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United States National Seismographic Network

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MASTER

Abstract

The concept of a United States National Seismograph Network (USNSN) dates back nearly 30 years. The idea was revived several times over the decades, but never funded. For example, a national network was proposed and discussed at great length in the so called Bolt Report (*U. S. Earthquake Observatories: Recommendations for a New National Network*, National Academy Press, Washington, D.C., 1980, 122 pp). From the beginning, a national network was viewed as augmenting and complementing the relatively dense, predominantly short-period vertical coverage of selected areas provided by the Regional Seismograph Networks (RSN's) with a sparse, well-distributed network of three-component, observatory quality, permanent stations. The opportunity finally to begin developing a national network arose in 1986 with discussions between the U.S. Geological Survey (USGS) and the Nuclear Regulatory Commission (NRC). Under the agreement signed in 1987, the NRC has provided \$5 M in new funding for capital equipment (over the period 1987-1992) and the USGS has provided personnel and facilities to develop, deploy, and operate the network. Because the NRC funding was earmarked for the eastern United States, new USNSN station deployments are mostly east of 105°W longitude while the network in the western United States is mostly made up of cooperating stations (stations meeting USNSN design goals, but deployed and operated by other institutions which provide a logical extension to the USNSN).

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Executive Summary

This document represents the Final Report to the U.S. Nuclear Regulatory Commission (NRC) by the U.S. Geological Survey (USGS) under an agreement to develop the United States National Seismograph Network (USNSN). This report consists of three parts: a brief description of the USNSN, a status report of the deployment of network field stations, and a technical summary.

The salient point of this report is that, although the network deployment is not yet complete, the USNSN has already provided the basis for major advances in seismic data recording, data processing, and data exchange within the United States. Through these advances, USNSN has had and will continue to have, positive and significant impacts on seismology in this country and abroad. Some significant examples are given below:

- Advance: The first extensive and non-military application of satellite telemetry for the routine, operational transmission of seismic data.
- Impact: This avoids dependence on costly and vulnerable land lines, gives flexibility in siting field stations, and provides data in real-time to a central processing center.

- Advance: The use of well-calibrated, modern, broadband seismometers with high dynamic range digitization in a continental-sized array.
- Impact: This provides data of the widest possible frequency and amplitude ranges for location and quantization of seismic sources, and for the study of Earth structure.

- Advance: The improvement of the data processing facilities of the National Earthquake Information Center (NEIC).
- Impact: Among other things, the NEIC can now carry out automatic analyses of incoming seismic data streams and provide on-line locations and magnitudes of seismic events at all distance ranges.

- Advance: The use of satellites for the two-way transmission of seismic data.
- Impact: The USNSN can provide the facility for the exchange of data between a national center and regional networks, and between regional networks themselves.

Finally, and most importantly, the USNSN is providing the technical foundation and stimulus for the development of a cooperative National Seismographic System. This is a concept under which the national network and regional networks are linked and work together to improve the timeliness, quality, and scope of earthquake information for the scientific community and for the public in general.

The USNSN is a reality. Field stations, the satellite master Earth station, the data processing facilities are all up and operating today. The installation of all of the field stations has not been completed, but the needed equipment is purchased and its deployment is well underway. Other cooperating stations, not part of the original plan, are joining the network. All of the major technical problems have been met and overcome. The USGS is proud of its achievements in the USNSN project and we look forward to extending the application and capabilities of the network beyond its original goals. However, we recognize that nothing could have been achieved without the generous cooperation of our seismological colleagues in the United States, and without the sustained support and enlightened management of the officers of the Nuclear Regulatory Commission. To these individuals we express our sincere and deep gratitude.

United States National Seismograph Network

by Ray Buland

Introduction

The concept of a United States National Seismograph Network (USNSN) dates back nearly 30 years. The idea was revived several times over the decades, but never funded. For example, a national network was proposed and discussed at great length in the so called Bolt Report (*U. S. Earthquake Observatories: Recommendations for a New National Network*, National Academy Press, Washington, D.C., 1980, 122 pp). From the beginning, a national network was viewed as augmenting and complementing the relatively dense, predominantly short-period vertical coverage of selected areas provided by the Regional Seismograph Networks (RSN's) with a sparse, well-distributed network of three-component, observatory quality, permanent stations. The opportunity finally to begin developing a national network arose in 1986 with discussions between the U.S. Geological Survey (USGS) and the Nuclear Regulatory Commission (NRC). Under the agreement signed in 1987, the NRC has provided \$5 M in new funding for capital equipment (over the period 1987-1992) and the USGS has provided personnel and facilities to develop, deploy, and operate the network. Because the NRC funding was earmarked for the eastern United States, new USNSN station deployments are mostly east of 105°W longitude while the network in the western United States is mostly made up of cooperating stations (stations meeting USNSN design goals, but deployed and operated by other institutions which provide a logical extension to the USNSN).

USNSN Design and Implementation

The USNSN was designed, with extensive input from the seismological community and industry, to serve the purposes of the National Earthquake Information Service (NEIS), the NRC, and the seismological research community. The goals that evolved were to provide highly reliable, highly linear, real-time, three-component, well calibrated, broadband, on-scale monitoring of moderate to large earthquakes at local, regional, and teleseismic distances. In short, the USNSN was intended to apply observatory quality instrumentation to continental scale seismological problems (in real-time).

During 1987-1989, the USNSN was planned, specified, and underwent a lengthy competitive procurement process, including rigorous production sample testing. Equipment for the field, telemetry, and the central control and processing system was selected. During 1990, hardware was delivered and development was begun on the critical system integration software. The USNSN became operational and was dedicated in April 1991. Since then, extensive work has been done on stabilizing the real-time processes, enhancing functionality, deploying field equipment, and adding cooperating stations.

The USNSN is based on the following hardware:

1. In the field, Guralp Systems CMG-3 seismometers and CMG-5 accelerometers are interfaced with a six channel, 80 sample/s, 24-bit Quanterra station processor. There is no local data storage except processor buffer memory. The principal band of interest is from 200 s to 30 Hz.
2. Telemetry is provided by a Scientific Atlanta Ku-band, time division multiple access (TDMA), very small aperture (satellite) terminal (VSAT) system. A VSAT connects each station processor to the master earth station (MES) located at the National Earthquake Information Center (NEIC) in Golden, Colorado via the GE K-2 geosynchronous telecommunications satellite using the X.25 communications protocol.
3. The network processor system at the NEIC runs on four Digital Equipment Corporation (DEC) μ VAX 3000/4000 32-bit microcomputers (under the VMS operating system) configured as a local area VAXcluster. Scratch storage is provided by two System Industries Cluster III multi-ported disk subsystems. The network processor receives X.25 data from the MES via Simpack coprocessors. Archival data storage is provided by an Aquidneck Systems write once optical disk jukebox.

USNSN Software Architecture

The USNSN components are integrated together by USGS supplied software which extends from the seismological processing in the field to all network processor functionality at the NEIC. In the field, USNSN station processors generate data streams at rates of 1, 10, 20, 40, and 80 samples/s from six analog to digital converters. The 1 sample/s "long-period" data are transmitted continuously with a lag of 120 s. The 40 sample/s "broadband" data are transmitted for events (from either the seismometers or the accelerometers depending on amplitude). The 80 sample/s "high frequency" data are transmitted from the accelerometers for accelerations exceeding 100 μ g. Event detection is done in the frequency domain using a fixed point FFT algorithm. Data are divided into USNSN/RSN telemetry packets in the USNSN compression format for transmission.

The network processor automatically estimates phase arrival times and locates events. Event associated phase and waveform data as well as continuous long-period and high frequency event data are stored in the on-line data base. Comprehensive review and analysis tools are available for the NEIS analysts. The data base is designed to support waveforms with asynchronous timing, different sample rates, different numbers and types of channels per station, and to store data arriving in different binary data formats efficiently.

The network processor software has been designed to be very flexible, both in terms of load and capability. The multi-processing design with automatic load balancing provides redundancy and handles the highly variable (and rapidly growing) real-time load. A multi-programming implementation with extensive interprocess (and interprocessor) communication makes the functionality extensible. In addition, the system is self monitoring and self repairing. Broadband and traditional short and long-period data already arrive in three different protocols (raw synchronous, X.25, and TCP/IP) and in four different formats (raw synchronous and two dialects of USNSN/RSN telemetry format—one exchange format is pre-processed into USNSN/RSN telemetry format before entry into the system proper). The front end software treats each type of data separately to maximize capability and then reduces all data to a common format to make data differences transparent to subsequent processing. Support for additional protocols and (if absolutely necessary) formats can be added as needed.

Current Network Status

There are currently nine USNSN stations located at Golden, Colorado (GOL; the USNSN prototype); Mont Chateau, West Virginia (MCWV); Chapel Hill, North Carolina (CEH); Albuquerque, New Mexico (ALQ); Topopah Springs, Nevada (TPNV; in cooperation with the Southern Great Basin Seismograph Network [SGBSN]); Mineral Point, Wisconsin (JFWS; in cooperation with St. Louis University using STS-1 sensors); Wichita Mountains, Oklahoma (WMOK); Mount Ida, Arkansas (MIAR); and Caribou, Maine (CBM). Although station deployment has been slow due to various start-up problems, these difficulties have been overcome without compromising the technical capability of the system and field work is continuing as rapidly as manpower, budget, and weather permit. The locations of these stations are shown in figure 1 by the circles.

There are currently eight cooperating USNSN stations located at Harvard, Massachusetts (HRV; with Harvard University); Cathedral Cave, Missouri (CCM; with the Incorporated Research Institutions for Seismology [IRIS] and Saint Louis University); Isabella, California (ISA; with the California Institute of Technology); Adirondack, New York (RSNY; USGS operated Regional Seismic Test Network [RSTN] station); Black Hills, South Dakota (RSSD; USGS operated RSTN); Tucson, Arizona (TUC; with IRIS and the University of Arizona); Columbia College, California (CMB; with the University of California at Berkeley), and Whiskeytown Dam, California (WDC; with Berkeley). These stations fall into two broad categories: IRIS/IRIS-like and "other". The IRIS-like stations depend upon custom coding provided by Joe Stein of Quanterra to send data of interest in the USNSN transmission format. At the "other" stations, digital data streams from broadband sensors have been interfaced to a USGS developed, DEC LSI-11/23 based station processor which emulates most functions of the USNSN stations. The locations of these cooperating stations are shown in figure 1 as squares.

Figures 2-4 illustrate some of the capabilities this network has already demonstrated. Figure 2 shows short-period filtered broadband recordings of the recent magnitude 3.6 Oklahoma event recorded on new USNSN stations in the Midwest. The rapid reporting of this felt earthquake was greatly facilitated by the enhanced coverage. Figure 3 shows raw broadband recordings the destructive magnitude 7.0 tsunamagenic Nicaraguan event and a magnitude 5.5 aftershock. This striking evidence for a very unusual source time function

was available from half a dozen stations within minutes of the earthquake. Figure 4 shows (filtered) short and (raw) long-period recordings of the destructive magnitude 7.5 tsunami-genic Indonesian event at PKP range. The availability of calibrated long-period information from each USNSN site has greatly improved the rapid reporting of surface wave amplitude information.

Planned USNSN Deployments

USNSN deployments by Spring of 1993 are being planned for Dugway, Utah (DUG; with DARPA); Battle Mountain, Nevada (BMN; with the SGBSN); Godfrey, Georgia (GOGA); Standing Stone, Pennsylvania (SSPA; with Pennsylvania State University using KS-36000 sensors); Newport, Washington (NEW); Lakeside, Connecticut; Murphy, North Carolina; and Blacksburg, Virginia (BLA, with Virginia Tech). These stations are also shown on figure 1 as circles. Cooperating stations planned for addition to the network through Spring of 1993 include the San Andreas Observatory, California (SAO with Berkeley); Cumberland Plateau, Tennessee (RSCP; USGS operated RSTN, now being revived); Boulder, Wyoming (BDW; using Deployable Seismic Verification System [DSVS] equipment); and Lajitas, Texas (LTX; with the U. S. Air Force). These stations are also shown on figure 1 as squares.

The USNSN is projected to grow to approximately 60 stations spanning the contiguous United States. Plans to improve this coverage and to extend it into Alaska, Hawaii, and Puerto Rico will be pursued as funding permits. In addition, arrangements to exchange subsets of event detected waveform data with both the Canadian and the Mexican National Seismograph Networks have been made as well as arrangements to acquire data retrieved by telephone ("gophered") worldwide by the IRIS Data Management Center in the first hour following an event. Because of the type and quality of the instrumentation and the network distribution, greatly enhanced by the highly cooperative nature of the project, the USNSN has a research potential for new studies on regional and continental scales which is unprecedented.

The National Seismic System

The monitoring capabilities of the USNSN are greatly enhanced through the seamless integration of USNSN, cooperating USNSN, and RSN data at the NEIC. There are currently 103 short-period verticals, 7 long-period verticals, and 1 three component long-period station coming into the USNSN data base from the so called U. S. Seismograph Network (USSN). These data are subsets of the various RSN's which are digitized at the RSN processing centers using USGS hardware (12-bits at ~20 samples/s), and transmitted via telephone lines to the NEIC. The routine use of these combined data sets is the first concrete manifestation of the proposed National Seismic System (NSS). The current "NSS" network is shown in figure 5 (with the USSN stations denoted by open triangles).

The next phase of NSS implementation in the USNSN context is to facilitate communications between the USNSN and the RSN's and among the RSN's. To this end, VSAT's have been installed at Memphis State University, Menlo Park, Caltech, Saint Louis University, Berkeley, the University of Kentucky, and the University of Utah. Additional installations are planned at the University of Washington, the University of Nevada at Reno, Boston College, and Columbia University (Lamont) by the Spring of 1993. Although not strictly RSN's, similar installations have been made at Harvard University and at NRC headquarters. USNSN stations installed (or to be installed) will provide similar connectivity for the University of North Carolina, Virginia Tech, and the University of South Carolina. At each of these sites, RSN triggered short-period data will be sent to the NEIC and/or USNSN data of interest (and

possibly RSN data from adjacent networks) will be transmitted back in near real-time. Thus, the RSN component of the USNSN data base will continue to grow in volume and importance, including data at higher sample rates and from more stations. Nodes in this USNSN-RSN communications network are shown in figure 6.

In addition, USNSN satellite communications is being applied to the task of providing high quality, low cost, digital data communications from RSN field sites to RSN data processing centers. For example, data from the cooperating USNSN station HRV is already being "looped back" in real time to Harvard University. Similar links are being developed at Saint Louis University and are planned for Caltech, Berkeley, and Boston College. Also, the USNSN will act as a communications provider for one or more RSN sub-networks from the field to the respective institutions for Memphis State University and the University of Nevada at Reno (shown on figure 6 as diamonds). Additional links of this kind are planned for Saint Louis University and Lamont.

Data Distribution

Data distribution in the NSS context is (near) real-time and is in the USNSN/RSN telemetry format. A near-real-time satellite broadcast distribution of all broadband event data is still under discussion and would be in the same format. The data will also be available in the SEED format both by Internet access (using the Federation of Digital Seismograph Networks Data Request Manager standard now being developed) and CD-ROM distribution.

Acknowledgment

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Map of existing and planned USNSN and cooperating USNSN stations

Figure 1. The map shows existing and planned (for deployment by April 1993) USNSN stations (filled circles) and cooperating USNSN stations (filled squares).

Recordings of the 17 December 1992 Oklahoma earthquake

Figure 2. Short-period filtered broadband recordings of the 17 December 1992, mblg = 3.6, Oklahoma earthquake from stations WMOK (top) and MIAR (bottom). These stations were 1° and 3° from the epicenter respectively.

Recordings of the 2 September 1992 Nicaragua earthquake

Figure 3. Raw broadband recordings from station JFWS (at a range of 31°) are shown for the 2 September 1992, $M_s = 7.0$, Nicaragua earthquake (top) and an $m_b = 5.5$, Nicaragua aftershock from the same day (bottom) for comparison.

Recordings of the 12 December 1992 Indonesia earthquake

Figure 4. Short-period filtered broadband (top) and raw long-period (bottom) recordings from station CBM (at a range of 141°) are shown for the destructive 12 December 1992, $M_s = 7.5$, Indonesia earthquake.

Map of USNSN stations, cooperating USNSN stations, and USSN stations

Figure 5. The map shows USNSN and cooperating USNSN stations. (as in figure 1) in relation to the USSN stations (open triangles).

Map of the USNSN-RSN VSAT communications network

Figure 6. The map shows the USNSN-RSN VSAT communications network. The squares show existing (or to be installed by Spring, 1993) cooperating data centers and the diamonds show RSN sub-network nodes.

Status Report of Deployment of Network Field Stations

Installed Stations as of February 1, 1993

On February 1, 1993, ten USNSN- or USGS-operated broadband stations and nine cooperating broadband stations were transmitting waveforms to the master station.

NSN Stations			Cooperating Stations		
ALQ	Albuquerque Seismo. Lab.	NM	BW06	Boulder Array	WY
CEH	Chapel Hill	NC	CBM	Caribou	ME
GOL	Bergen Park	CO	CMB	Columbia	CA
MCWV	Mont Chateau	WV	HRV	Harvard Observatory	MA
MIAR	Mt. Ida	AR	ISA	Isabella	CA
NEW	Newport	WA	JFWS	Mineral Point	WI
RSNY	Adirondack RS Obs.	NY	LTX	Lajitas	TX
RSSD	Black Hills RS Obs.	SD	TUC	Tucson	AZ
TPNV	Topapah Springs	NV	WDC	Whiskeytown	CA
WMOK	Wichita Mountains	OK			

Stations to be installed in calendar year 1993

At least the following ten USNSN and nine cooperating broadband stations will be installed during the remainder of 1993. Satellite telemetry will also be installed at several regional network centers.

NSN Stations			Cooperating Stations		
AAMB	Ann Arbor borehole	MI	CCM	Cathedral Cave	MO
BINY	Binghamton	NY	COR	Corvallis	OR
BMN	Battle Mountain	NV	ELK	Elko	NV
DUG	Dugway	UT	KNB	Kanab	UT
GOGA	Godfrey	GA	MNV	Mina	NV
LBNH	Lisbon	NH		Ottawa (data exchange)	ON
LSCT	Lakeside	CT	OXF	Oxford	MS
MYNC	Murphy	NC	SAO	San Andreas Geophy. Obs.	CA
WVOR	Wildhorse Valley	OR	SSPA	Standing Stone borehole	PA
YSNY	Yorkshire	NY			

Stations to be installed after calendar year 1993

Equipment has been purchased or funded for the following planned sites of the NSS. The dates of installation depend upon the delivery of the hardware.

NSN Stations			Cooperating Stations
AL1)	Alabama	AL	
BLA	Blacksburg borehole	VA	
DE1)	Delaware	DE	
HKT	Hockley	TX	
IA1)	Iowa	IA	
IL1)	Illinois	IL	
IN1)	Indiana	IN	
KS1)	Kansas	KS	
ND1)	North Dakota	ND	
MN1)	Minnesota	MN	
OSOH	Columbus	OH	
RI1)	Rhode Island	RI	
TUL	Leonard	OK	

Equipment Inventory

SUMMARY OF USNSN FIELD SITE ACTIVITY (22-JAN-93)

Sites = 74

CT CODE	LOCATION	ST	LAT	LONG	HOST	MOA	FUNDS	VSAT F O D S I	PROCESSOR F O D S I	SEISMOMETER F O D S I	DC	SITE PREP	STATUS (1=OP)
11 ALQ	ASL	NM	34.94	-106.46	USGS	1	NRC	2 2 2 2 2	2 2 2 2 2	1 s	1	1	1
11 CBM	Caribou	ME	46.93	-68.00	BC	1	NRC	1 1 1 1 1	1 1 1 1 1	1 g	1	1	1
11 CEH	Chapel Hill	NC	35.89	-79.09	UNC	1	NRC	1 1 1 1 1	1 1 1 1 1	1 g	1	1	1
11 GOL	Bergen Park	CO	39.70	-105.37	USGS	0	NRC	1 1 1 1 1	1 1 1 1 1	1 g	0	1	1
11 MCWV	Mont Chateau	WV	39.66	-79.85	WVGS	1	NRC	1 1 1 1 1	1 1 1 1 1	1 g	1	1	1
11 MIAR	Mt. Ida	AR	34.55	-93.58	NFS	1	NRC	1 1 1 1 1	1 1 1 1 1	1 g	1	1	1
11 WMOK	Wichita Mtns.	OK	34.74	-98.78	Pvt	1	NRC	1 1 1 1 1	1 1 1 1 1	1 g	1	1	1
12 CMB	Columbia	CA	38.03	-120.38	UCB	1	USGS	1 1 1 1 1	1 1 1 1 1	1 s	1	1	1
12 HRV	Harvard Obs.	MA	42.51	-71.56	HU	1	NRC	1 1 1 1 1	1 1 1 1 1	1 s	1	1	1
12 ISA	Isabella	CA	35.66	-118.47	CIT	0	USGS	1 1 1 1 1	1 1 1 1 1	1 s	1	1	1
12 TUC	Tucson	AZ	32.31	-110.78	UAZ	0	USGS	1 1 1 1 1	1 1 1 1 1	1 s	1	1	1
12 WDC	Whiskeytown	CA	40.58	-122.54	UCB	1	USGS	1 1 1 1 1	1 1 1 1 1	1 s	1	1	1
13 BW06	Boulder Array	WY	42.78	-109.57	USGS	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
13 NEW	Newport	WA	48.26	-117.12	USGS	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
13 RSMY	Adirondack RS Obs	NY	44.55	-74.53	USGS	1	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
13 RSSD	Black Hills	SD	44.12	-104.04	USGS	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Berkeley	CA	37.90	-122.30	UCB	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Cambridge	MA	42.38	-71.11	HU	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Lexington	KY	38.03	-84.50	UKY	0	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Memphis	TN	35.12	-89.93	CERI	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Menlo Park	CA	37.60	-122.30	USGS	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Pasadena	CA	34.15	-118.18	CIT	0	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Rockville	MD	39.08	-77.17	NRC	1	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Saint Louis	MO	38.60	-90.20	SLU	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Salt Lake City	UT	40.75	-111.92	UUT	1	DARPA	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
14	Weston	MA	42.38	-71.32	BC	1	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
15 MARKED	Marked Tree	AR	35.54	-90.43	CERI	1	USGS	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
15 YMT0	Yucca Mt.	NV	36.82	-116.47	YMP	1	GRA	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
11 AL1	Alabama	AL	33.10	-87.50	?	0	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
11 AAMB	Ann Arbor	MI	42.30	-83.66	UMI	0	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
11 BINY	Binghamton	NY	42.20	-75.99	Count	0	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1
11 BLA	Blacksburg	VA	37.21	-80.42	VPISU	1	NRC	1 1 1 1 1	1 1 1 1 1	1 t	1	1	1

CT CODE	LOCATION	ST	LAT	LONG	HOST	MCA FUNDS	VSAT F O D S I	PROCESSOR F O D S I	SEISMOMETER DC F O D S I	SITE STATUS PREP (1=OP)
11 BMN	Battle Mountain	NV	40 43	-117 22	UNR	1 GRA	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 DE1	Delaware	DE	38 70	-75 40	DEGS	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 DUG	Dugway	UT	40 20	-112 81	UU	1 DARPA	1 1 1 1 1	1 1 1 1 1 q	1 1 1 0 0 g	1 1
11 COGA	Godfrey	GA	33 40	-83 50	UGA	1 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 1 0 0 g	0 0
11 HKT	Hockley	TX	29 95	-95 83	?	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 IL1	Illinois	IL	40 50	-87 70	?	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 LBNH	Lisbon	NH	44 20	-71 90	Pvt	1 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 1
11 LSCT	Lakeside	CT	41 70	-73 20	L-D	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 MN1	Minnesota	MN	44 00	-96 40	Pvt	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 MYNC	North Carolina	NC	35 10	-84 20	NFS	1 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 1 0 0 g	0 0
11 ND1	North Dakota	ND	46 60	-100 30	?	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 OSOH	Columbus	OH	40 00	-83 10	OSU	0 NRC	1 1 1 0 0	1 1 0 0 0 q	1 1 0 0 0 b	0 0
11 RI1	Rhode Island	RI	41 60	-71 70	?	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 TPNV	Topopah Spring	NV	36 93	-116 22	YMP	1 GRA	1 1 1 1 1	1 1 1 1 1 q	1 1 1 0 0 g	1 1
11 WVOR	Wildhorse Valley	OR	42 30	-118 70	UNR	1 GRA	1 1 1 1 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
11 YSNY	Yorkshire	NY	42 40	-78 65	L-D	1 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
12 CCM	Cathedral Cave	MO	38 06	-91 24	SLU	1 NRC	1 1 1 1 1	1 1 1 1 1 q	1 1 0 0 0 g	1 1
12 COR	Corvallis	OR	44 59	-123 30	OSU	0 USGS	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 s	0 0
12 KS1	Central Kansas	KS	38 90	-99 00	SLU	0 NRC	1 1 1 0 0	1 1 0 0 0 q	0 0 0 0 s	0 0
12 IN1	Indiana	IN	39 10	-86 50	?	0 NRC	1 1 1 0 0	1 1 0 0 0 q	0 0 0 0 s	0 0
12 IAT	Iowa	IO	41 00	-95 00	?	0 NRC	1 1 1 0 0	1 1 1 1 1 q	1 1 1 0 0 s	1 1
12 JFWS	Mineral Point	MS	42 70	-90 50	Pvt	1 NRC	1 1 1 1 1	1 1 1 1 1 q	1 1 1 0 0 s	1 1
12 LTX	Lajitas	TX	29 33	-103 67	AFTAC	1 NRC	1 1 1 1 1	1 1 1 1 1 q	1 1 1 0 0 s	1 1
12 OXF	Mississippi	MS	34 51	-89 41	UMS	0 NRC	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 g	0 0
12 SAO	Hollister	CA	36 76	-121 44	UCB	1 USGS	1 1 1 1 0	1 1 1 1 0 q	1 1 0 0 0 s	0 0
12 SSPA	Standing Stone	PA	40 64	-77 89	PSU	0 NRC	1 1 1 1 1	1 1 1 1 1 q	1 1 0 0 0 s	1 1
12 TUL	Leonard	OK	35 91	-95 79	OGS	0 DARPA	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 s	0 0
13 RSCP	Cumberland Pl	Ob	35 60	-85 59	USGS	1 NRC	1 1 1 1 1	1 1 1 1 1 q	1 1 0 0 0 s	1 1
13		NV	0 00	0 00	GRA	1 GRA	1 1 0 0 0	1 1 0 0 0 q	1 1 0 0 0 s	0 0
14	Columbia	SC	34 00	-81 00	USC	1 USGS	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 s	0 0
14	La Jolla	CA	32 83	-117 27	UCSD	0 DARPA	1 1 1 0 0	1 1 1 0 0 q	1 1 0 0 0 s	0 0
14	Livermore	CA	37 67	-121 77	LLNL	0 LLNL	0 0 0 0 0	0 0 0 0 0 q	0 0 0 0 0 s	0 0

CT CODE	LOCATION	ST	LAT	LONG	HOST	MOA FUNDS	VSAT F O D S I	PROCESSOR F O D S I	SEISMOMETER DC F O D S I	PWR PREP (1=OP)	SITE STATUS
14	Ottawa	ON	45.35	-75.70	CanGS	0 NRC	1 1 1 0 0				0
14	Palisades	NY	41.00	-73.90	L-D	0 USGS	1 1 1 0 0				0
14	Reno	NV	39.50	-119.80	UNR	1 GRA	1 1 1 1 0			0	0
14	Seattle	WA	47.60	-122.30	UWA	1 USGS	1 1 1 0 0				1
14	State College	PA	40.80	-77.90	PSU	0 USGS	0 0 0 0 0			0	0
15	New Madrid	MO	36.60	-89.50	SLU	1 USGS	1 1 1 0 0	0			0
15	Charleston So. U.	SC	32.98	-80.06	CharS	1 USGS	1 1 1 0 0	0		0	0
21	TUVUM	Tuzandepetl. V.C.	MX	18.00	UNAM	0 USGS	1 1 1 1 1	1 1 1 1 1	1 1 1 1 1	1	0
31	YKGM	Cape Yakataga	AK	60.00	USGS	0 USGS	1 0 0 0 0	1 1 0 0 0	1 0 0 0 0	0	0
32	COL	Fairbanks	AK	64.90	GIA	0 USGS	1 0 0 0 0	1 1	1 1	1 1	0
<hr/>											
						43	73 70 37 38 33 28	28 12 24	24 35	15	
							71 40	38 14	27 7		

16 KEY:

CT CODE	LOCATION	ST	LAT	LONG	HOST	MOA FUNDS	VSAT		PROCESSOR		SEISMOMETER		DC	SITE STATUS				
							F	O	D	S	I	F	O	D	S	I	#	PWR PREP (1=OP)

C	COMMUNICATIONS SATELLITE CODE																	
1	Scientific Atlanta (conterminous U S)					Funded	F					F						
2	Morelos (Mexico)					Ordered		O					O					
3	(Alaska)					Delivered			D					D				
4	(West Indies)					Shipped				S					S			
5	GSE					Installed					I					I		
6	Peacesat					TYPE OF STATION PROCESSOR												
7	Panamsat					USNSN QUANTERRA												
T	SITE TYPE					IRIS QUANTERRA												
1	USNSN fully equipped station					Other												
2	Cooperative station. USNSN telemetry					q												
3	Non-standard USGS station					i												
4	Regional network recording center					o												
5	Regional narrowband station or network node					TYPE OF SEISMOMETER												
						CMG-3, CMG-5												
						CMG-3B, CMG-5												
						STS-1, STS-2												
						KS-36000												
						Other												
						Regional (SP or BB)												

USGS

NEIC

United States National Seismograph Network Technical Summary

17 November 1992

Introduction

As of mid-December 1989, signed contracts were finally in place for all major components of the U. S. National Seismograph Network (USNSN). These include: 1) seismometers, 2) station processors, 3) satellite telemetry, and 4) network processor. Figure 1 shows an overview of the placement and interconnection of these elements. The details of interfacing between critical subsystems was finalized with the vendors in January 1990. Interfaces of particular concern include: 1) seismometer to station processor, 2) station processor to telemetry subsystem, and 3) network processor to station processor (via telemetry subsystem) control of absolute timing. A prototype USNSN station was installed in Bergen Park, Colorado (GOL) in May 1990. Network processor integration and the USGS supplied portion of the station processor software were well enough developed to begin operation of GOL in test mode utilizing the full USNSN data path by October 1990. Meanwhile, plans for auxiliary subsystems including: 1) field site preparation, 2) field site power, 3) network status display, 4) archival mass storage, and 5) data distribution were being finalized. The first two production stations were deployed in March 1991 at Mont Chateau, West Virginia (MCWV) and Chapel Hill, North Carolina (CEH).

At this point, further station deployments were suspended pending the resolution of performance problems introduced into the seismometers as a result of modifications requested by the USGS to optimize interfacing with the station processor. After several iterations, we are confident that all problems have been resolved and new deployments began in July 1992. Meanwhile, significant progress has been made at the network control center, located at the National Earthquake Information Center (NEIC) in Golden, Colorado. A preliminary version of a very flexible, very ambitious multi-programming/multi-processing software system was demonstrated in April 1991. This system handles all data acquisition and processing functions for traditional short period vertical stations telemetered to the NEIC from the various Regional Seismograph Networks, USNSN stations, and cooperating USNSN stations. The network processing system was promoted from test to operational status in August 1991 and operated in parallel with existing Earthquake Early Alerting Service procedures until it became the primary system in December 1991. Support for long-period data was added in January 1992 and the integration of the broad-band data was completed in February 1992.

At the same time a fourth USNSN station at Albuquerque, New Mexico (ALQ) was added in January 1992 using borrowed STS-1 seismometers (a configuration which was duplicated for the cooperative station at Mineral Point, Wisconsin (JFWS)). Support for older IRIS-like Quanterra stations was completed in February 1992 with the addition of the Harvard, Massachusetts (HRV) IRIS station. Support for the newer style IRIS-like

Quanterra systems was completed in April 1992 with the addition of the Isabella, California (ISA) Terrascope station. Subsequently, Berkeley stations with similar station processors at Columbia College, California (CMB) and Whiskeytown, California (WDC) were added to the network. Support for the IRIS-1 systems was also completed in April 1992 with the addition of the Cathedral Cave, Missouri (CCM) station. Support for the IRIS-2 stations (via the IRIS GSN Data Processor subsystem) was completed in March 1992, and was tested at Tucson, Arizona (TUC) in September 1992. Support for the USGS operated RSTN stations was completed in July 1992. During the summer of 1992 a cooperative station was added at Topopah Springs, Nevada (TPNV) using CMG-4 sensors. Production USNSN stations have been deployed at Mount Ida, Arkansas (MIAR), the Wichita Mountains, Oklahoma (WMOK), and Caribou, Maine (CBM). Currently, data is being received from 97 short period and 8 long period Regional Seismograph Network stations. In addition, three component data is being received from 17 broad-band stations. Acquisition software for all planned USNSN and cooperative USNSN station configurations has now been written and tested. New stations of the types already addressed can be added, with complete calibration information, in an hour.

Data from all sources is integrated seamlessly into a common database. Archiving on optical disk has been partially automated. The loopback of data from a cooperating station to the cooperating institution was completed in March 1992. The distribution of selected waveforms to a cooperating institution was demonstrated in April 1992 and became fully operational in October 1992. Local access to the data for routine waveform processing was implemented in September 1992. Although much remains to be done, nearly all of the planned USNSN functionality has been provided in at least a minimally acceptable form. The major exception is that additional forms of data distribution (described below) including network access, satellite broadcast, and CDROM have yet to be addressed (look for progress in the winter of 1992). Considerable work has been done on telemetering regional seismograph network (RSN) data and support in this area should be available as needed.

In the following, the technical details of each element of the USNSN will be discussed, including information on interfacing other seismological equipment to the USNSN satellite telemetry system. Also, some sample waveforms from USNSN and cooperating USNSN stations have been included to give the reader a feeling for the type of data being collected. A deployment plan is presented in Attachment A and is described briefly below. Attachment B describes the USNSN telemetry format which has extension for other types of data which might be telemetered via the USNSN system. The USNSN standard time code and USNSN data compression algorithm are described in this section. Note that several small, but significant changes have been made in the header format since the last edition of this document. In the following, the first four sections describe the major elements of the USNSN system from the sensors to the central processing system. Sections one through three describe elements of the USNSN field system (shown in the block diagram in figure 2 for reference). Sections three and four describe the major elements of the central processing system (section three describes the telemetry system which links the field and central site equipment and so is part of each). Sections five through seven describe auxiliary central site functionality. Section eight discusses the overall integration strategy in general and the network processor software architecture in particular. Sections nine and ten discuss other field site issues. Sections eleven through thirteen discuss the details of various interfaces. Section fourteen describes the sample waveform data, section fifteen discusses deployment plans, and section sixteen discusses interfacing other seismological equipment to the USNSN telemetry system.

Figure 7. USNSN configuration

Figure 8. USNSN station processor

1. Seismometers

Seismometers are being supplied by Guralp Systems Ltd. The high-gain sensors are a version of the CMG-3 seismometer with custom modifications made to meet specific requirements of the USNSN and are available in both surface mounted and borehole configurations. The low-gain sensors are essentially a stock version of the CMG-5 accelerometer, which will be surface mounted only. The high-gain sensors have the following characteristics:

1. Each component is completely independent, is housed in a cylindrical pressure jacket 7.5" tall (5.9" for the horizontals) and 3.25" in diameter, and weighs 8 lb. At each site, up to three sensors are connected with a single feedback electronics (FBE) module which mediates all interconnection with the outside world and manages control functions by means of a CMOS microcomputer. The FBE provides isolated ground, DC/DC power regulation and distributes power to the sensors. For each sensor, the FBE provides one differential signal output and one single ended mass position output. The FBE accepts one single ended calibration input as well as control inputs for mass centering and calibration enable. A single mass centering control line enables recentering of all three sensors. However, recentering will only be performed for sensors for which the mass is further from center than about 10% of full scale. A separate calibration enable is provided for each sensor. The calibration signal will be passed to the sensor which is currently enabled. Mass unlocking and centering are implemented by means of internal motors and can be initiated by switches mounted on the FBE. Mass unlocking will only be performed during maintenance visits. All control functions may also be performed via appropriate software on an IBM PC compatible computer interfaced through an RS-232C asynchronous port on the FBE. Control is asserted by +5 V logic levels. The subsystem is powered by an external, unregulated 24 VDC (20-28 VDC) supply and draws less than 3 W. Power is surge protected and regulated within the FBE.

2. The sensor is based on a leaf spring design with capacitive position sensing and electromagnetic force feedback. The sensor response in the feedback loop is proportional to acceleration at long periods with a sensitivity of 7200 V/m/s² and is proportional to velocity at short periods with a sensitivity of 1500 V/m/s. The feedback operates over the frequency band 0-30 Hz with the crossover between acceleration and velocity occurring at .031 Hz. Outside the feedback loop, a one pole high pass AC coupling filter with a corner at .005 Hz and a two pole low pass anti-aliasing filter with a corner at 30 Hz are applied to the feedback loop output to form the seismometer output. In addition, a jumper selectable amplifier has been provided outside the feedback loop with a gain which increases linearly with frequency above 1 Hz. When selected, this amplifier will artificially limit dynamic range so that the analogue-to-digital converter (ADC) can resolve signals near the sensor noise floor at high frequencies. The sensor outputs are balanced with range of ± 10 V (± 20 V across the differential circuit). The mass position output is flat to acceleration in the frequency band 0-.03 Hz. Calibration is accomplished by injecting the calibration voltage through a calibration resistor into the forcing coils. The resistor has been selected so that a 5 V input results in an output of about 7% of full scale.

3. The noise floor, clip level, and dynamic range of the sensor are shown in dB (relative to 1 m/s²) as a function of frequency in figure 3. The base figure was prepared by J. Peterson. Noise levels are equivalent peak estimates derived from RMS values averaged over one third octave bands in frequency. The low noise model (LNM) is a composite from the best stations in the world at their best, derived from the literature. The high noise model is representative of noisy sites at their best and was derived from Global Digital Seismograph Network (GDSN) data. Average peak values for earthquake signals were

Figure 9. The response characteristics of the USNSN sensors

derived by H. Kanamori for sources at 30°. The high frequency, near field, peak acceleration data was provided by J. Stein. The dashed lines in the noise floor denote interpolation where the test data was relatively poor. The result of the optional amplification on the effective clip level at high frequencies is also shown by a dashed line. Note that the numerical value of the dynamic range is highly sensitive to the approximation used to make noise and clip levels comparable and to the degree of smoothing applied. What is unequivocal is that the sensor is capable of resolving earth noise at a quiet site in the band .03-10 Hz, is capable of well recording strong signals in the band .005-30 Hz, and should not clip on any but the very largest events which are at least 30° away or events of magnitude 5 or less at any distance (4+ with the optional amplification).

4. The sensors provide a linearity of at least 107 dB and a cross axis coupling of no more than -62 dB (an upper limit due to the linearity of the shake table). They have no observed sensitivity to normal fluctuations in atmospheric pressure and the geomagnetic field. A thermal change of at least 16°C is required to drive the horizontal sensors from zero to full scale. The thermal stability of the verticals is about five times better than the horizontals.

In a borehole configuration, the CMG-3 sensors are stacked vertically. The holelock provides mechanisms for orienting and leveling the package. Installation is facilitated by a DC winch.

The low-gain sensors have the following characteristics:

1. Each component is completely independent and is housed in a cylindrical pressure jacket. All three components are sealed in a larger cylindrical enclosure 4" tall and 8.6" in diameter. The three component assembly weighs 9 lb. The package has a single differential output for each sensor. As for the high gain sensors, one single ended calibration input is passed to the sensor currently selected by one of three calibration enable control inputs. Control is asserted by means of a +5 V logic level. Mass unlocking is not required and sensor offsets are nulled at installation time by electrical trimming. The assembly is powered by an external, unregulated 24 VDC (20-28 VDC) supply and draws .45 W. Power is internally surge protected and regulated by means of an isolated ground DC/DC converter.

2. The sensor is based on a leaf spring, force balance design. The sensor response in the feedback loop is proportional to acceleration over the frequency band 0-30 Hz with a sensitivity of 1.0 V/m/s². Outside the feedback loop, a two pole low pass anti-aliasing filter with a corner at 35 Hz is applied to the feedback loop output to form the accelerometer output. The output is balanced with a range of ± 10 V (± 20 V across the differential circuit) to yield one half full scale output at an acceleration of ± 2 g. Calibration is accomplished by injecting the calibration voltage through a calibration resistor into the forcing coils of the selected sensor. A 5 V input results in an output of about 50% of full scale.

3. The noise floor, clip level, and dynamic range of the CMG-5 are shown along with the CMG-3 results in figure 3 using the same approximations. Note that the 2 g design limit has been taken as the effective clip level. A dashed line shows where the noise floor estimate has been extrapolated due to relatively poor test data. Note that even with the proposed CMG-3 modification, the CMG-3 and CMG-5 dynamic ranges overlap by at least 80 dB in the range .1-30 Hz. This overlap is intended to make the selection of high or low-gain broadband channels for transmission during an event detection reasonably unambiguous (both high and low-gain long period channels will be transmitted continuously).

4. The sensors provide a linearity of at least 66 dB and a cross axis coupling of no more than -40 dB (again an upper bound due to the resolution of the test apparatus-a different test than used above). They have no observed sensitivity to normal fluctuations in atmospheric pressure and the geomagnetic field. The thermal sensitivity of the mass position is, for all practical purposes, negligible.

2. Station Processor

The station processor, supplied by Quanterra, Inc., is a CMOS (low power) 68000 microprocessor based subsystem running under the OS-9 real-time operating system. It includes: 1) 24-bit ADC's (one per seismometer input), 2) a precision clock, 3) seismometer control and calibration circuitry, 4) real-time state-of-health (SOH) monitoring, 5) 1.4 Mbytes of memory, and 6) four asynchronous RS-232C ports. Software functionality provided by Quanterra includes: 1) drivers for all hardware devices, 2) the collection and decoding of all seismometer, SOH, and clock data, and 3) digital filtering and decimation of the seismometer data. Software functionality provided by the USGS includes: 1) data buffering, 2) event detection, 3) output queue management, 4) absolute time monitoring, and 5) command acquisition and execution. The system features an internal watchdog timer, the ability to force a system reset by a remotely generated break signal, downloadable operating software, and the ability to synchronize absolute time with remotely generated timing signals. The station processor operates from unregulated 24 VDC (20-28 VDC) and draws about 21 W (in a six channel configuration). Internal surge protection and isolated ground DC/DC power regulation are provided. All Quanterra supplied software (exclusive of OS-9) is written in the Pascal higher level language and all software supplied by the USGS is coded in C.

The three high-gain and three low-gain seismometer outputs are acquired by six 24-bit ADC's at 80 samples/s (sps), providing full power below a 30 Hz corner with less than -80 dB aliasing in the passband (a three channel, high-gain only configuration is also possible). The ADC's, implemented with an oversampling design, have a single differential input with a 60 K Ω input impedance and more than 80 dB common mode rejection. They have a worst case (at high frequency) equivalent peak noise (averaged over octaves) of less than -143 dB (referenced to full scale) which improves to about -157 dB by .05 Hz (note, it is the additional averaging which allows these numbers to exceed the nominal dynamic range of the ADC output), a differential linearity (bit-to-bit consistency) of 120 dB, an integral linearity (volt-to-volt consistency at constant temperature) of 80 dB, and an absolute precision (over the operating temperature range) of 40 dB. The ADC's are configured to produce output samples synchronized to less than 1 μ s (with a channel to channel slew of about 60 μ s).

Additional broadband channels are derived by digital filtering (with linear phase FIR filters) and decimation to rates of 40 sps (full power to 15 Hz), 20 sps (full power to 7 Hz), and 1 sps (full power to .3 Hz). Aliasing is less than -80 dB in the passband for all filters except the 1 sps channel where it is -130 dB. Also, a simulated short period channel may be derived from any seismometer at a rate of 10 sps (for helicorder display). In normal operation, the six 1 sps channels and optionally the helicorder channel will be telemetered in real time. On an event, either the three high-gain or the three low-gain channels will be telemetered at 40 sps. On a strong event, the three low-gain channels will also be telemetered at 80 sps (yielding free field recordings for ground motions exceeding about 100 μ g). The 20 sps data stream is provided for possible applications requiring continuous "broadband" data. The output queue management provides a store-and-forward capability with intelligent data pruning in the event of a telemetry outage.

The station processor clock provides synchronized timing control for all ADC's and maintains the time of day relative to the initiation of data acquisition. Its temperature compensated oscillator provides stability of at least .5 ppm/°C over the operating range of the unit and can be trimmed over a range of ± 10 ppm to a resolution of .01 ppm under software control to compensate for drift. The clock is capable of time tagging the leading edges of positive going RS-232C level pulses with a duration of at least 1 ms on an external control line. Control lines are available for delivering +5 V logic levels (at 1 mA) under program control to center the masses on the high gain sensors or to enable the calibration signals on all sensors. 5 V step calibration signals (at 10 mA) can be generated for each set of sensor independently under program control. The SOH hardware provides signal conditioning and low rate (up to 1 sps) low resolution (8-bit) monitoring of the external supply voltage, external and internal temperature, the enclosure door open/close state, and the high gain sensor mass positions.

Three of the asynchronous RS-232C ports provide communications with the telemetry system: 1) a "console" port for downloads and remote monitoring, 2) a data port for commands, configuration information, and data, and 3) a port dedicated to identification information accompanying the external timing pulses. The fourth port can be used to collect additional SOH information from the power conditioning equipment (input side) and/or to provide a real-time digital data stream for local users (output side). Note that 1 Mbyte of random access memory (RAM) is the only local storage medium available and that telemetry is the only form of data delivery to the NEIC. 256 Kbytes of erasable programmable read only memory (EPROM) are available for resident software with the remainder of the memory being RAM dedicated to system tables. A remote reboot will be initiated either by the watchdog timer or by a break received on the console port. Only software modules which have been altered need be downloaded at boot time (superseding modules stored in EPROM). Station processor failures can be analyzed by remotely downloading diagnostics. Software is being developed and maintained using a development system located at the NEIC. The station processor is housed in an environmental enclosure which is sealed to withstand humidity, corrosion, and thermal extremes.

3. Telemetry Subsystem

The telemetry subsystem, supplied by Scientific Atlanta, Inc., is a general purpose, bi-directional, host-to-host, computer network in a star configuration implemented by means of a time division multiple access (TDMA), Ku-band (14-16 GHz), very small aperture telecommunications (VSAT) satellite network. A VSAT unit, including a 1.8 m (diameter) antenna, feedhorn electronics, and decoding and control electronics, will be located at each field site. All VSAT's communicate with and are controlled by a master earth station (MES) located at the NEIC. The MES includes a 4.6 m antenna (with active deicing), feedhorn electronics, up/down converter, uplink modulators, burst demodulators, packet switch, and control/monitoring equipment. The network link budget is designed to yield a bit error rate (with forward error correction) of 10^{-7} with 99.8% availability. All communication traffic is further embedded into a modified X.25 protocol providing multiple virtual circuits per VSAT, flow control, and error detection and packet retransmission. The corrected bit error rate is no higher than 10^{-12} . The space segment is being carried on the General Electric K-2 satellite which is located at 81° west longitude in a geostationary (equatorial) orbit. Note that the K-2 Ku-band footprint covers the continental U. S. only. Alaska, Hawaii, Puerto Rico, and the Virgin Islands will be covered by leased service from other communications providers.

The MES handles inbound (field to NEIC) and outbound (NEIC to field) communications on 56 Kbit/s channels, each requiring 200 KHz (including guard bands) of satellite transponder bandwidth. The MES may be configured for up to 14 inbound channels and 8 outbound channels for an aggregate data rate in excess of 1.2 Mbit/s. It features 45 W of uplink power and frequency agile upconverters (i.e., the carriers can be reprogrammed as needed). A block diagram of the MES equipment is shown in figure 4. Each inbound channel may be shared by many VSAT's, each with a configurable priority. TDMA slots may be dynamically allocated among currently active VSAT's to optimize instantaneous throughput. Each outbound channel may also be shared by many VSAT's, each with a configurable priority. In addition, data traffic may be highly asymmetric with VSAT's on up to eight inbound channels sharing the same outbound channel. Further, each VSAT supports multiple concurrent virtual circuits. The MES can support up to 500 virtual circuits simultaneously. VSAT's at USNSN sites have at least one virtual circuit with a 2.4 Kbit/s guaranteed throughput connected at all times. The MES communicates with the network processor by means of up to 14 host ports, each supporting up to 256 virtual circuits under the 1984 X.25 protocol on a 56 Kbit/s synchronous connection. Except for the antenna (which is passive) and feedhorn electronics (for which on-site spares are available), all critical MES components feature automatic fail-over redundancy.

Each VSAT listens continuously to one outbound channel for control and data information addressed to it and bursts data into one inbound channel using 1.5 W of uplink power during TDMA slots assigned to it. Data to and from the local user (the station processor in this case) is routed to one of four RS-232C ports. For the USNSN application, the VSAT software downloaded at startup time implements a packet assembler/disassembler (PAD) protocol on three of the ports with remote configuration and break generation capabilities as recommended by the X.3 and X.29 standards. For maintenance purposes, the third port may be set for local access as recommended by the X.3 and X.28 standards. In the PAD configuration, each port is mapped to a separate virtual circuit. The net result is that bi-directional data traffic on each port is effectively independent. Each port may be configured independently for asynchronous communications at up to 9600 Baud. However, the throughput is controlled by the MES. In practice, the aggregate throughput of a VSAT is about 11 Kbit/s (due to the PAD software). The two X.29 ports are connected to the station processor data and console ports with the data port configured for 8-bit transparent inbound communications.

The downloaded VSAT software also includes a task written for the USNSN which collects and formats (into ASCII) internally generated identification information related to hardware timing signals. This information is output via the fourth asynchronous port. The hardware timing signals are RS-232C level pulses with durations of at least 4 ms which are generated on the DSR (data set ready) pin of the same port every 12.96 s following receipt of a start-of-frame (SOF) message by the VSAT. In other applications, this third RS-232C port would typically also be configured as another PAD port. Under a different set of downloadable VSAT software, two of the ports can be configured for synchronous X.25 traffic at rates of up to 19.2 Kbit/s each. In this case, the other two ports would not usually be used. However, one of the remaining ports could still be configured to supply the ASCII timing information as an asynchronous data stream.

The VSAT antenna is an elliptical plan, offset feed horn, parabolic design which may be mounted on a king post set into the ground, bolted to a structure, or set on the roof of a building using a non-penetrating base. Passive (hydrophobic coating) and active deicing (electrical) are available, but full active deicing requires considerable power ($\approx 1 \text{ KW/ft}^2$). The antenna, feed-horn electronics, and cabling are designed for environmental extremes. However, the decoding and control electronics are not. The

Figure 10. The USNSN master station

VSAT may be operated on either AC or DC power. The DC configuration operates from a 24 VDC (18-36 VDC) unregulated supply and draws 128 W. The AC version draws 241 W. Active deicing will be configured to operate from line AC only.

4. Network Processor

The network processor function is implemented on a local area network (Ethernet) with four μ VAX 3000/4000 processors supplied by the Digital Equipment Corp. Each processor features the full 32-bit VAX architecture, with integral virtual memory and floating point support implemented with CMOS LSI technology, and benchmarks at about 3.8 MIPS and .6 MFLOPS. All processors run under the VMS operating system and are loosely coupled under local area VAXcluster (LAVC) software. Each processor is independently booted from a high performance local disk, but also has disk channel access to a read/write shared disk farm. The disk farm has been implemented using two Cluster III multiported controllers and currently supports 6 high performance Fujitsu disk drives, with an aggregate capacity of 6.4 Gbytes, all supplied by System Industries Inc. Two groups of two processors each (for redundancy) are dedicated to two main tasks: 1) data routing and 2) on-line data analysis. The routing processors acquire data from the MES (and other sources) via multiple synchronous lines running at 56 Kbit/s. The X.25 protocol translation is handled by Simpac ICP co-processors. Routing processors perform automatic network monitoring and alarm functions, station processor downloads and control, data buffering, and routing of data to the analysis processors, real-time displays, archival storage, and other users as appropriate. The analysis processors perform phase picking and automatic earthquake location functions. A block diagram of the network processor system is shown in figure 5.

Analyst access to the on-line database is by means of VAXstation II/GPX and VAXstation 3100 workstations also acquired from the Digital Equipment Corp. The VAXstations feature the same architecture as the μ VAX's with an LSI graphics co-processor, a 19" color monitor, and a mouse. The graphics has a resolution of 1024 x 864 pixels, can display 256 colors from a palette of 16 million, and can draw vectors at a rate of 1 Mpixels/s. The workstations also run under the VMS operating system and are part of the LAVC, but they access the shared disk farm via Ethernet (served by one of the μ VAX's). The workstations are diskless, but alternate boot nodes can be configured for redundancy. Five workstations are available to facilitate the quick handling of critical alarm events by the National Earthquake Information Service (NEIS) analysts.

The network processor equipment, exclusive of the workstations, is housed in a conditioned, raised floor, computer room environment. The 5 tons of air conditioning currently available provides capacity for expansion. Power is distributed through a 200 KVA distribution panel. Critical equipment is powered through a 20 KVA uninterruptible power supply (UPS) system which is backed up by a 125 KVA diesel generator. While the UPS system is dedicated to USNSN equipment, the generator is shared with other computer equipment and emergency building lighting.

5. Network Status Displays

Real-time network status is displayed in two ways: 1) plasma panels and 2) helicorders. Four IBM 591 plasma panels provide (relatively) flat, wall mounted, monochrome (orange on black), 17", graphics displays with a resolution of 960 x 768 pixels each. They are easily readable and may be filmed or videotaped under normal office lighting conditions. The plasma panels display continuously updated station/epicenter maps, waveforms, and related alphanumeric information. The network processor

Figure 11. USNSN network processor system

communicates with the plasma panels via a DEC LSI 11/23 16-bit microcomputer which provides graphics intelligence, buffer memory, and interfacing logic. In addition, selected, digitally synthesized, short and long period data are displayed in real-time on helicorders. Relevant data is routed from the network processor to another LSI 11/23 which buffers the data, synchronizes timing, adds time marks, and synthesizes the helicorder inputs via digital-to-analogue converters (DAC's). Absolute timing is obtained from a Kinemetrics Truetime WWVB receiver (WWVB is broadcast from Fort Collins, CO about 50 miles away). The helicorder records are considered essential for quick visual assessment of alarm events, monitoring potential sensor problems, and for the edification of visitors and the media.

6. Archival Mass Storage

An archival, dual drive, write once read many times (WORM), optical digital disk autochanger (jukebox) subsystem has been supplied by Aquidneck Systems International (as well as a compatible single drive subsystem). The intelligent microcomputer based controllers makes the optical drives appear to be standard 9-track tape drive while still taking advantage of the random access nature of the optical disks. Once loaded into the jukebox, disks may be mounted in either drive in an average of 7 s and numerous logical tape images may be accessed from each disk all without human intervention. Disks must be manually loaded into the single drive subsystem. The jukebox, drives, and disks are manufactured by the Sony Corporation. Each disk is capable of storing 6.8 Gbytes using both sides (3.2 Gbytes for the single drive subsystem). The jukebox has 50 slots for media and will hold a total of 320 Gbytes on line. Recording is done by heating an exotic bi-metal substrate through a polycarbonate encapsulation with a solid state laser to form an alloy with a very different reflectivity. Because this recording method is not ablative and does not employ an organic substrate, the projected archive lifetime is at least 100 years (with a bit error rate no higher than 10^{-12}). The single drive subsystem has been interfaced directly with the network processor system for archiving during the development phase. For the long term, the jukebox is being interfaced to a μ VAX II which will be clustered with the NEIS VAX 8350. The μ VAX II will act as a mass storage server both to the NEIS machine (via the cluster) and to the network processor (via remote tape access software).

7. Data Distribution

Three different methods of general data distribution are being planned: 1) remote access, 2) satellite broadcast, and 3) CDROM. In addition, local access for research use, the loopback of data from cooperating stations and RSN nodes, and programmed real-time point-to-point data distribution will be supported. Local access will not be discussed further as it is of limited interest to most users. Loopback and point-to-point distribution will be discussed in the last section, "Interfacing Other Equipment to the VSAT". Remote access will be supported primarily via public computer networks (although dial-up access can be provided if the demand warrants). We will be concentrating on making data available through the Internet (TCP/IP) and SPAN (DECnet). Remote access will be isolated from the network processing system proper, by utilizing the μ VAX II mass storage server. Easy access will be provided in near-real-time for recent events. This service is expected to be prototyped in the Winter of 1992.

Although remote access is the easiest and most obvious means of providing access to the USNSN data, it is also potentially costly, time consuming, and awkward for the end user due to the interactive nature of the Data Request Manager, particularly if large amounts of data are desired. A much more efficient alternative is to provide a 9.6-19.2 Kbit/s,

unidirectional, broadcast satellite channel which would be on the air full time. It is estimated that all three component, broadband triggered data from the entire network could be broadcast in this manner with room left for continuous three component long period data from a subset of the network as well as bulletin type data. The tentative strategy would be to transmit the bulletin data as soon as it is available and to transmit the long period data in near-real-time. The triggered data would be queued for transmission as it is received and would be sent out as capacity becomes available. Although data would typically be available in ten or twenty minutes, it could be delayed for as much as a few hours in the event of a large earthquake (and aftershock sequence). On the other hand, a very large amount of data can be delivered over such a channel at a nominal cost. The channel probably will be implemented using a video channel sub-carrier and will hopefully be available in 1993. Initial estimates are that receiving gear at each user site would cost \$2-4 K. It is anticipated that each user will probably wish to parse the data and save only a subset of immediate interest for further processing. Of course, the user is free to keep everything if sufficient storage capacity is locally available (potentially 200 Mbytes/day).

The final method of data delivery, CDROM, is the least costly, most convenient, and most comprehensive. However, data will not be available for several months after it is collected. Event only data would be distributed in much the same way that data is currently distributed from the global digital stations. The CDROM's will adhere to the Sony-Phillips hardware recording standard and the ISO 9660 file structure. Data will be formatted according to the internationally adopted Standard for the Exchange of Earthquake Data (SEED). Operationally, the data will be prepared for distribution using the analyst workstation interface and transmitted over Ethernet to an IBM PC based TMS Disc Architect system for pre-mastering. Each CD holds up to 650 Mbytes and can be mastered and replicated in a few weeks. A criteria for the selection of events to be included in the CDROM distribution will be developed along the same lines as the current global station criteria. CDROM's should be available beginning in 1993.

8. System Integration and Network Processor Architecture

The preceding sections have described the characteristics of hardware (and imbedded software) selected for use in the USNSN. Transforming this equipment into a working system has been a matter of both hardware and software integration. Integrating the field equipment has been a matter of unit testing, cabling, laying out the sites, civil works, providing power and timing, and interconnecting all of the equipment to make a working station. These issues will be discussed in the following sections. Integrating the central site hardware has been a matter of interconnecting the network processors, multi-ported disks, master earth station, and the optical disk jukebox; configuring each subsystem to our requirements; ensuring that sufficient conditioned (and backed up power) and air conditioning was available; and, most importantly, providing custom network processor/station processor software needed to "glue" all of the components together into a functioning, coherent whole. In the following, the focus will be on the USGS developed software. The network processor and station processor software are very closely coupled and so are most conveniently discussed together.

The network/station processor software architecture has been designed to meet USNSN operational goals including: 1) cradle-to-grave data handling (acquisition, collection, organization, distribution, and archiving), 2) NEIS Earthquake Early Alerting Service requirements (automatic real-time event detection, arrival time estimation, and earthquake location as well as analyst interfacing for re-picking phases and re-locating events), and 3) support for other seismological data. The software design has also been strongly influenced by auxiliary requirements for: 1) reliability, 2) security, 3) efficiency,

4) automation, 5) flexibility, and 6) maintainability. The design that emerged seeks to meet USNSN goals in a multi-programming, multi-processing, automatic load balancing, self monitoring, distributed database environment providing reliability, data security, and flexibility. Thus far, most of the required functionality has been provided (though without all of the bells and whistles) and the system is performing very well. Although the USNSN concept requires automated data handling, additional features of the network processor system are also being automated for reasons of reliability, timeliness, and convenience. These features include the automatic starting and re-starting of USNSN images, archiving, and most aspects of data distribution.

A block diagram of the network processor functionality is shown in figure 6. Data flow is from the top to the bottom. Software in the USNSN and RSTN (and to a lesser extent the IRIS/GSN) station processors is an extension of the network processor front end software. The data received via satellite enters the network processor through the Simpac protocol translator in parallel with older USNET data (a subset of various RSN's which has been telemetered to the NEIC for decades). The USNET data is digitized in the field by a "Phoenix" unit and transmitted via telephone lines to LSI 11/73 front ends and into the VAX through a parallel interface (DR11-WA). The NSNICP process provides the interface and distribution mechanism for the Simpac hardware. The DBCON process interfaces to the USNSN database. Between these processes are the network dependent "filters". The filters rationalize differences in sample rate, bits per sample, data format, time keeping, etc. Below DBCON, all data is in a common format and all analysis tools deal with all data in a consistent, unified manner. In the center, the automatic arrival time estimation and earthquake location (TRIGGER), the analyst interface (REWORK), the NEIS bulletin preparation interface (CULL), the earthquake and maintenance monitor (MONITR), and a bit of the data distribution system are shown as well as an outline of some elements of the database system. Around the periphery, the shaded boxes show other processors performing various functions. From left to right they are a regional network processor co-located with the NEIC (Southern Great Basin Network), the helicorder display processor (DAC4), the NEIS bulletin preparation system (NEIS), and the plasma panel processor.

The enormous capability of this system is just beginning to be realized. The speed, reliability, and convenience of seismological data interpretation will continue to increase with time as more features are implemented. The flexibility of the system has already proven itself again and again. In principle, it should enable the network processing system to remain stable through future generations of seismological field equipment. Already it has enabled us to seamlessly integrate data of very different character and from more than half a dozen different types of field equipment all into one unified database. In addition, the reliability and automation of the system will continue to increase as planned features are implemented.

9. Field Site Preparation

Although full advantage will be taken of existing sites, many installations will be made at sites never before occupied. Wherever possible, the electronics and sensors will be placed below ground in separate pre-fabricated fiberglass enclosures for thermal stability and security. The antenna installations use a permanent king post mounting for maximum durability and performance (particularly during strong winds). Cable runs between elements of the system are buried to minimize lightning strike risk and are enclosed in PVC pipes for protection from water and animals. Optical fibers will be used between the station processor and the VSAT to provide additional isolation and protection where required. An

Figure 12. Network processor functionality

environmental enclosure with an electronic heat pump will be provided for the VSAT decoding and control electronics as needed.

Every effort has been made to eliminate any moving parts (e.g., fans, etc.) in normal operation to minimize vibrations from the equipment coupling into the earth. Similarly, the antenna will be located as far from the sensors as practical to minimize wind noise. Signal attenuation on cable runs limits this to about 200 m. However, an alternative configuration in which the VSAT and the station processor/sensor elements are separated has been planned. In this case, the VSAT to station processor connection requires four channel multiplexed asynchronous telemetry via modems at an aggregate rate of at least 2400 Baud. Fiber optics are the preferred solution for this link, but limit the separation to about 5 km. The timing pulses, which are being implemented as RS-232C control signals, can be carried along with the other RS-232C data.

Stations are located absolutely using a commercially available global positioning system (GPS) with a precision of about 20 m horizontally and 25 m vertically. Accurate positioning of the station is not only a seismological necessity, it also facilitates VSAT setup. Special purpose test equipment is used to establish and tune the VSAT link. From this point, the field installers can communicate with NEIC personnel or the MES by plugging an IBM PC compatible laptop into a VSAT port and placing a call through the PAD. The same PC is used to check out the station processor (and through the station processor, the seismometers). After the installation of all equipment, end-to-end system tests are performed from the NEIC.

Seismometer installation is always an issue, particularly for broadband instrumentation. For the USNSN, a concrete pad is poured as the floor of the seismometer enclosure and the sensors are set up on their metal feet. The currently favored technique for the CMG-3 sensors is to place them close together, but not touching and to pot them in plaster of Paris. The whole assembly is then covered with a Styrofoam cooler. This technique seems to provide good coupling at all frequencies and adequate insulation from thermal fluctuations and air currents. The CMG-5 installation is not so critical, but they are being provided with tie downs in the form of brackets screwed to bolts set into the concrete. The top of the brackets fit over a flange on the sensor enclosure preventing movement during large accelerations.

10. Field Site Power

Due to the relatively high power required for the VSAT's, most (if not all) sites will have access to public utility 110 V, 60 Hz AC power. Power is conditioned and distributed via one or two charger/battery systems to the VSAT and the station processor/sensor equipment. One charger is used in most cases with a timed shutdown of the high power VSAT. Two chargers will be used where the VSAT is remotely located from the station processor. The intention is to keep the VSAT on the air for at least 30 minutes following a power outage (in the event that the outage was caused by a nearby earthquake) and to keep the station processor/sensor equipment operating for at least 24 hr. Note that data acquired by the station processor during a telemetry outage will be selectively stored in CMOS memory for later transmission. The batteries selected are 24 VDC with a capacity of 80 Amp-hr. Sealed batteries are being used to avoid problems with venting. Monitoring of the battery levels for the station processor/seismometer equipment is done by the station processor SOH circuitry as described above. Monitoring of the input AC power and battery levels for the VSAT will be done separately and transmitted to the station processor via the fourth RS-232C asynchronous port. Data on this port will be ASCII, low rate, and unidirectional (into the station processor only). Within the station processor, the remote

SOH information will be combined with the locally acquired SOH information for transmission to the NEIC.

When the station processor/sensor equipment is located remotely from the VSAT, it could be powered by solar panels as this equipment only draws about 25 W all together. It appears to be feasible, but costly, to power the entire system by solar panels almost anywhere in the continental U. S., if absolutely necessary. All together, a fully DC powered system would draw about 155 W. It appears to be possible to reduce the station processor/sensor power requirement to as little as about 10 W. There is also some commercial demand for low power DC VSATs which may eventually prompt the industry to produce a lower power subsystem.

11. Seismometer to Station Processor Interface

The seismometer to station processor interface is very complex. Between the three high-gain and three low-gain sensors there are six differential sensor outputs, three single ended mass position outputs, two single ended calibration inputs, and seven single ended control line inputs. In particular, the sensor output impedance has been conditioned to be as low as possible due to the relatively low ADC input impedance. Everything else has been matched as carefully as possible. Steps have been taken to ensure that all connectors from both vendors are compatible and are keyed such that connections are possible only between the modules intended.

Great care has been taken in devising an overall grounding strategy for the station processor/sensor subsystem. Grounding is, of course, important in any case to minimize surge problems. For differential signals it is doubly important as the seismometer and ADC ground reference must be well defined and common to both units without introducing ground loops. In a borehole configuration this is a particular problem as the two sets of sensors will be separated by at least 100 m. The strategy adopted is to define a "mecca" ground using a copper rod driven into the earth or equivalent and to tie the case grounds of the station processor, the CMG-3 FBE, and the CMG-5 to it. To avoid ground loops, the CMG-3 cases are electrically isolated by using sapphire ball bearings between the metal feet and the cases. Plastic sheets are inserted between the CMG-5 and the earth during installation to provide electrical insulation (the tie downs are also insulated). Within the CMG-3 FBE and the CMG-5, the DC/DC converter commons are tied to "mecca".

Within the station processor, all of the digital electronics are also tied to "mecca". However, the analogue front ends for each set of sensors have their own DC/DC converters with ground isolated from the digital electronics and from each other. That is, each analogue front end ground is tied to the ground of its respective sensor set. In a borehole installation, the borehole casing provides the "mecca" ground and the CMG-3 cases are grounded to it via the stacking tube and holelock. In this case, the FBE tube must be insulated from the borehole casing.

12. Station Processor to VSAT Interface

The station processor to VSAT interface consists of three standard RS-232C asynchronous connections and one control line for the timing signals. The RS-232C ports are implemented with five lines each at the station processor (including transmit, receive, data terminal ready, data set ready, and common) and as standard DB-25 connectors at the VSAT end. The three ports are used for: 1) data, 2) console, and 3) auxiliary timing information. In addition, the station processor and the VSAT each have a fourth RS-232C port. The fourth station processor port will support low rate ASCII SOH data (input only)

from the power conditioning equipment as discussed above. The fourth VSAT port is generally not used except for installation and maintenance purposes. DSR on the data port is monitored to ensure that the VSAT is active. This minimizes the risk of the station processor sending data to the VSAT when the VSAT is down, or when the call from the network processor is down.

The data port has a virtual circuit connected at all times. Data flows out of the station processor in 8-bit transparent mode. That is, all bits are passed to the network processor or, alternatively, no bit patterns are interpreted as control characters by the VSAT. The VSAT controls data flow on this circuit by sending XON/XOFF characters to the station processor as its buffers empty and fill. Also, remote commands and configuration information destined for the station processor are sent on this port. The command data rate is so low that there is no need for the station processor to control data flow from the VSAT. A virtual circuit is connected to the console port as needed for downloads and diagnostics. Downloads are sent in printable ASCII characters in Motorola S-RECORD format. Because all information transmitted via the console port is encoded in ASCII, XON/XOFF flow control is used in both directions. However, no flow control is necessary (or possible) during downloads as the station processor is otherwise idle.

The VSAT is capable of generating a true break condition of up to 25.5 s duration on any port. Custom logic in the station processor traps a 3.2 s break condition on the console port and asserts a system reset signal on the bus (in order to force a remote reboot). The station processor ignores framing errors typically interpreted by operating systems as break (and typically resulting in a processor halt). This keeps the station processor from halting when the VSAT loses power. Ignoring short breaks minimizes the chances of the VSAT electronics accidentally mimicking break during a crash. The station processor timing port accepts low rate ASCII information identifying the timing pulses, giving their quality and the VSAT time offset. There are no special requirements on this port. Scientific-Atlanta has provided a pulse width of at least 4 ms to avoid potential problems with long cable runs. The clock synchronization input will accept a wide range of voltages including the RS-232C levels being supplied by the VSAT.

13. Timing Control

All clocks drift, particularly with temperature. The drift of field clocks always seems to cause long term problems for data management and research use. The approach taken here is to attempt to effectively eliminate clock drift at the station processor. The strategy is to use a hierarchy of increasingly good time standards all synchronized by a series of software implemented "phase locked loops". At the lowest level, the station processor clock maintains time in 1/5120 s ticks since start of data acquisition. The absolute time of the next VSAT timing pulse is loaded via the console at startup. From this time on, the station processor can maintain absolute time by counting ticks from its clock.

The station processor clock time tags subsequent VSAT timing pulses which are uniquely identified via the timing port. A phase locked loop within the VSAT cleans up spurious SOF pulses and fills in any missing pulses. Information about the quality of the SOF pulses is also provided via the timing port. The VSAT position and elevation dependent time offset is compensated for in the VSAT so that the SOF pulses output will be synchronous within ≈ 16 ms (due primarily to satellite drift) across the network. Using the same absolute startup time and the known interval between SOF pulses (12.96 s), an independent time standard is developed which is stable to the accuracy of the MES master clock (10^{-9} /yr in a conditioned environment). Drift of the station processor clock relative to

this standard is compensated to a resolution of 1 ms by the station processor software by slewing the station processor clock reference frequency.

Finally, a VSAT has been co-located with the MES. Its timing signals and timing port are monitored by the LSI 11/23 playing data out on the helicorders. These signals are time tagged using the known time pulse interval as in the station processor. A third independent time standard is developed by monitoring the Kinometrics Truetime WWVB receiver. The network processor then monitors differences between the computed and measured absolute times associated with the SOF marks. As needed, the network processor will issue clock correction commands via the VSAT's which will update the absolute time maintained by the station processor. This scenario requires that all VSAT's participating in the master timing loop are using the same outbound channel since SOF timing between outbound channels is not synchronous (although they all use the same master clock).

14. Sample Waveform Data

Figures 7-16 illustrate various aspects of the USNSN system through waveform data from some recent earthquakes. Figure 7 shows (short period filtered) three component broadband records of a local Colorado event recorded at GOL. Figures 8-10 are derived from the March 13, 1992, magnitude 6.8 Erzincan, Turkey earthquake. This was the largest well recorded event up to this point in the development of the network processing system and it was gratifying to see it no where near clipping. Figure 8 shows (short period filtered) broadband records from CEH (top) and MCWV (bottom). Figure 9 shows the raw long period record from CEH. The bottom figure is just a blow up of top figure to show the body waves prior to R1 more clearly. Note that the P wave is nearly 50% of the size of the surface wave. This is not true when the record is filtered to look like a WWSSN LP indicating that much of the long period P wave energy is in the same band as the microseism peak. Figure 10 shows the vertical (top) compared with a horizontal (bottom). Both records have been filtered to simulate a WWSSN long period. Figure 11 shows the (short period filtered) broadband waveform of the March 10, 1992, magnitude 2.8 Long Island, NY event recorded at HRV. This record was significant because it was one of the first events recorded on HRV which was the first cooperating USNSN station. The record proved to be critical in the first minutes after the event because the NEIS has access to relatively few seismometers in this area and this was the only record for which there was good calibration information.

Figures 12-14 are derived from the March 24, 1992, magnitude 5.5, intermediate depth (280 km) Bali Sea event. They show an unusually fine PKP "section" using a combination of short period (RSN) and broadband (USNSN) data telemetered to the NEIC and integrated into the USNSN database. Notice, in particular, the strong PKP precursors at ALQ and FVM; the PKPbc move out on LVNJ, NAV, and CEH; and the clear arrivals of all three PKP branches at HBF. These figures illustrate the power of combining data from the numerous traditional RSN stations with the sparse broadband stations of the USNSN (i.e., effectively the beginnings of the National Seismic System). Of course, all of this data was available to the NEIS in real-time. Figures 15-16 show data from some recent large California earthquakes. Figure 15 shows the broadband waveform of the April 23, 1992, magnitude 6.2 Joshua Tree, CA earthquake recorded at ISA (the second cooperating USNSN station). Finally, figure 16 shows the broadband (top) and raw long period (bottom) waveforms from the April 25, 1992, magnitude 7.0 Cape Mendocino event recorded at CEH.

15. Network Deployment

Our current network deployment plan is shown in Attachment A including equipment which has already been installed. New installations have been ordered by priority and ease of deployment. This order is, of course, subject to change at any time. Installation will proceed as rapidly as funding and other resources permit. Note that approximately 40% of the proposed stations are existing or planned three component broadband stations installed and operated by other institutions (i.e., the USNSN cooperating stations). These data will be telemetered to the NEIC, under cooperative agreements with various institutions, and will form a logical extension to the USNSN. The cooperative stations will supply data which is comparable in quality with the USNSN (i.e., three component, broadband, high dynamic range, etc.), but with different operating characteristics. For example, the IRIS/GSN type stations feature improved very long period performance, but a lower high frequency corner. Cooperative plans have also been made with both Canada and Mexico to improve azimuthal coverage for events on the edges of the network. Note that the USGS operated RSTN stations (KS-36000 and S-750 sensors) have been included as part of the USNSN although they are not strictly broadband stations. The accompanying map shows the proposed network configuration. The circles show USNSN (or cooperating station) sites. The triangles show proposed RSN field data collection points and processing centers as well as telemetry links to some cooperating institutions.

16. Interfacing Other Equipment to the VSAT

The USNSN telemetry subsystem should be well suited for other seismological data communications applications. In particular, both cooperating USNSN and RSN telemetry from the field to the host institution processing center have been considered. In the following, the discussion will be directed towards the problems of the RSN's. The exact same mechanisms will be used for the cooperating USNSN stations, but most of the configuration and installation will be taken care of by USNSN installation personnel. Operationally, data is transmitted from the field site by means of a standard VSAT to the USNSN MES (all transfers must pass through the MES). At the NEIC, the data is made available to the network processing system and then, in most cases, returned to the host institution through another standard VSAT by one of two data distribution mechanisms as discussed above: 1) loopback or 2) programmed real-time point-to-point data distribution. Because of the USNSN telemetry resources these distribution methods require, it is only practical to provide these services to institutions requiring real-time access to some subset of the data received at the NEIC (generally the cooperating institutions). The loopback provides a bit-for-bit copy of data received from a particular source and may include command traffic back to the field site. Nominal delays on the loopback are 2 s each way end-to-end (1 s per satellite hop). The point-to-point distribution is more like the broadcast distribution discussed above, but for a limited number of stations, generally one or more nearby USNSN stations or stations from a neighboring RSN. In the following, options for configuring and interfacing USNSN telemetry equipment with non-USNSN seismic equipment will be discussed in some detail.

Possible configurations for field equipment are limited by a number of practical considerations. First, due to the high cost of the VSAT equipment ($\approx \$10.5\text{K/site}$), it is generally impractical to install a VSAT at each station site. Instead, it is much more cost effective to collect continuous raw data from a sub-network of RSN stations at a single point where sub-network processing equipment and the VSAT will be co-located. Note that a USNSN station could also be co-located with the VSAT if desired. (For cooperating USNSN stations, VSAT's are provided by the USNSN for each station.) Whether the

Eastern Colorado 10/19/90

00:32 UTC M_L 2.3 1.7°

Filtered BB (1-15 H_z)

Figure 13. Broadband records of a Colorado earthquake recorded on station GOL

CEH/BHZ F 3/13 17:31:20.08 eP
 $\Delta = 85.9$ 17:31:28.50 ipP

mb: 2307/1.48 Md:103.3 ML: 3380/1.75 Lg: 829/0.85

MCWV/BHZ F 3/13 17:31:08.32 eP
 $\Delta = 83.6$ 17:31:17.55 ipP

mb: 5254/1.79 Md:22.5 ML: 5295/1.80 Lg: 112/0.95

Figure 14. Records (stations CEH and MCWV) of 13 March 1992 Erzincan earthquake

Turkey 13 March 1992 17:18

CEH/LHZ F 3/13 17:31:20.08 eP

$\Delta = 85.9$ 17:31:28.50 ipP

17:59:20.60 LR

mb: 2307/1.48 Md:103.3 ML: 3380/1.75 Lg: 829/0.85

MS: 5741/21.8

CEH/LHZ F 3/13 17:31:20.08 eP

$\Delta = 85.9$ 17:31:28.50 ipP

17:34:52.53 PP

17:41:54.04 S

17:42:59.88 SP

17:59:20.60 LR

mb: 2307/1.48 Md:103.3 ML: 3380/1.75 Lg: 829/0.85

MS: 5741/21.8

Figure 15. Long-period records (CEH) of 13 March 1992 Erzincan earthquake

CEH/LHZ F 3/13 17:31:20.08 cP
 $\Delta = 85.9$ 17:31:28.50 ipP
 17:34:52.53 PP
 17:41:54.04 S
 17:42:59.88 SP
 17:59:20.60 LR

mb: 2307/1.48 Md:103.3 ML: 3380/1.75 Lg: 829/0.85

MS: 5741/21.8

CEH/LHN F 3/13 17:59:20.60 LR

Figure 16. Vertical and horizontal records of 13 March 1992 Erzincan earthquake

HRV/BHZ F 3/10 23:51:14.53 cPn
 $\Delta = 1.7$ 23:51:18.18 cPg
 23:51:34.86 cSn

mb: 1160.30 Md:136.8 ML: 10900.30 Lg: 5500.80

Figure 17. Broadband record of 10 March 1992 Long Island, NY, earthquake

RMW/SHZ F 3/24 17:37:42.17 ePKPdf mb: 72/0.41 Md: 20.3 ML: 72/0.41 Lg: 64/0.91
 $\Delta = 116.1$

DUG/SHZ F 3/24 17:37:59.30 ePKP mb: 41/0.61 Md: 37.8 ML: 41/0.61 Lg: 33/0.71
 $\Delta = 124.7$

ALQ/BHZ F 3/24 17:38:00.71 ePKP mb: 14/0.55 Md: 35.5 ML: 92/0.65 Lg: 98/0.80
 $\Delta = 131.4$ 17:38:14.28 iPKPdf

Figure 18. Records from the 24 March 1992 Bali Sea earthquake

FVM/SHZ F 3/24 17:38:21.30 iPKP mb: 62/0.61 Md: 40.5 ML: 62/0.61 Lg: 47/1.01
 $\Delta = 140.6$ 17:38:29.23 ePKPpdf

PWLA/SHZ F 3/24 17:38:32.19 iPKPc mb: 168/0.51 Md: 156.8 ML: 168/0.51 Lg: 91/0.71
 $\Delta = 144.0$

LVNJ/SHZ F 3/24 17:38:36.83 iPKPdc mb: 20/0.51 Md: 89.8 ML: 310/0.71 Lg: 310/0.71
 $\Delta = 145.2$ 17:38:37.95 iPKPab mb: 33/0.61 Md: 7.8 ML: 33/0.61 Lg: 13/0.91
 17:43:08.58 ?

Figure 19. Records from the 24 March 1992 Bali Sea earthquake

NAV/SHZ F 3/24 17:38:38.02 ePKPdc mb: 132/0.61 Md: 0.0 ML: 409/0.51 Lg: 362/1.01
 $\Delta = 146.1$ 17:38:39.28 iPKPbc

CEH/WHZ F 3/24 17:38:41.72 ePKPdc mb: 1433/0.45 Md: 154.0 ML: 3390/0.45 Lg: 1634/0.75
 $\Delta = 148.0$ 17:38:45.01 iPKPbc

HBF/SHZ F 3/24 17:38:45.69 ePKPdc mb: 199/0.61 Md: 20.8 ML: 451/0.51 Lg: 294/0.71
 $\Delta = 149.8$ 17:38:50.01 iPKPbc
 17:38:56.74 iPKPab

Figure 20. Records from the 24 March 1992 Ball Sea earthquake

California Earthquake of April 23, 1992 recorded on Isabella Broadband Station

Figure 21. Record from the 23 April 1992 Joshua Tree, CA, earthquake

CEH/BHZ F 4/25 18:12:58.70 eP mb: 6135/0.90 Md: 0.0 ML: 6447/0.95 Lg: 6447/0.95
 $\Delta = 35.4$

CEH/LHZ F 4/25 18:12:58.70 eP 18:22:52.32 LR mb: 6135/0.90 Md: 0.0 ML: 6447/0.95 Lg: 6447/0.95
 $\Delta = 35.4$

Figure 22. Records from the 25 April 1992 Cape Mendocino, CA, earthquake

regional sub-network data arrives at the collection point in analogue or digital form, by telephone line or radio is immaterial. Functionally, the sub-network processor needs to acquire the data (in digital form), time tag, merge, and queue it for transmission. In its turn, the data is forwarded to the regional processing center via the VSAT, the MES, and another VSAT. Although the VSAT is capable of a sustained inbound throughput of 38 Kbit/s under optimal conditions, rates of 1.2-9.6 Kbit/s more appropriate for most uses due to the aggregate throughput limitations of the PAD software. A minimum data rate is ensured by balancing VSAT's on each inbound channel. The relatively low data rate requires that the sub-network processor reduce the telemetry load and average it over time by event detecting the data and buffering it. (For cooperating USNSN stations, event detected broadband and continuous long period data would be telemetered.)

For example, a sub-network processor collecting eight stations and digitizing them with a 12-bit ADC at 100 sps would accumulate about 72 Kbyte/min or about 9.6 Kbit/s. If the VSAT had been allocated a throughput of at least 2.4 Kbit/s, a two minute detection would take more than 10 min to transmit (with overhead). With a 5% detection rate, the VSAT would be transmitting no more than 6 hr/day. If the other users on the same inbound link adhered to the same 25% duty cycle, the VSAT would typically transmit only about 1.5 hr/day or about 80% of real-time. In the case of a swarm or aftershock sequence, the events could accumulate faster than they could be telemetered. Assuming 16 Mbytes of memory are available for buffering, approximately 100 events could be saved. Under typical conditions, and with a 16 Mbyte buffer, the system could run for almost 16 hours triggering continuously without data loss. However, in the extreme case where all VSAT's on a given inbound channel were accumulating events very rapidly, it would only be possible to trigger continuously for 4 hours before losing data. Clearly, the performance of a particular sub-network processor will depend upon how fast data is being accumulated, the worst case VSAT throughput, the detection length and rate, the amount of buffer memory available, and the mix and characteristics of other users on the inbound link. In practice, other factors often further complicate the calculation. For example, many RSN operators have expressed an interest in telemetering some low passed and decimated continuous data for helicorder display. In this case, if two of the channels were processed to provide both 100 sps detections and 10 sps continuous data, this would increase the total amount of data to be transmitted by 50%.

Interfacing with a VSAT in the field is the same as for a USNSN station. The physical connection is made with a standard DB-25 connector for each asynchronous port required. A wide range of port configurations are available, but we generally use 9600 Baud, 8-bits, odd parity, and one stop bit. Prior to transmission, the data must be formatted according to the standards presented in Attachment B for compatibility with USNSN software. Generally, this involves breaking the data into packets and adding a standard header structure (i.e., no data reformatting is required). Using the standard format should not be burdensome because it is compact, efficient, and easy to program except for the optional rollback provision which requires 16 Kbytes of backing memory and the ability to process commands coming back on the data port. Because this is a binary format, the data sent to the VSAT will be in 8-bit transparent mode (usually with XON/XOFF flow control) as described above. That is, data written by the sub-network processor is 8-bit transparent, but data read by the sub-network processor is subject to the usual control character processing. Therefore, the VSAT may use XON/XOFF flow control on the sub-network processor, but not vice versa. While optional, the use of the XON/XOFF flow control is strongly recommended to ensure that all data reaches the VSAT. Similarly, the use of the optional rollback protocol is strongly recommended so that the USNSN network processor can ensure data continuity across virtual circuit

disconnections by requesting selective data retransmissions. For further information see the "USNSN Satellite Interface Primer" available from the NEIC.

Alternative means of flow control from the VSAT are possible and will be investigated on request. All four VSAT ports are available for sub-network processor use unless a USNSN station is co-located in which case only one port will usually be available. If absolutely necessary, more ports can be made available by configuring the VSAT for synchronous X.25 and providing external multiport PAD(s). Other VSAT facilities provided for the USNSN may also be adapted for cooperating station or RSN use if desired. For example, the generation of a true break of programmable length is available on all ports. The USNSN timing information is also be available if desired (although it uses one of the available VSAT ports). However, special arrangements will have to be made for downloading the absolute time from the NEIC at boot up. Note that if the sub-network processor console port is connected with the VSAT, processor halt on a framing error (usually reported as a break) should be disabled to avoid halting data collection when the VSAT is powered down. Also, DSR (data set ready) should be monitored on the data port to detect a VSAT not ready condition and avoid data losses. DSR is dropped if the virtual circuit is cleared and, of course, if the VSAT is powered down.

Data relayed from the field to the regional network processing center via the NEIC MES will arrive through a VSAT identical with the field version. There are two means of interfacing local processing equipment with the VSAT. The most straightforward method is to use the VSAT PAD facility. Data would then be delivered to the regional network processor on a standard asynchronous port. If several remote VSAT ports (perhaps from different VSAT's) were being monitored, they would arrive on separate PAD ports (i.e., each port in the field is mapped to one virtual circuit which is mapped to one port in the laboratory). The VSAT has four ports all of which are available. By configuring the VSAT for synchronous X.25 and using external PAD(s), this could easily be expanded to 16 ports. However, for more ports and higher aggregate data rates, the character interrupt overhead on the receiving processor may well be a problem. The best way to handle a large number of ports and/or a high aggregate data rate is to configure the VSAT for synchronous X.25 and to bring the X.25 data stream directly into the receiving processor. Hardware or software on the receiving processor then interprets the X.25 protocol to extract the various virtual circuits in the same manner as the PAD would have. Hardware protocol converters are strongly recommended since software converters (e.g., DEC PSI) can also have very high overheads. Note that in synchronous operation, the VSAT is limited to 19.2 Kbps each on up to two synchronous ports. In practice we find that this aggregate can only be achieved by using a large number of relatively low data rate virtual circuits.

Software for interpreting data acquired via the USNSN telemetry system has been written by USNSN personnel and is available from the NEIC anonymous ftp (gldfs.cr.usgs.gov). It is the users responsibility to ensure that complete data can be obtained from the terminal driver or protocol translator on the local receiving processor. The software provided is a model for interpreting this data. In particular, it shows how to synchronize with the data stream, how to interpret the packet headers, and how to decode both USNSN and Steim compressed data. This software has been ported (to SUN UNIX) at Harvard. Work on other versions is underway at Caltech and Saint Louis University.

Attachment A

Operating Sites

Symbol	Code	Location	State	Lat	Long
○	RSSD	Black Hills	SD	44.12	-104.04
○	RSNY	Adirondack RS Obs	NY	44.54	-74.53
○	ALQ	ASL	NM	34.94	-106.45
○	GOL	Bergen Park	CO	39.70	-105.37
○	CEH	Chapel Hill	NC	35.89	-79.09
○	MCWV	Mont Chateau	WV	39.60	-79.90
○	TPNV	Topopah Spring	NV	36.93	-116.22
○	CBM	Caribou	ME	46.93	-68.00
○	WMOK	SW Oklahoma	OK	34.70	-98.60
○	MIAR	Mt. Ida	AR	34.55	-93.58
□		Pasadena	CA	34.15	-118.18
□		St. Louis	MO	38.60	-90.20
△	ISA	Isabella	CA	35.66	-118.47
△	CCM	Cathedral Cave	MO	38.06	-91.24
△	HRV	Harvard Obs.	MA	42.51	-71.56
△	CMB	Columbia	CA	38.03	-120.38
△	WDC	Whiskeytown	CA	40.58	-122.54
△	JFWS	Mineral Point	WS	42.70	-90.50
△	TUC	Tucson	AZ	32.31	-110.78

Installed Sites

Symbol	Code	Location	State	Lat	Long
○	RSCP	Cumberland Pl. Ob	TN	35.60	-85.59
○	NEW	Newport	WA	48.26	-117.12
○	DUG	Dugway	UT	40.20	-112.81
□		Berkeley	CA	37.90	-122.30
□		Cambridge	MA	42.37	-71.10
□		Memphis	TN	35.12	-89.93
□		Menlo Park	CA	37.60	-122.30
□		Weston	MA	42.38	-71.32
□		Rockville	MD	39.08	-77.17
□		Lexington	KY	38.03	-84.50
□		Salt Lake City	UT	40.75	-111.92
△	BW06	Boulder Array	WY	42.78	-109.57
△	SSPA	Standing Stone	PA	40.64	-77.89
△	LTX	Lajitas	TX	29.33	-103.67
◇		Marked Tree	AR	35.52	-90.43
◇	YMT0	Yucca Mountain	NV	36.82	-116.47

Attachment A

Planned Sites

Symbol	Code	Location	State	Lat	Long
○	AL1}	Alabama	AL	33.10	-87.50
○	AAMB}	Ann Arbor	MI	42.30	-83.66
○	BINY	Binghamton	NY	42.20	-75.99
○	BLA	Blacksburg	VA	37.21	-80.42
○	DE1}	Delaware	DE	38.70	-75.40
○	GOGA	Godfrey	GA	33.40	-83.50
○	HKT	Hockley	TX	29.95	-95.83
○	IL1}	Illinois	IL	40.50	-87.7
○	LSCT	Lakeside	CT	41.70	-73.20
○	LBNH	Lisbon	NH	44.20	-71.90
○	MYNC	Murphy	NC	35.10	-84.20
○	OSOH	Columbus	OH	40.00	-83.10
○	RI1}	Rhode Island	RI	41.50	-71.30
○	ND1	North Dakota	ND	46.6	-100.30
○	YSNY	Yorkshire	NY	42.40	-78.65
○	BMN	Battle Mountain	NV	40.43	-117.22
○	WVOR	Wildhorse Valley	OR	42.30	-118.70
□		Palisades	NY	41.00	-73.90
□		Columbia	SC	34.00	-81.00
□		Seattle	WA	47.60	-122.30
□		La Jolla	CA	32.83	-117.27
□		Ottawa	ON	45.35	-75.70
□		Reno	NV	39.50	-119.80
□		LLNL (added)	CA	37.6	-121.8
□		State College	PA	40.80	-77.86
△	COR	Corvallis	OR	44.59	-123.30
△	SAO	Hollister	CA	36.76	-121.44
△	KS1}	Central Kansas (reloc.)	KS	38.85	-99.35
△	ELK	Elko	NV	40.74	-115.24
△	KNB	Kanab	UT	37.02	-112.82
△	MNV	Mina	NV	38.43	-118.15
△	TUL	Leonard	OK	35.91	-95.79
△	IO1}	SW Iowa	IO	41.0	-95.0
△	MN1	SW Minnesota	MN	44.0	-96.4
△	MS1	NE Mississippi	MS	34.9	-88.4
△	IN1	Indiana	IN	39.1	-86.5
◇		Charleston So. U.	SC	32.98	-80.06
◇		New Madrid	MO	36.60	-89.50

Planned Deployment of the USNSN

Appendix A

The following describes the USNSN telemetry packet format. This format will be used by all USNSN stations and it is highly desirable that regional seismic networks (RSN) also adhere to it. There are two basic packet types; data packets containing seismic traces and status packets containing auxiliary information. All packets have a 14 byte fixed header; a description of each byte in this header is listed first in the information attached (Generic Fixed Packet Header). Note that 'detection' is synonymous with 'event' (trigger condition indicating something is happening).

All trace data packets must have a 6 byte data header following the fixed header. The trace data comes after the data header and can be in any of the formats listed in the attached description of this packet type below (Generic Trace Data Packet). If another data type is desired, requests to do so must be submitted to the USNSN. A copy of the NSN specific packet is included.

All status packets must have a 2 byte status header identifying the status packet type. This follows the 14 byte fixed header and then whatever auxiliary information fills the remainder of the packet. A general format is presented below (Generic Status Packet), followed by some suggestions and specific examples (these are only examples and can be modified or disregarded). Additional input from the RSNs to the USNSN will be welcomed.

Note that VAX bit order is used (bits are numbered from the low order end of the word). VAX byte order is also used (e.g. in an I*4 word the lowest order byte is sent first).

An explanation of the USNSN time code is included in Appendix B. A FORTRAN subroutine (for a VAX) to decode the USNSN time code written by Dave Ketchum is also included.

USNSN Generic Fixed Packet Header Description

Byte	Description
<u>Fixed Header Portion of Packet (14 bytes)</u>	
1	Lead in character 1 (decimal 27, ascii ESC)
2	Lead in character 2 (decimal 3, ascii ETX)
	These 2 lead in bytes aid in 'syncing up' and to monitor packet integrity (all packets will be checked to be sure they have the correct number of bytes and are followed by lead in characters for the next packet).
3 - 4	Number of bytes in packet, rollback inhibit bit flag The maximum packet length (including headers) is 2038 bytes. The packet length must be even. This should be an l^2 variable with the low order byte stored first. Bits 0-10 = packet length (number of bytes). Bit 11-14 = reserved, set to zero. Bit 15 = rollback inhibit bit flag (see Appendix C).
5	Network Routing ID At least 2 Network IDs will be assigned to each RSN. One will correspond to data packets & the other to status packets. If the USNSN wants to look at certain status packets or a RSN wants to be able to sort status packets more finely at this level, the USNSN can assign additional IDs (eight/RSN will probably be the maximum).
6	Node ID A node corresponds to the processor attached to a single VSAT port. Node IDs are assigned by the RSN and should start at 1 and increment sequentially. The RSN must keep the USNSN informed about the correspondence between nodes and their IDs in order to ensure proper routing.
7	Station/Channel ID Identifier for a single data stream if this is a data packet and equal to zero if this is a status packet. Assigned by the RSN.
8	Packet Sequence No. This is a modulo 256 counter used for the roll back facility provided by the USNSN. A sequence number tags each packet leaving a node in sequence. The USNSN will check for continuity of the sequence numbers for each node as the packets come into the NEIC; if a problem is detected for a specific node a message will be sent back to the node requesting retransmission of data beginning at the last sequence number that was received correctly. In order to utilize this facility, the RSN node must buffer packets. According to the VSAT vendor, the maximum amount of data that could be lost due to a fade or hardware failure is 16000 bytes; this would correspond to buffering approx. 8 full packets. A RSN does not have to support this roll back facility but must provide a sequence number in any case.
9 - 14	Time code - USNSN 48 bit code (see Appendix B for more explanation) Byte 1 bits 1-7 = number of years that have passed since 1970 (unsigned integer). bit 0 = set if 256 needs to be added to the number of days decoded from byte 2 Byte 2 = modulo 256 of the day of the year. Bytes 3-6, bit 31 = unused bits 4-30 = Milliseconds since midnight bit 3 = set if this is a positive leap second day bit 2 = set if this is a negative leap second day bits 0-1 = unused If this is considered as an l^4 variable, the high order byte is sent first. If this is a data packet this time corresponds to the first sample. The correspondence

for status packets depends on the status packet type. A sample decoding routine is included in this package. Note that packets will not necessarily be received in order of increasing time; e.g. data sampled at lower rates will take longer to fill a packet, packets from one data stream may arrive in between packets from another stream, etc.

----- Variable Portion of Packet (max of 2024 bytes; # bytes must be even)-----

USNSN Generic Trace Data Packet Description

Byte	Description
<u>Fixed Header Portion of Packet (14 bytes)</u>	
1	Lead in character 1 (decimal 27, ascii ESC)
2	Lead in character 2 (decimal 3, ascii ETX)
3-4	Number of bytes in packet
5	Network data packet ID - assigned to each RSN by USNSN.
6	Node ID - node data transmitted from
7	Station/Channel ID - Identifier for this data stream.
8	Packet Sequence No.
9-14	Time code - USNSN 48 bit code - Time the first sample was taken.
<u>Data Header (6 bytes)</u>	
15	Data Format Code 0 = USNSN Compression. See Appendix D. 1 = Stein compressed 2 = 12 bit, 2's complement 3 = 16 bit, 2's complement 4 = 24 bit, 2's complement 5 = 32 bit, 2's complement 6 = gain ranged; RSTN 14+2 7 = gain ranged; 12+4 (SRO) 8 = gain ranged; 13+3 (GSS) 9 = gain ranged; other 14+2 Other formats may be added; please submit any suggestions for additions.
16	Data Flags These are bit flags describing things about the data. Bits 0 & 1 have been defined by the USNSN, suggestions for use of bits 2-7 are requested by RSN operators. bit 0 = end of detection bit 1 = calibration signal turned on during packet bit 2-7 = reserved
17	Day Detection Started Modulo 256 of the Julian day that this detection started on. Together this, the station/channel code, and the detection sequence number (below) create a unique label for a trace corresponding to a particular event. This unique ID is used by the USNSN network processor for quick keying of data.
18	Channel Sequence Number Unsigned, modulo 256, counter corresponding to the channel associated with the data in this packet. This counter starts over at 1 each time there is a new detection. Thus each channel will have a sequence no. or counter associated with it that starts at 1 and ends at the total number of packets required to send the entire trace for a particular detection. This allows the continuity of a particular trace to be checked without needing to decode the time.
19-20	Detection Sequence Number This 1*2 number tags each detection uniquely. This sequence number begins at 1 each day and increments by 1 for each new detection. The low order byte is stored first.
<u>Data (max of 2018 bytes - must be even)</u>	
21-...	Data bytes

USNSN Specific Trace Data Packet Description

Byte	Description
<u>Fixed Header Portion of Packet (14 bytes)</u>	
1	Lead in character 1 (decimal 27, ascii ESC)
2	Lead in character 2 (decimal 3, ascii ETX)
3-4	Number of bytes in packet
5	Network data packet ID - Zero for USNSN.
6	Node ID - node data transmitted from
7	Station/Channel ID - Identifier for this data stream. The modulo 3 of this byte gives the direction of the component: 0-N-S, 1-E-W, 2-Vertical. The rate of the data is as follows: 0-2-80 Hz, 3-5-40 Hz, 6-8-20 Hz, 9-11-10 Hz, 12-14-1 Hz.
8	Packet Sequence No.
9-14	Time code - USNSN 48 bit code - Time the first sample was taken. NOTE: When decompressing data starting with a block whose channel sequence number is not 1, the first sample returned will be one digitizing interval before this time. This occurs because the compression algorithm returns the forward integration code as the first sample when starting out and compares it to the last sample for continuity in latter buffers. For convenience, the USNSN processors take this into account when time tagging the first buffer of a series.
<u>Data Header (6 bytes)</u>	
15	Data Format Code 0 - USNSN Compressed (USNSN standard; see Appendix D)
6	Data Flags The USNSN uses the following definitions for the flag bits in its packets bit 0 - end of detection bit 1 - calibration signal turned on during packet bit 2 - Currently not used bit 3 - Partial flag. Certain long period packets are transmitted as smaller chunks and reconstructed into a full packet. This facilitates getting real time long period data on a more timely basis as more the 50 minutes of LP data might end up in a single packet. The first 1/2 of the data portion is the number of samples represented for the entire updated packet. The second 1/2 represents the offset in bytes in the data portion represented by the first data byte of this packet. Bit 4 - Indicates this partial buffer (bit 3 must be true for this bit to be on) is the last partial update of this record. This bit indicates the buffer under accumulation is complete. Bit 5 - Debugging/reserved bit. Currently used to indicate special continuous data streams from a normally triggered stream. Bit 6 - Debugging/reserved bit. Currently used to indicate trigger flag is on for continuous data (bit 5 must be on for this bit to be set). Bit 7 - Debugging/reserved bit. Currently used to flag special "power spectra" packets. Station channel byte for this debugging type are set to 127.
17	Day Detection Started Modulo 256 of the Julian day that this detection started on. Together this, the station/channel code, and the detection sequence number (below) create a unique label for a trace corresponding to a particular event. This unique ID is used by the USNSN network processor for quick keying of data.
18	Channel Sequence Number Unsigned, modulo 256, counter corresponding to the channel associated with the data in this packet. This counter starts over at 1 each time there is a new detection. Thus each channel will have a sequence no. or counter associated with

It that starts at 1 and ends at the total number of packets required to send the entire trace for a particular detection. This allows the continuity of a particular trace to be checked without needing to decode the time.

19-20 Detection Sequence Number

This 1*2 number tags each detection uniquely. This sequence number begins at 1 each day and increments by 1 for each new detection. The low order byte is stored first. This number is initialized to the number of seconds since midnight divided by 3 at program startup.

q

..... Data (max of 2018 bytes - must be even).....

21-... Data bytes

The data section is dependant on the data form code set above. The types currently used by the NSN are compressed data with or without partial update, 12 bit data suitable for real time analog display, and debugging power spectral packets. Sample routines for decoding and constructing these types is available. USNSN compression is described in Appendix D.

USNSN Generic Status Packet Description

Byte	Description
<u>Fixed Header Portion of Packet (14 bytes)</u>	
1	Lead in character 1 (decimal 27, ascii ESC)
2	Lead in character 2 (decimal 3, ascii ETX)
3-4	Number of bytes in packet
5	Network data packet ID - assigned to each RSN by USNSN
6	Node ID - node information transmitted from
7	Station/Channel ID = 0
8	Packet Sequence No.
9-14	Time code - USNSN 48 bit code
<u>Status Packet Header (2 bytes)</u>	
15	Status Packet Type
16	Reserved
<u>Status Information (max. of 2022 bytes - must be even)</u>	

Appendix B

USNSN Time Code Description

The USNSN time code is rather conventional in its use of the year, Julian day, and time in milliseconds since midnight. However, it is unconventional in its implementation of leap seconds. Imbedding the leap second flag into the time code assumes that the time keeper (perhaps in the field) knows that the current day will include either a positive or negative leap second before the day actually begins (so that the flag is correct for the entire day). The time keeper then either extends the day by one second or ends the day one second early before rolling the day over (time is kept by counting milliseconds since midnight). Note that in the code below, on a day when there is no leap second, there will be a maximum time of 23:59:59.999 (86,399,999 milliseconds). When there is a positive leap second, the maximum time returned by the code below will be 23:59:60.999 (86,400,999 milliseconds) rather than 24:00:00.999.

For the USNSN stations the leap second flag will be set by the station processor on command via satellite from the control center in Golden. The leap second flags will then be used when computing time differences which span a day boundary. Note that the time differences spanning more than 24 hours cannot be guaranteed to be correct without examining the leap second flags of time codes associated with the data on intervening days.

The following subroutine will decode the time on a VAX computer and will return the leap second flag. Note that this will only work on computers that store I*4 words with the low order byte in the lowest address. For those computers that use the opposite order the indices of the array 'byte' must be reversed (e.g. from '5-j' to 'j'). The time code is ordered such that if it is sorted as a 6 byte binary field it will collate in increasing time. Bit 0 is least significant bit.

Bytes	Bits	Description
1	1-7	Number of years that have passed since 1970 (unsigned integer).
1	0	Set if 256 needs to be added to the number of days decoded from byte 2.
2	0-8	Modulo 256 of the day of the year.
3-6	31	Unused. Byte 3-6 contain data such that if they are considered as an I*4, the highest order bits are in the lowest address byte (big endian).
3-6	4-30	Milliseconds since midnight.
3-6	3	Set if this is a positive leap second.
3-6	2	Set if this is a negative leap second.
3-6	0-1	Unused.

USNSN Time Code Decoding Subroutine (for a VAX)

```

subroutine yrday(ns,yr,day)
.....
c      Obtain year and day of year from an nsn time code
c
c      ns      NSN time code input
c      y r     i*4 year of time code
c      day     i*4 day of time code
c
c      D.C. ketchum Feb 1991
c
      logical*1 ns(6),byte(4)
      integer*4 yr,day,i4
      equivalence (i4,byte)
      i4=0
      byte(1)=ns(1)
      ioff=0
      if(iand(i4,1).ne.0) ioff=256
      i4=i4/2
      yr=i4+1970
      byte(1)=ns(2)
      day=i4+ioff
      return
      end

subroutine pyrday(yr,day,ns)
.....
c      Given a year and day create the first two bytes of NSN time code in NS.
c
c      D.C. Ketchum Feb 1991
c
      byte ns(6),byte(4)
      integer*4 ms,ims,i2,YR,DAY
      equivalence (i2,byte),(ms,i2)
      if(yr.lt.326) then
         i2=(yr-70)*2
      else
         i2=(yr-1970)*2
      endif
      if(day.ge.256) i2=ior(i2,1)
      ns(1)=byte(1)
      i2=mod(day,256)
      ns(2)=byte(1)
      return
      end

```

```

..... subroutine maknsn(yr,day,hr,min,sec,lms,leap,ns)
c .....
c Make a USNSN time code from the yr, day, hour, min, sec, ms and leap
c D.C. ketchum Apr 1990
c
  implicit integer*4 (a-z)
  byte ns(6),byte(4)
  equivalence (ms,byte)
  call pyrday(yr,day,ns)      ! stuff year and day into bytes 1-2
  ms=hr*3600+min*60+sec      ! compute milliseconds since midnight
  ms=ms*1000+lms
  ms=ms*16                    ! shift so low order is in bit 4
  if(leap.ne.0) then          ! is this a leap second day
    if(leap.eq.1) ms=ms.or.8   ! is it a positive leap second, or in bit 3
    if(leap.eq.-1) ms=ms.or.4 ! is it a negative leap second, or in bit 2
  endif
  do 1 j=1,4                  ! Note : Vax is little endian machine
    ns(j+2)=byte(5-j)         ! put MS and flags in bytes 3-6
1  continue
  return
end

..... subroutine nsnint(ns,yr,day,hr,min,sec,leap)
c .....
c Convert a USNSN time code in NS to the equivalent integer yr, day,
c hour, minute, sec and leap.
c
c D.C. Ketchum Apr 1990
c IMPLICIT INTEGER*4 (A-Z)
c logical*1 ns(6),byte(4)
c integer*4 i2,yr,day,hr,min,leap
c equivalence (i2,i4),(i2,byte)
c real sec
c integer*4 i4
c call yrday(ns,yr,day)      ! get day and year
c do 1 j=1,4                  ! Note : Vax is little endian machine
c   byte(5-j)=ns(j+2)        ! move from high order 1st to low ord
1  continue
  leap=0                      ! assume no leap
  if(iand(i4,8).ne.0) leap=1  ! set leap if bit set
  if(iand(i4,4).ne.0) leap=leap-1 ! Negative leap second
  if(leap.eq.0.and.iand(i4,12).ne.0) then
    type *,'Leap both ways???'
  endif
  ms=i4/16                    ! move ms down low order
  hr=ms/3600000               ! compute hours from ms
  ms=ms-hr*3600000            ! remove hours from ms
  min=ms/60000                ! minutes
  ms=ms-min*60000             ! remove minutes from ms
  sec=float(ms)*.001
  if(leap.eq.1.and.hr.eq.24) then ! its the last sec of leap second day
    hr=hr-1
    min=min+59
    sec=sec+60.
  endif
  return
end

```


Appendix C

USNSN Rollback Specification

The USNSN will support an optional rollback function to allow recovery of data lost during satellite transmission. Requests for rollback will be generated automatically by the software at the Golden receiving site for satellite locations that have indicated that they support the feature. Based on research by the satellite vendor it is estimated that 16 kB of data is the most that can be lost during a satellite outage assuming the site implements "call is up or DSR" flow control as well as XON/XOFF flow control. This represents all of the data that could be buffered in the DPU, in the Master Earth Station in Golden, and "in the air" at the time of a failure. Requests for roll back are received on the same line that the data are transmitted on and are generated at the Golden Master Earth Station. The definition of a control packet follows the general USNSN command packet protocol. A few terms used below are defined here.

Sequence number - A one byte sequence number that is included in every USNSN packet. It increments with each packet transmitted and rolls over from 255 to 0.

Command Packet - A general format that all commands from Golden to a field site follow. This format is designed to be self routing. Command packets are encoded from their "in memory" binary form to a printable ASCII form. This encoding is necessary so that the receiving equipment can use XON/XOFF flow control and to prevent special "control" characters from confusing the input driver.

Rollback Command Packet - A particular Command Packet used to cause the retransmission of packets from a field site when packets are lost for any reason. It communicates the sequence number of the last correctly received packet so the field equipment can choose where to start transmitting.

Call is up flow control - DSR (pin 6) of the DPU serial port is high when a X.25 call is up to the port. If this hardware line is down, no connection exists between the port and the computers in Golden. Field computers should monitor this line to insure that Golden is listening and inhibit transmission of data when the line is low.

Command Protocol - Commands must be reconstructed to their in memory definition. The two lead-in characters are sent as is. The remainder of the packet (byte 3 to end of command packet) is encoded as printable ASCII by splitting the 8 bits into two 4 bit nibbles and adding 32 decimal (20 Hex). The first character transmitted in each pair contains the 4 high order bits of the encoded byte. Hence, the number of bytes transmitted is given by :

$$nbytes=(n-2)*2+2$$

where n is the number of bytes in the command packet including the lead in bytes.

The general format of a command packet is :

Offset	Description
1	Lead in 1 always 27 decimal (ESC).
2	Lead in 2 always 3 decimal (STX).
3-4	Number of bytes in packet including lead ins, low order byte first in the encoded printable ascii form. The low order 11 bits are used for the count. The highest order bit is the "ROLLBACK inhibit bit". The remaining bits are

	not used and are reserved and should be zero. Note : The flag bits are ORed in with the byte count.
5	Netid - The network ID assigned to the network by USNSN.
6	Nodeid - The node id assigned to the field processor by the operator.
7	Station/Channel ID - assigned by the operator to identify a particular channel of data.
8	Sequence - Not used at this time
9-14	A USNSN time code optionally used by the command
15	CMD Code - Command codes 0-31 are reserved by the USNSN for NSN functions. The remaining command codes are assigned by the network operator.
16-nbytes	Command dependent data.

Rollback Packets - Each USNSN packet sent to Golden contains a byte sequence number. The Golden software monitors incoming packets for continuity of this sequence number. If the continuity is broken, and the USNSN packet "Rollback inhibit" bit is not set, and the NSN database indicates that the node supports rollback, a rollback command packet will be generated. The command code for a rollback packet is 4. There is only one command dependent byte and it contains the sequence number of the last received packet. Hence, a roll back packet contains 16 data bytes in memory and is transmitted as 30 encoded characters per the above formula.

Field Behavior on receipt of rollback packets - One bit in the USNSN packet format is the "Rollback Inhibit" bit. This bit indicates to the USNSN that the packet being received cannot trigger a rollback. There are only two times this bit should be set :

- 1) If the program has just started, set "Rollback inhibit" for the first 4 blocks sent out.
- 2) After receiving a rollback request set "Rollback inhibit" for the first 4 blocks in response to the request.

Note that the sequence number in the rollback request is the last received sequence. This is the sequence number of the first packet that should be transmitted. If that sequence number cannot be transmitted, the oldest data packet available and all of its successors should be sent. If no packets are available, continue sending data from the current point. In any case the next 4 packets transmitted after receipt of the rollback request must have the "Rollback inhibit" bit set.

Example : The USNSN field processors implement rollback in the following manner :

Variables	Definition
rollback_countdown	When > 0, the rollback inhibit bit will be set in outbound packets. It is set to 4 when the program starts and after a rollback request is received. The variable is decremented after each transmission until it reaches zero.
next_buffer_to_queue	Points at the buffer which will receive the next packet built by the acquisition program. Initialized at start to point to first buffer. It is incremented after each packet is received from the acquisition program.
next_buffer_to_transmit	Points at the buffer which will be sent out of the serial port next. It is initialized at start to point to the first buffer. It is incremented after the buffer is transmitted out the serial port.

This pointer chases the next_buffer_to_queue pointer as queued buffers are transmitted.

sequence_number

Contains the sequence number to assign to next packet received from the data acquisition program. It is used to set the sequence number in the USNSN packet after buffer is copied to the buffer pointed to by next_buffer_to_queue.

1) Initialization - Twelve buffers for USNSN packets are allocated in memory. The pointers next_buffer_to_queue and next_buffer_to_transmit are initialized to point to the first data buffer. As long as the pointers are equal no data is available for transmission. Variable rollback_countdown is set to four causing the first 4 buffers transmitted to have the rollback inhibit bit set.

2) When the new data from the acquisition program is available, a temporary variable is set to next_buffer_to_queue plus one and wrapped mod 12. The temporary variable is compared against the next_buffer_to_transmit. If they are the same, there is not a buffer available to queue the data (buffer overflow) and no action is taken. If they are different, the data are copied to the buffer pointed to by next_buffer_to_queue, the packet sequence number is set to sequence_number, the pointer next_buffer_to_queue is set to the temporary variable, and sequence_number is incremented.

3) When the data port is ready to transmit more data, the buffer pointed to by next_buffer_to_transmit is processed. If rollback_countdown is greater than zero, the rollback inhibit bit is set and rollback_countdown is decremented. The buffer is written out the serial port and next_buffer_to_transmit is incremented and wrapped.

4) If a rollback request is received, the sequence numbers of the twelve buffers are checked for the sequence in the rollback command. If a match is found, the next_buffer_to_transmit pointer is changed to that buffer. If no match is found, the oldest buffer is identified and next_buffer_to_transmit is set to point to that buffer. The variable rollback_countdown is set to four.

Steps 2-4 are repeated indefinitely.

Appendix D

The NSN Data Compression Algorithm

The NSN data compression scheme follows the same philosophy as all other data compressions methods in common use for seismological data today. Compression depends on the fact that seismological data acquisition systems are designed to record very large values of ground motion which are very rarely attained. Thus, the compression results from eliminating as much of the sign extension portion of each raw data value as possible in such a way that the original value is exactly recoverable. The algorithm is divided into two portions: preprocessing to minimize the fluctuations of the (preprocessed) data about zero as much as possible and encoding of the data values into variable length data fields and adding information in accompanying key fields to permit decoding. In addition, the algorithm makes provisions for effective use of fixed length (computer storage) records, imbedded header information (channel identification, time, status, etc.), and redundant information to promote fault recovery. The NEIC has programmed this algorithm in FORTRAN for little endian machines and in C for big endian machines. Conversion to other systems is not difficult.

In NSN compression, preprocessing is a simple first differencing which requires at least one integration constant to be recoverable. Encoding is patterned on a scheme developed at the Geological Survey of Canada by Ken Beverley. Each key field corresponds to a fixed number of fixed length data fields. Taken together, the data fields belonging to one key field always begin and end on an (8-bit) byte boundary in the computer storage, but will, in general occupy different numbers of bytes for different key values. The organization and definitions of the key values has been modified from the Canadian scheme to adapt it for fixed length records and to achieve less key overhead for small data values. A fixed length header section is provided for at the beginning of each fixed length record. A forward integration constant is provided at the beginning of each record as part of the header. Only the first constant is actually required. In addition, back pointers are imbedded into the encoded data and a reverse integration constant added at the end of each time series. This redundant information has been added to permit the recovery of as much data as possible should any portion of the compressed data be corrupted.

Before describing the algorithm in detail, it is useful to define some specialized terms to avoid ambiguity (as much as possible):

Data Value. The digitally encoded value of a sensor output. Note that the data values acquired by an analogue-to-digital converter and the data values used in a computer must be numerically identical, but may be encoded differently (e.g., fixed versus floating point or different sign representations). The format of a data value encoded into a data field may be different again and will have been preprocessed as well.

Time Series. A time series is a number of data values acquired from one sensor output at contiguous, equally spaced time intervals.

Byte. A number of contiguous bits in computer storage. Standardization in the computer industry has specialized the use of the term byte to mean eight contiguous bits. A byte is generally the smallest individually addressable unit of computer storage.

Record. A fixed length logical record of computer mass storage. Because of the organization of most modern mass storage devices, a moderately large power-of-two number of 8-bit bytes will provide both rapid access and compact storage.

Header. A fixed length section of (mostly) user defined information located at the beginning of each record. Note that a portion of the header is reserved for information required by the compression algorithm.

Trailer. A fixed length section of compression algorithm defined information located at the end of the last record of a time series.

Nibble. A variable number of contiguous bits of computer storage (a generalized byte). Thus, while all bytes will henceforth be 8-bit bytes, nibbles may be 4-bits, 6-bits, 8-bits, etc. The largest nibble used will be 32-bits (the length of a standard integer (long integer, longword, etc.)).

Data Field. A nibble containing one preprocessed, encoded data value.

Data Section. A number of contiguous data fields.

Key Value. An unsigned integer constant specifying the encoding of a data section.

Key Field. A nibble containing one key value.

Key Section. A number of contiguous key fields.

Frame. A key section and all of its corresponding data sections.

Block. A number of frames preceded by block header information and/or followed by block trailer information.

In NSN compression, each time series is preprocessed and encoded into a number of 2048-byte (2^{11}) records. Note that this implies that all data is demultiplexed. Demultiplexing is required as it is the continuity of data from one source which makes the first differencing preprocessing effective. All data values are presumed to be representable as fixed point numbers (integers) for encoding purposes. The length of the header is user definable, but must be constant once set. Six bytes of the header are required by the algorithm for a 4-byte, 2's complement forward integration constant and a 2-byte, unsigned number of first differences encoded in the record (subsequently called the record sample count). In the USNSN telemetry scheme, there is the 14-byte general header, the 6-byte data header, the 6-byte compression header (for 26 bytes), and 10-bytes reserved for the X.25 protocol. Therefore, there are 2012 bytes left for the compressed data (including keys, block delimiters, and the trailer). The trailer is 5-bytes long and includes a 1-byte, unsigned number of first differences encoded in the last frame (hereafter called the last frame sample count) and a 4-byte, 2's complement reverse integration constant. Note that the trailer appears only at the end of the last record of a time series and is used only for backwards decompression in the case that the last record has been corrupted. Excepting users defined information in the header, all information stored by the compression algorithm is in the form of fixed point numbers. All data values (integration constants and first differences) are represented in 2's complement notation and all control information (sample counts, key values, and back pointers) are unsigned.

If the time series is denoted by $A(0), A(1), A(2), \dots, A(n)$ then the preprocessed series can be denoted by $A(0)$ plus $B(i)=A(i)-A(i-1)$, $i=1, 2, \dots, n$, where $A(0)$ is the first integration constant and $A(n)$ is the reverse integration constant. Only the $B(i)$ are encoded into the compression frames. If $B(i)$, $i=1, 2, \dots, m$ first differences will fit into the first record, then the record sample count (in the header) will be m . However, there will actually be $m+1$ data values in the record as the first integration constant is an independent datum. The forward integration constant in the second record will be $A(m)$ and the first differences in the second record will begin with $B(m+1)$. Note that integration constants after the first are redundant. They are provided to permit maximal data recovery should any portion of the compressed data be corrupted. They are also useful as consistency checks. Because the forward integration constant is redundant, the record sample count in the header of the second record is the actual number of data in the record. Succeeding records are encoded in the same way with the trailer (including the reverse integration constant) added to the end of the last record. USNSN time codes attached to compression blocks reflect the fact that the first record of a compression set will return one more data value than subsequent packets. If it is necessary to begin decompression with a packet other than the first one, the time code must be corrected by minus one digitizing interval.

The compression algorithm encodes sequences of 4, 8, or 12 successive first difference values into a data section comprised of consecutive data fields of the same nibble size and assigns the data section a 4-bit key value. Nibble sizes of 4-bits, 6-bits, 8-bits, 10-bits, 12-bits, 14-bits, 16-bits, 20-bits, 24-bits, 28-bits, and 32-bits are supported. Note that data sections are an integral, but variable number of bytes long. The key section is made up of two keys and is thus 1-byte long. A frame consists of one key section followed by the two corresponding data sections. A block consists of seven frames followed by a 1-byte block trailer containing a back pointer. The back pointer is an unsigned integer specifying the number of bytes in the block. The back pointer can be used to decompress backward (from the reverse integration constant) and it provides a consistency check when decompressing in the forward direction. All records except the last consist of a header section and as many blocks as will fit. The last block may contain less than seven frames, but should contain as many frames as will fit in the record. All frames, including the last, must be completely filled with data values. The remainder of the record, following the last block trailer, must be zero filled.

The key values and their meaning is as follows:

key value	number of data fields	nibble length (in bits)	data section length (in bytes)
0	4	4	2
1	8	4	4
2	12	4	6
3	4	6	3
4	8	6	6
5	4	8	4
6	8	8	8
7	4	10	5
8	8	10	10
9	4	12	6
10	4	14	7
11	4	16	8
12	4	20	10
13	4	24	12
14	4	28	14
15	4	32	16

As in all compression algorithms, encoding the last record poses special problems. For all records except the last, the forward integration constant for the following record provides a reverse integration constant. Also, the sum of the data field lengths (specified by the keys) and the record sample count (specified in the record header) are redundant. This redundancy is needed for backward decompression. It is possible because of the zero fill at the end of the record and the fact that the back pointers must be non-zero (thus, the last non-zero byte of each record, except the last, is the back pointer for the last block). Because, in general, the amount of data in the time series will not fill the last record, the time series must be padded with zero first differences in order to fill the last frame of the last block. Note that this may require the entire second data section of the last frame to be padding. In forward decompression, the record sample count in the header will specify the true last point in the original time series. For backward decompression, a trailer is added to provide the desired redundancy. The trailer consists of a the 1-byte last frame sample count (the actual number of first differences, not padding, encoded in the last frame) and the reverse integration constant. The count is placed immediately after the back pointer for the last block and the reverse integration constant is placed in the last four bytes of the record. The bytes between the count and the reverse integration constant must be zero filled.

NOTE : When data compression packets are sent over the network, the reverse integration constant is stored as the last four bytes of the packet. The receiving program must check for 'end-of-file' bit in the packet and if it is found true, move the last four bytes of the packet to the end of the compression buffer and zero fill any bytes between where the reverse integration constant was store and where it is moved. Hence, if the compression block length is 2012 and a packet received via the satellite system is marked with end-of-file and indicates the compression block portion of the packet (i.e. the total packet length less non-compression block overhead) is 2006 bytes long, bytes 2003-2006 are copied to 2009-2012 and bytes 2003-2008 are zero filled. This is done so that packets going through the satellite system do not need to send the needless zero filled bytes. This is of course more important when the satellite packet is considerably shorter than a full packet.

Compressing data using the NSN algorithm is straightforward. Each record is constructed in memory and then written out. The data is first differenced as needed and is analysed in groups of four first differences to determine the nibble size which may be used. A four first difference look ahead is maintained at all times to determine whether a longer run can be encoded (for small nibble sizes) and if the record is full. Each time enough data is available, a frame is encoded. Every seven frames, the back pointer is computed and added. Determining the forward integration constants after the first is a little tricky due to the look ahead. Constructing the trailer is obvious. Problems with determining when a record is full are eliminated by the simplicity of the algorithm and the look ahead.

Forward decompression is also straightforward. Beginning with the first forward integration constant, frames are decoded and the first differences integrated to recover the input data values. At the end of each block, the back pointer should be checked for consistency. The number of first differences in the record can be used to determine when the last frame in the record has been processed. At the end of the record, the number of samples and the forward integration constant at the beginning of the next record should also be checked for consistency. In the last record, the number of first differences in the record should be used to determine both when the last frame has been reached and how many first differences in the last frame are data and not padding. The number of samples in the frame should be checked using the number of first differences in the last frame

from the trailer and the reverse integration constant should be checked for consistency. In fact, the presence of the number of first differences in the last frame count (which must be non-zero) is a flag for the last record (and hence, the end of the time series). Note that decompression may begin from any record in the time series if necessary.

Backwards decompression is not quite as easy. In this case, decompression begins from the end of a record. If this record is the last record, the integration constant is available from the trailer. The number of first differences in the last frame count can be found by skipping over the zero fill. The next byte backwards will be the last block back pointer. The back pointer is used to compute the location of the start of the block. From this point all of the key fields in the block may be located and decoded (to give the location of the next key field and the number of first differences in the frame). In this way, the number of first differences in the block can be computed (using the actual number of first differences in the last frame from the count). Note that the number of frames can be determined from the back pointer position. In fact, if the last frame processes does not end on the byte before the back pointer position, then the block is inconsistent. Once the number of first differences is known, the data can be decoded and backwards integrated to recover the original data values. Successive blocks are decoded in the same way, but are somewhat easier as there will always be 7 frames in each block and the last frame count is not needed. If they are available, the number of first differences in the record and the forward integration constant in the header can be checked for consistency. If backwards decompression begins in a record which is not the last, the procedure is the same except that the forward integration constant in the next record must be used as the reverse integration constant. Also, the last frame count will not be available, but will not be needed as the last frame will be full of data.

Note that the consistency checks are available to determine where the data may have been corrupted. If such a place is found, forward decompression cannot continue until the next header which is not corrupted is found. Some of the data between the next header and the corrupted location can be recovered by backwards decompression. Care must be exercised, however. As the backwards decompression uses the back pointers, they are not available as consistency

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