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Verification of a Comprehensive Test Ban Treaty from Space: A Preliminary Study

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Verification of a Comprehensive Test Ban Treaty from Space: A Preliminary Study

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Preface

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The Institute's work, which is based on the provisions of the Final Document of the Tenth Session of the General Assembly, aims at:

1. Providing the international community with more diversified and complete data on problems relating to international security, the armaments race and disarmament in all fields, particularly in the nuclear field, so as to facilitate progress, through negotiations, towards greater security for all States, and towards the economic and social development of all peoples;

2. Promoting informed participation by all States in disarmament efforts;

3. Assisting on-going negotiations on disarmament and continuing efforts being made to ensure greater international security at a progressively lower level of armaments, particularly nuclear armaments, by means of objective and factual studies and analyses;

4. Carrying out more in-depth, forward looking and long-term research on disarmament so as to provide a general insight to the problems involved, and stimulating new initiatives for new negotiations.

In publishing this series of research papers, UNIDIR wishes to make available to the international diplomatic as well as scientific community analyses prepared by the staff of the Institute or persons working within its framework who express their personal points of view on current questions. The papers will deal with a very broad range of subjects and will vary in scope, depending on the evolution of security, disarmament and arms limitation problems, as well as on the specialization of the authors, although it will invariably be related to the Institute's programme of work.

UNIDIR takes no position on the views and conclusions expressed in these papers which are those of their authors. Nevertheless, UNIDIR considers that such papers merit publication and recommends them to the attention of its readers.

Sverre Lodgaard
Director, UNIDIR

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I. Introduction

The first destructive use of the enormous amount of energy released when atoms of uranium disintegrate was carried out merely six years after the discovery of nuclear fission. The first nuclear weapon, called Trinity, tested on 16 July 1945 by the USA, used plutonium. The weapon, placed on top of a steel tower 30 m high, had an explosive power of 21 kiloton (kt) or an energy equal to about 21,000 kg of TNT.[1] However, the weapon that flattened most of the city of Hiroshima three weeks later on 6 August 1945 was an untested uranium weapon with an explosive power of about 13 kt. A duplicate of the Trinity bomb was dropped on Nagasaki only three days later. This one was a 23 kt bomb. All of these devices were fission weapons. Some seven years later the USA tested its first thermo-nuclear weapon on Eniwetok Atoll on 1 November 1952, soon to be followed by the then Soviet Union. The US weapon had a yield of 10.4 megaton (Mt). The Soviet Union tested its first fission weapon placed on top of a tower on 29 August 1949 and the first fusion weapon on 12 August 1953. The testing continued in spite of the desire from the political leaders to control or even to stop the development of nuclear arms.

One manifestation of this was the proposal made by the US President Eisenhower in his now famous Atoms for Peace speech to the United Nations General Assembly on 8 December 1953. In this he proposed to "begin to diminish the potential destructive power of the world's atomic stockpiles." Not only this but he also proposed "to begin now and continue to make joint contributions from their stockpiles of normal uranium and fissionable materials to an International Atomic Energy Agency... The Atomic Energy Agency could be made responsible for the impounding, storage, and protection of the contributed fissionable and other materials."

By the end of 1953, the USA and the Soviet Union had conducted 11 and six nuclear tests respectively. Concerns over the contamination of the environment began to emerge by about 1954 due to atmospheric tests. For example, the world's second largest thermo-nuclear explosion at Bikini Atoll carried out by the USA on 1 March 1954, resulted in very serious radioactive fall-out delivering very large doses of radiation to hundreds of inhabitants of Marshall Island. Unfortunately the captain of a Japanese fishing vessel in the vicinity, the Lucky Dragon, received lethal radiation dose and eventually died. His crew also

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[1] One kiloton is equivalent to 10^{12} calories of explosive energy.

received high doses of radiation. The desire to control further proliferation of nuclear weapons and to avoid more contamination of the environment, contributed to the first international proposal for a complete ban on testing nuclear weapons in April 1954 by India.[2] Since then, many studies, both at international and national levels, were carried out on the question of nuclear test ban. There were two major considerations in the debate on this issue; one was whether such a measure was in the national interest and the second was whether such a ban could be adequately monitored. For years the issue dragged on. An examination of the reasons for this falls outside this study. There are a number of adequate accounts of the history of negotiations and other relevant issues for a nuclear test ban.[3] Suffice it to say that inability to verify a treaty has been given as a main reason for not achieving a comprehensive test ban treaty (CTBT). This was in spite of such conclusions as "that a nuclear test ban was in the best interests of the United States - and of all mankind - and to think that such a ban could probably be adequately monitored."[4]

The Partial Test Ban Treaty (PTBT), which prohibited nuclear tests in the atmosphere, under the sea, and in outer space but allowed underground testing, was signed in 1963 with the hope that it would lead to a CTBT which would prohibit all testing in any environment and with any yield. Instead two partial measures were signed in 1974 and 1976 by the USA and the former USSR and ratified only in 1990. These were the Threshold Test Ban Treaty (TTBT) and the Peaceful Nuclear Explosion Treaty (PNET) respectively. The former prohibited testing underground explosions with yields exceeding 150 kt. The PNET prohibited yields of a single peaceful nuclear explosion above 150 kt. A "group explosion" may exceed the 150-kt limit and reach an aggregate yield as high 1,500 kt. Under the PTBT, no limits were placed on the yield but the treaty would be violated if any radioactivity leaked "outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted." (article I.1b)

During the summit between Presidents George Bush and Mikhail Gorbachev in December 1987, an agreement was reached to reduce the numbers and sizes of nuclear explosions. In 1988, negotiations began to set these limits and in June

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[2] *Official Records of the Disarmament Commission*, Supplement for April, May and June 1954, Document DC/44 and Corr. 1.

[3] Examples of these are H. York, *Making Weapons, Talking Peace*, New York: Basic Books, Inc., 1987; *The United Nations and Disarmament 1945-1970*, New York: UN, 1970; and T. Schmalberger, *In Pursuit of Nuclear Test Ban Treaty - A Guide to the Debate in the Conference on Disarmament*, UNIDIR, Geneva: United Nations, 1991.

[4] *Ibid.*, York, p.119.

1990 two protocols were signed and soon ratified. The protocol to the TTBT includes the right to place seismic detectors in the country being monitored for test above 50 kt and on-site inspection for tests above 35 kt. To ensure that parties are keeping within these limits, seismometers are placed at the test sites in the country being monitored.

Discussions on verification during these negotiations always focused on the national technical means (NTM). he latter consists of methods of collecting information using technical equipment not dependent on any cooperation by other countries. However, by and large, this has been classified and not generally available to others. Both the USA and the USSR were reluctant to share their NTM capabilities with others and when they shared information, it was with their closest allies only. In view of this, any future verification methods should take into account its availability to others if a potential multilateral CTBT is to be achieved. One such method is seismology, the corner stone of the debate on verification of a partial or a complete test ban treaty.

While much of the national seismic capabilities are still classified, enough is known about the basic technology involved and the capabilities of some of the international seismic arrays. Thus, for comparison, a brief review of this technique is useful. This is given in the appendix.

However, it should be remembered that under the bilateral the above accords, the USA and Russia could install seismometers at each others nuclear test sites while other states cannot establish a seismic network in the country to be monitored without specific agreements. Thus, they would have to depend on the two powers for information or establish a different non-intrusive method such as observations from outer space. It should be remembered that under a CTBT it may be necessary to detect the preparations for a test in order to prevent its occurrence. Should the detection of the preparation escape, it would be essential to determine that a test has taken place and its location. There will be no requirement for the knowledge of the yield. Then, in most cases, a considerable contribution could be made by observations from satellites.

In the following section a brief review of some of the existing and potential satellite-based techniques for monitoring nuclear tests is given.By and large the former belong to the USA and Russia so that the information gathered by such satellites is not generally available. Therefore, the use of commercial observation satellites is examined. It is indicated that observation satellites have been used in the past to observe preparations for a test. Thus, the role of such spacecraft is illustrated by monitoring preparations of some recent nuclear tests and some actual tests by observing their effects on the test site.

II. Monitoring Nuclear Tests in the Atmosphere and in Space by Satellites

The vast amount of energy released from a nuclear weapon originates from the nuclei of the nuclear explosive material. The rate at which nuclear processes take place is so great that nearly all of the energy is released in approximately one millionth of a second (or in about one microsecond). This energy is in the form of thermal (and light) radiation, blast and shock waves and nuclear (initial and residual) radiations consisting of gamma rays, X-rays, neutrons and charged particles as well as fission and fusion products. This accounts for about 90 percent of the total energy from a fission explosion in the lower atmosphere and up to 95 percent from a thermo-nuclear explosion. The residual radiation, consisting mostly of gamma rays and charged particles, continues to be released over a very long period (years). The distribution of energy from fission weapon exploded in the atmosphere at an altitude of about 30 km, for example, is shown in Figure 1. These proportions can be varied with different designs of the weapon. It is worth remembering that while long-lived fission products remain in the atmosphere or settle to the ground, thus can be detected by air sampling or monitoring of the surface for a long time after the explosion. On the other hand, for an underground burst, which is the most likely type to be employed in a clandestine nuclear test, the heat and nuclear radiation is absorbed in the earth and, therefore, do not propagate into space.

Thus, all the detection methods for a nuclear explosion in the atmosphere and in space depend on direct detection of some of these energies or the detection of their effects. A seismograph detects the effects resulting from the blast and shock waves in the earth. Many ground- and air-based systems depend on the detection of acoustic waves and sampling of debris. The latter can then be analysed by radio-chemical techniques which would provide a conclusive evidence of a nuclear test. It should be remembered that this technique could also detect nuclear explosions other than intentional controlled tests. An example of this is an accident at a nuclear reactor or a reprocessing facility. The gamma rays (or prompt gamma rays), emitted from the nuclear explosion and those produced by neutron interactions with the remaining material of a weapon or the surrounding medium, interact with air atoms and molecules to produce a sharp and relatively short but high intensity pulse of electromagnetic radiation called an electromagnetic pulse (EMP). The duration of an EMP is shown in Figure 1; the time sequences and duration of gamma rays and neutrons are also indicated. The processes which result in the production of an EMP are complex. Essentially, on absorption of gamma rays, electrons are removed from the atoms of the medium surrounding the explosion producing charged atoms or ions. The electrons move away from the ions and the rapid motion of these charged particles create intense electric and magnetic fields propagating outwards from the point of explosion at the speed of light. Thus, detection of EMP (or acoustic) signals provide the time of explosion to better than an hour, the approximate yield and height of the burst and the location of the explosion to within a circle of about 160 km. Nuclear explosions also produce changes in the magnetic field[5] and induce electric current[6] in the ground. The latter can be detected at considerable distances using telluric equipment consisting essentially of two electrodes embedded in the ground. Changes in magnetic fields, for example due to underground explosions, can be detected and measured using magnetometers on board satellites or on the ground. Moreover, microbarographs can detect changes in atmospheric pressures also.

An atmospheric nuclear test also generates an intense characteristic flash of light. This is due to the fact that a pulse of light, produced when X-rays heat the surrounding atmosphere to many thousands of degrees, escapes briefly the nuclear fireball. This initial light is blotted out for a short period because of the shock wave. It reappears as a second pulse but now considerably more intense than the first one - almost one hundred times more. The shape of this double light pulse is indicated in Figure 1. Such a light distribution curve is obtained from all atmospheric nuclear explosions conducted at an altitude below about 30 km. While the shape of the curve in Figure 1 remains the same for explosive yields other than 19 kt, the time at which the maxima and the minimum of the curves occur will be different. For an explosion of 19 kt these occur at 0.3 ms (about a third of a thousandth of a second), 130 ms and 12 ms for the first and the second peaks and the trough respectively (see Figure 1). The times at which the minimum and second peak occur are directly related to yield.[7]

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[5] "Magnetic Events Occurring Within Two Seconds After Nuclear Detonation; Upper Atmospheric Physics Laboratory, AFCRL", *Research Reviews*, Vol. 6, No 6, Office of Aerospace Research (OAR), June 1967, pp.16-17; and J.R. Johler and J.C. Morgenstern, "Propagation of Ground Waves Electromagnetic Signals with Particular Reference to a Pulse of Nuclear Origin", *Proceedings of the IEEE*, Vol. 53, No 12, December 1965, pp.1921-34.

[6] S.D. Abercrombie, "Ground Based Detection of Atomic Weapons", *IEEE Transactions on Nuclear Sciences*, NS-10 (1), January 1963, pp.254-72; and "High Altitude Nuclear Explosion Detected with Simple Equipment", *Naval Research Reviews*, Vol. 15, No 9, September 1962, pp.23-25.

[7] G.E. Barasch, "Light Flash Produced by an Atmospheric Nuclear Explosion", *Los Alamos Scientific Laboratory Report LASL-79-84*, November 1979.

Thus, nuclear explosion detection devices based in space consist of various types of detectors such as for example gamma ray detectors. The high degree of vacuum in space allows the radiation and fission products from a nuclear explosion in this environment to expand freely, unlike explosions in the earth's atmosphere. However, the presence in space of Van Allen radiation belts and solar flares complicates the detection of radiation by this technique. If a nuclear explosion takes place in the Van Allen belts, radiation caused by the explosion may not be detected by the devices on-board the satellites because there is already a very high level of radiation present in the belts.

To use satellites effectively to verify the observance of a complete test ban treaty, other techniques are required. A nuclear explosion produces many phenomena which may be used for the purpose. Beside the radiation detectors, for example, satellites could, and probably military spacecraft do, carry optical instruments which analyse the emission spectra of the most abundant chemical elements of the nuclear bomb or its fission products. Such a technique of detecting an explosion in space or in the atmosphere would not be hampered by radiation belts. Devices sensitive to X-rays, gamma rays and neutrons are used for detection of nuclear explosions in space. Moreover, an optical instrument called a "bhangmeter" detects and records the characteristic double flash from an atmospheric test.

Such devices have been deployed on-board US spacecraft called Vela satellites. The Russian satellites may have similar sensors. Each Vela satellite carries two bhangmeters which have different sensitives in order to cope with a wide range of light intensities. Between 1963 and 1970, the United States orbited 12 such satellites to monitor nuclear explosions in the atmosphere and in outer space. The first six satellites had sensors to scan deep space only. The remaining six had sensors pointing towards the earth. These were orbited at altitudes of some 110,000 km. However, only Vela 12, launched on 8 April 1970, may still be operating. This satellite detected what may have been a low-yield nuclear explosion over the sea in the South Atlantic near the South African cost on 22 September 1979. The characteristic double light flash was observed by the bhangmeter on board the satellite. The explosion was estimated to be between 2 and 4 kt in yield. However, the sensor on board the spacecraft could not accurately locate the position of the explosion.

A group of experts was appointed by the US Government to determine whether or not any other phenomenon could have produced the signals in the satellite sensor.[8] It was concluded that there was no malfunction of instruments and that the signal was due to a natural phenomenon occurring close to the spacecraft. This has been disputed.[9] In 1980, reports from South Africa, based on US intelligence information, stated that another nuclear explosion might have occurred on 16 December 1980, again in the South Atlantic region. This time it was a US early warning satellite which had registered a flash of light in the region, but it was reported that a large meteor entering the atmosphere caused this phenomenon.[10] It is interesting to note that when examining all references to the first explosion, no mention was found on data collected from early warning satellites. The mysterious flashes still remain mysterious.

In this context, it should be noted that under the US early-warning satellite programme, the Defense Support Program (DSP) initiated in 1966, some DSP satellites carried nuclear detection (NUDETS) devices on board to detect radiation from nuclear explosions.[11] The main purpose of such spacecraft is to detect launches of adversary's missiles thus giving an early warning of their approach. These satellites are orbited in the geostationary orbit over the earth's equator. They remain stationary relative to the earth. Usually, under the operational condition, three DSP spacecraft are orbited in such an orbit and placed over South America, the Central Pacific and the Indian Ocean. The NUDETS fly as piggy back. The development and production of the NUDETS sensors was funded by the Department of Energy. From the early 1980s, the NUDETS were orbited as piggy backs on board a series of satellites under the Defense Meteorological Satellite Program (DMSP). The main mission of the DMSP spacecraft was to collect detailed information on the atmospheric condition in order, for example, to predict clear weather for bombing and photographic reconnaissance missions.

While NUDETS were deployed on board DSP satellites from as early as 1971 (see Table 1), the USA planned to deploy nuclear explosion detection devices on-board their navigation satellites called the global positioning system (GPS) since

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[8] *UN document A/34/674*, Annex II, Appendix, 12 November 1979.

[9] G.E. Barasch, "Light Flash Produced by an Atmospheric Nuclear Explosion", *Report LASL-79-84*, Los Alamos, New Mexico: Los Alamos Scientific Laboratory, November 1979.

[10] "Early-Warning Satellite Picked up Flash Over S. Atlantic", *Defense Daily*, Vol. 114, No 34, 23 February 1981, p.271.

[11] C.R. Whelan, *Guide to Military Space Programs*, Arlington, VA: Pasha Publications Inc., 1994, p.81.

1979 (see Figure 2).[12] The first The first Integrated Operational Nuclear Detonation System (IONDS), developed under the Air Force funds, was deployed on board the GPS spacecraft in 1983 (see Table 1). Initial feasibility of IONDS was conducted during early 1975. The reported capability of such devices to locate an atmospheric explosion is such that "with the GPS fully deployed, and with so-called IONDS, the NUDET detection capability on board, to be able to detect nuclear detonations within 100 meters.".[13] After the full deployment of the GPS system, there are no reasons to believe that this the accuracy is any different today. Orbiting of more advanced radiation detectors (ARD) began in mid-1989.

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[12] "GPS to Test Nuclear Detonation Sensor", *Aviation Week & Space Technology*, Vol. 111, No 9, 27 August 1979, p.51.

[13] Testimony of Brig. Gen. B.P. Randolph, in US Congress, Senate Committee on Armed Services, *Department of Defense Authorization for Appropriations for Fiscal Year 1983*, Hearings before the Committee on Armed Services, S.815, 97th Congress, 2nd session, 1982, pp.4624-4625.

III. Monitoring Underground Nuclear Tests from Space

It is useful to consider briefly what is needed to prepare images before actually embarking upon their analyses.

1. Some Basics of Image Processing and Interpretation

In electro-optical systems, signals are transmitted directly to a ground station for processing if the satellite is in line of site or they can be recorded on a tape recorder or relayed via satellites. The signals are converted into images and processed for interpretation.

Image Processing

Since the information is recorded in digital form, it is transmitted to ground station where computers reconstruct the image. During the reconstruction of the image the computer decodes the binary data and allocates the appropriate tone to each pixel.[14] The image can then be displayed on a monitor screen or as a photographic print. However, at this stage the image is in a basic raw form which needs to be corrected for as number of factors. This is termed image processing.

Initially the data, as acquired from the satellite, has to be corrected for earth's curvature, its rotation and for the errors introduced due to the attitude of the satellite. For change detection, further correction would be necessary. For example, there will still be some geometric distortions resulting in uncertainties of a few kilometres in relative positions of objects in the scene. This is corrected by identifying a number of landmarks such as airport landing-strips and highway intersections on the image and on a map and then calculating least-square fit. The results are then used to correct the whole image. This is called the geometric correction.

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[14] In a scanning device, such as an electro-optical device, the concept of instantaneous field of view (IFOV) has been introduced. The IFOV is defined as the size of the spot on the ground seen by one particular point in the image or seen by a scanning sensor (a picture element or a pixel) at the instant of observation. A scanning device on board a satellite consists of a series of very small light sensors. Thus, when a resolution of a sensor is quoted as 30 m, it means each small sensor of the scanner records an area, or a pixel, 30 m X 30 m on the earth's surface. On the other hand for a photographic camera, the resolving power or resolution may be simply defined as the minimum distance between two identical small objects when they can still be distinguished as two separate objects.

The other aspect of image processing is called contrast stretching. Sensors on board remote sensing satellites are designed with sensitivity over a very wide range of spectral intensity and wavelength of radiation. Thus, a sensor could be used, for example, to monitor very reflective surface of ice and relatively dark surface of forests and vegetation. However, in practice, generally such a wide range of variation does not occur in a scene so that the image often appears murky and even-toned. This is overcome by spreading the recorded reflectance values across the whole of the tonal range available. In this way the distinction between tones becomes much more pronounced. Thus, during the computer processing, the minimum and maximum reflectance values of the pixels present in the image are assigned 0 and 255 respectively and then stretch out the rest maintaining the shape of the reflectance distribution curve. Thus, the tonal gaps between the values are widened. The result is a much more contrasting image. The process is called contrast stretching. In an electro-optical device, because the signal to noise ratio is much higher than that obtained on a photographic film (due to grain), it is possible to stretch the contrast. This would enable more information to be extracted from images from electro-optical devices.

The gradations between 256 different tones are not distinguished by eye. One way of overcoming this is to assign different colours to different tones or a group of tones. Thus, during computer processing, in a particular spectral band, a series of slices across the image are taken and assigned arbitrary a colour to the particular group of digital numbers representing a particular feature. The process is applied to the whole of the image. In this way a rough classification is also obtained. The process is called density slicing.

Apart from the above techniques to improve the ability to extract information and to interpret a digital image, edge enhancement is also used. This is the sharpening of edges to highlight objects of interest.

Image Interpretation

Generally optical and radar sensors are deployed on separate observation satellites. Examples of the former are the French SPOT and the US Landsat satellites, and those of the latter are the European ERS-1 and the Japanese JERS-1 spacecraft. The ERS-1 is operated in the C-band at 5.5 Ghz with a nominal resolution of 30 m while the JERS-1 operates at 1.275 GHz with a resolution of 18 m. While the SPOT satellites carry panchromatic as well as multispectral optical sensors, only the latter is deployed on board the current US Landsat satellites. However, the range of wavelengths over which the sensor is sensitive is much greater for the

Landsat satellites. Spectral sensitivities of some of the civil satellites are shown in Table 2. For monitoring underground nuclear tests, Landsat type data is more useful.

Atmospheric scattering is more pronounced in the visible bands and increases as the wavelengths decrease. These corresponds to Landsat TM bands 1, 2 and 3. Thus, in this report bands 3, 4 and 5 have been used in order to minimise the atmospheric effects. Most vegetation is strongly reflective in the near infrared (IR) (TM band 4). In colour IR photography, healthy forests and fields, for example, appear bright red. Fallow fields appear in grey or blue-grey hues. Coniferous forests appear dark red - sometimes almost black because of their overall low reflectance. Bands 5 and 7 normally measure reflected energy and are moisture sensitive. As plant and soil moisture increase, the amount of energy in these bands reflected by plants and soils decreases. Generally, the wetter the object, the darker it will appear in these bands. The TM sensor collects most thermal information using band 6 which detects emitted energy. However, the resolution is poor (120 m pixel size). Intense heat sources emit energy at shorter wavelengths, making it possible to see emitted energy in TM bands 5 and 7 also.

Combination of visible bands 1, 2 and 3 creates an image which appears normal to the eyes when the three bands are assigned blue, green and red colours respectively. Images collected in the infrared bands 4, 5, 6 and 7 are invisible to human eyes. Data from these bands can be displayed as black and white images or they can be in one or more of the blue, green and red colours as a composite to become visible. The most frequently-used combination displays bands 4, 7 and 3 in red, green and blue respectively.

Interpretation is a process of extracting information from images. The amount of information that can be obtained from a particular image and the accuracy with which it is interpreted depends on the knowledge of the objects and area in the scene and the experience that an interpreter has. The ability to recognize objects depends on such factors as the spectral and spatial resolution, contrast and of the image. Thus, interpretation essentially involves measuring objects in the scene, identifying them and using this and some "collateral information" to answer some specific questions. The latter could, for example, be material from open literature, field work and photo interpretation keys.

Apart from interpretation of images by humans, computer-aided interpretation is becoming very important. This is particularly so in treaty verification now because some of the recent treaties (for example, the INF) require detailed descriptions of weapon facilities and their line drawings. The latter could be computerised enabling the computer to automatically locate and identify a particular facility in a scene. This is called pattern recognition. While such techniques can be used for relatively simple patterns described in the INF treaty, automatic pattern recognition is complex and perhaps the capability is not widely spread in the civil field. This and other factors used in automatic interpretation techniques are summarised in Table 3. Interpretation in this report is interactive so that no automatic computer analyses were carried out.

It can be seen from Table 3 that spatial resolution is a very important factor in image interpretation process. Spectral resolution, when changes in the scene occur and stereoscopic images could also add considerably to the task of interpretation. Examples of these are the detection of the use of camouflage, changes in vegetation from nuclear radiation or the use and testing of biological weapons[15] and chemicals from chemical weapons tests, possible detection of an underground tests for explosives, particularly nuclear, and new constructions such as roads and mining activities. The image interpretation task is carried at essentially five levels: detection which is the discovery of the existence of an object without recognizing it; recognition is the ability to determine the identity of a feature or object in a scene; identification is the ability to place the identity of a feature or object in a scene as a precise type; description requires such items as size, configuration, components construction and count of equipment; and analysis in which precise description of a feature or an object or component in the scene is given. The resolutions of sensors required for these tasks will vary. Most of the time, resolution between 1 m and 30 m (pixel size) would be adequate for monitoring underground nuclear tests.

Before considering the analyses of some satellite imageries to detect underground nuclear tests, it is useful to identify some of the known nuclear tests sites, their locations and sizes. All the five nuclear weapon states conduct their underground tests at such sites.

2. Some of the Known Nuclear Test Sites

At present there are five known nuclear test sites. These are: (1) in the United States, the tests are being carried out at the Nevada test site, some 100 km north-

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[15] M. Goldman, S. Ustin, and E.A. Warman, "Radiation Exposure near Chernobyl Based on Analysis of Satellite Images", *US Department of Energy Report N. UCD-472-510*, December 1987; and K.J.L. Linthicum, C.L. Baily, F.G. Davies, and C.J. Tucker, "Detection of Rift Valley Fever Viral Activity in Kenya by Satellite Remote Sensing Imagery", *Science*, Vol. 235, 27 March 1987, pp.1656-1659.

west of Las Vegas; recent tests have been carried out at the Pahute Mesa, Rainier Mesa and the Yucca Flats in this region; (2) in Russia, currently there is only one site at Novaya Zemlya in the arctic; two other sites were on the Shagan River and at Degelen Mountain, usually referred to as the Semipalatinsk site but testing has now stopped; two other regions in this area where tests have been conducted are Konystan site near a town called Konystan and in the eastern Kazakhstan where most of the atmospheric tests were conducted; (3) the French test sites are in the Pacific at Moruroa and Fangataufa; (4) the PRC tests its nuclear weapons near Lop Nor; and (5) in India one test was carried out near Pokaran in Rajasthan. There are the so called threshold countries[16] which may have potential test sites. South Africa has now joined the NPT so that the question of nuclear weapons testing may not arise but, in 1977, attempts were made to prepare for a test in the Kalahari Desert. While Argentina and Brazil have signed the Tlatelolco treaty, it has been reported that Brazil had drilled 320 m deep shaft in preparation of a nuclear test.[17] The site, managed by the Brazilian Air Force, was located in the Cachimbo Mountain range in the Amazon near the border with the Grosso and Amazonas.

3. Nuclear Test Preparations

Two type of test facilities are prepared: in one a vertical hole is drilled in the ground and the weapon for testing is placed at bottom of it and in the second a horizontal tunnel is constructed and the weapon is placed at the end of the tunnel. The former is the most common method. Tunnel tests tend to be more expensive and time-consuming. In the United States, for example, vertical holes are prepared on the Pahute Mesa to test weapons with large yield while others are conducted on the Yucca Flat (see Figure 5). The tunnel tests are carried out in the Rainier Mesa and Aqueduct Mesa. The latter are usually for evaluating the effects of nuclear weapons on various military equipment and systems. These may include satellites and nuclear warheads. The testing of newly developed weapons are usually conducted in vertical shafts.

Depending on the depth and location of a test, some six to eight weeks are required to drill a hole, the diameter of which can be between 1.5 m to 2.5 m and the depth varies between 50 m to 2,000 m. Thus, at least some 10 thousand cubic metres of dirt and rocks have to be dug out. For horizontal tests, tunnels are drilled

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[16] These include Brazil, Argentina, Libya, Iran, Iraq, Israel, Pakistan, Taiwan, North Korea, South Korea, and South Africa.

[17] R. Bonalume, "Democratic Brazil Says No", *Nature*, Vol. 347, 4 October 1990.

into the rocks on the side of hills or mountains. This can take as long as one year to mine and shift some 30 thousand cubic metres of rocks.[18] The results of a test in either case are transmitted by electrical and fibre-optic cables to trailers placed around the ground zero. These contain recording equipment (see Figure 3). Often a security fence is also placed around the ground zero.

4. Analyses of Images over some Underground Nuclear Tests

Possible use of observations from space to monitor preparations for a nuclear test was first made in 1977. The former Soviet satellites detected the preparation by South Africa of its possible nuclear test in 1977.[19] Although the former Soviet Union did not disclose the source of its information, it is very likely that reconnaissance satellites were involved. Observations by two satellites, Cosmos 922 launched on 30 June and Cosmos 932 launched on 20 July, probably convinced the Soviet Government that South Africa was about to test a nuclear device in the Kalahari Desert.

A study of the ground tracks of Cosmos 922 indicates that it was an area-surveillance type (Figure 4a). It can be seen that the spacecraft made two passes over the presumed test site on 3 and 4 July 1977. It is possible that this satellite first detected the preparations for a nuclear test. The satellite was in orbit for 13 days and a week after its recovery, Cosmos 932 was launched. This was a manoeuvrable close-look type spacecraft (Figure 4b). On 22 July during the 27th revolution, the satellite was manoeuvred and its perigee lowered just before passing over the test area for the first time. This gave four good passes over the test site between 21 and 24 July. The weather conditions during the passes by both the satellites were such that the sky was practically free of clouds. Moreover, both the satellites passed over the region when the Sun was low in the sky so that objects in the desert would cast long shadows, thus facilitating the interpretation of the photographs. Cosmos 932, recovered on 2 August, presumably gave the Soviet experts enough time to analyse the data and inform, via their government, the USA on 6 August. The UK, France and the Federal Republic of Germany were also informed. Because of the pressures from these countries, apparently South

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[18] "The Containment of Underground Nuclear Explosions", *Office of Technology Assessment Report OTA-ISC-414*, US Congress, Washington, DC: US Government Printing Office, October 1989.

[19] It should be remembered that South Africa acceded to the NPT in September 1991 and accepted full-scope safeguards on its nuclear facilities the following year. However, it also declared that South Africa had built some 7? nuclear devices but these have been dismantled.

Africa abandoned its nuclear activities in the Kalahari desert. However, it should be remembered that in March 1993 President Frederik W. de Klerk declared that South Africa had built six nuclear weapons during the 1970s and 1980s. He also said that his government had ordered the dismantling of the weapons.[20]

Based on the above ground track analyses, monitoring from space of activities related to underground nuclear tests was suggested earlier.[21] There are a number of advantages of such observations. First, unlike other methods, it can predict a possible nuclear test so that preventative actions can be taken as was done in the case of South Africa. Second it enables the determination of the location of an explosion to within meters compared with that obtained from the seismic method to within tens of kilometres (see Appendix). Third, it would be difficult to hide from satellites a nuclear explosion in a seismic event. This is because on a multispectral image, an explosion would record a very localised spectral change resulting from the changes in soil chemistry, porosity and subsidence craters whereas a random pattern would appear in the case of an earthquake. Under some geological conditions, underground nuclear explosions carried out in tunnels under mountains can also give rise to spectral changes on the surface above the ground zero.

The detection of an underground nuclear explosion from space is possible because the preparations such as the constructions of roads and the area surrounding the drilling or the entrance to a tunnel can be seen in a satellite image. Moreover, after a test, its effects on the surface of the earth above the ground zero can also be detected. In a nuclear explosion enormous amount of energy is released in about a tenth of a microsecond ($1/10^7$ seconds). The temperature increases to several million degrees Kelvin, and, if it is an underground explosion, the pressure increases to many kilobars. All the material surrounding the explosive is melted and vaporized. The initial cavity thus formed by the explosion expands. A slight upward bulge occurs at the earth's surface above the ground zero and fracturing of the surface begins to occur. Once the cavity stops expanding, the molten materials drain down to the bottom of the drilled hole and the ground surface either returns to its initial level position or a crater may be formed. The latter occurs several seconds or hours or even days later. Thus, in a

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[20] P. Van Niekerk, *Washington Post*, 25 March 1993, pp.A1, A31.

[21] B. Jasani, "Military Satellites", in *World Armaments and Disarmament, SIPRI Yearbook 1978*, SIPRI, London: Taylor & Francis Ltd., 1978, pp.69-103; and B. Jasani and C. Larsson, "Remote Sensing, Arms Control and Crisis Observation", *Int. J. Imag. Rem. Sens. IGS.*, Vol. 1, No 1, 1987, pp.31-41; and "Security Implications of Remote Sensing", *Space Policy*, Vol. 4, No 1, February 1988, pp.46-59.

multispectral satellite image, a localised spectral change can be detected owing to the change in surface structure. Surface fracturing or a crater can also be detected.

It should also be remembered that at present only the USA and Russia can deploy seismic detectors at each others test sites. Therefore, other states have to rely on seismic measurements made from outside the territory being monitored or from satellite data.

Sensors on board satellites could be sensitive in the visible, near and far IR as well as in the radar regions of the electromagnetic spectrum. In this preliminary study, some of the US and Russian underground nuclear tests are examined using four images acquired by the US Landsat 4 and 5 satellites. The aim was to see whether preparations for a test and surface fracturing and cratering after a test could be detected. At present only preliminary results of attempts made to detect subtle spectral changes by using techniques like the density slicing or changes in the amount of light received by the sensors after a test are reported. Thus, the focus has been the use of optical multispectral sensors only. Three Landsat images dated 21 and 29 June 1989 and 14 October 1990 were acquired over the US test site. The names, dates and locations of all the US tests carried out between these dates are shown in Table 4. Images dated 21 June 1989 and 14 October 1990 were acquired by Landsat 5 and that on 29 June 1989 was from Landsat 4. A Landsat 4 scene over the former USSR nuclear test site in Semipalatinsk was also acquired. The scene photographed on 8 March 1989 was analysed. Some preliminary results over this area are also presented in this report.

Figure 5 shows a full Landsat 4 scene over the US nuclear test site. The scene is a composite of bands 2 (red), 3 (green) and 4 (blue). As was mentioned earlier, pixels in a digital image have intensity values ranging from 0 for dark to 255 for light. Thus, a light intensity histogram lists how many pixels have light intensity values of 0, 1, 2, 3, 4, and so on so that, if an intensity verses number of pixels is plotted, the horizontal values of such a distribution histogram would describe the brightness and the width of the histogram would describe the contrast of the image. The contrast stretch performed on the image in Figure 5 had the lower and upper limits of 13 and 184 respectively with the maximum number of pixels having an intensity of 87.

The areas in which some of the tests examined are Pahute Mesa (I), Rainier Mesa (II) and Yucca Flat (III) (see Figure 5). These are located in test areas 19 and 20 (Pahute Mesa), 12 (Rainier Mesa), and areas 3, 7, 9, and 10 (Yucca Flat). From the Table 4 it can be seen that between 21 and 29 June 1989, there were two tests carried out by the USA. The locations, and the depths of the explosives have been published. These tests were carried out in the Pahute Mesa area. Thus, the area I in Figure 5 was extracted from images dated 21 and 29 June 1989 and processed and enlarged. These are shown in Figures 7a and 7b respectively. The images were recorded in bands 2, 3, and 4 (colours blue, green and red respectively were assigned to these bands). The images were stretched between 23-159 for 21/06/89 and between 23-186 for 29/06/89 respectively) so that they appeared very similar. All of these images were enhanced by applying a sharpening filter.

The two tests carried out between these dates were "Contact" on 22/06/89 and "Amarillo" on 27/06/89. The nuclear explosives were placed at depths of 500 m and 600 m and the declared seismometer reading were 5.3 and 4.9 respectively. The seismometer readings suggested that the tests were of low yield weapons. The locations of the two tests were identified at **A** (Contact) and **B** (Amarillo) in Figures 6a and 6b since the coordinates of the tests were declared. A close examination of the area at **A** indicates that after the test, while no crater or fracturing at the site occurred, the surface of the site appeared to have changed to some extent in Figure 6b. Such a change is also noticed in the image even before it was stretched. It may be argued that this difference may be because of the atmospheric effects or even the differences in the calibration of the two instruments on board the spacecraft. The former effect was reduced by studying the site using band 4 only of the two images. The latter possibility exist as the satellites involved are different spacecraft. This was overcome by stretching the two images of Figures 6a and 6b equally. After the stretch for the final images, the histogram of image dated 21 June 1989 had the mean 69.98, standard deviation 24.92 and the median 70 while those for the image dated 29 June 1989 were 70.55, 24,41 and 70 respectively. Thus, the small differences in the images because of different sensors were compensated. As there was only a difference of eight days between the acquisition of the two images, it was assumed that the similar atmospheric conditions existed particularly when the images showed no clouds or haze. A factor that may affect the sensor response is if the images were acquired at different times of the day by the two satellites. However, the study of the orbital elements of the satellites indicate that they have very similar orbits. The right Ascension of the orbits of the two satellites differed by only 1.8^0 and the difference in the argument of perigees of the two spacecraft was about 3^0. These would indicate that the satellites came over the test sites almost at the same time so that there would not be any significant difference in the observation times. Thus, any change in the two images would be most probably due to the tests.

The human eye may not be able to distinguish the gradations in different shades of gray particularly when different tones are very similar. This is particularly true when the changes in images are very small. This was the case for sites **A** and

B which, therefore, were studied using the density slicing technique. The image processor was use to take slices across regions of the image with significant ground features which were not likely to change by human activities. This was used as a control to assign a different colour to represent the different combinations of gray tones characterising each feature. The image processor was then allowed to apply the coding over the whole image. In this it was possible to see changes in images acquired before and after nuclear tests. It was found that after density slicing the control areas in images in Figures 6a and 6b were very similar. The same density slicing was then applied to the test areas **A** and **B**. In this way a false colour image was prepared for the two sites, one before the test and one after (see Figure 7). It can be seen that it may be possible to detect small changes above ground zero due to low yield explosions when placed at some depth.

Consider the images dated 21 June 1989 and 14 October 1990. Over this period of some 16 months, 13 more tests were carried out on the Nevada test site, one of which was for the UK. These are listed in Table 4. The two tunnel tests, Disco Elm and Mineral Quarry are not examined in this report. The test Hornitos was located at **J** in Figures 6a and 9 (dated 14 October 1989). This site appears to be undisturbed in images dated 21 June 1989 and 29 June 1989 (Figures 6a and 6b). However, in the image dated 14 October 1990 (Figure 8), a crater can be detected at **J**. Seismic reading indicated a high yield test (M_b of 5.8). Thus, the existence of crater is not surprising.

In Figure 6a, the beginning of the preparations for the test Bullion can be seen at **F**. This was carried out on 13 June 1990 at a depth of 700 m. Again the test was for a high yield weapon as suggested by seismic measurement (M_b of about 5.8). In this case no crater was formed but considerable soil disturbance had taken place. In the case of the test named Tenabo, carried out on 12 October 1990, again no crater was detected. However, as can be seen in Figures 6a and 8 at **I**, considerable fracturing of the ground may have occurred. The test site appears to be on a level plane surface.

A test for the UK was conducted in area **UK$_1$** (Figure 6a and 8) on 8 December 1989 at a depth of 660 m. In Figure 6a the area for the test can be seen, most probably either ready or being prepared for the test. This is indicated by the clean regular shape of the test area. As was indicated earlier, in the near IR region ploughed but uncultivated fields appear in grey or blue-grey hues. This appears to be the case in Figure 8 at the UK$_1$ site indicating that only the soil disturbance may have occurred due to the test. The area at the site also appeared to have increased. A site UK$_2$ east of UK$_1$ may have been prepared for a second UK test which was conducted on 14 November 1990, only a month after the image in Figure 8 was acquired.

It is useful now to consider the possibility of predicting future tests by the use of civil observation satellites. Consider the site at **O** in Figure 6a. Here preparations appear to have started for a new test by 21 June 1989 (see Figures 6a and 6b). The site development continued at least until 14 October 1990 (see Figure 8). It is possible that this site was prepared for a test conducted on 4 April 1991. Similarly, site at **P**, to the west of the UK test areas, preparations for another test had begun by 21 June 1989 (see Figures 7 and 8). This may have been in preparation for a test on 16 April 1991. Similarly the site at **U** is being prepared for a test that was carried out on 26 March 1992. Site corresponding to some of these events are enlarged from 21 June 1989 and 14 October 1990 images and shown in Figure 9 for comparison. The changes that have occurred either because of a test or because of continuing build up of the site for a future test can be clearly seen.

All the test referred to above were declared tests. However, one event in the three images analysed above does not correlate to any declared tests. The site **X** in images 6a and 6b appear well defined without any crater or any other surface disturbances. However, between 29 June 1989 and 14 October 1990, a test was carried out which caused a crater which can be seen clearly in Figure 8 at **X**. If this were one of the events that was not declared by the USA, then this technique offers a way to add more information to that obtained by seismic means.

Many of the remaining tests listed in Table 4 were carried out in Yucca Flat. Similar analysis was made and most of the tests were identified. This area has the largest concentration of craters created by either underground or atmospheric tests. From the size of the craters which can be measured in an image acquired from space, it is possible to get some idea of the yield of a test. However, in a CTBT, the determination of the yield of an explosion is less important because initially parties to such a treaty would be interested only in knowing whether a violation of the treaty has occurred or not.

Only some preliminary data on the Russian tests is presented here. Figure 10 shows a Landsat 5 image over Semipalatinsk nuclear test site. The image was acquired on 8 March 1989 and is presented here in bands 2 (blue), 3 (green), and 4 (red). The Degelen Mountain (area I in Figure 10) and the Shagan River (area II) areas were examined. The geology of the Degelen Mountain region is composed of volcanic rocks and light-coloured granite. After an underground test considerable spalling and cratering occurs. After the earth above the ground zero has settled down, the spalled areas in the granite rock appear very reflective in a multispectral image in green, red and in the near IR bands.[22] Thus, in a composite image these areas appear white. On the other hand in the volcanic rocks, the spalled areas area is very reflective in green and red parts of the electromagnetic spectrum but less so in the near IR. The resulting combined image gives blue-green signature in the test areas.

The areas **I** and **II** in Figure 10 are enlarged in Figures 11a and 11b respectively. In Figure 11a a number of sites where tests have occurred can be identified. For example, at **1** a large crater can be seen. Note the white reflective area on the rim and close to the crater due to spalling effect. On the other hand, at **2** the large crater reflects considerable amount energy in the near IR region as suggested by the red colour. Between these two craters there are a number of small ones that can just be detected. It is difficult to identify these to particular tests because, so far, Russia has announced the locations and the depths of various tests for a period covering between 11 October 1961 and 28 December 1972 only.[23] None of these appears to been carried out in the area examined. All of these test have been tunnel tests conducted in the mountain ranges. Two other possible sites are at **3** and **4**.

Figure 11b shows a part of the Shagan River test site.A This area is, by and large, made up of Paleozoic sedimentary and volcanic rocks with granite and some alluvium.[24] Thus, the spalled areas are expected to appear blue-green in the Landsat image. Many of the sites, for example, at **1, 2, 3,** and **4**, have such a response. This area is largely flat so that most of the tests are carried out in vertical shafts. Some craters can also be detected. The sites are extensively linked by roads. Tests at **5, 6,** and **7** have a very strong reflectance in the near IR band as indicated by the red colour. This would suggest the presence of the granite. Again no attempt has been made to identify each of the tests.

IV. Some Estimation of Number of Images Needed and their Costs

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[22] W. Leith and D.W. Simpson, "Monitoring Underground Nuclear Tests", in *Commercial Observation Satellites and International Security*, M. Krepon, P.D. Zimmerman, L.S. Spector and M. Umberger (eds), New York: St Martin's and Carnegie Endowment for International Peace, 1990, pp.115-124.

[23] A list appeared in the ATOMNAYA ENERGIYA which was reproduced in the *Foreign Broadcasting Information Service*, 10 January 1990.

[24] *Ibid.*, Laith and Simpson.

Consider the Nevada Test site. It occupies an area of about $3.5x10^3$ km^2. To observe this area, one SPOT (area covered 3,600 km^2) or one Landsat image (area covered 34,000 km^2) would be required. Owing to its high spectral resolution, the Landsat imageries are most useful. In addition to the above six known sites, there could be some more potential sites. Assuming that there are 11 potentially new sites and assuming that each of these cover similar area as that of the Nevada Test Site, the total area to be monitored may be $3.5x17x10^3$ or about $60x10^3$ km^2. Thus, some 17 SPOT, or 17 Landsat type images would be needed. In the United Nations in Geneva at the Conference on Disarmament (CD), an *ad hoc* Group of Scientific Experts was established in 1976 to formulate a conceptual design, capability and costs for an International Seismic Monitoring System (ISMS) and to test its various components. In the Group of Scientific Experts Technical Test (GSETT), 34 member states are participating (see Appendix). Assuming that at least these may be interested in acquiring some data from space to verify a CTBT, the number of SPOT images required would be 17x32x5 or 2,720 and a similar number from Landsat satellites. It is assumed that states will monitor the area five times a year. Thus, the cost for the SPOT data would be 2,720x2,675 or just over $7 million per year and that for the Landsat data 2,720x4,400 or about $12 million dollars. This would amount to about £20 million per year for data only. To these, for example, costs due to manpower, facilities and equipment need to be added. It is clear a single verification agency would be most cost effective. Nevertheless, it should be kept in mind that once other satellites become operational, the cost of data is bound to come down.

To observe the preparations for a nuclear test, high resolution images such as those marketed by Russia would be very useful. Two types of high resolution panchromatic data are sold by Russia; film positive or negatives 18 cm x 18 cm in size covering an area of 40 km x 40 km on the ground and digital data covering an area of 12 km x 12 km on the ground. Both of these have photographic resolutions of about 2 m. This is to be compared with equivalent resolutions of about 20 m from SPOT and 60 m from Landsat satellites. Because of the high resolution of the Russian data, it should be used once to observe a site before a test and once again after the test. This is after the initial identification of the potential test site has been made by one of the other satellites. The cost of the Russian imageries is about $3,600 for film product and the digital data is sold at a rate of $10/$km^2$.[25]

V. Conclusions

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[25] Imagery - Russian Resolution, *Flight International*, 19-25 January, 1994, p.39.

The above preliminary examination of the use of commercially available observation satellite data indicates that the verification of a CTBT could be enhanced by the use of such data in conjunction with the more conventional methods such as seismology. It may even be said that observations from space would be essential because the detections of the preparations for a test non-intrusively is possible only by such means. This was amply demonstrated in 1977 when the former Soviet Union used its military reconnaissance satellites to detect the test preparation by South Africa. The method is important because once the preparations are detected, it is then possible to take some political actions to avert the test. The South African is a good example. As the preparations could take some weeks or even months, the evaluation of time-sequential imagery of a site would allow analyses of the development of the site and the determination of possible purpose of the activities. This could best be done by change detection method such as that illustrated in this study.

An underground explosion could cause the surface above the ground zero to fracture, or to spall or even form a crater. These effects can be detected from space allowing precise determination of the location of the explosion. Measurements of locations by seismic methods by and large tend to be crude. Thus, observations from space could enhance the seismic data. Moreover, by measuring, for example, the size of a crater formed above the ground zero, it may be possible to estimate the yield of the explosion. Although under a CTBT this is of less importance. Moreover, it would be difficult to hide from satellite observations a nuclear explosion in a seismic event. This is because, as was seen above, on a multispectral image, an explosion would record very localised spectral and surface structural changes which would not be the case in an earthquake.

Another important aspect of the observations from space is, if broadly the geology of the site is known from published information, it is possible to interpret the local geological conditions by the use of multi-spectral imageries. This is essential to know because the seismic response depends much on the medium in which the test is carried out.

Perhaps the most important aspect of monitoring from space is the fact that it could be used by anyone. Satellite imageries could be acquired commercially. Initially a test site could be effectively monitored by only a few images per year as underground tests are confined to specific sites which are very few. In addition, of course, new states parties to a possible CTBT would have to be monitored. But these may not amount to more than perhaps 10 to 11 countries. The above estimates of the number of images required took this into account. The reason for this is to avoid unnecessary global monitoring. It is reasonable to assume that countries without any significant nuclear research and/or nuclear power programme are less likely to embark upon nuclear weapons testing. It has been argued that disused mines could be used to test a small nuclear weapon. This is true, but between seismic detectors and satellite observations, the site for such a test could be detected. This could trigger further on-site monitoring.

It has recently been proposed that civil observation satellite data should be used to enhanced the safeguards procedures of the International Atomic Energy Agency (IAEA).[26] The Agency monitors the state parties to the 1970 non-proliferation treaty in order to ascertain that, for example, the nuclear materials are not diverted from the peaceful to non-peaceful activities. In a non-peaceful application, a country could divert the fissile materials to making nuclear explosives. Thus, logically the IAEA should monitor the flow of nuclear materials in a member state to the point when it is ready to test a nuclear explosive. In other words, it might be suggested that the Agency monitors a CTBT also. This has an advantage over the creation of an entirely new infrastructure in that the latter already exists and, hopefully, the Agency will begin to use civil remote sensing satellites to enhance its safeguards procedures. Then the infrastructure for image processing and interpretation capabilities would have been already established. Thus, the additional cost would be that of images only.

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[26] "The Role of Satellites and Remote Data Transmission in a Future Safeguards Regime", B. Jasani, W. Fischer, W.D. Lauppe and G. Stein, Paper presented at the IAEA Symposium on International Safeguards, Vienna, 14-18 March 1994. This has been published in the proceedings of the symposium.

Table 1: US Satellites Carrying Nuclear Explosion Detectors

Satellite	*Designation*	*Launch Date*
NUDETS/Advanced Radiation Detectors (ARD)		
NUDETS/DSP-2	1971-039A	5 May 1971
NUDETS/DSP-3	1972-010A	1 Mar. 1972
NUDETS/DSP-4	1973-040A	12 June 1973
NUDETS/DSP-6	1976-059A	26 June 1976
NUDETS/DSP-7	1977-007A	6 Feb. 1977
NUDETS/DSP-9	1981-025A	16 Mar. 1981
NUDETS/DSP-10	1982-019A	6 Mar. 1982
NUDETS/DSP-11	1984-037A	14 Apr. 1984
ARD-1/2-DSP-14	1989-046A	14 June 1989
ARD-1/2-DSP-15	1990-095A	13 Nov. 1990
ARD-1/2-DSP-16	1991-080B	24 Nov. 1991
NUDETS/DMSP-7	1983-113A	18 Nov. 1983
NUDETS/DMSP-8	1987-053A	20 June 1987
NUDETS/DMSP-9	1988-006A	3 Feb. 1988
NUDETS/DMSP-10	1990-105A	1 Dec. 1991
NUDETS/DMSP-11	1991-082A	28 Nov. 1991

Table 1: US Satellites Carrying Nuclear Explosion Detectors (continued)

Satellite	*Designation*	*Launch Date*
IONDS/NDS		
IONDS 1/Navstar 1A-8	1983-072A	14 July 1983
IONDS 2/Navstar 1R-9	1984-059A	13 June 1984
IONDS 3/Navstar 1R-10	1984-097A	8 Sep. 1984
IONDS 4/Navstar 1R-11	1985-093A	9 Oct. 1985
IONDS 5/Navstar 12	1989-013A	14 Feb. 1989
IONDS 6/Navstar 13	1989-044A	10 June 1989
IONDS 7/Navstar 14	1989-064A	18 Aug. 1989
IONDS 8/Navstar 15	1989-085A	21 Oct. 1989
IONDS 9/Navstar 16	1989-097A	11 Dec. 1989
NDS 10/Navstar 2A-17	1990-008A	24 Jan. 1990
NDS 11/Navstar 2A-18	1990-025A	26 Mar. 1990
NDS 12/Navstar 2A-19	1990-068A	2 Aug. 1990
NDS 13/Navstar 2A-20	1990-088A	1 Oct. 1990
NDS 14/Navstar 2A-21	1990-103A	26 Nov. 1990
NDS 15/Navstar 2B-22	1991-047A	4 July 1991
NDS 16/Navstar 2B-23	1992-009A	23 Feb. 1992
NDS 17/Navstar 2B-24	1992-019A	10 Apr. 1992
NDS 18/Navstar 2B-25	1992-039A	7 July 1992
NDS 19/Navstar 2B-26	1992-058A	9 Sep. 1992
NDS 20/Navstar 2B-27	1992-079A	23 Nov. 1992
NDS 21/Navstar 2B-28	1992-089A	18 Dec. 1992

NUDETS and ARD nuclear detection sensors were orbited on Defense Support Program (DSP) early warning of missile launch satellites and NUDETS also on board Defense Meteorological Satellite Program (DMSP); IONDS and NDS sensors were orbited on board the Navstar/GPS navigation spacecraft.

Table 2: Spectral Sensitivities of Some of the Civil Satellites

Satellite	Spectral range (Fm)	Resolution (m pixel)	Colour/ band
USA			
Landsat-4/5	0.45- 0.52	30	Visible blue/1
	0.52- 0.60		Visible green/2
	0.63- 0.69		Visible red/3
	0.76- 0.90		Near IR/4
	1.55- 1.75		Mid IR/5
	2.08- 2.35		Far IR/7
	10.40-12.50	120	Thermal/6
France			
SPOT 1,2,3	0.50-0.59	20	Green/1
	0.61-0.68		Red/2
	0.79-0.89		Near IR/3
	0.51-0.73	10	Panchrometic
India			
IRS 1,2	0.45-0.52	73	Visible blue/1
	0.52-0.59		Visible green/2
	0.62-0.68		Visible red/3
	0.77-0.86		Near IR
	0.45-0.52	36	Blue/1
	0.52-0.59		Yellow/2
	0.62-0.68		Red/3
	0.77-0.86		Near IR

Table 3: Summary of Techniques Used in Computer-Based Interpretation

Interpretation Elements	Spectral	Spatial	Stereo	Interpretation Techniques
Tone	§	-	-	Density slicing
Colour	§	-	-	Multispectral classification
Texture	§	§	-	Texture classification
Pattern	§	§	§	Spatial transforms and classification
Size	-	§	§	Segmentation algorithms and size feature classification
Shape	-	§	§	Syntactic classification
Site	-	§	-	A Priori, Modified
Association	-	§	-	Contextual classification

Source: R.J. Ondrejka, in *Arms Control Verification*, (edt) K. Tsipis, D.W. Hafemeister and P. Janeway (eds), New York: Pergamon/Brassey's, 1986, p.96.

Table 4: US Underground Nuclear Tests Carried Out between 21 June 1989 and 29 June 1989 and 14 October 1990
(Various tests are identified on the images by letters in brackets in the last column)

	Locations			Depth (m)	
Name of Test	North	West	Date	Tunnel	Vertical
USA					
Contact	37^{0}16'58"	116^{0}24'44"	22.06.89	-	500(A)
Amarillo	37^{0}16'32"	116^{0}21'13"	27.06.89	-	600(B)
Disco Elm	37^{0}14'09"	116^{0}09'46"	14.09.89	300(C)	-
Hornitos	37^{0}15'47"	116^{0}29'27"	31.10.89	-	600(J)
Mule Shoe	37^{0}06'24"	116^{0}00'48"	15.11.89	-	200(D)
Whiteface			20.12.89	-	- (M)
Metropolis	37^{0}06'45"	116^{0}03'19"	10.03.90	-	500(E)
Bullion	37^{0}15'42"	116^{0}25'12"	13.06.90	-	700(F)
Austin	36^{0}59'34"	116^{0}00'16"	21.06.90	-	300(G)
Mineral Quarry	37^{0}12'25"	116^{0}12'51"	25.07.90	400(H)	-
Sundown			20.09.90	(K?)	
Ledoux			27.09.90	(L)	
Tenabo	37^{0}14'52"	116^{0}29'39"	12.10.90	-	600(I)
	37^{0}15'58"	116^{0}29'50"			(X)
UK					
Barnell	37^{0}13'52"	116^{0}24'32"	081289	-	660(UK1)
-	37^{0}13'37"	116^{0}22'16"	141190	-	(UK2)

Figure 1: Various types of radiation and effects produced in an atmospheric nuclear explosion

Source: T.J. Lukeman and R. Williamson, "Nuclear Hardening of Equipment", *International Defense Review*, Vol. 14, No 11, 1981, pp.1444-1448.

Figure 2: The GPS Block II satellite with an X-ray sensor at **A** and an optical sensor (the bhangmeter) at **B**. The latter is shielded from the sun by the cone shaped sunshade. The X-ray detector to record radiation from a nuclear explosion in space.

Figure 3: Line drawing of a typical nuclear weapon test site.

Source: *Nuclear Weapons Databook*, *US Nuclear Warhead Production*, Vol. II, T.B. Cochran, W.M. Arkin, R.S. Norris and M.M. Hoening.

Figure 4: Ground tracks of Cosmos 922 **(a)** and Cosmos 932 **(b)** satellites belonging to the former Soviet Union over South Africa between 2 and 5 and 21 and 28 July 1977 respectively. The date and the orbit number are indicated for each ground track.

(a)

(b)

Figure 5: Full Landsat 4 scene of the US nuclear test site in Nevada. The image, acquired on 29 June 1989, is a composite of bands 2 (red), 3 (green) and 4 (blue). Pahute Mesa, Rainier Mesa and Yucca Flat are marked I, II, and III respectively. Scale: 1:1,070,000.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 6a: Extract from a full scene of the US nuclear test site showing Pahute Mesa. The image was acquired by the Landsat 5 satellite on 21 June 1989. The sites marked on the scene are discussed in the text. Scale: 1:130,000.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 6b: Extract from a full scene of the US nuclear test site showing Pahute Mesa. The image was acquired by the Landsat 4 satellite on 29 June 1989. The sites marked on the scene are discussed in the text. Scale: 1:130,000.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 7: Extracts of areas A and B from figures 6a and 6b. Here density slicing is applied to enable detection of changes in the surface above the ground zero after tests.

(a) 21/6/89 band4

(b) 29/6/89 band4

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 8: Extract from a full scene of the US nuclear test site showing Pahute Mesa. The image was acquired by the Landsat 5 satellite on 14 October 1990. The sites marked on the scene are discussed in the text. Scale: 1:130,000.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 9: Extracts from full scenes of the US nuclear test site at Pahute Mesa. The image shows different test locations observed on 21 June 1989 and 14 October 1990 for comparison. Extracts **O**, and **U** show preparations of the sites in their early stages in June 1989 and **UK$_2$** almost completed and ready for tests in October 1990. Extracts **I** and **UK$_1$** show the sites before a test in June 1989 and after a test in October 1990. Considerable amount fracturing of the surface above ground zero can be detected in extract **I**. In extract **UK$_1$** general spalling can be seen at main test site while the construction of a new one can be seen just above it.

O

U

I

UK$_1$

UK$_2$

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 10: A full Landsat 4 scene of the former Soviet nuclear test site at Semipalatinsk. The image is a composite of bands 2 (red), 3 (green) and 4 (blue). Part of the Degelen Mountain and the Shagan River test areas are marked **I** and **II** respectively. Scale: 1:1,070,000.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 11a: Extract from figure 10 showing part of former USSR's Degelen Mountain test area (**I**). Effects of some of the tests can be seen at **1, 2, 3**, and **4**.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Figure 11b: Extract from figure 10 showing part of former USSR's Degelen Mountain test area (**II**). Effects of some of the tests can be seen at **1-7**.

Source: EOSAT/Landsat; the image was processed at Defence Research Agency, Farnborough, UK.

Appendix

Verification by Seismic Means

The earth is mainly made up of three concentric shells: the innermost core, the mantle, and the crust forming the skin on the surface of the earth. An earthquake or an underground explosion generates many types of seismic waves which propagate these layers. At distances of more than 2,000 km (teleseismic distances), two types of waves are of interest: body waves which travel through the earth, and surface waves which propagate along the surface. The body waves could be divided into two kinds: the **P** or compressional wave and the **S** or shear wave. One type of surface wave is called a Rayleigh wave.

Generally the magnitude $\mathbf{m_b}$ of body wave is measured by the amplitude of the **P** wave at 1 Hz. The surface-wave magnitude $\mathbf{M_s}$ is measured by determining the amplitude of the Rayleigh wave at 0.05 Hz. The ratio $\mathbf{M_b/M_s}$ is used to distinguish between explosions and earthquakes. Ideally seismometers should be placed in the country being monitored or near it so that they are at regional distances (less than 2,000 km). In this case the regional signals travel mainly in the upper mantle and crust of the earth. A seismic detector at regional distances can detect body and surface waves propagated through the crust. An earthquake generates a significant amount of **S**-wave and surface wave energy because of shearing which occurs along its fault plane. In contrast, an explosion produces little shear energy and surface waves so that the ratio $\mathbf{m_s/M_s}$ is lower for an earthquake than for an explosion of similar magnitude. Moreover, since their propagation paths are different, regional signals include more high-frequency components than do teleseismic signals. As an explosion radiates higher seismic frequencies (1 to 30 Hz) than an earthquake, the ratio of **P**-wave spectral amplitudes at different frequencies could also be used to discriminate the two source types.

Thus, it can be seen that it is possible to differentiate between an explosion and an earthquake. Monitoring tests above 10 kt does not present any difficulty.[27] With seismic detectors placed outside the monitored state, distinguishing such tests from a chemical explosions for industrial applications is also possible since

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[27] "Seismic Verification of Nuclear Testing Treaties", *Office of Technology Assessment (OTA), Congress of the United States, OTA-ISC-361*, Washington, DC: US Government Printing Office, May 1988.

less than one explosion a year in the range of 1 to 10 kt occurs. Also such explosions usually end up, for example, in the development of the site for mining operation or construction purposes. Moreover, nuclear explosions are less likely to be carried out in or near populated ares. Also a surface or a shallow chemical explosion can be identified as such by the lack of any nuclear radiation or radioactivity. Since 1970, it has been shown that identification down to body wave magnitude of 4.5 or about 5 kiloton (kt) in hard rock and higher yields in dry alluvium was also possible with a high probability of success.[28] However, it has been estimated that by 1991, global seismic arrays had a capability to detect $\mathbf{m}_b$ 4.2 for any well coupled explosion in the of one to two kiloton.[29] Placing seismic monitors on the territory of the country being monitored, it is possible to detect a seismic signals smaller than 3.5 in magnitude which would correspond to an yield of 0.5 kt in hard rock.[30] Such low yield tests could be hidden in an earthquake event. However, using a filter to record mainly high frequency seismic waves, it is possible to filter out most of the response due to the earthquake.[31] Moreover, using at least four stations, the position of an explosion could be determine with an accuracy of 10-50 km.[32] The Group of Scientific Experts established by the UN at the Conference on Disarmament in Geneva estimates that location may be determine with an accuracy of better than 5 km if seismic stations were close to an explosion. If data were acquired from distant seismographs, a precision of about 20 km could be achieved.[33] It must be realised that with this technique, information on an event is obtained only after it has occurred so that it may be too late for any meaningful political action. Under a CTBT, a violation would occur when an explosion is carried out.

Considerable improvements in on-site seismometers were made to determine the yield of an explosion. The on-site detectors depend on the so called CORRTEX (Continuous Reflectrometry for Radius versus Time Experiment) method. In this hydrodynamic method, a cable is placed in the ground near the explosion. The rate at which the cable is crushed during the explosion is proportional to the yield of the blast. The protocol for the PNET includes the

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[28] *UN Document CCD/330*, 30 June 1971.

[29] *Ibid., OTA Report.*

[30] T. Schmalberger, *In Pursuit of a Nuclear Test Ban Treaty - A Guide to the Debate in the Conference on Disarmament*, UNIDIR, Geneva: United Nations, 1991, p.77.

[31] *Ibid., OTA Report*, p.12.

[32] *Energy and Technology Review*, May 1983, pp.50-65.

[33] *UN Document CD/1254*, 25 March 1994, p.7.

right to a local seismic network for group explosions over 150 kt. CORRTEX or similar devices would be deployed on-site.

As the progress in seismology continued, the Ad Hoc Group of Scientific Experts (GSE) established by the Conference on Disarmament in Geneva, also made some progress in its efforts to develop the concept of an International Seismic Monitoring System (ISMS). The GSE conducted, in 1984, its first global test under the programme GSE Technical Test (GSETT-1). This consisted of the exchange of basic data of seismic events using the World Meteorological Organization.[34] In its second test, GSETT-2 in 1991, more modern communications system was used to exchange some selected data from 60 seismometers in 34 countries. The data was distributed to four analyses centres but it was shown that four centres were un-necessary. A third test, the GSETT-3, is now underway. This is expected to be a realistic test on a global scale which will utilise a single International Data Centre (IDC). An experimental IDC for GSETT-3 has been established in Arlington, Virginia, USA.

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[34] *Ibid.*, UN, p.8.

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