Assessment of Nuclear-Test Monitoring and Verification

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In this presentation, I first describe the assessment of capabilities for nuclear-test monitoring and verification as published in the unanimous Report, *The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States,* of the U.S. National Research Council Committee on Reviewing and Updating Technical Issues Related to the CTBT[1].

This Committee was chaired by Dr. Ellen Williams, Professor of Physics at the University of Maryland and dealt not only with the question of capabilities of the International Monitoring System of the Comprehensive Test Ban Treaty Organization (CTBTO) but also of U.S. national technical means supplemented by open networks of seismometers and other sensors.

The 2012 Report (as I shall refer to it) addressed not only the question of verification and monitoring, but also three additional topics—the degree to which the United States can maintain its nuclear weapons safe, secure, and reliable without nuclear tests; the degree to which other states could conduct nuclear explosive tests without detection; and the potential technical significance of successful clandestine tests compared with testing unrestricted by a CTBT. The subject of this meeting is limited to monitoring and verification of nuclear

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[1] Available at http://www.nap.edu/catalog.php?record_id=12849

explosive tests, so I address the other important elements of the 2012 Report in a summary that the Committee has used in other public presentations.

POLICY AND GLOBAL AFFAIRS

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Introduction to briefing on
Advances in Nuclear-test
Monitoring and Verification
September 24, 2012
Hart Senate Office Building
SH-902
Convened by AAAS

The Study Committee

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LINTON BROOKS, Independent Consultant
THEODORE W. BOWYER, Pacific Northwest National Laboratory
DONALD D. COBB, Los Alamos National Laboratory (retired)
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RICHARD MIES, Independent Consultant
C. BRUCE TARTER, Lawrence Livermore National Laboratory (emeritus)

Subcommittee on Seismology
LYNN R. SYKES, *Subcommittee Chair*, Columbia University
HANS HARTSE, Los Alamos National Laboratory
PAUL G. RICHARDS, Columbia University
GREGORY VAN DER VINK, Terrametrics, LLC
WILLIAM R. WALTER, Lawrence Livermore National Laboratory

Caveats and Limitations

- Technical issues only, not policy
- Current as of early 2011 (limited updating)
- Public version
- Finding and recommendations are in **bold**

The Issues

- Can the U.S. maintain the stockpile without nuclear-explosion testing?
- Can the U.S. detect, locate, and identify nuclear explosions?
- What does the U.S. need to do to sustain the stockpile and the U.S. and international monitoring systems?
- What about evasive testing?

Overview: Maintaining the Stockpile

Conclusion

Provided that sufficient resources and a national commitment to stockpile stewardship are in place, the committee judges that the United States has the technical capabilities to maintain a safe, secure and reliable stockpile of nuclear weapons into the foreseeable future without nuclear-explosion testing.

Overview: Maintaining the Stockpile II

At the time of the *2002 Report*, the Stockpile Stewardship Program (SSP) was in its early stages, and there was uncertainty about maintaining the stockpile in the absence of nuclear-explosion testing.

The technical capabilities for maintaining the U.S. stockpile absent nuclear-explosion testing are better now than anticipated by the *2002 Report*.

Future assessments of aging effects and other issues will require quantities and types of data that have not been provided by the surveillance program in recent years.

The committee judges that Life-Extension Programs (LEPs) have been, and continue to be, satisfactorily carried out to extend the lifetime of existing warheads without the need for nuclear-explosion tests. In addition to the original LEP approach of *refurbishment*, sufficient technical progress has been made since the *2002 Report* that *re-use* or *replacement* of nuclear components can be considered as options for improving safety and security of the warheads.

Overview: U.S. Nuclear-Explosion Testing?

Conclusions

As long as the U.S. sustains its technical competency, and actively engages its nuclear scientists and other expert analyst in monitoring, assessing, and projecting possible adversarial activities, it will retain effective protection against technical surprises. This conclusion holds whether or not the United States accepts the formal constraints of the CTBT.

A technical need for a return to nuclear-explosion testing would be most plausible if the U.S. determined that adversaries' nuclear activities required development of weapon types not previously tested. In such a situation, the U.S. could invoke the supreme national interest clause and withdrawal from the CTBT.

Overview: Monitoring

The United States has technical capabilities to monitor nuclear explosions in four environments:

* Underground	* Underwater
* Atmosphere	* Space

Conclusion

Technical capabilities have improved significantly in the past decade, although some operational capabilities are at risk. Seismology now provides much more sensitive detection, identification, and location of explosions.

90 percent confidence levels for IMS seismic detection are well below 1 (kt) worldwide for fully coupled explosions.

Factoring in regional monitoring and improved understanding of the backgrounds, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kt (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection by the IMS.

Seismic Monitoring

- Seismology is the most effective technology for monitoring underground nuclear-explosion testing. Seismic monitoring for nuclear explosions is complicated by the great variety of geologic media and the variety and number of earthquakes, chemical explosions, and other non-nuclear phenomena generating seismic signals every day.

- **Technical capabilities for seismic monitoring have improved substantially in the past decade, allowing much more sensitive detection, identification, and location of nuclear events. More work is needed to better quantify regional monitoring identification thresholds, particularly in regions where seismic waves are strongly attenuated.**

On-Site Inspection

- **A CTBTO on-site inspection (OSI) would have a high likelihood of detecting evidence of a nuclear explosion with yield greater than about 0.1 kilotons, provided that the event could be located with sufficient precision in advance and that the OSI was conducted without hindrance.**

Sustaining U.S. Technical Capabilities

- Sustaining two technical programs are essential
  - U.S. nuclear weapons program
  - U.S. monitoring and verification program
  - Primarily an issue of resources. Concerns:
  - **High quality workforce**
  - Science, engineering, and technology
  - Weapons production complex
  - Weapons surveillance
  - Radionuclide collection
  - Satellite detection
  - Monitoring research and development
  - Also concerned with NNSA management of labs

CTBT Safeguards

- Six CTBT safeguards were proposed in 1995. We did not attempt a revision but have two recommendations.
- **Without agile production capabilities, it is not possible to promptly correct deficiencies revealed by surveillance or to remanufacture components or weapons when required.**
  - **The U.S. CTBT safeguards should include the maintenance of adequate production and non-nuclear-explosion testing facilities.**
  - **There is currently no mechanism that would enable Congress to assess whether the U.S. CTBT safeguards were being fulfilled after entry into force.**
  - **Under the CTBT, the Administration should prepare an annual evaluation of the ongoing effectiveness of safeguards and formally transmit it to Congress.**

Evasive Nuclear-Explosion Testing I

- **An evader determined to avoid detection would test at levels the evader believes would have a low probability of detection.**
- **Mine masking is a less credible evasion scenario than it was at the time of the *2002 Report* because of improvements in monitoring capabilities.**
- **With the inclusion of regional monitoring, improved understanding of backgrounds, and proper calibration of stations, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kiloton (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection for IMS and open monitoring networks.**

Evasive Nuclear-Explosion Testing II

- **For IMS and open monitoring networks, methods of evasion based on decoupling and mine masking are credible only for device yields below a few kilotons worldwide and at most a few hundred tons at well-monitored locations.**

- **The States most capable of carrying out evasive nuclear-explosion testing successfully are Russia and China. Countries with less nuclear-explosion testing experience would face serious costs, practical difficulties in implementation, and uncertainties in how effectively a test could be concealed. In any case, such testing is unlikely to require the United States to return to nuclear-explosion testing.**

Hydronuclear Testing

- **Hydronuclear tests would be of limited value in maintaining the United States nuclear weapon stockpile in comparison with the advanced tools of the Stockpile Stewardship Program.**

- **Based on Russia's extensive history of hydronuclear testing, such tests could be of some benefit to Russia in maintaining or modernizing its nuclear stockpile. However, it is unlikely that hydronuclear tests would enable Russia to develop new strategic capabilities outside of its nuclear-explosion test experience.**

- **Given China's apparent lack of experience with hydronuclear testing, it is not clear how China might utilize such testing in its strategic modernization.**

Technical Advances

- **Russia and China are unlikely to be able to deploy new types of strategic nuclear weapons that fall outside of the design range of their nuclear-explosion test experience without several multi-kiloton tests to build confidence in their performance. Such multi-kiloton tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.**

- **Other States intent on acquiring and deploying modern, two-stage thermonuclear weapons would not be able to have confidence in their performance without multi-kiloton testing. Such tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.**

Final Thought

- **Threats could arise by clandestine nuclear weapons activity. For instance, a country with no testing experience and a modest industrial base could confidently build and deploy a single-stage, un-boosted nuclear weapon without any testing, if it had access to sufficient quantities of fissile material. These advances could be made whether or not the CTBT were in force. However, it is highly likely that the United States could counter these threats without returning to nuclear-explosion testing and thus could respond equally well whether or not the CTBT were in force.**

An integral part of the 2012 Report is that of the “Subcommittee on Seismology,” as noted. The unclassified version of the Report of this subgroup is published as Appendix D. The 2012 Report was written as a classified document, containing both national security and classified nuclear-weapons-related information, but with a view to having it appear almost entirely in unclassified format, which is what is published on the website of the National Academies Press. None of the conclusions of the classified report differs significantly from those in the public document. The classified report does have some quantitative data on national technical means and on U.S. nuclear weapons that could not be published in the open Report.

The IMS sensors were only beginning to be deployed in the year 2000, when most of the previous NRC Report was complete, although its publication was delayed by security clearance procedures until 2002. At the time of completion of the 2012 Report (in 2011), the four sensor networks of the IMS were almost fully deployed—seismic, hydroacoustic, infrasound, and radionuclide detection. Furthermore, as amply documented through publications and performance of the CTBTO Provisional Technical Secretariat, the system had proceeded from experimental to essentially full production, with training programs for analysts, satisfactory experience on communications and data storage and the like.

Visits by members of the NRC and of the Seismology Subcommittee received the full cooperation of the CTBTO which has demonstrated, in my judgment, impressive performance on a strict timeline for response to and detection of events that were candidates for nuclear explosive tests.

It is not a function of the International Data Center (IDC) or the CTBTO to categorize an event as a nuclear explosion, but only to provide date that would allow member states to draw this conclusion. Still, the IDC can and does "screen out" certain events as not explosive tests, for instance, by the focal depth of a seismic event.

In building the IMS, there was considerable attention paid to high detection probability of a single nuclear explosion test of one kiloton (1 kt) yield or more, anywhere on land, in the oceans, or in the atmosphere. The following contour maps show the assessed capability of the IMS as it was operating in recent years, corresponding to 90% probability of detection by three or more of the Primary Seismometer stations of the IMS—nowhere on Earth exceeding about 0.3 kt.

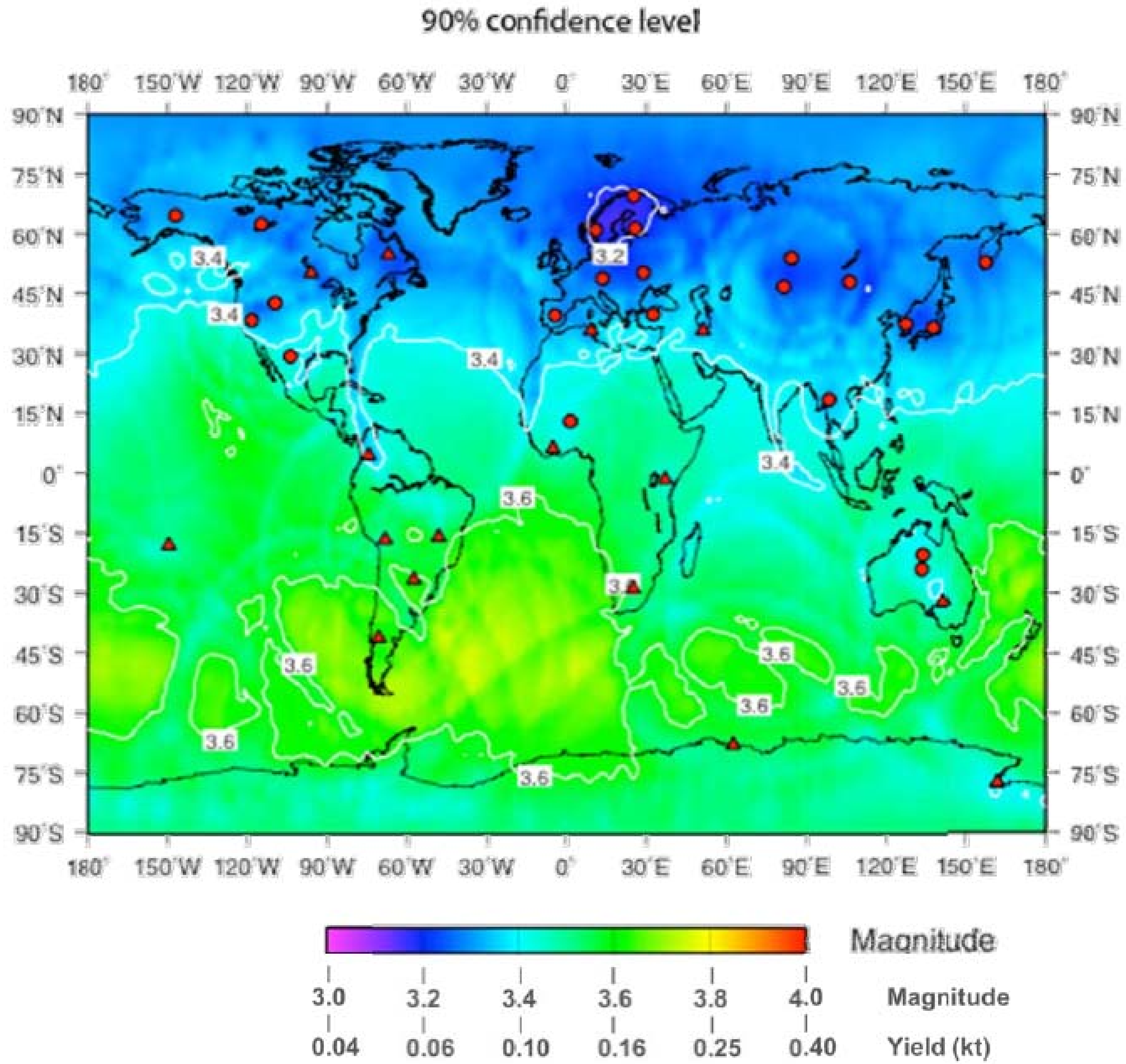

FIGURE 2-8: Detection Capability of the IMS Primary Seismic Network in late 2007, with 38 stations sending data to the IDC. Contours, indicate the magnitude of the smallest seismic event that would be detected with a 90 percent probability at three or more stations; that is, at enough stations to enable a location estimate. Red circles are seismic arrays, and triangles are

The 2012 Report Committee judged that a clandestine tester would not be satisfied with only a 10% probability of escaping detection by the IMS and judged that a more relevant detection threshold would be 10% probability of detection by three or more primary stations of the IMS seismic net. As seen from the following figure the corresponding contour maps have 10% detection probability for a yield approximately three times lower (0.5 seismic magnitude) than yields corresponding to 90% detection probability—nowhere exceeding about 0.1kt fully coupled explosive yield.

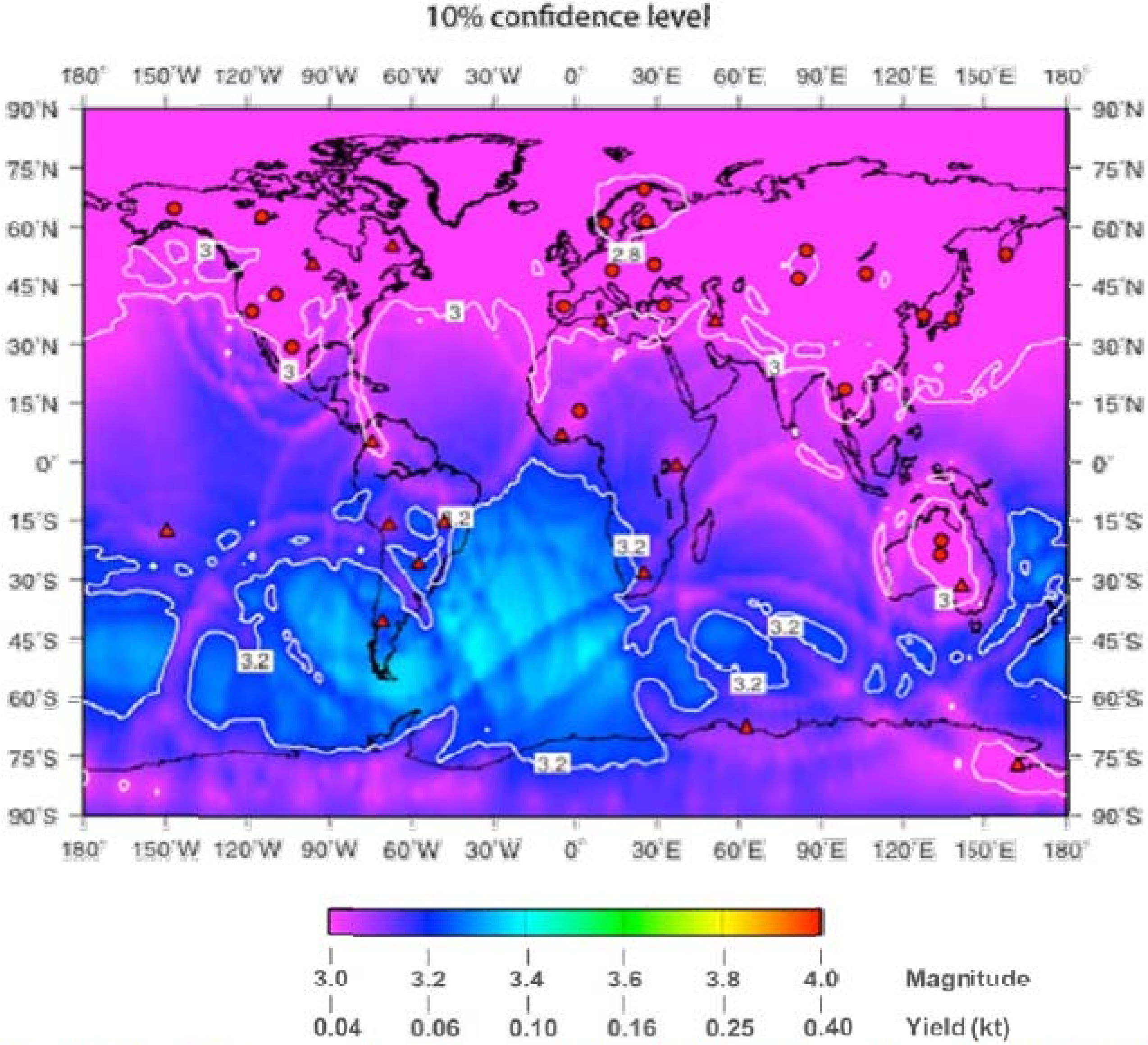

FIGURE 4-1: Map of 10 percent confidence detection levels (90 percent probability of avoiding detection) for the primary IMS Network (2007). The map represents detection capability of IMS primary seismic network, late 2007, with 38 stations sending data to the IDC. Contours indicate the magnitude of the smallest seismic event that would be detected with a 10 percent probability at three or more stations. Red circles are seismic arrays, and triangles are single seismic

Primary seismic arrays all provide data in real time to the IMS. Stations of comparable quality that provide digital data accessible on demand constitute the secondary stations, beyond which there are many seismometers operated by governments or universities that provide quality data also accessible via the Internet.

These seismic detection sites, numbering in the thousands, thus allow *regional* in additional to *teleseismic* detection, and at regional distances higher-frequency components of the seismic signal are available to provide enhanced discrimination between explosions and earthquakes.

The next panel of figures shows enhanced discrimination of the 2006 and 2009 North Korean nuclear explosive tests, in comparison with the many neighboring earthquakes, as illustrated in this figure from the report, that shows the utility of the metric “Pn/Lg” in the frequency band of seismic signals from 6-8 Hz.

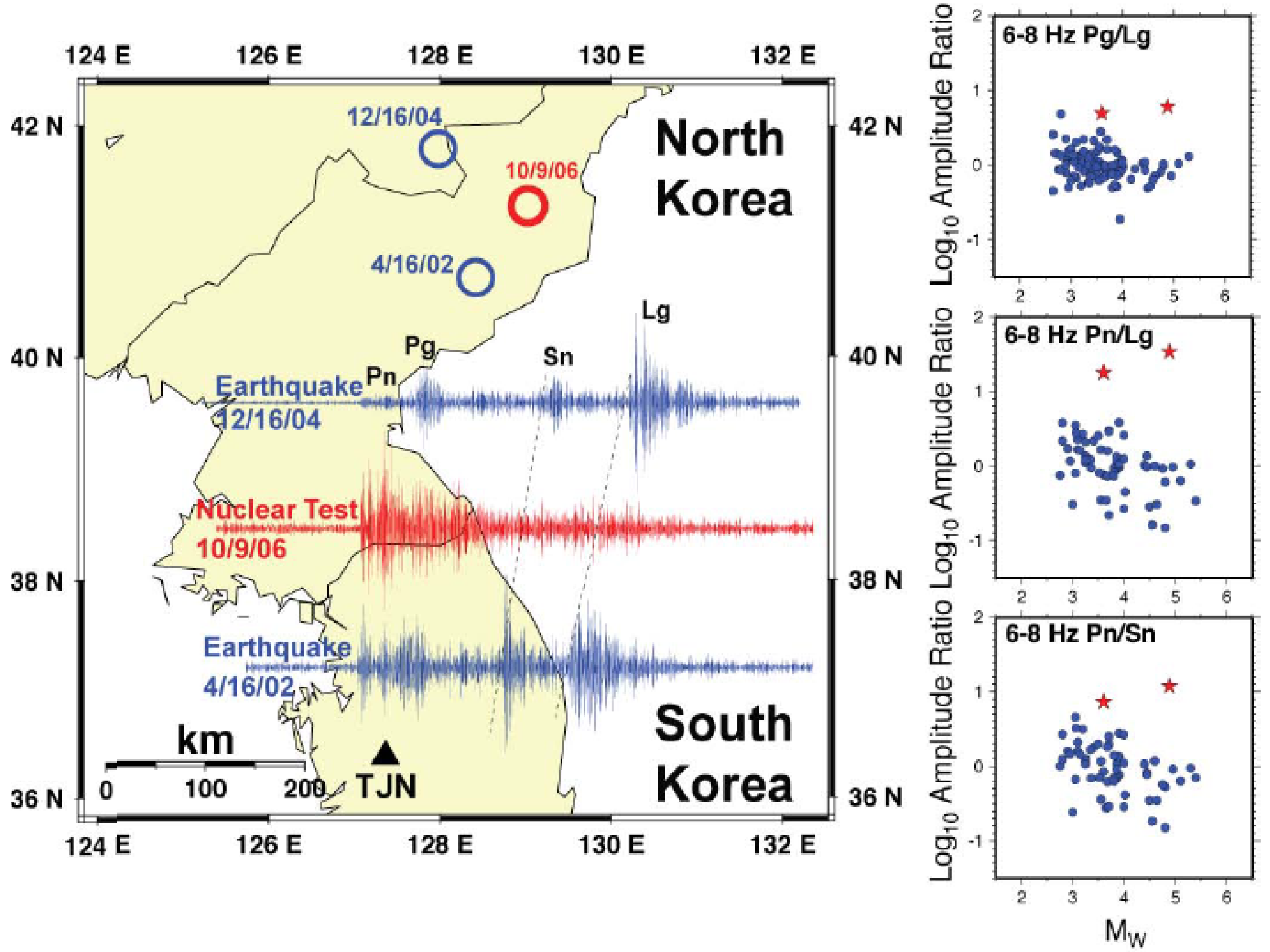

FIGURE D-10: Example showing how ratios of P-wave to S-wave amplitudes discriminate the 2006 and 2009 nuclear tests in North Korea (red seismogram represents data from the 2006 test, and stars on the right indicate 2006 and 2009 test data) from earthquakes in the region (blue seismograms and symbols). At distances of a few hundred kilometers the Earth separates P-waves into two groups, a mantle path (Pn) and crustal path (Pg). S-waves are similarly separated into Sn and Lg. As expected, the 2006 explosion shows stronger P-waves and weaker S-waves than do nearby earthquakes. When we measure these P/S amplitudes at high frequencies (e.g., 6-8 Hz here) and correct for path effects, we get the plots shown on the right (stations TJN and MDJ averaged), showing that the explosions stand out from the earthquakes. Seismologists can statistically combine such measures to achieve excellent explosion identification capability down to very low magnitude in this region. SOURCE: Adapted from Walter et al., 2007

The Report notes that supplementing the IMS data or using U.S. seismic arrays provides substantially better detection capability, although this cannot be quantified in the public report. Nevertheless, *regional* capability is far superior to reliance only on the Primary seismic sensors of the IMS, as shown in this graph of seismic improvement vs. year,

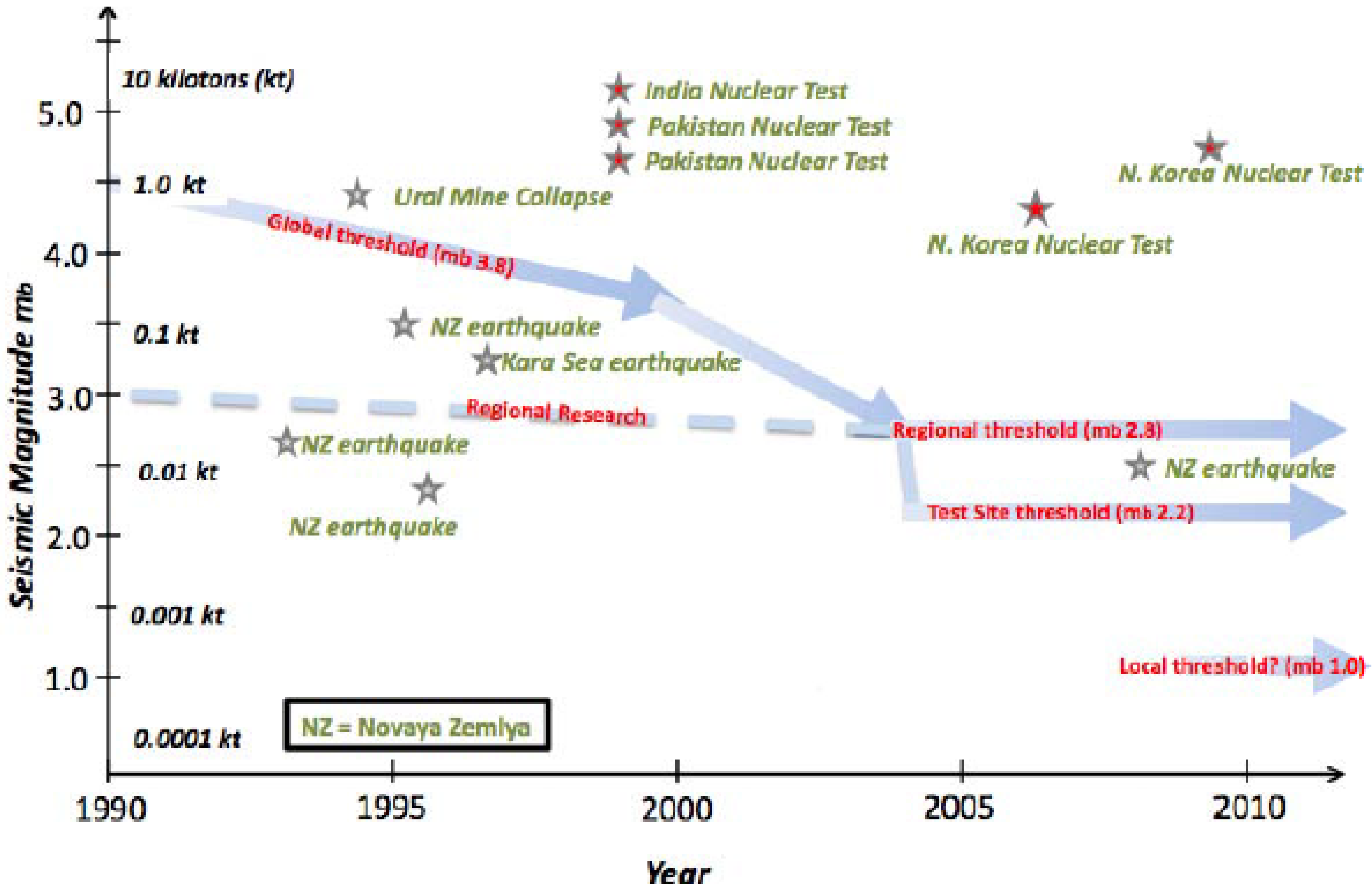

Figure D-1. Improvement in seismic monitoring over the last 20 years.

Of course, 75% of the surface of the Earth is covered by oceans, and there the *hydroacoustic* analog of seismic detection is far more sensitive, even though there are many fewer hydroacoustic monitors than there are seismic sensors in the IMS system. The Figure shows the performance of the hydroacoustic elements of the IMS.

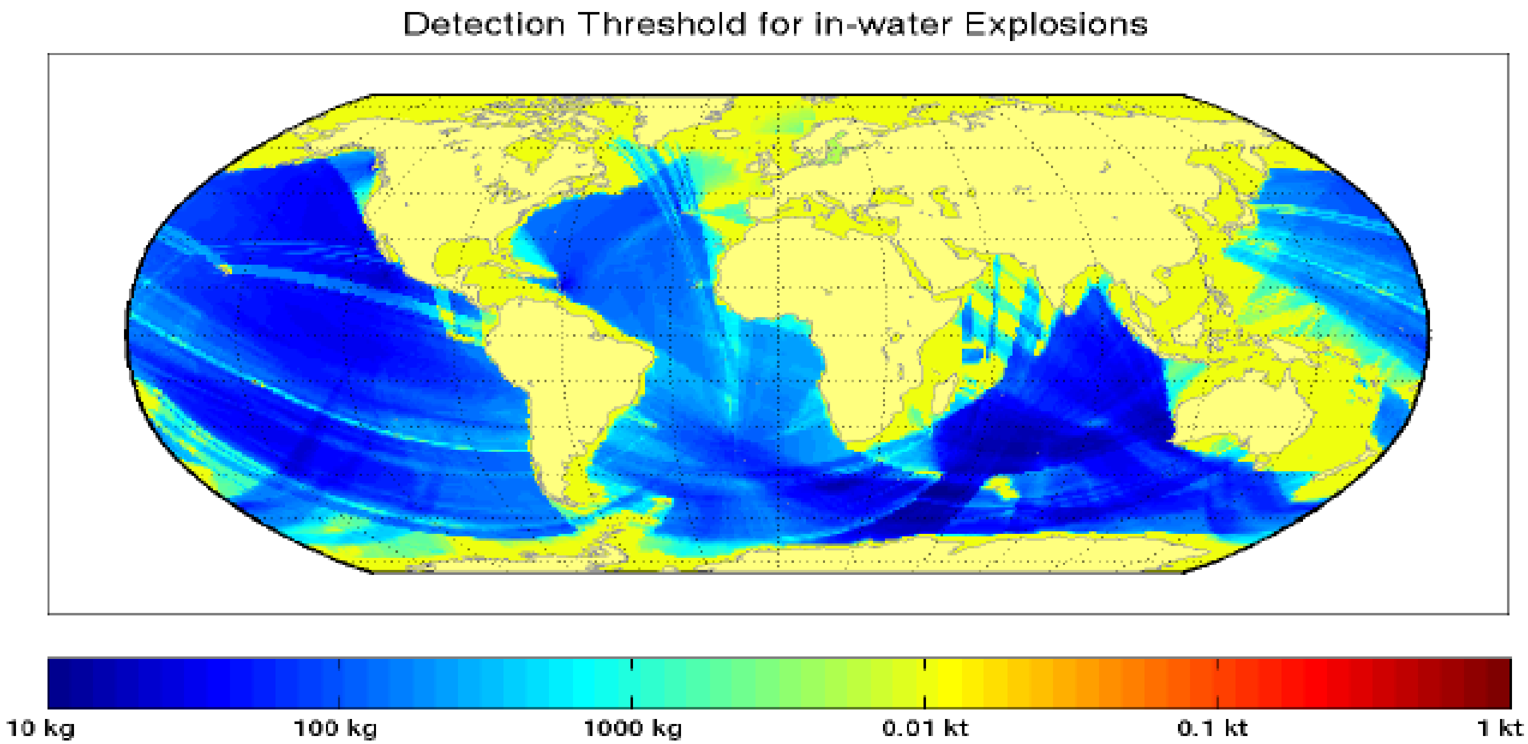

FIGURE 2-11: Map showing the IMS detection threshold in equivalent mass of TNT for in-water explosions detected on either the hydroacoustic or seismic IMS networks. Note that 1000 kg = 0.001 kt. Areas not covered by the hydroacoustic network—such as the Mediterranean Sea—are covered by the seismic network to a threshold of around 0.01 kt. SOURCE: CTBTO

Infrasound in the form of microbarographs has been used since the beginning of the nuclear age, and many surface explosions of high explosives for mining and other purposes are detected by the IMS network. Unlike the stable paths afforded to seismic waves, in which repeated small earthquakes from the same site can be overlaid, cycle-by-cycle in the wave form, the infrasound signal is substantially affected by temperature variations of the atmosphere, and especially by winds, which normally constitute a few percent of the velocity of sound in the atmosphere and correspond to comparable influences on delay time and location by time difference of arrival. Location by angle of arrival is even more affected by wind, a 4% (12 m/s) wind corresponds to the square root of that fraction (or about 0.2 radian, 11 degrees) of deviation under certain circumstances.

However, there has been substantial improvement in knowledge of the atmosphere as a function of time and position over the Earth, from both local and satellite measures, and that knowledge is now applied increasingly to the infrasound detections. Additional improvements are possible in the general process of converting “noise” into “signal,” by which extraneous events such as mining explosions are used to calibrate the air mass.

Vertical profiles of wind and temperature can result in anomalous detection sensitivity or insensitivity at certain stations, so that infrasound is largely thought of as confirmatory to seismic detection.

The final component is the IMS system, radionuclide detection, is demonstrated routinely by detection of emissions of radionuclides from activities in the nuclear fuel cycle, and, especially from the reactor failure at Fukushima Dai-ichi as the result of the Tohoku Earthquake and ensuing tsunami.

There is little doubt that an atmospheric explosion could readily be detected not only by the particulate radionuclides caught on filter papers at every radionuclide station of the IMS, but also by noble-gas detectors deployed at some fraction of the stations. These are, of course, supplemented by many such detection stations operated by individual governments and other entities throughout the world.

Of course, it is the winds that carry the radionuclides from the source to the detector, and satellite observations of the atmosphere at various levels (altitudes) provide a good indication when a sudden pulse of radiactivity at a given point and time would be detected (if at all) at various monitoring stations.

It is not just the presence of radionuclides that is detected, but also the nature and amount of the individual isotopes, so that if they come from a sudden burst of fission, there is a measurement from each station of the time of the event before detection.

Instead of the forward prediction of detection opportunities from an event at a given time, an actual detection of RN at a particular station and time poses the inverse problem of where the event might have been, even given the measured "age" of the radio nuclide sample. Clearly, major advances have been made in infrasound processing and in atmospheric modeling for RN distribution, but much more can be done.

Of course, it is not an easy matter to introduce new algorithms into a system that operates very well and on a strict timeline, but it is essential that the new algorithms be assessed and approved, and implemented on a trial basis, in order to continually improve the performance of the system.

Here is an example from the seismic domain, published in 2002, and cited in the 2012 Report. Here we see four Nordic seismometers looking in the direction of Novaya Zemlya (NZ) to detect any explosion of interest at the site. Each of the seismic arrays for a given assumed event time provides a trace as shown in the Figure. Given only a single array, there are many candidate signals, before one looks at the structure of the signal to see whether it has the typical P-emphasis of an explosion rather than the S-emphasis of an earthquake. And, of course, an event right at NZ would provide simultaneous signals on all four seismometers. One might be drawn to set a threshold of about magnitude 3.5 from the background "noise" of the individual seismometers, but, of course, this is not noise or even local noise, but the detection of actual earthquakes somewhere on the azimuth from the array to and through NZ. A better characterization of the detection threshold can be obtained by looking at those arrays for a given assumed event time that have the least signal, knowing that the seismic path is stable and not fluctuating as is the case of infrasound or sonar detection in the ocean. So the "smart array" sensitivity is about a full magnitude (factor 10) better than the high performance arrays considered individually or, in the usual way, by adding the signals in the arrays for an assumed event time.

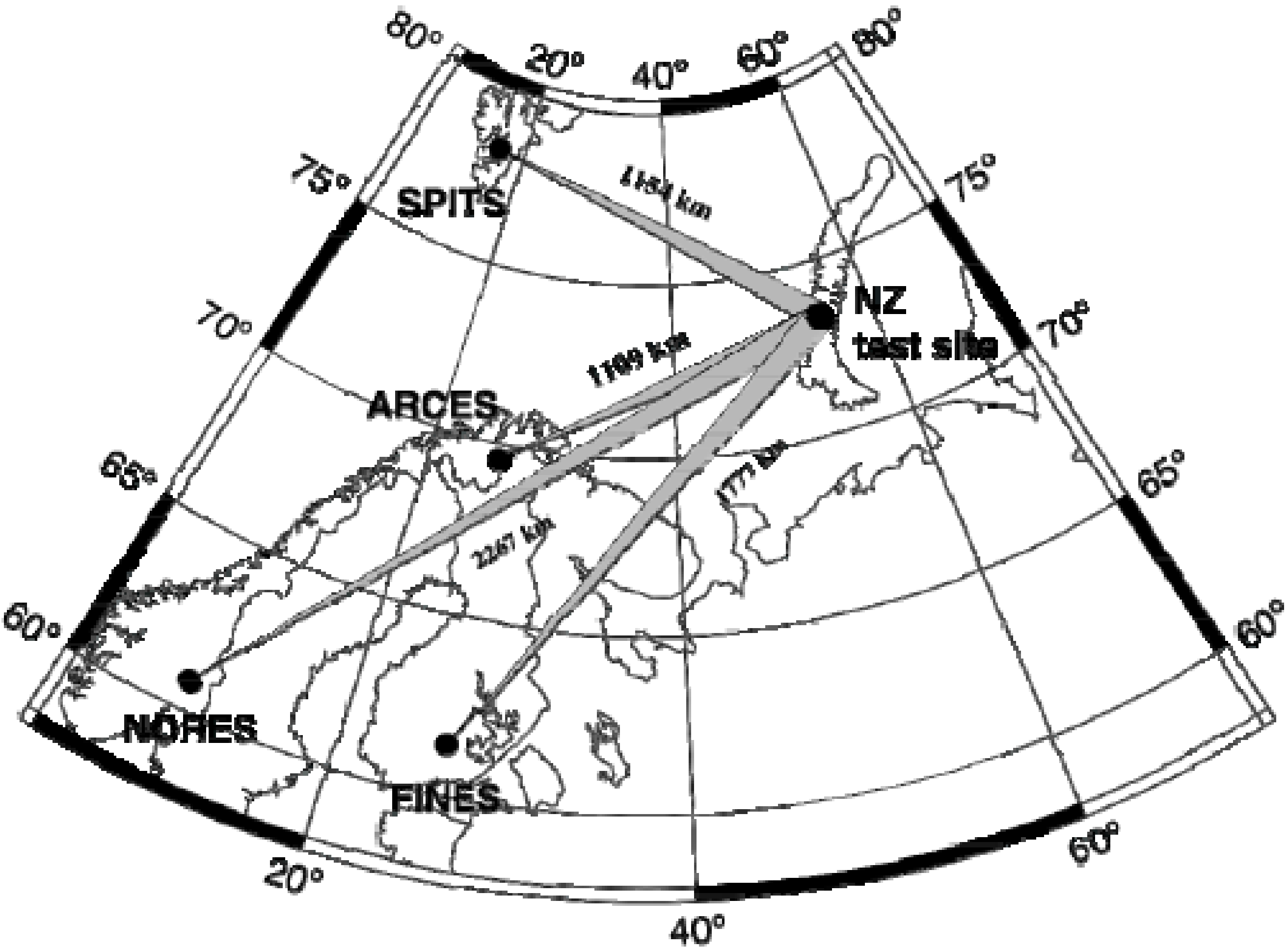

FIGURE D-3: Map of Novaya Zemlya and locations of four seismic arrays in Norway, Finland and Spitsbergen. SOURCE: Kværna et al., 2002

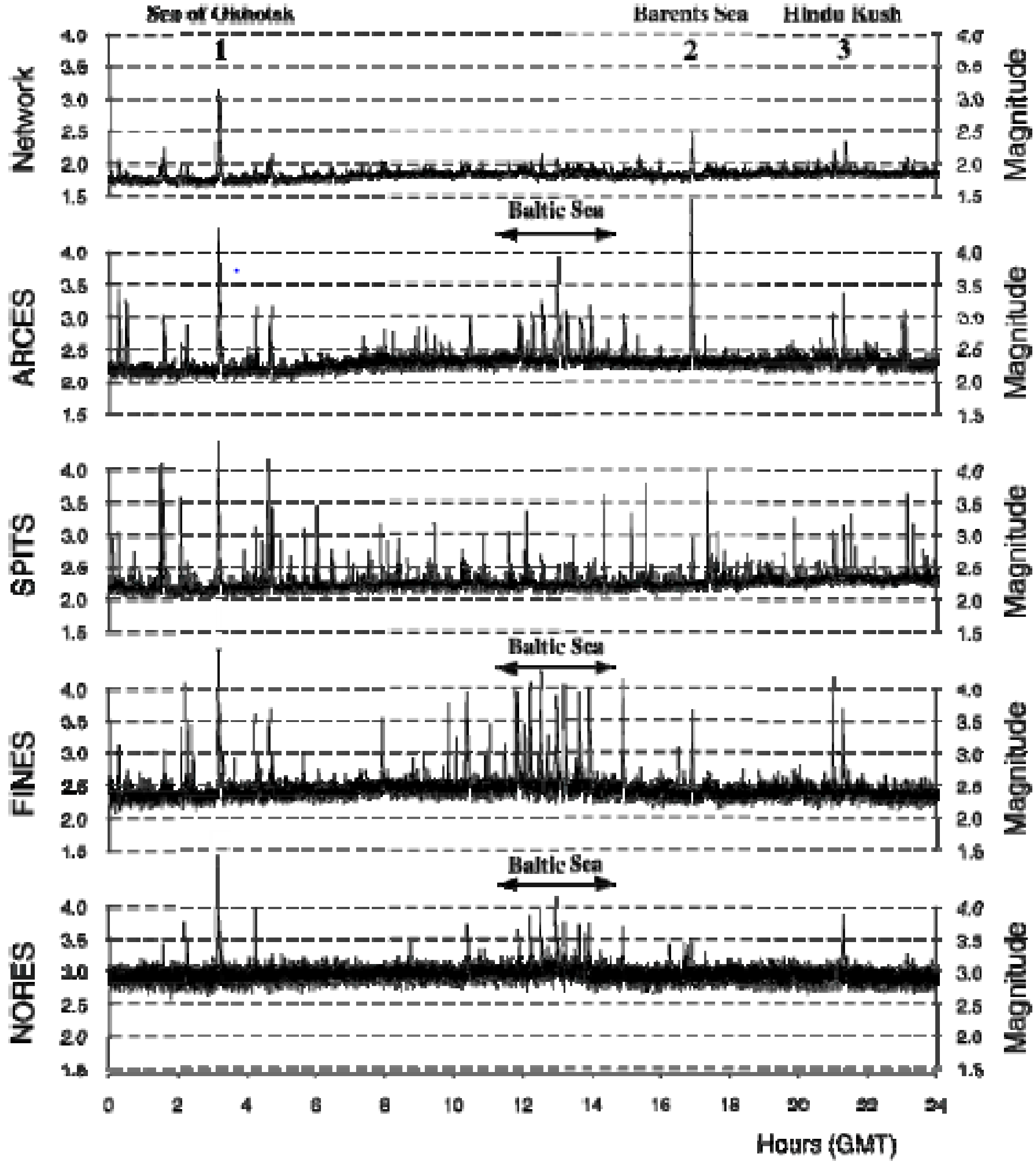

FIGURE D-4: Example of site-specific threshold ("smart network") monitoring for seismic events from Novaya Zemlya for 24 hours on February 9, 1998. SOURCE: Kværna et al., 2002

My own assessment is that the CTBTO and its various working groups have done an excellent job in deploying the IMS and in operating it, and that there is much improvement still to be made even in the four modalities incorporated in the IMS.

Space nuclear explosions, also forbidden by the CTBT and by the various moratoria and Limited Test Ban Treaty of 1963 are best detected by x-ray and gamma-ray detectors on satellites, which are not included in the IMS but exist for that purpose and for other purposes so that they can be exploited for nuclear test detection.

In addition to these physical means of detection, there are others, such as ionospheric measurements via GPS, to be presented here, and, of course, other means such as individuals involved in the test who might volunteer such information, signals intelligence, and the like. Nevertheless, without going into the implication of undetected tests at very low levels, it is perfectly clear that a test of a few tens of kg high-explosive equivalent could be conducted in a pressure vessel underground at a nuclear test site, without any signals being detected by the IMS. This would nevertheless constitute a clear violation of the CTBT, but without significant impairment of the security of other states.