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Effective CTBT verification: the evidence accumulates

David Hafemeister

The 1996 Comprehensive Nuclear Test Ban Treaty (CTBT) prohibits all nuclear tests of any yield in all places for all time.[1] It is an arms control measure that constrains nuclear weapon states from developing new nuclear weapons. It is also a non-proliferation measure that raises a barrier to the development of sophisticated nuclear weapons by non-nuclear weapon states.[2] The CTBT requires the fulfilment of a complete ban with respect to four parameters: number; yield; location; and time.[3]

The treaty has not yet entered into force, as it requires ratification by all 44 countries designated under Annex 2 as having an advanced civilian nuclear capability. As of 5 October 2004 173 states had signed the CTBT. Among the non-signatories are nations that are known to have nuclear weapons or to have aspirations in that regard, including India, Iraq, North Korea and Pakistan. Of the signatories, 119 have ratified the treaty, including three nuclear weapon states (France, Russia and the United Kingdom). Israel has signed the accord, but not ratified it, while China has said that it will only ratify the treaty when the United States does so. In October 1999 the US Senate rejected ratification by 51 votes to 48. (The current administration of President George W. Bush has underlined that it has no intention of ratifying the CTBT.)

Following the Senate's decision, then US President Bill Clinton asked General John Shalikashvili, Chair of the US Joint Chiefs of Staff, to head a high-level task force to analyze the issues that emerged in the debate. Shalikashvili, in turn, asked the US National Academy of Sciences (NAS) to convene a panel of experts to examine the technical questions that could affect the viability of a test ban.[4] The panel did not seek to evaluate the net benefit of the CTBT to the US, but rather the issues of verifiability, stockpile stewardship and national security vulnerabilities due to clandestine testing.[5] The Senate debate on the CTBT had been marred by claims that cheating could take place without detection at weapon test yields of up to 70 kilotons (kt). The NAS report—entitled *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty,* and published in 2002—strongly contradicted this claim. Drawing on its conclusions and subsequent technical developments, this chapter considers whether the CTBT is effectively verifiable.

An effective verification standard and process

Verification is the process by which governments collectively determine whether a treaty party has or has not violated the terms of an accord. States may also individually make their own assessment of compliance by other states.[6] Since arms control and disarmament agreements invariably affect national security, there needs to be a standard against which to judge their verifiability, preferably one that is determined while the agreements are being negotiated and considered for adoption. An estimate of the verifiability of a treaty helps a potential party determine the risk to its national security that might be expected from possible violations of the convention.

For the US this benchmark was established during Senate ratifications of the 1987 Intermediate-range Nuclear Forces (INF) Treaty and the 1992 Strategic Arms Reduction Treaty (START I). During hearings on the INF treaty, former Ambassador Paul Nitze defined effective verification in the following way: 'if the other side moves beyond the limits of the treaty in any militarily significant way, we would be able to detect such violation in time to respond effectively and thereby deny the other side the benefit of the violation'.[7] Thus, any militarily significant cheating must be detected in a timely manner before it can threaten national security. During the 1992 ratification hearings on START I, Secretary of State James A. Baker III repeated this definition, but added a new criterion: 'Additionally, the verification regime should enable us to detect patterns of marginal violations that do not present immediate risk to US security'. This chapter uses the Nitze definition in determining whether the CTBT is effectively verifiable.

Seismological means of verification

Since the 1963 Partial (or Limited) Test Ban Treaty was concluded, all confirmed nuclear tests have been conducted underground. Seismographs provide the primary tool for detecting underground tests, with other technologies supplementing this data. Earthquakes release compressional stress between two tectonic plates (or two regions within a plate), as one region slides past another over several seconds. Seismic traces from nuclear explosions differ from those of an earthquake in several ways. Seismic data from nuclear explosions have higher-frequency components than those from earthquakes because the duration of a nuclear explosion is much shorter than that of an earthquake. Furthermore, the ratio of the short-period, pressure body-wave magnitude (m_b) to the long-period, surface-wave magnitude (M_S), is significantly larger for nuclear tests than for earthquakes.

Over the past four decades the ability to detect underground nuclear explosions has improved considerably. Large seismic events are readily attributable to earthquakes, nuclear blasts or chemical explosions for mining. Since 1960, 72 events at various locations (out of some 700 Soviet nuclear tests) have appeared in the literature for which further study has been needed to determine their source. Lynn Sykes, Professor of Geophysics at Columbia University in New York, has examined these 72 events using accurate depth determinations, spectral ratios of seismic waves, first motions of P-waves, focal mechanisms and surface deformations.[8] Teleseismic stations measure distant sources (more than 1,500 kilometres away) by observing body waves that travel below the mantle. Sykes notes that advances in technology have lowered the threshold-detection region for problem events in seismic magnitude by two m_b units, from 4.3–5.6 30 years ago, to 2.0–3.5 today.[9] This improvement permits observation of wave amplitudes that are a factor of 300 smaller than before. This increased sensitivity lowers the yield threshold for problem events by a factor of 1,000.

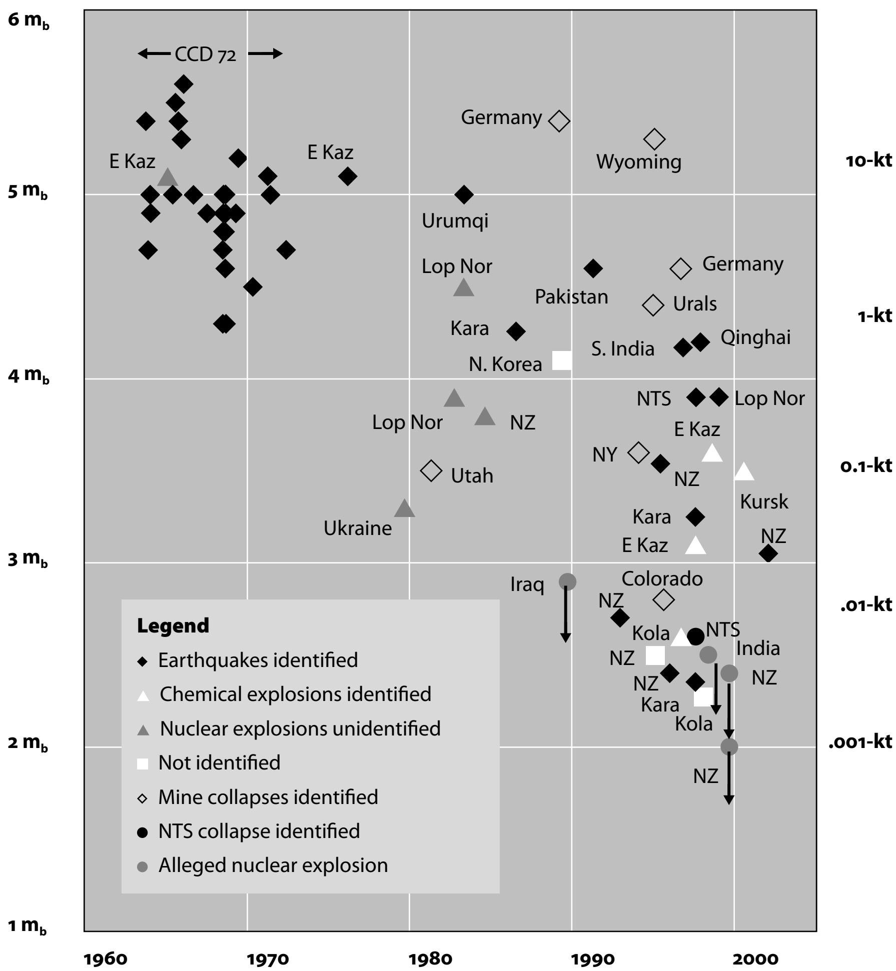
These results are shown in Figure 1. The yield scale on the right is appropriate for well-coupled nuclear explosions at the former Soviet test site at Novaya Zemlya, where the explosion is surrounded by rock and not a cavity. No seismic waves were detected for events with downward pointing arrows, indicating that the signals could not have been larger than background noise levels on those dates.

The International Monitoring System

The International Monitoring System (IMS), which is part of the verification regime for the CTBT, will, when complete, comprise 337 monitoring stations with seismic, hydroacoustic, radionuclide or infrasound sensors.[10] As of April 2004 there were 81 fully-functioning stations (with another 80 under construction or subject to contract negotiations).[11] The seismic part of the IMS network will employ modern, high-quality sensors at its 50 primary and 120 auxiliary stations.[12]

The IMS will have the capability to detect explosions with high confidence to an m_b level of 3–3.5 with 90 per cent certainty using confirmation data from three

Figure 1 **Sizes of anomalous and problem seismic events, 1960–2002**



Abbreviations Eastern Kazakhstan (E Kaz), Kara Sea (Kara), Kola Peninsula (Kola), Nevada Test Site (NTS), western New York (NY) and Novaya Zemlya (NZ).

Source Lynn Sykes, 'Four decades of progress in seismic identification help verify the CTBT', EOS, Transactions of the American Geophysical Union, vol. 83, no. 44, 29 October 2002, pp. 497–500.

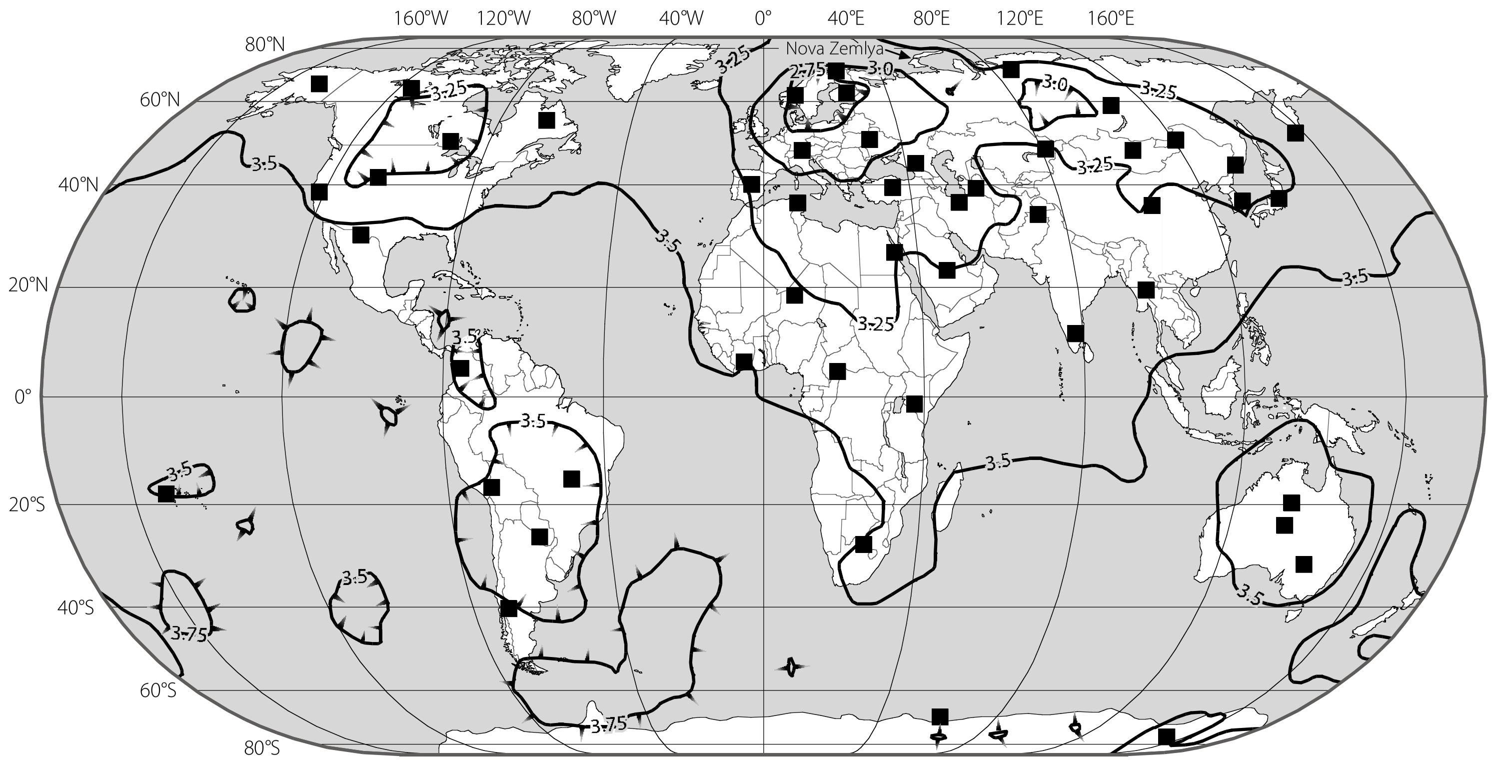


Figure 2 **IMS seismic monitoring magnitude limit (m_b)**

—— threshold-magnitude contours

■ stations of the IMS primary network

Source Center for Monitoring Research, Nuclear Testing Programs, Department of Defense, reprinted in National Academy of Sciences, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty*, National Academy Press, Washington, DC, 2002, p. 52-b.

monitoring stations. Figure 2 shows seismic threshold detection magnitude contours (with signal-to-noise amplitude greater than 3.2) at three or more IMS primary seismic network stations (solid squares). This capability captures 90 per cent of the events at the contoured magnitude or larger. The contour interval is 0.25 magnitude units.

The detection threshold for Asia, Europe and North America is in the range of magnitude 3–3.5 or lower. For most of Eurasia and North Africa this corresponds to a 0.03–0.1-kt yield from a 'tamped explosion' (where the nuclear device is in direct contact with hard rock rather than being surrounded by a cavity). The result is shown in the threshold contour limits in Figure 2. These findings confirm the calculations of US national laboratories and universities. Explosions in soft rock couple less efficiently, raising these yield limits by a factor of up to ten. For Novaya Zemlya the m_b detection threshold is less than 2.5.

The threshold-magnitude contours of Figure 2 are translated into explosive-yield contours in tons in Figure 3, showing the projected detection threshold contours for the IMS network of 50 primary stations. The contours are given in tons of explosive yield for 90 per cent-probable detection, using signals from three seismic stations. The IMS detection threshold is below 0.1-kt for all of Eurasia and below 0.2-kt for all continents. In 1999, with 33 stations, the IMS detected 0.1-kt underground chemical explosions and a 0.025-kt explosion at the former Soviet test site in Semipalatinsk, Kazakhstan.

From this, it can be concluded that the IMS network can detect to a threshold of less than 0.1-kt for explosions tamped in hard rock for all of Eurasia, North Africa and North America. This is better by a factor of ten than the one kiloton limit originally projected for the IMS by treaty negotiators and system designers.

Regional seismic stations

The above threshold estimates are, however, too cautious in that they do not take into account the possibility of utilizing close-in regional seismic stations within 100 kilometres (or more) of the seismic event. For sub-kiloton explosions, signals at teleseismic stations—those located more than 1,500 kilometres from the source—can be too weak to be detected by single stations. For these smaller signals, monitoring must be done using regional signals. Some IMS stations, when they are situated relatively close to the source, are already acting as regional stations. More

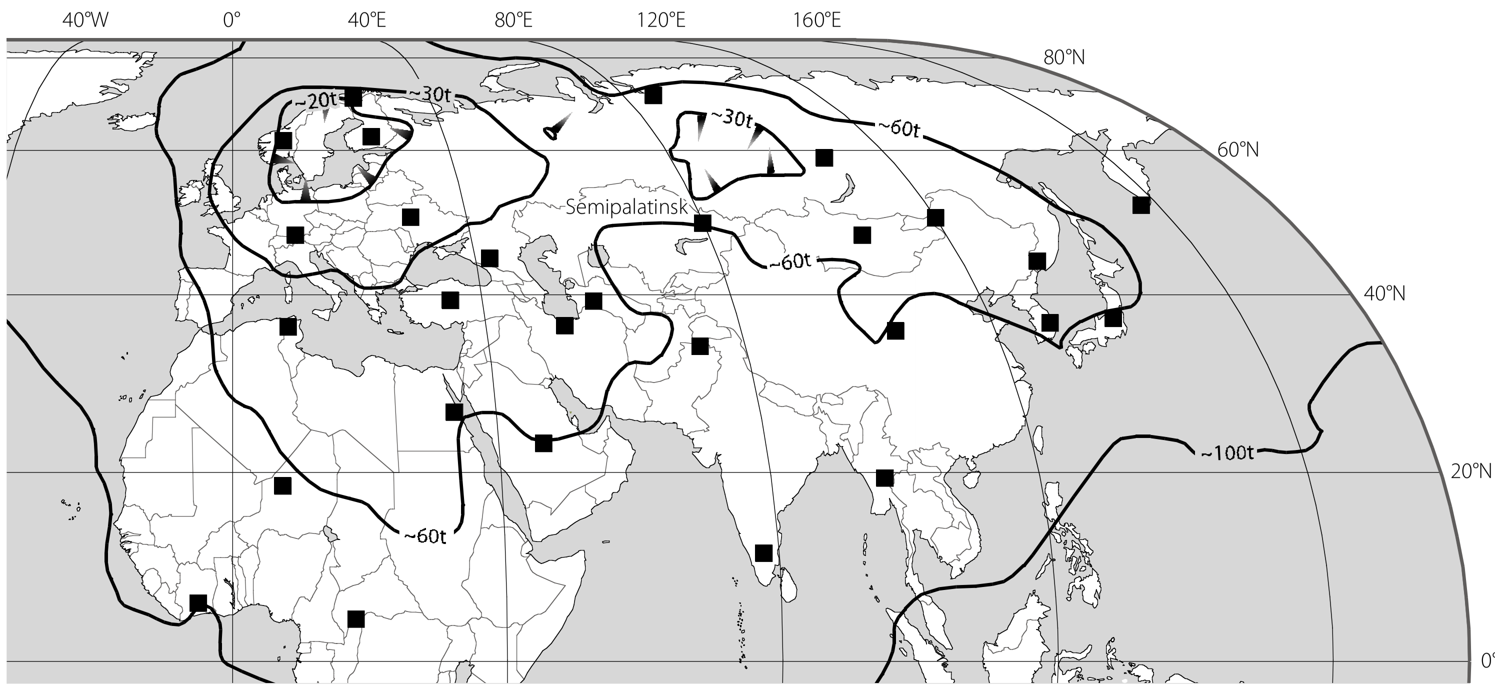


Figure 3 **IMS seismic monitoring limit (tons)**

— explosive yield contours in tons

■ stations of the IMS primary network

Source Center for Monitoring Research, Nuclear Testing Programs, Department of Defense, reprinted in National Academy of Sciences, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty*, National Academy Press, Washington, DC, 2002, p. 52-c.

regional stations could be located near areas of concern to improve further the IMS projections mentioned above. Regional waves propagate at depths of less than 100 kilometres and at higher frequencies, up to 20 Hz. Regional seismic magnitudes are referenced to teleseismic m_b magnitudes to simplify discussion. Cavity decoupling is much more detectable at frequencies above five to ten Hertz, thus regional seismographs can help to detect and identify clandestine testing. Because the local geological structure affects regional waves, making them more complex, research must be carried out to interpret them.

According to Russian sources, 340 underground nuclear tests took place from 1961–89 at Semipalatinsk.[13] At the end of the Cold War, only 271 of these tests were described in the open technical literature with well-determined origin times, coordinates and magnitudes. Good unclassified documentation was lacking for the other 69 tests until Vitaly Khalturin, Tatyana Rautian and Paul Richards obtained regional seismic data from seismographs located 500–1,500 kilometres from the Kazakhstan site.[14] As a result, they have been able to assign magnitudes to eight tests that had been previously located but whose magnitudes were unknown. For 31 tests they were able to estimate the origin times and magnitudes—and for 19 of these they were able to determine locations based on seismic signals. Of the remaining 30 poorly documented tests, 15 had announced yields that were less than one ton and 13 occurred at the same time as another test that had been detected. There were only two tests, with announced yields of over one ton, for which they were unable to recover seismic signals. This is an impressive achievement, arrived at with seismographs employing old technology. Regional seismic data from seismographs based on new technology will enhance the ability to identify and locate small nuclear tests with a yield of approximately one ton. Large chemical explosions are identifiable because they are usually ripple-fired in a line to enhance the fracturing of rock. In addition, the CTBT provides for voluntary notification of chemical explosions greater than 0.3-kt, which reduces suspicions about them.

Seismic detection of an explosion in a cavity

Very little data is available on nuclear devices exploded in cavities, which is known as decoupling. Coupling of waves to the earth is reduced since pressure is reduced when the wave hits the distant cavity wall.[15] If a nuclear weapon is placed in a cavity of sufficient size, the blast pressure on the cavity wall will fall below the material's elastic limit, which avoids cracking and nonlinear effects. This can reduce the effective seismic yield by a theoretical factor of seven at 20 Hz and 70 at lower frequencies. The only fully decoupled test took place in 1966, when the 0.38-kt Sterling device was exploded in a Mississippi salt cavity with a 17 metre radius (created by the previous 5.3-kt Salmon nuclear explosion). The Soviets carried out a nine kiloton test in the Azgir cavity in western Kazakhstan in 1976, but it was only partially decoupled, as the weapon was too large for the cavity's 36 metre radius (created by a previous 64-kt test).[16]

If the blast pressure exceeds the elastic limit of the cavity wall, sufficient energy is absorbed to crack it, increasing coupling to the wall, and thereby increasing the seismic signal. Critical cavity size depends on the explosion depth, but it is usually assumed to be about one kilometre.[17] From this, a 70-kt explosion needs a cavity radius of 60–100 metres (equivalent to a 25-story building) to achieve full decoupling, an extraordinary engineering challenge when one considers the secrecy required to carry out such a test clandestinely. Even if such a test is conducted without radiation being leaked, it would have an amplitude that could easily be detected and identified by the IMS network.

Most cavities of such large sizes are close to the earth's surface. If a cavity is constructed less than one kilometre from the surface, the cavity size must be increased. For example, the critical radius for a one kiloton explosion is at least 30 metres at a depth of 600 metres. This is twice the size of the oft-quoted 15 metre radius at greater depth.[18] It is cheaper to construct non-spherical cavities than spherical ones. However, if a cavity is too asymmetric, the cavity area closest to the weapon is exposed to pressures over 150 atmospheres, raising the likelihood of radioactive releases. The portion of the cavity wall that is closest to the explosion will also experience considerably more radiation, increasing the likelihood that an ablation shockwave from the vaporized cavity wall will produce a detectable seismic signal.

Other monitoring technologies

In addition to seismic monitoring, the IMS will deploy 60 infrasound stations capable of detecting a nuclear test below 0.5-kt in the atmosphere. The IMS will also deploy 11 hydroacoustic stations capable of detecting nuclear tests in the world's oceans, mostly to less than one-millionth of a kiloton yield (one kilogram). (In the worst case, the threshold would be 60 kilograms yield.) Explosions in the ocean are readily detectable, since water is almost incompressible, allowing acoustic energy to propagate with little attenuation.[19] The IMS will also deploy 80 radionuclide stations that can detect atmospheric nuclear tests above a threshold of 0.1 to one kilotons. Recent progress, such as the increased ability to detect radioactive xenon, should lower these thresholds.[20]

As well as these internationally owned and operated means of verification, several nations now have their own National Technical Means (NTM) to monitor the CTBT, including satellite reconnaissance of many types, electronic intelligence (ELINT), human intelligence (HUMINT) and other '-ints'. The CTBT allows states to submit such data from NTM to the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) in Vienna, Austria, if a non-compliance concern arises. Instruments on satellites produce images using optical, infrared and radar technologies. The US has optical bhangmeters on some of its satellites to detect characteristic, double-peak optical signals from atmospheric explosions. Other sensors on satellites monitor nuclear tests in the atmosphere and space by detecting gamma rays, x-rays, neutrons and electromagnetic pulses. Data from IMS and NTM technologies can be combined synergistically to enhance monitoring sensitivities. The fear of being spotted by IMS and NTM technologies should deter most states from cheating, and these measures will be buttressed by on-site inspections (OSIs) in case of suspicious events.

Interferometric synthetic aperture radar

Information on a new CTBT monitoring technology was published in December 2003 by Paul Vincent et al.[21] Signatures of three underground nuclear tests from 1992–93 were obtained using unclassified data from interferometric synthetic aperture radar (INSAR) operated by the European Space Agency (ESA). A synthetic aperture radar (SAR) has been used to obtain detailed pictures of Venus in spite of the planet's dense cloud cover. A SAR satellite transmits and receives reflected radar pulses as it moves along its flight path, effectively creating a large aperture antenna. A greater amount of time for collection leads to the procurement of more data for computer analysis, which increases the effective size of the radar antenna. This results in SAR radar images with a higher resolution.

INSAR combines individual SAR images acquired from nearly identical viewing geometries by 'beating' the image pixels obtained before and after an underground nuclear test against each other (known as 'interfering') to obtain an interference pattern. The fringe pattern corresponds to topography (which can be removed) plus any change in topography (deformation) that may have occurred between image acquisitions. This allows for measurements of subsidence of the earth after such a test to within 0.5 centimetre accuracy. This approach is successful whether or not a visible crater is formed. INSAR data currently have a horizontal resolution of better than 30 metres, which is much smaller than a typical crater size, which have radii of more than 100 meters. A typical radar frame covers 100 kilometres by 100 kilometres (100,000 square kilometres), sufficient to search wide areas.

INSAR data can also determine the 'relaxation' rate, the rate of slow subsidence over longer periods. This approach can locate older tests carried out prior to the existence of INSAR data. This has allowed Vincent and his colleagues to locate and characterize 12 additional explosions, as well as a dozen or so others nearby, at locations where there was no INSAR data prior to the explosion. Initial measurements of the subsidence rates varied between 0.43 and 6.95 centimetres per year. These fluctuated widely because of the different geology, the different nuclear explosion situations and the different time histories. They also measured the reduction of subsidence rates over time, giving exponential decay time constants, in most cases, of 0.01 to 0.06 per year.

Long-term subsidence occurs as underground rock damage above the explosion cavity relaxes over time, as the pressure head naturally subsides. When underground tests were conducted near confined aquifers (for example in the Yucca Flat region of the Nevada Test Site (NTS), Vincent et al. found that the water pressure head, initially over-pressured by the underground nuclear tests, relaxed from 1,400 feet to 1,250 feet between 1992 and 1999.

INSAR will be a powerful tool for accurately directing OSI teams to the correct location (within 50–100 metres) to enable them to collect radioactive proof that a nuclear test has taken place. The CTBT requires that the proposed area for an OSI must be less than 1,000 square kilometres. INSAR more than fulfils this requirement. It will be interesting to discover the ultimate sensitivity of INSAR in detecting small nuclear tests. Overall, INSAR will be an important addition to CTBT monitoring.

Conclusion

The NAS panel concluded that tamped explosions in hard rock can be detected with high confidence in Eurasia, North Africa and North America at yields of over 0.1-kt. On evasive testing, the panel concluded that: 'the only evasion scenarios that need to be taken seriously at this time are cavity decoupling and mine masking'.[22] It considered many issues that affect the probability of successfully hiding a nuclear test in a cavity. For example, covert testing is complicated by the possibility of radioactive gases from the explosion venting, which can easily be detected. Thirty per cent of Soviet nuclear tests vented, while the US experienced severe venting problems during its first decade of underground testing. Venting from smaller tests is often harder to contain than venting from larger ones: the last four US tests that vented had yields of less than 20-kt. The tendency to vent at lower yields may be explained by the hypothesis that smaller explosions may not adequately enclose cavities with glassified rubble, and the cavities may not rebound sufficiently to seal fractures with a stress 'cage'.

The NAS panel noted seven situations that need to be mastered or avoided by nations that conduct covert nuclear tests:

- all radioactive gases and particles must be trapped;
- accurate estimates of the explosive yield must be made to avoid yield 'excursions';
- materials removed to create a test shaft and cavity must be hidden from satellites;
- crater and surface changes due to testing must be hidden from INSAR and other technologies;
- the cheater must avoid the detection of weaker seismic signals by closer regional seismographs;
- a series of nuclear tests must be conducted to develop significant nuclear weapons; and
- the cheater must prevent the detection of human and other intelligence that can provide unexpected information that reveals test preparations.

The probability of hiding a covert test is the product of the probabilities of success of each of the individual tasks involved. For example, if violators are 100 per cent successful in respect of four tasks, and only 90 per cent successful with regard to three tasks, they will be only 73 per cent successful at hiding the test.[23] For this reason, the NAS panel did not use a decoupling factor of 70 times the 0.1-kt limit to obtain a maximum cheating limit of seven kilotons. Rather, '[t]aking all these factors into account and assuming a fully functional IMS, we judge that an underground nuclear explosion cannot be confidently hidden if the yield is larger than 1 or 2 kt'. This limit could be further reduced by about 50 per cent (0.25 m_b units) if the 120 IMS auxiliary stations were to report continuously to the IMS network, instead of reporting only on request. The use of additional close-in regional seismic stations near areas of concern would lower the detection threshold further.

Despite the high probability that a clandestine nuclear test would be detected, the question still arises as to what practical benefit a state conducting such a test would obtain in terms of acquiring or enhancing its nuclear arsenal. According to the NAS report, nations with less nuclear testing experience than the five nuclear weapon states recognized by the 1968 Nuclear Non-Proliferation Treaty (NPT) could use small clandestine nuclear tests (one to two kilotons) to carry out equation of state studies to determine the compressive properties of plutonium. In addition, these states could: carry out high-explosive lens experiments; certify bulky inefficient unboosted fission weapons (gun-type weapons, without deuterium and tritium); conduct one-point safety tests; make limited improvements to unboosted fission weapons; and perform proof tests of compact weapons with yields of up to one to two kilotons (with difficulty and without an excursive yield).[24] Countries with considerable nuclear testing experience (the five nuclear weapon states) could also partially develop new primaries for thermonuclear weapons through small clandestine nuclear tests. They could also validate designs for unboosted fission weapons with yields of up to 0.1-kt. The CTBT thus prevents the development of low-yield boosted fission weapons and the full testing of primaries for fission weapons over one to two kilotons and thermonuclear weapons.

Arms control treaties must be shown to be effectively verifiable before the US Senate will ratify them. By using the definition of effective verification employed by Nitze for the INF treaty and Baker for START I, the CTBT can be shown to be effectively verifiable. Seismic monitoring by the IMS can detect tamped, underground nuclear explosions to levels less than 0.1-kt. This is an improvement of a factor of ten over the one-kiloton level that was originally projected for the IMS system. When the NAS panel took all factors into account, it concluded that muffled explosions detonated in cavities can be detected to a level of one to two kilotons. Regional seismic stations, placed closer to national test sites, can further improve these results. The declassification of interferometric synthetic aperture radar results shows that surface subsidence from nuclear testing can be measured to within 0.5 centimetres. This new tool nicely complements CTBT monitoring technologies (seismic, infrasound, hydroacoustic and radionuclide) and NTM. In terms of the potential gains from successful clandestine tests, the NAS panel concluded that: 'Very little of the benefit of a scrupulously observed CTBT regime would be lost in the case of clandestine testing within the considerable constraints imposed by the available monitoring capabilities'.

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Endnotes

1 The author is grateful to Paul Richards, Lynn Sykes and Paul Vincent for comments on the draft manuscript.

2 The zero threshold was chosen because a finite limit, for example, of one kiloton (kt), has the effect of legalizing testing below that level. In addition, the determination of whether a particular test exceeds a threshold limit adds potential for error, which can become politicized, as it did in the case of the 1974 Threshold Test Ban Treaty (TTBT). Monitoring the 150 kiloton threshold yield of the TTBT was complicated by geological differences in the tectonic plates of the former Soviet Union and the United States at the test sites. The seismic magnitude of a body pressure wave is $m_b = a + b + c \log Y$, where m_b is the magnitude of a one-Hertz (Hz) body wave, a is the 4.1 magnitude of a one kiloton explosion, b is the bias correction for a test site, c is the slope of 0.74 and Y is the yield in kilotons. A 150-kt yield at the Nevada Test Site has an m_b of 4.1 + 0.74 log150, which equals 5.71 (4.1 + 1.61), while a 150-kt explosion at the Soviet Semipalatinsk site with a bias of 0.4 is 6.11. The US initially and incorrectly assumed that there was no bias between the two sites ($b = 0$), which gave a false impression that a Soviet explosion at 6.11 m_b was a violation with $Y = 10^{[(6.11 - 4.1 - 0)/0.74]} = 520$-kt. Later a value of $b = 0.2$ was used, but this was also too low. The incorrect US assessment of 'likely violation' of the TTBT by the former Soviet Union greatly hindered negotiations on the CTBT.

3 For further information on the CTBT, see the websites of the Comprehensive Nuclear Test Ban Treaty Organization (www.ctbto.org), the Independent Commission on the Verifiability of the CTBT (www.ctbtcommission.org), the Coalition on the CTBT (www.clw.org/pub/clw/coalition/ctbindex.htm), the US Department of Energy/National Nuclear Security Administration (www.nemre.nnsa.doe.gov/cgi-bin/prod/shared/index.cgi), Incorporated Research Institutions for Seismology (www.iris.edu) and the American Geophysical Union (www.agu.org/sci_soc/policy/test_ban.html).

4 National Academy of Sciences, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty,* National Academy Press, Washington, DC, 2002. Further details can be found in David Hafemeister, *Physics of Societal Issues,* Springer Verlag and American Institute of Physics Press, New York (forthcoming 2005).

5 Classified meetings were held at the Department of State, the Department of Energy and the NAS in Washington, DC, and at the Lawrence Livermore National Laboratory in Livermore, California, with representatives of the US nuclear weapon laboratories, the intelligence community and the Department of Defense's Strategic Command, as well as with other government and non-government scientists.

6 Condition 7 of the Strategic Arms Reduction Treaty (START) Resolution of Ratification (October 1992) required President George H. Bush to file a report (a) listing all violations of nuclear arms control treaties, (b) listing reductions in nuclear arms under the arms control treaties, and (c) comparing the military significance of the actions listed in (a) and (b). The report clearly shows that the military significance of the cuts far outweighed the military significance of the violations.

7 US Senate Committee on Foreign Relations, *The START Treaty*, Executive Report 102-53, September 18, 1992, Washington, DC, pp. 27.

8 Lynn Sykes, 'Four decades of progress in seismic identification help verify the CTBT', *EOS*, *Transactions of the American Geophysical Union,* vol. 83, no. 44, 29 October 2002, pp. 497–500.

9 The seismic m_b magnitude units are for one Hz pressure waves that travel through the body of the earth.

10 Oliver Meier, 'Nuclear test ban verification: work in progress', *Verification Yearbook 2000,* Verification Research, Training and Information Centre (VERTIC), London, 2000, pp. 25–41; Trevor Findlay and Oliver Meier, 'Test ban verification: technical progress confronts political uncertainty', *Verification Yearbook 2001,* VERTIC, London, 2001, pp. 43–60; Oliver Meier, 'CTBT verification: technical progress versus political stasis', *Verification Yearbook 2002,* VERTIC, London, 2002, pp. 37–52; Hein Haak and Laslo Evers, 'Infrasound as a tool for CTBT verification', *Verification Yearbook 2002,* VERTIC, London, 2002,

pp. 207–221; Christine Comley and Owen Price, 'CTBT radionuclide verification and the British laboratory', *Verification Yearbook 2003,* VERTIC, London, 2003, pp. 141–150.

11 Ben Mines, 'The Comprehensive Nuclear Test Ban Treaty: virtually verifiable now', VERTIC Brief, 3 April 2004. Data obtained from the CTBT Provisional Technical Secretariat, Vienna, Austria (26 primary seismic, 11 auxiliary seismic, four hydroacoustic, 17 infrasound and 23 radionuclide).

12 All of the IMS seismic stations have modern, high-quality sensors. This means that they have 'broadband' sensors that can detect the teleseismic surface and body waves, as well as the higher-frequency regional waves. They digitally record the motions in three directions (up/down, north/south and east/west). Many of the IMS stations have arrays of sensors that detect the vertical components. The arrays consist of five to 30 sensors with high-frequency response that are spread over several square kilometres.

13 National Academy of Sciences, p. 39.

14 Vitaly Khalturin, Tatyana Rautian and Paul Richards, 'A study of small magnitude seismic events during 1961–1989 on and near the Semipalatinsk Test Site, Kazakhstan', *Pure and Applied Geophysics*, vol. 158, pp. 143–171, 2001.

15 Lynn Sykes, 'Dealing with decoupled nuclear explosions under a CTBT', in Eystein Husebye and Anton Dainty (eds), *Monitoring a Comprehensive Test Ban Treaty,* Kluwer Academic Publishers, Dordrecht, Netherlands, 1996, pp. 247–293.

16 The cube root of yield ratio (64-kt/5.3-kt) is 2.3. The Salmon crater radius of 17 metres times the 2.3 yield factor is 39 metres, close to the Azgir radius of 36 metres.

17 One expects that the critical radius R_c is proportional to $Y^{1/3}$, since the work required to fill the volume of the cavity to a critical pressure is proportional to the yield, or $Y \alpha P\Delta V \alpha R_c^3$. A quick (adiabatic) expansion gives a critical *radius for decoupling* that increases with yield to the third power, according to R_c = (15–25 meters)$Y^{1/3}$, with Y in kilotons. The partial decoupling at Azgir (nine kilotons in a cavity with radius of 36 metres) implies that the 15 metre lower-bound estimate is too low.

18 Lynn Sykes, 'False and misleading claims about verification during the senate debate on the CTBT', *Public Interest Report,* vol. 53, no. 3, Federation of American Scientists, Washington, DC, www.fas.org/faspir/v53n3.htm.

19 National Academy of Sciences. See Figures 2-2 to 2-6 (pp. 52a–52f) for graphical representation of thresholds.

20 Theodore Bowyer, Keith Abel, Charles Hubbard, Mark Panisko, Paul Reeder, Robert Thompson and Ray Warner, 'Field testing of collection and measurement of radioxenon for the Comprehensive Test Ban Treaty', *Journal of Radioanalytical and Nuclear Chemistry,* vol. 240, 1999, pp. 109–122.

21 Paul Vincent, Shawn Larson, Devin Galloway, Randell Laczniak, William Walter, William Foxall and John Zucca, 'New signatures of underground nuclear tests revealed by satellite radar interferometry', *Geophysical Research Letters,* vol. 30, 2003, pp. 2141–2145.

22 National Academy of Sciences, pp. 57–59.

23 The probability of total success in hiding a covert test is the product of all of the success probabilities for each individual task. For I tasks, each with a success probability of P_I, the total success is $P_{success} = \prod_I P_I$

24 National Academy of Sciences, pp. 61–68.