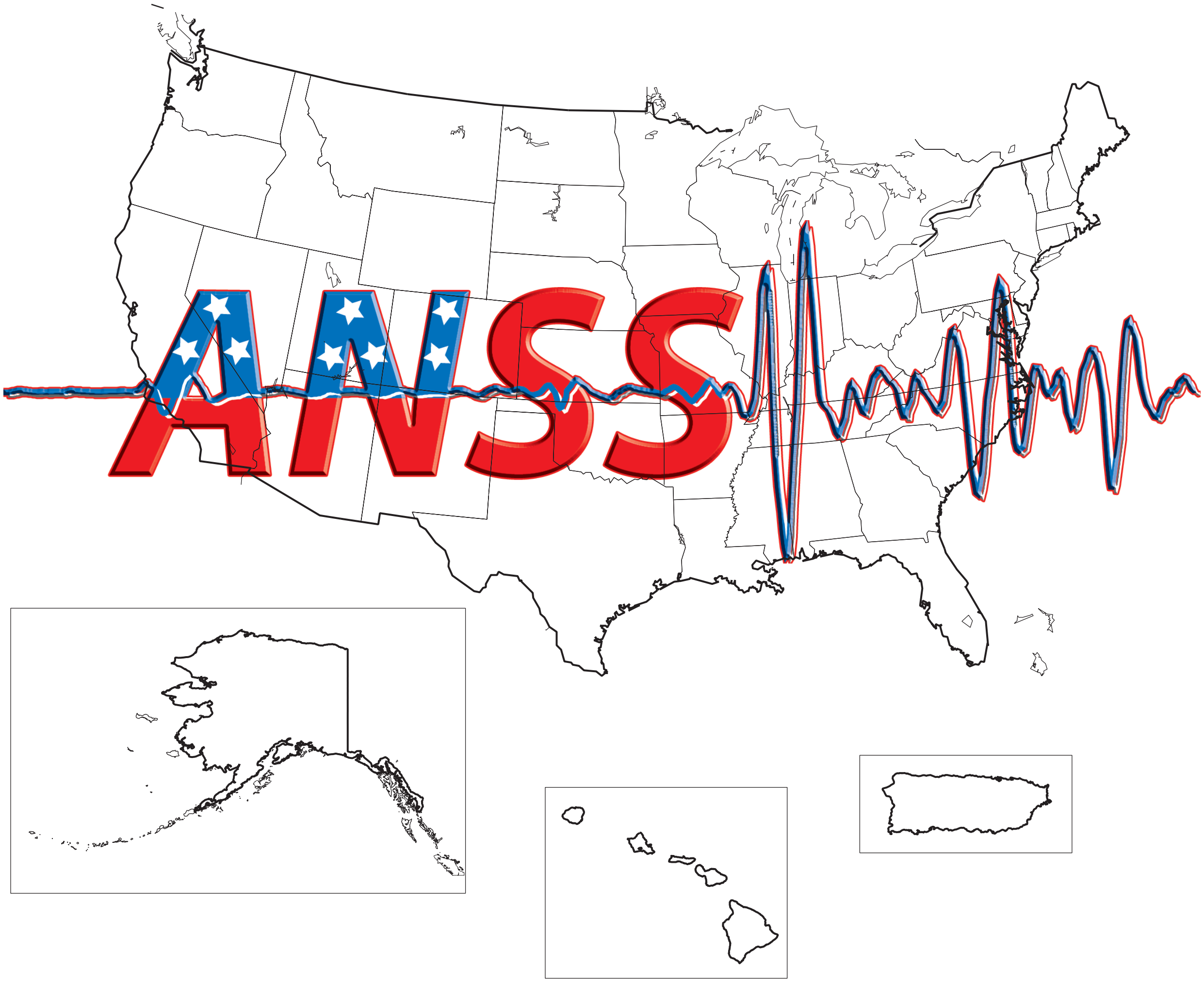
Technical Guidelines for the Implementation of The Advanced National Seismic System—Version 1.0

Prepared by *ANSS Technical Integration Committee*

Open-File Report 02-92



U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Technical Guidelines for the Implementation of The Advanced National Seismic System—Version 1.0

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[1] Members listed in Appendix A

1 Introduction

1.1 Overview

The Advanced National Seismic System (ANSS) is a major national initiative led by the US Geological Survey that serves the needs of the earthquake monitoring, engineering, and research communities as well as national, state, and local governments, emergency response organizations, and the general public. Legislation authorizing the ANSS was passed in 2000, and low levels of funding for planning and initial purchases of new seismic instrumentation have been appropriated beginning in FY2000. When fully operational, the ANSS will be an advanced monitoring system (modern digital seismographs and accelerographs, communications networks, data collection and processing centers, and well-trained personnel) distributed across the United States that operates with high performance standards, gathers critical technical data, and effectively provides timely and reliable earthquake products, information, and services to meet the Nation's needs. The ANSS will automatically broadcast timely and authoritative products describing the occurrence of earthquakes, earthquake source properties, the distribution of ground shaking, and, where feasible, broadcast early warnings and alerts for the onset of strong ground shaking. Most importantly, the ANSS will provide earthquake data, derived products, and information to the public, emergency responders, officials, engineers, educators, researchers, and other ANSS partners rapidly and in forms that are useful for their needs.

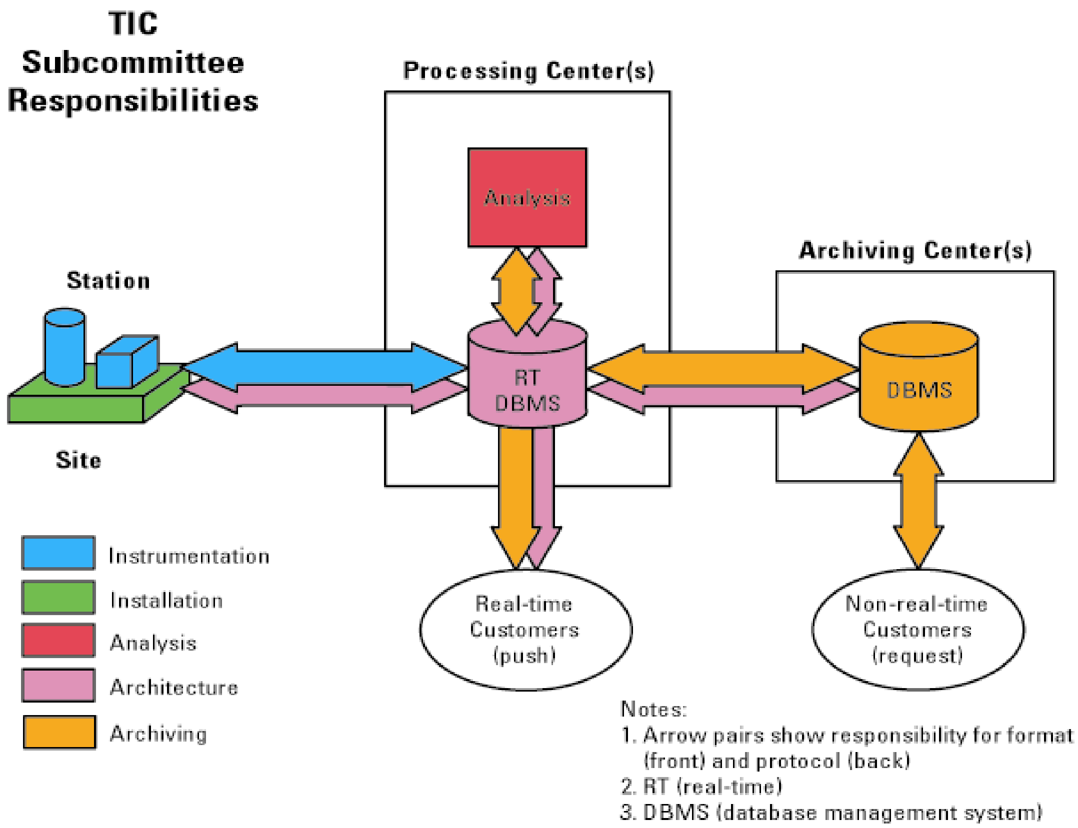
The ANSS Technical Integration Committee (TIC) oversees the organization and activities needed to develop the technical basis for the ANSS. The strategy for ANSS implementation relies on recent advances in seismic instrumentation, wide area computer networking, data analysis, and earthquake products, all of which address the needs of a variety of users in all parts of the country. The *Technical Guidelines for the Implementation of the Advanced National Seismic System, Version 1.0* (hereafter, *Technical Guidelines*) augment these advances by establishing guidance that is applicable to the national system and by identifying specifications for new equipment and software that will better meet the needs of the users of the ANSS. This document describes the key design and performance characteristics of the integrated ANSS.

The implementation of the ANSS will undoubtedly cause significant changes in current regional networks. The result will be a new national system, built from standardized components, which may include local modifications for special situations.

The TIC and its subcommittees extracted ANSS design goals from USGS Circular 1188, interpreting and expanding them as deemed necessary. The subcommittees then worked to develop functional specifications and high-level design elements. The most important element discussed has been an overall system organization that forms the framework for all subsequent design work. The technical architecture and its development are highly dependent on this organizational structure.

The proposed ANSS organization has clear similarities to the current configuration of the National Seismic System (NSS). The dependence on local expertise to interpret the data, a regional level approach to data acquisition and processing, a national operation center to provide a global overview, and a national archiving system all build on concepts of proven worth. However, the organization also reflects ANSS goals of coherent national integration, highly dependable rapid response, uniform, high-quality earthquake products, and widely available data sets.

As part of the process of developing these consensus guidelines and standards for the ANSS, the Technical Integration Committee formed five subcommittees to address particular aspects of the system: Archiving and Distribution, Data Analysis and Products, Instrumentation, Network Architecture and Interconnection, and Siting and Installation. Figure 1 illustrates the responsibilities of the various functional components of the ANSS as covered by these committees.



Notes:
1. Arrow pairs show responsibility for format (front) and protocol (back)
2. RT (real-time)
3. DBMS (database management system)

Figure 1: Functional diagram of ANSS components, color-coded by the responsibility of the TIC subcommittees. Primary elements include stations, operation centers, archiving facilities, and the links among them. The white boxes indicate ANSS users. The ANSS will have both real-time (RT) and archival Data Base Management Systems (DBMS).

1.2 Vocabulary

In describing the design of the ANSS it is important to use a well-defined nomenclature. For the purposes of this document the following meanings for commonly used terms are followed. Some of these terms have a different emphasis or specific meaning than some current uses.

waveforms – raw, unprocessed, but possibly reformatted ground motion time series

metadata - information needed to process or interpret seismological waveforms (station location, instrument calibration, site geology, site velocity structure, etc.)

products - routinely produced earthquake parameters or other results of automatic and manual processing (picks, hypocenters, peak accelerations, shake maps, etc.)

data - referring to any or all of waveforms, metadata, and products

information – interpreted seismological data (tectonic framework, hazard evaluations, building safety, etc.)

operation center – A physical facility housing staff and equipment for the routine operation and maintenance of ANSS hardware and software and routine data processing. Staff includes operators, technicians, analysts, etc.

ANSS user - anyone interested in acquiring ANSS waveforms, products, or information (also referred to as end users or customers)

Outlet – Any facility that has a standing request for waveforms or products (i. e., data and/or products are delivered to the outlet as soon as they are available at the respective operation center or archive facility). The many types and responsibilities of outlets more fully described in Appendix D.

data archive system – one or more physical facilities housing staff and equipment for the long-term storage and distribution of data. Staff includes operators, technicians, and data base specialists.

(data) client - a software module accessing a shared resource in a distributed system. For example, real-time modules within an operation center are clients to the shared buffer. Also, a module handling real-time data input at an operation center is a client to a remote data source.

As a system, the ANSS will consist of various functions conducted at one or more facilities. The following five main functional activities are at the core of the ANSS.

Instrumentation: Activities related to the installation, operation, and maintenance of field equipment (seismometers, accelerometers, DASes, etc.).

Concentration: The process of consolidating telemetered, digitized waveforms from various station equipment, converting to a common format, and forwarding to one or more operation centers. Concentration takes place at data concentrators, which may be collocated with other facilities.

Processing: Activities related to the routine analysis of waveforms to produce summary parameters and other products. Routine processing is performed at operation centers. Real-time products are pushed to critical users from the operation centers.

Archiving: Functions related to the permanent storage and distribution of ANSS data and products and their distribution to end-users.

Interpretation: Activities related to the generation of scientific, engineering, and emergency response information. These include the public and civil authorities involved in earthquake response as well as scientists and engineers involved in research and development. Interpretation activities also can include feedback for the development of new operational capabilities. Interpretation is performed at (data or information) outlets.

Each of the above functions is performed at one or more ANSS facilities and a facility may house more than one of these functions. ANSS facilities generally can be classified into:

National: Activities or operations pertaining to the Nation as a whole.

Regional: Activities or operations pertaining to one of the ANSS regions.

Information outlet: Activities related to interpreting and providing information to end-users.

Research and Development: Activities pertaining to improvements of ANSS processing or information products.

Contributing: Activities or operations in ANSS partner networks that are not part of the ANSS core infrastructure but that exchange data with or augment the ANSS in some way (public-private partnerships, State or other Federal agencies, foreign entities, etc.).

1.3 Existing seismic network situation

Many models of ANSS architecture may be constructed from a combination of functions and facilities. Before discussing the ANSS architecture recommended herein, we begin with the current system.

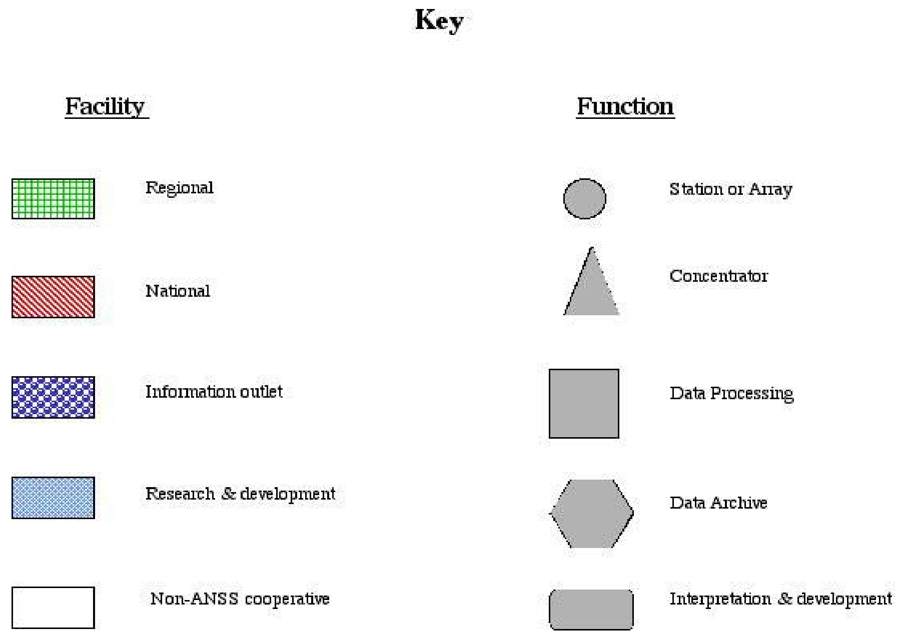


Figure 2. Key colors and symbols used for subsequent diagrams of ANSS organization. Note that functions (routine operation, interpretation and development, etc.) are represented by different symbols while types of ANSS facilities are represented by a different fill colors/patterns.

The current state of national earthquake monitoring is illustrated in Figure 3, where there are activities at both the contributing and national level. Symbols in close proximity on this figure imply that the functions are collocated at the same facility. At the contributing level are the existing regional seismic networks, some supported by the USGS and others not. The current activities of these networks (station operation and maintenance, data processing, information production and distribution, and archiving) are generally characterized by a wide-range of hardware and software solutions and are not uniform across all networks. No “regional” (new ANSS meaning of “regional”) activities or facilities are illustrated in Figure 3. Although the contributing networks are beginning to organize along regional lines, no regional centers have been officially designated. The National Earthquake Information Center (NEIC) represents the current level of national activities, involving station operations, processing, and information distribution. All of the currently contributing centers (RSNs) that receive some USGS funding have established data exchange with the NEIC and, in some cases, with other centers. There is no true national archiving facility at this time, although some contributing networks archive data at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) while others have established local archives.

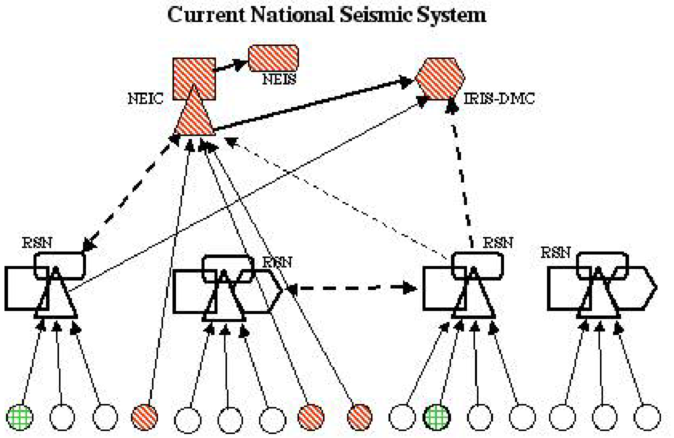


Figure 3: In the current system, the local processing centers are characterized by a wide range of hardware and software. Functionality of the system elements is highly variable though each center usually houses all functions mixed together. Data exchange between centers is highly variable.

Although many aspects of the seismic monitoring in the United States have improved in the last few years, the current operations do not represent a true "system". In fact, the majority of seismic monitoring stations in the US are still short period stations, and strong motion sensors often are not digitally recorded. Although some components perform extremely well, others do not. Overall, the current state of seismic monitoring lacks a coherent and integrated structure. This is one of the major problems that the ANSS addresses.

The current state of seismic monitoring is characterized by a complex topology, which is highly heterogeneous (different hardware and software in the different components) as well as highly asymmetric (different levels in the system performing different functions). Most current networks perform all functions at the same place with the same personnel. Products are ad hoc and not universally available and no uniform standards are applied. The existing system also has some fundamental vulnerability due to several operating facilities being located in areas of high seismic hazard.

1.4 Basics of the ANSS organization

It is clear from Circular 1188 (a basis for the authorizing legislation for the ANSS) that a change from the current organizational structure is needed. Based on a review of circular 1188 and related documents, reports of the TIC subcommittees, and review and discussion within the TIC, we recommend an organizational structure with a strong and relatively standardized regional and national structure for routine monitoring operations and a separation of the development and interpretation functions from routine processing. This model is based on the following assumptions and characteristics:

1. The ANSS is a complex system. A system is "hardware, software, and people working together to solve a particular problem, or to produce a desired effect." All components of the system need to be considered in order to produce the

ANSS. A "systems engineering" approach will be applied to the detailed design of the ANSS.

2. To maximize reliability and produce uniformly high quality waveforms and products the operation of the ANSS will be undertaken by a dedicated operations staff. At the same time, to make ANSS products relevant and effective, ANSS design and management should be undertaken by scientists and engineers.
3. Close coordination between the routine operation functions and the design/interpretation functions is essential.
4. The ANSS is organized into regions, a national operation center, and a national archiving system, with one primary and perhaps other secondary operation facilities within each region. The regional operation centers will be responsible for managing the instrumentation and data collection within the region and for routine processing, and reporting on earthquakes in their geographical area. Each state or territory falls within a region.
5. The ANSS must provide mechanisms for distribution of earthquake information and products to a wide variety of users over a broad range of time scales. The operation centers have the responsibility to provide earthquake waveforms and products to time-critical users, while the archiving facilities distribute waveforms and products to non-time-critical users.
6. The ANSS will have a single long-term archiving system that is decoupled from the real-time routine processing functions. This may be a distributed system or it may be a single archive facility. Proper care must be taken for the ultimate recovery of all archived data in case of facility failure, and recent data must be recovered quickly. Ultimately the archiving system must insure that the system functions through periods of natural disasters and insure the long-term safekeeping of all data and derived products for future use.
7. The requirements for the ANSS will evolve as the system develops and even after it is fully deployed. Mechanisms to allow changes and evolution in the technical and functional specifications and design as development efforts are evaluated will be established.

The ANSS requires multiple routine operational centers to avoid single points of failure and to be able to adapt quickly and efficiently to special regional conditions or situations. Therefore the ANSS requires robust and reliable exchange of a variety of data and products among facilities or components of the system. There is little difference between the national and various regional operating centers other than size and geographic areas of responsibility. In general there will be only one primary operational center per ANSS region at which routine data processing for the whole region will be done. The national level operation center will act as backup for all regions as well as coordinate issues between regions. One or more of the regional centers (or a separate facility) will also act as backup for the national center responsibilities in the event of a failure at the national center.

A fundamental difference between the ANSS and the current monitoring situation is a clear separation of the routine operation of the ANSS from the development and interpretation aspects, as discussed in Appendix D. While in some of the currently operating network centers there is some separation of these responsibilities there is rarely a formal distinction. The interpretation and development personnel are involved with operations from time to time at nearly all existing networks. The capabilities of modern computer networking obviate the requirement that they be housed in the same physical facility though in some cases there may be reasons to do so. Figure 4 illustrates the ANSS organizational structure: the functions of routine operation are separate from interpretation and development. A contributing (currently operating) network closely involved with a regional ANSS operation is included. Connecting arrows represent data or information flow paths. Line thickness is proportional to data volume.

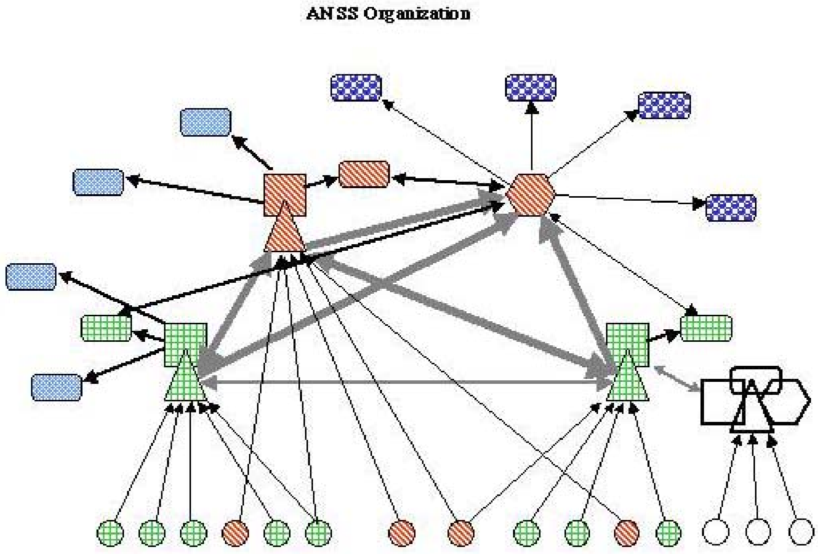


Figure 4: This figure illustrates the ANSS organizational model, consisting of regional and the national centers with associated interpretation functions distributed more widely. A contributing network is shown with open symbols but is not an official part of the ANSS.

Generally the flow of data through the proposed model for the ANSS is from bottom to top. At the bottom, seismic stations measure ground motion that is telemetered to data concentrators collocated with operation (data processing) centers. Data concentrators may be installed at remote locations to concentrate data from several seismic stations, perhaps reformat the data into standard ANSS data packets, and forward these data to operation centers over high capacity data communication circuits. National backbone stations are telemetered directly to the national operation center on independent circuits. Note that data telemetered into a data concentrator are immediately passed on to other centers as well as the local center. Automated earthquake products are produced at the operation centers and immediately distributed to interpretation outlets. Automated products are coordinated system wide through a set of business rules.

The critical task of interpretation of ANSS data is conducted at information outlets. While the real-time ANSS infrastructure has been simplified in the interest of reliability, information outlets encompass everyone involved in translating seismic waveforms and products into earthquake information. Note that information outlets have access to as many waveforms and products as needed to perform their function.

The modularization of data acquisition, processing, and consumption (at the outlets) provides considerable flexibility in the ANSS infrastructure. For example, data concentrators could be remote from any operation center, concentrating stations onto high-speed communications links, and providing the data to multiple operation centers. Alternatively, station data could be multicast from the field to several operation centers and an archive facility through collocated data concentrators. The ability to collocate a concentrator with an operation center means that the design of the operation centers or archive facilities is independent of the field telemetry architecture.

The concept of an outlet is very general and many types are envisioned. Outlets involved in rapid response activities (state offices of emergency services (OESs), emergency manager's trusted sources, and institutions interpreting the data for the media) are fed data and products directly from operation centers. Non-time critical outlets (e. g., research and development) are fed data from the data archive facilities to ensure complete data sets and to prevent burst loads on critical real time facilities. Outlets fed from the archive facilities may still be performing mission critical ANSS tasks (catalog production, hazard studies) and may still receive data in real time. Outlets may be operational (involved in reviewing real-time products) or informational. Outlets may be involved in the development of new ANSS products, procedures, or algorithms.

Each operation center serves as a production outlet, interacting with the data archive to provide authoritative reviewed products, maintain metadata, and perform quality control (QC) functions. Quality control encompasses activities that assure the user of the quality of distributed data and products and may include manual product review, station calibration, metadata validation, and monitoring of field clock quality. Reviewed products (including quality controlled waveform data) are transmitted to the data archive facility as soon as they are completed. The one-to-one association between these special production outlets (shown in the same color as their respective operation centers in figure 4) is necessary to ensure that reviewed products have the same authoritative status as automatic products. Note that it is not essential that all operational functions be conducted in one production outlet per operation center. For example, it might be useful to collocate the rapid review of products with the operation center to enhance reliability while metadata maintenance functions are done elsewhere. For a more complete description of outlets, see Appendix D.

The ANSS must establish appropriate standards for operation. Detailed standards are beyond the scope of this document. However, they should be established early in the development of the technical components of the system and be based on sound practice and technical capabilities. These standards for operation should be reviewed and updated as appropriate at a national level.

The ANSS is a revolutionary effort to modernize the seismic monitoring system within the United States. The design of the ANSS should not be hampered by the state of seismic monitoring prior to the start of ANSS. Nevertheless, it is important to define an evolutionary path from the current situation to the final model, without interrupting operations. Implementation of this transition will be the responsibility of the ANSS Implementation Committee assisted by the regional working groups; however the TIC assumes that most current network operations will become involved in some aspect of the ANSS organization. Some of the existing network operations centers may become regional operation centers. Others will take on the important tasks of interpreting ANSS data and helping with development of new ANSS capabilities.

Detailed aspects of the ANSS system design and functional specifications for its various components are covered in the following chapters. Each is largely based on the respective subcommittee reports. In particular the “Network Architecture and Interconnection” chapter is critical to the system as a whole.

1.5 Evolution of the Technical Guidelines

The *Technical Guidelines* is the first step in the implementation of the ANSS. It outlines the basic architecture of the ANSS and provides general guidelines on key technical issues regarding data collection, archiving, and analysis; instrumentation; site installation; and dissemination of products. Detailed technical standards are beyond the scope of this document, but will be developed based on these guidelines, sound seismological practice, and technical capabilities as technical components are developed throughout the implementation of the ANSS.

This document represents the collective wisdom of a large portion of the seismological and earthquake engineering communities, summarized in technical reports from five subcommittees that form the basis of this document. The ANSS Technical Integration Committee (TIC) edited, reorganized, and repackaged the subcommittee reports, adding text as necessary. The Technical Integration Guidelines is very much influenced by the state-of-the-art today, and yet attempts to be visionary. This document is intended to be a living document that forms the technical framework for the ANSS. The TIC understands that as the system develops, technical questions relating to the development, deployment and operation of such a large system will require additional input. The Technical Integration Guidelines will continue to evolve and adapt to changing requirements as necessary. Revisions of the Technical Integration Guidelines document (exclusive of attachments) will be published as higher version numbers (e.g., a minor revision to accommodate the first attachment might be version 1.1, while a major revision of one or more chapters might be published as version 2.0).

The TIC anticipates that input of a technical nature will continue to be needed by the ANSS. For this reason we recommend that the TIC continue to exist throughout the life of the ANSS to provide technical input and direction to the National Implementation Committee. We further recommend that the six members of the TIC continue to serve terms such that two members rotate off the TIC on an annual basis and two new members rotate on to the TIC. From time to time the TIC may populate a variety of temporary subcommittees or working groups where specific expertise is needed. In this manner the ANSS can continue to respond to new technological challenges as they arise.

2 Network Architecture and Interconnection

2.1 Overall Organization

The TIC recommends a regionalized architecture for the ANSS with a primary operation/processing center in each ANSS region and a single national operation/processing center. This model provides multiple processing centers for redundancy, while allowing for customization for regional needs. This model also provides a natural scale for addressing issues of data quality control, scalability of processing systems, redundant reporting, product quality control, and flexibility and responsiveness to local contacts. Besides the primary operation/processing center for each region, there may be multiple operation centers for station and telemetry maintenance and multiple information outlets. Existing local networks likely will be transformed into an operation center or information outlet. The regional model of the ANSS implies consolidation and coordination of effort among the participating networks. The facilities of some local networks may become maintenance and data concentrators with processing activities occurring at the regional center. Local network operators may continue to be involved in station operation and maintenance, but their scientific expertise also will be devoted more to interpretation, research, and development using data from any subset (or all) of the ANSS.

The rest of this chapter concentrates on the initial design of the routine operation part of the ANSS. While scientists and design engineers will be involved with development work on these components, professional engineers, programmers, and operators will perform the actual implementation and operation.

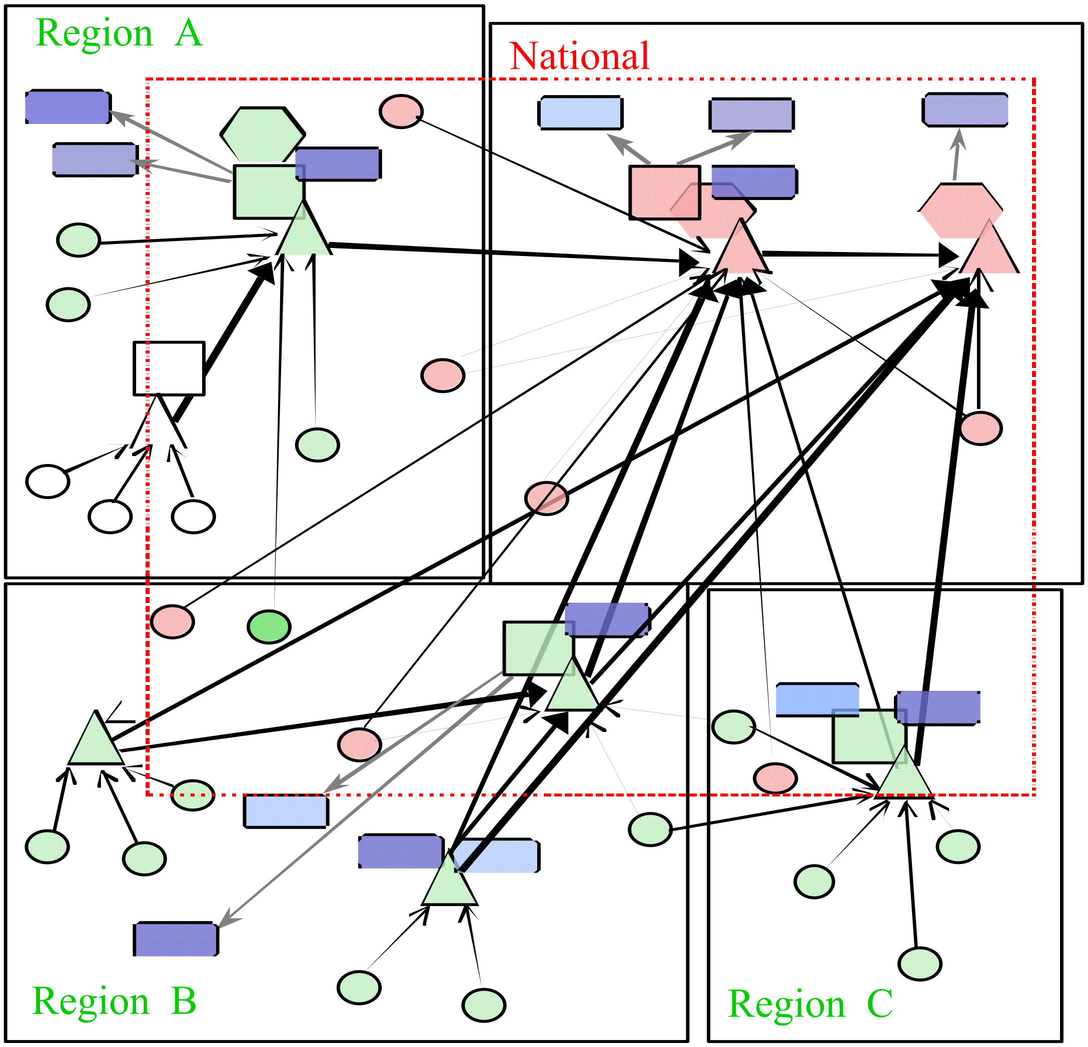


Figure 5: A map view of the hierarchy illustrated in Figure 4. This figure shows 4 adjoining regions with various ANSS elements. Note that existing networks are shown as collocated data concentrators and outlets. Regional and national centers are shown with the associated outlet collocated (collocated concentrators are not shown). Also, a distributed archive is hypothesized with both national and regional elements.

The ANSS is a complex system, partly due to the number of nodes and interconnections. Therefore the TIC recommends minimizing the number of regional centers and concentrators within individual regions. The model calls for establishing one processing center per region, but recognizes that there may be exceptions. The advantages of locating the regional processing centers away from areas of significant seismicity are obvious. At a minimum, ANSS centers must be placed in facilities where appropriate earthquake resistant mitigation efforts have been completed. Note that local expertise will be available at many of the data outlets

In this model, the regional processing center will be the central hub of routine operations in an ANSS region. This center will have primary responsibility for rapid earthquake processing and notification. While the regional processing center will receive waveform and parametric data from different components of the system, and from adjoining regions, it will be the authoritative source of information on earthquakes in its region and will have responsibility for distribution of this information in near-real time to a multitude of information outlets. This role in the processing and distribution of rapid earthquake information makes the regional processing centers critical elements of the ANSS, requiring high levels of performance and robust and reliable operation. The national processing center will have similar capabilities and will receive data from all regions and the national stations and be capable of acting as backup for all regional processing functions. The national processing center will also act as coordinator between regions and arbitrate between discrepancies in products provided by different regions for the same event. The success of this regionalized model depends on the requirement that operators adhere to ANSS performance standards.

2.2 General Issues and Recommendations

Quality control for the ANSS is crucial and must be a fundamental part of the ANSS system. Due to the number of seismic stations, number of channels, volume of waveform data, and abundance of products, quality control will most likely have to be much more automated than in the past. Systems must be designed to routinely monitor the characteristics of waveforms, including time, and data quality (dropouts, noise, etc) and alerts must be generated when parameters fall outside acceptable limits. Part of the system specification will clearly identify the performance standards.

Major types of quality control must address items such as 1) waveform timing, 2) quality of instrument calibration including schedules for calibration, 3) accuracy of station metadata, 4) data availability statistics (uptime), 5) error estimates of measured parameters such as phase picks, and 6) error estimates of calculated parameters such as hypocentral locations or moment magnitudes. System wide quality control techniques (for example, using mining blasts to check station timing) will be important. Metadata will be maintained at the regional centers and techniques to test the accuracy of the metadata will be necessary.

Quality control is an ANSS-wide issue. The methods and techniques used to monitor data quality should be standard. Although individual regions may have specific problems, the development of quality control techniques and standards should be consistent across the entire system.

Distributed reporting of rapid earthquake information raises questions about robust data delivery if a regional processing center is disabled. Although the ANSS could implement a “nearest-neighbor” regional backup model, having the national processing center act as the backup to each region is the simplest model. At least one regional processing center (or a separate facility) must be able to reproduce the capabilities of the national processing center in terms of global monitoring in the event of a failure at the national processing center.

Rapid notification requires rapid review in order to confirm event validity or to remove spurious events. It is anticipated that each production outlet involved in rapid review will require a staff member to be either on site or on call at all times – with the expectation that earthquake alarms will be reviewed within a few minutes after notification.

The generation of reviewed earthquake products will be performed in each region. Strictly speaking, the system architecture is relatively insensitive to the location of this activity. Although some aspects of design are simplified if this is centralized at a national facility, it seems clear that each region can provide more local understanding and should be responsible for its earthquake products. Production outlet(s) closely associated with the national processing center will be responsible for coordinating regional products, producing uniform national products, and producing and reviewing products for global events. Appropriate business rules and mechanisms will be required to keep the national and regional products synchronized.

The ANSS will be a real-time system with all stations connected to real-time telemetry links (including structure-monitoring arrays). While some channels may be telemetered only when triggered by strong shaking, the system must be capable of telemetering all channels in real-time, with possible minor delays (seconds) in extreme cases.
We assume that there will be no fundamental difference between the way weak and strong motion data are handled. Network design goals for real-time strong-motion stations are, in principle, the same as for other seismic instrumentation. However, some data will not arrive in real time, either because of telemetry failure or network congestion, particularly during large events. Thus the ANSS must be designed to handle late data as well as data that arrive out of order.

The size of the data channels, both within processing systems and for telemetry between centers, is well within the technical limits of computer and networking technology, particularly since this technology continues to advance at a rapid rate. The aggregate data rate of all ANSS seismic channels is assumed to be less than 20Mb/s (see Appendix B). Including data from non-ANSS sources will increase this rate but it should still be within technical limitations of even current capabilities.

Standardization, particularly as it relates to software, is a tricky issue. Using the exact same software is desirable to maximize efficiency and provide uniform products. However, uniformity often stifles innovation and in any case the system must be designed so that it has flexibility to deal with special local or regional problems. The TIC proposes that software for routine operations be largely standardized, but allow for local customization where warranted. The TIC sees no reason to require standardization at outlets other than the production outlets. Rather, software diversity at most outlets should be encouraged to promote the development and testing of new operational as well as interpretation algorithms.

2.3 Functional Design

To address the issues of functional design for the ANSS, this section is organized into several subsections:

- System Attributes and Issues
- Data Flow among Elements of the ANSS
- Data Distribution within Processing Centers
- Rapid Data Delivery
- Offline or Manual Review

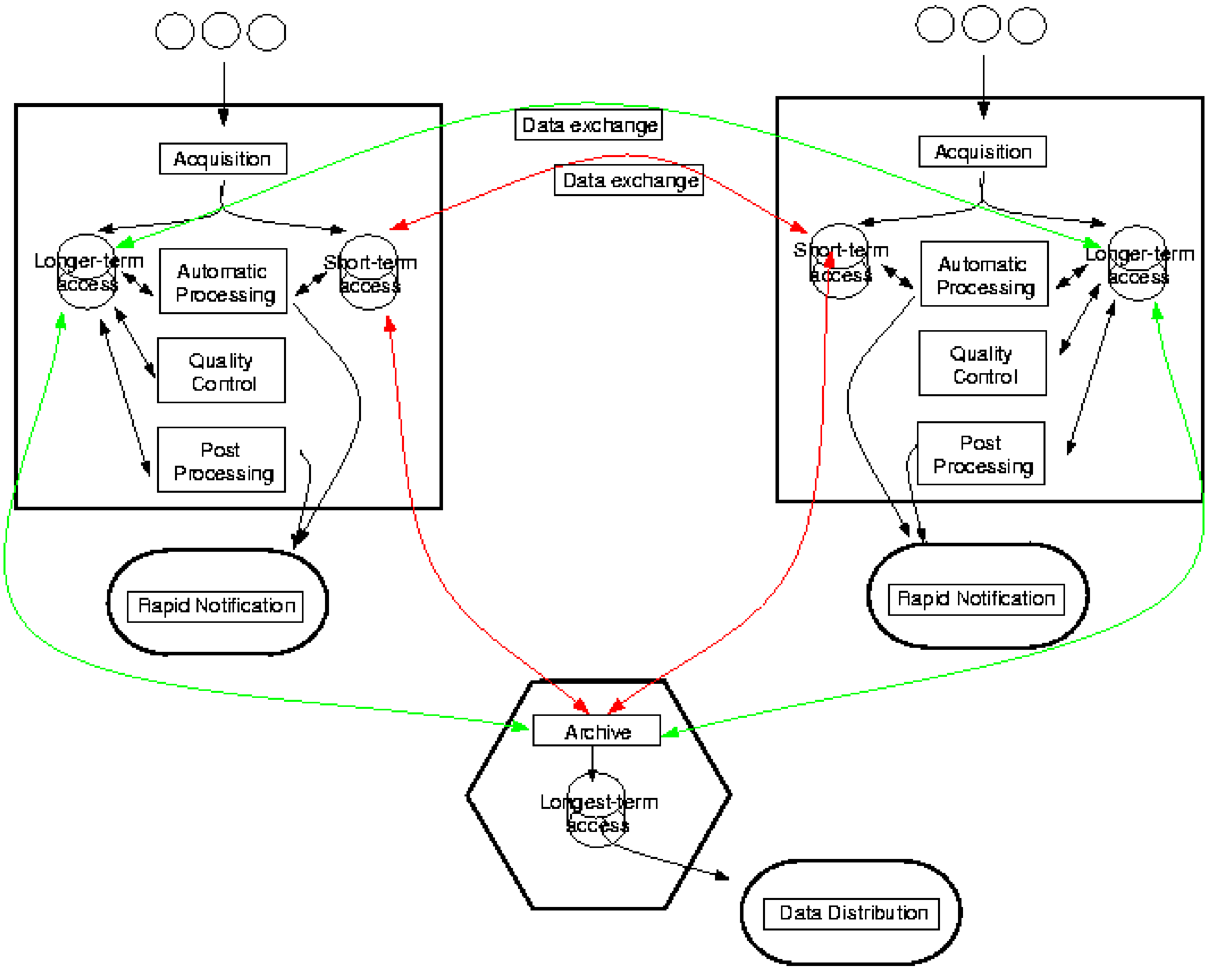


Figure 6: Schematic illustration of ANSS functions and data flow among ANSS elements. The large rectangles encompass the tasks of regional/national processing centers and production outlets.

To facilitate the discussion of these issues, Figure 6 illustrates the ANSS design in greater detail. This figure uses the symbology of Figure 2, but does not attempt to identify different levels of functionality. For example, the processing operations (square) include components for data acquisition, "online" or automated processing, "offline" or manual review processing, and quality control (encompassing data concentrator, processing center, and production outlets). There are also elements for rapid notification, archiving, and data distribution. Colored lines among elements of Figure 6 indicate communication links where waveforms, metadata and products may flow. Some of these transactions will be continuous (for example, waveform exchange among the processing centers and to the archiving facilities) while others will be on-demand (for example, possible use of database interactions).

Figure 6 also illustrates the different levels of data persistence or storage that may be required by the ANSS. Processing systems will use two levels of data buffers. One provides for relatively recent data and will be designed so that real-time processing applications associated with the processing center can access data in the appropriate time frame. The second level of data buffer is provided for intermediate-term storage associated with production outlets for rapid review and other QC purposes. The distinction in terms of the timeliness of data access is important, depending on the type of request.

2.3.1 System Attributes and Issues

2.3.1.1 Evolution

From telecommunications to computational capabilities to networking to storage capacity, the technological underpinnings of the ANSS will change dramatically over its life span. It is essential that the ANSS be developed so that it can grow and evolve over time, both to take advantage of these changes as well as to respond to changes in the needs of the user community. In order to evolve, it is critical that the ANSS system be based on an open and extensible architecture, widely adopted standards, modern software concepts, and platform independence.

2.3.1.2 Standard Networking Tools

The ANSS should use standard networking techniques including TCP/IP, domain name servers, and route determination using commercial standard routing protocols. The ANSS development should NOT take on the design of alternate networking techniques.

2.3.1.3 Standardized Interfaces, Protocols, and Formats

All data flow, whether within or between elements of the ANSS, should use the same interfaces, protocols, and formats. All data access functionality must be provided to data client processes via a standard, well documented Application Programming Interface (API). This approach will reduce costs, and increase flexibility, scalability, and maintainability. For the purpose of system architecture, ANSS data falls into several distinct classes:

- waveforms (with triggered waveforms as a special case)
- parameters (such as picks, hypocenters, moment tensors, station metadata)
- binary, large objects (a.k.a. BLOBs, such as ShakeMaps).

The ANSS must be able to handle these three fundamental classes through the establishment of standardized interfaces for data exchange. In addition to supporting these three data classes, the ANSS will support the two following types of requests:

- Standing order (continuous and on-going feed)
- Discrete request (one-time request for a specific set of data)

.

An example of the standing order request might be the exchange of continuous waveform data between processing centers. The exchange of associated station metadata could also be considered a standing order, but of the parametric class. In contrast, a request for a particular waveform time segment, say, to fill in a data gap, would be an example of a discrete request of the waveform class.

In designing the APIs, the ANSS must bear in mind the following four different classes of clients:

- Elements within the routine operation of ANSS
- ANSS interpretation and development outlets
- Non-ANSS networks
- Users of ANSS products

2.3.1.4 Modularity

The ANSS software and hardware components should be highly modular. That is, each function in a system should be encapsulated in a separate module and each module should operate independently. While this design principle may not be possible to adhere to in all cases, it has a number of advantages. In particular, it allows new functionality to be added without compromising existing capabilities.

2.3.1.5 Scalability

The ANSS must be scalable. The current proposals for the ANSS call for approximately ten thousand monitoring sites. However, given recent advances in microelectronics, this number could increase by more than an order of magnitude if inexpensive, small sensors are distributed widely and used to monitor buildings, bridges, and lifeline networks. Such a capacity may be achieved by dividing processing tasks among many instances of the same processing module, each running on a different processor and each handling a subset of the total data set. This modular "divide and conquer" approach, if correctly designed, can provide relatively open-ended scalability. Note that in order to achieve scalability by adding hardware, the software architecture must be designed for distributed processing from the ground up. The ANSS must leverage modern approaches to software design and development to insure scalability.

2.3.1.6 Complexity

It is important to recognize that functionality (number of fancy features in the system) and performance tend to be inversely related. Therefore, critical subsystems (e.g., communication substrate and buffers) should avoid extra complications or processing “features”. Wherever possible, the capabilities of existing communications protocols and widely available operating systems features should be used. For example, this could mean relying on the checksums and packet-dropout detection of TCP/IP or on operating system features such as threading for multitasking or by leveraging multicast technology if appropriate.

2.3.1.7 Data volume

An important issue for the design of the ANSS is sizing of communications links and processing systems. While adjoining regional processing centers may implement partial waveform exchange, the national processing center and the archiving facilities will see the full data flow in real time. At a minimum, each element of the system should be sized to allow for complete data recovery and processing for the largest earthquakes in normal operation and to quickly recover from partial telemetry outages. This will require telemetry and processing capacity to exceed the nominal data throughput. Note that a single $M = 8$ earthquake in Central California will involve collecting and processing a significant fraction of available ANSS waveform channels.

Appendix B provides estimates of the data volume that the TIC believes to be relevant for system design. In general, continuous streams of data from all instruments must flow from stations to processing centers. Network triggering will significantly reduce the data volume from the strong motion instrumentation, but data from broadband seismometer channels will be continuous all the way to the permanent archive.

2.3.1.8 Buffering

The system must be capable of buffering all available ANSS waveform and parametric data to ensure both complete processing when capacity is degraded and complete and error free transmission throughout the system (from field stations to end users) when communications links fail. While it is not practical to plan for all contingencies, at least one week of data should be buffered at all data concentrators, processing centers, and production data outlets. Buffering recommendations for field stations are discussed in chapter 3.

2.3.1.9 Speed

The requirements of early warning, calculation of real-time location and magnitude, and real-time data distribution dictate that data delivery and processing delay (latency) are minimized. The system should add no systematic delays to the latency inherent in delivery from the data source. Since a data packet cannot be resent until it is fully received, store-and-forward type of data delivery relays should be minimized and data packet lengths for high digitization rates should be no more than a few seconds of data. Additionally, the latency associated with data buffers, the number of "hops" in the data paths, and steps in data processing must be reduced as much as possible.

Late data - whether from triggered data streams or from communication outages - will be a fact of life. The ANSS must be designed to process late data. Late data should be organized seamlessly with data already received and late data should be incorporated in ANSS data products to the greatest extent possible as they become available. Also note that some products of the ANSS (e.g., waveform data for seismological research) require high levels of data completeness. At a minimum, the tradeoff between latency and completeness will require that older data must be transmitted out of order after a communications outage to minimize the latency of current data.

2.3.1.10 Security

The ANSS must be a secure system. The design must ensure that critical computers are secure against intrusion, denial of service attack, and “hacking”. Authentication should be used to allow data service only to authorized clients. Rapid notifications should also be protected against "spoofing". The TIC does not feel that data authentication, as used by the CTBTO, is necessary.

2.3.1.11 Reliability

The simplest statement of the ultimate reliability specification of the ANSS is that a total system failure during any significant event is unacceptable. In practical terms this means that enough of the ANSS must be operational at all times to provide reasonably high quality information about any potentially damaging event in the U.S. throughout the life of the system. On the other hand, it is expected that the full performance of the system in terms of response time and accuracy should be available a very high percentage of the time. This is inevitably a cost-performance issue. 100% availability is, in practice, impossible to guarantee and the cost of closely approaching this ideal grows exponentially. This is the best single argument for multiple, geographically isolated, data processing centers with national backup.

2.3.1.12 Robustness

While multiple data processing centers, data outlets, and archive facilities greatly enhance system reliability, they also significantly increase the probability that parts of the system will be unavailable at any particular moment. Therefore, the ANSS must perform as well as possible under all likely partial failure scenarios. For example, it would be unacceptable to delay notification because all data were processed with inadequate capacity. Similarly, dropping 1 second of data every 20 seconds because of inadequate communications bandwidth would make all the data useless. One mechanism that has been found to enhance the performance of systems under stress is to prioritize the data so that all data delivered are usable and processing is still effective and timely, even though the data set processed in real-time may be incomplete.

2.3.1.13 Communication Links

Mission-critical communications, at all levels, should be over a variety of independent physical paths to increase reliability. Path diversity is already built into some telemetry systems, especially commercially supported ones. For example, Internet routing is dynamic and "self healing". However, no single medium is 100% reliable and the ANSS should not have "all of its eggs in a single communications basket," be it a physical link or technology type. Multiple links must be considered for major paths such as between processing centers and to the archive facilities. Designs for using multiple paths include switching from one route to another quickly and automatically if a fault is detected, splitting communications among different paths so that a failure only affects part of the data flow, and dynamic shifting of the load when links degrade.

Necessary attributes of the data exchange protocols are that they be robust and reliable. Possible implementation considerations are the ability to prioritize data to allow for graceful degradation, using heartbeats and handshaking to insure completeness, error detection to avoid corrupted packets, and filtering to allow selection of particular data products.

2.3.1.14 Health and Status Monitoring

The ability to measure the health and status of the ANSS will be a critical aspect of the design. The operators of the ANSS need the ability to easily identify problems or failures in the system, ranging from loss of data due to communication problems, to the failure of processing computers or equipment. The implementation of system monitoring components will include elements such as the assessment of sensor health, connectivity to sensors, communication between and among centers, data latencies, status of processing elements, status of computers, routers, and other hardware, and ability to perform data distribution.

2.3.1.15 System Testing

In addition to monitoring individual elements, it is necessary to provide "total" assessments of ANSS functionality. This should include both off-line simulations of typical and worse case conditions (for example a large earthquake during a partial telemetry loss) and on-line injection of test events/signals (without loss of real data) for testing the system as a whole. Similarly, new algorithms and configurations should be well tested before they provide information to ANSS users.

2.3.1.16 Ease of Operation

Experience operating large seismic networks shows that substantial time and effort are required for reliable operation. The ANSS development should have significant effort devoted to making the system easy to operate. Issues that should be addressed include configuration, initialization, upgrading software, and reconfiguration of the system. Alternate systems for operational procedure training should be provided. Complete and well-organized documentation must be kept accurate and current.

> *Configuration* - Network and monitoring configurations must be easy to establish and check. Configuration information includes things such as station metadata, telemetry connections, hostnames, and other information. Configuration information must be part of the basic ANSS database system (i.e., configuration parameters must be available through the same mechanisms as other parameters). Configuration information entered into the system must be propagated automatically to all modules needing it. It would be desirable for "smart" field instrumentation to propagate information about changes in the field as they occur.
>
> *Initialization of System* - The system, or any part of it, must self-initialize when started and provide positive information that it restarted properly and is operational. The injection of test data, possibly waveforms, into the system on initialization might be used for system verification.
>
> *Reconfiguration of System*. - The ANSS system must be reconfigurable while it operates. It should not normally need to be restarted to re-read configuration information but rather reconfigure dynamically without exiting or loss of data. Reconfiguration must support versioning or journaling such that if a new

configuration is discovered to have problems it should be easy to revert to an earlier configuration.

Alternate computers for maintenance and development. – Backup hardware for critical parts of the system must be available for redundancy and would be used for both emergency backup and routine maintenance of primary systems.

Diagnostic Tools. - The ANSS should provide the ability to monitor system load and diagnose software and hardware problems while the system is in operation. Tools for both hardware health and software conditions should be routinely available and used by system operators. Commercial monitoring techniques and protocols such as SNMP should be used where appropriate. Software tools should allow operators to view results anywhere in the processing.

Operational Procedures. - The ANSS should establish systematic operational procedures to insure the health and maintenance of the system. Operators should make routine checks of various aspects of system operation but also be well enough trained to recognize problems or conditions which fall outside those detected by the routine checks.

Documentation. - The ANSS must provide simple, straightforward operational procedures documents as well as more detailed technical documents for both problem solving and development purposes. Documents must be completed and reviewed before any referenced process or procedure becomes operational. Patches or changes to software or procedures must be fully documented as they are made. Significant clerical effort should be part of the development and operational process to insure that both relatively static and dynamic documentation is well maintained.

Knowledge Base and Discussion Forum. - To assist with operation and development the ANSS should provide three things: (1) a knowledge base so that users can find information about the system on their own, (2) training classes so that operators and users of the system can be educated in the system, and (3) a discussion and problem-solving forum for the dynamic solution to problems and development of new techniques. Suitable forums include face-to-face meetings, telephone conferencing, e-mail distribution lists and WEB based notes of the discussions.

2.3.2 Data Flow among Elements of the ANSS

2.3.2.1 Data Concentrator

The data concentrator is the heart of the telemetry system. The concentrator will receive waveforms from stations, check for validity, and pass them on to one or more processing or archiving centers. The data concentrator may convert waveform packets into a standard format. This node could be a small, remote facility where multiple field stations are consolidated onto high bandwidth telemetry links or it could acquire data for a collocated processing or archiving system. Concentration nodes will require significant data buffering to ensure complete data across communications outages.

2.3.2.2 Data Tracking

The ANSS must be able to track the lineage or provenance of its data. Given the potential for distributed data acquisition and exchange among multiple components, tracking data as it flows through the system is a requirement. In addition to documenting the path, the tracking tag also assures the non-ANSS data provider of appropriate attribution. Although the complete solution is beyond the scope of this document, data tracking should at least include identification of the initial source of the data as well as the ability to indicate any processing or modification of the data and the agency that performed those operations.

2.3.2.3 Distributed databases

It will be necessary to synchronize the data holdings of processing centers and production outlets with archiving facilities. This concept is discussed in Chapter 5.

2.3.3 Data Distribution within Processing Centers

The requirements for data flow within an ANSS processing center are very similar to those for communication among centers and from centers to outlets. However, there are some special considerations to be addressed for data delivery within a center. These requirements are controlled by the processing function or functions with the most extreme demands for data volume, data delivery speed, and buffering (data persistence).

2.3.3.1 Buffering

The heart of the processing center will be the mechanism to buffer data received from the concentrators for use by all interested clients. The system must buffer the data long enough for client applications to have a reasonable chance of successfully getting all the data they need to do their work. This data buffering may be shared with a collocated concentrator. Data buffering also allows out-of-order data to be sorted before use. A common buffer within the data transport system avoids duplication of the data into many application-specific buffers.

2.3.3.2 Other requirements

Security and client management - The processing system as a whole must manage clients to assure predictable behavior and guarantee service to mission critical clients. Authentication will be used to allow data service only to authorized clients.
System management - Tools will be provided to report and monitor the performance and load of the system.
System topology - The system topology must be flexible. It must be able to distribute modular functions over multiple hosts and they should be free to move from host to host. Single-points-of-failure will be reduced to an absolute minimum within any one center. All critical functions will be offered by redundant servers. Switching from one server to an alternate will be simple, fast and, where possible, automatic. The system will be able

to handle additional data volume by adding modules or hosts. Dynamic load balancing would enhance the reliability of the system.
Stable load - Where possible, the behavior and resource consumption of the system will be steady and predictable.
Exception handling - Exception handling must be part of the ANSS software. The software must fix or report corrupted, out-of-order, or incomplete data. It must allow clients to specify and handle time-outs for data requests.

2.3.3.3 Data Clients

Data clients include components of the data distribution system, real-time processing modules, post-processing modules, quality control modules, and updates and information transfer to the archive. Data clients have a need to make standing orders or discrete requests (from either the fast or slow buffer). However, client connections must be stateless (each new connection must negotiate the data stream).

The number of client modules in an operating center may be large. Data transport architecture between the common buffer and client processes must provide adequate throughput, low latency, and reliable delivery.

2.3.4 Rapid Data Delivery

Rapid earthquake notifications will be one of the most important responsibilities of the ANSS and a key to the usefulness of many products. Rapid data and product distribution is distinguished from distribution from the archiving system primarily because of the time-critical need for the data. The system should be capable of rapidly generating many types of earthquake products, and each type must be automatically delivered in standard formats via multiple mechanisms.

2.3.4.1 Early Warning

The ANSS earthquake processing system must provide information on a number of time scales but the fastest is essentially in real-time: information must go out to end users before the shaking from a large earthquake is over (possibly before shaking starts at some places (early warning)). While such speeds may not be attainable early in the system development, the goal for the ANSS must be to support continuous improvements in speed of production over the life of the system. The ANSS will be designed so that the system distributes earthquake information as quickly as it is determined. The system must allow for improvements in processing capability that accelerate rapid notifications. When the notifications are fast enough, early warning will be available.

2.3.4.2 Improvement with Time

A fundamental principle of earthquake data processing is that information about an earthquake improves with time. As time passes, the acquisition system acquires more data and the processing system has more time to process the data. Given more time, more sophisticated algorithms can be used and with enough time, human interaction with the data is possible, allowing greater improvements in accuracy and completeness.

All data and products must be uniquely labeled and versioned to distinguish between new items and updates. A time-stamp and the identity of human reviewers should be included as well. When products are updated the latest update should take precedence over any earlier products of the same type for the same event. However the system must retain access to previous published versions of the products.

2.3.4.3 Precision and Accuracy

Data and products distributed by the ANSS must include an associated assessment of their accuracy and the precision with which they are produced. Methods for determining the accuracy of the data and products must be agreed upon and used nationally. The assessment of quality will naturally vary by data type. Quality tags are needed to provide product recipients with a measure of how the information should or should not be used. When products improve with time, quality measures become particularly important. These measures may also be used as flags for some users who are interested in only the highest quality information.

2.3.4.4 Best Answer

The ANSS will provide a single published description for any earthquake in the U.S. With multiple processing centers producing earthquake information, implementing the "one authoritative answer" approach will be challenging (particularly since some region boundaries cross seismic zones). The technique of providing the one and best solution for public use must be based on clear and programmable 'business rules'. Such rules will be based primarily on speed and quality (i.e. the fastest best result becomes the public one). As new or different solutions for a particular event become available within the system there must be a clear way to rapidly determine if they should supercede the current public version or not. Manual over-ride of the automatic system must be available, including the ability to cancel a spurious event out right.

2.3.4.5 User Formats

Some end users will require messages in specific formats or delivered by special channels or protocols. While the details of these are best left up to the specific implementation, the ANSS policy should be to attempt to provide as much information in as standard a format as possible.

2.3.5 Offline or Manual Review

The ANSS must support multiple levels of product review and analysis. Although "review" is probably a continuous process, it is possible to distinguish two types. The first is the rapid review of alarm events, while the second is the typical "post-earthquake" analysis.

Rapid review is performed immediately following an alarm and must be completed within a few tens of minutes after the origin time of the earthquake, with the goal of insuring the completeness and correctness of the rapid notifications. Corrections and updates to the automatic notification messages will be made through routine rapid review, typically performed at production data outlets.

Post-earthquake analysis is typically completed between tens of minutes to days to weeks (in some exceptional cases), with the goal of improving the automatic solution, using all possible data, and producing the most comprehensive and uniform data summary for an event. The continuum between rapid review and post-earthquake response is the periodic update of products as additional information becomes available. Post-earthquake analysis will be performed at production or other information outlets.

2.4 References

Report of the Network Architecture and Interconnection Subcommittee, http://quake.geo.berkeley.edu/anss-nai/, 55pp.

3 Instrumentation

3.1 Introduction

USGS Circular 1188 recommends that the ANSS include permanent and portable instrumentation. However, the portable instrumentation recommended represents less than 1% of the ANSS network. Herein, the TIC recommends standards to be used in procuring the basic instrumentation that will sense ground motion and store the resulting signals in a local data acquisition system (DAS) for the permanent broadband (national and regional) and urban monitoring (structures, reference and free field) deployments.

Methods for handling the data flow upstream from the DAS are defined and described in Chapter 2. Those recommendations will influence some aspects of the communication and networking protocols in the DAS.

Siting and installation procedures for the sensors and acquisition hardware are described in Chapter 4. There may well be constraints on size, packaging, power, and other factors, imposed by those standards or recommendations.

3.2 Approaching the Problem

A basic assumption underlying ANSS instrumentation recommendations is that issues are addressed from the framework of existing technology. Some ANSS-specific requirements may encourage new developments, and they will be incorporated insofar as they are feasible and cost-effective. In addition, an attempt was made to specify as few different types of instruments as possible. This approach may over-specify instruments in some settings increasing capital costs, but reduces maintenance costs in the long run by decreasing the size of the spares pool and the number of different types of instruments that must be maintained. It may be possible to achieve significant capital cost savings with little or no loss of capability by relaxing specifications for certain environments (e.g., reference stations in noisy urban areas). Early consideration must acknowledge the different instrumentation systems that will make up ANSS, as summarized in the following.

3.2.1 National stations

- Meet the needs of national and global monitoring.
    - High resolution in the band 0.01 to 15 Hz, on-scale recording, and latencies less than about 30 s.
- Meet the needs of national and global earthquake research.
    - Resolution below ambient noise in the band 0.04 Hz to 10 Hz, on-scale recording, high fidelity, and complete continuous data.
- Capture strong ground motion where generated by large nearby events.

  - Sensitivity in the band 0.02 to 50 Hz, a clip level of 4 g, constant absolute sensitivity, and low hysteresis.

3.2.2 Regional stations

- Meet the needs of local and regional monitoring.
  - High resolution in the band 0.02 to 35 Hz, on-scale recording, and latencies less than about 10 s.
- Meet the needs of regional scale seismological research.
  - Resolutions below ambient noise in the band 0.04 to 10 Hz, on-scale recording, high fidelity, and complete continuous data.
- Capture strong ground motion where generated by large nearby events.
  - Sensitivity in the band 0.02 to 50 Hz, a clip level of 4 g, constant absolute sensitivity, and low hysteresis.

3.2.3 Free field and reference stations (non-structural installations)

- Provide information about the strong motion wave field and local site effects with little (reference) or no (free field) contamination from major structures.
  - Sensitivity in the band 0.02 to 50 Hz, a clip level of 4 g, constant absolute sensitivity, low hysteresis, and latencies less than about 10 s.

3.2.4 Structural arrays

- Provide information about the response of a structure to strong ground shaking.
  - Requires sensitivity in the band 0.02 to 50 Hz, a clip level of 8 g, constant absolute sensitivity, low hysteresis, and latencies of approximately 10 s.
  - Consider the use of emerging technology to measure the response of structures (i.e. Electronic Distance Measuring (EDM) or Global Positioning System (GPS) devices to measure structural displacements directly).

3.3 General Goals & Expectations

Data delivery must be reliable and suitable for a variety of communications technologies. Equipment must operate reliably over long periods of time (at least 10 years) in hostile environments (extreme temperatures, moisture, "dirty" power, and pests).

3.3.1 Bandwidth

Bandwidth goals for national stations are based on USNSN specifications. The low frequency specification is based on research needs while the high frequency specification is limited by attenuation over distances comparable with the inter-station spacing. Bandwidths for regional and strong motion stations are based on observed practice.

3.3.2 Sensitivity & dynamic range

The clipping levels are true maximum ground motions that are to be recorded within specifications.

3.3.3 Data latency

Short latencies for free field and reference stations are to support "shake map" generation. Latencies for structural arrays are based on the need for rapid assessment of structural damage (especially for critical structures).

3.4 General Design Concepts

Some basic decisions about the behavior of ANSS stations either have or can be made *a priori* based on experience, technological trends, and the stated goals of the ANSS.

- The need for wide bandwidths and linear high dynamic range probably dictate feedback sensor designs.
- The need for high resolution dictates on-site digital recording and digital telemetry.
- Seismological research and engineering practice and research require three component data.
- Technological trends suggest standardizing on Internet protocols (IP).
- Strong motion data should have continuous access to telemetry when ever possible.
- Sites with limited telemetry bandwidth will be accommodated by event segmented strong motion data, compressing all data, and adopting the lowest sample rates consistent with requirements.
- The need for complete data suggests on-site storage for all types of stations.
- Reliable communications requires error correction and packet retransmission, which requires bi-directional communications. Variable communications latencies require on-site timing.
- Small data delivery latencies require short packets and reasonably fast communications speeds with minimal routing/buffering delays.

The combination of on-site storage and short latencies requires that old data be caught up while current data flows uninterrupted. That is, after a communications outage, older data should be transmitted in time sequential order in parallel with the real-time data but at a lower priority.

3.5 Functional Specifications

The specifications for national and regional seismometers are sufficiently similar that they could both be satisfied by the same sensor. This is reflected in the following specifications (e.g., the high and low frequency specifications have been extended for the national and regional seismometers respectively). If different national and regional seismometers are chosen (e.g., for cost reasons), these specifications should be modified by making the national seismometer bandwidth 0.01 to 15 Hz and the regional seismometer bandwidth 0.02 to 35 Hz.

Free field, reference, and structural instruments are judged to have similar enough requirements that they are considered together. The primary difference seems to be that free field and reference stations will require three components while structural arrays require elements that may be from one to three components and multi-channel recording systems.

The specifications call for the sensors and the DAS to be able to report model specific information such as nominal transfer function and device specific information such as serial number and sensitivity. Because this is a feature that is not available in current equipment, the ANSS will need to work with vendors to see it implemented in an acceptable form.

3.5.1 National station

3.5.1.1 Seismometer

- Three orthogonal component differential outputs with a response nominally flat to velocity in the band 0.01 Hz to 35 Hz (amplitude response may be 3 dB below the peak response at 0.01 Hz and at 35 Hz).
- Non-coherent noise floor at least 3 dB below the ASL New Low Noise Model (NLNM) in the band 0.05 Hz to 10 Hz. Non-coherent noise within 10 dB of the NLNM between 0.01 Hz and 15 Hz and within 20 dB of the NLNM between 15 Hz and 35 Hz.
- Dynamic ranges of at least 155 dB in the range 0.01 to 0.05 Hz, 150 dB in the range 1 to 10 Hz, and 140 dB in the range 10 to 15 Hz (see Appendix C).
- Nominal distortion less than -80 dB and nominal cross axis coupling less than -40 dB.
- Operating temperature range of 0 to 40 degrees C. Instrument sensitivity shall remain within +/-5% of nominal value over entire temperature range. Output offset and mass position voltages shall remain within operating limits for a +/-10 degree C temperature change.
- Transfer function shall be supplied with each instrument and shall be accurate to within 1% in amplitude and 4 degrees in phase over the pass band of the instrument.

- Instrument response after being over-driven (clipped) shall return to normal linear operation within 5 minutes after being over-driven by ground motions or calibration signals at or above the clip level of the instrument.
- Calibration input and remote lock/unlock, mass center, calibrate enable functions.
- Mass position outputs for each sensor component.
- Instrument output shall be unaffected by reasonable changes in magnetic field and atmospheric pressure and reasonable levels of radio frequency interference (see Appendix C).
- Instrument shall be designed for a 10-year (minimum) life and shall be demonstrated to have a 40,000 hour (minimum) mean time between failures (see Appendix C).
- Power consumption shall not be greater than 1 watts at 12 VDC (operational mode, leveling and/or mass centering motors not running).
- Sensor must provide the following information to the DAS on request (see Appendix C):
  - Manufacturer name
  - Sensor type
  - Sensor serial number
  - Factory calibration parameters including nominal poles and zeros response.

3.5.1.2 Accelerometer

- Three orthogonal component differential outputs with a response flat to acceleration in the band 0.02 to 50 Hz.
- Clip level of 4 g.
- Dynamic range of at least 145 dB in the range .02 to 2 Hz and at least 130 dB in the range 2 to 50 Hz and at (see Appendix C).
- Nominal distortion less than -60 dB and nominal cross axis coupling less than -40 dB.
- Operating temperature range of -20 to +60 degrees C. Instrument sensitivity and output offset shall remain within 1% of nominal value over a temperature range of 0 to 40 degrees C and within 2% over entire temperature range. Gain stable to 1% under all conditions.
- Transfer function shall be supplied with each instrument and shall be accurate to within 1% in amplitude and 4 degrees in phase over the pass band of the instrument.
- Hysteresis in acceleration offset shall be less than –100 dB referenced to full scale under all conditions.

- Calibration input, remote calibration enable function, and manual offset adjustment, which shall be lockable to prevent non-linear effects.
- Instrument output shall be unaffected by reasonable changes in magnetic field and atmospheric pressure and reasonable levels of radio frequency interference (see Appendix C).
- Instrument shall be designed for a 10-year (minimum) life and shall be demonstrated to have a 40,000 hour (minimum) mean time between failures (see Appendix C).
- Power consumption shall not be greater than 1 watt in operational mode at 12 VDC.
- Sensor must provide the following information to the DAS on request (see Appendix C):
    - Manufacturer name
    - Sensor type
    - Sensor serial number
    - Factory calibration parameters including nominal poles and zeros response.

3.5.1.3 Data Acquisition System

- Six-channel, 24-bit format analogue-to-digital converter (ADC) with differential input range matched to the sensors. Resolution shall be at least 23 bits from 0.01 to 15 Hz and at least 21 bits from 15 to 50 Hz (see Appendix C).
- The sensitivity of each digitizer channel (counts per volt) shall be accurate to 0.1% or better at DC (0 Hz).
- External time reference accurate to 1 ms absolute and a free running oscillator with a maximum temperature sensitivity of 0.1 ppm/degree C and a maximum drift rate (at constant temperature) of 0.1 ppm/day.
- Data samples on all channels running at the same sample rate shall be taken simultaneously to within 1% of the sample interval.
- Operating temperature range of -20 to +60 degrees C. Sensitivity stable to 1% over range 0 to 40 degrees C and to 2% over entire temperature range.
- Capable of generating control signals matched to sensors, such as lock/unlock, mass center, calibrate enable, initiate ring-down or free period test, damping test, etc. Capable of generating step, sine, and random binary telegraph calibration signals configurable to provide sensor outputs between 5% and 50% of full scale.
- All channels shall be derived from raw digitizer sample rate using linear phase "brick-wall" filters with high frequency corner f_c at least 80% of the Nyquist frequency and stop band amplitude (Nyquist to higher frequencies) at least 120 dB below the pass band. Pass band (DC to f_c) ripple shall be less than 5%.

- Capable of sampling continuous 3-component data from the primary sensor at up to 100 samples/s. Capable of sampling 3-component data from the secondary sensor at up to 200 samples/s. Capable of providing multiple simultaneous sample rates from broadband and strong motion sensors.
- Capable of detecting, and storing on local storage media, events on all channels of each sensor, flagging events in the continuous data from the primary sensor, and buffering triggered data for transmission from the secondary sensor.
- Capable of providing state-of-health (SOH) monitoring including mass position, internal temperature and voltages, external voltages (e.g., AC and batteries), absolute time quality, and latitude, longitude, and elevation (if a GPS clock is used). SOH parameters shall be available in continuous telemetry packets for ease of monitoring SOH without special requests.
- Capable of data compression at all sample rates. Packets will have a maximum length of 1000 samples to provide adequate latency.
- Data telemetry must be error corrected, must support standard IP communications protocol(s), must support a variety of communications technologies, and must be capable of transmitting backlogged and triggered data without interrupting real-time data delivery.
- Capable of buffering a minimum of 7 days of seismic data (in the event of a telemetry outage) in on-site storage media.
- Instrument output shall be unaffected by reasonable changes in magnetic field and reasonable levels of radio frequency interference (see Appendix C).
- Instrument shall be designed for a 10-year (minimum) life and shall be demonstrated to have a 40,000 hour (minimum) mean time between failures (see Appendix C).
- Power consumption: Not greater than 1 watts average, 2 watts peak at 12 VDC.
- Capable of acquiring sensor configuration parameters (i.e., manufacturer name, sensor type, sensor serial number, and factory calibration parameters) from both the seismometer and accelerometer and external power system (e.g., battery charger, UPS, or solar array) configuration and status as specified in Appendix C.
- Configuration information stored in each DAS should allow reconstruction of the complete DAS transfer function for all active data streams. Configuration information should include:
    - Manufacturer name
    - DAS type
    - DAS serial number
    - Board serial numbers and version numbers
    - Factory calibration parameters including:

  - Nominal poles and zeros response if applicable
  - Fir filter coefficients
  - A/D conversion factors for each channel

3.5.1.4 Power System

- Provide backup 12 VDC power to sensors, data acquisition system, and communications equipment for a minimum of 7 days in the event of main power source failure. For planning purposes, the power consumption of a national or regional station (six components) would average less than 3 W and a strong motion station (three components) less than 2 W exclusive of the communications system.
- Provide surge suppression, filtering, and stable 12 VDC output from AC mains with an input range of 90-130 VAC.
- Provide auto-cutoff of DC output voltage when it falls below 10.5 VDC to avoid damage to batteries or equipment.
- Provide state-of-health (SOH) monitoring to the DAS on request (see appendix C) including:
  - Manufacturer
  - Model
  - Input voltage
  - Internal alarm conditions

3.5.2 Regional station

3.5.2.1 Seismometer

- Same as for national station. Note that linear phase FIR filters are known to create acausal artifacts that can cause problems for automatic picks from stations very near to an event. Despite this drawback, the IS recommends that linear phase filters should be used for regional stations because of the enhanced value for later research. The IS suggests that acausal artifacts can be reduced to acceptable levels for real-time processing by attenuating high frequency energy using minimum phase filters.

3.5.2.2 Accelerometer

- Same as for national station.

3.5.2.3 Data Acquisition System

- Same as for national station, except:
  - Data buffering for 6 hours instead of 7 days.

3.5.2.4 Power System

- Same as for national station.

3.5.3 **Strong motion station (free field and reference)**

The accelerometer, the DAS, and the power system in this case shall be delivered as an integrated system, even though these three items may be physically separate modular units connected together with cables. The inter-module cables, with connectors, shall also be delivered as part of this integrated system. Cable lengths will be specified at the time the order is placed, and will be specific to each site. It is likely that a standard cable length will be appropriate in most cases.

3.5.3.1 Accelerometer

- Same as for national station.

3.5.3.2 Data Acquisition System

- Same as for national station, except:
  - Resolution of 21 bits in the band .02 to 50 Hz. Note that with 21-bits of resolution and a 4g sensor, theoretically a magnitude 2.5 event at 10 km should be well recorded and empirically a magnitude 1.8 event at more than 35 km can be recorded well enough to determine the peak acceleration. That is, ambient noise is likely to be the limiting factor in station performance, not the 21-bit resolution.
  - 3 channels (minimum) instead of 6.
  - A maximum sample rate of at least 200 samples/s.
  - Capable of on-site storage of a minimum of 2 hours of triggered data indefinitely in non-volatile memory (instead of 7 days continuous data).

3.5.3.3 Event detector

- Shall be triggered by accelerations from 0.0008g up to 4g.

3.5.3.4 Power System

  - Same as for national station.

3.5.4 Strong motion station (structural)

The accelerometer and its power system and the DAS and its power system shall be delivered as integrated subsystems, even though these items may be physically separate modular units connected together with cables. The inter-module cables, with connectors, shall also be delivered as part of this integrated system. Cable lengths will be specified at the time the order is placed, and will be specific to each site. It is likely that a standard cable length will be appropriate in most cases (between components at one location). Note that cables between the accelerometer and the DAS are not included. Wireless technology will be considered to allow easy distribution of sensors throughout an existing structure provided that it can be shown to be sufficiently reliable.

3.5.4.1 Accelerometer

- Same as for reference station, except:
  - Must be available in 1, 2, and 3 component packages
  - Must have an option for a clip level of 6g instead of 4g with a gain stability of 3%.

3.5.4.2 Data Acquisition System

- Same as for reference station, except:
  - Must be available in configurations including 3 to 24 channels.

3.5.4.3 Power System

- Same as for reference, except:
  - Power must be available at each accelerometer and at the central multi-channel DAS.

3.6 System Packaging

Vendors may address some of the specifications above including RFI, magnetic, and pressure shielding through equipment packaging. In addition, packaging will meet the following requirements:

- All equipment:

    - Operate in 100% relative humidity.
    - Survive temporary shallow submersion in water (see Appendix C).
- All seismometers and accelerometers:
    - Provided with leveling legs.
- Structural strong motion station:
    - Accelerometer plus data power system shall not weigh more than 25 pounds.

3.7 Evaluation of Competing Systems

- RFP must be written with testable specs (see Appendix C)
    - Sensor dynamic range shall be computed according to the recommendations of the Standards for Seismometer Testing Workshop, July 1989
    - Digitizer resolution computed according to the Modified Noise Power Ratio test.
- Manufacturers shall provide their own test results
- Pre-productions or prototype units provided during evaluation phase of contract will be fully tested
- Production units must also comply with specs and will be spot checked at random to assure compliance (using a subset of acceptance tests)

3.8 Data Format

At a minimum, data packets (both seismic and SOH) generated by the DAS shall include information that:

- Uniquely identifies the station and channel
- Provides information needed to decode and use the data including:
    - Data type and format
    - Packet length
    - Record number
    - Time correction

In addition, the DAS shall be capable of formatting the manufacturer, equipment type, serial number, and metadata (e.g., response information) for the DAS and collocated sensors and power equipment for occasional transmission. The goal is to make field equipment as self documented as possible. Note, however, that it must be possible for the ANSS processing system to override erroneous metadata collected from the field if necessary.

3.9 Station Architecture

The above specifications seek to make DAS and sensor equipment self identifying and capable of providing their own response metadata. It also seeks to provide SOH information from the DAS (e.g., location), sensors, and power system (e.g., power history). The model specified places the DAS in the central role of collecting the identification, metadata, and SOH information from all other subsystems and integrating it in a single data stream to the outside world. In addition, the roles of metadata and SOH information have been specified in an arbitrary fashion (e.g., AC voltage has been specified as an SOH stream derived by the DAS, but it could also be metadata provided by an UPS). In fact, other models are possible and may be advantageous (e.g., DAS, sensors, and power system all reporting through a separate communications controller). In practice, any functionally equivalent station architecture will be considered.

4 Siting and Installation

4.1 Introduction

Seismic instrumentation provides data that serve three primary purposes:

- Rapid response to potentially damaging earthquakes,
- Seismic monitoring, and
- Seismological and engineering research.

Traditionally, siting and installation have been designed to provide good coverage of geological and manmade structures of interest and good recordings of events of interest. Coverage implies that events are recorded at a range of azimuths and distances adequate to derive required products and structures are instrumented adequately to understand their dynamic deformation. As a trivial example, accurate hypocentral determination requires good azimuthal coverage and ideally a range of distances including very close stations. Good recordings require seismically quiet sites, good coupling with the bedrock, and highly sensitive seismometers and recording equipment. Engineering studies require strong motion information around and throughout structures.

The ANSS is focused on upgrading traditional seismic instrumentation with state-of-the-art broadband seismometers and accelerometers and high resolution (e.g., 24-bit) digitizers. Through the use of negative feedback technology, broadband sensors are capable of recording earth noise at a quiet site as well as large amplitudes with a high degree of linearity over a broad frequency band. However, to take advantage of the sensitivity and bandwidth of broadband sensors, it is necessary to consider traditional siting and installation issues as well as new issues such as thermal stability and tilts due to atmospheric pressure.

4.2 Site Characterization

Detailed understanding of the subsurface geology and soil/rock properties is important for understanding of the contribution of site response to measured ground motions and for the classification of measured ground motion parameters, particularly at strong motion reference stations. A good review of methods for site characterization is found in ASTM Standard D420-98 “Guide to Site Characterization for Engineering, Design, and Construction Purposes.”

For ANSS broadband and strong motion reference stations, some level of site characterization studies should be required for every station. At a minimum, the surface geology should be determined and available site information from previous local or regional studies should be obtained and added to the station’s auxiliary information. Surface geology provides a primary description of the site and should be obtained from geology maps or observations by a knowledgeable person. Note that surface geology can be a poor estimator of subsurface soil or rock properties, especially for sites geologically classified as rock.

In addition to thorough geologic descriptions, site-specific characterization information should also be obtained at strong motion reference stations. At a minimum, the NEHRP/IBC site class should be determined. The NEHRP/IBC site class is important for comparison of measured ground motions with building code seismic design levels. These site classes, denoted A-F, are formally described in the 2000 International Building Code's seismic design provisions as follows:

A. Hard rock with measured shear wave velocity V30>1500 m/s
B. Rock with 760m/s<V30<1500m/s
C. Very dense soil and soft rock with 360m/s<V30<760m/s
D. Stiff soil with 180m/s<V30<360m/s
E. A soil profile with V30<180m/s
F. Soils requiring special investigations (liquefiable soils, sensitive clays, or very weak soils)

V30 is the effective average shear wave velocity (1/average slowness) in the upper 30 meters. NEHRP/IBC classes require some kind of measurement of V30.

A more complete understanding of the contribution of site response to the measured earthquake shaking at a strong motion reference station will require a more complete subsurface site characterization. These additional detailed measurements are considered optional with respect to these guidelines, but are strongly recommended for all strong motion reference stations, whether on open ground, in small buildings, or in densely urbanized areas.

4.2.1 Obtaining Existing Site Information

Site characterization information is part of the station metadata and provisions must be made to maintain, archive, and distribute it along with other metadata. A literature search can be a very inexpensive source of information on site geology and even subsurface soil and rock properties. In most populated areas there will have been previous geological studies of the region and perhaps even local environmental, ground water, or planning studies. These can contain a wealth of information that will assist in site characterization.

Potential sources of information on a regional basis are government geological or natural resources agencies. An example is the U.S. Geological Survey. For local studies, sources of information are the local government planning agency, local universities, private water companies, and even local water well drilling companies. If the strong motion station is near a building, it is possible that the construction documents will contain some soils reports.

4.2.2 V30 Determination for NEHRP Categorization

V30 (recommended for strong motion reference stations only) can be estimated using noninvasive surface methods, or can be directly measured using either a minimally-invasive seismic cone penetrometer or more invasive drilling and logging methods. Drilling and logging methods have the added advantage that subsurface geology can be directly observed during drilling.

Two available surface methods for estimation of V30 are surface wave methods and seismic refraction. Note that these methods are relatively inexpensive and can provide a good estimate of V30 at many sites when performed properly. However, these methods can and have provided erroneous or biased data at sites when improperly performed or when site characteristics are not optimal (i.e. not flat layering). One should be prepared to use one of the direct measurement methods if these indirect surface measurements are suspect at a site.

A cone penetrometer (CPT, a metal probe pushed into the soil) is also an inexpensive way to obtain information about shallow (<30 meters) soils. If a "seismic cone" tool is used, shear wave velocity can be directly measured using a method equivalent to the downhole method. While the seismic cone does provide accurate measurement of the shallow shear wave velocity profile, it may be limited in depth of penetration at rock, stiff soil, or gravelly sites. It may not be possible to reach 30 meter depth and therefore not possible to accurately measure V30.

V30 can be measured at all sites using a combination of drilling and shear-wave velocity logging. Drilling can be done using the auger method if the soils are relatively soft; this will be less expensive. In many cases, however, the rotary method (mud or air) will be needed to reach 30 m depth. If desired, drive-type (SPT) sampling can be done to obtain disturbed samples for determination of site lithology. [For more information, see Isihara, K., Soil Behavior in Earthquake Geotechnics: Oxford Engineering Science Series, No. 46, Clarendon Press; ISBN 0198562241, 1996.]

4.2.3 Detailed Subsurface Investigations

Obtaining the most complete site characterization of a strong motion station will require drilling of an exploratory borehole, obtaining high-quality geotechnical samples for laboratory testing, and borehole geophysical logging.

A detailed site investigation can consist of:

- Drilling a borehole to the depth of "engineering rock" (Vs>750m/s)
- Lithology logging during drilling
- Obtaining samples for laboratory testing
- Seismic velocity logging
- Laboratory testing of samples for index properties
- Laboratory testing of samples for nonlinear properties

These investigations can be a major effort, requiring heavy equipment and expensive measurements and laboratory testing.

4.3 Station Documentation

A new or existing ANSS station should be well documented. A user of the recorded waveform data or derived parameters should be able to obtain all of the metadata needed to identify the station, its instrumentation, its station configuration/construction, its site conditions, and any other information which might have an effect on the data.

4.3.1 Basic Station Data

The basic documentation of a station should include the following, defined as the Basic Station Data:

- Station identification (name, ID number, etc.)
- Station location (coordinates, location description within site; detailed information may need to be protected in the property owner's interests)
- Station access information (contacts, keys, etc.; may be protected information)
- Station construction (type, description)
- Site geology
- NEHRP/IBC category/V30 value (strong motion reference only)
- Station instrumentation details
- Station calibration data
- Station history (installation date, modification descriptions/dates, etc.)
- Ambient noise spectra (national and regional broadband sites only)

These data must be available in two forms: an online database and an archival distribution media.

4.3.2 Auxiliary Station Information

Other information about a station that should be documented includes:

- Photographs of the station construction
- Photographs of the station instrumentation installation
- Photographs of the station vicinity (showing nearby buildings, topography, or other features)
- Site map
- Plots/numeric data for site characterization information
- Other descriptive information about the site

As for the Basic Station Data, the Auxiliary Station Information must be available in two forms: an online database and an archival distribution media.

4.4 National and Regional Stations

USGS Circular 1188 specifies that the ANSS national stations are to be distributed as uniformly as possible across the US. The primary frequency band of interest is 0.01 to 15 Hz. Higher frequencies are not of interest because propagation distances are typically less than the mean inter-station spacing (~300 km). At the long period end, the national backbone can provide higher spatial sampling to complement the even longer period instrumentation of the Global Seismograph Network (GSN) for continental scale structural studies as well as improved coverage for long period source studies. Note that the ANSS plan calls for a backbone of 100 stations of which 80 would meet ANSS specifications and 20 would meet GSN specifications. GSN stations have similar requirements to the ANSS backbone stations except that there is interest in periods as long as 100,000 s.

Locations of the regional broadband stations are the responsibility of the regional working groups and will not be discussed further here. The primary frequency band of interest is 0.05 to 35 HZ. At the high frequency end, small events very close to the station are of interest. At the long period end, fundamental and higher mode surface waves should be recorded.

The siting and installation requirements for both national backbone and regional broadband stations will be considered in the following. Although the requirements for these elements of the ANSS are somewhat different, as discussed below, their siting and installation have much in common. The common elements and concerns are described in the following subsections.

4.4.1 Network Design

Seismic network design is always a compromise between network goals and funding. The ANSS has chosen high resolution, broadband sensor technology that establishes the cost of each station. Funding then limits the number of stations available to meet program goals. This situation is further complicated by the multiple uses most networks serve. For example, rapid response requires sensors near urban areas while monitoring requires some coverage in areas of low to moderate seismicity. Similarly, sensors near seismic zones are needed for some research projects while other research requires more uniform regional coverage.

Ultimately, the success of a network design depends on the ability of the network to produce the products required with the desired accuracy and timeliness. To some extent, this can be modeled theoretically. For example, the timeliness and accuracy of earthquakes in known locations can be tested. Of course, these results must be used with caution as station performance can be highly variable (short period noise can easily vary by 40 dB from site to site) and difficult to predict. Thought must also be given to the problem of network utility at various stages of completeness. Even with adequate funding, networks installation is typically performed over a number of years, and (broadband) network uptime rarely exceeds 90% in practice.

4.4.2 Seismic Noise

Over the frequency band of interest to the ANSS (~0.01 to 35 Hz), seismic noise falls into three distinct regimes. At high frequencies (0.5 to 35 Hz), seismic noise is dominated by wind, running water, and cultural effects. Wind couples into the ground through trees, towers, antennas, structures, and even rough topography. Rapids and waterfalls couple into the ground directly, Cultural noise is generated by cars, trains, airplanes (on the ground), mining, manufacturing, and agriculture. In fact, almost anything people do in their daily lives contributes to cultural noise.

At mid-frequencies (0.05 to 0.5 Hz), seismic noise is dominated by surface waves generated by ocean waves breaking on shorelines. This so-called 6-second microseism peak is huge (at least 20 dB above the high frequency noise and 40 dB above the long period noise). Although the microseisms are significantly larger near the ocean, they are a pervasive, worldwide phenomena.

Long period noise (0.0001 to 0.05 Hz), is dominated by tilt noise due to thermal and atmospheric pressure effects. This counter intuitive result is due to the sensitivity of broadband sensors to nanoradian tilts. Thermal effects include the differential heating of structures or even rough topography inducing small deformations. Passing weather fronts differentially deforming the ground similarly induces pressure tilts.

4.4.3 Site Selection

The best sites are located on (or even better, in) hard, uniform, competent bedrock; remote from populations centers, heavily traveled roads, train tracks, and heavy industry; and away from trees, antennas, buildings, rapids, and windy locations such as mountain peaks or saddles. Needless to say, these conditions are difficult to achieve and most seismic sites are a compromise between network design goals and site characteristics. This problem becomes even more difficult when power, communications, access, and security are considered.

Seismic noise is heavily influenced by local geology. Installation on unweathered bedrock is best. Harder rock provides a higher signal to noise ratio and less complex geology provides less distortion in propagating waves, particularly at higher frequencies. However, weathered bedrock and well-consolidated sediments can also make useful seismic sites. Generally, softer, low impedance material amplifies both signal and noise, but results in a net loss in the signal to noise ratio. Softer materials are also much more prone to long period tilting, particularly due to thermal effects. Poorly consolidated material generally makes a poor seismic site and should be avoided if possible.

Geologic, topographical, and political maps can be useful for preliminary siting work. Geologic maps help to determine if outcrops are available and what types of bedrock might be encountered. Topographical maps can provide a feeling for the roughness of the terrain, vegetative cover, and accessibility. Political maps can provide a guide to natural and cultural noise sources. Local seismic network experience can also be invaluable.

Once preliminary sites are selected, they must be surveyed for suitability based on potential local noise sources, accessibility, availability of power, communications drops or lines-of-site, security, and property ownership. Finally, it is important to operate broadband portable instruments with 24-bit recording at the most promising sites to determine the best ones empirically. It is necessary to use broadband instrumentation and to record for at least a day or two at each site to determine both the long and short period site noise characteristics because good short period sites are often poor long period sites and vise versa. Shallow seismic profiling can be useful in determining the complexity of the subsurface geology and the depth to competent bedrock.

Although finding good seismic sites is never easy, there is hope because most noise sources are relatively high frequency and high frequency noise from surficial sources doesn't propagate very well. For instance, quite good performance is sometimes possible only a few kilometers from major highways and only 30 m from tall trees and antennas. For more information about siting see the New Manual of Seismological Observatory Practice (Bormann, 1999; http://www.seismo.com/ msop/nmsop/nmsop.html). For more information on the recommended distances from a variety of high frequency noise sources see the Manual of Seismological Practice (Wilmore, 1979; http://www.seismo.com/msop/msop79/msop.html).

4.4.4 Installation Types

Various types of installation in mines or caves and at the surface in vaults or smaller structures will be discussed. Boreholes can be useful for emplacing sensors into bedrock when no outcrops are available and for reducing long period noise. However, because of the high cost and typically low cost-benefit ratio, boreholes are not recommended for use in the ANSS.

Although the cost of drilling a shallow tunnel can be prohibitive, abandoned mines and to a lesser extent caves can provide outstanding seismic sites. This is because underground sites are often in hard rock, are thermally stable, and to some extent isolated from pressure effects. However, underground sites can also be difficult because of owner liability (e.g., due to the dangers of rock falls, radiation, and other hazardous materials) and environmental issues (e.g., cave decorations and endangered species). Underground locations also require special considerations for moisture and long cable runs (for power, communications, and GPS antennas). Partitions with tightly fitting doors are sometimes used to minimize air circulation, and moisture can be controlled through the use of gunnite.

By far the most common type of seismic installation, however, is at or near the earth's surface. Installations in buildings have not proven effective because buildings significantly distort the wave field and are not recommended. Recent work has shown that the massive WWSSN style vaults are not necessary for good long period performance. Existing vaults are useful, but it is not recommended that the ANSS build more. Rather two types of surface installation are recommended: 1) small buried vaults and 2) barrels or pipes.

The small vault is typically a concrete structure containing an isolated pier with a surface area of about 1 square meter, room for electronics, and a small maintenance working space. The floor of the vault would typically be buried at least 2.5 m below the surface of the ground. The top of the vault should be buried at least 30 cm. If possible, the DAS should be collocated with the sensors and the communications and power equipment should be placed in a separate enclosure (in either a shelter above the vault or in a subsurface room near the vault; see Hanka, 2001; http://www.gfz-potsdam.de/geofon/agu_pub/)

The barrel or pipe installation is typically constructed using large diameter, commercially available, concrete or galvanized pipe or heavy, plastic, toxic waste barrels. Typically, the pipe or barrel is set into concrete so that the top of the enclosure protrudes about 15 cm above the ground. The hole outside the enclosure is also filled with concrete. In this type of installation, the concrete at the bottom of the enclosure acts as the pier. The sensor must be placed deeply enough that the top of the insulating material above the sensor is still below the surface of the ground. If possible the DAS should also be placed in the seismic enclosure (see McMillan, 2001, USGS Open File Report, in preparation). Note that in this type of installation, the communications and power equipment are typically placed in a separate shed or enclosure away from the sensors. Note that barrel installations have also been used with some success in mines to provide thermal insulation and minimize convection.

In all cases, the sensors are placed on a smooth concrete surface that is well coupled with the underlying rock. Bedrock is exposed by removing surficial soil and scraping off weathered material (preferably with a backhoe). The surface of the rock should be reasonably smooth and free of dirt before the concrete is poured. Chemicals that improve the adhesion of the concrete and resistance to moisture are often added.

4.4.5 Minimizing Environmental Effects

Environmental factors act on seismic stations by either directly affecting the sensor(s) or indirectly affecting the sensor(s) through interactions with the seismic enclosure. Factors considered include electromagnetic interference (EMI), magnetic fields, wind, temperature variations, and pressure fluctuations. All of these factors can directly effect the sensor. Temperature and pressure also act indirectly through the enclosure.

High performance seismic equipment generally employs differential circuitry to reject common mode signals such as EMI. EMI also can be minimize by keeping the analogue signal cables between the sensor and the DAS as short as possible. Most broadband sensors are well shielded against magnetic and pressure effects by heavy external steel cases. However, seismometers vary widely in their thermal sensitivity. Some sensors can be driven onto their stops by temperature changes as small as a few degrees C while others can withstand an order of magnitude greater variation. Broadband sensors typically accommodate thermal variations by mechanically re-centering their masses. In most cases, this process can be automated and remotely commanded. However, the data are useless during the re-centering process, which can last for minutes to hours. Therefore, thermal stability is essential to the effective operation of seismic sensors.

Choosing sheltered sites, using subsurface installations, and separating any aboveground shelter and antenna from the sensors can minimize wind noise coupling directly into the enclosure. Choosing sites in hard rock, with only moderate topography and sealed subsurface installations helps minimize pressure effects. In a vault installation, isolating the pier (which is firmly coupled to the bedrock) minimizes the effect of the vault tilting.

In a barrel installation, the whole subsurface structure is coupled to the bedrock and no isolation is necessary. Warpless baseplates developed for several very long period sensors have been shown to be effective at controlling the effects of very long period tilts due to pressure (e.g., Holcomb and Hutt, 1992, Open File Report 92-302, USGS or Hanka, 2001; http://www.gfz-potsdam.de/geofon/agu_pub/).

Choosing a site out of direct sunlight (or installing a cover or low lean to roof over the sensors), burying the sensors, using concrete without aggregate or reinforcing steel (to avoid differential expansion), and using adequate insulating material can minimize thermal effects. The concrete pier (or barrel floor) should also be vibrated to remove entrained air bubbles that can also result in differential expansion. Because long period seismic signals (and very long period seismometers themselves) are sensitive to very small thermal variations, the insulation of sensors is a highly developed art. The experts recommend at least 10 cm thick foam insulation sealed all around the sensors with an R value of at least 35 (e.g., Uhrhammer, Karavas, and Romanowicz, 1997; http://www.seismo.berkeley.edu/seismo/bdsn/instrumentation/guidelines.html). Note that in a vault installation the insulation and supporting structure around the sensor(s) amounts to a vault within a vault.

Because broadband seismometers are active, they dissipate a small amount of heat. Therefore, if the insulation is too good, the sensors can overheat. Also, the heat dissipation can result in thermal convection around the sensors. This is combated by keeping the thermal enclosure around the sensors as small as possible and by filling the enclosure with foam beads or with fine playground sand. Either material kills convection and contributes to thermal stability. Sand has also been observed to improve seismic coupling between the sensor and the pier and helps to keep high aspect ratio sensors upright during strong shaking.

Surprisingly, 24-bit digitizers are also sensitive to thermal variations and to air convection, which can increase electronic noise. Generally, they are housed in sealed environmental enclosures. However, because DASs draw more power than sensors (3 to 25 V), stabilizing their temperature is problematical. Low power DASs should be installed in the subsurface seismic enclosure if their size permits, but with less insulation than the sensors. Higher power DASs should be installed in a separate enclosure. Because of the environmental housing and their self heating, higher power DASs stabilize their own temperature to some extent, albeit at a rather high level (typically 35° to 40° C).

4.4.6 Installing the Equipment

Installing the equipment requires consideration of:

- seismic coupling
- sensor orientation
- electrical grounding
- cabling
- isolation of equipment that generates acoustic noise

Note that the location of the sensors must be determined to within 10 m referenced to the WGS84 datum.

At low frequencies, the weight of the sensor is typically adequate to provide good coupling just by placing the sensor on the pier. However, coupling at frequencies above about 20 Hz is much more difficult as evidenced by spurious spectral bumps (probably due to the feet of the sensor chattering on the pier). Recommended coupling methods include surrounding the sensor with sand, potting the sensor(s) in plaster of Paris, or epoxying the feet of the sensor to the pier. Strong motion sensors should be attached to the pier with bolts or straps to avoid being overturned during very large accelerations. Seismometers should never be bolted or strapped to the pier because of the danger of contaminating small seismic signals.

For near surface installations, experiments have shown that it is possible for a trained technician to orient sensors to about 1 degree from a compass heading (accounting for local magnetic declination and presuming no magnetic anomalies). To orient sensors in tunnels and deep vaults or to check the orientation of surface sensors a comparison of microseisms with a reference sensor at the surface has proven valuable (e.g., Holcomb, 2001, USGS Open File Report, in preparation). This method can be highly accurate even with sensor separations of several kilometers because of the strength and long wavelength of the microseisms.

Adequate grounding is essential to get the best performance from sensitive electronics. For example, a lack of grounding has been observed to increase the electronic noise in high performance digitizers. For electronic purposes, the grounding wires do not have to be very heavy. However, more substantial grounding wiring may be required if the equipment is equipped with internal surge suppression. The electronics should not be grounded into the same point as the A/C power if at all possible.

It is also important to eliminate ground loops, as they can add significant noise to the seismic signal. It is best to ground all equipment to a common point. Care must be taken because sensors can also be grounded through the pier. One possibility is to install the sensors on a heavy glass plate mortared to the pier. This has the added benefits of providing a smooth level surface and acting as a moisture barrier.

Electronic equipment installed in racks or on shelves should be tied down to avoid damage during large accelerations. Excess cable should be kept to a minimum. Sensor cables, in particular should be laid in gentle arcs on the vault floor or suspended to avoid any strain on the sensor. Improperly laid cables can introduce noise into sensors as they expand and contract.

Equipment that generates acoustic vibrations such as transformers (e.g., in battery chargers) and fans in electronic equipment must be located at least 10 m away from the sensor. Ideally, power and communications equipment should be located in a separate enclosure (a small shed or fiberglass enclosure mounted on a concrete pad is often used for this purpose). Installation of such equipment on soft foam rubber at least10 cm thick can greatly reduce the acoustic coupling into the ground.

4.4.7 Protecting the Station

Delicate seismic equipment must be protected from:

- lightning and other power surges
- flooding
- vandalism
- corrosion, dust, and mold
- rodents and other pests

It is possible, but generally expensive, to protect seismic equipment from direct lightning strikes (though the station will usually be taken down). Because direct lightning strikes are rare (at least through most of the US) and because the cost of seismic equipment is rapidly declining, heroic measures for lightning protection (e.g., massive grounding, Faraday cages, etc.) are probably not cost effective and are not recommended for the ANSS. It is worthwhile to avoid siting stations in high lightning risk locations (e.g., the tops of tall mountains). It is also worthwhile burying cable runs at least 20 cm below the ground to avoid attracting lightning.

For stations operating from A/C power, surges due to nearby lightning strikes (or other sources) carried to the station through the power grid are a much more significant problem. Operating all seismic equipment from batteries and only using main power to charge the batteries has proven an effective solution to surges through the power grid. Surge protection built into most seismic equipment (given adequate grounding) is generally sufficient to protect the electronics from surges that make it through the batteries.

Power in rural areas can have many problems other than surges including high or low voltages, phase discontinuities, and extended outages. A combination of batteries and DC-DC converters (built into most seismic field equipment) effectively deals with these problems. Because power is such a common source of station outages, it is worthwhile monitoring battery voltages as an aid to remote diagnosis. Monitoring A/C power is even more useful, but risky since it creates a direct path between the power grid and the DAS (bypassing the batteries). Also, field equipment should be equipped with low voltage cut-off circuitry to protect the batteries from complete discharge during extended power outages.

Water in seismic vaults or electronics enclosures is also a significant problem, particularly if they are underground. Water typically gets into enclosures through the access cover, the floor, or the cable conduits. It is much less likely that water will penetrate the walls of the enclosure unless they are cracked. Any cracks or holes in the enclosure should be well sealed with concrete patch or silicon caulk. Dampness in vaults can be channeled away from equipment into a sump. In smaller enclosures the air can be dried using desiccant.

Enclosure access doors, panels, or lids should fit tightly, be sealed with a gasket, and be designed to avoid water. Double doors or a low lean to roof over the vault (also useful as a sunscreen) can also be effective. The concrete used in the floor and pier of a vault or floor of a barrel installation should be treated with chemicals that improve water resistance. If an isolated pier is used, the isolation gap should be filled with asphalt or a similar material to seal out water. Finally, cable conduits need to be tightly fitted through the enclosure wall and carefully sealed using gaskets or silicon caulk. The conduits themselves should be run downhill going away from the sensor enclosure and should be plugged with expanding (aerosol) foam insulation. Equipment other than the sensor should be installed above the floor (e.g., above the sensor insulation, on pallets or shelves, or onto walls) to avoid water damage. Note that sensors are usually hermetically sealed, but that their associated control electronics aren't always watertight.

Sadly, vandalism can also be a significant problem at seismic sites. The best way to avoid vandalism is to make the station as unobtrusive as possible (e.g., by installing the equipment underground). Above ground enclosures should be out of sight from nearby roads and trails if possible. If above ground equipment (e.g., satellite or radio antennas) are likely to attract attention, other security measures should be taken. Camouflage, fencing, locks, and installation on public land or near rural dwellings can all be effective security measures. Note that the requirements for good security are diametrically opposed to the requirements for quiet sites.

Steps taken to control flooding are also usually effective against dust, rodents, and other pests. Paradoxically, environments where flooding is not a problem (e.g., above ground electronics enclosures or tunnels) are often poorly sealed and are more prone to problems with dust and pests. Sealing enclosures and drying the air inside using desiccant can also combat corrosion and mold. Tunnels and large vaults usually offer a protected, thermally stable environment. However, it is still worth using enclosures (e.g., barrels, etc.) to protect the equipment from dust, mold, and pests. This is particularly true for any equipment that is not housed in its own environmental enclosure and to protect cable contacts from corrosion.

4.4.8 Recommended Installation – National Stations

Tunnel and small vault installations are recommended for the GSN specification national backbone stations because thermal stability is so critical to long period performance. Vaults should be buried at least 2.5 m and thick insulation should be installed. Warpless baseplates should be used if possible to minimize the effects of pressure fluctuations. DASs should be installed in the seismic vaults for thermal stability. Power and communications equipment should be installed in a separate enclosure at or near the surface. Note that the depth to unweathered bedrock dictates the depth of burial of seismic vaults. The maximum vault depth that may be used is determined by the strength of the vault and cost. Installations as deep as 5 m should be considered.

Tunnel and barrel installations are recommended for the remainder of the ANSS national backbone stations. In most parts of the US, burial of 0.5 to 1 m is adequate and easily achieved using barrels or pipes. If possible, DASs should also be installed in a subsurface enclosure for thermal stability. Power and communications equipment should be installed in a separate enclosure. If barrels must be installed at the surface, they should be buried with soil or loose rock leaving about 15 cm exposed. For additional protection from direct sunlight and thermal isolation, it is recommended that the barrels be covered with sloping door set into a wooden frame and filled with foam peanuts.

4.4.9 Recommended Installation – Regional Stations

Tunnel and barrel installations are recommended for regional broadband stations. In most parts of the US, burial of 0.5 to 1 m is adequate and easily achieved using barrels or pipes. If possible, DASs should also be installed in subsurface enclosures for thermal stability. Power and communications equipment should be installed in a separate enclosure. If barrels must be installed at the surface, they should be buried with soil or loose rock leaving about 15 cm exposed.

4.5 Urban Stations

The siting and installation requirements for free field, reference, and structural recording are described in the following.

4.5.1 Important Issues in Station Siting and Design (Non-Structural)

Perhaps the three most important technical issues related to the topic of non-structural strong motion station siting and design are: 1) minimization of effects of structures on recorded motions; 2) design of the instrument foundation to minimize its effect on recorded motions; and 3) the need for characterization of the station site. Background for these three issues is briefly summarized below.

4.5.1.1 Building Foundation Motions

A goal of strong ground motion measurements is to accurately record the combined effects of earthquake source, propagation path, and geological/geotechnical site effects at a particular location within the range of amplitudes (<0.001 to 2g) and frequencies (0 – 50 Hz) needed for the various alerting, assessment, and research applications. Localized effects on the measurements of man-made features of the particular location, including the station itself, should be minimized. Earthquake ground motions near a building may be affected by the interaction between the structure and the soil. Therefore, in an urban area it may not be possible to find a completely uncontaminated site for a strong motion station. The concept of an Urban Reference Station, as opposed to a Free-Field station, accepts this characteristic.

4.5.1.2 Instrument Foundation Motions

When a strong motion station is located away from buildings on soil, it will have its own small foundation for supporting the recorder and/or sensor. The instrument foundation can affect the recorded motions at high frequencies, and if the soil is soft, at frequencies as low as 10 Hz. ANSS and other strong motion station designs, especially those on open ground, should consider this issue of instrument foundation response and strive to create a station that has horizontal and vertical transmissibilities of 1.0 over the 0 – 50 Hz frequency range.

4.5.1.3 The Need for Site Characterization

The engineering properties of the soil or rock under a strong motion station can have a large effect upon the recorded motions. Most strong motion network operators do not routinely perform extensive site characterization studies for their new stations; the main reason is the cost of such studies. Strong motion station sites are often characterized by the surface geology. The recent ROSRINE project (http://geoinfo.usc.edu/rosrine) has shown that surface geology alone can be a poor predictor of subsurface engineering properties. A detailed understanding of the subsurface geology and soil/rock properties at a strong motion station is important for understanding of the contribution of site response to the measured ground motions. Site characterization studies are needed at every ANSS strong motion reference station.

4.5.2 General Siting Criteria

Locations of ANSS free-field, reference and structural response stations shall be prioritized within a system of global priorities considering the following issues:

- Desired density of coverage
- Locations of existing stations – consider regions with inadequate coverage based on the desired density of coverage
- Probability of shaking – consider the highest likelihood of shaking, both short period and long period
- Probability of property damage – consider areas with elevated risk due to the type or number of structures or facilities
- Probability of loss of life and indirect losses – consider areas with elevated probability of loss because of increased likelihood of casualties, death or human suffering due to the fragility of the infrastructure
- Probability of learning – consider areas of major uncertainty in knowledge about earthquake generation, seismic wave propagation, ground motion attenuation, or site response in order to improve the understanding of the hazard in those areas
- Value for emergency response – consider locations of strategic value for providing effective ground shaking information for emergency response

4.5.3 Reference Stations on Open Ground (Free Field Stations)

Ideally, an urban strong motion reference station (either the entire station or just the sensor) will be installed on open ground in an attempt to minimize contamination of the recorded motions by structural response. This section contains siting criteria, a discussion of siting issues, and recommended station designs for strong motion reference stations on open ground.

4.5.3.1 Siting Criteria

A strong motion station located on open ground will be considered a "Strong-Motion Reference Station: Open Ground" (SMRS-OG) if it meets the following criteria:

- It is not sited on locally anomalous soft or hard soils that might create ground motions not expected to be experienced by nearby sites of interest;
- It is not sited in or on a localized topographic feature such as a hill, ridge, or valley that might create ground motions not expected to be experienced by nearby sites of interest;
- It is located a distance of at least one major structural dimension (height or length, whichever is greater) from any large building (>4000ft sq. ft in plan or >2 stories in height) or any building with a significant basement or foundation;
- It is located a distance of at least one major structural dimension (height or length, whichever is greater) from any non-building structure likely to cause significant soil-structure interaction effects that will contaminate the data; and
- Station construction is designed to minimize soil-structure interaction in the frequency range 0.02 – 50 Hz.

4.5.3.2 Siting Issues

There are many issues to be considered in the location of a strong motion station. Perhaps the most important issues are those of site availability, permission, and permitting. A discussion of these issues and many other siting issues is beyond the scope of these guidelines. Four other important siting issues for SMRS-OG stations are briefly discussed below. These topics and discussions are not comprehensive, but are intended to raise main issues for further consideration.

4.5.3.2.1 Background Vibration

Although not as serious a problem as with high-gain broadband stations, SMRS-OG stations should be kept away from potential sources of vibration. These can include:

- Large motors, pumps, or generators;
- Large pipelines with active flow;
- Large masts, poles, or trees;
- Heavy vehicle traffic; and
- Industrial activities

When in doubt, it is suggested that the background vibrations at a potential site be monitored. Peak ground vibrations should be less than 0.001g.

Even if the steady-state background vibrations are small, care must be taken to avoid locations where large vibrations could be induced during a strong earthquake. Large valves, pumps, or other mechanical or electrical devices that could activate or fail during earthquake shaking and transmit abnormal energy pulses also should be avoided.

4.5.3.2.2 Security

In both urban and remote areas, vandalism can be a problem for SMRS-OG stations. One must make provisions for security in the station design. This can be accomplished using stout enclosures, locks, tamper-proof external hardware, and fenced enclosures. If fencing is used, care must be taken to minimize contamination of ground motions by the vibration of the fence; lightweight is best. The best security measure is providing a low profile for the station.

4.5.3.2.3 Power

Modern strong motion instrumentation, especially with real-time digital communications, will require a reliable power source of as much as a few tens of watts. For an SMRS-OG station, this power issue can provide a significant challenge. Solar power options are available, but several large solar panels will be required for most strong motion reference stations. This power issue should be carefully considered during planning and design for strong motion reference stations on open ground. One must also take care to minimize contamination of ground motions with vibrations from large solar panels and their supports. In any case, a battery system with enough capacity for 4 to 7 days of operation without power is needed.

4.5.3.2.4 Communications

The ANSS strong motion reference stations will be connected to some form of digital communications for data transfer and maintenance purposes. During the planning phase of a new station, one must consider the availability of appropriate communications. It may be difficult to connect wire- or fiber-based communications to a self-contained open ground station; one can consider wireless options in this case. One must also take care to minimize contamination of ground motions with vibrations from large antennae masts near the strong motion sensor.

4.5.3.3 Recommended Station Design

There are many different strong motion station designs that have been used in both past and present. However, note that some of these designs use large foundation blocks or piers, which may not be appropriate for the definition of a strong motion reference station contained in these guidelines.

Installation at an open ground location requires constructing a reinforced concrete mounting pad with a lightweight enclosure. A small concrete slab/pad and a lightweight enclosure will help meet the goal that the transmissibility of the installed strong motion station be 1.0 over the frequency range 0.02 – 50 Hz.

To provide a standardized design for ANSS strong motion reference stations, recommended station designs for both self-contained stations (containing all electronics within one enclosure) and remote sensor stations (containing only the sensor, other electronics remote) are fully described in Document C-USGS-2000-01, Ver. 0.92 (COSMOS Guidelines for Installation of Advanced National Seismic System Strong Motion Reference Stations), pages 13 and 14.

Other station designs, if used, should be experimentally or analytically studied to verify that the completed station does not significantly affect the recorded ground motions.

4.5.4 Reference Stations In Small Buildings

An acceptable strong motion reference station can also be installed within a building small enough to have minimal effect upon the earthquake shaking. This section contains siting criteria and a discussion of siting issues for strong motion reference stations in small buildings.

4.5.4.1 Siting Criteria

A strong-motion station will be considered a "Strong-Motion Reference Station: Small Building" (SMRS-SB) if it meets all of the following criteria):

- It is located within a small building (<4000 sq. ft in plan and <2 stories in height);
- It is installed on grade;
- It is located in a building without significant basement;
- It is located in a building with a small foundation (flat slab preferred, no pile foundations or deep spread footings);
- It is located in a building of relatively lightweight construction (wood frame preferable, but reinforced masonry acceptable); and
- It is located a distance of at least one major structural dimension (height or length, whichever is greater) from any large building (>4000 sq. ft in plan or >2 stories in height) or any building with a significant basement or foundation;
- It is located a distance of at least one major structural dimension (height or length, whichever is greater) from any non-building structures likely to cause significant soil-structure interaction effects that will contaminate the data.

4.5.4.2 Siting Issues

Siting issues are generally the same as for SMRS-OG stations with the following exceptions.

4.5.4.2.1 Background Vibration

Strong motion reference stations in buildings should be kept away from potential sources of ground and structural vibration. These can include:

- Large motors, pumps, or generators;
- Unsupported floor slabs;
- Localized human activity;
- Heavy vehicle traffic outside; and
- Industrial activities.

Care should also be taken to protect the sensor from impact of falling objects. It is recommended that a clear space of 2m (minimum) be maintained around the sensor, and that the general area of the sensor be maintained free of furniture or contents that could move during an earthquake and contaminate the measured motions with impact vibrations.

4.5.4.2.2 Security

Vandalism can be a problem for strong motion stations in buildings. One must make provisions for security in the design of a strong motion station. A dedicated room with a locked door is recommended. Some installations also have a steel fence cage around the sensor within a non-dedicated room.

4.5.4.2.3 Power

For a strong motion station in a building, power may not be a major issue. However, sufficient power reserve should be provided in case of power failure, through batteries or an UPS, for operation for 4 to 7 days. Power conditioning is also a good idea.

4.5.4.2.4 Communications

In a building, communications may not be a major issue as with stations on open land, but it is still an important issue to be considered.

4.5.4.3 Recommended Station Design

There is no one recommended design provided here for a strong motion reference station within a small building, because each building situation will be different. However, following are several strongly recommended features of a building installation:

- The sensor, recorder, and all auxiliary components must be bolted or fastened securely to a major part of the structure, preferably the floor slab;
- The location within a building should be as secluded as possible, away from human traffic;
- The location within a building should be as far as possible from any structural or nonstructural building components that may strongly amplify the ground shaking. When in doubt, an experienced structural engineer should be consulted for appropriate location; and
- The location should not be in the center of an unsupported floor slab.

4.5.5 Reference Stations in Densely Urbanized Areas

Risk to life and property is often greatest in the densely urbanized sections of large metropolitan areas such as downtown and high-rise areas of San Francisco, Los Angeles, Seattle, and New York. These areas often include older structures built prior to modern codes and in many cases may include structures on soft soils near embayment and coastal areas. Soil-structure interaction effects of tall structures, bridges, and other transportation structures in the downtown areas will likely contaminate ground motions. Seismic background noise in these areas will be variable and especially high during rush hours and construction periods. Nevertheless, it is these areas for which thorough measurements of ground motion and the performance of structures are of highest priority and critical for improvements in public earthquake safety.

4.5.5.1 Siting Criteria

A strong-motion station will be considered a “Strong-Motion Building Reference Station: Densely Urbanized Area” (SMBRS-DU) if it meets the following criteria:

- It is located so as to measure representative base floor motions in the densely urbanized areas;
- It is located within a building 10 stories or less in height;
- It is located on the base floor of the building (i.e. the lowest floor level, whether parking or basement).

Reference stations located in densely urbanized areas should be sited with SMRS-SB criteria wherever possible. In those densely urbanized areas for which SMRS-SB type sites are not available SMBRS-DU criteria should be used. If possible, the building in which an SMBRS-DU station is located should also be instrumented for structural response to allow the building response to be removed from the ground or ground floor motions. Data from SMBRS-DU stations will be used for comparison with those of nearby reference stations located on open ground or in small buildings.

A suggested goal for a densely urbanized area with high seismic hazard, in which SMRS-OG or SMRS-SB stations are not possible, is to have one SMBRS-DU station for every 2 million square feet of building space or at a density that will ensure documentation of rapid changes in underlying geology. Density of stations based on the 2M sq. ft. guideline translates into spacing depending on the type of zoning. For zones of dense high-rise buildings this may be 1 to 2 square blocks, for zones of low-rise industrial buildings 1 to 2 square miles, and for urban residential zones several square miles or more. A combination of geologic and zoning criteria is required to determine spacing. In densely urbanized areas with moderate or low seismic hazard, a rational risk-based approach should be considered for optimization of SMBRS-DU station locations.

4.5.5.2 Siting Issues

Siting issues are generally the same as for SMRS-SB stations with the following exceptions. Note that finding good locations for GPS antennas in downtown areas so that signals are not blocked by tall buildings can be an especially challenging problem for reference stations. This needs to be considered in the initial site permitting process for the instruments.

4.5.5.2.1 Background Vibration

Seismic background noise levels will in general be much higher in a densely urbanized downtown area than in an area located in a park or away from local cultural noise sources.

When in doubt, it is suggested that the background vibrations at a potential site be monitored, so as to locate the instrument in feasible locations within a city block area with the smallest levels of peak acceleration during rush hours.

4.5.5.3 Recommended Station Design

Recommendations for station design for SMBRS-DU stations are similar to those for SMRS-SB stations (previous section). The recommendations are not repeated here.

4.5.6 Structural Response Stations

"Structural Response Stations", denoted SRS, are ANSS stations designed to measure and record the response of civil structures to strong earthquake shaking. Civil structures of main interest for ANSS are buildings, bridges, and dams. Other types of structures may also be included. The main purpose for these stations is to provide information on structural response to earthquake shaking that can be used to improve the safety of design and construction practices for new structures, or to assess or reduce the hazards posed by existing structures in earthquake-prone regions. For some critical structures, especially lifeline structures, SRS information may have more immediate emergency response applications such as state-of-health monitoring of structures or generation of regional damage indices.

4.5.6.1 Structural Response Parameters

The following structural response parameters are of interest:

- Building translation and rotation in plan
- Interstory displacements and overall displacement response (including mode shapes and periods)
- Rocking motion (overturning)
- Floor accelerations and floor load distributions
- Base input motion

These data are used to:

- Evaluate design practices and procedures
- Determine the severity of damage in a region
- Assess the health of a structure
- Identify structural failure mechanisms
- Assess effects of ground motion characteristics (period, amplitude, duration) on structural response
- Establish threshold levels of damage
- Verify or identify proposed nonlinear mathematical models of a structure
- Study soil-structure interaction at the foundation interface
- Evaluate earthquake rehabilitation methods
- Assess earthquake hazard potential of existing structures

4.5.6.2 Siting Criteria

In general, ANSS SRS should be installed in structures or structure types deemed important for either local or national information needs in accordance with ANSS global siting priorities. It is recommended that structure selection and structure-specific design of an SRS be done by experienced personnel, and that each SRS design be reviewed by appropriate ANSS staff or committees.

Table 1 – Model Building Classifications Recommended for Instrumentation *(reference CSMIP 1985)*

Building Type	Estimated Prevalence in Built Environment
1. Wood frame (low rise)	High
2. Light metal (low rise)	Low
3. Unreinforced masonry bearing wall (low, medium, high rise)	High
4. Frame with unreinforced masonry infill (low, medium, high rise)	High
5. Reinforced masonry shear wall with moment frame (low, medium, high rise)	Low
6. Reinforced masonry shear wall (low, medium, high rise)	High
7. Reinforced concrete shear wall with moment frame (low, medium, high rise)	Low
8. Reinforced concrete shear wall (low, medium, high rise)	High
9. Steel braced frame (low, medium, high rise)	High
10. Steel perimeter moment resisting frame (low, medium, high rise)	Medium
11. Steel distributed moment resisting frame (low, medium, high rise)	Low
12. Ductile concrete moment resisting frame (low, medium, high rise)	Low
13. Nonductile concrete moment resisting frame (low, medium, high rise)	High
14. Concrete tilt-up (low rise)	High
15. Precast concrete frame (low, medium, high rise)	Low
16. Long span (low rise)	High
17. Base isolated (low, medium rise)	Low
18. Rehabilitated	Low

Following are general criteria to be considered in SRS siting:

- **Probability of Shaking**: as SRS stations will represent a large investment, they should be installed in regions of high probability of shaking. An exception to this guideline may be representative unique regional building types in areas of lower seismicity. Regions with a seismic hazard greater than 0.1g peak ground acceleration with a 10% chance of exceedance in 20 years shall be considered for structural response stations.

- **Probability of Learning**: SRS stations should be sited to maximize the potential of learning in needed areas of earthquake engineering understanding.
- **Potential for Loss:** SRS stations should be sited in regions with a large population or densely built environment that will result in a high potential for earthquake loss due to seismic hazard, building inventory, or structure vulnerabilities.
- **Location Strategy**: In general, structures selected for SRS installation should logically fit into a regional plan considering both regional and national needs for structural performance data. Locations of building structural response stations shall be distributed throughout the building inventory such that all model building classes are represented and the number of each is consistent with the distribution of buildings in the built environment. Model building classifications recommended for instrumentation are listed in Table 1. Location of structural response stations in non-building structures (dams, lifelines) shall be based on regional needs and locally important structures. An exception to this may be the desire to instrument important, unique structures for emergency response or research purposes.
- **Nearby Structures**: SRS design shall consider the effect of nearby structures on the response of the instrumented structure. Where possible, stations should be sited away from structures likely to cause significant soil-structure interaction effects that may be recorded in the data.
- **Site Conditions:** SRS siting should avoid unusual soil or topographic conditions which might affect the structural response, unless these unusual conditions are of specific interest to ANSS.
- **Structural Configuration:** In general, buildings selected for SRS installation should be regular structures without significant vertical or plan irregularities in mass or stiffness, unless these conditions are of specific interest to ANSS. The presence of irregularities will complicate the response of the structure and limit the usefulness of the data for conclusions regarding general structural response.

4.5.6.3 Recommended Station Design

The exact configuration of sensors within an SRS shall be optimized for information needs and budgetary constraints. If possible, a pre-analysis of the structure should be performed to assist in system design by estimating the global response and identifying locations of interest for local structural response. It is recommended that SRS configuration design be done by experienced personnel and reviewed by appropriate ANSS staff or committees.

4.5.6.3.1 Configuration

Following is generic guidance regarding SRS configuration:

- **Ground Motion Reference:** A free-field or reference ground motion sensor shall be provided near the structure. This shall measure triaxial acceleration. Where possible this reference sensor installation shall meet the requirements of COSMOS/ANSS SMRS-OG station.
- **Structure Base Motion Reference:** One triaxial acceleration sensor should also be installed at the base of the structure at or below grade to measure "base motion."
- **Sensors for Global Response:** Sufficient acceleration sensors shall be distributed in the structure to resolve linear modal response (frequencies and gross mode shapes) based on the global response predicted for the structure. Both translation and torsion shall be considered.
    - **Global translation:** Consider installing single-component sensors at the roof and at each intermediate level of low-rise buildings up to three stories in height; at the roof and two intermediate levels of mid-rise buildings four to seven stories in height; at the roof, two intermediate levels and locations of stiffness discontinuities in high-rise buildings more than eight stories in height.
    - **Global torsion:** Consider installing pairs of single-component sensors at opposite ends of a floor plate at each instrumented level of a building. Differences between these measurements will estimate the torsional response.
- **Sensors for Local Response:** Other sensors shall be distributed as required to measure important local responses, such as relative displacements or component strains identified as key parameters in a pre-analysis. Sensors for local response need not be limited to accelerometers. Use of extensometers, strainmeters, and electronic distance measuring technology should be considered.

4.5.6.3.2 Specifications

An SRS should be designed and installed to provide appropriate data for understanding the response of the structure. General guidance for installation is provided below (guidance for acceleration instrumentation is provided in chapter 3):

- **Measurement Types:** Acceleration and displacement based quantities should be the main quantities measured. Sensors other than accelerometers shall be considered in SRS design when appropriate. Recording shall be digital.
- **Triggering**: For triggered recording systems, trigger thresholds shall be appropriate for the expected earthquake and structural response motions. Pre-event times shall be sufficient to capture the P-wave upon S-wave triggering; 10 seconds is a recommended minimum. Post-event times should be adequate to capture significant free response of the structure after ground shaking has stopped.

30 seconds is a recommended minimum, but more will be required for low-frequency structures such as high-rise buildings or long-span bridges.

4.5.6.3.3 Installation

- **General:** SRS instrumentation shall be installed with normal standards of professional care. The need for long-term reliability shall be foremost in the installation work plan and details.
- **Station Location Accurac**y: Documented accuracy of one ten-thousandth of a degree in latitude and longitude.
- **Sensor location accuracy**: Within the structure, sensor location accuracy should be 1m or better in all three axes relative to a designated reference sensor.
- **Sensor Orientation**: Sensors within a structure shall be oriented in a logical manner, either to compass points or in line with the structure's primary axes. Sensors shall be mounted within 2 degrees of the desired orientation within the structure. Sensor orientation is critical to data interpretation and shall be well documented and controlled.
- **Anchoring:** All sensors, recorder and auxiliary components shall be anchored securely to the structure to prevent relative motion.
- **Site Documentation**: An SRS installation should be extensively and formally documented, with narrative and photographic descriptions of each component of the instrumentation system. This documentation shall also include sufficient site condition data for evaluation of local site effects and soil-structure interaction.
- **Maintenance Program**: A post-installation maintenance program is essential to the success of an SRS.

4.6 References

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5 Data Archiving and Distribution Subsystem

5.1 Introduction

This chapter describes the high level requirements for the Data and Archiving Distribution System (DADS), a sub-component of the ANSS. The DADS will rely heavily upon the Network Architecture and Interconnection (see Chapter 2) to receive and transmit its information, and similarly will be driven by the needs identified by the Data Analysis and Products (DAP, Chapter 6) component to determine the types of data and information that must be handled.

This summary is presented at a rather high level. Developing lower level requirements, in increasing detail, will be necessary in order to build the complete DADS system.

At this point, this document does not address any design or implementation issues. For example, a requirement for a highly reliable DADS may necessitate a design with a dual redundant data center architecture. However, the requirements should specify only the target reliability. Only after this requirement is agreed upon can a design consistent with meeting the requirement be developed.

5.2 Operational Concept

The DADS provides a mechanism for collecting together raw data, derived parameters, and metadata produced by the stations and processing centers comprising the ANSS. Data are acquired from data concentrators and/or data processing (operation) centers. Data may be transmitted to the DADS continuously, in near-real-time, or in batch mode, though receiving data via continuous telemetry is strongly preferred. Note that if waveforms are telemetered directly to a DADS facility from the field, they will be acquired and reformatted as needed by a collocated concentrator.

Quality control of data is the responsibility of the processing centers, but the DADS will have basic QC capabilities where these capabilities make sense, particularly for functions that depend on the aggregations of data within the DADS. However, the processing centers are solely responsible for producing the definitive version of any data. The DADS shall have the capability to synchronize holdings with processing centers and production outlets for the purpose of obtaining or maintaining definitive versions of the data. Users will thus be able to receive the same version of data, whether they are receiving the data from a regional processing center or from the DADS. The DADS must be able to properly identify and track data from multiple sources through a data tracking and versioning system.

The DADS distributes the waveforms, all metadata necessary to use the waveforms, and derived products in standard formats with the goal of supporting only a single standard format for each type of data. Data can be distributed in arbitrary (custom) aggregations, and regardless of whether the data are associated to a particular event or are unassociated.

Supported data distribution mechanisms shall include continuous near-real time transmission, data requests, and data subscriptions (standing orders).

The DADS archives all data and products indefinitely, and in a manner that provides data security and allows continuing operation during regional-scale natural disasters or technology infrastructure disruptions. Operational concept highlights include:

- Receive data (time series and discrete measurements)
- Receive products derived from data
- Receive metadata that describe the raw data
- Archive data, metadata, and products
- Distribute data, metadata, and products
- Synchronize holdings with processing centers
- Define and support a single format for incoming waveform data
- Define and support a single format for each outgoing data type
- Perform only limited, non-definitive, quality control (QC) on the data
- Receive and distribute raw data and data products via multiple data transfer mechanisms
- Be highly available

5.3 Requirements

The requirements are categorized in several ways. System level requirements are presented first. To the extent possible, these requirements address only capabilities required of the overall system, and not specific functional behaviors. The second category of requirements are those which apply to interfaces between the DADS and other systems or entities. Finally, requirements that address the specific functional behavior of the system are presented.

5.3.1 System Level Requirements

The DADS is a subsystem of the ANSS, with interfaces to other subsystems, and an architecture suitable for fulfilling its requirements. This section addresses those requirements that apply to the entire DADS subsystem. Note that these system requirements all lead to more detailed interface and functional requirements, but herein only the most fundamental requirements of the DADS are characterized: receiving, archiving, and distributing data. Although the DADS will be capable of distributing data in real time for the general scientific community, the real time needs of the operation centers and production outlets will not, in general, rely upon the DADS.

The Data Archiving and Distribution Subsystem:

- Shall be capable of receiving all of the types of data collected by the ANSS
    - Time series (waveform) data
    - Discrete measurements
- Shall be capable of receiving all products derived by the ANSS
- Shall be capable of receiving all metadata associated with received data
- Shall be capable of receiving the *entire volume* of data produced by the ANSS

- Shall manage only those data for which complete metadata are also provided
- Shall archive all data, metadata, and products received
- Shall be able to distribute, on demand, any of the archived data, metadata, or products
- Be essentially continuously available, with no outages during
    - Natural disasters
    - Regional-scale infrastructure disruptions (power failures, communications failures, etc.)
- Shall satisfy specific availability requirements (which are to be determined) for such areas as:
    - Availability of the system for data import
    - Availability of the system for data export
    - Acceptable latencies, which in general will be greater than latencies required of the ANSS processing centers
- Shall provide a high degree of data security

5.3.2 Interface Requirements

The DADS must interface with multiple entities, including processing centers and data users. The structure of some of the interfaces will be determined by the Network Architecture and Integration subsystem.

The Data Archiving and Distribution Subsystem:

- Shall receive and transmit data, metadata, and data products from and to processing centers with minimal delay introduced at the centers
    - Protocol(s) determined by NAI subsystem
    - Formats determined by the DADS
- Shall exchange information with processing centers for the purpose of synchronizing holdings
- Shall support a synchronization protocol (a request/response language built on a format and an underlying protocol)
    - Protocol(s) and formats determined by DADS
- Shall provide data (and corresponding metadata) and products in response to
    - Custom requests
    - Subscriptions (standing orders)
- Shall provide
    - Derived data products
    - Continuous waveform feeds
    - Engineering products

5.3.3 Functional Requirements

These requirements attempt to address the specific behavior of the DADS. Note that a distinction is made between data formats and data exchange protocols. Requirements related to data formats and data exchange protocols will need to be pushed down to much greater detail, and this work must be done in conjunction with the several other subsystems that are affected by these formats and protocols. The requirements stated here reflect the fact that the DADS needs to be flexible in some ways (e.g. by importing data via multiple protocols) and yet rigid in other areas (e.g. controlling the number of formats supported).

5.3.3.1 Data import

- Multiple data transfer protocols shall be supported for receiving continuous and non-continuous (segmented) data from cooperating organizations
  - Acknowledged, point-to-point protocols
  - Ring-buffer-based protocols
  - Client-server push or pull protocols
- Shall support receiving data via bulk data shipments
  - Electronic transfer (e.g. FTP)
  - Physical media (e.g. tape)
- A single protocol shall be supported for importing data from processing centers and production outlets for the purpose of synchronizing holdings (synchronization protocol)
- Shall support receiving data/metadata/product updates for data previously received (versioning)
- Shall support tracking of the path/mechanism by which data were received

5.3.3.2 Data export

- Multiple data transfer mechanisms shall be supported for distributing continuous and non-continuous (segmented) waveforms, metadata, and parameters
- A single protocol shall be supported for exporting data to processing centers for the purpose of synchronizing holdings (synchronization protocol)
- Multiple user data request mechanisms will be supported
  - E-mail
  - Web (GUI)
  - Interactive query results
- Shall satisfy data distribution timeliness requirements, which are to be determined
- Timeliness requirements shall be established for:
  - Class of user (e.g. processing center, end user, etc.)
  - Data requested (e.g. data type, data age, volume of data, etc.)

5.3.3.3 Formats

- Data received from processing centers or data concentrators shall be in a single standard format
  - No format conversion is required for these data
- Will maintain ability to re-construct raw data, by either:
  - Preserving raw, unconverted, data
  - Preserving descriptive information about raw data (e.g. original segment boundaries, etc.)
- A single standard format is supported for data archiving

- Legacy data are archived via encapsulation in (or translation to) the standard archiving format
- A single standard format is supported for data distribution
- Format shall include both data and corresponding metadata
- Mechanisms to distribute waveform data alone and/or metadata alone will also be provided but will be closely tied to the standard format
- Software for converting the standard format into widely used community consensus formats will be provided.

5.3.3.4 Synchronization

- Shall support specific rules for updating holdings
- Shall have the capability to initiate a synchronization request
- Shall have the capability to receive a synchronization request
- A synchronization request may serve to:
  - Push updated data to another site
  - Pull updated data from another site
  - Seek data to fill gaps in holdings
  - Verify the version or accuracy of data in a site's holdings
- Shall have the capability to receive or transmit data to achieve synchronization with a processing center
- Shall have the capability to update the archive when updated (replacement) data are received

5.3.3.5 Archiving

- Shall have the capability to archive all data types collected by the ANSS
  - Includes time-series data of any sample rate
  - Includes discrete observations
  - Specific data products to be archived will be determined by Data Products committee
- Shall have the capability to archive all processed (including QC'ed) time series data produced by the ANSS
- Shall archive all metadata associated with archived data
- Shall have the capability to archive all processing results (parametric information) produced by the ANSS
  - Specific data products to be archived determined by Data Products committee
- Archive both the raw or equivalent and processed time series data.
- Shall archive all data, metadata, and products such that queries to a DBMS may exploit relationships between these classes of information
  - Note: this does not imply that waveforms must be stored directly within a DBMS
- Shall archive data indefinitely
- Shall maintain a data management policy, reviewed annually, that addresses

  - Data storage migration to avoid extinction of formats/and storage media as well as the storage device technology
  - Data security (loss prevention)

5.3.3.6 Quality control

- Primary data quality control shall be performed by the operation centers and production outlets
- The DADS shall have the capability to perform limited quality control
  - To verify the integrity of holdings
  - Where such quality control can only reasonably be performed on aggregations of data only present within the DADS
  - Certain routine assessments of data quality such as signal to noise ratios, power spectral density functions, and other automatic quality control procedures

5.4 Other Issues

The architecture of the DADS has been extensively discussed in the DADS meetings, but no final recommendations are included herein. Instead, one or more working groups will develop the DADS and address these issues:

- A centralized rather than distributed architecture (i.e., a centralized archive).
- Redundant archives to promote high availability.
- Off-site storage for data security.

6 Data Analysis and Products

6.1 Introduction

The ANSS must provide a timely, standardized, coordinated, automatic supply of authoritative earthquake data and products. The data collected, products generated, and the methods used to generate products need to be clear and fully documented in order for interested parties to use them confidently. The ANSS must provide robust, timely, interactive distribution of data and products system-wide and provide assistance with understanding the data and products to those who need it.

The ANSS must distribute earthquake data and products to a wide variety of users over a broad range of time scales. In particular, regional and national processing centers and production outlets have the responsibility to provide rapid earthquake information to time-critical users, while the archiving facilities distribute data and information to non-time-critical users.

6.2 Users

The logical flow of data is from field instrumentation to processing, distributing, and archiving of data and information products. At each step, user requirements should govern the system design and performance. This section identifies several categories of anticipated ANSS users, briefly summarizes their primary activities, and describes their needs for seismological data and products.

6.2.1 Earthquake Emergency Responder

Primary activities:

- Identify areas and levels of damage
- Assess level of damage/functionality at specific buildings or facilities
- Understand related phenomena such as tsunami, landslide or volcanic activity

Data and information needs:

- Fair-quality digital data from densely instrumented urban areas
- Good-quality digital building data from special-interest buildings
- Near real-time processed data and derivative products
- Access to expert knowledge and training regarding data and products

6.2.2 Media, Public Officials, K-20 Educators, and the General Public

Primary activities:

- Be informed about what is happening
- Make better risk management decisions at public and personal levels

Data and information needs:

- Raise earthquake hazard awareness and understanding of the earth
- Near real-time derivative products that are easy to understand and reliably delivered to large numbers of recipients
- Interpretation provided by local experts

6.2.3 Earthquake Engineer

Primary activities:
- Evaluate building performance as a function of reference ground motion
- Update structural seismic design requirements based on strong motion recordings, processed data, and damage correlation studies
- Advise building owners/occupants about safety and functionality of instrumented buildings

Data and information needs:
- Unclipped strong motion waveforms from 3-component reference stations and instrumented buildings and other structures
- Near real-time and archived processed strong motion data
- Detailed information about site conditions, sensor locations, and building design
- Structural state-of-health monitoring reports
- Measurements of global and local structural deformation

6.2.4 Seismic Hazard Analyst

Primary activities:
- Characterize seismic sources by style of faulting, depth of faulting, stress drop
- Use earthquake catalogs to assess recurrence
- Estimate seismic hazards

Data and information needs:
- Uniformly processed catalogs of earthquake source parameters including magnitude, depth, focal mechanism, stress-drop, and fault association
- Identification of aftershocks
- Attenuation and site response information

6.2.5 Engineering Seismologist and Geotechnical Engineer

Primary activities:
- Determine attenuation of ground shaking with distance and source characteristics
- Evaluate site response as a function of source characteristics and site geology

Data and information needs:
- Good-quality digital data from dense arrays near causative fault
- Data from a wide range of site conditions
- Unclipped waveforms from 3-component strong motion reference stations
- Real-time and archived data, both unprocessed and processed
- Detailed geotechnical site characterization of all instrumented sites

6.2.6 Regional Seismologist

Primary activities:

- Study regional earthquakes, determine source parameters and characteristics
- Study regional crust and mantle structure and properties
- Associate earthquakes with faults and tectonic features
- Study earthquake source processes
- Provide earthquake information to all interested parties in near real-time

Data and information needs:

- High-quality, 3-component, high dynamic range broad-band digital data on regional and local scales
- Real-time and archived raw and derived data

6.2.7 Global Seismologist

Primary activities:

- Study the locations, source parameters, and characteristics of worldwide earthquakes
- Provide earthquake information to all interested parties in near real-time
- Study large-scale earth structure and properties
- Study earthquake source processes

Data and information needs:

- High-quality, 3-component, high dynamic range broadband digital data on global and continental scales
- Real-time and archived raw and derived data

6.3 Rapid Products

When an earthquake of potential general interest occurs, the ANSS should routinely provide:

- Real-time seismograms - Media, technical staff, researchers, and public like access to real-time visual seismograms.
- Phase picks - Currently single component phase picks are common. Recently three component picks have been developed.
- Origin time - Time should be available in UTC format and local time formats.
- Hypocenter – Locations should be available in both degrees-minutes and decimal degrees format. Depth should be available. Quality information such as error estimates, number of phases used, and distribution of stations should be available.
- Distance from reports - Distances from cities (small, medium, and large), quarries, faults, and historical large events. Distances from seismic stations are often requested.
- Magnitudes - A wide variety of magnitudes should be available including mb, and Ms, Mcd, Ml, Me, Mw. Quality information should be available such as number of stations, and components used in solution.

  - A single representative, authoritative magnitude should be chosen for distribution to the public and press
- Earthquake reports – Easily understandable event summaries distributed in many ways including emails and pages.
- Ground Motion Amplitudes – A wide variety of ground motion types including acceleration, velocity, displacement, spectral acceleration and velocity, and energy.
- ShakeMaps – Graphical representation of shaking information is rapidly becoming essential information.
- Event review pages – Rapid evaluation of automatic solutions supported by specially designed review pages that show waveforms, automatic phase picks and other information (for use by skilled staff only)
- Moment tensors and focal mechanisms – A variety of techniques should be supported.
- Structural state-of-health monitoring reports – the ability to assess the condition of an inventory of structures in an automated way would be useful in emergency response scenarios.
- Measurements of global and local structural deformations – direct measurement of structural displacements will help in post earthquake assessment of structures, and in future engineering research.

6.4 Information Products

Information will be provided by the ANSS on a regular schedule for each region and for the nation as a whole. These should include but are not limited to the following:

- Intensities listed by city or landmark – Intensity reports on a city-by-city basis may provide more useful information to the public than magnitude reports.
- Community intensity map – The public contributes to produce an intensity map based on public reports.
- Maps – Printed and Web based maps showing recent events in a geographical area are popular and important.
- Catalog of quakes – Some users continue to favor text based earthquake catalog formats.
- Operation reports – summaries of station installations, problems and changes and other operational events.
- Event and continuous waveform data - The seismological research community will look to the ANSS to provide continuous waveform data for studies in earthquake and volcano processes and Earth structure. This will require both archives of continuous waveforms and event-based waveforms.
- Derived time series – The engineering community is vitally interested in both raw time series as well as in derived time series (acceleration, velocity and displacement). Details about the processing steps used to obtain the product are essential to its use.
- Spectral data series – The engineering community also wants response spectra, distributed in standard formats with documentation of damping values, periods, and the computational algorithm used.

- Station metadata - Station coordinates, DAS and sensor type, instrument response. For strong-motion data, additional information about the near-surface geology and shear wave velocity is needed.

The ANSS will provide specialized reports on subsets of all data - at all stages. For example, it is increasingly common to request a subset of all the data available, and then to perform additional processing using just this data subset. For example, partners may be interested in information from ANSS stations collocated at their facilities. The ANSS will support this type of data report.

6.5 Interpretation

The routine operation of the ANSS will provide many standardized products, mostly in computer generated and readable forms. These will be distributed to a wide variety of users, many of who lack sufficient experience or training to use or even fully understand these products. The ANSS must provide functionality to assist many users with the interpretation and understanding of the routine products. Examples of these functions or personnel are the following:

- Public/press – interface with the general public and news media.
- Policy issues – interface with government and civil authorities regarding hazard mitigation or emergency preparedness.
- Science – interface with other seismologists, geologists, engineers about specifics of the data and products
- Data access – Database access issues for special requests.

The personnel involved in the interpretation of the ANSS routine data and products can contribute greatly to the development and evolution of new procedures and products. Feedback from the users will play an important role in maintaining high quality and relevant products.

6.6 Authority

The distributed ANSS system will be capable of providing authoritative earthquake parameters and rapid response data and products at all times. At a minimum, the ANSS will have a national production outlet that is staffed 24 hours a day, seven days a week. The ANSS will provide continuous system monitoring, system control, and authoritative earthquake parameter and rapid response information. The ANSS will operate under “incident command and response rules” that provide clear guidelines as to who is in charge. The national production outlet will serve as an arbiter among the regions in resolving divergent views of the same earthquake. Appropriate business rules and mechanisms will ensure that a single authoritative set of parameters is available for each event at any time. The ANSS archive system will synchronize data with processing centers to ensure that data holdings are complete and current. The national production outlet will have the responsibility to construct a comprehensive seismicity catalog that is a superset of the regional and global events. Regional production outlets will have ‘on call' staff available to respond rapidly to significant earthquakes in their region and to review routine data and products with the national production center.

6.7 Data Processing

The ANSS should be responsible for providing uniform software and technical support for all centers and outlets (national and/or regional) producing ANSS standard products. Data shall be processed in accordance with the time-critical nature of their intended use.

Table 2. Data Processing

Product	**Latency range**	**Comments**
Early Warning	0-90 sec	Used for life safety actions and rapid mitigation
Preliminary automatic hypocenter	30 sec	The automatic determination of the hypocenter will depend on the location of the earthquake with respect to the network. Shorter time frames will be available in areas with denser instrumentation
Updated automatic hypocenter; Preliminary automatic magnitude	60 sec - 120 sec	Updated estimates of the hypocenter should be issued within 1-2 minutes. An automatic estimate of the magnitude should be available on the same time scale.
Preliminary automatic ground shaking maps	3 - 5 min	Preliminary maps of strong ground shaking should be issued within a few minutes following a qualifying event. As with hypocenters, this will depend somewhat on the distribution of stations. Depending on the location of the event, some maps may depend more on predicted motions than on observed data.
Updated automatic magnitude; Preliminary automatic seismic moment tensor	5 - 6 min	Updated automatic magnitude estimates will be issued for some events as more stations become available or as additional processing is completed.
Rapid review	5 - 10 min after notification	Alarm events will require rapid review within a few minutes after notification.
Mapped PGA and Intensity (ShakeMap)	5 - 15 min	Used for situation assessment, estimation of disaster scope, determination of mobilization level, focused reconnaissance, mutual aid activation, and staging areas
Revised review	within 72 hrs	Updated information and recovery estimates

The numbers in this Table are applicable to normal system operation. If a component fails (say, if one of the regional processing centers is crippled), then the latencies are naturally longer to allow for the propagation of seismic waves to more distant stations.

7 Appendices

Appendix A – TIC and Subcommittee Members

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Appendix B – Data Rate and Volume Estimates

Below is a summary table of a data flow model prepared by the TIC for the ANSS. The model starts with a description of network elements or data sources including the number of stations per element, the number of components, sample rate, and field triggering percentage for both seismometers and accelerometers at each station, and the average number of bits per sample. The bits per sample represent the mean output of a compression algorithm (including compression overhead).

Given this information, telemetry data rates, intermediate data buffer volumes, and archival volumes are estimated. Data rates include 20% telemetry overhead (data record and protocol packet headers, etc.). Intermediate data buffer storage is needed at the production outlets to support rapid review of automatic products, at the processing centers to support network triggering of continuous data, and at data concentrators and processing centers to provide complete data through telemetry outages (to other centers). Archive volume calculations provide for the possibility of a different compression amount and for discarding additional data at the operation centers (after telemetry from the field). Derived products and station metadata have not been included in the exchange rates because they are negligible. Products and metadata have been included in the archive totals as an overhead. Note that the data exchange rate would also apply to data exchanges between operation centers.

The TIC recommends that national backbone broadband, regional broadband, urban reference, and urban free field data will all be telemetered from the field continuously in real-time. Low gain channels from national backbone and regional stations should be triggered. 1 Hz long period channels will be generated from the broadband data for both national backbone and regional broadband stations (note that this has been represented in the spreadsheet by making the sample rates slightly higher). Structural arrays should be event triggered, but the telemetry will be continuously available and capable of transmitting all data in real time. Note that rather than showing structural arrays as 3000, 3 component stations, they have been shown as 375, 24-channel arrays. Also note that 150 Hz sampling provides the full engineering bandwidth using brick-wall FIR filters. All data should be compressed in the field.

At the operation center(s), all data will be acquired and buffered. Reference and free field data will be network triggered from this buffer. Data exchanged among regional processing centers and transmitted to the national processing and archiving centers will include only the event triggered reference and free field data. All data and products will be forwarded to the archive facilities as soon as they are available and will be provided to the community indefinitely. Note that the waveform data will be archived in compressed form.

Acquisition, processing, and archiving of continuous broadband data from national and regional stations seems to have wide community support. Given the availability of continuous broadband data, there seemed no compelling reason to telemeter collocated low gain channels continuously as well. The choice to telemeter urban reference and free field data continuously is less clear. However, it was felt that the ability to extract small events from the data would be better supported at the operation center(s) (using network triggers) than in the field. The choice to provide continuously available, full rate telemetry for structural monitoring was motivated by the desire to certify critical structures as safe or unsafe within 10-20 minutes of an event. Given that only short triggers from strong events are of interest, the telemetry data rate could probably be safely reduced to as little as 10% of the full data rate. The choice to use compression from the field was motivated by the high data rates and experience indicating that compression is an effective way of reducing bandwidth requirements provided that adequate excess bandwidth is available during events.

The aggregate telemetry data rate (received) would be spread out over the regional and national operation centers. Data rates from individual stations are shown in the second able. Note that the telemetry data rate doesn't include stations that are transmitted to multiple operation centers from the field. The aggregate data exchange rate is the same as the aggregate telemetry rate except that the urban reference and free field data has now been triggered as well. This would represent the aggregate data flow into the archive facilities and, perhaps, into the national processing center. The exchange data rate also provides a rough estimate of the data exchanges among regional processing centers (e.g., nearest neighbors exchanging subsets of waveform data).

Compression Tutorial

For those not familiar with seismic compression techniques, our ability to compress data depends on two factors: 1) about 95% of all seismic data is background noise and 2) most of the available dynamic range is rarely used. That is, only a small part of the available waveform data contains seismic events and large seismic events are very rare. The crudest seismic compression technique is to simply discard noise and keep events. Such "triggering" algorithms are generally effective, but typically have 100% false alarm rates and may still miss small events.

The second class of seismic compression algorithms is loss-less. In these methods, all data samples are retained, but unused dynamic range (i.e., the high order zeros in each sample) is discarded. Differencing or even double differencing the data can enhance this process. Note that additional information (overhead) must be embedded into the compressed data to allow its recovery. At a quiet site, loss-less algorithms can typically compress data from more than 24 bits to less than 6 including overhead.

The disadvantage of loss-less compression is that the data volume expands during events when the compression becomes less effective. The differencing which is also less effective when compressing frequencies near the Nyquist emphasizes this effect. Theoretically, under worst case conditions, compression could actually lead to more bits per sample than uncompressed data. In practice, the correlation of data samples due to the anti-aliasing filters precludes this scenario. Experience has shown that allowing about 50% excess bandwidth is adequate to ensure real-time telemetry essentially all the time. Additionally, because of the attenuation of the earth, periods of degraded compression efficiency are typically short compared with the earthquake wave train.

Table 1

ANSS Data Rate/Volume Estimates

	Stations								Telemetry Data Rate per	
		High Gain			Low Gain			Sample		
Data Source	No. Stations	No. Comp	Rate (Hz)	Trig %	No. Comp	Rate (Hz)	Trig %	Size (Bits)	Station (Kbps)	Source (Mbps)
National Backbone	100	3	51	100	3	50	10	8	1.61	0.16
Regional	1000	3	101	100	3	100	10	8	3.20	3.20
Urban Ref + Free	3000				3	150	100	8	4.32	12.96
Urban Structure	375				24	150	2	8	0.69	0.26
Totals:	4475	3300			21300					16.58

	Buffering		Archiving				
			Trigger				
Data Source	Save for (Days)	Data Volume (GB)	HG %	LG %	Sample Size (Bits)	Exchange Rate (Mbps)	Archive Volume (TB/yr)
National Backbone	7	10.161	100	100	8	0.16	0.56
Regional	7	201.4	100	100	8	3.20	11.03
Urban Ref + Free	7	816.48		10	8	1.30	4.47
Urban Structure	7	16.33		100	8	0.26	0.89
Totals:		1044.4				4.91	16.96

Total number of channels: 27900

Table 2

ANSS Data Rate Per Station

	High Gain			Low Gain			Sample	Telemetry Data Rates		
Data Source	No. Comp	Rate (Hz)	Trig %	No. Comp	Rate (Hz)	Trig %	Size (Bits)	Average (Kbps)	Worst Case (Kbps)	NRT Trigs (Kbps)
National Backbone	3	50	100	3	50	10	8	1.58	2.38	
Regional	3	100	100	3	100	10	8	3.17	4.75	
Urban Ref + Free				3	150	100	8	4.32	6.48	
Urban Structure				8	150	100	8	11.52	17.28	1.73
"				16	150	100	8	23.04	34.56	3.46
"				24	150	100	8	34.56	51.84	5.18
"				32	150	100	8	46.08	69.12	6.91

1. Worst case rates include excess bandwidth for degraded compression during events.
2. Near-real-time (NRT) triggers shows data rates to transmit data in 1/10 real-time (a 30 s trigger could be transmitted every 5 minutes).

Appendix C – Instrumentation Testing

The following provides details of standards referred to in chapter 3.

Dynamic Range

The dynamic range of seismic sensors is to be computed according to the recommendations of the Standards for Seismometer Testing Workshop, July 1989. That is, dynamic range as a function of frequency shall be defined to be the ratio in decibels of the RMS clip level and the RMS noise floor as a function of frequency. The RMS clip level shall be taken to be the RMS value of a sine wave of the appropriate frequency that just clips. The noise floor shall be taken to be the non-coherent noise between two identical sensors recorded at a quiet site (or just the sensor noise if it is well above ambient earth noise). The RMS noise floor is computed by averaging power over half octave bands centered on the desired frequency, multiplying by the half octave bandwidth (to make the units power rather than power/Hz), and taking the square root.

Vendors are required to provide a plot of the RMS noise floor in decibels (referenced to the RMS clip level) versus log frequency including at least the frequency band $.01 < f < 50$ Hz for each component of each sensor proposed. For reference, each plot shall include the USGS New Low Noise Model (NLNM) and representative earthquake RMS spectra (including a model 2.5 Mw event at 10 and 100 km) averaged over half octave bands. Note that the NLNM and model event spectra will be provided by the ANSS.

Resolution

The resolution of digitizers is to be computed according to the Modified Noise Power Ratio test as described in Sandia National Laboratories technical report SAND 94-0221, “Modified Noise Power Ratio Testing of High Resolution Digitizers”, by T. S. McDonald, 1994. The test involves driving two identical digitizer channels with pseudo random, band limited, Gaussian noise and measuring the noise power ratio (NPR), defined as the ratio of the RMS input noise to the RMS non-coherent noise floor (both averaged over the digitizer pass band). The resolution is estimated indirectly by comparing the NPR as a function of RMS input noise against ideal digitizers. Copies of SAND 94-0221 will be provided by the ANSS.

Vendors are required to provide a plot of NPR in decibels versus loading factor in decibels compared with theoretical curves for ideal digitizers of varying dynamic ranges (i.e., number of bits). The loading factor is the ratio of the digitizer clip level to the RMS input noise. The NPR must be determined at RMS input levels between the RMS shorted input and clipping in 10 dB steps. Vendors are also required to provide a plot of shorted input power in decibels versus frequency and at least one plot of the phase of the non-coherent noise in degrees versus frequency. Both plots must including at least the frequency band $0 < f < 50$ Hz.

Magnetic Fields

When equipment is operated in the presence of magnetic field intensity changes of up to 10 milligauss, there shall be no detectable effect in the output signal.

Atmospheric Pressure

Sensitivity to atmospheric pressure changes shall not be detectable at the output of the instrument including changes due to passing fronts and thunderstorms.

Radio Frequency Interference (RFI)

When equipment is operated in the presence of RFI there shall be no detectable effect in the output signal provided that the RFI does not exceed FCC standards. For relevant standards see “Limits for General Population/Uncontrolled Exposure” (FCC document “A Local Government Official’s Guide to Transmitting Antenna RF Emission Safety: Rules, Procedures, and Practical Guidance”, June 2, 2000).

Mean Time Between Failures (MBTF)

MTBF shall be estimated by the Bell Communications Research (Belcore) method. The method is defined in "Reliability Prediction Procedure for Electronic Equipment" (Belcore document number TR-332, Issue 6) and may be computed using commercially available software (e.g., RelCalc).

Configuration Information

Sensors and power equipment shall be capable of reporting and DASes of receiving manufacturer, model, serial numbers, and other relevant information as specified (e.g., nominal response information for sensors and power status information for power systems). Data shall be communicated in the ASCII character code via a 1-wire network (MicroLAN) as described in http://www.maxim-ic.com/1st_pages/tb1.htm.

Temporary Shallow Submersion in Water

The International Electrotechnical Commission (IEC) standard 60529 specifies degrees of protection provided by enclosures, also known as the IP code. ANSS requires IP67 level protection, which means 1) the enclosure shall be dust tight and 2) the ingress of water shall not be sufficient to damage the electronics when submerged under 1 m of water (measured from the base) for 30 minutes.

Appendix D – Production, Interpretation, and Outlets

The Advanced National Seismic System (ANSS) real-time and off-line processing systems should be constructed from four modular hardware/software building blocks. In particular, the heterogeneity and number of the three types of modules (data concentrators, operation centers, and data archiving facilities) that are between the sensors and the users should be kept to a minimum for reliability and cost reasons. However, the fourth module type (outlets, which directly support ANSS participants and end users as well as some production tasks) should be diverse and numerous, involving the whole community and supporting the whole spectrum of ANSS related uses.

Production functions (including those performed at outlets) should be logically separate from interpretation functions (also performed at outlets). Separating production and interpretation allows a system design that supports the goals of a highly reliable production environment and a highly diverse interpretation environment. Specialization does have negative aspects including problems in communication and coordination among groups of specialists. However, other large-scale organizations have developed effective strategies for dealing with these issues. While some of these problems have already been addressed by the ANSS management structure, others must be addressed as the ANSS develops.

Introduction

This *Technical Guidelines for the Implementation of the Advanced National Seismic System, Version 1.0* (hereafter, *Technical Guidelines)* presents a blueprint for the next generation technological infrastructure for fixed network seismology in the US. While most of the technical discussion has found wide acceptance within the community, the non-technical proposal of a formal separation of production and interpretation functions has proven to be more controversial. In the body of the *Technical Guidelines*, the operation center technical construct is associated with production and the outlet technical construct with interpretation (but also some production). It seems likely that the multiplicity of roles envisioned for outlets has further confused these issues.

The concern expressed by the seismological community is natural considering that the separation of production and interpretation suggests the dismantling of highly successful procedures and strategies evolved by Regional Seismograph Network (RSN) operators over decades. Inevitably, the scope of the proposed organizational shift has also created concerns at many seismological institutions about their future role within the emerging ANSS structure.

In the following, ANSS tasks and their identification with ANSS technical constructs will be examined. In particular, the dual nature of outlets will be explored. With a common nomenclature established, the recommendation to separate production and interpretation will be examined. Finally, the consequences of modularizing ANSS tasks in general and separating production and interpretation in particular will be explored.

ANSS Structure

The ANSS organizational structure favors the modularization of various production and interpretation functions. Production is identified with both the automated collection and processing of seismic waveforms and the routine manual activities that comprise seismic practice. In this context seismic practice includes quality control (QC) activities and the construction of derivative products such as catalogs. QC includes the review, rapid and otherwise, of automated products as well as removing artifacts from waveforms (e.g., timing problems) and monitoring the state-of-health of field and processing equipment. Each of these tasks may be accomplished by one or more cooperating organizations.

Similarly, interpretation is identified with non-routine activities that require specialized knowledge, insight, and creativity. Thus, interpretation includes interpreting data for emergency managers and the media, the development of new algorithms for routine analysis and research work, seismological research, and engineering studies. Again, each of these tasks may be accomplished by one or more cooperating organizations. For clarity, the output of production functions (e.g., waveforms, automated products, routinely produced manual products, etc.) is referred to as data. Conversely, interpretation organizations can be thought of as consuming data and producing information.

The *Technical Guidelines* recommends a modular technical structure comprised of data concentrators, operation centers, data archiving facilities, and outlets. This structure is hierarchical in the sense that waveform data is generated by widely distributed field equipment. It is then concentrated onto communication backbones by data concentrators, delivered to operation centers where automated products are derived, and finally delivered to data archiving facilities where it is organized and stored to satisfy future requests. Field equipment, data concentrators, operation centers, and data archiving facilities are all automated and performing tasks of a routine nature and therefore are all part of ANSS production.

In addition, data flows in real-time from operation centers and archiving facilities to outlets where humans become involved for the first time. Technically, an outlet is defined by the machinery needed to ensure the reliable delivery of data pushed from one or more operation centers and/or archiving facilities and to organize the data for a variety of non-real-time (although perhaps time critical) uses. Organizationally, an outlet is any group of people with a standing request for data from one or more operation centers and/or archiving facilities.

The outlet formalism turns out to be a convenient way of implementing a wide variety of ANSS tasks fulfilling both production and interpretation functions. For example, the rapid review of automated products, waveform QC, and the construction of catalogs are all production functions that would be performed at outlets. Similarly, the interpretation of data for emergency managers and the media, developing new products and/or algorithms, and research are all interpretation functions that also would be preformed at outlets.

Development of the Guidelines

The controversy over the proposed separation of production and interpretation raises the question of why the *Technical Guidelines* addresses this fundamentally non-technical issue. After all, the *Technical Guidelines excludes* other non-technical issues such as the structure of the field deployment and maintenance effort, the organization of education and outreach, and institutionalizing (human) feed back mechanisms among disparate elements of the ANSS. The answer, of course, is that the technical and organizational structures of the ANSS are inextricably intertwined. In particular, it has proven very difficult to visualize whether technical elements of a nationally coherent ANSS are workable without some organizational context.

The same considerations were applied to developing the organizational framework and the technical structure. That is, a conscious effort was made to be forward looking and to take advantage of past experience without being unduly constrained by current implementations. The impact on the whole system of each organizational and technical module was considered in the light of ability to meet ANSS goals and to satisfy the needs of ANSS funding sources, participants, and end users.

The idea of separating functions that have traditionally been closely coupled arose from several different lines of reasoning. In the following the requirements for production and interpretation facilities and the needs of production and interpretation personnel are considered. These considerations lead to the conclusion that the production environment should be centralized and standardized while the interpretation environment should distributed and heterogeneous.

Production and Interpretation

Automated elements of the ANSS production environment such as data concentrators, operation centers, and data archiving facilities are in the primary path from field equipment to users and must be highly reliable to avoid the loss of waveforms and automated products vital to effective rapid response. In contrast, outlets are at the end of the data path and though they are also essential to meeting the goals of the ANSS, the failure of an outlet will not compromise the timeliness or completeness of automated products. Of course, the loss of an outlet involved in rapid review or rapid response would affect the early confirmation or interpretation of automatic results. However, outlets involved in other areas of production and interpretation are not essentially real-time operations and although they need to be reliable, they can tolerate some down time.

This analysis suggests a hierarchy. The more tightly a task is coupled to real-time, the higher the risk of losing data, and the less outages of any length can be tolerated. It is easy to show that redundancy reduces the probability a total system failure, but enhances the probability of a partial failure due to increased complexity. That is, critical facilities should be centralized, but not too much. Therefore, the best balance between redundancy and complexity favors a small number of operation centers/archiving facilities and rapid review/response outlets, but doesn’t rule out making other types of outlets more distributed.

A reasonable degree of centralization coupled with standardized software make it easier to produce standardized automated products, coordinate the release of products among centers, and reduce capital, developmental, operational, and maintenance costs. Reducing the cost of expensive support professionals (including seismic analysts working 24-hour shifts, system engineers, and data base administrators) is critical to the long term health of the ANSS. Although standardization tends to stifle innovation, experience indicates that support personnel generally work more effectively in a relatively stable environment. These arguments also favor centralizing and standardizing production facilities.

The problem with centralization is that it excludes the participation of people who don't work at the centers. This is unacceptable if the ANSS is to meet the goal of providing effective local interpretation of earthquake data for emergency managers and the press. Also, fostering innovation is important not only in ANSS related research, but also in developing new products and algorithms to keep the ANSS current and relevant. Innovation requires a heterogeneous, dynamic environment in order to experiment with new technologies. Also, research and development personnel tend to thrive in a dynamic environment.

Of course, dynamic, heterogeneous environments increase the risk of system failures. Placing tasks requiring such an environment outside of the primary data path (i.e., to outlets) makes sense. It also makes sense to isolate (i.e., modularize) interpretation tasks that require higher and lower degrees of reliability. For example, an interpretation outlet acting as a trusted source for emergency managers must function, even when software under development fails. Conversely, scientists and engineers should do science and engineering instead of keeping non-critical research systems operational 24 hours a day. Striking a balancing between tasks and personnel favoring a centralized, standardized, stable environment and tasks and personnel favoring a distributed, heterogeneous, dynamic environment leads inevitably to treating production and interpretation in different ways.

Modularization

One way to satisfy the divergent requirements of production and interpretation is to make a formal separation between them. In organizational terms, this separation means that production and interpretation tasks would be performed by different groups of people. In technical terms, this separation is implemented as a clean interface between operation (data processing) centers and (interpretation) outlets. Notice that this separation is formal in the sense that it allows, but does not require that production and interpretation tasks be physically separated. It could imply something as simple as production and interpretation groups (with separate management) working side by side on separate hardware/software systems connected by an operation center/outlet interface. However, this same structure could equally well support an isolated group of researchers allowing them the same degree of participation in ANSS as researchers collocated with a production group.

Of course, ANSS modularization will necessarily be far more extensive than simply separating production and interpretation. As we have seen, modularization (into data concentrators, operation centers, and archiving facilities) is required in the production environment by the diversity of tasks and by geography. Modularizing other production tasks (into outlets) is advantageous because it isolates the load on automated real-time processing systems, though it does add overhead (in the operation center/outlet interface). Modularizing production tasks also adds considerable flexibility. For example, it allows tasks such as rapid review, waveform QC, and catalog construction to be performed at different locations if desired. Similarly, it makes sense to modularize different types of interpretation facilities because of the wide variety of tasks, the geographical distribution of participating institutions, and widely varying requirements for reliability.

While modularizing ANSS roles and responsibilities on technical, economic, and community participation grounds makes sense, there is the disturbing implication of compartmentalizing the associated personnel. Of course, the modularization of tasks and the compartmentalization of personnel are ubiquitous in large organizations because complex projects must be broken down into manageable pieces and personnel are more efficient when they can specialize. However, the resulting decrease in communications between groups of specialists and the indirect nature of controlling an organization through layers of management are well known problems. Fortunately, effective strategies for ensuring adequate communications among groups of specialists and for ensuring that organizations remain responsive to the needs of customers have been developed.

Scale Issues

Although the compartmentalization of specialists is minimized in an ideal RSN environment, where a small, close knit group designs the network, deploys stations, writes processing code, informs the public, and conducts research, it is an open question whether this advantage can be maintained as the ANSS grows. Nor is it obvious that the role of the scientist-manager can (or should) be preserved. In fact, it is not at all clear that this model applies to the larger RSNs even today. For example, the Northern California Seismic Network (NCSN) has small, but distinct groups of specialists maintaining stations, maintaining the processing system, and analyzing the data. Further, although a scientist manages the NCSN, managing the network effectively leaves little time for research.

The ANSS is projected to grow to more than three times as many stations as are currently operated by all of the RSNs together and to more than ten times the number of channels. In addition, national integration means that all of these stations and channels must be considered to be part of one very large system. ANSS production inevitably will require a full time staff of dedicated specialists including field technicians, computer hardware and software maintenance personnel, programmers, data base administrators, and seismic analysts.

Examining other large seismological organizations (e.g., the Incorporated Research Institutions for Seismology (IRIS) or even the National Earthquake Information Center (NEIC)) suggests that some degree of compartmentalization of personnel is inevitable and, in fact, should be planned. The NEIC experience suggests that maintaining the role of the scientist-manager is pointless. Large networks require full time management. The IRIS experience suggests that professional managers can be beneficial, providing full time management for operations and freeing scientists and engineers to specialize in science and engineering.

Managing the ANSS

While the *Technical Guidelines* call for modularization of tasks to provide the flexibility ANSS will require, it doesn't discuss the organizational mechanisms that must be implemented to ensure responsiveness to both short and long-term community needs, interaction among groups of specialists, and interaction between the community and specialists. The operation and management of IRIS provides important clues about how these problems might be addressed. In fact, this is why the ANSS was organized along IRIS lines with professional management advised by a hierarchy of committees representing community interests.

The National Steering Committee and the Regional Advisory Committees may be thought of as providing the long term guidance for ANSS evolution in much the same way as the IRIS Executive Committee and the Standing Committees. The IRIS experience indicates that the advice of the community is carried out more effectively if full time managers have strong geophysical backgrounds ensuring that they understand the needs and share the interests of the community. Similarly, the ANSS should look to working seismologists and engineers to fill the positions of Director and National/Regional (network) Coordinators.

Of course, the ANSS also has unique management problems related to its real-time monitoring mission. Of particular concern is the ability of the ANSS to react to the community desire to focus monitoring resources on transient phenomena such as volcanic swarms or aftershock sequences. To address these issues, the ANSS organization includes the National and Regional Working Groups, a unique layer of community involvement, potentially dealing directly with day-to-day network issues. In addition, ANSS professional management should be available and responsive to the community on a day-to-day basis.

The concern has been expressed that community input through the advisory committees and working groups is not as effective as the direct control of a scientist-manager. This is undoubtedly true and to some degree inevitable through the transition from a confederation of regional networks to a single national system serving the entire community. Thus far, it appears that the ANSS working groups are capable of providing the degree of "control" that the community desires. Undoubtedly striking the right balance between the needs of the national community and the local needs of particular institutions will be a learning experience. However, ultimately it is within the power of the community to ensure that the ANSS organizational structure evolves to meet their needs.

IRIS has also addressed communication among groups of specialists. For example, the exchange of station configuration and QC information between network operations and maintenance personnel (part of the Global Seismograph Network (GSN)) and data collection personnel (part of the Data Management Center (DMC)) has been successfully institutionalized. Although IRIS chose to collocate operation and data collection groups, these groups are managed separately. In addition, research feedback on data quality and data management issues has been instituted in the form of Data Problem Reports. The ANSS needs to consider institutionalizing similar types of communications to ensure the effective development and operation of the network.

Finally, IRIS has addressed the issue of operational specialists providing seismologists and engineers with the information needed to make the best use of the data. For example, most global seismologists don't have a hands-on “feel” for the behavior of GSN field equipment. However, through workshops educating them in GSN data characteristics and direct experience with the data they have managed to adapt and to produce quality research. Similarly, the ANSS will make every attempt to provide seismologists and engineers with the information the need to make the best use of the data.

Conclusion

Modularizing both the organizational and technical structure of the ANSS will provide the flexibility needed to meet ANSS goals in an evolving organizational, technological, and funding environment. In particular, formally separating production and interpretation functions is the key to providing both a stable, reliable, cost effective production environment and a diverse, dynamic interpretation environment. However, this specialization of functions among modules potentially creates problems in communication and coordination between groups of specialists, in adapting production to meet short-term scientific goals during transient phenomena, and in providing scientific guidance for the evolution of the production environment. Effective strategies for dealing with some of these problems have evolved in other large-scale seismological programs. Some of these strategies have already been adopted in the ANSS management structure. The ANSS community requires that strategies already implemented are effective and that new strategies evolve as needed to ensure that the ANSS is responsive to their needs.