TRENDS IN NUCLEAR EXPLOSION MONITORING

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ABSTRACT

Nuclear explosion monitoring is as important today as it was at the dawn of the atomic age. Over the past several decades the scientific understanding and technological sophistication that underpin monitoring have advanced tremendously. We still face challenges, however, because the United States (U.S.) needs to monitor a growing range of events, from earthquakes to mining explosions that can cause confusion in detecting and identifying nuclear explosions.

Trends in nuclear test ban monitoring agreements reflect the challenge of global consensus building. We have seen the most pressing need change from monitoring large atmospheric tests to monitoring moratoria. Existing test ban agreements comprise bilateral and multilateral treaties in addition to declarations of moratoria.

As we grapple with real world realities, we benefit from science that has evolved and taken advantage of the data and processing capability provided by improved instrumentation and technology. Whereas once we modeled explosions as isotropic point sources, now we are developing ever more realistic distributed source models. Our understanding of radionuclide plume migration and infrasonic wave propagation was once based on ad hoc climate models, but now we have near-real-time weather models and realistic seasonal models of the upper atmosphere. As our science has matured, we have moved from investigating a broad range of topics with perhaps only an indirect monitoring connection to focused research with plans laid well in advance for integration into the monitoring system.

We have harvested the best of the revolution in communications. Data communication in the early 20th century consisted of manually prepared and typeset bulletins, or telexes for the most urgent transmissions. Today, we have real-time automated seismic alerts that soon will be transmitted over a global wireless broadband infrastructure. Data storage has moved from smoked paper or microfiche to random access memory (RAM) disks, sophisticated database systems, and disk arrays. Data processing has moved from slide rules and other types of analog computers, to mainframe computers, desktop workstations, and Linux clusters. The ways that we control digital data processing have evolved from coding in assembly language, to programming "high-level" languages such as Fortran, to integrating applications with platform independent web technology.

Trends in instrumentation are providing us with progressively more and better data, and at lower cost. Sensors have evolved from narrow band analog systems with limited dynamic range to high-fidelity, wideband, digital instruments with more than 120 decibels of dynamic range. Advancing technology has allowed us, in some cases, to replace custom-engineered components with commercial off-the-shelf products. Whereas observation stations were once manpower-demanding facilities, sensors now are progressively more autonomous, and the electrical power required by the stations can be provided by more compact facilities.

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

Introduction

The purpose of this paper is to state the obvious trends impacting nuclear explosion monitoring. While the overall mission of nuclear explosion monitoring has not changed since the beginning of the atomic age, what is being monitored has changed, as well as the technology used. Such an exposition of trends will hopefully provide insight and interesting context for this year's program review.

Monitoring Agreement Trends

From monitoring large atmospheric tests to monitoring moratoria – a monitoring agreement trend
The first test ban treaty, the Limited Test Ban Treaty (LTBT), initially signed by the U.S., the United Kingdom (U.K.) and the Soviet Union, and entered into force in 1963, was a multilateral treaty of profound impact. Prohibiting nuclear weapons tests in the atmosphere, in outer space, and under water was intended to achieve "an end to the contamination of man's environment by radioactive substances." Restricting nuclear tests to the underground environment also was instrumental in advancing seismology as a major field of science.

In anticipation of negotiations toward a comprehensive test ban treaty, the U.S. declared and entered a moratorium on any further nuclear testing in 1992, and other nuclear weapons states have made similar declarations. With the moratoria in effect, the drive to distinguish possible nuclear explosions from natural phenomena, and other explosions, represents a tremendous technical challenge.

From bilateral to multilateral test ban treaties – a monitoring agreement trend
The Threshold Test Ban Treaty (TTBT) is a bilateral treaty signed by the U.S. and the Soviet Union in 1974. The U.S and the Soviet Union agreed to verification provisions in 1990, and the treaty went into force that year. The TTBT limits weapon testing to specific designated test sites to assist verification and includes a protocol on technical data to be exchanged. The data to be exchanged – including rock density, water saturation, and depth of the water table – are useful in verifying test yields because the seismic signal produced by a given underground nuclear explosion varies with these factors at the test location. After an actual test has taken place, the geographic coordinates of the test location are to be furnished to the other party. This helps to place the test in the proper geological setting and therefore, in assessing the yield and thus determining that the 150 kT threshold, specified as the upper limit allowed, under the treaty, has not been exceeded.

The Comprehensive Nuclear-Test- Ban Treaty (CTBT) is a multilateral treaty that opened for signature in 1996 and has been signed by 172 member states as of August 2004 (http://www.ctbto.org/). The CTBT would ban all nuclear explosions for any purpose and in any environment. However, entry into force is unlikely in the foreseeable future because of opposition by several key countries, which are required to sign and ratify the treaty, but have stated that they will not sign. In the mean time, the Provisional Technical Secretariat is installing monitoring stations called for by the treaty, and data sharing amongst treaty signatories is ongoing. Even without the CTBT entering into force, in order to support the U.S. policy, there is a need to monitor for any nuclear testing occurring anywhere in the world.

Science Trends

From an isotropic point source to realistic source models – a science trend
Many measurements made at a sufficiently large distance from a source can be interpreted as if the source existed at a single point in space and time. Seismologists, for example, made great advances by treating earthquakes as point sources. These advances are locating earthquakes from the initial onset times of arrivals, discovering the existence and sizes of major parts of the earth, and measuring relative sizes of earthquakes from maximum amplitudes. As seismologists know, even the determination of seismic moment tensors, to learn the "shape" and orientation of the stresses related to a fault slip, represents an earthquake as a point in space and time.

Therefore, it is hardly surprising that the seismic study of underground explosions began with the assumption that an explosion might be quite well approximated as point sources, with a purely isotropic moment tensor to represent their force system. This representation provides a physical basis for understanding many of the methods for distinguishing explosions from earthquakes, including the predominance of P wave energy over S wave energy and the absence of a simple spatial pattern in the polarity and amplitude of P wave amplitudes.

For a variety of reasons, some of which we still only partly understand, seismic observations do not completely match predictions based on an isotropic point source model. Some of the likely causes, such as tectonic release and spall, are well known and might be represented by including nonisotropic (double-couple and CLVD) terms in a point source moment tensor. Scattering from topography and internal structure may play a role in generating S waves larger than we would otherwise suspect. Nevertheless, transverse S wave amplitudes are sometimes inexplicably large in the absence of other evidence for tectonic release. The Murphy-Mueller source model has come to be widely used, but also has its limitations. New models that better represent the frequency-dependence and source-size scaling of S wave amplitudes are being developed. It remains to be seen how best to evaluate these new models in the absence of further very large underground explosions.

Source models in other monitoring domains are also inadequate. In the ocean, the source of laterally propagating hydroacoustic waves from under-sea earthquakes is still not completely solved. In the atmosphere, further small explosions at different altitudes may be necessary to develop a good infrasonic source model.

From simple, homogeneous earth models to more realistic heterogeneous stochastic models – a science trend
Seismic monitoring of nuclear explosions began as a principally teleseismic discipline. At great range, seismic wave propagation paths dive deep into the interior of the earth, traveling predominantly through relatively simple, homogeneous portions of the planet. To predict travel times and other seismic wave characteristics, monitoring groups turned to the models of the earth devised from teleseismic observations – principally constructed as a series of homogeneous concentric spherical shells. This level of earth model sophistication sufficed for monitoring compliance with the LTBT and TTBT treaties.

In the last two decades, monitoring practice has been shifting from teleseismic to regional scales, especially with the advent of the CTBT. The propagation paths for the relevant seismic waves are in the relatively heterogeneous upper mantle and crust, leading to far more significant variations in waveforms, and waveform parameters such as phase arrival times and amplitudes. The simple models of the past are inadequate to predict regional observations. Higher resolution models estimated tomographically with the many millions of regional observations are one of the principal trends, and are needed to detect, locate and identify the very small events likely to be of current or future monitoring interest. Higher resolution models are one of the principal motivations and justifications for large-scale database development and the use of massively parallel computing resources (Linux clusters) alluded to earlier.

No matter how many observations are available, there will always be a limit to the resolution of geophysical models of the earth. Earth models will be uncertain at all scales, with the degree of uncertainty increasing at smaller and smaller scales. An alternative to the deterministic models of the past is the representation of the earth with stochastic geophysical models. These and the radically different tomographic algorithms required to develop them offer the possibility of properly accounting for model and observational uncertainties, incorporating prior constraints and using disparate data types simultaneously to constrain geophysical structure. Stochastic models offer an even greater justification for the use of strategic computing, now becoming widely available.

From linear extrapolation to kriging – a science trend
High-resolution seismic velocity models, real-time weather models, and empirical travel times, from events with ground truth locations, self-evidently have the potential to improve locations of seismic or infrasonic events. But in attempting to use these models, and empirical data, we are faced with the question of how to compute a new location using signals that may have propagated outside of the model or in the vicinity of several empirically calibrated paths. Simple-minded interpolation or extrapolation is not the best solution, since we already have background velocity models. Ground-based nuclear explosion monitoring (GNEM) has been in the forefront of implementing kriging in order to best take advantage of the empirical travel times, the best regional velocity models, and background models. Kriging will continue to be an important tool as we collect more ground truth locations and develop better regional models for more areas.

From maximum intensity to MDAC – a science trend
An frequently repeated remark, in historical seismology and seismic hazard analysis, is that the sizes of earthquakes that occurred before the 20th century are less certain because there were no seismograph stations to record them. The work of Charles Richter and other seismologists, in creating a means to compare the sizes of different earthquakes, is well known to all seismologists and is perhaps the seismological accomplishment that is most widely known among the general public. Defining different magnitude scales for earthquakes that were reliably observed

only as long-period surface waves, teleseismic body waves, or as a particular regional phase was another important success, even if it sometimes confused non-seismologists. A logarithmic magnitude scale has come to be so widely used and understood that magnitudes of historical earthquakes now are estimated retrospectively by analyzing intensity reports. Even physically based, absolute measures of earthquake size, such as seismic moment and radiated seismic energy, are often expressed using magnitude scales (M_W and M_E) that are designed to be as consistent as possible with established magnitudes.

Several of the most sophisticated ways of analyzing seismic amplitudes have been developed to support nuclear explosion monitoring. One of these is maximum likelihood magnitude, based on the absence of measurable amplitudes at some stations, or upper bound magnitude, if no appropriate amplitude can be measured at any station. Another is local and regional coda magnitude, which is important for small events recorded at just a few stations because it takes advantage of scattering so that each station can represent an average, of a significant portion, of the focal sphere. Use of magnitude-distance-amplitude-corrections (MDAC) replaces the classical use of teleseismic m_b:M_S ratios in explosion monitoring, instead basing event identification directly on amplitudes that have been corrected for event size or yield.

Coda magnitudes and MDAC analysis are each part of a broader trend to tie event location and identification closer to the waveform data. As we move forward, we are likely to place far less emphasis on making simple measurements from waveforms, computing source parameters from the measurements, and making inferences about the event from the source parameters. Instead, source parameters are likely to be computed directly from waveforms. Eventually, we may make inferences about events by comparing new waveforms with libraries of observed waveforms from previous events, and with synthetic waveforms computed from realistic source models and stochastic earth models.

From ad hoc climate models to near-real-time weather models – a science trend
Seismology, as a GNEM science, fundamentally requires numerical measurements of seismic phase travel times. The numerical knowledge of how a seismic phase travels though the interior of the earth provides the capability to detect, associate/locate, and identify events. An equivalent capability is necessary to fully realize the power of radionuclide signatures. Observation of certain radionuclides indicates with physical certainty that a nuclear weapon test has occurred; what is missing is a technically sound assertion of the source location of the radionuclides. Understanding the pathways from source to sensor, that a nuclear particle can traverse, will provide a location estimation capability. Initially, this capability may serve as confirmatory to a seismic location estimate. However, climate and weather model research is an active scientific field and it is fully expected that this research will be leveraged into GNEM capabilities. As the integration of regional weather models and real-time observations increases in maturity, detection of radionuclides could become a principal indicator that a nuclear test has occurred.

Because the signals for infrasound and radionuclide systems are often transmitted through the air, one of the main sources of errors in location for these techniques has been modeling the effects of weather. In the past, data from weather balloons and ground stations was collected by hand and would be used to retrace what the weather conditions were. The improvements in data acquisition systems and networking allows almost real-time data to be inserted into vastly improved numerical modeling codes to predict what the weather patterns were at the time of the event and the changes in them after the event. As satellite data becomes more available many of the models now also incorporate higher resolution, National Oceanic and Atmospheric Administration (NOAA) and Defense Meteorological Satellite Program (DMSP), data.

From ray theory to spectral elements – a science trend
The "infinite frequency" approximation of the ray theory has, like point source models, been a useful tool for many of the fundamental discoveries in seismology. The ray theory was used to compute accurate depths of boundaries between major parts of the earth, and is still used today in many tomographic inversions for three-dimensional earth structure. Ray theory is used to compute derivatives of travel times when locating seismic events and to compute "take-off" angles when determining fault plane solutions from P wave first motions, pP/P amplitude ratios, and S wave polarizations.

But interpreting information in seismograms beyond the initial motion of arrivals requires more complete solutions of the wave equation. Modal theory serves seismologists well in interpreting surface waves and free oscillations, and the WKBJ approximation is useful in many situations requiring synthetic seismograms computed from one-

dimensional earth models. In regional seismology, however, we require wave equation solutions for earth models that depart significantly from laterally homogeneous, isotropic and/or perfectly linearly elastic. This requirement leads us to undertake computationally intensive numerical modeling of propagation, even if only to develop simpler yet reliable ways of monitoring earthquake and explosion monitoring.

Among the computationally-intensive methods for solving the full wave equation, finite differences is appealing because of its conceptual simplicity, straightforward implementation, and proven utility in a wide range of engineering and scientific applications. Unfortunately, finite difference solutions to the wave equation introduce nonphysical artifacts that grow to be significant if used to simulate propagation to the distances that we require. This problem has been worked around in a variety of ingenious approaches to coupling finite difference calculations in small regions with more analytical methods for simulating propagation over typical distances to stations. We may be in the midst of yet another revolution in numerical simulation of propagation. The spectral element method eliminates the artifacts inherent in finite difference simulation of wave propagation and computers, which we can expect within approximately ten years, should be capable of spectral element calculations at the frequencies and distances that we require for almost all applications.

From research reports to integrated research products – a science trend
To successfully monitor for nuclear explosions, access to large quantities of detailed technical and contextual information is needed. The smaller, regional distance events, expected in the emerging monitoring environment, require a significant increase in the amount, type, and detail of information provided to both automated systems and human analysts. The interdependences among research products contributed to the operational user are a challenge that cannot be met without diverting limited resources away from operations. Therefore, it is necessary to integrate the research products prior to delivery to the user. The National Nuclear Security Administration (NNSA) Knowledge Base aims to provide this mass of information in a form that is ordered, consistent, easily accessed, well documented, reproducible, accurate, and relevant. The integration process is published (Gallegos, et al. 2003) along with a contributor's guide (Carr, 2003) so that less iteration is required and broad participation in the integration process is possible.

Technology Trends

From manual bulletins to real-time automated alerts – a technology trend
After inventing one of the first seismometers that could be readily replicated, transported, and installed in many remote locations, in the first decade of the 20th century, John Milne began to routinely compile locations and times of earthquakes around the world. Milne's data collection was facilitated by the existence of the British Empire, but in an era when printed reports of arrival times were manually typeset and transported by ship publication was, nevertheless, delayed until years after the earthquakes. Even with this delay, many of the epicenters were not computed from arrival times at all because of tedious manual computations that were abandoned if Milne or his assistant recognized that the pattern of arrival time differences was not significantly different than the pattern of another earthquake.

Milne's compilation evolved into the International Seismological Summary (ISS), published originally by the British Association for the Advancement of Science and later by the British Geological Survey. Like other summaries prepared during the first half of the 20th century, the ISS was published years after the earthquakes. Computations were greatly aided by the use of an analog computer that consisted of a large globe inscribed with the locations of important seismological observatories, and a brace with a slider and a pencil for tracing arcs around the stations and distance inferred from S minus P times. Thus, even epicenters far from major cities could be given to an accuracy of one-half or even one-quarter degree of longitude and latitude.

The ISS and several other global summaries were superseded by the more standardized and comprehensive "Bulletin of the International Seismological Centre". The ISC granted free use, at night, of new-fangled digital computers in the banks of Edinburgh. The ISC staff finally implemented routine use of the already venerable "Geiger's method" for iteratively solving the nonlinear equations, leading to epicenters with unreasonable precision and wildly optimistic uncertainties.

Since then, the U.S. National Earthquake Information Center (NEIC) has been among the agencies producing ever more timely global earthquake bulletins. Today NEIC produces its daily global report, "Quick Epicenter

Determinations", one week after the earthquakes. Global earthquake bulletins were produced within a day for a very short time, during the Group of Scientific Experts Technical Test 2 (GSETT-2), and continuously, since January 1, 1995 for GSETT-3 and later by the CTBTO International Data Centre (IDC). Completeness of the GSETT-3 and IDC bulletins depends partly on automatically generating an event list within one hour and then retrieving waveform segments from auxiliary stations near the preliminary event locations.

Automated alerts for significant earthquakes around the world are now available within an hour from several sources, including the NEIC and the European-Mediterranean Seismological Centre (EMSC). The NEIC and EMSC alerts both depend on real-time international exchange of seismic data, which is now widespread. Automation has facilitated distributing alerts minutes after moderate earthquakes within many regional seismic networks, and initiating emergency responses seconds after citywide dense networks of accelerometers detect dangerous seismic shaking. The U.S. Advanced National Seismic System is planned to provide a range of different types of information products for significant earthquakes in the U.S., beginning with location information within tens of seconds to minutes and shake maps within tens of minutes.

From telexes to global wireless broadband – a technology trend

For almost any type of earth observation, what can be learned from a network vastly exceeds the sum of what can be learned from each station in isolation. Thus, to a greater degree than laboratory sciences, earth sciences require prompt and effective data exchange. This requirement has engendered a history of cooperation among most earth scientists and prompted early and continued development of effective data exchange infrastructure.

The earliest international exchanges of seismic data involved shipping typeset reports of arrival picks to other seismological observatories. As transoceanic cables became more common, telex came to be widely used to exchange seismic data promptly. The 1979 edition of the Manual of Seismic Observatory Practice (Wilmore, 1979) describes a standardized format for telexing seismic arrival times and amplitudes. Telexes were expensive and charged by the character, so seismic telex format compromises completeness (e.g., the year of the arrivals is not required) in favor of brevity. While reports of arrivals times are no longer exchanged in telexes, this history echoes into our time in the form of e-mails formatted in seismic telex format.

Exchanging waveforms was difficult early in the 20th century, when data were recorded as ink on paper or as traces in smoked paper. Xerox machines made it easier to exchange waveforms, and dispatching Xeroxes of waveforms requested by professional seismologists became an important responsibility of seismic observatories. WWSSN waveforms were recorded on microfilm, which was reproduced and distributed to several archives. Even seismologists as young as the authors of this paper have spent time in WWSSN film archives extracting data for their early projects.

Digital recording revolutionized our ability to exchange data. More than a decade before the music industry realized the implications of all but perfect reproduction of digital data, seismologists eagerly established digital waveform centers to make waveforms widely available. Long before web users complained about slow downloads, seismologists saw the limitations of the Internet and resorted to exchanging computer tapes. In the 1990's AutoDRM servers came to be a common means of offering automated responses to e-mail data requests. Today, many stations and networks maintain web sites with routinely updated images of their most recent data as well as web browser-based interfaces for retrieving waveform segments.

Seismologists have been transmitting continuous waveforms, at least over short distances, using radio-frequency analog signals for 30 years. For the past 10 years, at stations with sufficient infrastructure, the Internet has been used to re-transmit 24-bit, 40 s.p.s. 3-component continuous waveforms around the world, and the Albuquerque Seismic Laboratory's Live Internet Seismic Server (LISS) has helped us to avoid collectively overwhelming links to individual stations. Nevertheless, transmitting data with absolute security and reliability still requires expensive installation of a dedicated system, as is being pursued by the Comprehensive Nuclear Test Ban Treaty Organization with its Global Communications Infrastructure. In the future, with the establishment of global wireless broadband communications, multicasting technology may eliminate the need for discipline-specific tools such as LISS, we look forward to more readily starting transmission of data from newly installed stations such as PASSCAL deployments, and we hope to transmit continuous authenticated digital waveforms in near-real-time from remote sites almost anywhere in the world, even without reliable and plentiful electrical power. Widespread deployment of the

available advances in communications technology bodes well for monitoring ease and reliability, and the technology is still advancing rapidly.

From microfiche to RAM disks – a technology trend
The early data generated by GNEM monitoring systems was very likely to be waveforms on paper rolls or film. This demanded a large group of well-trained analysts to evaluate the data by hand. Data was only collected when the roll of paper needed to be replaced and there was a much greater risk of failure from complex mechanical systems. The trend from analog data to digital data has permitted individual stations to not only store an almost unlimited amount of data, but has also increased reliability. Now a single analyst can download data from many of the different GNEM stations in real-time to allow one-person access to data from a large number of stations simultaneously. This allows a smaller number of analysts to bring together all the resources that are needed to solve a problem. The reduced cost of on-site storage has also provided a large buffer against data loss by allowing a longer period of time for network repairs to be made before any data will be lost.

From slide rules to Linux clusters – a technology trend
CPU power and memory size has historically followed Moore's Law – a doubling every 18 months. All of 25 years ago, the calculation time for the inverse of a 15 by 15 matrix was measured in tens of minutes. Today that same inverse can be calculated in fractions of a second. Dual processor workstations are readily available today, while 25 years ago the desktop computing environment was rare.

Present computing possibilities also include super-computers that are constructed by gluing together (with wires and software) desktop computers. Users on a super-computer "LAN" can use all available CPU cycles from idle desktop systems. The future of research computation will include "LAN" type super-computers with mostly open source operating systems (e.g. Linux) and abundant technical software that is constructed from open source code. Recently, for example, a Linux cluster version of the Community Climate System Model (CCSM) was released that achieves 80% of the performance of the CCSM on a supercomputer using processors that are 10 times less expensive (Renold, 2004).

The scientific research environment of the future may be limited only by the sophistication of software and the efficiency of the human-computer interface. The gap between analysis speed and human thought will be reduced dramatically as computer input evolves to include voice and finger-touch interaction.

From hand-coded assembly language to platform independent web technology – a technology trend
No one would disagree that the common language of science is mathematics. However as the computer became a research tool, other scientific languages emerged. Mathematics was translated to assembler code in the early days of the computer and through the evolution of the computer the research and business world has seen FORTRAN, BASIC, PASCAL, COBOL, C++ and many other languages, each with their claim as "the" language of the future. No less is true of operating systems. As with all modern scientific endeavors, GNEM is a mission filled with diverse computer platforms, operating systems and analysis codes. In the context of scientific computation, efficient communication of analysis results to a broader audience is becoming very important. This is driven to a great degree by the cross-disciplinary nature of GNEM. The broad communication expectations on the GNEM community will become sharpened in the future and will fully utilize the World Wide Web. Platform independent web tools will, in the future, provide the capability to seamlessly link operating systems and analysis codes. From a web tool, a scientist will be able to access and run a diverse suite of analysis codes and distribute the analysis to colleagues around the globe in a fraction of a second.

The earliest computer programmers using assembly language had to write sequences of instructions that explicitly copied values to input registers, executed multiplication instructions, and saved values from output registers. Subsequently, "high-level" languages, such as C and Fortran allowed, programmers to concentrate on aspects of an algorithm that are closely related to the original problem and to trust the compiler to create the machine-level instructions. This great advance allowed several generations of seismologists to write ever more complex programs, often with little help from professional programmers. These programs helped to advance our science tremendously, based on acceptable, if sometimes quirky, implementations of wide ranges of algorithms for locating earthquakes and computing synthetic seismograms, among many other tasks.

These user-written computer programs also created their own problems. Despite the use of high-level languages, programs written for one computer often would work on no other computer. Subroutines that performed reliably in one program produced nonsense when used in another program. When one program needed results from another, it sometimes seemed as if the only way to communicate the results was for a person to read the first results and manually type them into the other program. Modifying a program to produce a slightly different result, or to store the result in a different data system, seemed to take longer than it took to write the program originally. Effectively monitoring even the smallest nuclear explosions requires us to deal with pervasive clutter that includes earthquakes, mining explosions and bolides. Thus, monitoring requires an efficient interactive decision-support system that integrates data from different sensor types, uses a wide variety of background or historical information, and carries out routine processing reliably. The complex requirements for the complete system require several cross-disciplinary teams, who may use different types of computer hardware, programming languages, and data systems. Assembling their diverse components into a reliable and efficient system requires us to take advantage of the latest and best tools, including object-oriented programming and web technology for interprocess communication.

From file cabinets to databases with sophisticated search engines – a technology trend
Seismology often is at its best when comparing the differences between related seismic events (interpreting relative observations) and when extracting patterns from large numbers of observations. For these reasons the discipline is concerned more than most with record keeping, and assembling long-term, large-scale, permanent archives. In the early years records were kept in file cabinets and libraries of permanent paper catalogs of seismic events. These were difficult to search when seeking past events for comparison with new events and expensive to maintain. Catalogs devised by many individual observatories around the planet were inconsistent in format and difficult to collate and reconcile manually.

Electronic databases developed for the business sector were adapted to the seismological archival task in the 80's and 90's. These reduced the cost of maintaining archives and made possible efficient, large-scale searches for events and observations needed to carry out monitoring research and development. Database holdings on the scale of a few million events and many tens of millions of event parameters and waveforms are becoming the standard for cutting-edge research in this empirical discipline. Seismology is in a transition from ad hoc analysis of small collections of events to large-scale systematic searches for patterns.

Databases increasingly are the engines for integration of many scientific results. Automatic catalog reconciliation is now a reality for scores of formats. Databases are used to integrate and index waveform observations from thousands of stations in many formats into structured collections of uniform data amenable to sophisticated data mining approaches. Increasingly the construction of databases will be automated with autonomous agents scouring the Web for new catalog results and waveform data collected across the Internet in continuous streams. The convergence of communication technology, storage technology, sophisticated software tool development and database technology will put terabytes of organized information in the hands of researchers through largely automated processes.

Instrumentation Trends

From sensors as filters to high-fidelity instruments – an instrumentation trend
The expected seismic, hydroacoustic or infrasonic record of an event can be written as a convolution of a source function with several filters that represent the response of the earth and the seismic sensing and recording system. The objective of sensor engineering is to design a system that represents earth motion as truly as possible, thus minimizing information filtered out of the record by the instrumentation

Many seismometers from the very early 20th century produced signals for earth vibrations only in a narrow frequency band, and sometimes in a band that was not especially useful. Due to limited engineering, in addition, some early seismometers were under damped and consequently suffered resonances that might obscure all information other than the initial arrival time. Instruments of the World Wide Standardized Seismograph Network (WWSSN) were deliberately designed with non-overlapping passbands to exclude microseisms induced by atmospheric storms over ocean. Many instruments had frequency-dependent phase delays and a dynamic range that prevented them from recording either the smallest detectable signals or signals from the largest earthquakes.

Seismometers in the 21st century have overcome most of the previous limitations. The use of force-balance accelerometers (FBAs) has expanded the dynamic range of sensors to the point that very few applications cannot be met. Further development of the electronics in FBAs has expanded the passband so that now seismologists anticipate sensors that are effective from several tens of Hz to the fundamental periods of lunar and solar tides. Digital recording, with its wide dynamic range and its potential for subsequent digital filtering when necessary, has obviated the need to avoid sensing microseism frequencies. For all but the most demanding applications, moderately broadband sensors are affordable and can be readily installed and maintained. Thus, quite rapidly now, broadband stations are being much more widely deployed in both permanent and temporary networks.

From custom-engineering to COTS – an instrumentation trend
At the start of the ground-based nuclear explosion monitoring (GNEM) program, systems were typically constructed as one-of-a-kind custom designed systems that could accomplish the tasks, but were expensive and difficult to maintain or upgrade. As a general push in engineering to save money and to leverage previous design work, the GNEM program has moved in the direction of COTS equipment whenever possible. Using COTS equipment has resulted in teaming with industry to promote development of off-the-shelf equipment that meets or exceeds the requirements for many of the computational and data acquisition subsystems being used by the current monitoring technologies.

Radionuclide sensors have come to rely on commercial production of several components. For the Automated Radioxenon Sampler/Analyzer (ARSA), which has hundreds of valves in each unit, commercial production provides us with affordable very low temperature valves that are sufficiently small to avoid unacceptable product losses. The ARSA data acquisition system also depends on commercial products, in this case laboratory electronic building blocks known as Nuclear Instrumentation Method (NIM) modules. The electronic coincidence system for future Radionuclide Aerosol Sampler Analyzer (RASA) devices is also based on commercial electronics components.

From manpower-demanding monitoring stations to autonomous stations – an instrumentation trend
Teams of seismologists, engineers and technicians often operated the earliest seismic stations. Installing a seismometer sometimes resulted in the development of an entire Observatory Institute. Seismologists at the Observatory Institute were responsible for overseeing a variety of maintenance tasks, for interpreting the records of the seismometers, and for communicating their interpretations (but often not the original records) to the world. The Observatory Institute seismologists developed skills that were unique to their particular site that might enable them, for example, to recognize the seismogenic zone from which a signal originated from a mere glance at the data.

The early days of operating a global network for teleseismic monitoring of large nuclear explosions involved deploying large detachments of personnel. Even if the sensors themselves could operate unattended, the associated gear to transmit data from array elements and record it at a central site required regular maintenance and daily operational work. Detachment personnel again developed skills that were unique to their particular site.

Single-site stations and arrays now are expected to operate without maintenance for months at a time, recording data locally or transmitting it to an analysis center that might be located anywhere in the world. Near-ground radio transmission of data, especially from array elements where power may be very limited to a central recording or transmission-relay site, remains less reliable than other aspects of station operations, requiring a mobile maintenance staff for station repairs. Staff members at the analysis center develop network-wide skills that enable them to recognize correlations and inconsistencies among the data from different stations.

In the future, a common point of failure represented by an array's central site will be eliminated. Even within the power requirements at array elements, communication within arrays using global wireless communication technology may be used for preliminary processing. If bandwidth limitations delay transmission of continuous data, then data segments may be transmitted to a remote analysis center based on evaluation from the preliminary processing or demands from the analysis center.

From car batteries to fuel cells – an instrumentation trend
In a typical modern station, an external source of electrical power is required for the digitizer, the data logger, the clock, and (since we no longer use passive pendulum seismometers for many applications) the sensor. A permanent station must be connected to the electric power grid but still requires a backup battery for reliable operations, and the

battery unit is probably an Uninterruptible Power Supply (UPS) that executes a controlled shutdown if power is lost for so long that the battery runs low.

Temporary stations deployed far from any infrastructure will have the same types of electrical gear as a permanent station, and perhaps a transmitter as well. Thirty years ago, many field systems that integrated the digitizer, clock and data logger (such as the Sprengnether DR-100) could run on 12-volt DC power. This was a convenient standard, since the power requirements were substantial and 12-volt car batteries are readily available almost anywhere in the U.S.. A fully charged car battery could operate a DR-100 for about one week. A motel with a door to the outside was preferable to one with a door to an interior hallway, so that a battery could be left charging outside the door each night. Typical field gear included several pairs of jeans with holes where battery acid had spilled on them during previous deployments. Using a common "COTS" power source had a downside: battery theft was a significant cause for station down time, and sometimes necessitated moving a station.

Today, low-power active sensors, digitizers and recorders require approximately 1 Watt of power each for a 3-component system. A transmitter may require substantially more power, depending on the distance to the receiver and the transmission technology. Solar panel-charged batteries allow such systems to operate for months at a time, but the visibility of the solar panels increases risks to the station, including vandalism and theft. Further reduction in power consumption is being actively pursued, and within several years we might expect to require less than 1 Watt in total for all of the systems required at a station. Fuel cells with external fuel tanks (which could be buried) probably can replace solar panels in the near future. At current best efficiency, 1 liter of methanol drives a 1Watt system for 100 days. The Defense Advanced Research Projects Agency (DARPA) foresees a doubling of usable energy density by 2008, and a further re-doubling by 2018 to 2025 (Nowak, 2000).

Summary

As we look ahead, it is useful to see how far we have come in monitoring nuclear explosions. True global consensus on banning nuclear tests remains elusive in spite of significant agreement: from monitoring large atmospheric tests to monitoring moratoria; and from bilateral to multilateral test ban treaties.

Science understanding continues to grow: from an isotropic point source to realistic source models; from homogeneous earth models to heterogeneous stochastic models; from linear extrapolation to kriging; from maximum intensity to MDAC; from ad hoc climate models to near-real-time weather models; from ray theory to spectral elements; and from delivering research reports to integrating research products for operational usefulness prior to delivery.

Technology has dramatically changed how the monitoring data is recorded and analyzed: from manual bulletins to real-time automated alerts; from telexes to global wireless broadband; from microfiche to RAM disks; from slide rules to Linux clusters; and from hand-coded assembly language to platform independent web technology; and from file cabinets to databases.

Instrumentation improvements have provided for the collection of more and better data: from sensors as filters to high-fidelity instruments; from custom-engineering to COTS; from manpower-demanding monitoring stations to autonomous sensors; and from car batteries to fuel cells.

These trends suggest that a next generation monitoring system should integrate the best of the science, technology and instrumentation trends to further monitoring and global consensus on test bans. Such a system would clearly move toward more autonomous sensors, advanced event characterization and improved understanding of what is being monitored.

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