Global Seismic Network
Design Goals Update 2002

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GSN ad hoc Design Goals Subcommittee

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Introduction

The GSN Design Goals Subcommittee (DGS) agreed that the appropriate approach was for us to couch this effort in terms of an update of relevant portions of the 1985 document "The Design Goals for a New Global Seismographic Network" prepared by the SCGSN Instrumentation and Data Collection Subcommittees. That document was redistributed, and studied by the DGS. Our focus is directed at updating the GSN design goals to provide input to the Instrumentation Committee, which will then be tasked to develop technical specifications. Design goals are framed by the context of both scientific goals of the research community and by general philosophy of network design and recording system attributes that service the scientific applications of the data.

From the perspective of today's GSN, major elements of the 1985 Design Goals document have been implemented in several respects. That document emphasized 20 sample/sec broadband digital recording with real-time or near real-time data telemetry of all teleseismic ground motions (assuming about 20 degrees station spacing) for earthquakes as large as $M_w = 9.5$ (equivalent to the 1960 Chile earthquake) by a uniform global network of about 100 stations, with low noise instrumentation and environment, standardization of system modules, and linearity of response. The intent was for total system noise to be less than the ambient ground noise over the operating bandwidth.

Some provision was made for the possibility of additional short-period data channels to record local signals or high frequency teleseismic signals, as well as for low-gain channels, possibly with additional sensors, to record the largest accelerations experienced by the stations. Over the ensuing 17 years, the GSN has achieved significant global coverage (large gaps persist within oceanic regions and continental coverage is non-uniform), and high dynamic range, broadband instrumentation has been deployed at all formal GSN stations. Short-period recording has extended beyond the general statements of the 1985 document to encompass 40 sample/sec continuous recording at most stations, along with 80 to 125 sample/sec triggered recording, with short-period sensors supplementing the basic broadband instrumentation. Strong ground motion instrumentation and triggered channels have been added to stations in earthquake prone areas, and low-gain 1 sample/sec channels are continuously recorded.

Limitations

The driving motivation for the GSN has been to record with full fidelity and bandwidth all seismic signals above the Earth noise, accompanied by some efforts to reduce Earth noise by deployment strategies. The primary limitations at many GSN stations at this time are site noise related. Despite extensive effort, political and logistical situations have resulted in some GSN stations being located in noisy environments. The 1985 Design Goal framework does not address the reality of compromised site selection. The most useful stations are those that provide abundant high signal-to-noise ratio data, but there is always some trade-off with geographic coverage. While the goal should be to have low noise sites in general, there will be compromises. Site selection and site construction should be such that there is reasonable assurance of substantial data return, with the goal being to maximize the bandwidth and useful dynamic range of the GSN signals.

In particular, many stations with useful vertical component signals have horizontal components that are much lower in quality. Further development of strategies for improved horizontal component stability and noise reduction is recommended. Discussion of procedures for installation involving shielding of sensors from temperature and pressure variations should be undertaken to define practices that optimize horizontal component stability in vaults and boreholes.

A significant concern is that as new station deployment has given way to long-term operations and maintenance of the network, we find that there are significant non-uniformities in the instrumentation comprising the GSN today, largely as a result of the historical evolution of the network. This seriously complicates maintenance of the network. As GSN renews and expands its instrumentation, efforts toward network-wide standardization of instrument performance, if not instrumentation, should be a priority, even as flexibility is retained due to variable site attributes. The extent to which compromises in individual station performance are tolerated must be weighed against the scientific gains to be had and the increased complexity of network O&M.

Future Directions

So, is sustaining the status quo the recommendation of the DGS? There are actually several major concerns that warrant a re-articulation of the design goals for the network and a vigorous effort to develop next generation instrumentation for the GSN.

Adaptation of GSN design goals to accommodate emerging scientific directions has been, and should continue to be, an ongoing process. However, since 1984 there has not been a community-wide discussion of scientific directions to guide or modify a future vision of GSN instrumentation. Renewal proposals for IRIS funding from NSF have included updated applications of GSN data, but there has not been a forum for broad thinking on expanded roles or capabilities for GSN in the future. Thus, the present work of DGS is framed by a general sense that, at a minimum, the existing instrumentation strategy is serving the community rather well and the original design criteria need to be sustained.

Two sorts of network enhancements have been considered: enhancements improving network performance, maintainability, and flexibility within existing design goals and enhancements expanding the scope of the GSN design goals. The most obvious enhancement of maintainability is to select new instrumentation to replace aging and/or obsolete equipment currently in the field. The most obvious enhancement to performance and flexibility would be to seek equipment that can be operated under a wider variety of site conditions. Lower power equipment, in particular, would make many potentially lower noise sites viable as well as reducing power related maintenance problems.

For stations that are intrinsically excessively noisy (to the point where the advantage of geographic siting is outweighed by the paucity of useful signal recovered) it may prove viable to pursue noise suppression strategies. For example, if auxiliary channels for pressure, temperature and tilting need to be recorded to suppress noise on the horizontals, this should be pursued. Alternatively, mini-arrays may prove useful for signal enhancement in specific pass bands. The potential improvements in signal recovery using array deployments for GSN island stations and possibly for ocean bottom stations warrant detailed consideration in the context of specific scientific applications.

In addition, enhancements of the GSN may be intrinsically desirable. In particular, the exploration of geophysical platform concepts, modified station density design (e.g., the fixed NSN/GSN network accompanying USArray), and improved ocean environment coverage are all obvious candidates. Further, there is increasing scientific interest in ultra-long period signals, such as the Earth's spectrum of continuously excited modes and tides. For example, super conducting gravimeters have demonstrated superior response to existing GSN instrumentation for very long-period free oscillations, and inclusion of a subset of these gravimeters at very quiet sits in the GSN may prove very attractive in the future. The value of high fidelity recording throughout the tidal band is not self-evident, and community discussion of the role GSN should play in data collection at frequencies below the normal mode band (as for some ocean oscillations) should be undertaken.

Overall Criteria for the GSN

The current characterization of optimal GSN instrumentation capabilities is shown in the attached Figure 1. A combination of sensors is utilized to realize this full response, and if advances in sensor design can achieve greater performance (while retaining linearity, resolution, bandwidth and dynamic range) over the full seismic spectrum it would be attractive to incorporate such instrumentation into the GSN in the future. Definition of scientific enterprises that 'push' the margins of the GSN capabilities, such as in the very long period range, the very high frequency range, or the low noise range is worthy of discussion, but the DGS does not have a clear sense of major enterprises that are inadequately serviced by the existing level of instrumentation. The DGS recommends that in the best possible situation (not limited by local noise conditions), the GSN design goal is to achieve at least the bandwidth and dynamic range indicated in this figure, as is presently achieved by the optimal GSN instrumentation. This should guide the development of instrumentation specifications for all future GSN instrumentation.

Design Goals

The following design goals are derived from the scientific mission of the GSN.

1. Maintain a global network of at least 140 uniformly spaced stations (adequate to resolve lateral heterogeneity to about angular order 8). GSN stations are to be coordinated with other Federation of Digital Broadband Seismic Network stations.
2. Provide high fidelity digital recordings of all teleseismic ground motions (adequate to resolve at or near ambient noise up to the largest teleseismic signals over the bandwidth from free oscillations (10^{-4} Hz) to teleseismic body waves (up to approximately 15 Hz)).
3. Bandwidth to record regional earthquake waves at all stations (up to about 15 Hz or higher, as warranted by regional wave propagation considerations).
4. Extend the bandwidth and/or the clip level at selected stations (i.e. those with high probability of nearby activity) to include local events and/or strong ground motions.
5. Provide real-time or near real-time data telemetry (to support event monitoring, provide data for scientific analysis in a timely manner, and improve maintenance response time).

6. Equipment must be robust, sustaining high up-time performance.
7. Data return must be high.
8. System environmental requirements should not constrain site selection.

Extensions for ocean bottom stations:

1. Hydrophones should be included.
2. Bandwidth for both seismic sensors and hydrophones extended to about 100 Hz. (The upper limit has not been definitively determined. The few observations that exist suggest that P and S waves may propagate in the oceanic lithosphere to distances of 4000 km with frequencies of up to 35 Hz. Coupled seismoacoustic T waves in the seafloor have been observed with frequencies of 80 Hz at 2000 km distance. Local microearthquakes in the oceanic crust have frequency contents exceeding 80 Hz.)

Functional Specifications

The functional specifications are derived from the design goals by considering detailed limits of the general scientific goals. Note that at this stage, discussions of how well we can do are irrelevant. If the state-of-the-art isn't adequate, we need to improve it. It it's better than we need, we're paying for a capability we're not using. In general, it's worth making the instrumentation about an order of magnitude better than our ability to model the parameters being measured. Thus, if we hope to model amplitudes to 20%, the aggregate sources of amplitude error (gain stability, cross axis coupling, and cross talk) should be less than 2% and individual contributions should be less than that.

1. On-scale broadband recordings of earthquakes as large as $M_w = 9.5$ (equivalent to the 1960 Chile earthquake) at 30 degrees. On-scale low-gain recordings of all earthquakes at 1 sample/sec.
2. Noise below ambient earth noise.
3. Bandwidth spanning all solid earth free oscillations and regional body waves (up to 15 Hz or higher as regional wave propagation considerations dictate).
4. Linearity sufficient to record signals near ambient noise in the presence of signals near clipping at well separated frequencies.
5. Response known to 1% across the bandwidth (adequate for amplitude modeling which at best is good to about 20%).
6. Sensor cross axis coupling less than about 1% (adequate for amplitude modeling).
7. DAS channel cross talk less than about 1% accounting for the difference in gains between adjacent channels (adequate for amplitude modeling).
8. Timing adequate to measure teleseismic body wave arrivals to 0.01 s.
9. Optional high frequency sensors must record the full bandwidth of small local events.
10. Optional low gain sensors must record the largest expected free field ground motion.
11. System should provide robust, low cost telemetry of all data in real-time.

12. DAS should be sufficiently modular in design as to permit variable channel configuration for differing numbers of sensors at GSN sites.
13. Equipment must be isolated from environmental problems including corrosion, water damage, dust, radio frequency interference, electrical surges, atmospheric pressure changes, and to some extent temperature changes. The equipment should be highly reliable.
14. On-site data storage must be provided for telemetered sites and removable non-volatile storage must be provided for non-telemetered sites.
15. Equipment should be operable in extreme temperatures, corrosive environments, small vaults, and sites without mains power.

Trade-offs

The task of translating functional specifications into a finished system inevitably leads to compromises. In particular, the availability and cost of instruments as well as the cost of site preparation are always factors at some level.

1. Given digital data and precise transfer functions, it is no longer necessary for stations to provide uniform responses. Given the wide range of site conditions and ambient noise characteristics encountered throughout the GSN, the level of uniformity of equipment becomes a trade-off between the cost of capitalization and the cost of maintenance. Requiring uniform equipment at all sites increases capital costs because less capable and hence less expensive equipment would be adequate for the noisier sites (perhaps the majority of sites). Heterogeneous equipment requires stocking more spares and more training for maintenance personnel. Experience indicates that if the increase in capital costs is small for homogeneous equipment, the reduction in out-year costs and improved network stability is worthwhile. On the other hand, if the increase in capital cost is large, it may be that the cost of allowing some heterogeneity is offset by the lower cost of amortization. Customizing sensors to individual sites would require rather extensive site noise survey, and would add time to site deployment so it may be useful to define threshholds for different system configurations.
2. Providing the horizontal performance of the best broadband borehole sensors while retaining the vertical performance of the best surface mounted broadband sensors is a complex tradeoff. Boreholes and borehole sensors are expensive to procure, install, and maintain. However, tilt compensation for surface mounted sensors, while intriguing, has yet to be adequately developed. Ultimately, this trade-off will depend on the characteristics of available sensors and the development of compensation technologies.
3. Lower power systems are desirable because they make sites without mains power more accessible and reduce maintenance issues at all sites. However, lower power designs may compromise system performance and mixing high and low power equipment makes the network more heterogeneous.
4. Because long distance telemetry equipment (e.g., satellite) sometimes requires significant power, separating sensors from telemetry systems by short haul communications links is attractive. However, such systems add significant complexity and reduce reliability. In

some locations, lower power long distance telemetry options would reduce complexity, but might also require unattended operation.

5. At many sites, display and processing facilities are provided for the local host. While it is recognized that an interested host increases station up-time, not all stations have hosts or even caretakers. Developing systems that can operate unattended is desirable. The reliability of an unattended system can be enhanced by eliminating unused sub-systems (e.g., the operator workstation), however, this increases network heterogeneity.
6. Telemetry with suitable on-site storage can be as reliable as non-volatile, removable storage in some cases. It is attractive to consider eliminating removable storage in such cases to avoid the cost of maintaining the recording equipment, changing the media, and processing the media at a DCC. However, there will always be situations where on-site recording will result in higher data recovery.
7. In separated systems, data is currently recorded on a hard drive when the telemetry link to the recording facility is down. This results in improved data recovery, but requires frequent visits to the digitizer and special processing at the operator workstation. In designing a new system, the cost effectiveness of greater flexibility versus complexity in such situations needs to be carefully considered.

Suggested Technical Specifications

The Instrumentation Committee will derive technical specifications from the functional specifications after considering available technology and the relevant trade-offs. However, some of the technical specifications follow so directly from the functional specifications that it seems worthwhile to list them here.

1. Clip level of 5.8 mm/s rms over the band 10^{-4} (or below) to 15 Hz, while resolving the USGS low-noise model.
2. Resolution of 3 dB below the NLNM is sufficient, but not necessary at all sites (or at any site at all frequencies).
3. Bandwidth of 10^{-4} (or below, depending on priority for tide and very low frequency earth motion resolution) to about 15 Hz (or higher as warranted by regional wave propagation considerations).
4. Digitizer linearity of ~140 dB. Seismometer linearity of 90 dB or greater.
5. Calibrations good to 1% and gain stability of 1% between calibrations.
6. Sensor sensitive axis orientation accurate to 0.6 degrees (minimum). Note, cross axis coupling goes as the sine of the angular error between components. Three mutually orthogonal components of motion should be recorded.
7. DAS channel cross talk –135 dB (maximum). This is difficult to guesstimate because the shaping of the signals is different between the high gain and the low gain sensors.
8. The DAS must provide a free running oscillator sufficiently stable to maintain a timing accuracy of 1 ms across a 3 hour interval without absolute time (~.1 ppm). Note that a typical crystal oscillator will do .1 ppm/degree C and .1 ppm/year at constant temperature. So we either need a really good oscillator or really good temperature stability.

9. Optional high frequency sensors must provide a bandwidth of 1 to 35 Hz (at least 100 Hz for ocean sites).
10. Optional low gain accelerometers must provide a clip level of 2 g over a bandwidth of just above 0 to 50 Hz (From an operational point of view, an instrument with flat acceleration response all the way to DC is very nice because it lends itself to easy on-site calibration check: turn it upside-down and you should have a 2g change on the vertical component; turn it 90 degrees and you should have 1 g on the corresponding horizontal component.) Optional low gain velocity sensors must record the largest expected free field ground motion and be able to detect surface waves from teleseismic events as small as M6.0.
11. All intra- and inter-site communications must be by means of IP protocols.
12. Equipment must meet relevant standards for packaging and radio frequency interference. It must have no appreciable sensitivity to atmospheric pressure and temperature changes (except for clock sensitivity which is specified elsewhere). The equipment should have a MTBF of 10,000 to 20,000 hours.
13. Telemetered data must be buffered for 3 days (minimum), ~48 MBytes. Non-volatile, removable storage should have a capacity of at least 1 year, ~12 Gbytes.
14. Equipment must be operable over a temperature range of -25 to +75 degrees C. All sensors, the DAS, and (at least local) telemetry should be designed for low power requirements.

We hope that this input updates the GSN design goals that will guide development of specifications for the next generation GSN systems. We encourage SCGSN to consider workshop activities that may extend the vision of GSN instrumentation beyond the current concept, as warranted by evolving scientific applications and priorities.

Figure 1 (adapted from Figure 2 of Peterson, USGS OFR 89471). Idealized recording range of the GSN system. The approximate recording ranges of the WWSSN LP and SP channels are shown for comparison. Earthquake spectra from sources at 30 degrees distance were provided by H. Kanamori, California Institute of Technology. The low Earth Noise model is from Jon Peterson [Observations and Modeling of Seismic Background Noise, USGS Open File Report 93-322, 1993]. The lowest and highest acceleration levels shown are for an ideal combination of Very Broad Band (STS-1), High Frequency Broad Band, Low Gain Seismometers, and 24-bit digitizers. While Low-Gain Seismometer response may be flat all the way to DC offset, the very large displacements implied for long period high acceleration motions are not achieved in normal Earth motions.