The Scientific Roots and Prospects for the CTBTO and the IMS

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I am delighted to have the opportunity to address this Science and Technology 2011 meeting of the CTBTO. Despite your essential, personal interest in your own work, the ultimate purpose is to contribute to and to advance the means available for monitoring compliance under the Comprehensive Test Ban Treaty.

It is self evident that we would not have a CTBTO, the International Monitoring System (IMS), and the International Data Center (IDC) without a strong interest among States, all but 13 of which are parties to the CTBT of 1996, signed by 182 and ratified by 153, and needing ratification by 6 signatories and adherence and ratification by India, Pakistan, and North Korea before it can enter into force as foreseen in the Treaty. The Parties have defined, created, and supported the CTBTO in a remarkable technical and political achievement to be compared with CERN, the European Organization for Nuclear Research, based near Geneva, Switzerland.

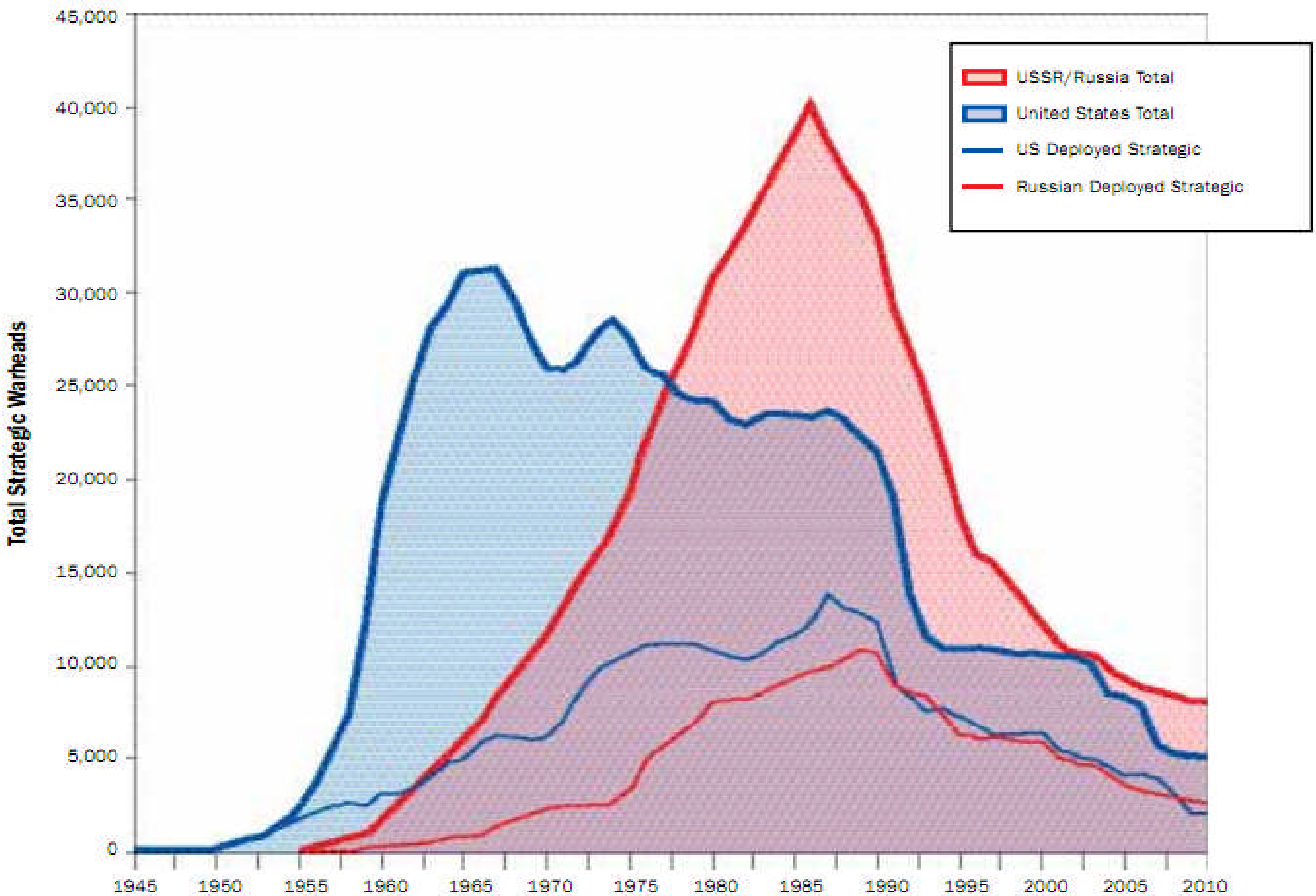
Much of the detail of the CTBTO and its detection capabilities are in the Treaty itself, the result of difficult and complex negotiations among the participants. This, in turn, draws on the very early work in several States which I want to sketch here.

Only two nuclear explosive were used in wartime, in 1945 by the United States against the Japanese cities of Hiroshima and Nagasaki. Those explosions, of 13 and 20 kiloton yield, respectively, enhanced the destructive power of individual weapons by a factor thousand or more; furthermore, J. Robert Oppenheimer in a speech in November, 1945, predicted that in a war between nuclear-armed States, such weapons would be used by the thousands or the tens of thousands.

The scientists who had created the nuclear weapon predicted that the fact of the explosions of August 1945 together with the extraordinary jump in destructiveness conferred by this new weapon would result in its acquisition by another State within four or five years, and on August 29, 1949, the Soviet Union tested a weapon of similar design and yield to the Nagasaki bomb.

Many scientists around the world had been arguing for the internationalization, control, or abolition of nuclear weapons, and the acquisition of nuclear weapons by a second State both spurred the competition and increased interest in control over nuclear weapons, especially in view of the political antagonism between the two nuclear-weapon states. The world changed, from a few nuclear weapons in the hands of the United States to possession by two political adversaries and as is shown in the figure, the number of nuclear weapons in the national arsenals grew rapidly.

US and Russian Strategic Nuclear Warheads, 1945-2010



Source: Hans M. Kristensen, Federation of American Scientists and Natural Resources Defense Council, presentation to UN panel on nuclear de-alerting, Oct. 13, 2010.

It had long been evident that although the weapons based on nuclear fission had an upper limit to their practical yield, there would be no such limitation on a thermonuclear weapon that would obtain energy from the fusion of the lightest elements, especially the nuclear reaction of deuterium on deuterium that would yield in 50% of the cases He-3 plus a neutron and in the other half of the reactions, tritium (H-3) plus a proton. And it was known that at temperatures achievable with a fission bomb, the tritium would react rapidly with deuterium to form He-4 plus a neutron.

Since 1943, with the creation of the Los Alamos Scientific Laboratory with Robert Oppenheimer as its Director, the United States had a small effort on thermonuclear weapons, led by

Edward Teller with a few collaborators. In January 1950, two months after his announcement of the Soviet nuclear test, U.S. President Harry S. Truman announced that the United States would develop the thermonuclear weapon—the “hydrogen bomb.” The first H-bomb test took place November 1, 1952, with an explosive yield of 11 megatons—almost 1000 times the yield of the Hiroshima bomb.

Although the 1949 Soviet nuclear test was at a remote site in Kazakhstan, the nascent United States Atomic Energy Detection System—USAEDS—detected it and acquired samples of the debris on airborne filters. Many more nuclear tests were to follow, by the United States, Soviet Union, Britain, France, and China, with a single test by India in 1974 and several more by India and Pakistan in 1998. North Korea had two nuclear test explosions underground in 2006 and 2009.

Atmospheric testing soon aroused opposition, especially because of the fallout of radioactive materials—the fission products from the bomb itself, un-reacted plutonium, and radioactivity induced by bomb neutrons in the materials of the surrounding soil and atmosphere.

Largely for reasons of public health, most nuclear-weapon testing moved underground, giving rise to a new technology to ensure containment of the debris in the explosion-created underground cavity in a horizontal "drift" or mineshaft or at the lower end of a large-diameter drilled hole. A few explosions were conducted in space, as well, beginning in 1958 with three very small ones, launched by rocket from the deck of a U.S. Naval ship in the South Atlantic Ocean.

With the perfection of the thermonuclear weapon, especially in the form of a two-stage “radiation implosion” system, not only was it possible to make air-deliverable nuclear weapons with a yield range of tens of megatons, but it was also possible to make much more economical, smaller, and safer nuclear weapons in the range of yields accessible by pure fission weapons. Indeed, that was the rather unexpected major application of the concept of radiation implosion.

Although most of the effort regarding nuclear weapons was expended in testing, developing, and producing them, and especially their costly means of delivery and protection, responsible leaders and many others, especially in the scientific community, explored the possibility of limiting or banning nuclear weapon test explosions, if not nuclear weapons themselves. And that has long been a principal line of arms control.

When a responsible leader or government asks for the pros and cons of a potential ban on nuclear tests, many troubling questions are raised. Will potential adversaries comply? If not, what is the probability of detection, so that one side will not be disadvantaged by doing without nuclear tests, while the other side proceeds with clandestine nuclear tests.

In an April 28, 1958, letter to Soviet leader Nikita Krushchev, U.S. President Dwight D. Eisenhower said the failure to achieve a ban on nuclear testing, "*would have to be classed as the greatest disappointment of any administration -- of any decade -- of any time and of any party....*"

In fact, no test ban was to be achieved before President Eisenhower left office in 1961, with the inauguration of President John F. Kennedy, for whom the nuclear test ban was also a priority. Nevertheless, the United States and the Soviet Union did impose a moratorium on their nuclear tests from October 31, 1959 to August 31, 1961, and Eisenhower had put in motion the beginning of a technical basis for a potential CTBT—a treaty completed and signed in 1996.

SCIENTIFIC BACKGROUND

The story is told well by Paul G. Richards and John Zavales[1], and in abbreviated form by Frank Press[2], Science Advisor to President Jimmy Carter.

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[1] "Seismological Methods for Monitoring a CTBT: The Technical Issues Arising in Early Negotiations," at www.ldeo.columbia.edu/~richards/earlyCTBThistory.html.
[2] "Earth science and society," *Nature* **451,** 301-303 (17 January 2008).

Following the October 4, 1957 Soviet launch of the Sputnik satellite, President Eisenhower established the President's Science Advisory Committee—PSAC. The Sputnik had demonstrated Soviet capability in space, and intercontinental ballistic missile delivery of nuclear and thermonuclear weapons was an early probability. By that time the United States had had enough experience with strategic air defense to know some of the problems involved in protecting the nation against nuclear weapons delivered by aircraft, and although it was and to this day remains hopeful for ballistic missile defense, the possibility of stemming the arms race and the technical development of new weapons was appealing. In early 1958, the President's Science Advisor, James R. Killian, chairman of PSAC, appointed an inter-agency panel chaired by Hans Bethe, physicist, of Cornell University to study the technical feasibility of monitoring a test ban. In April 1958 the Bethe Panel reported that 24 seismic stations in the USSR could detect underground explosions at a level of one or two kiloton yield. As pointed out by Richards, the only prior underground nuclear explosion was the RAINIER test of September 19, 1957.

When on March 31, 1958 the USSR announced that it would impose a moratorium on its nuclear tests if the U.S. and the UK did likewise, the Soviet Union had just concluded a series of nuclear explosion tests, while the U.S. was about to begin one. Despite the position of the Soviet Union that a ban on tests was a political matter and should precede technical monitoring capabilities, and the view of the United States to the opposite, a Conference of Experts to Study the Methods of Detecting Violations of a Possible Agreement on the Suspension of Nuclear Tests opened on July 1, 1958 at the U.N. in Geneva, although not under U.N. sponsorship.

James Fisk, head of Bell Telephone Laboratories, chaired the U.S. delegation supported by Robert Bacher and Ernest O. Lawrence and about a dozen physicists and seismologists as advisors to the delegation.

This first Conference of Experts found that atmospheric nuclear explosions could be well monitored, including the collection of debris, but that detection of underground nuclear explosions was much more difficult. The Soviet Union maintained that existing seismographic stations, in place for earthquake monitoring, would be adequate for the underground test monitoring role, but the UK and the U.S. argued that many more stations would be required and that automatic seismic stations with appropriate attention to integrity of data would be needed, for instance to ensure that the detection of "first motion" could be relied upon to separate earthquakes from explosions. The first motion from an explosion (nuclear or conventional) would be outward, whereas for an earthquake, although at some azimuth and dip angles the first motion would be outward, there would be some at which it would be inward, thus providing a diagnostic that could separate explosions from earthquakes.

The first Conference of Experts ended on August 21, with a recommended seismic monitoring system based on a UK proposal, but with the issue of on-site inspections unresolved.

Formal negotiations on a CTBT began October 31, 1958, but the two month interval saw multiple nuclear tests by the USSR, the U.S., and the UK. The Conference on the Discontinuance of Nuclear Weapons Tests was contentious, taking into account additional underground tests and the argument by the United

States that a threshold for 90% probability of detection would be in the range of 20 kt. The detection is probabilistic, in view of the differing attenuations from the explosion site to the various detectors, and the varying level of background signal (“noise”) at the various detectors.

A Panel on Seismic Improvement, appointed by Killian and chaired by Lloyd Berkner, reported in March 1959 on improvements that could be made by increasing the number of seismometers at the seismic array stations. The Panel recommended, specifically, a major increase in funding for research and basic seismology. The resulting appropriations had an enormous impact on seismology and on geophysics in general. According to Kai-Henrik Barth, “… from 1959 to 1961, funding for seismology increased by a factor of 30 and remained at this level for the better part of the 1960s.”

After many adventures, the Treaty Banning Nuclear Weapon Tests in the Atmosphere, Outer Space, and Under Water (the "Moscow Treaty") was signed by the USSR, the U.S., and the UK on August 5, 1963. It was ratified within a few weeks, and restricted the parties to underground nuclear testing only. It was opened to others and signed and ratified by many, but not by France and China. The last atmospheric test having been conducted by China in 1980, and both France and China have signed the CTBT..

The inclusion of the fourth medium—underground—was delayed for many years in part by the technical discovery that an explosion in a sufficiently large, pre-existing cavity filled with air rather than water or rock, could reduce the signal by a factor about 70, leading to the exaggerated claim that a party to the Treaty could successfully evade detection of a 70-kt nuclear explosion, with the seismic wave similar to that of a normal 1-kt explosion, assuming a 1-kt threshold of detection for the system.

DECOUPLING OF UNDERGROUND NUCLEAR EXPLOSIONS

On p. 40 of his memoir, "The Road from Los Alamos," Hans Bethe writes of the

> *"… possibility of deliberate concealment of explosions by a process known as decoupling, or muffling.*
>
> *A very powerful method has been proposed by Albert Latter … His method consists of making an enormous underground cavity and setting off the atomic bomb in the middle of the*

cavity. One can calculate that the apparent size of the explosion is thereby reduced by a factor about 300. (Now better estimated as a factor of about 70).

Latter's decoupling theory was invented about January 1959, and was then checked by many scientists, including me. It was experimentally verified with small explosions of conventional high explosive in Louisiana early in 1960. …"

Bethe was at first skeptical of the validity of the Latter proposal, but writes on p. 43 of "The Road from Los Alamos,"

"I had the doubtful honor of presenting the theory of the big hole to the Russians in Geneva in November 1959 ... The Russians seemed stunned by the theory of the big hole … Two of the Russian scientists presented to the Geneva Conference

their supposed proof that the big hole would not work. A day or two later, Latter and I gave the counterproof and showed, with the help of the Russian theory itself, that the Russian proof was wrong, and the theory of the big hole and the achievable decoupling factor were correct. We have been commended in the American press for this feat in theoretical physics. I am not proud of it."

Soviet negotiators, according to Bethe, were extremely unhappy with the discussion of the prospects for evasion of detection of an International Monitoring System, but Edward Teller, on the other hand, without suggesting that the United States would cheat on its obligation under a treaty, recommended that the U.S. study in great detail not only the possibility of evasion but work out the details of such evasion. Bethe writes, quoting Teller,

“(Teller:) ‘We in the United States should continue determined research to find out further methods of decoupling, further methods of reducing the signal from an underground explosion. …’ This may be so, but should we really spend our time and effort drawing up a blueprint for a violator of the treaty, and also do the engineering for him?”

Since the 1959 discussion of big-hole decoupling, that possibility has dominated discussions of detection of clandestine nuclear tests. It is generally accepted that the radius of the cavity for full decoupling in either salt or rock is 25 meters for a 1-kt explosive, with the volume of the required air-filled cavity increasing linearly with the yield to be decoupled. The teleseismic amplitude does not diminish further with additional increase in big-hole volume.

I suppose that is what at first led Bethe (and the Russians) to reject the validity of the big-hole decoupling approach. Imagine a cavity in competent rock, filled with air at atmospheric pressure and of a size that the response of the rock to the sudden increase in pressure from a nuclear explosion is elastic. Because of the 2000:1 density ratio between rock and air, if one imagines the nuclear explosion to result in a sudden uniform heating of the contained air to a pressure on the order of 200 bar that would be contained in most rock, there is simply a step-function increase in pressure, which is the "boundary condition" for the surface of the cavity. This is then coupled to the deformation of the rock, which in the vicinity of the cavity is a static problem, and not a wave propagation problem. However, at a radius comparable to the reduced wavelength in the rock ($\lambda/2\pi$) the near-field distortion gives way to propagating elastic waves, which in isotropic rock would correspond to a spherical P-wave.

What happens to the wave beyond the immediate region of the cavity is determined by the layered geology and especially by the free surface between rock and free atmosphere, as well as by surface topography, and the like. But we are interested here only in the source term, and that is a local matter.

For a given yield, *Y*, of the nuclear explosive device, the increase in energy density in the cavity is inversely as the cavity volume. And the pressure likewise. For a cavity small compared with $\lambda/2\pi$, the static falloff of pressure, *P(r)*, in a homogeneous elastic medium between cavity radius *a* and $\lambda/2\pi$ goes like $1/r^3$, specifically, $P(r) = P(a)\,(a/r)^3$, so that $P(\lambda/2\pi) = P(a)\,\{a/(\lambda/2\pi)\}^3$. Since $a^3 P(a) = Y_0$, $P(\lambda/2\pi)$ is independent of cavity radius, *a*, so long as the *a* is large enough for the rock to be in the elastic range. Here Y_0 differs from the nuclear yield, *Y*, by factors like $(4\,\pi/3)$ and the polytropic exponent of the gas in the cavity.

That this is true means that in this realm, a larger cavity does not provide further decoupling, and that is, perhaps, what misled Bethe. But in the inelastic realm, for a tamped explosive, the detonation of the nuclear weapon or even of a conventional explosive far exceeds the strength of competent rock. The rock is crushed, vaporized, and liquefied, and in general thrust out into a shock-heated and then frozen shell that thus corresponds to a seismic source that is a monopole. Again, there is no inherent length or time scale in this initial problem, so that the volume of the cavity thus produced by the explosion increases linearly with the yield of the explosive; so the question is to compare, for a given yield, this monopole source from the cavity creation in the rock, with the monopole source for the modest increase in pressure of the air in the pre-existing decoupling cavity. This is not a simple problem; the result is the maximum cavity decoupling factor of about 70.

I provide here, perhaps for the first time for most of this audience a 7-page excerpt from my Los Alamos notebook of July, 1950. These notes are written by Enrico Fermi, who was calculating the seismic source from a 100-kt nuclear explosion in an underground cavity of radius 33 m. Of course we have no time to follow the analysis during my talk, but I note that for this partially decoupled analysis (the cavity radius to “fully decouple” 100 kt would be 116 m), Fermi estimated that 5% of the explosive energy would be radiated as seismic waves.

Explosion in underground cavity

(E. Fermi in R.L. Garwin's notebook LANB 3616)

Total energy $= 5\times10^{21}$ ergs $= W$

Initial radius $R = 33$ m

Initial volume $\frac{4\pi}{3}R^3 = 1.25\times10^5\ m^3$

$$p = \frac{W}{V}(\gamma-1) = \frac{5\times10^{21}}{1.25\times10^{11}}\frac{2}{3} = 2.7\times10^{10}$$

From p. 6

Assume equation of state of rock

$$E = \frac{1}{2}k(v_0-v)^2 = \text{en. per cc}$$

$$p = (v_0-v)k$$

$$c = \sqrt{k v_0^2}$$

$v_0 = .4$ $c = 5\times10^5$ $k = 1.57\times10^{12}$

From 3rd Hugoniot

$$\frac{1}{2}k(v_0-v_1)^2 = \frac{1}{2}p\,(v_0-v_1)$$

$$v_0-v_1 = \frac{p}{k} = \frac{2.7\times10^{10}}{1.57\times10^{12}} = .0172$$

$v_0 = .4000$

$v_1 = .3828$

"Explosion in underground cavity," seven pages by Enrico Fermi in R.L. Garwin's Los Alamos notebook (LANB 3616), calculating the radiated wave from an explosion in an underground cavity of initial radius 33 m, and total energy 100 kt. (070050.EF)

07/00/50

30

From 2nd Hug

$$U^2 = \frac{v_0^2}{v_0-v_1}p = \frac{.4^2}{.0172}\,2.7\times10^{10} = 25.1\times10^{10}$$

From 1st Hug

$$u = \frac{v_0-v_1}{v_0}U = \frac{.0172}{.4}\,5\times10^5 = 2.15\times10^4$$

radial expansion $q'-1$ q = new radius

lateral " $\frac{q}{r}-1$

Density of elastic energy

$$\frac{\alpha}{2}\left[(q'-1)^2 + 2\left(\frac{q}{r}-1\right)^2\right] + \beta\left[\left(\frac{q}{r}-1\right)^2 + 2\left(\frac{q}{r}-1\right)(q'-1)\right]$$

Elastic energy =

$$W_{el} = \int 4\pi r^2 dr \{ \quad \}$$

Minimum problem

31

$$r^2 q'' + 2r q' - 2q = a$$

Solution

$$q = r + \frac{a}{r^2}$$

$$\frac{q}{r} - 1 = \frac{a}{r^3} \qquad q' - 1 = -\frac{2a}{r^3}$$

$$W_{el} = 4\pi(\alpha-\beta)\frac{a^2}{r_0^3}$$

$$p_{el} = 2(\alpha-\beta)\frac{a}{r_0^3} = 2(\alpha-\beta)\frac{q_0 - r_0}{r_0}$$

$$\frac{\alpha}{2} + \beta = \frac{3}{2} k v_0^2$$

$$\sigma = \frac{\beta}{\alpha+\beta} = \text{Poisson ratio} = .3$$

$$.7\beta = .3\alpha \qquad \alpha = \frac{7}{3}\beta$$

$$\left(\frac{7}{6}+1\right)\beta = \frac{3}{2}\, 1.57\times10^{12} \times .16 = .378\times10^{12}$$

$$\beta = 1.74\times10^{11} \qquad \alpha = 4.06\times10^{11} \qquad \alpha-\beta = 2.32\times10^{11}$$

32 Adiabatic gas expansion

$$p(r^3)^{5/3} = \text{const}$$

$$p r^5 = 2.7\times10^{10} \times 3300^5 = 1.1\times10^{28}$$

$$2(\alpha-\beta)\frac{q_0 - r_0}{r_0} = \frac{p_0 r_0^5}{q_0^5} \qquad \frac{q_0}{r_0} = x$$

$$x^5(x-1) = \frac{p_0}{2(\alpha-\beta)} = \frac{2.7\times10^{10}}{2\times2.32\times10^{11}} = .058$$

$$x = 1.046$$

$$.046 \times 3300 = 152 \text{ cm}$$

$$\frac{W}{x^2} = \text{en. in gas}$$

$$W_{el} = 4\pi(\alpha-\beta) r_0 (q_0 - r_0)^2 = 4\pi(\alpha-\beta) r_0^3 (x-1)^2$$

$$= 4\pi r_0^3 \cancel{(\alpha-\beta)} \frac{p_0^2}{4(\alpha-\beta)^2 x^{10}}$$

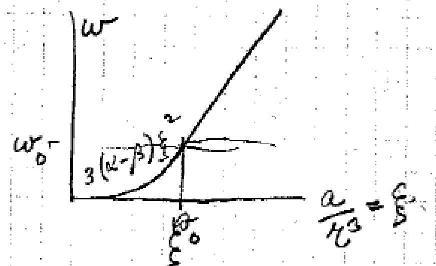
$$W = \frac{p_0 V_0}{\gamma - 1} = \frac{3}{2} p_0 V_0$$

5% of energy is elastic radiation

period of order .040 sec

Assume plastic flow for energy density $> w_0$

En density



$$w = \begin{cases} 3(\alpha-\beta)\xi^2 & \text{when } < w_0 \qquad \xi < \xi_0 = \sqrt{\frac{w_0}{3(\alpha-\beta)}} \\ w_0 + 6\xi_0(\alpha-\beta)(\xi-\xi_0) \end{cases}$$

$$W = 4\pi\int_{r_0}^{\infty} w\, r^2\, dr = 4\pi\int_{r_0}^{r_1}\left[w_0 + 6\xi_0(\alpha-\beta)\left(\frac{a}{r^3}-\xi_0\right)\right]r^2 dr +$$

$$+ 4\pi\int_{r_1}^{\infty} 3(\alpha-\beta)\frac{a^2}{r^6}r^2 dr \qquad \frac{a}{r_1^3} = \xi_0$$

$$\frac{W}{4\pi} = (\alpha-\beta)\frac{a^2}{r_1^3} + 3(\alpha-\beta)\left(\xi_0^2 - 2\xi_0^2\right)\frac{r_1^3 - r_0^3}{3} + 6(\alpha-\beta)\xi_0 a \ln\frac{r_1}{r_0}$$

$$\frac{W}{4\pi} = (\alpha-\beta)\xi_0 a + (\alpha-\beta)\left(\xi_0^2 - 2\xi_0^2\right)\left(\frac{a}{\xi_0} - r_0^3\right) + 2(\alpha-\beta)\xi_0 a \ln\frac{a}{\xi_0 r_0^3}$$

$$\frac{\partial V}{\partial a} = 4\pi \qquad \frac{\partial W}{\partial V} = p = \frac{1}{4\pi}\frac{\partial W}{\partial a}$$

$$\frac{p}{\alpha-\beta} = \xi_0 + \xi_0 - 2\xi_0 + 2\xi_0\ln\frac{a}{\xi_0 r_0^3} + 2\xi_0$$

$$= 2\xi_0 + 2\xi_0\ln\frac{a}{\xi_0 r_0^3}$$

$$p \doteq 2(\alpha-\beta)\xi_0 + 2(\alpha-\beta)\xi_0\ln\frac{a}{\xi_0 r_0^3} \qquad \frac{r_1^3}{r_0^3} = 1.03$$

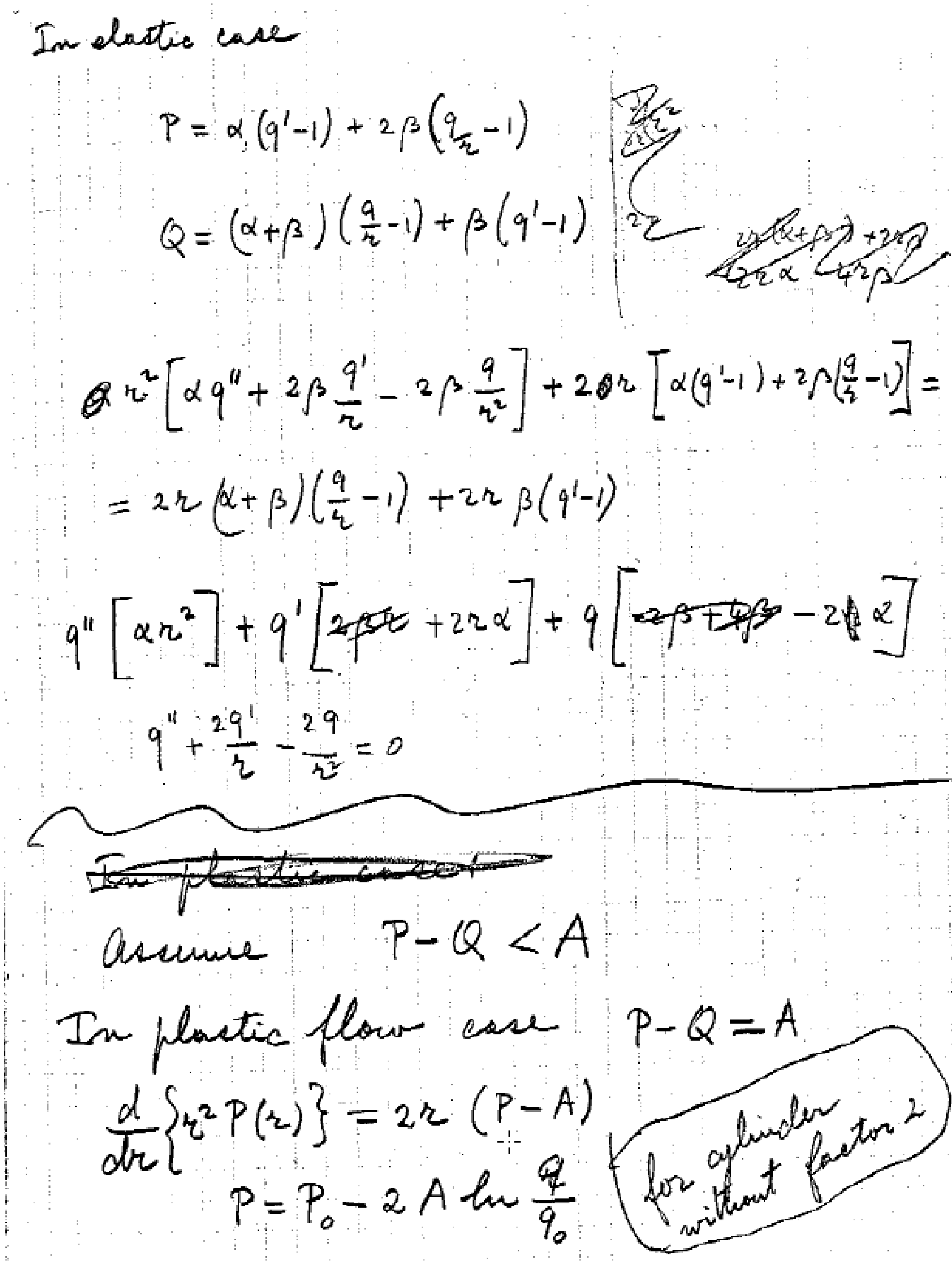
Assume $\xi_0 = .01$

$$\frac{20}{400} = .05 = .01 + .04$$

$$P = p_{rr} \qquad Q = p_{\perp\perp}$$

$$\frac{\partial}{\partial r}\left\{r^2 P(r)\right\} = 2rQ \qquad (\text{for sphere})$$

$$\frac{d}{dr}\left\{r P(r)\right\} = Q \qquad (\text{for cylinder})$$



In the wave zone, for a given frequency component of the propagating wave, the pressure, velocity, and acceleration all vary alike as a function of radius. Because the area of a successive shell of rock increases as r^2, an outgoing spherical wave thus has amplitudes that decrease as *1/r*. This wave is then reflected at discontinuities, refracted at those same interfaces, just as is the case with light and sound, except that even in an isotropic solid, one has not only the waves of longitudinal motion (P-wave) but the waves of transverse motion (shear), S-waves. In addition, there are additional waves guided by interfaces, especially by the Earth's surface.

From the advent of the big-hole decoupling analysis in 1959, it has been at the forefront of the question of effectiveness of long-range detection of underground nuclear explosions. Latter indicated also that in addition to not having pre-existing faults, the rock, which is only elastically deformed by modest pressures in the fully decoupled region, must not be put into tension. And this means that the depth to the top of the spherical cavity should be such that the post-explosion cavity air pressure should be less than half the lithostatic pressure on the rock. In fact, if the cavity pressure exceeds the hydrostatic pressure (0.1 bar per meter of depth), there would be no barrier to noble gases and perhaps other gaseous fission products escaping through water-filled cracks in the rock.

The focus on seismic detection in the early days was largely on teleseismic detection, but with the vastly increased numbers of digital seismometers, and the availability of their digital outputs continuously in real time, or in most cases by automated file transfer upon request, it is evident that regional detection of seismic waves is often practical, with the formation of regional arrays. This makes possible observations at far higher frequency than the 1-Hz typical of teleseismic observations, with greater sensitivity to short-time features such as reflection from the Earth's surface.

John Tukey was on the U.S. team at the Conference of Experts, and his work and that of others emphasized a discriminant between explosions and earthquakes based on depth. A seismic source deeper than 10 km can hardly be an explosion, so it is highly desirable to determine depth. How can this be done? For multi-station teleseismic detection, with a range of dip angles of the seismic rays from the explosion to the different stations, and with the accumulations of site-specific corrections, the travel time differences from the deep source will force the solution to "close" at the actual depth of origin, so that the many earthquakes of focal depth of tens of km will be screened out as candidates for a nuclear test. But there is another way to determine focal depth, even on a single teleseismic detection.

Because of the very great density difference between rock and air, and the even larger ratio in stiffness between rock and air, there is almost 100% reflection of the seismic wave coming from below at the surface above the explosion or earthquake. This is determined by the acoustic impedance, $Z=\rho c$, where, substituting $c = (Y/\rho)^{1/2}$, $Z = (Y\rho)^{1/2}$. The air provides pressure release at the ground surface, and at great depths (or great distances for a teleseismic wave that curves upward for detection at distances of thousands of km) the signal is similar to that which would have been produced by the explosion itself at the initial range and position in what would now be an infinite rock medium, although with a kind of "dotted line" to mark the boundary that existed between rock and air. The teleseismic signal, though, would be that signal from the explosion itself, plus a signal from a simultaneous anti-explosion in the rock above the initial interface—"anti-explosion" because every component of pressure or velocity would be reversed in sign.

For very short waves (wavelength short compared with the double depth of burial), there would be two time-resolved peaks in the motion detected by a seismometer. In fact, these peaks would be mirror images of one another; in the frequency domain, there would be cancellation where the double depth of burial is equal to a wavelength or some integer multiple of the dominant wavelength under consideration.

This leads to a "scalloping" of the signal power when viewed in the Fourier domain, and if one takes the Fourier Transform of the logarithm of the spectrum of the signal itself, then this "cepstrum" has a peak corresponding to the depth of burial. This is a powerful technique for discrimination.

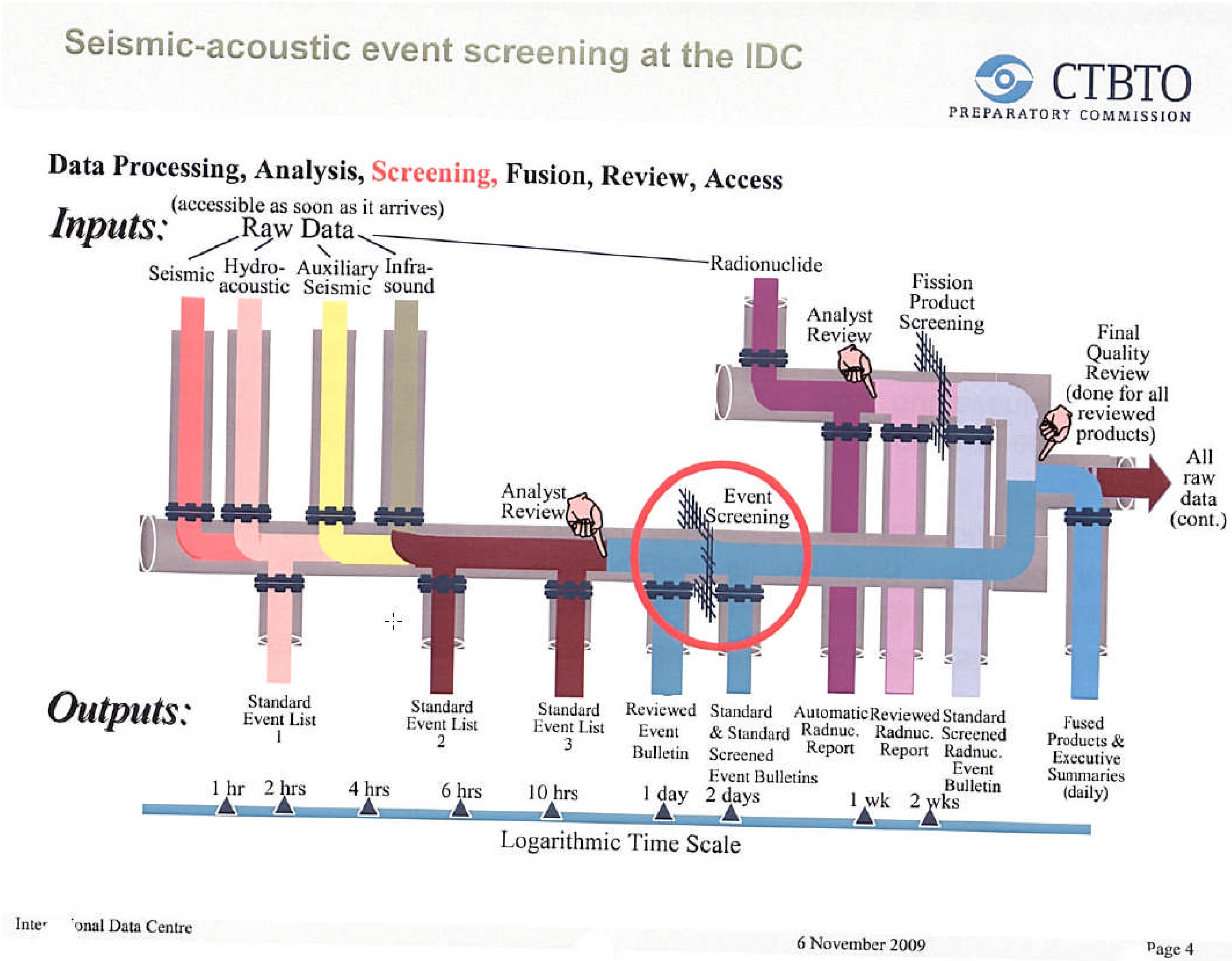
Following the 1959 Berkner report, the U.S. government created the Vela Program, conducted by the Defense Advanced Research

Projects Agency. Vela UNIFORM (the initial “U” for Underground) can be credited with stimulating much of the improvement in seismic methods over the decades. Vela HOTEL (“H” for High) resulted in the development and deployment of a series of 12 “Vela satellites” in 118,000-km orbits, that monitored for explosions in space and on the surface of the Earth. Vela satellites operated from October 1963 until 1984, by which time nuclear explosion detection systems were carried on many other satellites. Vela housed detectors of neutrons, x-rays and gamma rays, as well as two optical “bhangmeters” that were sensitive to the “double-humped” light pulse from an atmospheric nuclear explosion on the visible face of the Earth, but without capability to further locate the light source.

IMS MODALITIES AND REPORTING TIMELINE

The IMS monitors with four modalities: seismic; hydroacoustic (for explosions in the oceans); infrasound (for explosions in the atmosphere); and radioactive particulates and gases (which can detect atmospheric explosions and very many underground explosions unless the test has been adequately sealed against leakage). In fact, even for skilled practitioners such as the United States and the Soviet Union/Russia, more than 50% of the underground tests leaked significant amounts of radioactive materials.

The IMS sensor results go to the International Data Center (IDC) and are available to member countries, which have in many cases a great interest in checking, duplicating, and carrying further the analyses of the IMS. The timeline of these activities, from a presentation during my visit to the CTBTO in November, 2009 is shown on the following chart.



Seismic-acoustic event screening at the IDC
CTBTO
PREPARATORY COMMISSION
Data Processing, Analysis, Screening, Fusion, Review, Access
Inputs:
(accessible as soon as it arrives)
Raw Data
Seismic
Hydro-acoustic
Auxiliary Seismic
Infra-sound
Radionuclide
Analyst Review
Fission Product Screening
Final Quality Review (done for all reviewed products)
All raw data (cont.)
Analyst Review
Event Screening
Outputs:
Standard Event List 1
Standard Event List 2
Standard Event List 3
Reviewed Event Bulletin
Standard & Standard Screened Event Bulletins
Automatic Radnuc. Report
Reviewed Radnuc. Report
Standard Screened Radnuc. Event Bulletin
Fused Products & Executive Summaries (daily)
1 hr
2 hrs
4 hrs
6 hrs
10 hrs
1 day
2 days
1 wk
2 wks
Logarithmic Time Scale
International Data Centre
6 November 2009
Page 4

There are 50 *primary* IMS seismic sites, many of them arrays of several 3-component seismometers. The IMS also includes 120 *secondary* seismic sites, which do not report continuously in real time to the IDC but which do record and the digital data from which can be transmitted automatically on request by the IDC. In addition to the IMS sensors, there are supplementary sensors—many thousands of digital seismometers operated by universities or national agencies primarily for earthquake monitoring and research.

Having perhaps the most difficult task, the seismic monitoring of underground explosions and the discrimination of earthquakes is probably the most advanced of the modalities of the IMS. It is continually refined by research in seismology, practically motivated by earthquake detection and characterization, and major strides have been made. For instance, the sole discriminant of direction of first motion discussed in the 1958 has been supplemented at least two other major techniques.

The first of these is depth determination, essentially by the failure of seismic records detected at different azimuths and distances all to close at a specific point on the surface. Given a full understanding of the seismic velocity vs. depth of the Earth, such detections typically do close at a depth equal to that of the earthquake or explosion. A source with actual depth exceeding 10 km is evidently not an explosion. Essential to the qualification of this technique has been the enormous number of digital records over the last decades of earthquakes in every part of the world. In addition, artificial signals created by "thumpers" together with modern digital signal processing can provide such information without explosions, in giving the equivalent of an artificial explosion anywhere the thumper is permitted to operate.

The more intense production of P waves relative to the S-wave by explosions compared with earthquakes continues to be exploited as a discriminant, the distortions of propagation reduced with the use of the Magnitude-Distance-Amplitude Correction (MDAC) technique. The resulting amplitude ratios are illustrated in the Figure. The best-performing spectral band, 6-8 Hz, is not available for teleseismic detections. Cross-spectral ratios (not shown) show promise as well, where the high-frequency amplitude of one phase is compared with the low-frequency band of another phase.

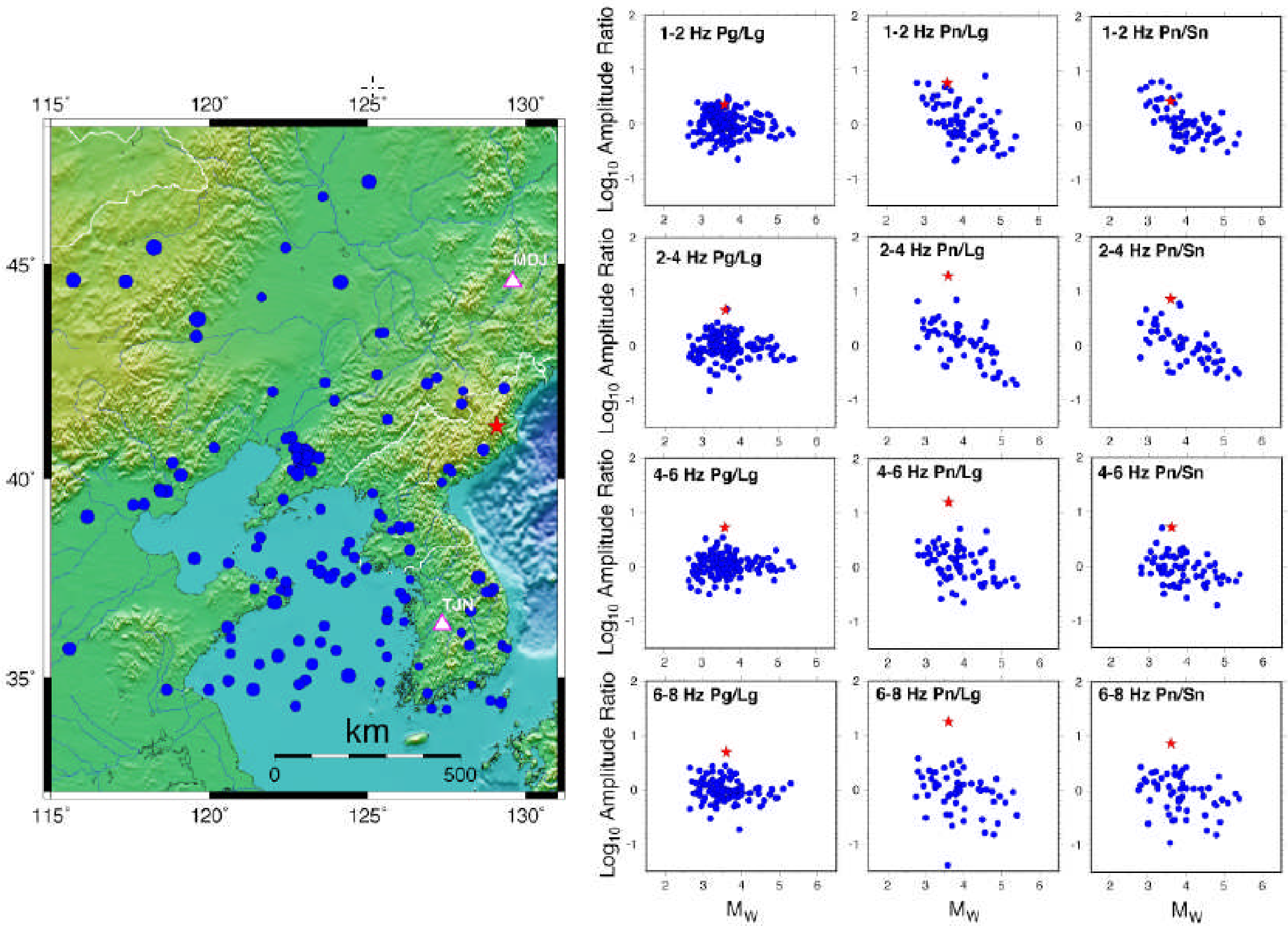


Figure 3. The map shows earthquakes (blue circles) and the October 9, 2006, North Korean nuclear test (red star) observed at seismic stations MDJ and TJN. The scatter plots show the MDAC path corrected *P/S* ratios at each station (average when both available) for three different *P/S* ratios in four different frequency bands.

From "REGIONAL SEISMIC AMPLITUDE MODELING AND TOMOGRAPHY FOR EARTHQUAKE-EXPLOSION DISCRIMINATION," by W.R. Walter, M.E. Pasyanos, E. Matzel, R. Gök, J J. Sweeney, S.R. Ford, and A.J. Rodgers, in NNSA 2008 Monitoring Research Review.

INFRASOUND

Among the earliest systems deployed for the remote detection and location of atmospheric nuclear explosions is the microbarograph or infrasound detector in the range of 0.2-2.0 Hz. In the full IMS each of the 60 infrasound stations will consist of 4-15 gravel-covered stars of porous tubes (wind-noise-reducing system) deployed over an aperture of 1-3 km; 43 are now certified (www.ctbto.org/map). While awaiting signals from an atmospheric nuclear test, the infrasound system routinely detects quarry blasts, bolides, and industrial accidents as shown in this slide.

Phase association

Examples of Large Candidate Events for REB/LEB bulletins in 2009

Explosive events

- **Gas pipeline** (Russia), *13 January 2009*: **3** stations
- **Explosion of ammunition depot** (Tanzania), *29 April 2009*: **3** stations
- **Gas pipeline** (Russia), *25 June 2009*: **2** stations
- **Event off-coast of Namibia**, *29 June 2009*: **2** stations
- **Failure of Bulava ballistic missile** (Russia), *15 July 2009*: **4** stations
- **Meteor explosion (Sulawesi)**, *8 October 2009*: **15** stations

Rocket launches/Re-entries

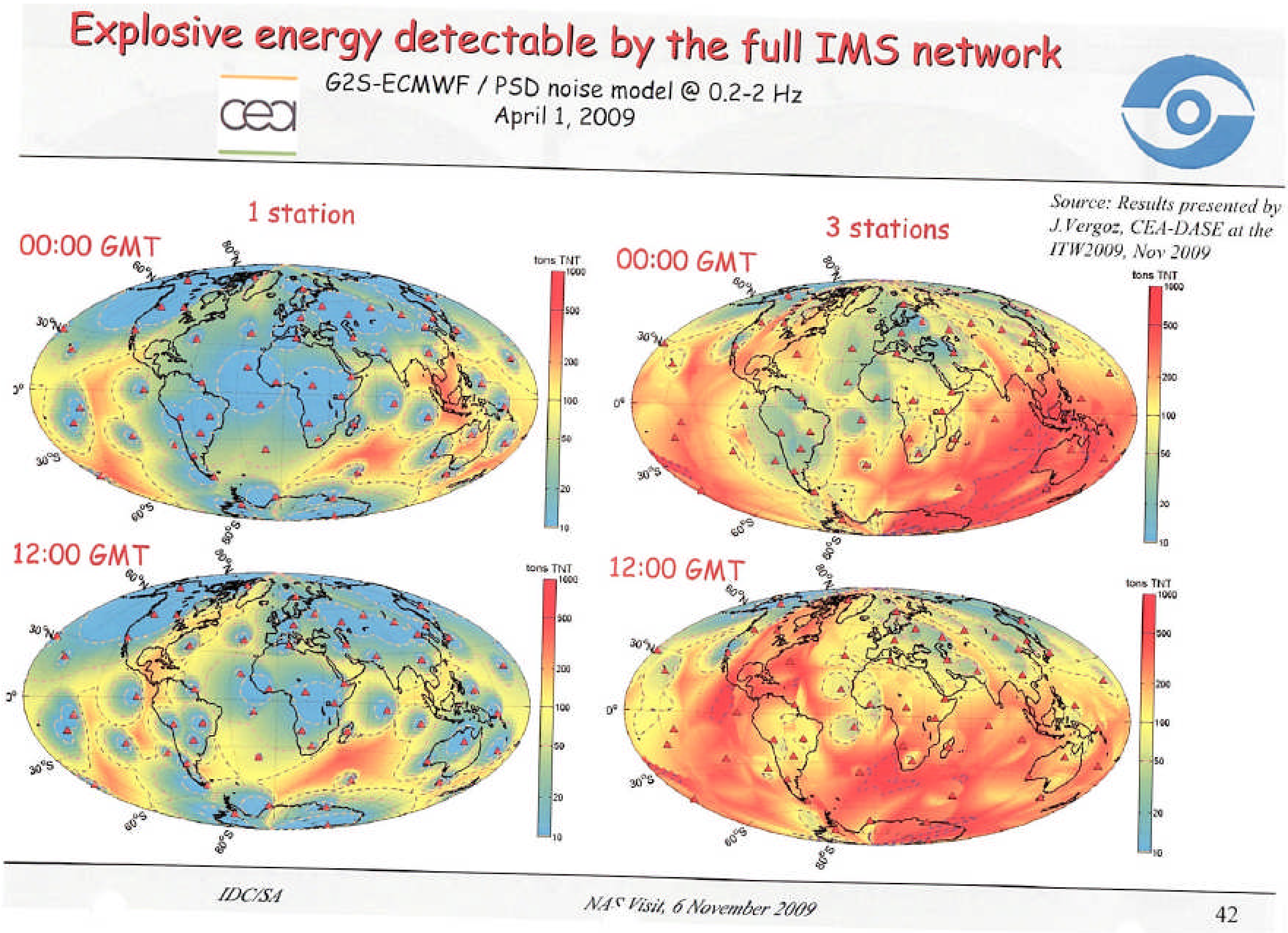
- **Discovery Space Shuttle** STS-119 (USA), *15 March 2009*: **6** stations
- **Unha rocket** (DPRK), *5 April 2009*: **3** stations (launch), **2** stations (re-entry)
- **Atlantis Space Shuttle** STS-125 (USA), *11 May 2009*: **4** stations
- **Endeavour Space Shuttle** STS-127 (USA), *15 July 2009*: **4** stations
- **Proton-M** (Russia), *11 August 2009*: 2x **4** stations (launch and re-entry)

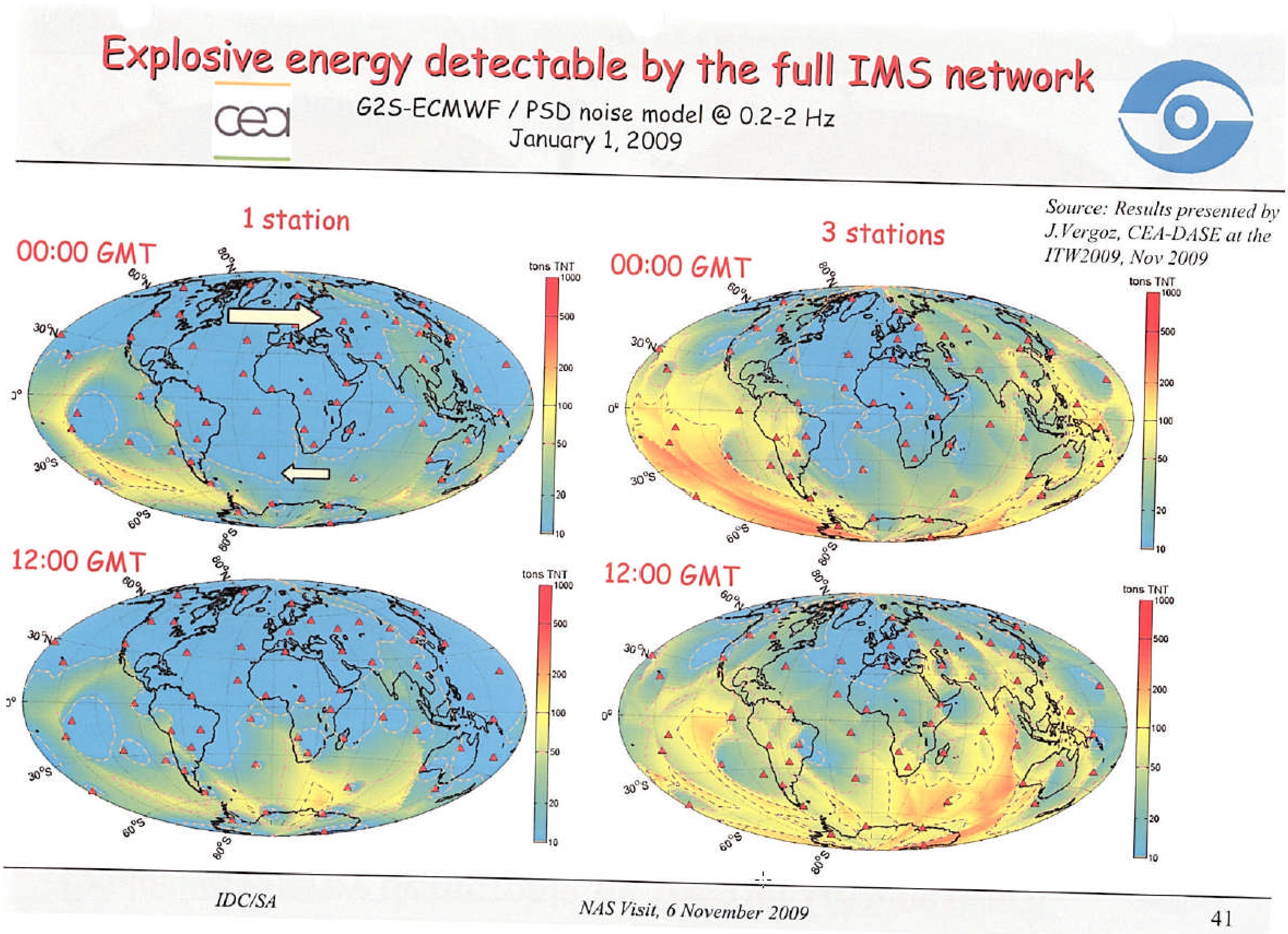
Volcanic eruptions

- **Rabaul** (Papua New Guinea), *18 January 2009*: **2** stations
- **Mt. Redoubt** (Aleutians, USA), *March-April 2009*: **6** stations
- **Galeras** (Colombia), *25 April 2009*: **3** stations
- **Tungurahua** (Ecuador), *11 June 2009*: **3** stations
- **Sarychev Peak** (Kuril Islands, Russia), *12 June 2009*: **6** stations

IDC/SA *NAS Visit, 6 November 2009* 26

With no time to discuss this fascinating field in more detail, I provide here a map of the sensitivity of the infrasound array to an assumed surface-burst nuclear explosion, on a particular day. Because of the thermal structure of the atmosphere and the winds aloft vary with season and with time, the detection threshold varies substantially, but is amenable to calculation as shown on the following slides,


Explosive energy detectable by the full IMS network
G2S-ECMWF / PSD noise model @ 0.2-2 Hz
April 1, 2009
Source: Results presented by J.Vergoz, CEA-DASE at the ITW2009, Nov 2009
1 station
3 stations
00:00 GMT
12:00 GMT
tons TNT
IDC/SA
NAS Visit, 6 November 2009
42


Explosive energy detectable by the full IMS network
G2S-ECMWF / PSD noise model @ 0.2-2 Hz
January 1, 2009
Source: Results presented by J.Vergoz, CEA-DASE at the ITW2009, Nov 2009
1 station
3 stations
00:00 GMT
12:00 GMT
tons TNT
1000
500
200
100
50
20
10
IDC/SA
NAS Visit, 6 November 2009
41

The result of all of this work, both operational and developmental, with great contributions by the scientific community, is the timeline of the products of the IDC, as indicated, although I have slighted the hydroacoustic detection and the radionuclide detection network.

In general, the product of the IDC, supplemented by the national technical means of the member states, provides a sound basis for the request for an on-site inspection of a designated area not to exceed 1000 square kilometers in area.

Components of the Verification Regime

CTBTO
PREPARATORY COMMISSION

International Monitoring System

321 stations:
seismic,
hydroacoustic,
infrasound,
radionuclide,
16 radionuclide labs

International Data Centre

collect,
analyse,
distribute
data & products

On-Site Inspection

prepare for
conduct of
on-site
inspection

Int· ·onal Data Centre

December 2007

Page 2

If such an inspection were to take place in the vicinity of an actual underground nuclear explosion test, I have little doubt that local detection of radionuclides and active seismological studies would provide hard evidence of such a test.

POTENTIAL IMPROVEMENTS TO THE IMS AND IDC

Equally interesting science and technology underlie the three non-seismic modalities of the IMS, and much information can be deduced about these.

Furthermore, the detection and location by one modality permits the generation of a synthetic signal (for instance an explosion detected by seismic means can be taken as the source of an infrasound wave, and comparison with observed infrasound signals can augment or negate what might be a false inference in the seismic domain.

Aside from organizational strictures, budgets, and the like, in any technical organization there is the opportunity for improvement, and that improvement can include the possibility of major reduction of effort to perform some of the existing tasks. Even so, there must be appropriate balance between initiative and approval, in order that the amount of effort devoted to automation and cost reduction be balanced against the potential improvement. Furthermore, there are no doubt competitive ideas and individuals, and again, these must be selected with good taste and judgment.

The national data centers and independent research groups perform a substantial amount of investigation into improved and more efficient techniques. So exactly where these innovations originate and are tested and are provisionally deployed is an important question that I will not take up here. What might these innovations be?

1. Automation via artificial intelligence or machine learning to maintain or improve performance standards and to reduce cost.

2. Converting noise into signal in order better to discriminate amongst signals.

3. Routine incorporation of additional data into IMS processing.

I will take an example of each.

(1.) The digital records of the IDC provide fertile soil for work in automated "phase" picking

(2.) In many fields of signal processing, it is desirable to emphasize the signal (for instance, from one location), while discriminating against noise. A common approach is a beamformer, and that is what is done with the individual arrays that are elements of the IMS seismic and subsystem. Forming an array either in real time or later from the digital records of the individual seismometers can enhance signals (and noise) coming from a particular azimuth (more precisely, a given azimuth and dip angle). The “array gain” is just the number of seismometers involved, if they are far enough apart to constitute independent antenna elements—a half wavelength or more.

However, a strong earthquake far off the center of the angular beam thus formed, can leak into the side lobes of the array. But more can be done with those same seismometers in the local array, and the first step is to form an array to view the irrelevant earthquake, then to determine those array delays and coefficients, to be subtracted from the array focused on a target in the desired direction. This "sets a null" in the direction of the interfering earthquake, although the process is less effective than in the analogous electromagnetic case, with only a single velocity of propagation.

An even more sophisticated tool that can discriminate not only against earthquakes from other directions but from an earthquake source within the angular beam of the array is to form a virtual network. This provides not only the gain of a single array of seismometers near a single station, but forms a network of multiple arrays from quite different locations, with their signals time shifted so as to align at the location of interest. In this time shifting, one is greatly aided by the large numbers of small earthquake that are observed over the years, that calibrate precisely the travel time from almost any location on Earth to an individual seismometer. The variation of seismic signals with azimuth and dip normally prevents the use of waveform coherence in different directions, limiting the network performance to “incoherent” rather than coherent processing.

The virtual network does not require that from minute-to-minute the weight of the individual arrays remain constant in the virtual array. In particular, if there is a distant large earthquake on the same azimuth as the location of interest at array A (but likely at quite different range), then array A can be deleted (i.e., given zero weight) during the period of strong interference, and the other arrays used to form the virtual array—a “smart network.” The figure shows the multiple traces of just such an experimental smart network[3]. In the example (first panel in the figure) the array detection threshold dropped from magnitude 3.0 or more for the static virtual array to magnitude 2.0 for the dynamic smart network.

[3] Kvaerna, T., F. Ringdal, J. Schweitzer, and L. Taylor (2002). Optimized seismic threshold monitoring—part 1: regional processing, Pure Applied Geophysics, 159, 969-987.

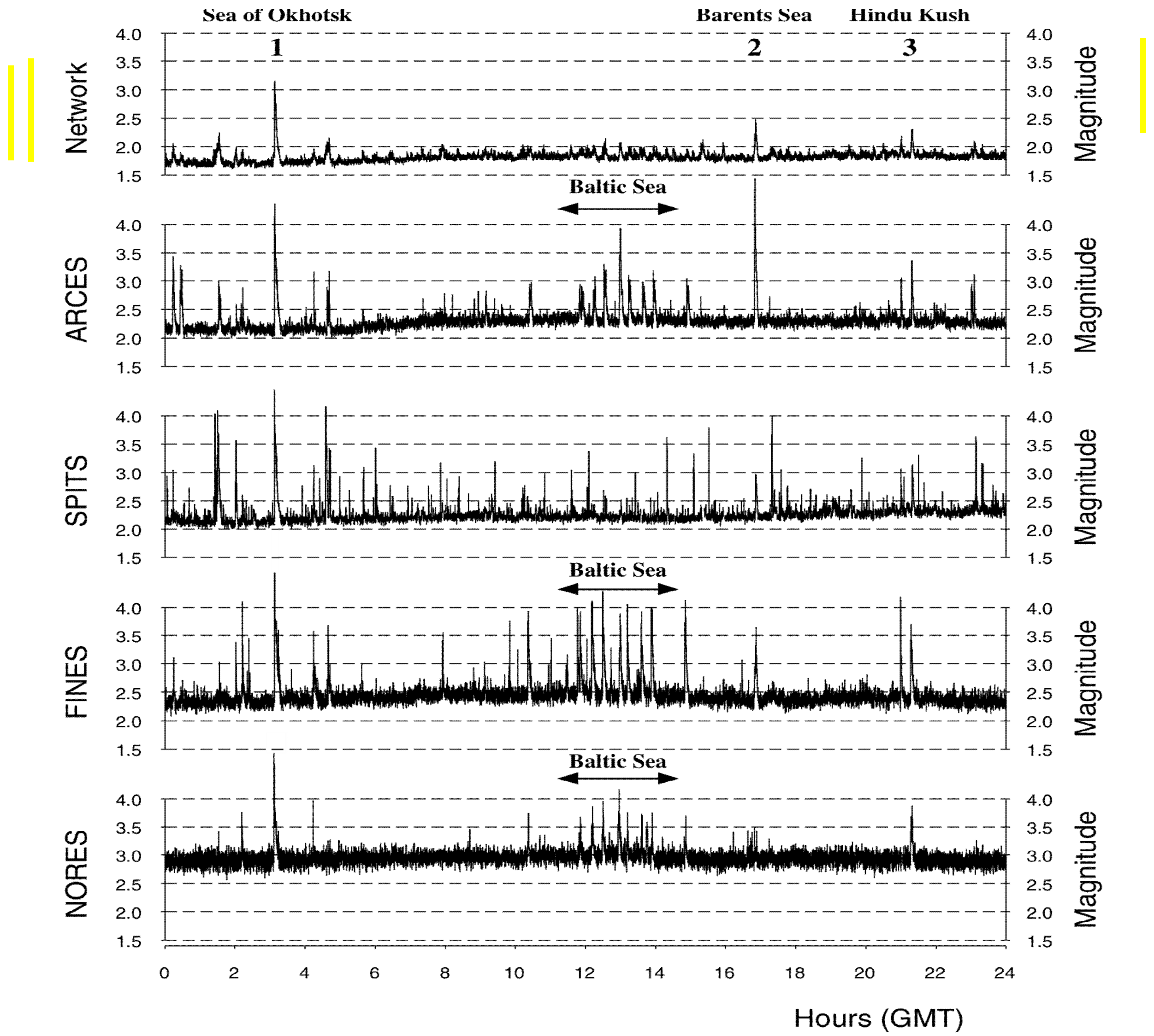


Figure 1. Example of “smart network” threshold monitoring for seismic events from Novaya Zemlya for 24 hours on February 9, 1998 (Kværna et al., 2002).

Of course, with a vitally important system in continuous production of crucial data, it is essential to be able to operate proposed and purportedly tested improvements in parallel with the existing business practice, in order to make a considered judgment as to when "improvement" can responsibly be made.

EPILOGUE

I was one of the authors of the 2002 report of the U.S. National Academies of Science, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty*, available for reading and PDF download at http://www.nap.edu/openbook.php?record_id=10471
Incidentally, from June 2, 2011 almost all 4000 reports and books of The National Academies Press can now be downloaded free from www.nap.edu.

The body of the 2002 Report contains three chapters,

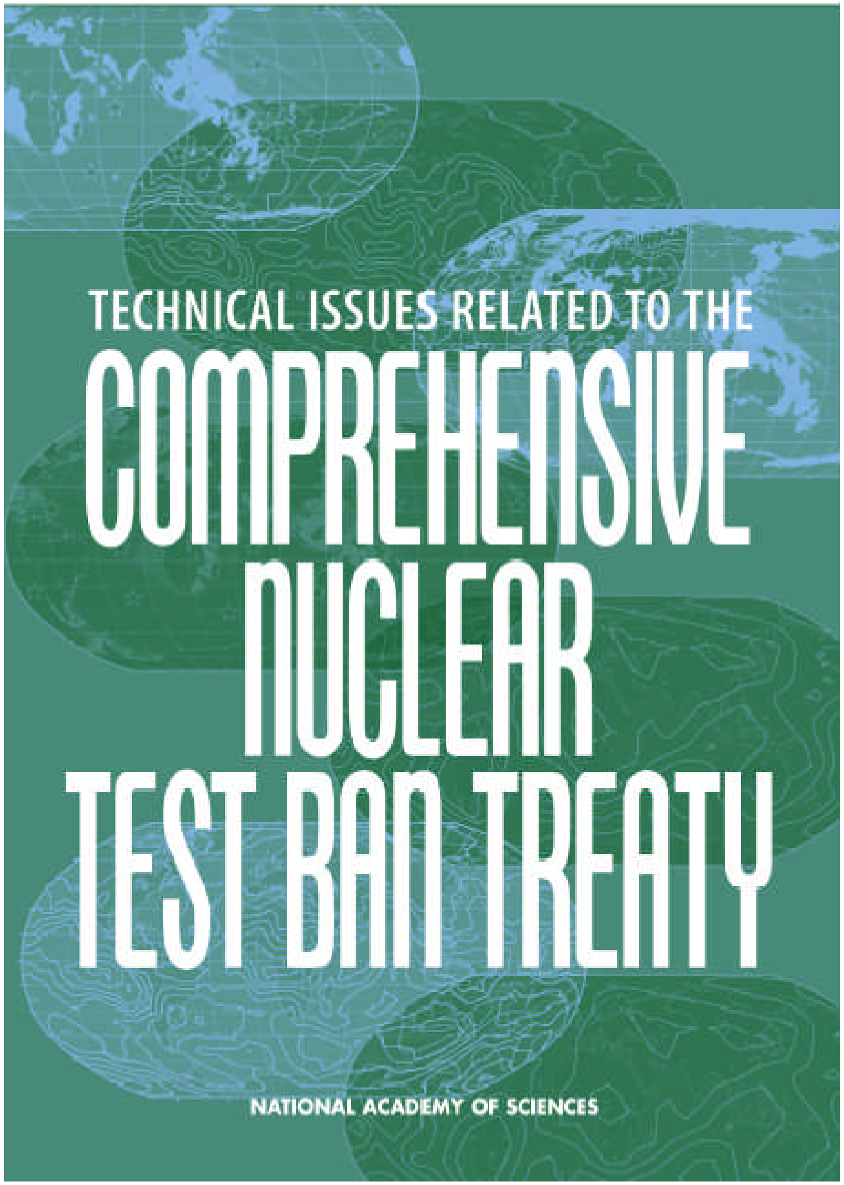
1. Stockpile Stewardship Considerations: Safety and Reliability Under a CTBT

2. CTBT Monitoring Capability

3. Potential Impact of Clandestine Foreign Testing: U.S. Security Interests and Concerns

Although only the second is related to the CTBTO, and the remainder is very U.S.-centric, I commend the report to your attention.

An Update to this report has been prepared by a group assembled by the National Academies of Science, which has not been published in time for this meeting. I hope that it will soon be available at www.nap.edu, providing an assessment that takes into account an additional decade of stockpile stewardship without nuclear explosion tests, and the demonstrated capability of the International Monitoring System and the International Data Center of the CTBTO.



2002 Report, http://www.nap.edu/openbook.php?record_id=10471