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

Michael Hasting and Sergio Barrientos

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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.

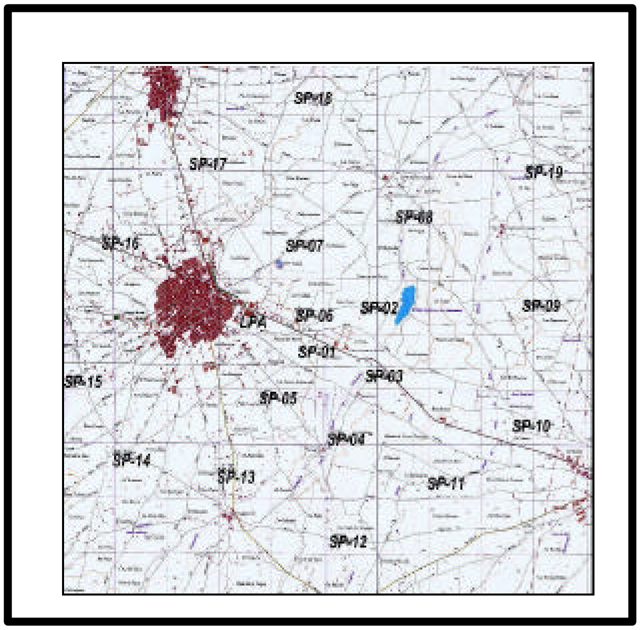


Figure 1. Map of PS40 Array showing the location of array elements and proximity of Sonseca, SP01=ES01.

Figure 2. GCI Dish installed on side of CRF.

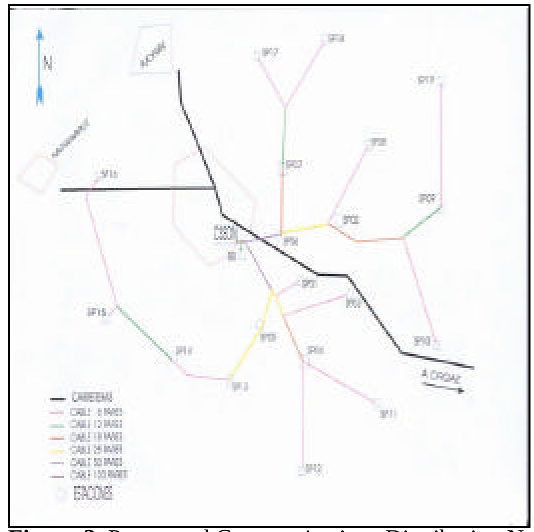


Figure 3, Power and Communications Distribution Network.

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.

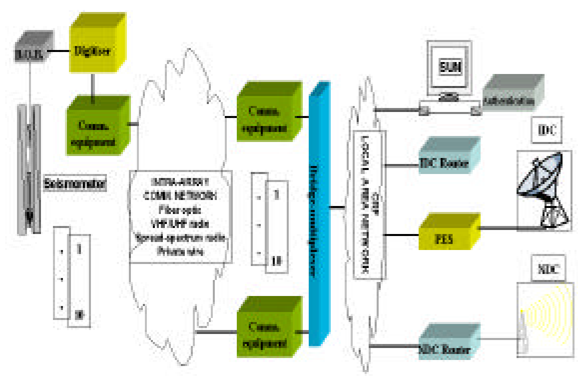


Figure 9. Block diagram of major components of the array.

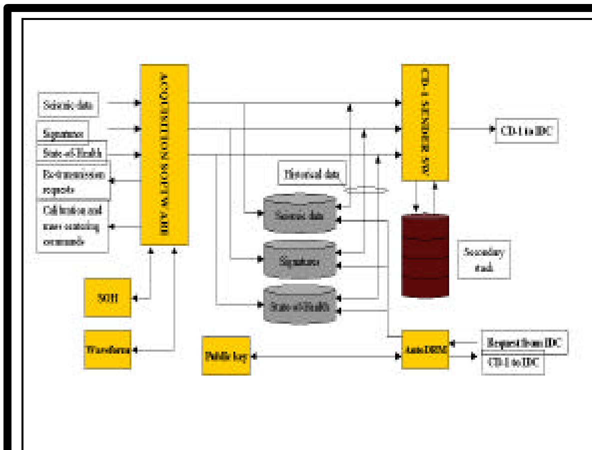


Figure 10. Data flow diagram of NAQSServer.

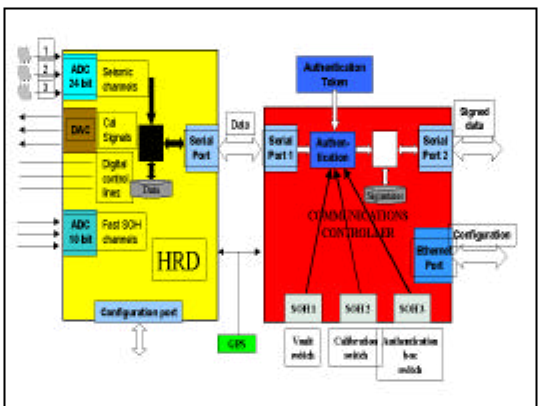


Figure 7. Internal data flow of the new digitizer.

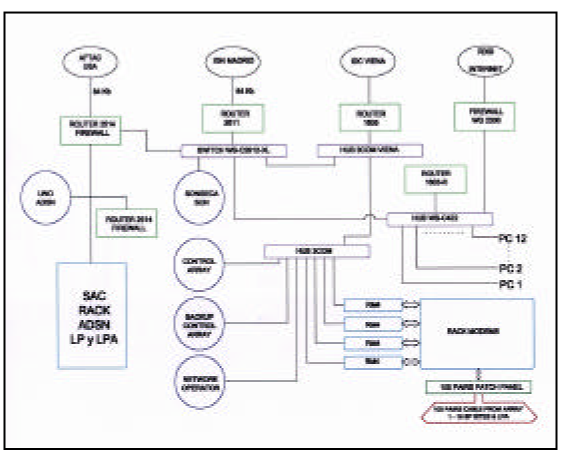


Figure 8. CRF equipment inter-connection showing new equipment configuration and physical connections. Flow to AFTAC still has LP elements going to them.

Figure 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

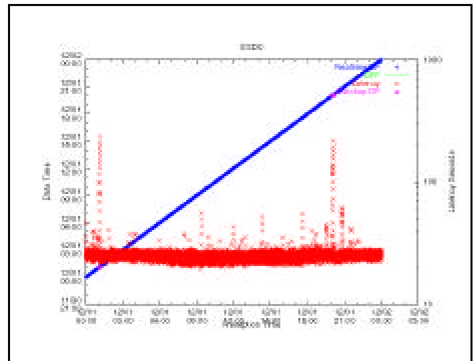
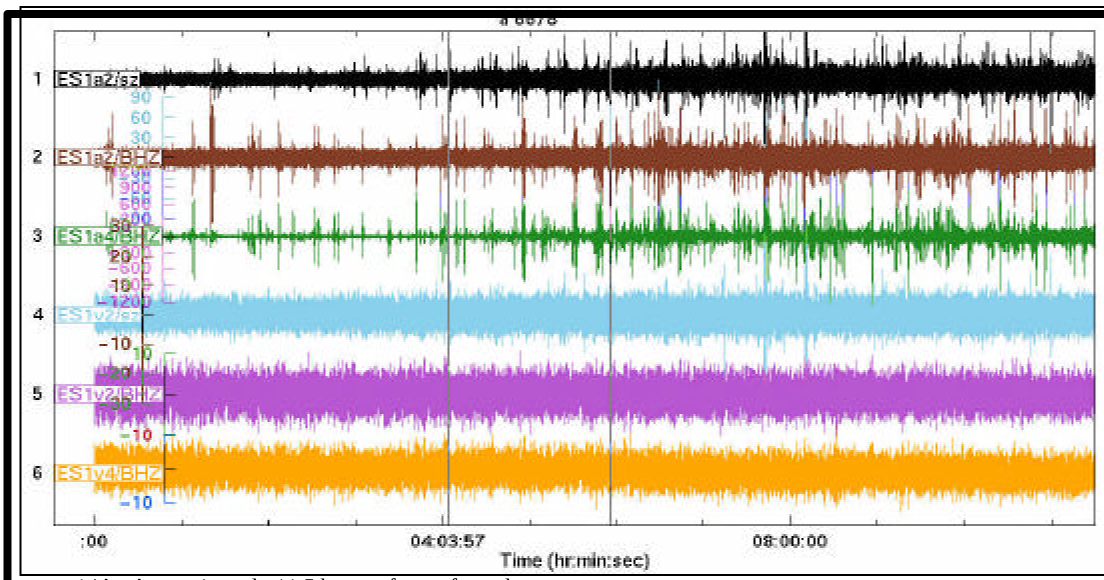
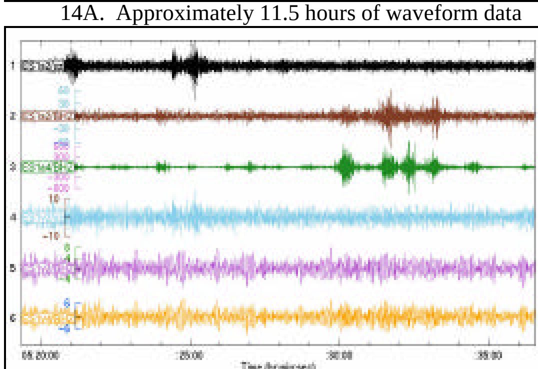


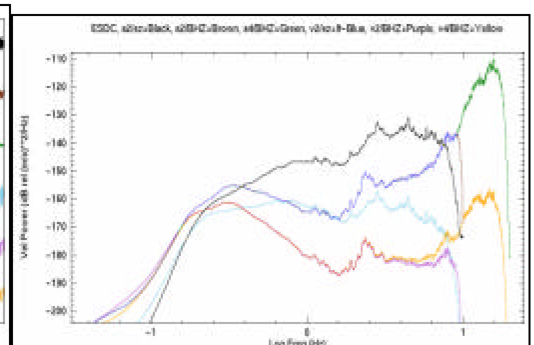
Figure 13. Plot of Received CD1 Frames, Y1=time that the data was recorded, X=time frame was received by IDC, Y2=log of latency time. Blue line plots the "Realtime" frames, red X is the difference of the X-Y1 times.



14A. Approximately 11.5 hours of waveform data



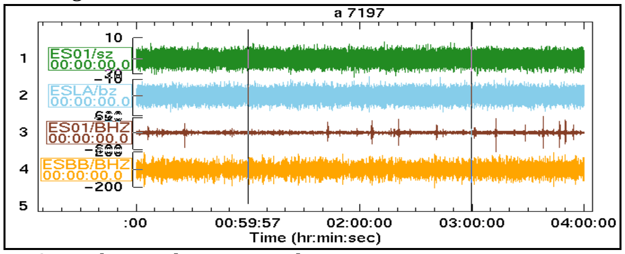
14B, Approximately 45 minutes of waveform data



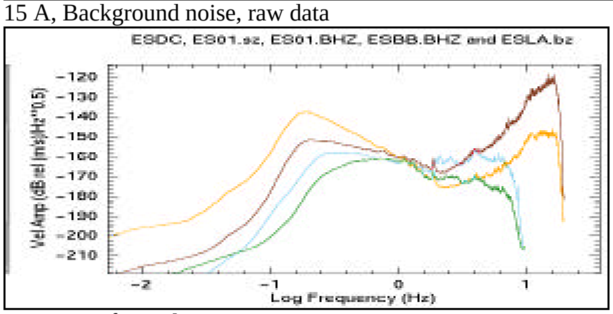
14C, FT plot of data between lines in 14A, no correction for instrument response.

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.

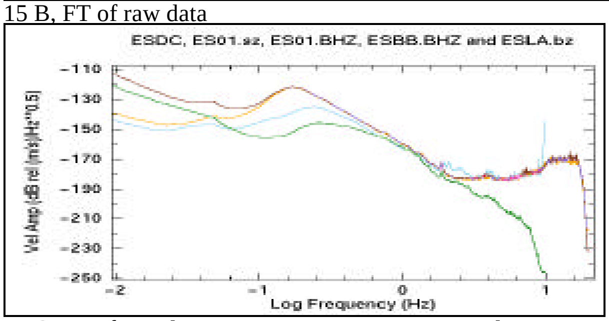
Figures 15 A-D



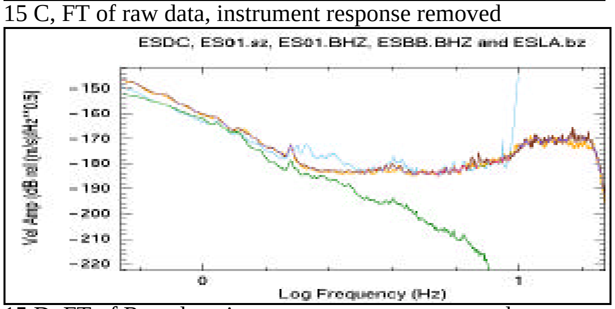
15 A, Background noise, raw data



15 B, FT of raw data

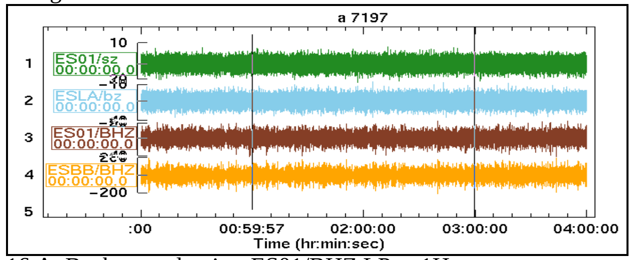


15 C, FT of raw data, instrument response removed

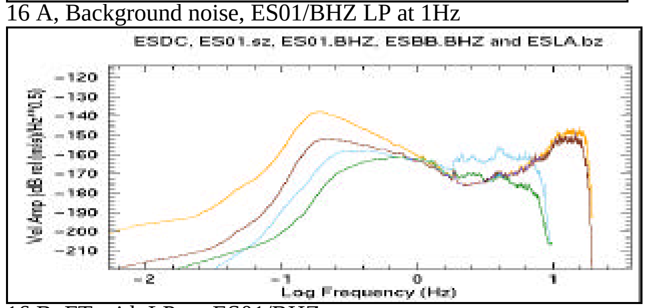


15 D, FT of Raw data, instrument response removed

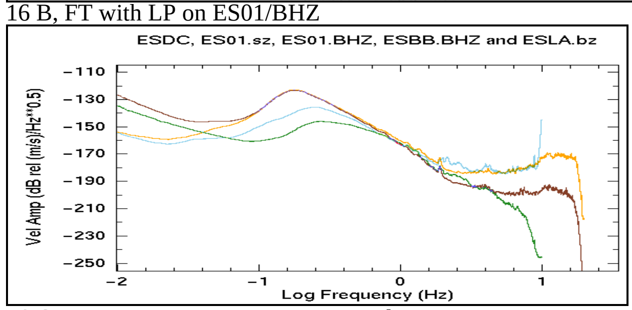
Figures 16 A-D



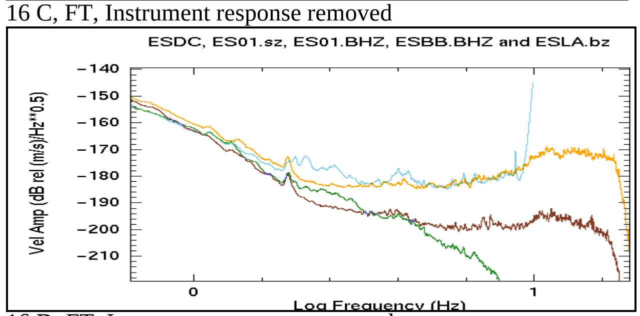
16 A, Background noise, ES01/BHZ LP at 1Hz



16 B, FT with LP on ES01/BHZ



16 C, FT, Instrument response removed



16 D, FT, Instrument response removed.

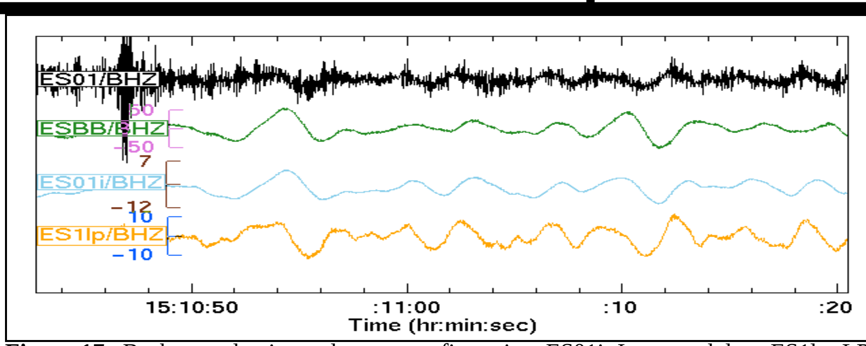
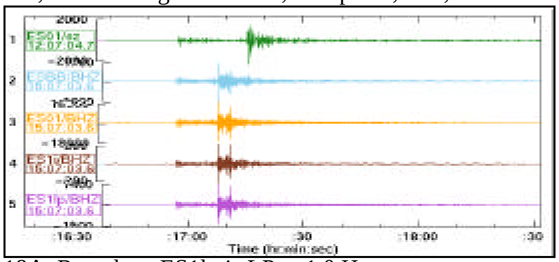
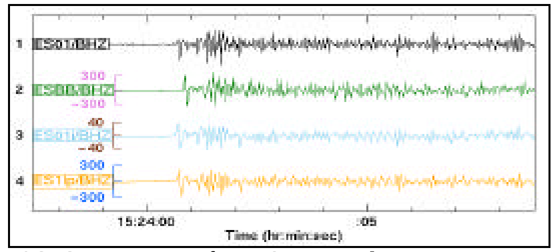


Figure 17. Background noise under new configuration, ES01i=Integrated data, ES1lp=LP at 1Hz

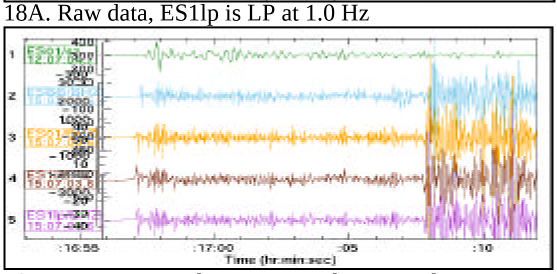
Figure 18 A-D, Comparison of Regional Earthquakes, ES01/sz=Old Vel, ES01/BHZ=New Acc, ESBB=Broadband Vel, ES01i=Integrated to Vel, ES1lp=LP, 1Hz, 1st order



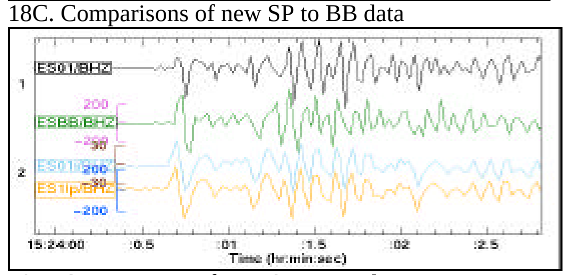
18A. Raw data, ES1lp is LP at 1.0 Hz



18C. Comparisons of new SP to BB data

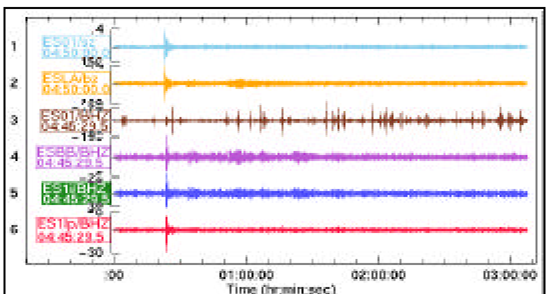


18B. First 15 seconds, note secondary arrivals.

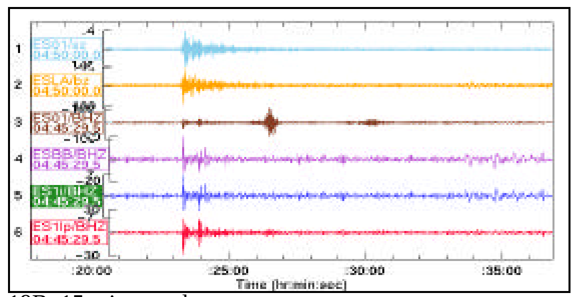


18D. Comparisons of new SP to BB data

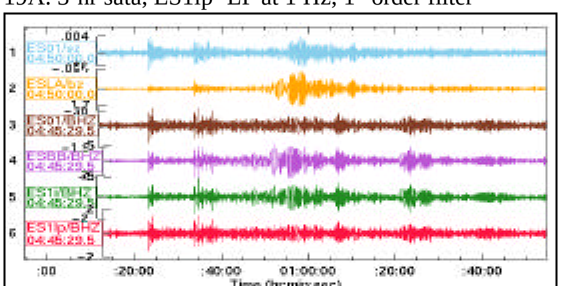
Figure 19 A-E, Comparison of Chile earthquakes, ES01/sz=old vel, ESLA/bz=KS54000 vel, ES01/BHZ=new acc,



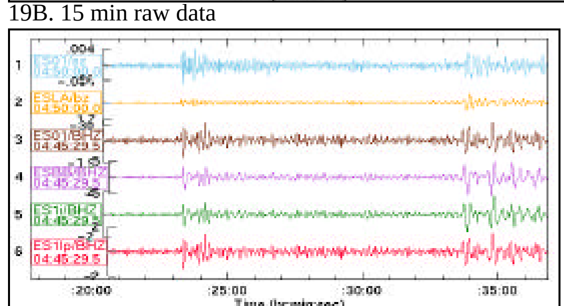
19A. 3-hr sata, ES1lp=LP at 1 Hz, 1st order filter



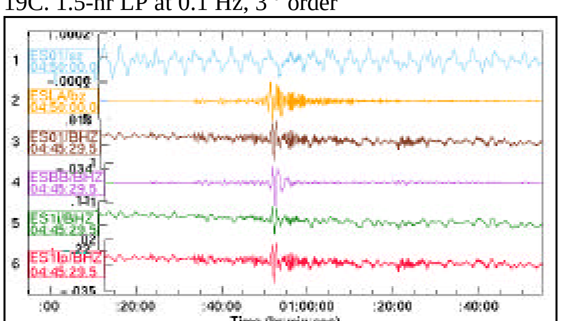
19B. 15 min raw data



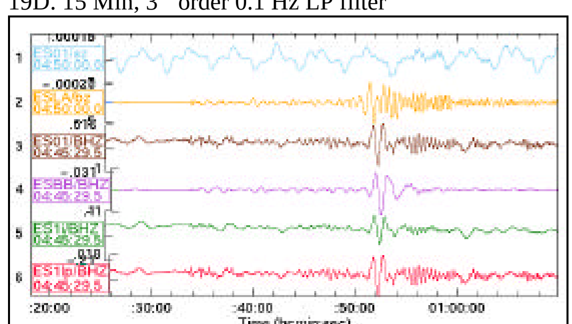
19C. 1.5-hr LP at 0.1 Hz, 3rd order



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.