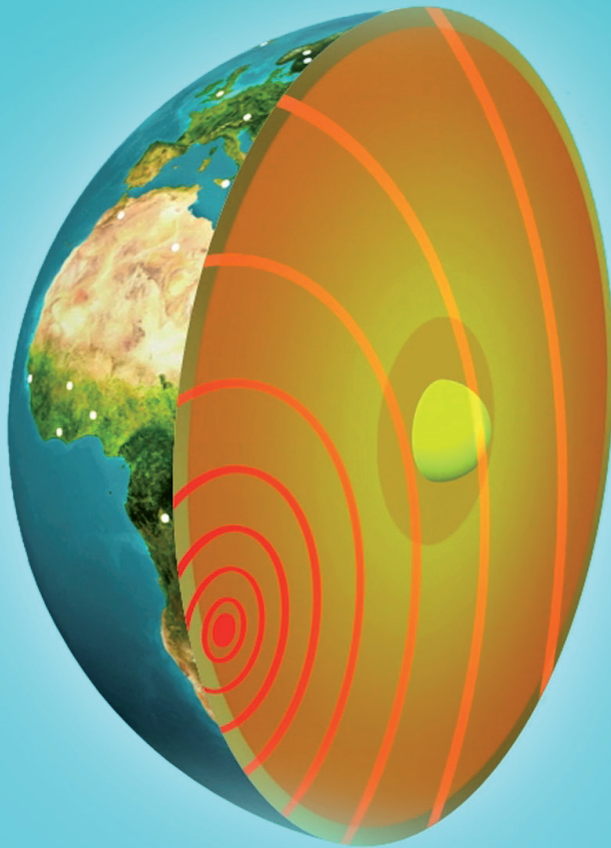


# Seismology

BY LYNN R. SYKES AND PAUL G. RICHARDS



# Seismology

BY LYNN R. SYKES AND PAUL G. RICHARDS

## FACT BOX

The Seismology topic area of the ISS project has involved a series of studies concentrating on understanding and increasing the capabilities of the global detection and location of seismic events. Scientists have also explored how seismic information can be used to characterize events more fully and increase understanding of the Earth's interior.

Seismology is a key technology for verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). By the time the CTBT enters into force, the seismic network will consist of 50 primary stations and 120 auxiliary stations that provide data for detecting, locating, identifying and determining the size of underground nuclear explosions, earthquakes and chemical explosions. Primary stations send data continuously in real time to the International Data Centre (IDC) in Vienna and are used to make the first detections and locations of events; segments of data from auxiliary stations are sent upon request.

The IDC now processes signals from around one hundred events per day, nearly all of which are earthquakes. This is demanding work that extends—for each event—from about an hour from the time of its initial automatic detection at different stations around the globe, to the production of the principal IDC product, the Reviewed Event Bulletin (REB), about one week later.

The key role of seismology was evident at the ISS Conference (ISS09) where 66 abstracts were submitted and 53 posters were displayed. Seismology was also well represented in the data mining and system performance posters. Posters and oral presentations covered the following themes:

- The detection and location capabilities of the seismic components of the International Monitoring System (IMS), both globally and regionally.
- Identification of seismic events as either explosions or earthquakes.
- Comparisons with the capabilities of national and other international agencies.
- Synergies with other IMS technologies such as hydroacoustics and infrasound.
- Seismic signal detection.
- The uses of seismic information for hazard and disaster assessments.
- Studies of Earth structure and deformation.

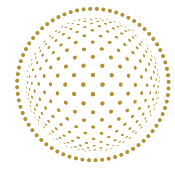
It is noteworthy that the ISS09 attracted representation of leading organizations engaged in seismic research and earthquake monitoring. This included the vice-president and secretary-general of the International Union of Geodesy and Geophysics; the president and secretary-general of the International Association of Seismology and Physics of the Earth's Interior; the director of the International Seismological Centre; the president and director of planning of the International Research Institutions for Seismology (IRIS) Consortium; and participation of leading seismologists from India and China as well as from Africa, Europe, Australasia, and the Americas.

## DETECTION AND LOCATION CAPABILITIES

About 70 percent of the IMS seismic stations are currently sending data to the IDC (Coyne et al., SEISMO-10/J; Kväerna and Ringdal, SEISMO-15/J). Early goals for seismic detection capability of the IMS primary stations were about magnitude (mb) 4.0 and 1 kiloton (kt) for tamped (well coupled) explosions.

One of the hardest tasks in seismic monitoring, which the IDC is required to perform quickly and on a global scale, entails a series of steps to associate the correct signal detections at different stations and arrays with a particular seismic event—when their multiple signals can be interlaced at each station. There are substantial infrastructures and assets worldwide that contribute successfully to this work and they continue to improve because of needs to understand and mitigate earthquake hazard. These assets are triggered in part by the IDC's work.

A 2002 report by the U.S. National Academy of Sciences predicted that if all IMS stations were built and operated to specifications, then in the absence of evasive testing: "Underground explosions can be reliably detected and can be identified as explosions, using IMS data, down to a yield of 0.1 kt (100 tons) in hard rock if conducted in Europe, Asia, North Africa, and North America," which the report associated with



magnitude 3.5 to 3.0 or lower. In some locations of interest such as Novaya Zemlya in the Arctic Ocean, capability was expected to extend down to 0.01 kt (10 tons) or better.

Kværna and Ringdal (SEISMO-15/J) report on the actual operating experience of the IMS over several years, and their figure (below)\* indicates that the detection capability for the year 2007 with existing stations is mb 3.4 or better for the four areas mentioned above. It could be improved by 0.1 to 0.2 mb units for Asia and Africa if all primary stations operated. The failure of those remaining stations to contribute data to the IMS results largely from political rather than technical or logistic problems. Seismic capabilities in the southern oceans are slightly poorer but hydroacoustic stations compensate for this by

providing better coverage. New IMS and other digital stations in Niger, the Persian Gulf and Afghanistan also improve detection capabilities. In summary the observed detection capabilities of the IMS today are considerably better than envisioned when the CTBT was opened for signature in 1996.

The detection capability mentioned above is not a single station capability but rather concerns detection at enough stations to provide a location estimate. The capability of individual stations is of interest, and those with the best record of detecting small events worldwide are in shield regions of Australia, Niger, North America, Kazakhstan, and South Africa (Coyne et al., SEISMO -10/J; Kværna and Ringdal, SEISMO-15/J; Estabrook et al., SEISMO-64/K).

\* Dahlman, O., S. Mykkeltveit and H. Haak (2009). Nuclear Test Ban – Converting Political Visions to Reality, Springer, ISBN 978-1-4020-6883-6

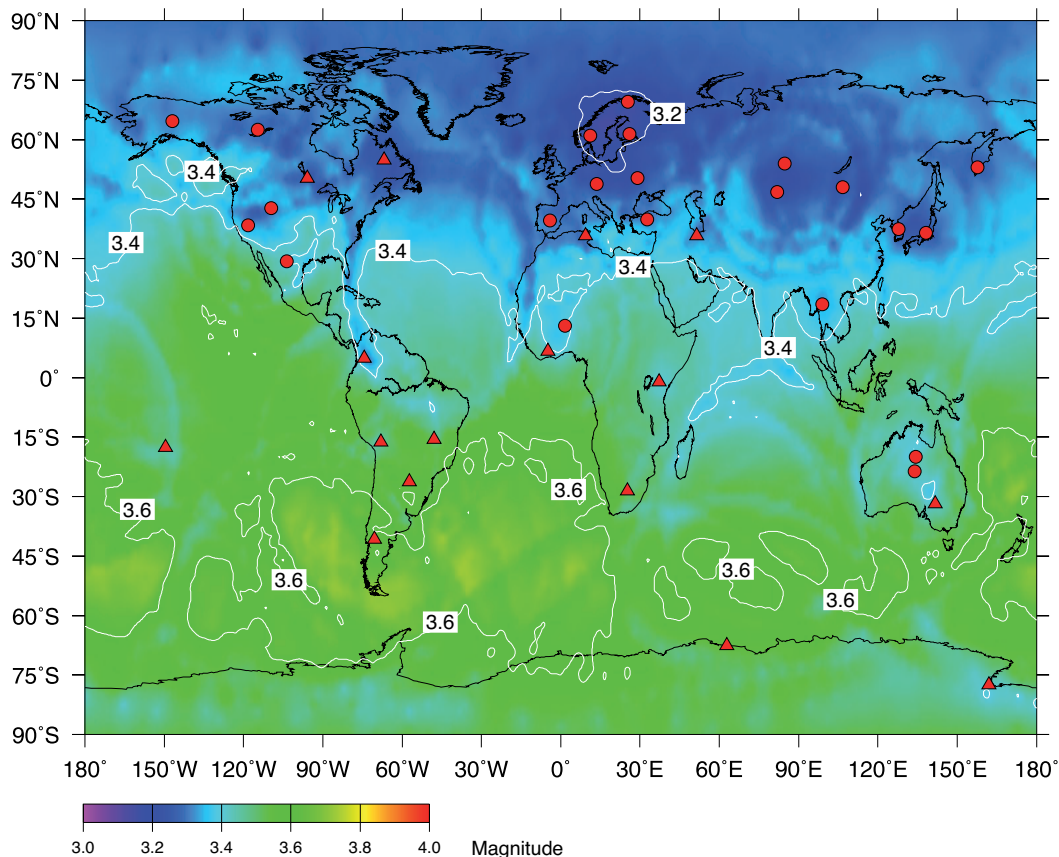


Figure 1 showing the detection capability of the IMS primary network in late 2007, with 38 stations sending data to the IDC. The capability is represented by the magnitude of the smallest seismic event that would be detected with a 90 percent probability at three or more stations (that is, enough stations to enable a location estimate). Completion of this network (50 stations) would reduce these magnitudes by about 0.1 or 0.2 units for Asia, much of Africa, and the Indian Ocean (Kværna and Ringdal, SEISMO-15/J).

Several ISS posters evaluated the location capability of the IMS and the IDC, either by comparison to locations determined from other networks, including local networks (Kebede and Koch, SEISMO-06/I; Giuntini et al., SEISMO-07/I), or to “ground truth” location of events subjected to special studies (Bergkvist and Johansson, SEISMO-02/I; Bergman and Engdahl, SEISMO-03/I). Location can be carried out more effectively with data from IMS stations once calibration of these stations is performed to high standards. Although the location uncertainty of events listed in the REB appears typically less than 20 km in certain studies (e.g. by comparison with locally determined locations for events in Italy), other rigorous studies indicate that the uncertainty can often be more than 20 km. This is not surprising, given that for key regional waves (notably Pn), travel times at a given distance can have values ranging over more than  $\pm 5$  percent which translates to  $\pm 50$  km over a path length of 1000 km. There is room for improvement in the quality of REB event locations, and the necessary progress can come from studies to obtain appropriate travel-time calibration as a function of distance and azimuth for regional waves observed at each IMS station.

### IDENTIFICATION CAPABILITIES

The identification of nuclear explosions and problem seismic events is reserved for CTBT Member States. Nonetheless, the IDC is permitted to use several screening criteria to identify events that are earthquakes or chemical explosions. These include events in the deep oceans and deep earthquakes. Sykes and Nettles (SEISMO-26/I) and Kim et al. (SEISMO-27/I) studied the discrimination of seismic events from 2000 to 2008 within 100 km of six nuclear test sites. About half occurred near Lop Nor in China. No events were recorded near the Indian and Novaya Zemlya, former Soviet Union, sites. All of the seismic events detected by the IMS near Lop Nor, the Nevada Test Site, USA, and the North Korean test site were identified using data from IMS and other stations that are available in real or near real time. Pan et al. (SEISMO-20/J, p.106, [http://www.ctbto.org/fileadmin/user\\_upload/ISS\\_2009/ISS09\\_Book\\_of\\_Abstracts.pdf](http://www.ctbto.org/fileadmin/user_upload/ISS_2009/ISS09_Book_of_Abstracts.pdf)) showed that P/S spectral ratios effectively discriminated between earthquakes and explosions in a study of more than 1000 earthquakes and 78 explosions in northwest China. Furthermore they showed

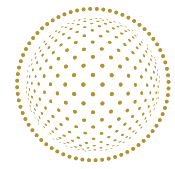
that such a discriminant that worked well for medium and large events also performed well for low magnitude events (even down to around magnitude 2).

The ratio of high-frequency P to Lg waves at regional distances provides discrimination of earthquakes and explosions down to the smallest located events. Hence, a common conclusion that identification is about 0.5 mb units worse than detection is not correct when regional data are available. The two are nearly identical when adequate and calibrated regional data are available. The high-frequency technique remains to be applied to Pakistani test sites where other discriminants work for  $mb > 4.1$ . More work is needed to apply the method to areas far removed from past nuclear explosions.

Centroid moment tensor (CMT) focal mechanism solutions can identify seismic events as earthquakes or explosions and provide an estimate of earthquake depth. They can be used with seismic waves with periods of 30 to 100 seconds where earth noise is often lower than that for the older Ms-mb method. The CMT technique, which has been used for 25 years, is routinely applied to events worldwide for  $mb > 5.2$ . Sykes and Nettles (SEISMO-26/I) and Hellweg et al. (SEISMO-21/I) presented CMT solutions for events as small as  $mb$  3.5 using data from regional stations. Materni et al. (SEISMO-22/I) applied a variety of discriminants for five test sites.

Determining that an event’s depth is greater than 10 km with high confidence identifies it as an earthquake. The depths of most seismic events near the Chinese and Pakistani test sites are greater than 10 km (Sykes and Nettles). Better depth determination using the seismic waves pP, sP, Lg and Rg (e.g. Husebye et al., SEISMO-14/I) is an active area of research. Ford et al. (SEISMO-23/I) studied the numbers of aftershocks of underground explosions, which generally are not as large or as numerous as those of earthquakes. Clear downward (dilatational) first motions of P waves (also a discriminant), a technique that was found to be largely inapplicable 50 years ago for discrimination, can be observed today for some seismic events given the greater global distribution of stations and use of broadband sensors.

Observing clear dilatations, consistent depth phases and aftershocks and obtaining CMT solutions should be pursued more widely so as to increase the percentages of seismic events that can be identified as earthquakes. The award



for the best poster in Vienna (Carluccio et al., SP-12/C), which was in the section on system performance, seeks to improve the identification of seismic events within two hours of their occurrence. T phases detected by hydroacoustic stations help to screen out many seismic events in oceanic areas. Jepsen and Fisk (HYDRO-06/H) report that over 80 percent of seismic events reported by the REB as occurring in deep water that had an unblocked oceanic path to a hydroacoustic station were screened out as being consistent with natural sources, namely earthquakes. Much more work on event identification is probably occurring at national CTBT agencies using data from the IMS, other stations and various National Technical Means.

North Korea in May 2009 is still being studied. Several posters presented special analyses of its location, how well it could be identified, and estimates of its yield. Its REB magnitudes were somewhat unusual for an underground nuclear explosion (although it was not screened out), having moderately strong surface waves given the strength of its body waves (mb 4.5, Ms 3.6). But the event was unambiguously explosive on the basis of its high-frequency spectral ratios (see Figure 2) and estimates of its moment tensor (see Figure 3 on page 10).

**SEISMOLOGY'S ROLE IN DISASTER ASSESSMENT, MITIGATION AND RESEARCH**

**ANALYSES OF SPECIAL EVENTS**

In general, the evaluation of monitoring capabilities emphasizes what can be achieved with routine procedures. But special events also attract non-routine procedures including the use of whatever data may be available, which for seismic methods opens up ever-growing opportunities in view of the many new and planned national and regional seismographic networks. The second nuclear explosion announced by

In addition to detecting nuclear explosions the CTBTO's global coverage can offer a wide range of applications in other fields. These include tsunami warning, quick assessment of damage in large earthquakes, improving estimates of hazards and risks for future earthquakes, and research on the Earth's structure and the physics of earthquakes. History shows that seismology moves to new levels of capability following large damaging earthquakes in developed and developing countries, and this trend can be expected to continue. The importance of earthquake monitoring in the

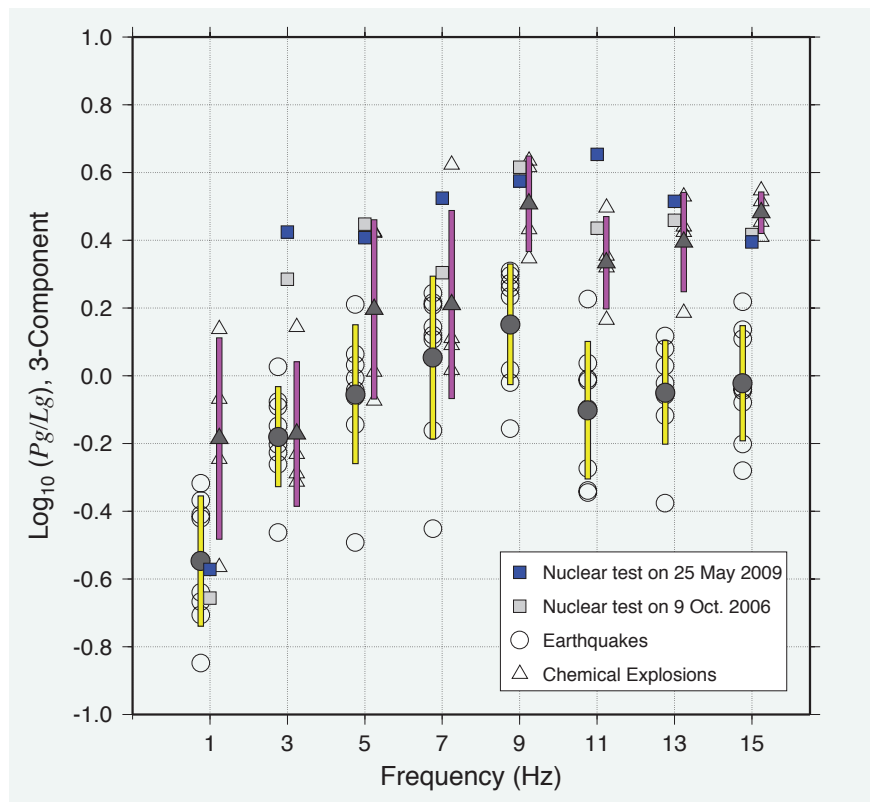
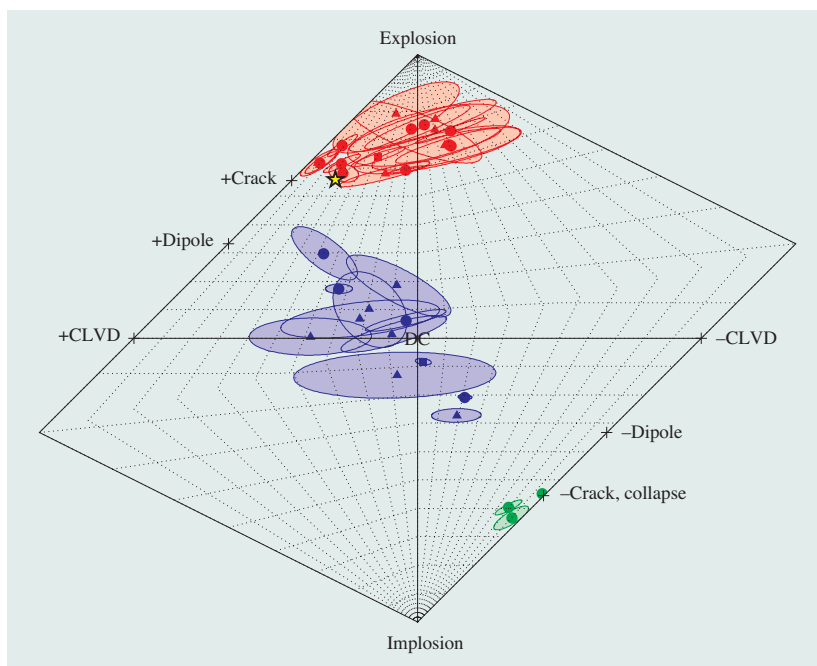


Figure 2 showing three-component Pg/Lg spectral ratios at eight discrete frequency points used in discrimination analysis are plotted for earthquakes, chemical explosions, and the North Korea test explosions of 2006 and 2009. Data are from the open station MDJ, about 370 km north of the test explosions. This station has also recorded earthquakes and chemical explosions in the general vicinity of the North Korea test site. A mean value at each discrete frequency point is plotted for earthquakes (solid circles) and explosions (solid triangles), with their coloured arms representing the scatter (standard deviation). The explosions have higher P/S ratios than the earthquakes, and the separation of the two populations is better achieved at high frequencies. The events of 9 October 2006 and 25 May 2009 (squares) fall in the explosion population. From Kim et al. (SEISMO-27/1).



**Figure 3**  
A plot characterizing the source type of the seismic event in North Korea on 25 May 2009, based on an estimate of its moment tensor (shown here as the yellow star). The estimate was obtained by modelling seismic waveforms in the period range 10 to 15 s as recorded by four regional stations, whose data are openly available via cooperative programs between station operators in South Korea and China, and data managers in the U.S. Geological Survey and the IRIS Consortium. Source types such as earthquakes (shown in blue), explosions (red), mining collapses (green), and various cracks, all have different moment tensors and fall into different locations in this figure, which uses ellipses to indicate uncertainty. The North Korean event of 25 May falls within the explosion population. From Hellweg et al. (SEISMO-21/I). It is noteworthy that this diagram was obtained by 27 May. Subsequent efforts to improve the estimate of the moment tensor of the 25 May event (using more stations and additional analysis to update the diagram) have confirmed its location in the explosion population (Ford et al, in press with Geophysical Research Letters, 2009).

context of seismic hazard mitigation is likely to move the entire field forward.

The U.S. Geological Survey now receives near real time seismic waveform data from about 1000 stations, and recently implemented continuous beam-forming (a signal processing technique used in sensor arrays to enhance the signals coming from a particular direction) of 21 of the IMS arrays to improve its automated event detections, and association of detections with specific events (Buland et al., SEISMO-33/K). Helffrich and Wookey (SEISMO-47/K) used sensitive arrays to detect exotic core phases of great scientific interest (such as S-waves, apparently split by anisotropy in the Earth's inner core). Seismology and infrasound assist aviation safety by detecting volcanic eruptions along major air routes. Ito et

al. (HYDRO-13/H) detected submarine volcanic activity in several parts of French Polynesia using broadband seismic arrays on the ocean floor. Seismic waves were detected from explosions and/or building collapses associated with several terrorist attacks including the World Trade Center in New York City in 2001. CTBTO Spectrum12, which appeared in April 2009, describes potential civil and scientific applications on page 28 in more detail. Key to many seismic studies is access to relevant data and the careful archiving of waveforms from long-running stations. As archives continue to grow, new seismic events that appear problematic can often be best resolved by comparing their signals with those of previously recorded events from the same region (Simpson and Willemann, SEISMO-56/K).



## BIOGRAPHICAL NOTE

**PAUL G. RICHARDS**

has been a professor at Columbia University since 1971, where he co-authored an advanced text on seismology in 1980 (updated, translated, and still in print).

He has researched methods of explosion and earthquake monitoring since the mid-1980s, has written about thirty professional papers on these subjects in the last ten years, and has spent two separate years in U.S. government service (on leave from academia) working on technical issues of nuclear explosion monitoring and test ban treaty negotiations.



## BIOGRAPHICAL NOTE

**LYNN R. SYKES**

is Higgins Professor Emeritus of Earth and Environmental Sciences at the Lamont-Doherty Earth Observatory of Columbia University in Palisades, New York.

He has authored or co-authored a number of scientific papers including 40 on the verification of nuclear testing and was part of the U.S. delegation that negotiated the Threshold Test Ban Treaty in 1974. He is also a member of the U.S. National Academy of Sciences and the American Academy of Arts and Sciences.