Technical Guidelines for the Implementation of the Advanced National Seismic System

Version 2.0-D

Prepared for
U.S. Geological Survey and
ANSS National Implementation Committee

Prepared by
ANSS Technical Integration Committee[1]

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1 Introduction

2 Network Architecture and Interconnection

3 Instrumentation

3.1 Introduction

In this Chapter, the TIC recommends standards and specifications to be used in selecting and procuring the instrumentation that will sense ground motion and store the resulting signals in a local data acquisition unit (DAU) for long-term earthquake monitoring station deployments. These standards and specifications are derived from specifications and requirements for data needed to address the nation's emergency response, engineering, and scientific needs as identified in USGS Circular 1188. Data needs are discussed in terms of National, Regional and urban scales of monitoring, and structural response monitoring in Section 3.2. Functional specifications for instrumentation are introduced in Section 3.3 and discussed in detail in Section 3.4. Procurement aspects, including testing, are addressed in Section 3.5, 3.6, and 3.7.

Although USGS Circular 1188 recommends that the ANSS include portable instrumentation, specifications to this element are not specifically addressed in this version of the Technical Guidelines. At the present time, the instrumentation for volcano monitoring is also not specifically addressed herein.

Methods for handling the data flow from the DAU are defined and described in Chapter 2. Those recommendations will influence some aspects of the communication and networking protocols in the DAU. 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 instrumentation specifications imposed by those standards and recommendations.

3.2 Data Needs and Types of Seismic Monitoring Stations

3.2.1 Data Needs

The specifications for earthquake monitoring stations include the planning, siting, and installation of suitable instrumentation, all collectively specified to acquire the data required to address the goals of ANSS. Thus the determination of specifications for different types of stations directly derives from the specifications of the data. ANSS data needs include measurements to provide:

1. Nation-wide monitoring adequate to locate MX.X and larger earthquakes and to quantify their salient properties including focal depth, magnitude, and source characteristics.
2. Regional monitoring adequate to provide detailed information on scientifically or societally important earthquake source regions and zones, including active faults. Of particular importance is detailed recording of large earthquakes within the distance range of less than 20 km for both scientific and engineering purposes.
3. Ground shaking from felt or damaging earthquakes for scientific and engineering uses and for preparation of ShakeMap for rapid response, public information, and other purposes. ANSS has prioritized 26 urban areas for ground shaking monitoring.
4. Detailed response characteristics of engineered civil systems including buildings, geosystems (such as embankments and earthen dams), and infrastructure (such as bridges

and other transportation and utility system components), for use in improving understanding and predictive modeling of the response of structures and in aiding post-earthquake response and recovery.

These needs for data lead naturally lead to instrumentation specifications. Generically, the data are required to have the following specifications:

- Accurate waveforms from the P-wave through surface waves.
- On-scale waveforms obtained by using high clipping levels combined with wide dynamic range, or by collocating instrument with overlapping dynamic ranges (including the use of nested arrays).
- Accurate absolute timing at every sample throughout the record.
- Minimum loss of data due to instrumentation and data communication malfunctions
- Timely transmission of continuous or segmented data for the required analysis applications
- Minimum internal and external noise contamination

Detailed instrumentation specifications are discussed in Sections 3.3 and 3.4

The needs for data also lead to specifications for the sites at which the instrumentation is located, such that the spatial distribution, the seismic characteristics of the sites, and the logistical aspects of instrumentation installation and operation do not compromise the needed data. These geometrical and site-specific factors must be considered for all scales of monitoring from the national scale through the regional scale (seismically active regions and well-defined active faults) to urban areas and individual buildings or structures.

To address these data needs, ANSS stations must satisfy planning siting, and installation criteria as represented in the following steps, along with the specifications of the instrumentation.

Step 1: Station Planning. Based on the desired data to be collected, appropriate station deployments are identified. Station planning includes selecting the type of station with its associated instrumentation specifications, defining the desired spatial distribution of stations, and defining acceptable site characteristics for the stations so they provide useable data.

Step 2: Station Siting. Specific candidate sites that meet the station planning requirements are identified and are evaluated with respect to logistic suitability, environmental characteristics, and site-use permitting.

Step 3: Station Installation. For the planned instrumentation at each site, the minimum requirements for installing the station are specified, including power, communications, GPS reception, security, anchorage to soil or bedrock, and thermal isolation.

These steps will be discussed further in Chapter 4.

3.2.2 Types of ANSS Seismic Monitoring Stations

The monitoring systems in ANSS, as noted in USGS Circular 1188, were characterized in terms of the National backbone network, Regional networks, and urban monitoring networks. The concepts of National-, Regional-, and urban-scale monitoring are readily understandable by federal and state funding agencies and officials and by the general public. However, based on the experience of the initial five years of implementation of ANSS, some refinement within these categories is needed to provide an up-to-date framework for selecting and instrumenting sites as ANSS stations. The traditional distinctions between National, Regional, and urban stations, described respectively as having broadband, high-gain short-period, and strong-motion instruments, have blurred. In particular, the various networks have evolved to record more effectively the continuum of earthquake-caused motions at all frequencies and amplitudes. Another practical consideration relates to budgetary constraints on the full funding of ANSS, which now require an evolutionary approach to achieve the modernization and other goals of ANSS. Thus these revised instrumentation guidelines provide for the inclusion of some legacy seismic instrumentation, consistent with a longer development time and lower rate of capital investment for ANSS.

In this and the following Chapter, four categories of ANSS seismic-monitoring stations are identified—National, Regional, and urban monitoring stations, together with a separate category for specialized instrumentation of structures. The first three categories involve monitoring of vibratory ground motions; the fourth, monitoring of structural response to ground motions. As expanded on below, while these categories do not represent any fundamental change from Circular 1188, their refined description and instrumentation specifications provide an improved framework to guide the planning, siting, and installation of ANSS stations.

- **National monitoring stations** are elements of a broad grid or network deployed on a national-to-global scale (spacing of hundreds of kilometers) intended for uniform seismographic surveillance of the United States and its territories as well as supporting the detection of nuclear tests and tsunamigenic earthquakes outside U.S. boundaries. Within the ANSS framework, these stations generally are elements of the ANSS/EarthScope National backbone array, the legacy U.S. National Seismic Network (USNSN), or the Global Seismic Network (GSN). Operational responsibilities for these stations currently fall to the USGS in partnership with the National Science Foundation through its IRIS-managed programs. National-scale monitoring emphasizes the recording of longer-period data at very-low-noise sites with sensitive, low-noise seismographs; accelerometers are included to assure on-scale records of strong shaking.

- **Regional monitoring stations** are elements of Regional-to-local-scale grids or networks (station spacing of ~100 km to ~10 km) deployed for (a) the systematic seismic surveillance of all or part of a regional seismic belt, ANSS region, or state jurisdiction and/or (b) high-resolution monitoring of active faults and other seismic source zones within those domains. Within the ANSS framework, such stations generally have been elements of traditional regional seismic networks. Regional monitoring stations require diverse instrumentation and variable station spacing to meet different requirements such as the assured on-scale recording of moderate-to-large local earthquakes, high-quality broadband waveforms for moment-tensor inversions, the detection and fine-spatial resolution of microseismicity associated with active faults, and near-fault recording of strong earthquake ground shaking on both rock and soils.

  Some local-scale monitoring within ANSS regions may be carried out by entities in coordination with ANSS, such as seismo-volcanic monitoring by the USGS volcano observatories, or in some cases independent of ANSS, such as localized monitoring by public- or private-sector groups of seismicity associated with impounded reservoirs, geothermal fields, and mining operations. Regional- and local-scale monitoring are invariably complementary in space and time, and real-time monitoring and response should be coordinated to the greatest extent possible. In the case of volcano monitoring, Regional monitoring stations not only provide information about the surrounding tectonic setting (relevant to the interaction between volcanic and tectonic processes), but they also provide backup on-scale recording in the event of large eruptions that can cause the volcano-monitoring stations to go off scale or even destroy them.

- **Urban monitoring stations** are designed for on-scale high-fidelity recording of seismic ground motions in the built environment, especially in areas of moderate to high seismic hazard and high seismic risk. In near-real-time after an earthquake, urban monitoring stations provide vital information on the severity and extent of actual ground shaking for impact assessment and emergency response. They also inform earthquake engineers about ground motions that were input to structural response monitoring stations, and their data enable predictive modeling of ground shaking in future earthquakes for defensive design. In some areas, feasibility studies are under way aimed at using urban monitoring stations for early warning when a destructive earthquake is in progress. Urban monitoring stations must be closely spaced (<5 km) with high clipping levels. Where active faults are close, the instrumentation can provide good P- and S-wave recordings for locating microearthquakes (depending on the urban noise levels).

- **Structural-response monitoring stations are** arrays of instruments installed in or on structures including buildings, geosystems (geotechnically engineered structures such as landfills and dams), and infrastructure (principally utilities and transportation systems) to measure the earthquake response of such engineered civil systems. This kind of monitoring requires engineering design of the layout and specifications of sensors to properly address the application of the data to improve understanding and predictive modeling of engineered civil systems, which lead to advances in seismic design codes and practices and in damage assessment and other immediate post-earthquake activities.

In Section 3.4, different configurations of seismic instrumentation are described for these four categories of ANSS monitoring stations. Aspects of station planning, siting, and installation other than instrumentation are addressed in Chapter 4.

In this instrumentation guidance, an attempt is made to specify as few different types of instruments as possible. This approach may over-specify instruments in some settings, resulting in increased capital costs, but it has the virtue of reducing long-term maintenance costs by decreasing the size of the pool of spare parts 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 matching specifications for certain environments (e.g., using Class B accelerometers at stations in noisy urban areas). Another factor that must be considered when deciding upon specifications for instrumentation is its long-term total cost, including capital cost, station siting and permitting, station installation, data telemetry, state-of-health monitoring, routine maintenance, equipment repairs, and expected lifetime of instrumentation components.

3.3 General Design Concepts and Considerations

3.3.1 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. However, there is still a useful role in some localities in active fault monitoring for single-

component, high-gain, short-period sensors interspersed between active fault monitoring stations and Regional monitoring stations.

- Technological trends suggest standardizing on Internet protocols (IP).
- Strong motion data should have continuous access to telemetry whenever possible and practical. However, if cost or technical issues render continuous telemetry impractical, dial-up telephone or other intermittent connections are satisfactorily engineered for minimum latency.
- Stations with limited continuous telemetry bandwidth can be accommodated by segmenting full-sample-rate strong motion data by events, compressing all data, and adopting the lowest sample rates consistent with requirements.
- The need for complete data implies substantial on-site buffer/backup storage for all types of stations.
- Reliable communications requires error correction and packet retransmission, which implies bi-directional communications. Variable communications latency requires on-site timing.
- Small data delivery latency requires short packets and reasonably fast communications speeds with minimal routing/buffering delays.
- Instrumentation systems should be warranted for a period of at least three years, and vendors should provide spare parts and service for their systems for a period of at least 10 years after purchase.

3.3.2 General Goals and 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).

3.3.2.1 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 and scientific and engineering needs.

3.3.2.2 Sensitivity and Dynamic Range

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

3.3.2.3 Data Latency

Short latencies for the accelerometer data at various types of stations are to support ShakeMap generation. Latencies for data from instrumented civil systems are based on the need for rapid assessment of structural damage (especially for critical structures).

The combination of on-site storage and short latencies requires that old data be caught up while current data continue to flow 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. This requirement also implies that both vendor-supplied and ANSS-supplied receiving software will tolerate and properly manage and re-sequence such out-of-sequence catch-up data.

3.3.3 Dense Arrays of Urban Monitoring Stations

Currently, the typical density of urban monitoring stations has station spacing of as close as 3 to 4 km. As discussed in Appendix 3.1, the variability of ground motions recorded by nearby stations is high unless the station spacing is reduced to about 1 km or less. Such dense arrays of urban monitoring stations are thus needed to confidently interpolate ground motions for use in detailed post-earthquake urban damage assessments and for other purposes. The dense arrays may be formed as “nested arrays”, anchored with state-of-the-art Class A accelerographs and augmented by Class B or other accelerographs to provide high spatial resolution (1 km or better mean station spacing), initially in selected areas of high priority. Priority arrays are likely to be five to 30 km across. Early regions of high priority for dense arrays are areas thought likely to have moderate to major earthquakes in coming decades and having one or more of the following characteristics: (1) urban centers with dense populations and dense infrastructure; (2) near-source regions, giving preference to those in and near urban and suburban areas; (3) urban and suburban regions thought likely to suffer from localized effects, such as basin-edge or strong site effects, causing neighborhood-scale “hot spots” of high shaking strength; or (4) NEHRP site-class E soils (and the neighboring area). Projects combining more than one of these conditions will be given priority for ANSS funding. Potential candidate areas include the Hayward fault in the vicinity of Oakland or the San Andreas system faults in the vicinity of San Bernardino.

3.4 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.

There are several types and classes of instrumentation (including both sensors and Data Acquisition Units) whose capabilities span the different monitoring needs described in Section 3.2 above. Table 3.4.1 below indicates which Instrument Type/Class is appropriate for each application. The notes below Table 3.4.1 describe the different instrument types and classes.

Table 3.4.2 gives a more detailed breakout of different classes of strong-motion accelerograph systems and their estimated costs in 2005 dollars.

Specifications for Sensors (seismometers and accelerometers), Data Acquisition Units (DAU), and Data Acquisition Systems (DAS, which includes the DAU and the Sensor) are given in tabular form in Table 3.4.3.

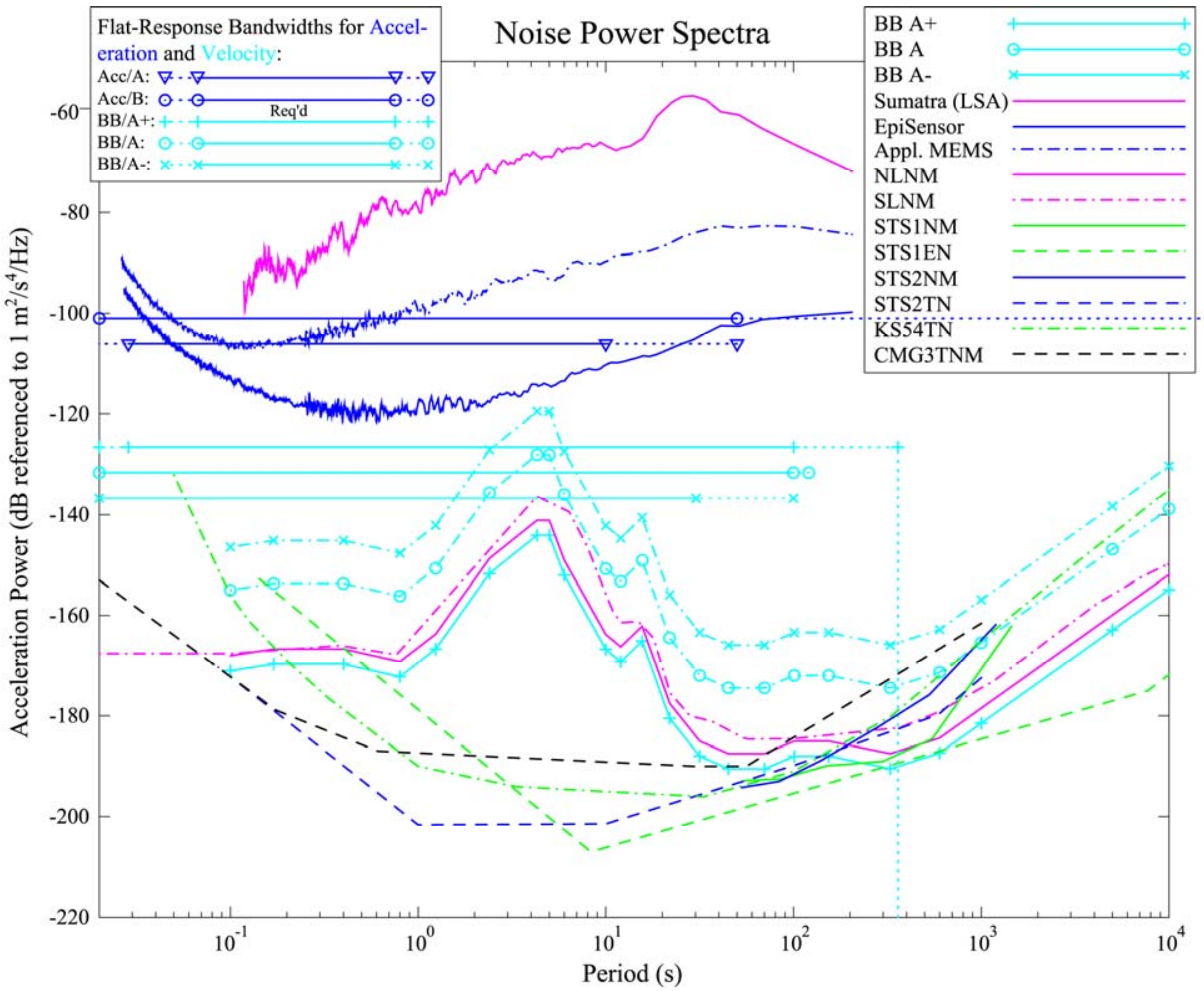


Figure 3.4.1. The Noise Power Spectra figure above depicts the noise levels of a few sensors compared to several reference noise models. The required flat-response bandwidths for the different classes of instruments are shown as horizontal lines. In addition, the power spectrum of the broadband signal from station LSA (Lhasa, PRC) for the Sumatra M9.0 event is shown. The epicentral distance is 26.65 degrees. Explanation of right-hand legend:

- BB A+, BB A, and BB A–: Sensor noise floors required for respective Classes of broadband velocity sensors.
- EpiSensor: Noise PSD from Kinematrics EpiSensor accelerometer, 4 g full scale.
- Appl. MEMS: Noise PSD from RefTek MEMS 131A accelerometer, 3.5 g full scale.
- NLNM: USGS New Low Noise Model (Peterson)
- SLNM: Old USGS Noise Model (Peterson)
- STS1NM: Measured STS-1 Seismometer Noise (LP band only)
- STS1EN: Theoretical STS-1 Seismometer Electronic Noise
- STS2NM: Measured STS-2 Seismometer Noise (LP band only)
- STS2TN: Theoretical STS-2 Seismometer Noise
- KS54TN: Theoretical KS54000 Seismometer Noise
- CMG3TNM: Measured CMG-3T Seismometer Noise

Table 3.4.1. ANSS applications *versus* instrument types/classes — an instrument selection menu.

Applications		Instrument Type/Class* BB/A+	BB/A	BB/A-	SP/A†	SP/A‡	Acc/A	Acc/B	Other
	Teleseisms and some regional events: **<u>Global (GSN) monitoring</u>**	**Primary**	Noisy sites				**Primary**		
	Regional events; some telesisms; some locals: **<u>National monitoring</u> (Interstation Spacing >70 km; ANSS backbone ~300 km)**	Very quiet sites	**Primary**	Noisy sites			**Primary**		
Regional Monitoring	***Local and regional events; some teleseisms:*** **<u>Broadband</u> (Interstation Spacing 50 - 70 km) [Option RF.1]**		Very quiet sites	**Primary**			**Primary**		
Regional Monitoring	***Primarily local and regional events:*** **<u>Short period</u> (Interstation Spacing 10 - 30 km) [Option RF.2]**				**Primary**		**Primary**	ANSS Option	
Regional Monitoring	***Primarily local and regional events:*** **<u>Short period</u> (Interstation Spacing 10 - 30 km) [Option RF.3]**					**Primary**	**Primary**	ANSS Option	
Urban Monitoring	***Strong-motion and Regional:*** **<u>Inclusive of broadband</u> (Interstation Spacing 50 - 70 km) [Option U.1]**		Very quiet sites	**Primary**			**Primary**		
Urban Monitoring	***Strong-motion and Active-Fault:*** **<u>Inclusive of short period</u> (Interstation Spacing $\leq$4 km) [Option U.2]**				**Primary**		**Primary**		
Urban Monitoring	***Strong-motion and Active-Fault:*** **<u>Inclusive of short period</u> (Interstation Spacing $\leq$4 km) [Option U.3]**					**Primary**	**Primary**	ANSS Option	
Urban Monitoring	***Strong-motion only:*** **<u>Acceleration only</u> ($\leq$4 km) [Option U.4]**						**Primary**	Noisy sites	
Urban Monitoring	***Strong-motion only:*** **Infill for <u>Dense strong-motion array</u> (Interstation Spacing $\leq$2 km) [Option U.5]††**							**Primary**	
Civil Systems (Structural)	**<u>Reference station(s)</u> (configuration designed for each Civil System and corresponding, specified data requirements)**						**Primary**	ANSS Option	**GPS Sensors**
Civil Systems (Structural)	**<u>Structural array</u> (instrumentation and configuration designed for each Civil System and corresponding, specified data requirements)**						**Primary**		**Displacement, Strain, and GPS Sensors**

*"Classes" are defined in all cases as follows: "Class A" (and "A–", "A+", etc., finer distinctions) are at or near the state-of-the-art, currently about 20 to 24 bits resolution over the dynamic range of the corresponding sensor types.
"Class B" (and "B–", "B+", etc., finer distinctions) are the next significant step down in resolution, currently about 16 to 19 bits resolution across the dynamic range of the corresponding sensor types.
This shorthand is a convenient terminology for all instrument types. (In all cases, a "+" means "best in Class" and a "–" means "least in Class".)
Types "BB" = "BroadBand", "SP" = "Short Period", and "Acc" = "Accelerometer". BB "Classes A+", "A", and "A–" are defined in Table 3.4.3. Accelerometer Classes are defined in Tables 3.4.3 and 3.1.2.

†Options RF.2 and U.2, Class "SP/A" instruments (left column), are short-period systems comprising three Class-A accelerometers and three components of 0.5- to 1-Hz weak-motion sensors all in continuous telemetry.

‡Options RF.3 and U.3, Class "SP/A" instruments (right column), are digital replacements of older analogs stations comprising three Class-A accelerometers and a vertical 0.5 to 1-Hz weak-motion sensor in continuous telemetry.

††Option U.5 Class-B stations are typically operated by ANSS and ANSS Commercial Partners. We anticipate about three Class-B stations per Class-A station, currently only within special test-and-demonstration arrays.

Table 3.4.2. Classes of strong-motion accelerograph systems.

Class	Resolution*			Estimated Retail Cost (Quantity One)†
	dB	μg	…Bits in ±3.5 g	
A	>111	<6.7	^{3}20	~$10,000
B	87.3-111	6.7-107	^{3}16 to <20	~$4000
C‡‡	63.2-87.3	107-1709	^{3}12 to <16	~$2000‡
D‡‡	<63.2	^{3}1709	<12	~$1000

*For dB, uses RMS noise *versus* RMS of clipping sine (as in Appendix C), but for this Classification **using the full noise band 0.1 to 35 Hz**. One count, the LSB, is assumed equal to this noise RMS.

†Complete from sensors through telemetry, and GPS for Classes A and B. Timing in Classes C and D may be more innovative.

‡ $500 should be attainable at "commodity" quantities.

‡‡"Urban Superdense" stations run by earthquake insurance companies, amateurs, schools, and **not by the ANSS** so not discussed further here. Long-term goal is about 12 Class-C or -D stations per Class-A station. Data from these stations still will be used for ANSS engineering and research, so they will add effective density to ANSS networks. Compression and ZigBee (802.15.4) to proximal PCs (thence to the Web) or to drive-by receivers are one likely data-retrieval mechanism.

Table 3.4.3a. Instrument Specifications.

	Specification	Broadband			Short Period	Accelerometer		Civil Systems (Primary)[1]
		Class A+	Class A	Class A-	Class A	Class A	Class B	
Sensors	Components: Sensor	3			3/1	3		1 - 3 Acc. (and Displ., Strain, GPS)
	Clip-level	³±0.013 m/s for a sensitivity of 1500 Vs/m			³±1.5 mm	³±3.5 g	³±3.5 g (at ANSS option, ³±2 g)	³±3.5 g (³±6 g as option)
	Sensor Dynamic Range	155 dB, 0.01-.05 Hz 150 dB, 1 - 10 Hz 140 dB, 10 - 15 Hz	143 dB, 0.01-.05 Hz 138 dB, 1 - 10 Hz 128 dB, 10 - 15 Hz	131 dB, 0.01-.05 Hz 126 dB, 1 - 10 Hz 116 dB, 10 - 15 Hz	138 dB, 1 - 10 Hz 128 dB, 10 - 15 Hz	145 dB, 0.02 - 2 Hz 130 dB, 0.2 - 50 Hz	87.3 dB, 0.1 - 35 Hz	Same as Class-A Accelerometers
	Corner Freq. (force feedback) or Natural Freq. (open loop)	≤0.0033 Hz	≤0.01 Hz	≤0.033 Hz	0.5 - 2.0 Hz	³100 Hz	³300 Hz	
	Flat Response (–3 dB Points) Bandwidth required	Velocity 0.01 - 35 Hz	Velocity 0.01 - 50 Hz	Velocity 0.033 - 50 Hz	Velocity 1.0 - 35 Hz	Acceleration 0.02 - 50 Hz	Acceleration 0.1 - 35 Hz	
	Bandwidth desired	Velocity 0.00278 - 50 Hz	Velocity 0.0083 - 50 Hz	Velocity 0.01 - 50 Hz	Velocity 0.2 - 50 Hz	Acceleration 0 - 100+ Hz	Acceleration 0.02 - 100+ Hz	
	Generator Constant at Output	1000 - 2400 Vs/m at 1 Hz			100 - 2000 Vs/m at 1 Hz	0.583 or 0.291 Vs^2/m at 1 Hz[2]		
	Max. non-coherent noise[3]: Bandwidth required	3 dBa < NLNM 0.01 - 35 Hz	13 dBa > NLNM 0.01 - 50 Hz	21.6 dBa > NLNM 0.033 - 50 Hz	13 dBa > NLNM 1 - 35 Hz	Average –95 dBa, over 0.02 - 50 Hz	Average –52 dBa, over 0.1 - 35 Hz	
	Bandwidth desired	3 dBa < NLNM 0.00278 - 50 Hz	13 dBa > NLNM 0.0083 - 50 Hz	21.6 dBa > NLNM 0.01 - 50 Hz	13 dBa > NLNM 0.2 - 50 Hz	Average –101 dBa, over 0 - 100+ Hz	Average –58 dBa, over 0.02 - 100+ Hz	
	Sensitivity Accuracy	1 % <1 Hz; 1.5 % <10 Hz; 5 % <50 Hz			1 % at 20 °C	1 %		
	Cross axis coupling	≤60 dB						
	Linearity	³90 dB						
	Temperature-Induced Output Offsets	Stays on scale over ±10 °C without mass recentering			Offset <2 %FS over –20 to +40 °C Offset <1 %FS over 0 to 40 °C			
	Operational Temperature Range	–30 to 45 °C						
	Clip recovery	<5 minutes			<10 s			
	Expected Lifetimes (manufacturer to justify)	Five Years					Ten Years	
	Output Seismic Signal	±20 V			see Generator Const.	±20 V or ±10 V		
	Retrievable sensor parameters	Upon request, sensor provides manufacturer name, model number, serial number, and factory calibration parameters including sensitivity and nominal transfer function.						
	Sensor Compensation	All sensor compensation, whether in sensor hardware, sensor firmware, DAU firmware, or laboratory software, shall be seamless and transparent with uncompensated data inaccessible to casual users. Compensation process shall be ANSS auditable.						

Table 3.4.3b. Instrument Specifications.

	Specification	Broadband			Short Period	Accelerometer		Civil Systems (Primary)[1]
		Class A+	Class A	Class A-	Class A	Class A	Class B	
Data Acquisition Unit	Components: DAU	6			6/4	6/4/3	3	1 - 24+ Acc
	Sampling rates	0.1, 1, 20, 50, 100, and 200			1, 20, 50, 100, and 200			Same as Class-A Accelerometers (ANSS may require significantly higher sampling rates)
	DAU Amplitude Resolution at 200 sps	³24 bits nominal 23 bits, 0.01-15 Hz 22 bits, 15-30 Hz	³22 bits nominal 21 bits, 0.01-15 Hz 20 bits, 15-30 Hz	³20 bits, all frequencies	³22 bits nominal 21 bits, 0.01-15 Hz 20 bits, 15-30 Hz	³22 bits nominal 21 bits, 0.01-15 Hz 20 bits, 15-30 Hz	³16 bits, 0.1-35 Hz	
	Preamplifier Gains	1			1,10,100	1		
	Gain Stability	Gain stable to 1% over 0 to 40 °C, to 2 % over full operating temperature range, and to 0.1% at DC, 20 °C						
	Ground currents, supply- and reference-voltage stability	No part of the analog system, including amplifiers and ADC, shall suffer disturbance greater than the system's quiescent noise floor at any time due to disk spin up, GPS or telemetry power up, or any other system activity.						
	Worst Timekeeping Error with Regular GPS Locks[4]	<1 ms					<2 ms	
	Internal time reference accuracy (free running)	0.1 ppm/°C and 0.1 ppm/day (at ANSS option, WebSync[5] capability)					Ditto, but at double the values.	
	DAU Recording	Complete and continuous; storage buffer ³12 hours, with compression enabled					**Req'd:** buffer ³1 hour **Desired:** As Class-A	
	Trigger Store-and-Forward	**Required:** ³60-s pre- and ³90-s post-event; save largest; storage buffer ³8 Mbytes **Desired:** ³120-s pre- and ³180-s post-event; save largest; storage buffer ³32 Mbytes						
	Trigger Algorithms for High-Rate Store-and-Forward	At least STA/LTA or equivalent, threshold (≤0.0008 to ³1.0 g), and timed triggers, as well as any more sophisticated algorithms vendors may wish to supply					Required: Threshold Desired: as Class A	
	Telemetry Latency	≤30 s					Generally triggered; deliver ShakeMap parameters within 120 s of trigger	
	Telemetry	Format: IP required (TCP preferred); Carriers: Vsat, CDMA, ISM, ISPs, Frame Relay, …						
	Expected Lifetime	Ten Years (manufacturer to justify)						
	DAU sensor input	±20 V			±20 V	±20 V or ±10 V (matching sensors)		
	Temperature Range for Meeting **All** Specifications not otherwise indicated	–20 to 40 °C						
	Operational Temperature Range	–40 to 60 °C						
	Control signals	Lock/unlock and mass center (broadband only), self-test enable, ring-down or free period test, damping test, produce sine, step and random binary calibration signals, all to provide sensor output of 5 and 50 %FS.					**Desired:** Same as Class-A Accelerometers	
	Acquiring Sensor Parameters	Capable of acquiring parameters from seismometer and accelerometer. See also Appendix C.						

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

Table 3.4.3c. Instrument Specifications.

Specification		Broadband			Short Period	Accelerometer		Civil Systems (Primary)[1]
		Class A+	Class A	Class A-	Class A	Class A	Class B	
Power	Average Power Consumption	All sensors plus the DAU shall draw a total of <2 W, worst-case 24-hour average (10.8 to 16.0 VDC at battery, negative ground)						
Power	Power Supply Capabilities	Provide 10.8 to 16.0 VDC power to DAS for at least seven days at 2W average draw, surge level sufficient for DAS worst case, including telemetry; provide automatic output cutoff below 10.8 VDC.						
Power	Power Supply Capabilities	Provide surge suppression and noise filtering from mains power; tolerate 90-130 VAC mains power. Offer solar-panel option.						
Packaging	Connector Standardization	ANSS, in consultation with vendors, will create standards for the interconnection between the DAU and sensors, the DAU and its 12 VDC power supply, the 12 VDC system and solar panels, the 12 VDC system and mains power, and the DAU and GPS signals.						
Packaging	Environmental Considerations	All DAU, sensor, GPS and power supply systems shall meet IP67 requirements and be capable of operating permanently in 100% relative humidity, excepting that power supplies need withstand only heavy spray, not immersion.						
Packaging	Environmental Considerations	Neither the sensors nor the DAU shall suffer disturbance above its quiescent noise floor in response to barometric variations of ±0.025 bar about ambient, ±1000 nT over 0.0033 to 50 Hz.						
Packaging	Environmental Considerations	RFI performance of the DAU shall conform to IEC61326:2002 (EN55022 for emissions, EN61000-4-3 for immunity, and Annexes A, C, E, and F, for equipment types and usage circumstances).						
Packaging	Environmental Considerations	Both sensors and DAU shall survive 30 cycles of 100-g 1-ms half-sines over an interval of 10 s, alternating polarity, and 30-s of 5-g RMS Gaussian white noise, these paired intervals repeating in round-robin among the axes.						
Packaging	Leveling	All sensors shall be supplied with leveling devices. All accelerometers shall be supplied with tie-down devices.						
Packaging	Mass[6]	DAS (less power supply): <20 kg			DAS (less power supply): <15 kg	DAS (less power supply): <15 kg		Sensor and its power <11 kg

Definitions: "DAU", Data Acquisition Unit = Amplifiers + ADC + storage + telemetry + timing source (GPS); "DAS", Data Acquisition System = DAU + Sensors. "FS", Full Scale (peak-to-peak).

Notes:

[1] For Civil Systems (Structures), only accelerometer specifications are shown here.

[2] Assumes unity gain for ±3.5 g into ±20 or ±10 V.

[3] All dBa figures are in terms of acceleration power spectral density, referenced to 1 $m^2/s^4/Hz$.

[4] All ANSS GPS systems shall be capable of operating in "overdetermined clock mode" when so programmed by the operator. That is, they shall be able to determine time from a single satellite if given their geographic location and elevation.

[5] WebSync is described by Evans et al., *Earthquake Spectra*, **21**, no. 1, 91–124, 2005.

[6] ANSS strongly prefers less massive systems because of their advantages in remote installations and rapid response situations where portability is essential.

3.4.1 National Station

- Meet the needs of national and global monitoring.
    - High resolution in the band 0.01 to 15 Hz (0.00278 Hz to 15 Hz for Global stations), 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 (0.00278 Hz to 10 Hz for Global stations), 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 3.5 g, constant absolute sensitivity, low hysteresis, and 200 samples per second.

(These specifications must be harmonized with Table 3.4.3.)

3.4.1.1 Seismometer

As seen in Table 3.4.1, broadband (BB) weak-motion seismometers are suitable for National stations. Stations meeting the specifications of the Global Seismographic Network (GSN) would require Class BB/A+ instrumentation, with emphasis on low noise at long periods. National monitoring stations (spacing 70 to 280 km) need to resolve higher frequency bands, with less emphasis on the long period band. The best of these stations (at low noise sites) would require Class BB/A instrumentation, whereas the noisiest of these stations would use Class BB/A- instrumentation. The bandwidth and dynamic range specifications listed in Table 3.4.3 reflect these varying requirements. The maximum non-coherent sensor noise specifications were derived from contour plots across the US of seismic noise in various bands, as observed by the US National Seismic Network. See Table 3.4.4 below summarizing the seismic noise requirements derived from those plots.

Table 3.4.4: USNSN Measured Background Noise

Period (s)	Site Noise – NLNM (dBa)	
	BB/Class A	BB/Class A–
0.08839 (0.1)	21.0	36.5
0.1768	17.0	25.0
0.3536	13.0	23.0
0.7071	10.0	20.5
1.414	5.0	14.5
2.828	5.0	10.5
5.657	16.0	20.5
11.31	22.0	26.0
22.63	15.0	19.5
45.25	10.5	18.0
90.51	9.0	23.5
Means	13.0	21.6

"BB/A" site is near the Colorado-New Mexico border; "BB/A–" is in east-central California. (D. McNamara, http://geohazards.cr.usgs.gov/staffweb/mcnamara/PDF_PLOTS/maps.html)

3.4.1.2 Accelerometer

The clip level specification was changed from 4 g in the original version of this document to 3.5 g, to allow a larger range of manufacturers to be responsive. The maximum credible ground acceleration is 3 g, so 3.5 g should give enough extra range to record unusually high ground accelerations.

3.4.1.3 Data Acquisition Unit (DAU)

The DAU digitizer resolution requirements are matched to the dynamic range of the seismometers. Note that all DAUs shall be capable of sampling at a rate of at least 200 sps. Less resolution is needed to resolve signals at higher frequencies (e.g. up to 15 Hz, and 15-30 Hz) because of typically higher noise levels in these bands. Also, it is well known that digitizers running at higher sampling rates are not capable of the high resolutions possible at lower sample rates.

3.4.1.4 Power System

The power system shall adhere to the specifications listed in Table 3.4.3a. State-of-health (SOH) monitoring functions for the power system shall reside entirely within the DAU and shall be comprised of the following:

- The DAU shall sample at least once per second (and at least five times faster than the interval at which the SOH is transmitted, whichever is faster) the ~10.8 to 16 VDC voltage input to the DAU by the power system, as referenced to the master ground. This sampling shall be at a resolution of 0.01 VDC or finer.

- For the interval between each SOH message, the DAU shall calculate the mean, minimum, maximum, and RMS of this power-system voltage to a precision of 0.01 VDC or finer.
- The DAU shall report these four values in each of its regular SOH messages to an accuracy of 0.01 VDC or finer.
- To permit diagnosis of mains failures and other disruptions to power systems, DAU SOH messages shall be reported at least four times per day, preferably twelve or more times.

3.4.2 Regional Station

- Meet the needs of regional monitoring in areas of moderate to low levels of seismicity and very infrequent large events.
  - High resolution in the band 0.02 to 35 Hz, on-scale recording, and latencies less than about 10 s.
- Meet the needs of National and large-scale Regional 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 3.5 g, constant absolute sensitivity, low hysteresis, and 200 samples per second.

(Harmonize with Table 3.4.3.)

3.4.2.1 Seismometer

The seismometer may be same as for a National station. However, the noise requirements are less stringent and there is a need for response to higher frequencies due to the interstation spacing of 50-70 km, implying the possible use of a different seismometer meeting these specific requirements.

3.4.2.2 Accelerometer

Same as for National station.

3.4.2.3 Data Acquisition Unit

The DAU for a Regional station needs somewhat less resolution than a DAU for a National station. Note that linear phase FIR filters used in modern digitizers 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.

3.4.2.4 Power System

Same as for National station.

3.4.3 Active Fault Monitoring Station [This Section needs to be merged with Section 3.4.2 Regional Station]

- Provide information about the characteristics of the infrequent larger events (M>5) as well as microearthquakes. Data from less urbanized and even remote active faults are essential to augment and more rapidly improve understanding the behavior of active faults in urban settings and near critical engineered facilities.

- Due to the wide magnitude range of earthquakes to be recorded close in, accelerometers need to be co-located with weak-motion sensors at many stations. Typical configurations are 3-component broad-band seismometers and 3-component accelerometers, or 3-component accelerometers and one vertical short-period velocity seismometer. The station spacing needed is 10 km, with a mixture of six-component and four-component stations, along with legacy single-component short-period stations to be converted to modern instruments as funding permits.

3.4.3.1 Seismometer

When present, the broad-band seismometer is same as for a Regional station. Vertical or triaxial short-period seismometers are used for closely spaced stations for active-fault and volcano monitoring.

3.4.3.2 Accelerometer

Same as for Regional station.

3.4.3.3 Data Acquisition Unit

The DAU for an Active-Fault station should be similar to that for a Regional station. Note that linear phase FIR filters used in modern digitizers 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; however, acausal-to-causal correction filters or recording a strictly causal signal are preferable solutions. [Comment from one WGD member: Shouldn't they be made causal by apropos filtering instead of throwing away information?]

3.4.3.4 Power System

Same as for National station.

3.4.4 Urban Monitoring Station

[As a general comment, we should ***not*** be repeating here the specifications given in Table 3.4.3, but only explaining their logic. Therefore, I would proceed as follows (and similarly in other sections):]

The specifications in Table 3.4.3a,b are designed to provide the following:

- Provide information about the strong motion wave field and local site effects with little (reference) or no (free field) contamination from man-made structures.
- Provide data quickly enough to produce ShakeMaps and other information products within five minutes for emergency response, public media, and rapid recovery purposes.
- At sites where Active-Fault or Regional planning considerations indicate the need, include broadband or short-period sensors.

As indicated by Table 3.4.3a,b and above, the ANSS is interested in both 3 and 6-channel systems. Further, the sensors, the DAU, and the power system may be delivered as an integrated system or as physically separate modular units connected together with cables. [For reasons of modularity, shouldn't we remove or modify the last sentence to favor the modular approach?]

In the latter case, the ANSS will collaborate with manufacturers to standardize connectors and modularization schemes. Tentatively, the sensor cable shall be included with the sensor, the GPS cables with the GPS receiver, the power and telemetry cables with the DAU, external storage unit cables with that unit, and any telemetry antenna cables with the telemetry transmitter.

3.4.4.1 Accelerometer

- Same as for National station, or may use Class B accelerometers.

3.4.4.2 Data Acquisition Unit

With 21-bits of resolution and a 3.5 g sensor ("Class A"), 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.

For Class B, the expectation is events of primary engineering and emergency response interest are well recorded, including those which are likely to exhibit nonlinear soil response. Additionally, studies of the causes of spatial variance in strong motion are a critical target, beginning with proximal events of M>3, which will be well recorded.

3.4.4.3 Event detector

While most ANSS recording is, and in the future will to an even greater extent be, continuous recording, buffering, and telemetry, there remains a need to use at least basic triggering for (1) temporarily boosting sample rates during large events, (2) maintaining the option of reducing telemetry costs by operating selected systems only in triggered mode, and (3) operating Class B accelerograph systems principally or only in triggered mode to lower their life-cycle costs.

Table 3.4.3b specifies a minimum complement of trigger algorithms and specifics but leaves open the field for the range of more sophisticated triggers that many vendors have implemented. The latter are welcome additions seen as distinguishing features in bid packages.

3.4.4.4 Power System

  - Same as for National station.

3.4.5 Engineered Civil System Response Monitoring Stations

[Revisions are yet to be done in this section.]

3.4.5.1 Accelerometer

- Same as for urban monitoring station, except:
  - Must be available in 1, 2, and 3 component packages
  - Must have an option for a clip level of 6 g instead of 3.5 g with a gain stability of 3%.

3.4.5.2 Data Acquisition System

- Same as for urban monitoring station, except:
  - Must be available in configurations including 3 to 1000 channels.

3.4.5.3 Power System

- Same as for urban monitoring station, except:
  - Power must be available at each accelerometer and at the central multi-channel DAU.

3.5 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:

Need to add the standardization of external connectors for power, sensors, communications, and GPS antenna.

- 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.

3.6 Evaluation of Competing Systems

- RFP must be written with testable specifications (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 in accordance with Section 3.7.
- Pre-productions or prototype units provided during evaluation phase of contract will be fully tested.
- Production units must also comply with specifications and will be spot checked at random to assure compliance (using a subset of acceptance tests).

3.7 Testing Procedures and Standards

3.7.1 Overview

Performance verification testing shall be performed by manufacturers or their contractors under ANSS supervision and shall test samples of all items in the specifications sections above that are applicable to that particular sensor, DAU, or DAS. Random and targeted acceptance tests of instruments (the deliverables) will be performed by ANSS to verify ongoing compliance with specifications and will test all or portions of applicable specifications, as deemed appropriate by ANSS. Routine operational tests will be performed by ANSS to maintain data quality and monitor ongoing performance of instruments and will test all or portions of applicable specifications, as deemed appropriate by ANSS. From time to time, ANSS may perform or contract out NIST-traceable calibrations of various instruments to test performance of its networks or the compliance of deliverables to contract requirements, and will test all or portions of applicable specifications, as deemed appropriate by ANSS.

The intention of vendor and ANSS testing described here is to reduce the lifecycle cost of these instruments and to verify their performance. Therefore, significant initial expense is tolerated where it is likely to reduce long term expense, failures, and uncertainties in performance or reliability or the validity of the data for its intended uses — the ultimate purpose of ANSS and all its expenditures.

Finally, should it be unclear later, the devices to which Sections ***3.7.2*** and ***3.7.3*** apply should be representatives of a distinct model or series, not of each individual requisition — such testing should not be repeated for each requisition. Once the performance of the model or series is established, only the testing described under Section ***3.7.5*** applies per requisition or persistently. Nevertheless, should a significant problem with a model or series be discovered through the testing in Section ***3.7.5***, there may be a need to revisit portions of the testing in Sections ***3.7.2*** and ***3.7.3*** by some means.

3.7.2 Validation Testing

Validation testing, as deemed necessary by manufacturers, shall be unsupervised, and used by them to prepare for performance verification tests described in ***3.7.3***. Results from such testing may not be substituted for the results of NIST-traceable supervised tests in ***3.7.3*** for the purposes of bid qualification unless meeting all standards set forth therein. Such validation testing is otherwise presumed to be part of the vendors' research and development, pre-qualification, and manufacturing-development processes leading to their confidence in their product.

Manufacturers shall make a formal bid based upon their validation tests, and include specifications of their products based upon these validation tests. Their products shall meet or exceed both those ANSS specifications cited in the particular requisition and the manufacturer's own specifications as stated in their bid package and published literature.

3.7.3 Performance Verification Testing

Manufacturers, in a NIST-traceable manner, or NIST-traceable testing laboratories contracted by manufacturers, shall complete formal performance verification testing of final versions of two sensors, DAUs, or DAS (whichever is proposed in their bid package). The test devices shall be selected at random from a batch of eight or more final manufactured copies of final versions of the proposed sensor, DAU, or DAS (neither prototypes nor manufacturing prototypes shall be used, only a true manufacturing run). All such tests shall be witnessed in person by an ANSS calibration professional. All such tests shall be recorded in video and sound by ANSS. Testing performed in Section ***3.7.2*** may be substituted only if meeting all the requirements of this Section, ***3.7.3***.

Feedback to the manufacturers from the ANSS witness regarding the intent of ANSS specifications is permitted, however, no substantive assistance of any kind to the manufacturer or laboratory from the witness is permitted.

All test data shall be handed to the ANSS witness immediately upon conclusion of the testing.

The ANSS may, at its discretion, choose to repeat portions of the performance-verification tests, either itself or by contract, for purposes of authentication.

3.7.4 Contract Award

Contracts are awarded conditioned upon successful performance in Section ***3.7.3***, upon the overall value of the bid package relative to the other qualified bid packages, upon the deployment needs of the ANSS, and upon the past performance of the vendor (including the manufacturer's use of ANSS as a "debugging service" and any similar history of dereliction).

3.7.5 Post-Award Testing

After award of contracts, the ANSS will perform three additional types of tests:

3.7.5.1 Acceptance Tests

Acceptance tests of randomly selected units will be performed upon delivery or shortly afterward to verify whether they meet ANSS specifications. If they do not: (i) the unit will be returned to the vendor for repair, (ii) additional units of similar manufacturing lots or serial numbers will be tested by ANSS, and (iii) if a pattern of vendor non-compliance emerges, that the vendor's history may be considered substantially unresponsive in subsequent requisitions.

3.7.5.2 Routine Operational Tests

ANSS will perform various *in-situ* and laboratory routine operational tests to verify the continuing performance of DASs and supporting systems it operates. These routine operational tests may include automatic self-testing by the DAS; on-site flip tests, voltage checks, and so forth by maintenance personnel; and tests done in the laboratory that are similar to but generally less extensive than performance-verification tests.

3.7.5.3 NIST-Traceable Calibrations

From time to time, ANSS may deem it appropriate to perform or to contract out NIST-traceable calibrations of all or portions of particular sensors, DAUs, or DASs to monitor the performance of vendors and of ANSS networks. Such tests will be generally similar to all or portions of performance-verification tests.

3.7.6 ANSS Owned, Contracted, and Cooperatively Operated Calibration Facilities and Tests

For acceptance tests, a portion of the routine tests, occasional NIST-traceable calibrations, and possibly for authenticating portions of vendors' performance-verification testing, as deemed advisable prior to final award of contracts (using either vendor-donated or first-article examples of the instruments), ANSS may (1) maintain a testing laboratory at the USGS Albuquerque Seismological Laboratory, (2) cooperate with Sandia National Laboratory and other ANSS and IRIS institutions in the use of their testing facilities, and (3) contract some tests to NIST-traceable testing facilities.

Appendix 3.1

The Need for Dense Arrays

The ability of a strong-motion network to resolve wavefields is appropriately described by dynamic range (dB), station spacing (km), and bandwidth (Hz), that is, by amplitude, spatial, and frequency resolution. The first and last of these criteria have received a great deal of attention, culminating in instruments substantially exceeding 120 dB dynamic range ("20 bits") and usable bands from tens of seconds to 50 Hz or broader. However, in the seven decades of viable strong-motion instrumentation (e.g., McLean, 1983) there has been little practical opportunity to address spatial resolution.

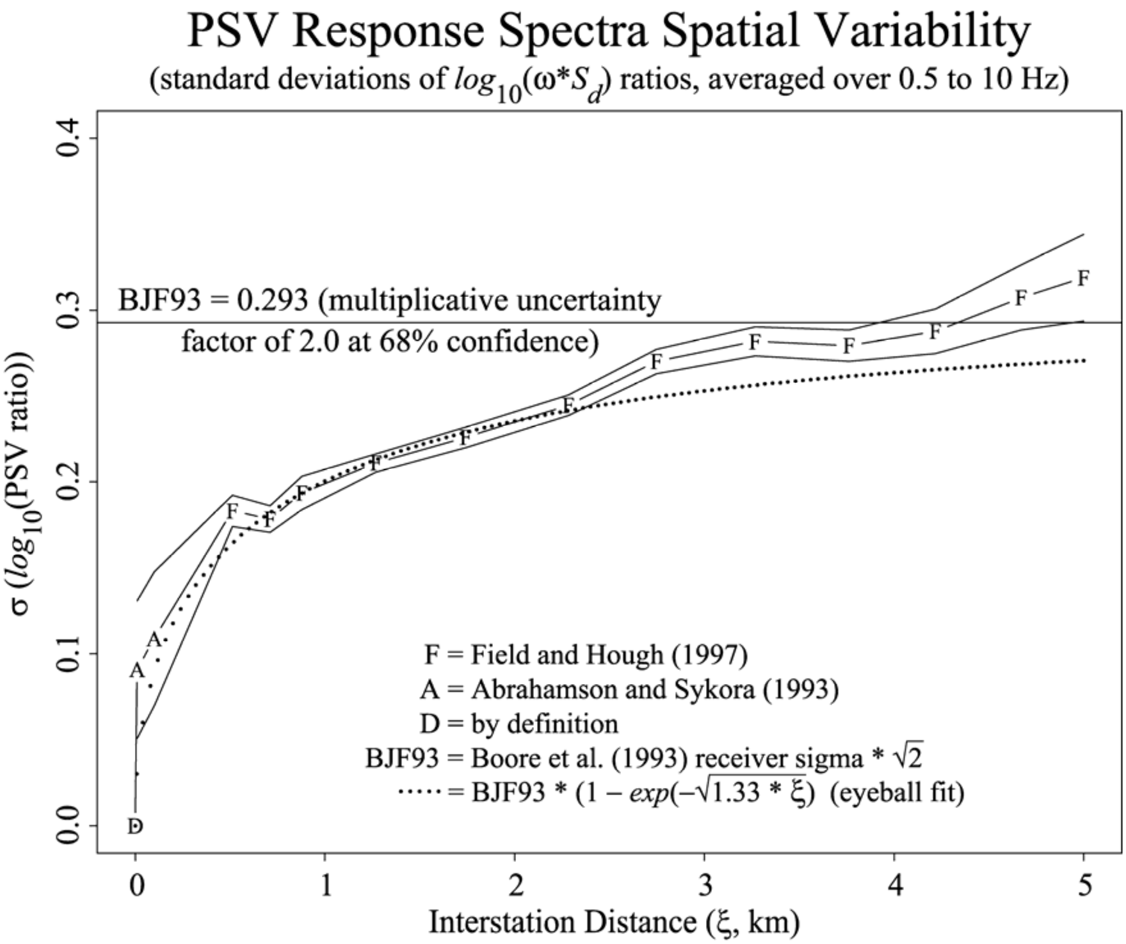
A very economical accelerograph is needed to achieve the spatial densities required for well resolved ground-motion mapping. The degree to which this is true is demonstrated by Figure 1 (Evans et al., 2005) or the similar, somewhat flatter Figure 2 by Boore and others (2003). These results show that the correspondence between ground motions at two neighboring sites decreases rapidly with increasing separation between the sites.

Specifically, Figure 1 shows the log-normal standard deviation of response spectral pseudovelocity (PSV), averaged over 0.5-10 Hz. If one imagines the second site to be the unobserved point at which the shaking must be estimated, the uncertainty in the predicted shaking at that point rises sharply in the first kilometer away from the accelerograph at $\xi=0$. At 500 m away, the log-normal standard deviation is ~0.16 — a multiplicative uncertainty of 1.5×. At 2 km the uncertainty rises to a factor of 1.7×, most of the way to the asymptotic limit of 2.0×, a limit typical of all good attenuation relations known to us. These are only 1-σ, 68% confidence values. These are uncertainties exceeding most structural tolerances at one-third of the sites very close to observed points. Figure 2 shows a comparably bad situation for peak horizontal acceleration, with a somewhat flatter curve, but still is at an uncertainty factor of 1.5 at 2 km, on its way to an asymptote uncertainty factor of 1.8

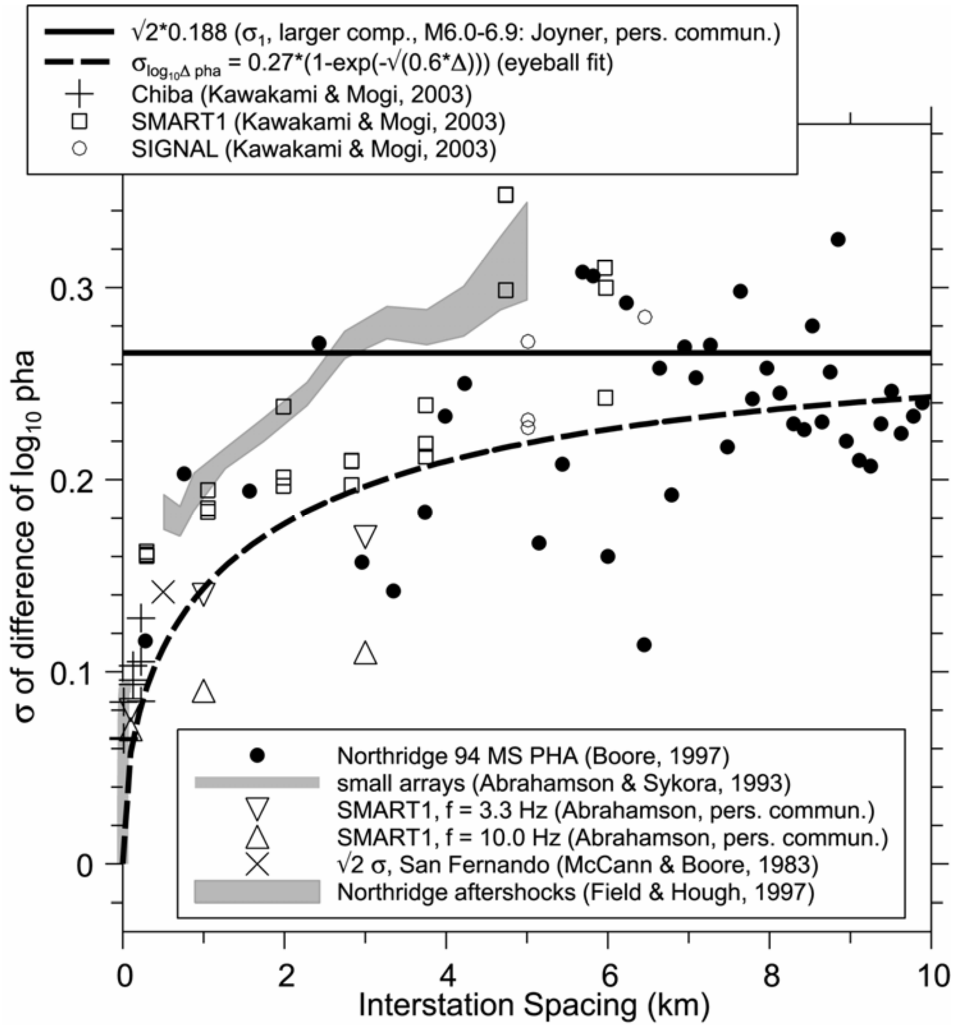
To improve upon this roughly factor-of-two uncertainty by adding observations — by making the array denser — Figure 1 suggests that one must consider arrays with station densities approaching one station per km^2. That is, one must limit to the range of 500 to 1000 m the distance from the least-well observed place to the nearest station ($\xi=500$ to 1000 m). Any such array clearly requires a very large number of instruments with a commensurate demand on supporting resources — a daunting proposition.

Such density, however, provides an opportunity to address earthquake engineering, emergency response, code, and seismological research questions that have been largely beyond reach. Among these issues are differentiating the relative contributions of shaking strength, design, construction quality, and maintenance to the ultimate performance of structures. This dissection cannot commence without a clear picture of the shaking impinging a structure, yet the best attenuation relations leave the factor-of-two uncertainty at the great majority of structural sites. The same spatial variance decreases the accuracy of rapid damage assessments and emergency response efforts, even with ShakeMap (Wald et al., 1999) and the improved coverage afforded by the early stages of the ANSS (Advanced National Seismic System), generally ~5-km-spaced. There also are examples of pockets of serious damage going underobserved (Sherman Oaks, California, 1994; Santa Cruz County, California, 1989), or incorrectly inferred to be the primary damage locus (Santa Monica, California, 1994), or of being in unexpected places due to interference phenomena superseding site conditions (Kobe, 1995). These pockets have been small in one or both spatial dimensions. Understanding the degree and causes of spatial variance, thus improving predictive models of it, requires densely sampled wavefields to drive and test those efforts. Other motivations for such arrays include the inadequate data for attenuation relations and spatial variance in the near field and for NEHRP Site Class E soils (e.g., Boore et al., 1993; W. Joyner, personal comm., ca. 1997; recent observations of both Parkfield variance and on-fault attenuation), the need to develop rapidly a viable strong-motion data set for Alaska and several other regions, and the need to test microzonation models based on surface geology.

It is evident to all who have operated or planned an accelerograph array that approaching 1- to 2-km spacing requires a radical reduction in lifecycle instrumentation costs (acquisition, siting and permitting, installation, and maintenance). The opportunity provided by the convergence of MEMS and other robust, lower cost sensors with reliable cost-effective wireless telecommunications, particularly Internet-enabled systems, sharply lowers both acquisition and maintenance costs. Innovative instrument dissemination and maintenance methods (including methods for mass-permitting, entrainment of nontraditional groups in the deployment and maintenance of systems, use of WebSyncing and “overdetermined clock mode” for GPS, and numerous other innovative opportunities) provide an economically viable means of achieving this high spatial density.



Appendix 3.1 Figure 1. Site-to-site PSV variance *versus* station separation at firm-soil sites. Data are from Abrahamson and Sykora (1993) and Field and Hough (1997). "BJF93", Boore et al. (1993).



Appendix 3.1 Figure 2. Standard deviation of difference of log of the larger peak horizontal acceleration as a function of interstation spacing (from Boore et al., 2003, Appendix A).

Appendix 3.2

Detailed Test Requirements and Specifications

Tests of Long-Period, Weak-Motion Sensors

Tests at ASL or Sandia

- The ADC will be tested by the method described in SAND 94-0221, Modified Noise Power Ratio Testing of High Resolution Digitizers (McDonald, Sandia National Laboratory, 1994).
- Sensor, DAU, and DAS self-noise tests in hard-rock vault and Faraday cage.
- Test sensitivity, linearity, and cross-axis response on precision tilt/step table (the Wielandt/Lennartz design, possibly with the addition of a long-arm side-table actuated it). If possible, test dynamic response and obtain transfer function on this table.
- Test temperature sensitivity of gain and offset in a thermal chamber large enough to accommodate the Wielandt tilt table (0 to 40°C). Also look for and evaluate any spurious behavior by the sensor.

Contracted Tests

- Barometric testing: Barometric chamber volume must be sufficient for largest sensor with the largest DAU. Test over pressure range 0.05 bars peak-to-peak and a mean of 1 bar. Observe, at 200 sps, (1) variations in DC offset and (2) any spurious signals. Record DAU output with both live sensors and shorted inputs during at least 50 pressure cycles having periods swept from 60 s to 600 s over a 5-hour or longer contiguous test run. Compare, to a similar record taken at constant 1-bar pressure. Make this comparison in both the spectral and time domains. Spectral analysis shall be a power-spectral ratio of entire time series (or ensemble average thereof) between the test and reference time series. Time-domain studies shall test baseline stability with running medians and running "50% inside means" (the mean after discarding largest and smallest 25^{th} percentiles) using at least window lengths of 3, 11, 51, 201, 1001, and 2001 points. Also detect spikes and steps (algorithms comparing running medians to original or to running mean series are likely to be successful, and will be supplied by the ANSS).
- Magnetic-field generator to ±1000 nT; volume as with barometric chamber; field fluctuation frequency swept 0.0033 to 50 Hz. Record and evaluate signals in the time and frequency domains with both a live sensor and shorted inputs to the DAU in the same manner as for pressure testing.
- RFI performance of the sensor shall be tested per IEC61326:2002, including EN55022 for emissions, EN61000-4-3 for immunity, and Annexes A, C, E, and F, which detail equipment types and usage circumstances. ***[NB: We particularly solicit comment on these requirements.]***
- ANSS may contract out MTBF tests, IP67 tests, and various other tests of sensor and DAU robustness that it deems worthwhile.

Tests of Strong-Motion Sensors

Tests at ASL or Sandia

- During many tests, precision accelerometers (high-end Honeywell™ Sundstrand™ aeronautical accelerometers) will operate in parallel with the sensors under test as reference devices.
- Sensor (sensor + reference filters + reference Quanterra) self-noise tests in hard-rock vault using one of the following methods: (1) single-sensor method, if site is known to be significantly quieter than the sensor under test, (2) incoherent-noise method between two carefully co-aligned equivalent test sensors, or (3) simultaneous recording with a carefully co-aligned Sundstrand™ reference sensor, where the latter's noise characteristics have already been characterized and can be removed to yield an accurate estimate of concurrent Earth noise, this Earth noise to be used to isolate the test-sensor noise from total-record test-sensor noise. Finally, (1) presumes that the reference filters and Quanterra have also been characterized and removed and all presume that this factor is a constant.
- Test linearity, sensitivity, and hysteresis to ±1 g on high-angle tilt table.
- Test sensor's ability to return to rest position from approximately ±1-g excursions on a precisely horizontal flat-ground surface, thus testing one form of sensor linearity.
- Test linearity, sensitivity, and hysteresis to ±5 g in precision centrifuge equipped with accelerometer-flip mechanism.
- Thermal chamber (–20 to +60°C) to verify gain and baseline stability. Time- and frequency-domain analysis will be used as for weak-motion sensors, but with 20-minute time series (after the recorder's internal temperature stabilizes).
- Shake table(s): horizontal and vertical.
    - 0.2 to 50 Hz.
    - Horizontal table must have linearity (roughness of path; cross-axis) no worse than 0.1 arc sec in the vertical plane, the up-down direction, and <1% (–40 dB) in the horizontal plane, the left-right direction.
    - Vertical table must have linearity (roughness of path; cross-axis) to <1% (–40 dB).
    - Must be drivable with sine waves, user-programmable arbitrary waveforms, and band-limited square waves.
    - Accelerations to ±5 g at all frequencies (limited only by maximum displacements).
    - Displacements to at least 30 cm, preferably 100 cm (peak to peak).
    - Linear displacement sensor accurate to 0.01 mm over entire range of table.

Contracted Tests

- Barometric chamber: as above.
- Magnetic field: as above.
- RFI performance of these sensors shall be tested as for weak motion sensors.
- MTBF, IP67, and ANSS-specified robustness tests: As above.

Tests of DAUs and DASs

To test DAUs for either strong- or weak-motion DASs, the following are needed:

Tests at ASL or Sandia

- The ADC will be tested by the method described in SAND 94-0221, Modified Noise Power Ratio Testing of High Resolution Digitizers (McDonald, Sandia National Laboratory, 1994).
- System (sensor + DAU and shorted-input DAU) self-noise as for weak motion systems and also test for baseline-stability and long-period and spurious noise (sensor + amplifier + ADC + $1/f^a$ noise + random walk + popcorn noise + other spurious noise sources): Self-noise with live sensors and with shorted inputs, in particular looking for noise caused by episodic hardware and firmware events, particularly permanent-storage cycling, GPS cycling, and cyclic firmware events. The noise record that is subjected to spectral and time-domain analysis will be at least 24 hours or 10 permanent-storage cycles in duration, whichever is longer. The entire record will be reduced to a single amplitude or power spectrum, reducing spectrum variance by ensemble averaging of spectra from sub-samples at least as long as one permanent-storage cycle. Time-domain analysis also will be used as for contracted tests of weak motion sensors to track baseline stability
- In thermal chamber, test to –20 to +60°C the gain and baseline stability of DAU and DAS. Time- and frequency-domain analysis will be used as for contracted tests of weak motion sensors, but with 20-minute time series (after recorder's and sensors' internal temperatures stabilize).

Contracted Tests

- Barometric chamber: as above.
- Magnetic field: as above.
- RFI performance of the DAU shall be tested as for sensors.
- MTBF, IP67, and ANSS-specified robustness tests: As above.
- Other tests, (such as software verification, storage media reliability, etc.) as specified.

Equipment and Facilities now Available in ANSS Laboratories

- Hard rock vault reaching to about the (NLNM – 3 dB).
- Weak-motion precision tilt/step table (e.g., the Wielandt/Lennartz design), possibly with the addition of a long-arm side-table actuated by this Wielandt tilt/step table in order to produce even smaller tilts.
- 0.0033 to 50 Hz bandwidth step.
    - Sine wave or band-limited step.
    - Cross-axis <0.1% (–60 dB).
- High-angle tilt table for strong-motion sensors (360° transit, precision 15 arc sec between ±180°).
- Thermal chamber capable of operating between –20 and +60°C. Ideally, one should be able to isolate the test equipment from chamber vibrations.

- Precision, digitizing voltmeter (≥200 sps) for calibrating the relative gains of Quanterra 4128 channels. The Agilent 3458A is appropriate.
- Quanterra 4128 or equivalent truly ≥24-bit sampling multichannel ADC (with ~10^{-6} phase and amplitude linearity or better), used for calibrating DAU ADCs, seismometers, and accelerometers. This sampling ADC with precisely known phasing between channels is required in coherence analysis for determining ADC performance and sensor and DAU self-noise.
- Gaussian white-noise generator, 0 to 50 Hz (ADC resolution test).

Equipment and Facilities NOT now Available in ANSS Laboratories

- Horizontal and vertical weak-motion shake table(s):
  - 0.0033 to 50 Hz bandwidth
  - linearity (roughness of path) <<1% (–40 dB)
  - sine waves
  - band-limited random binary sequences
  - band-limited steps
  - arbitrary waveforms.
- Horizontal and vertical strong-motion shake table(s):
  - 0.2 to 50 Hz.
  - Horizontal table must have linearity (roughness of path; cross-axis) no worse than 0.1 arc sec in the vertical plane, the up-down direction, and <1% (–40 dB) in the horizontal plane, the left-right direction.
  - Vertical table must have linearity (roughness of path; cross-axis) to <1% (–40 dB).
  - Must be drivable with sine waves, user-programmable arbitrary waveforms, and band-limited square waves.
  - Closed-loop drive system reproducing input displacement waveforms to within 3% of amplitude and 3% of phase throughout operating envelope described here.
  - Accelerations to ±5 g at all frequencies (except as limited by maximum displacements).
  - Displacements to at least 30 cm, preferably 100 cm (peak to peak).
  - Linear displacement sensor accurate to 0.01 mm over entire range of table.
  - Closed-loop drive system that does not allow table to exceed safe displacement limits.
- A precision (low vibration, constant speed) 5-g centrifuge with accelerometer-flip mechanism
- Three axes, precision reference accelerometers (navigation grade Honeywell™ Sundstrand™ aeronautical accelerometers).
- Arbitrary waveform/function generator, 0.01Hz – 20 MHz
- Precision voltage source
- Two precision-ground flats, one fixed, granite about 2×2 m, the other of Invar (or something else with low CTE), about 0.5×1.5 m. These will be used as a base for horizontal-tilt and shake work, a surface to do the linearity flip test on, the ramp from the Wielandt tilter, and so forth.

- Also needed are a 12-inch (or longer) machinist's precision level; a large precision angle plate (90°); precision angles (30°, 45°, 90°); and a collection of brass and stainless steel shim.

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4 Siting and Installation

4.1 Introduction

The deployment of seismic stations must be guided by defined needs for data. In Section 3.1, this concept was developed in terms of five types of monitoring stations that derive from the data to be collected: National, Regional, active fault, and urban, and engineered civil system. For each of these five monitoring stations, the means to collect the desired data can be determined through the following steps (repeated from Chapter 3):

> Step 1: Station Planning. Based on the desired data to be collected, appropriate station deployments are identified. Station planning includes selecting the type of station with its associated instrumentation specifications, and defining the desired spatial distribution of stations, and defining acceptable site characteristics for the stations to be able to provide useable data.
>
> Step 2: Station Siting: Specific candidate locations that meet the station planning requirements are identified, and are evaluated with respect to minimum suitable logistics and environmental characteristics.
>
> Step 3: Station Installation: For the planned instrumentation at each site, the minimum requirements for installing the station are specified, including power, communications, GPS reception, security, anchorage to soil, and thermal isolation.

Furthermore, we intend that overlapping, interleaving networks should be mutually supporting to the greatest practicable degree. For example, the ANSS Backbone should provide data useful to Regional networks in and near which the ANSS Backbone sites lie, while broadband stations in the Regional networks should provide viable data to the ANSS Backbone. Similarly, active-fault monitoring stations in and near urban areas and urban-monitoring arrays in active-fault monitoring areas should be actively sharing fully compatible data. Such synergistic opportunities should extend to planning and siting efforts as well.

Many aspects of station planning, siting, and installation are almost instinctively handled by experienced individuals. However, there are some relatively new data needs at hand: ShakeMap inputs, monitoring regions with infrequent seismic events, near-fault ground motions, site response and other geotechnical problems to be studied in the field, and structural response monitoring. At the present time, a detailed guideline is being prepared for ANSS structural monitoring, and an NSF-supported COSMOS workshop series is starting in October 2004 that will provide needed input for geotechnical arrays. These activities and the resulting guidance will be very useful, but clearly there are additional topics for which station planning and siting guidance is urgently needed.

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 response. 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 response studies require strong motion information around and throughout structures of interest.

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 National and Regional Monitoring Stations

4.2.1 Station Planning

USGS Circular 1188 specifies that the ANSS Backbone National stations are to be distributed as uniformly as possible across the US. The primary frequency band of primary interest is 0.01 to 15 Hz (because propagation distances are typically less than the mean inter-station spacing, ~300 km). However, instruments compatible at their upper frequency cutoff with regional needs are to be used to provide synergy with other networks. Similarly, 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.

As indicated in Section 3.2, Regional stations are intended to collect data from regionally distributed earthquakes. Planning these stations must take into account regional wave propagation characteristics as well as historical seismicity and regional variations in tectonic activity. Although the instrumentation is similar to that of National stations (Table 3.4.1) in the ANSS Backbone, the spatial distribution of the stations within a region would not typically be uniform, but would be biased to more seismically active areas. There is also overlap with the siting considerations for Active-Fault and Urban monitoring. Planning for Regional stations is the primary responsibility of the regional working groups, in coordination with adjacent regions and with ANSS National Steering Committee oversight. 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 combined ANSS Backbone National stations and Regional stations will be considered together 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.

- Prefer sites classified as rock (NEHRP A or B), with accelerometers located within one meter of the ground surface and attached to a concrete pad anchored to the rock so the data are suitable for engineering applications.

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 stations 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.

4.2.2 Station Siting

4.2.2.1 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.

4.2.2.2 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 amplification effects tend to limit the utility of the data for source or propagation studies. Softer materials are also much more prone to long period tilting, particularly due to thermal effects. Poorly consolidated material generally makes a poor seismic station 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. The inclusion of a geologist on the initial siting team(s) will also be invaluable to not only conduct generalized geologic assessments and explore existing sources of geotechnical data, but also to avoid installation in geologically unfortunate locations.

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 station 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).

4.2.3 Station Installation

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. DAUs 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, DAUs 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.

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, DAUs 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.

Accelerometers at the stations must be installed in a manner consistent with the installation of ground response stations, so that strong-shaking data can be used for engineering purposes. This requirement implies, among other things, that free-field and reference sensors must be within one meter of the Earth's surface. Furthermore, in order to provide the extremely stable baselines required for double integration of acceleration signals, it has become clear that all accelerometers must have heavy thermal insulation, much as broadband seismometers. Therefore, a ≤15-cm thickness of dense construction insulation shall be provided on all sides of the accelerometers and this insulation shall be well sealed to the base slab to which the accelerometers are attached. Additional steps shall be taken where practical, particularly to shield the installation from direct sunlight.

4.2.3.1 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 broadband 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 generally recommended for use in the ANSS. If a borehole is used, at least reference accelerometers should be installed near the ground surface next to the wellhead.

Although the cost of drilling a shallow tunnel can be prohibitive, abandoned mines and, to a lesser extent caves, can provide outstanding seismic stations. 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). Strong-motion sensors should be installed within one meter of the ground surface. 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 DAU 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/). However, the strong-motion sensors need to be placed within a meter of the ground surface, so will probably be in a small, separate vault.

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 broadband 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 DAU 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 broadband sensors and, if possible, accelerometers, 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.

4.2.3.2 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 radio frequency interference (RFI), 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 RFI. RFI also can be minimize by keeping the analogue signal cables between the sensor and the DAU 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.

High resolution digitizers are also sensitive to thermal variations and to air convection, which can increase noise. DAUs should be installed in the subsurface seismic enclosure, but perhaps with somewhat less insulation than the sensors, and in a separate enclosure. The amount of insulation should be chosen to prevent overheating of the DAU.

4.2.3.3 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.

4.2.3.4 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 DAU (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 stations. 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.

4.3 Active-Fault Monitoring Stations

4.3.1 Station Planning

Many of the active fault zones and active seismic source zones in the US are currently being monitored with seismic stations specifically deployed to record microearthquakes and major earthquakes in the zones for purposes of understanding the physics and geophysics of each source and the characteristics of the associated hazard. This monitoring has evolved significantly since the days of Wood-Anderson instruments in the early twentieth century and the early days of telemetered networks in the 1960s. Now, seismic source monitoring typically includes a mixture of broadband, strong-motion, and short-period instruments, along with GPS stations and, in a few networks, surface or borehole strain monitors. These instruments are intended to collect data that cover a broad bandwidth of signals, a wide dynamic range from earth noise to greater than 2 g, and both triggered and continuous time intervals.

In planning Active-Fault monitoring stations, synergy among all types of ANSS stations needs to be considered (see Section 4.1) to optimize the use of ANSS and other resources. Network station planners need to carefully consider their data needs versus available capital and operational funding. They also need to consider the ANSS performance standards (reference?) and the needs of the users of the data and data products.

4.3.2 Station Siting

An overriding issue for station planning is the translation of an ideal grid or spatial distribution of stations into individually sited stations, considering such matters as:

- obtaining permission to install and operate the station
- establishing reliable communications (continuous or dial-up)

- finding satisfactory seismic noise conditions (natural and man-caused)
- etc.

Many key siting considerations discussed in Section 4.2.2.2 with respect to National and Regional stations are appropriate for active-fault stations. Due to the need to detect, locate, and analyze waveforms from microearthquakes (M1 to M3), close station spacing (on the order of 10 km) is needed. Depending on ground noise levels, Class A accelerometers combined with short-period seismometers (Table 3.4.1, Options AF.2 and AF.3) can provide on-scale records along with good resolution of P and S waves. This is practical and more economical than installing stations with broadband sensors at closer spacing intervals than 50 km. Experience in station siting is a valuable resource for a seismic network to efficiently and successfully site stations; such experience is available at many seismic networks in the nation, and should be shared among the ANSS regions.

4.3.3 Station Installation

- This section needs to be prepared by an experienced station installer of modern dense networks.
- A key element is some thermal isolation for accelerometers.

4.4 Urban Monitoring Stations

4.4.1 Station Planning

The planning of urban monitoring stations must involve careful consideration of the utilization of the recorded data for engineering and emergency response purposes, providing direct public benefits such as ShakeMap notification of emergency responders and refinement of engineering design codes and practices, as well as use in the academic and research communities. Careful planning and prioritization of the geographic distribution of stations must consider the following conditions and needs within the urban region:

- Regional distribution of residential, commercial, industrial, and lifeline land use to assure adequate ShakeMap coverage of population, buildings, and infrastructure
- Regional surficial geology conditions so that adequate measurements can be made of the variety of site conditions in the urban region.
- Regional mapping of liquefaction and landslide susceptibility so that monitoring can be used to improve future assessments of these geologic hazards and their risk.
- Indications of potential regional variations in ground response due to lateral variations in crustal structure down to basement rocks.
- Location of instrumented structures to assure the placement of reference stations

- Permitting opportunities, pitfalls, and restrictions

Early in the implementation of ANSS, most urban areas can begin to be instrumented simply by reviewing maps of land use and the built environment, surficial geology, and geologic hazard susceptibility and installing stations to provide fairly uniform coverage of the urban region with station spacing of about 4 km. As this station density is approached, more careful assessment will need to be made to optimize the benefits of added stations. Such considerations could include one or more of the following:

- Placement of surface and downhole arrays to measure the performance of pathologic soils in critical areas of the built environment.
- Installation of nested arrays of instruments (see Appendix 3.1) to refine the accuracy of ShakeMap interpolations in areas, for example, of rapid lateral changes in soil characteristics, basin edge effects, or uniform building stock.
- Rapid lateral changes of geologic structure due to active faulting and sedimentary basins.

4.4.2 Station Siting

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.

4.4.2.1 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 2+ g) 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.

4.4.2.2 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.

4.4.2.3 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.

4.4.3 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

4.4.4 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.

4.4.4.1 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.

4.4.4.2 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.

4.4.4.2.1 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.

4.4.4.2.2 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.

4.4.4.2.3 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.

4.4.4.2.4 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. One must also consider reliability of data transmission in the event of a large earthquake.

4.4.4.3 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.

4.4.5 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.

4.4.5.1 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 ($\leq$4000 sq. ft in plan and $\leq$2 stories in height);
- It is installed on grade;
- It is located in a building without a 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) that has a low likelihood of significant non-linear behavior or collapse; and
- It has a natural frequency greater than 10 Hz (optimal), or?? [This needs further review. No one can determine this without an instrument and a study]
- 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.

4.4.5.2 Siting Issues

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

4.4.5.2.1 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.

4.4.5.2.2 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.

4.4.5.2.3 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.

4.4.5.2.4 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.

4.4.5.3 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.

4.4.6 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.

4.4.6.1 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.

4.4.6.2 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.

4.4.6.2.1 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.

4.4.6.3 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 Engineered Civil System Response Monitoring Stations

[To be done]

4.5.1 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

4.5.2 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.

4.5.3 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.

4.5.3.1 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.
    - o **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.
    - o **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.

4.5.3.2 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.

4.5.3.3 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° 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 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 urban monitoring 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 National, Regional, and urban monitoring 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 and confirmed in the field by a geologist. (Use of coarse geologic maps alone with result in a misclassification rate of at least 25%, and in many cases even higher.) Surface geology can be a poor estimator of subsurface soil or rock properties, especially for sites geologically classified as rock. Nonetheless, in the absence of direct measurements, a generalized geologic assessment of surface conditions provides the best first-order characterization of site conditions.

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 V_{S30}>1500 m/s
B. Rock with 760m/s<V_{S30}<1500m/s
C. Very dense soil and soft rock with 360m/s<V_{S30}<760m/s
D. Stiff soil with 180m/s<V_{S30}<360m/s
E. A soil profile with V_{S30}<180m/s
F. Soils requiring special investigations (liquefiable soils, sensitive clays, or very weak soils)

V_{S30} is the effective average shear wave velocity (1/average slowness) in the upper 30 meters. NEHRP/IBC classes require some kind of measurement of V_{S30}.

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. Site characterizations would additionally be useful at other stations as well; such information cha be critical for many types of analysis that involve waveform amplitudes.

4.6.1 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 relatively 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. The retrieval of existing site characterization data, however, can be a time-consuming process, and is most efficiently undertaken by a geologist who is familiar with the types of data and their use.

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.

4.6.2 V_{S30} Determination for NEHRP Categorization

V_{S30} (particularly 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 V_{S30} are surface wave methods and seismic refraction. Note that these methods are relatively inexpensive and can provide a good estimate of V_{S30} 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 a relatively 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 V_{S30}. The CPT approach performs best at soft-sediment sites (generally NEHRP class D); even at these sites it is often not possible to reach 30 meters.

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.]

4.6.3 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.

4.7 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. Station documentation should be available via a Web-based database that allows for archival of station updates.

4.7.1 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/ V_{S30} value (particularly urban monitoring stations)
- 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. The online database should allow for archival of updated information, for example, a history of maintenance problems at a site or improved site characterization information.

4.7.2 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.

4.8 References

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