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Capabilities of the IMS Seismic Auxiliary Network

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The 2002 US National Academy of Sciences study, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty*, concluded that increased monitoring confidence would be obtained at the 100-ton level if the auxiliary IMS network were utilized more fully.[1] If there were evidence that an event may have occurred, the auxiliary network data would be examined to study the issue. It would be useful to know how the threshold level of the IMS seismic network would be improved by including the auxiliary data. This could be presented with global maps and contours by the ISS study, comparing the primary network alone versus the primary and auxiliary, together. **The NAS study concluded that thresholds "would drop generally by about 0.25 magnitude units in Europe, Asia, and North Africa, and by about 0.5 magnitude units in some regions** (such as Iran)."[2] The NAS study also discussed four additional enhancement approaches: (1) Augmentation with data from areas of concern, (2) correlation analysis that compares past data from near an event with new data, (3) Threshold Monitoring that combines signals from many IMS stations and (4) examine data from the Global Seismic Network and the International Seismological Center with about 3,000 seismic stations. It would be useful if the ISS study examined these conclusions.

This paper lists past estimates of the threshold detection levels for nuclear explosions for various seismic networks, showing how seismic detection has improved over time.[3] **Our pedagogical calculation shows that the average reduction in threshold level is about 0.25 magnitude units for the Total IMS network of 170 seismic stations (Primary plus Auxiliary) as compared to the Primary network of 50 stations.** It would be useful if network simulations obtained threshold level maps for both the Total and Primary networks for the June 2009 ISS meeting. Since the Auxiliary network can be used in both a spotlight mode when needed or in continuous mode, it would be useful to have more accurate calculations of this affect.

Improved Threshold Detection

Simulation estimates of threshold detection levels of nuclear explosions have been carried out over the decades for a variety of seismic networks. These simulations began with cases of the United States and the Soviet Union, but now these simulations are carried routinely carried out on a global scale. These results have improved over the decades as seismic technology advanced for a variety of reasons:

- analog to digital seismographs
- narrow-band to broad-band seismographs
- single axis to triple axis to array seismic stations
- from magnitude picks to full seismic patterns to correlate template patterns
- increased density of seismic stations
- from teleseismic data to using close-in regional data
- improved earth models used in regional seismology with improved algorithms
- spectra above 6 Hz can discriminate the source term
- an understanding of geological bias factors with preferential absorption
- improved ability to use other technologies to assist seismology

Past Estimates of Seismic Threshold Detection Levels

The detection levels listed below are determined for high confidence detection (90 percent detection probability) and detections are observed at three or four seismic stations.

Sykes/Evernden (1982)[4]	15 internal (USSR), 15 external, 4 station detection 3.3–3.7 m_b, 2.2–2.5 L_g
Sykes/Evernden/Cifuentes (1983)[5]	3 of 25 internal (USSR), 15 external, 3 m_b
Evernden/Archambeau (1986)[6]	5 of 25 internal (USSR), 15 external 1 kt fully decoupled
Hannon (1985, 1988)[7]	internal to USSR, 4 station detection 10 single axis (3.6 m_b) 30 single axis (3.3 m_b) 30 arrays or high freq. (2.7 m_b)
U.S. OTA (1988)[8]	30 internal USSR arrays or 50 triple-axis, 4 stations (2.2–2.5 m_b) 0.1–0.01 kt coupled, 1 kt decoupled
Claassen, Unger, Leith (1993)[9]	79 stations, Africa, Asia, Europe 3.6 $m_b(L_g)$ (2.6–3.9) with 4 stations (p-wave) 128 stations, Africa, Asia, Europe 3.2 $m_b(L_g)$ (2.6–3.4) with 4 stations (p-wave) 2.8 (2.2–3.2) with 4 stations (2p and 2s)
U.S. National Academy of Sciences (2002)[10]	3 of 50 IMS primary stations 3.5–3 (0.03–0.1 kt), 1–2 kt decoupled Europe, Asia, N. Africa, N. America NZemlya, NORSAR 2–2.5 m_b (0.01–0.003 kt) 120 auxiliary in near-real time lowers m_b by 0.2
Provisional CTBT Technical Secretariat (2009)[11]	40 of 50 stations (March 2009) N America-Eurasia, 3 < 3.5 m_b, <2.5 at NZ not including 90 of 120 auxiliary stations

Calculation of the Threshold Level as a function of the Density of Seismic Stations

The technical prowess, geographic coverage and analysis techniques have vastly improved the science of seismology and its ability to detect, discriminate and locate nuclear test explosion. With the advent of more seismic stations, closer access to seismic sources has reduced geometric spreading and absorption. The literature on IMS monitoring almost universally discusses only the capability of the 50 Primary stations, *without quantifying* the additional capacity available from the 120 Auxiliary stations. A higher density of stations gives both more data and better data from the more numerous, closer stations. The additional data is useful in ruling out background earthquakes, which increase in number by a factor of ten as the threshold is reduced by one magnitude unit.

The Primary Network (P) will have 50 seismic stations and the Auxiliary Network will have 120 seismic stations. The total IMS Network will use both the Primary and Auxiliary networks (PAux) for a total of 170 stations. The ratio of the number of stations for the two modes is significant with

$$\textbf{(Prim. + Aux.)/Prim} = \textbf{PAux/P} = \textbf{170/50} = \textbf{3.4.}$$

The higher density of seismic stations per square kilometer for the Total Network gives closer access to nearby seismic sources. We assume that the primary and auxiliary networks are uniformly spaced. The square root of the ratio of number of seismic stations for the PAux and P networks gives the ratio of access distances:

$$r_{PA}/r_P = 1/(3.4)^{1/2} = 1/1.84 = 0.54 = 0.5.$$

Thus, PAux stations might be 750 km from an event, while P stations might be 1500 km from that event. Greater proximity reduces geometric spreading, increasing seismic amplitudes at nearby seismic stations since conservation of energy favors proximity. In addition, greater proximity is helpful to reduce seismic attenuation, particularly at higher frequencies that are useful to discriminate between explosions and earthquakes. But we ignore that issue here.

We start with a cautious assumption that understates the total impact of the auxiliary network. Taylor and Hartse used an **L_g amplitude that falls as the inverse of the square root of the distance ($1/r^{0.5}$)** from the source.[12] We use energy conservation below to show that waves in idealized horizontal waveguides behave in this manner. **This ignores the faster fall-off of the more important P_g wave amplitude that fall as the inverse of the distance (1/r). We also ignore the frequency dependent attenuation factor, Q(f), which reduces the amplitude of the very relevant higher frequency waves.**

We assume uniform geological strata in all directions, but gravity increases density with depth, creating a waveguide of thickness *H*. This gives a constant seismic power flux (p_{seismic} in W/m^2) for all azimuthal angles at a particular distance. Seismic power flux varies with depth in the wave guide, but we treat this as constant. The total seismic power P_{seismic} is spread over a cylindrical area of depth H and circumference $2\pi r$, giving an average seismic power flux of

$$p_{\text{seismic}} = P_{\text{seismic}}/H2\pi r.$$

We assume the maximum seismic power is proportional to the yield of the explosion Y, giving seismic power flux proportional to yield over distance.

$$p_{\text{seismic}} \; \alpha \; Y/r.$$

The maximum wave amplitude squared (or maximum oscillation velocity squared) is approximately proportional to the yield of the explosion divided by the distance of the event. Both PAux and P stations are sensitive to the same maximum amplitude (or velocity). The more distant P seismograph is sensitive to a threshold amplitude (A_T) from a threshold yield Y_T at a distance r_T

$$A_T = c\,(Y_T/r_T)^{1/2},$$

where c is a constant. If the approach distance of, say, 1500 km is reduced by one-half to 750 km, the detectable yield is also reduced by a factor of 0.5 to maintain the same threshold amplitude at the seismograph.

The seismic magnitude is typically

$$m = a \log(Y) + b,$$

where a is the slope, Y is in kton and b is the bias factor that depends on regional-scale geology. The reduction in threshold magnitudes from the P network to the PAux network is

$$\Delta m_T = m_{TP} - m_{TPAux} = [a \log(Y_{TP}) + b] - [a \log(Y_{TPAux}) + b]$$

$$= a \log(Y_{TP}/Y_{TPAux}) = a \log(2) = (0.8)\,(0.30) = 0.25.$$

The reduction of a factor of two in transition explosion yield and a reduction of by 0.25 magnitude units are consistent with the results from the National Academy of Sciences. **The NAS study concluded that thresholds "would drop generally by about 0.25 magnitude units in Europe, Asia, and North Africa, and by about 0.5 magnitude units in some regions (such as Iran)."** A magnitude reduction of 0.25 corresponds to a yield reduction by a factor of two.

This result **understates the case** in that we did not use the larger inverse distance fall-off (1/r) of P_g wave amplitude used by Taylor and Hartse. **The pedagogical result for P_g waves would be $\Delta m_T = 0.5$.** Our above result also **does not take into account the frequency dependent attenuation,** which rises from Q of 400 at 1 Hz, to 840 at 6 Hz to 1100 at 10 Hz for P_g waves. It rises faster with frequency for L waves from a Q of 400 at 1 Hz, to 1300 at 6 Hz, to 1800 at 10 Hz. **Thus, the effect should be larger than we have estimated and the data is already paid and available**, with modest additional computing needed. **But there are factors that reduce this conclusion, such as increased background noise and more complex discrimination at lower magnitudes. Perhaps, these effects cancel and the net improvement of $\Delta m_T = 0.25$ with the auxiliary network is about correct.** Clearly this a pedagogical calculation, that would be greatly aided by network simulation calculations that take into account specific locations of the stations, the geological media, the background noise, the response functions of the seismographs and the source function for nuclear explosions.

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[1] National Academy of Sciences, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty* (National Academy Press, Washington, DC, 2002). www.nap.edu/catalog.php?record_id=10471

[2] NAS-CTBT, pp. 49-50.

[3] D. Hafemeister, "Progress in CTBT Monitoring Since its 1999 Senate Defeat," *Science and Global Security 15,* 151-183 (2007). www.princeton.edu/~globsec/publications/SciGloSec.shtml. Presented at Article XIV EIF-CTBT Conference, Vienna, September 2007. D. Hafemeister, "The Comprehensive Test Ban Treaty: Effectively Verifiable," *Arms Control Today 38*(8), 6-12 (October 2008). www.armscontrol.org/act/2008_10/Hafemeister

[4] L.R. Sykes and J.F. Evernden, " *Scientific American* 247 (October 1982): 47–55:

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[10] *NAS–CTBT*, Center for Monitoring Research, Dept. of Defense: 52–53.

[11] Preparatory Commission of CTBTO, *Annual Report 2007* (Vienna: CTBTO, February 2008) and IDC simulation results from 10 March 2009.

[12] S. Taylor and E. Hartse, "A Procedure for Estimation of Source and Propagation Amplitude Corrections for Regional Seismic Discriminants," *Jour. of Geophysical Research* 103(B2), 2781-2789 (1998). M. Fisk and S. Taylor, "Applications of a Contstrained Inversion and an Extended Kriging Method to Improve Source Path and Site Corrections for Regional Seismic Phases," *Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies* 40-49 (2008).