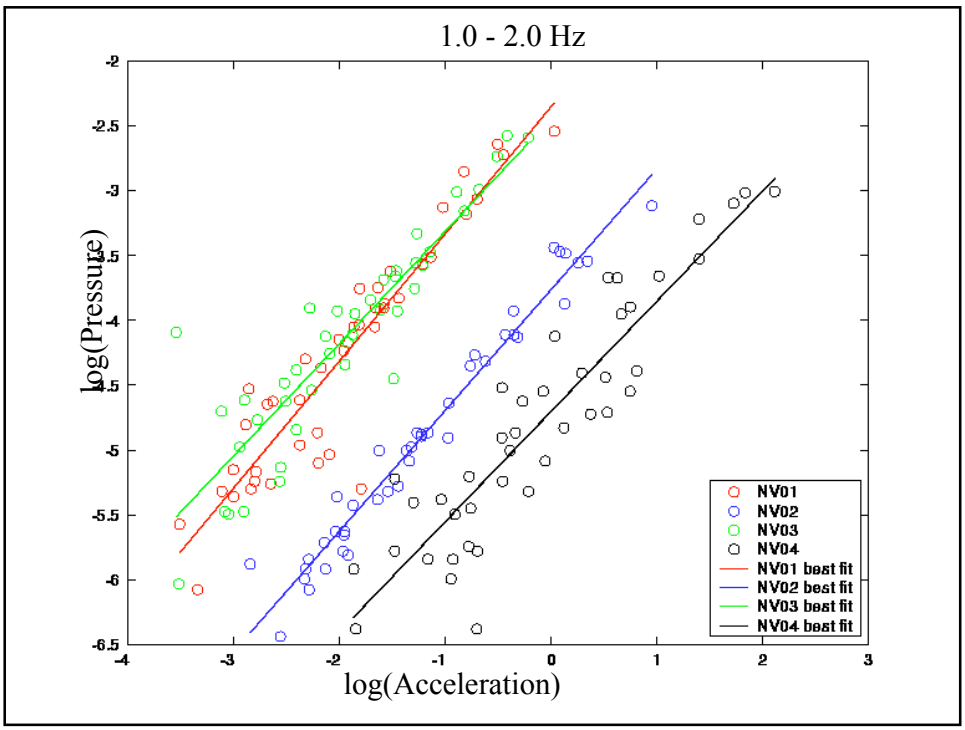


Figure 5. NV04/NV01 peak acceleration ratio for teleseismic events. The results are similar to the regional events. The maximum peak acceleration variations (for stations NV01 and NV04) is close to a factor of six, and the maximum variation across the whole array is close to a factor of eight



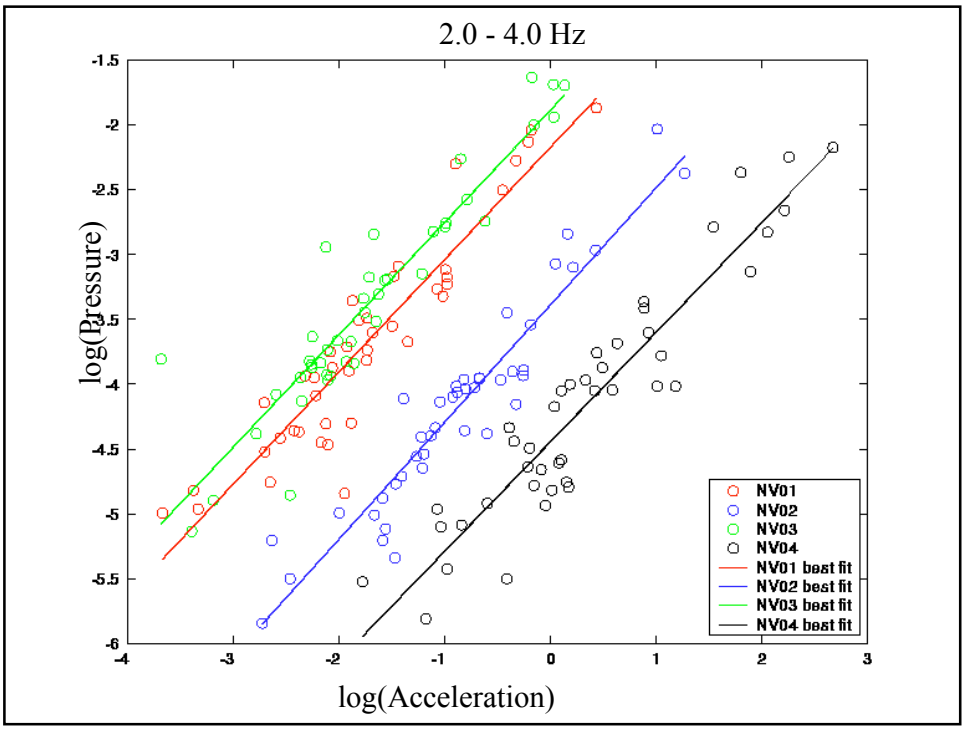


Figure 6. RMS Pressure versus RMS Acceleration for seismo-acoustic events. The data below 1 Hertz is contaminated by noise, and above 4 Hertz the response of the infrasound sensor hoses can further bias the measurements. The difference between NV01, NV03 and NV02 is likely to be due to the weathering effects. The difference between NV04 and the rest of the channels is due to the change in local geology. The Pressure Units are Pa; the acceleration units are nm/s^2.

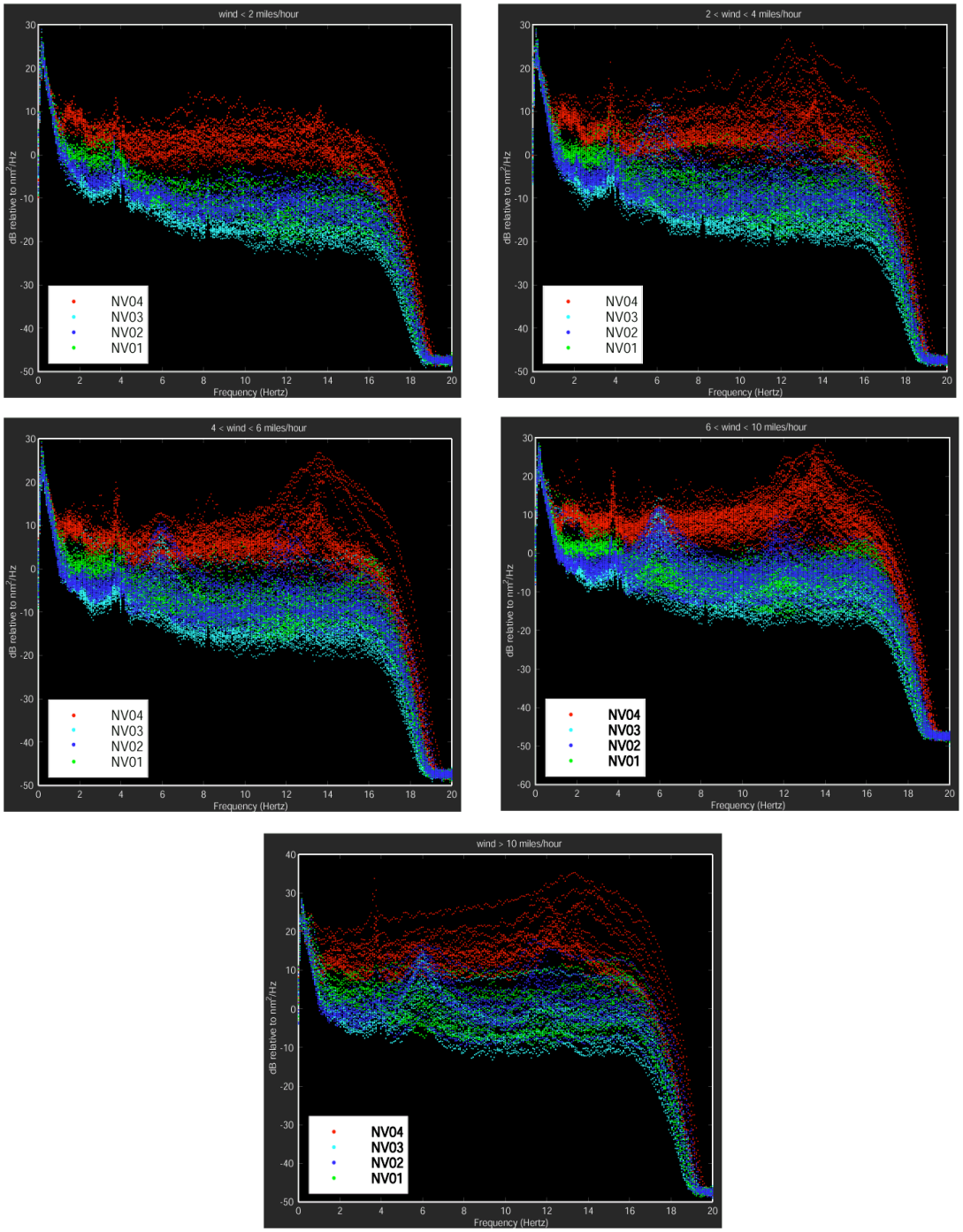


Figure 7. Power Spectrum Density Function for a suite of 160 noise samples. Here are shown only the elements of the inner array (NV01, NV02, NV03 and NV04). The wind velocities are: less than 2 miles/hour (upper plot left), 2-4 miles/hour (upper plot right), 4-6 miles/hour (middle plot left), 6-10 miles/hour (middle plot right), above 10 miles /hour (lower plot).

These effects are not related to or influenced by atmospheric noise. The noise analyses (Figure 7) show that the atmospheric noise is more important at frequencies above 1 Hz. The median noise difference for NV04 and NV01 between the peak at around 6 Hz exhibited by NV01 and the peak at around 14 Hz exhibited by NV04 is approximately constant and is around 10 dB, regardless of wind strength. The maximum difference can reach 25 dB. At 1 Hz the median difference is 5 dB. The broad peaks that appear around 14 Hz (for NV04) and around 6 Hz (for NV03 and NV01) represent the combined effect of geology and topography.

To fully understand the geological structure responsible for these site effects refraction profiles will be carried out in the field. Taking advantage of the depth of the seismometers, true velocities can be obtained for the upper 40 feet using the seismometer as a static receiver and moving the source away from it in a "walk-away" technique. In this way the presence of a low-velocity layer that may exist near site NV04 can be detected. Additionally, shear velocity refraction profiles might be necessary because of the complicated geology. It is desired to investigate the structure to a depth of at least 30 m, the standard depth used by engineers to classify site characteristics.

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SEISMIC DATA ACQUISITION SYSTEM (SDAS) COMPONENT EVALUATION

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ABSTRACT

Sandia National Laboratories has tested and evaluated the Geotech DB24 Remote Digitizer and SAIC SAN2000B Authenticator/Formatter as components of the AFTAC Sensor Site Subsystem (SSS) of the Seismic Data Acquisition System (SDAS).

Geotech DB24 tests included response to static and dynamic input signals, data time-tag accuracy and seismic application performance. Configurations tested include:

DB24	3 Channel	40 Samples per second	Geotech KS54000 Broadband Seismometer Gain
DB24	3 Channel	4 Samples per second	Geotech KS54000 Long-Period Seismometer Gain
DB24	1 Channel	20 Samples per second	Geotech 23900 Seismometer Gain

A subset of component tests was performed on multiple Sensor Site Subsystems.

The SDAS equipment is proposed for some stations that may be part of the International Monitoring System (IMS). In these cases, IMS data surety requirements and guidelines must be met for station certification. SAIC SAN2000B data surety was tested to verify correct operation in the station environment and ensure data surety requirements are met. These tests included data authentication (CD-1.1 format), intrusion monitoring, remote command authentication, and remote key management operations.

This paper describes the evaluation of the SDAS digitizer, authenticator/formatter components and performance within the subsystem.

OBJECTIVES

Introduction

The Air Force Technical Applications Center (AFTAC) is tasked with monitoring compliance of existing and future nuclear test treaties. To perform this mission, AFTAC uses several different monitoring techniques to sense and monitor nuclear explosions, each designed to monitor a specific physical domain (e.g. space, atmosphere, underground, oceans, etc.). Together these monitoring systems, equipment and methods form the United States Atomic Energy Detection System (USAEDS). The Seismic Data Acquisition System (SDAS) is part of the USAEDS program. Some USAEDS seismic stations may be included in the International Monitoring System (IMS).

Sandia National Laboratories has tested and evaluated the Geotech DB24 Remote Digitizer and SAIC SAN2000B Authenticator/Formatter as components of the AFTAC Sensor Site Subsystem (SSS) of the SDAS.

Evaluations Performed

Sandia evaluated the overall technical performance of the Geotech DB24 remote digitizer component of the AFTAC SDAS. Distortions introduced by the high-resolution digitizers were measured. Sandia also evaluated the performance of the Geotech DB24 remote digitizer as a component installed in the SSS of the AFTAC SDAS. The additional distortions and noise introduced into the DB24 by the SSS were measured. The results of these evaluations can be compared to relevant AFTAC SDAS and IMS application requirements or specifications.

Sandia evaluated the data surety performance of the AFTAC SDAS for data authentication, command authentication, key management operations, and intrusion monitoring. These tests are intended to verify correct operation of the SAIC SAN2000B Authenticator/Formatter component and the Operation and Maintenance Subsystem (OMS) in an IMS station environment.

RESEARCH ACCOMPLISHED

Geotech DB24 Remote Digitizer

The DB24 borehole remote digitizer was built by Geotech Instruments, LLC, Dallas, TX. Geotech provided 'dsutil' data acquisition software for the DB24 digitizer. It operated on a PC Workstation under Windows 2000 and communicated with the DB24 through a direct-connect serial connection. Data were acquired in real-time in CSS 3.0 flat-file records. GPS was provided to the DB24 using a SAIC GPS/splitter.

Testing was performed at Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) Site (Figure 1).

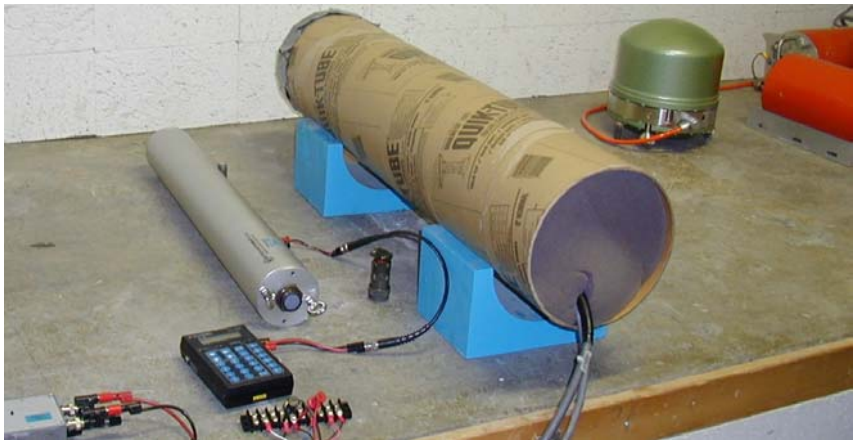

Figure 1. DB24 Testing at FACT Site

Three configurations of the DB24 were tested:

1. DB24, 3-Channel, 40 Samples per Second, Geotech KS54000 Broadband Seismometer Gain [1]
2. DB24, 3-Channel, 4 Samples per Second, Geotech KS54000 Long-Period Seismometer Gain [2]
3. DB24, 1-Channel, 20 Samples per second, Geotech 23900 Short-Period Seismometer Gain [3]

DB24 Digitizer Performance Tests and Results

The following tests were conducted on the DB24. This is a subset of tests as outlined in the Sandia Ground-based Monitoring R and E Technology Report [4].

Static Performance Tests

Input Terminated Noise (ITN) Test: Measure the Input Terminated Noise of the DB24.

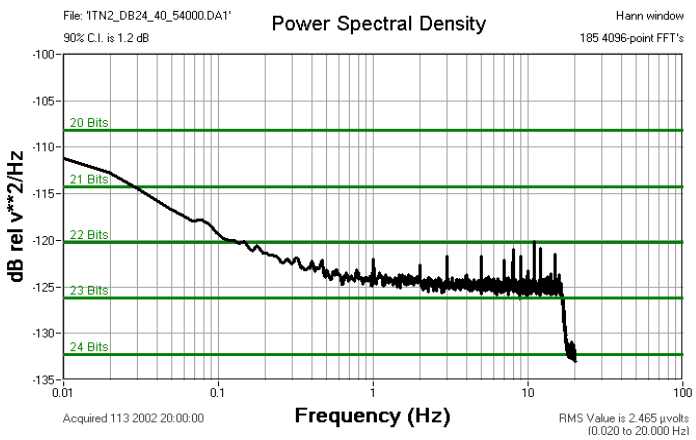

Figure 2. DB24 Channel 1 Input Terminated Noise with Integer Hz Peaks

ITN Test Results: Figure 2 indicates that the DB24 has < 0.7 count RMS noise and integer hertz spurious peaks. There is very little power in these peaks.

Maximum Potential Dynamic Range (MPDR) Test: Compute Maximum Potential Dynamic Range using data from the ITN Test.

Table 1. DB24 Channel 1-3 MPDR

Channel	RMS Noise µV 0.02 to 20 Hz	RMS Full-Scale Volts	MPDR
1	2.465	14.14	135.2 dB
2	2.474	14.14	135.1 dB
3	2.570	14.14	134.8 dB

MPDR Test Results: Table 1 indicates that the DB24 Maximum Potential Dynamic Range is greater than 134.8 dB.

Tonal Dynamic Performance Tests

Total Harmonic Distortion (THD) Test: Measure the linearity of the DB24 digitizers using Total Harmonic Distortion.

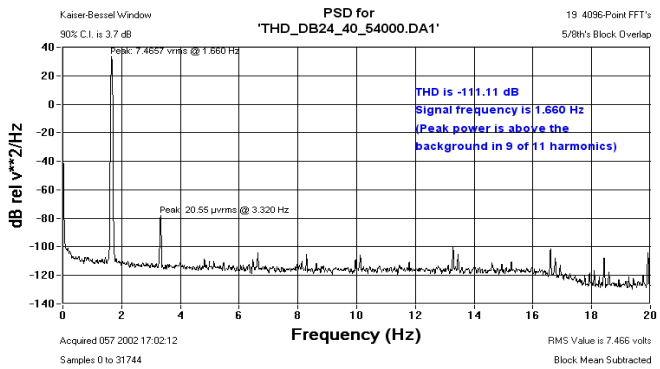

Figure 3. DB24 Channel 1 Total Harmonic Distortion

Table 2. DB24 Channel 1-3 THD

Channel	THD
1	111.11 dB
2	109.09 dB
3	109.88 dB

THD Test Results: Figure 3 and Table 3 indicate that the DB24 Total Harmonic Distortion is better than -109 dB.

Crosstalk (CTK) Test: Measure the amount of digitizer channel-to-channel crosstalk.

Table 3. DB24 Channel 1-3 Crosstalk

Channel	RMS Input	RMS Crosstalk	Crosstalk
1	4.96 V	0.51 µV	-139.8 dB
2	4.94 V	0.61 µV	-138.2 dB
3	4.92 V	0.47 µV	-140.4 dB

CTK Test Results: Table 4 indicates that the DB24 crosstalk is better than –138 dB.

Common Mode Rejection ratio (CMR) Test: Measure the ability of the digitizer to reject common-mode signals.

Table 4. DB24 Channel 1-3 Common Mode Rejection

Channel	Peak Input	Peak Common-mode	CMRR
1	10.0 V	0.512 mV	85.8 dB
2	10.0 V	0.937 mV	80.6 dB
3	10.0 V	0.197 mV	94.1 dB

CMR Test Results: Table 5 indicates that the DB24 CMR is better than –80 dB at 1 Hz.

Broadband Dynamic Performance Tests

Modified Noise Power Ratio (MNPR) Test: Determine DB24 performance using broadband signals.

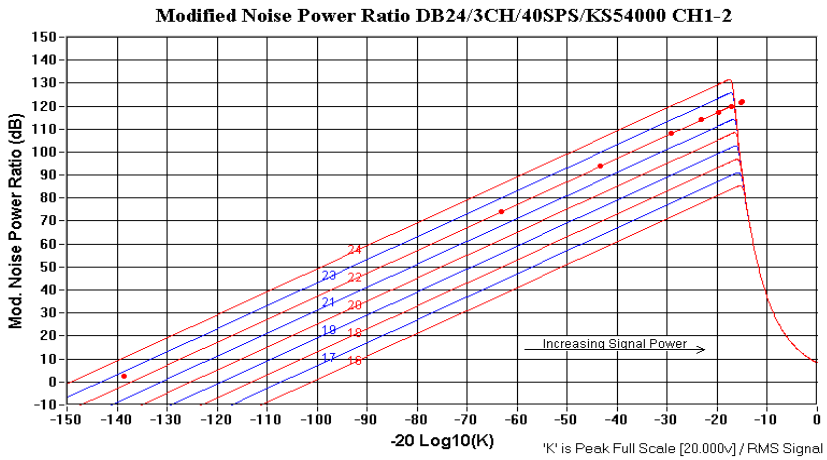

Figure 4. DB24 Channel 1-2 Modified Noise Power Ratio

MNPR Test Results: Figure 4 indicates that the DB24 has 22-bit performance using broadband signals.

Seismic Application Tests

Seismic System Noise (SSN) Test: Determine ability of the DB24 to resolve the expected seismic background using a KS54000 seismometer.

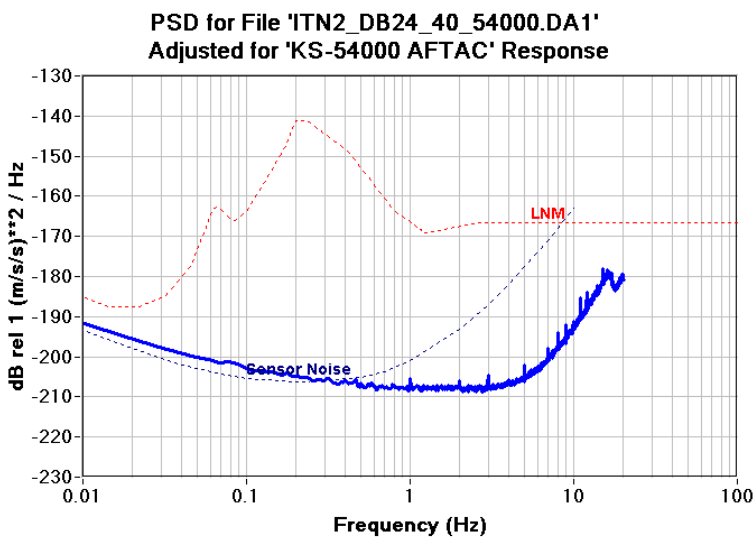

Figure 5. DB24 CH1 Seismic System Noise

SSN Test Result: Figure 5 indicates that the noise of the DB24 digitizer was at least 8 dB below the USGS New Low Earth Noise Model (NLNM) between 0.02 and 16 Hz when used with a Geotech KS54000 seismometer.

Sensor Site Subsystem - Geotech DB24 Remote Digitizer

SSS Testing was performed at the Pinedale Seismic Research Facility (PSRF) (Figure 6).

Figure 6. SSS Testing at PSRF

Three configurations of the DB24 were tested at PSRF:

1. DB24, 3-Channel, 40 Samples per Second, Geotech KS54000 Broadband Seismometer Gain [4]
2. DB24, 3-Channel, 4 Samples per Second, Geotech KS54000 Long-Period Seismometer Gain [4]
3. DB24, 1-Channel, 20 Samples per second, Geotech 23900 Short-Period Seismometer Gain [4]

Input Terminated Noise (ITN) Test: Measure SSS Input Terminated Noise on broadband DB24. Compare to FACT ITN Test.

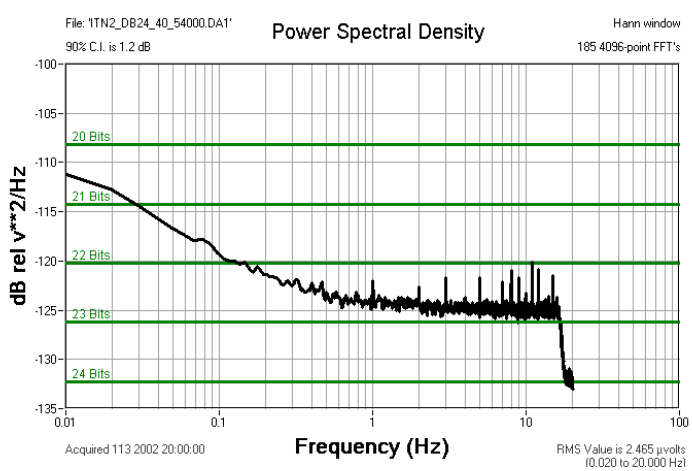

Figure 7. FACT Broadband DB24 Channel 1 Input Terminated Noise with Integer Hz Peaks

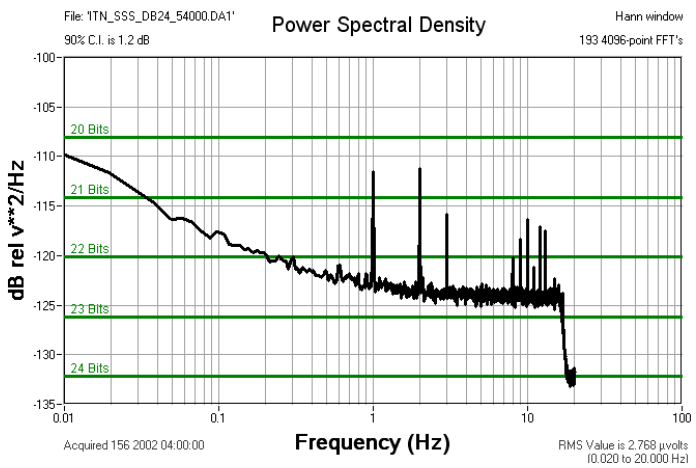

Figure 8. PSRF SSS Broadband DB24 Channel 1 Input Terminated Noise with Integer Hz Peaks

ITN Test Results: Figures 7-8 indicate that DB24 ITN testing at FACT showed < 0.7 count RMS noise with moderate integer hertz spurious peaks. SSS DB24 ITN testing at PSRF showed < 0.75 count RMS noise with increased integer hertz spurious peaks.

Input Terminated Noise (ITN) Test: Measure SSS Input Terminated Noise on short-period DB24. Compare to FACT Test.

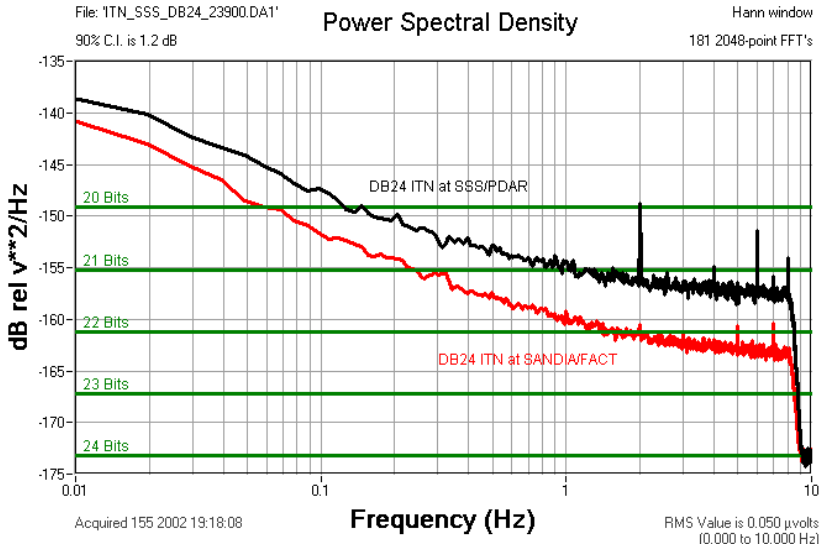

Figure 9. FACT and PSRF Short-period DB24 Channel 1 Input Terminated Noise

ITN Test Results: Figure 9 indicates that DB24 ITN testing at FACT showed < 0.95 count RMS noise with low integer hertz spurious peaks. SSS DB24 ITN testing at PSRF showed increased noise < 1.77 count RMS with increased integer hertz spurious peaks.

SDAS Data Surety

Data Surety Requirements

The PTS has developed requirements to ensure that data from IMS stations is reliable and authentic. These requirements cover data surety aspects of the station, including data authentication, command authentication, key management operations, and intrusion monitoring. Our tests are intended to verify correct operation of the SDAS equipment in an IMS station environment. IMS station data surety requirements, summarized from PTS documents [6], are listed here.

1. All IMS data must be signed at the sensor sites.
2. Data must be digitized and signed within a secure (tamper-detecting) environment.
3. Signature must be calculated within a dedicated, tamper-indicating hardware authentication device.
4. Data must be formatted for signing as specified by an approved protocol.
5. DSS (DSA with SHA-1) must be used with 1024-bit public key.
6. Signature device must generate DSA keys internally.
7. Signature device must provide public key components to user.
8. Signature device must not disclose private key directly to user or leak private key during operation.
9. Commands originating remote from the station must be signed by the originator and verified at the station.
10. A remote key change command must be supported for each authentication device; the authentication device must securely generate a new key pair and securely transmit the new public key.

The PTS strongly recommends that a PC Card device certified to FIPS 140-1 Level 2 be used for DSA operations and private key storage.

Test Configuration

The testing of the SDAS equipment described here was performed during May and June 2002. The following test environment was assembled at the Sandia National Laboratories FACT site (Figure 10, 11).

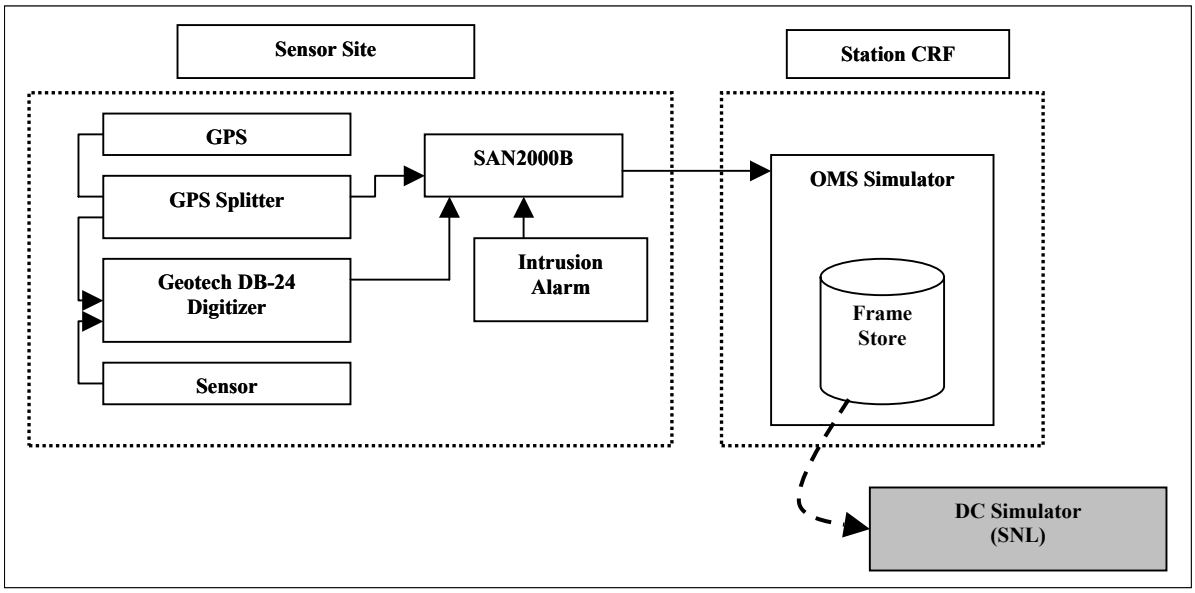

Figure 10. FACT Site Test Configuration

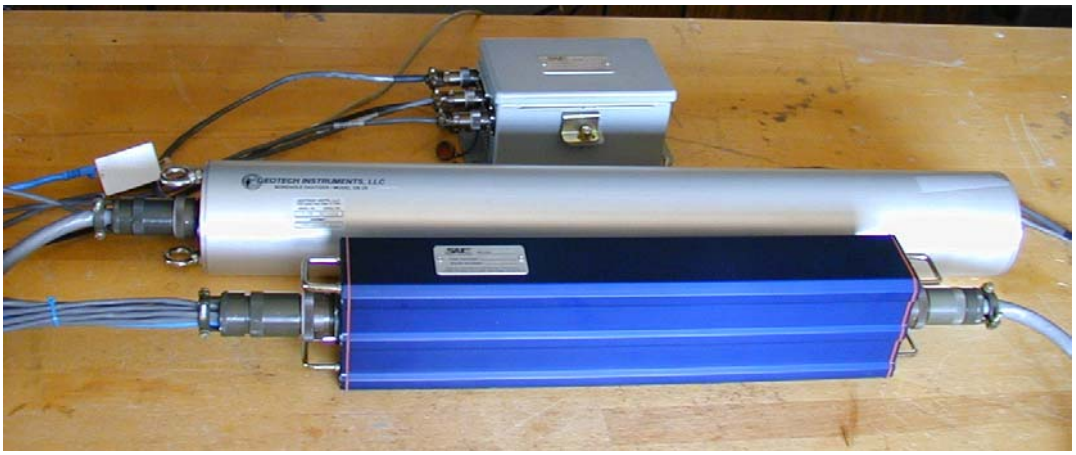

Figure 11. FACT Site Test Configuration

The DC Simulator is a computer at Sandia National Laboratories configured with software to parse the SAIC Frame Store files (the *saic_rip* program). It displays the CD-1.1 format data in a human-readable format, checks the validity of the format, and verifies authentication signatures using the *authd* program. The Station CRF is a Sun Ultra 60. Frame Store files were built on the Station CRF then manually transferred to the DC Simulator using FTP. The SAN2000B and Station CRF were connected on a 10BaseT LAN.

Data Surety Tests and Results

System Design Review Test: Determine that the SAN2000B and OMS, as part of the SDAS station environment, are designed to meet IMS surety guidelines; that system security, data authentication, and command authentication are incorporated in the equipment design and meet minimal criteria.

Test Results: The evaluation of the overall data surety of the station has not been completed. Additional system documentation is needed that describes which components sign, store, and exchange data, how commands are received, verified, and processed, how authentication keys are generated, signed, and distributed, and the physical security of the hardware components.

Data Authentication Test: Determine that the SAN2000B correctly calculates DSA signatures for sensor data in CD-1.1 format; that the station equipment transmits signed data that can be verified using the public key retrieved from the station.

Test Result: CD-1.1 data frames were successfully retrieved and parsed from the SAN2000B. The frames included the correct configuration, status information and were signed correctly. Data signatures were correctly verified using the public key retrieved from the SAN2000B. The SAN2000B has an internal Fortezza card for signature generation and public key protection. The Fortezza card is certified to FIPS 140-1 Level 2, and meets IMS guidelines for security of authentication operations. It has not yet been verified that the Fortezza card is used securely within the SAN2000B.

Intrusion Monitoring Test: Determine that intrusion detection hardware is monitored correctly by the SAN2000B; that the SAN2000B sets the appropriate intrusion flags in the signed data; that the data transmitted from the station has these flags set correctly.

Test Results: The SAN2000B correctly monitored opening of its own enclosure. External intrusion monitoring (vault/wellhead open alarm) could not be tested at the FACT Site with the hardware supplied to date. Procedures are in development to allow access to the external intrusion alarm inputs.

Remote Key Change Command Test: Determine that the key change operation works correctly on the SAN2000B and OMS.

Test Results: It was determined that the SAN2000B will generate a new key pair on command, then start to use the new key on a second command. This was tested by entering commands directly to the SAN, which uses test-mode software in the SAN. A software bug was discovered and has been reported to be fixed. It was also discovered that the key change operation is performed differently when requested from operator software on the OMS workstation. This additional OMS software is needed to test the key change operation in the station environment.

Remote Command Authentication Test: Determine that all commands issued remote from the station are signed at the remote location and verified at the station.

Test Results: SDAS command authentication has not yet been evaluated. Additional software and documentation is needed to test this function.

CONCLUSIONS AND RECOMMENDATIONS

DB24 Digitizer Performance Tests

The DB24 digitizer performed at the 21 to 22 bit performance levels depending on seismometer gain and sample rate. The moderate amount of integer Hertz noise was identified at low levels that will not be seen above the seismic background. It is recommended that the source of these spurious peaks be determined and removed if possible.

The DB24 amplifier configuration for 23900 seismometer application may be insufficient for quiet sites. It is recommended that a DB24 amplifier be developed for quiet site applications.

Data Surety Tests

At the time of this writing, several data surety tests have not been completed. Data authentication performance is acceptable, but command authentication, key management operations, system security, and intrusion monitoring require further evaluation. Additional hardware, software, and documentation are needed to complete the evaluation. We expect to receive these items soon and complete testing of the data surety of the SDAS by October 2002.

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