EMERGING TECHNOLOGIES FOR VERIFICATION OF ARMS CONTROL TREATIES

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ABSTRACT

Progress in the technical means of monitoring to verify compliance to arms control treaties is discussed in the following areas: Real-time surveillance with charge-coupled devices in the visible and infrared; image enhancement with digital image processing and with adaptive optics; imaging with radars based on satellites and on the ground; seismic monitoring with high frequency discrimination and with unattended in-country seismic stations; and nuclear weapons test monitoring with the global positioning satellite system.

I. INTRODUCTION

Military technologies for fighting wars have made remarkable progress in the last decade. For example, the accuracy of missiles has improved considerably as cruise missiles use terrain mapping techniques, submarine launched ballistic missiles use guidance from stellar locations, and other missiles will use the accurate locations and velocities from the NAVSTAR global positioning satellites. Along with this progress, there has also been considerable progress in the technologies (1) which allow the monitoring of the military activities and systems of "the other side." These new technologies are not only extremely interesting in a scientific sense, but they are also encouraging in that they have strengthened the ability to verify compliance with the provisions of arms control treaties. These improvements have been both in quality, with better resolution and data management, and in scope, with new methods of measuring.

In the past, when there have been disagreements over compliance with existing treaties, confidential discussions have been held between the Americans and the Soviets in the Standing Consultative Commission (SCC). Recently both sides have complained publicly about the compliance of the other side with various treaties. It appears that future progress on arms control treaties will depend on the resolution of some of these issues. For this reason, we feel that it is timely to discuss the progress on some of the technical means of verification. Part of this paper is derived from a conference (and book) (2) on Technical Means of Verification of Compliance with Arms Control Treaties which was held at the Massachusetts Institute of Technology in February of 1984.

The technical means of monitoring foreign military endeavors are extremely important for arms control for three fundamental reasons:

1. If Soviet or American military planners are convinced that there is a reasonable chance that they would be discovered in a violation of a treaty, one would expect that they would tend to be deterred from cheating since they would not wish to encourage an opponent to increase its armaments and respond drastically in other arenas.

2. Reconnaissance satellites and other technical means of monitoring are stabilizing since their data may contradict "worst-case" analysis. President Johnson commented on this aspect in 1967 when he indicated that the \$35-40 billion for space had been well spent, because "*I know how many missiles the enemy has.*"

3. In order for an arms control treaty to be successfully negotiated by the Executive Branch and ratified by the U.S. Senate, these bodies must be convinced that the technical and nontechnical means of verification are "adequate." They must be convinced that the U.S. would have enough "timely warning" so that its national security would not be threatened significantly by a "break-out" by the Soviets from arms control treaties. And this debate must be carried out in public, so that there must be some public understanding of verification problems and possibilities.

II. VERIFICATION IN CONTEXT

A clear majority of Americans want arms control, but they also mistrust the Soviets. For example, the freeze resolutions that require a ban on the production, testing, and deployment of nuclear weapons and their delivery systems, also require that these bans be "mutually verifiable." Arms control agreements must rely on more than trust to know that the other side does not violate the terms of the treaties. The technical means are often synergistic in that, when the various means are used together, they are most effective in determining what the other side is doing. The technical means are often directed where to look for violations by information gathered by human intelligence (HUMINT) and by intercepted phone calls, or signal intelligence (SIGNIT). These more clandestine processes have come a long way since Secretary of State Stimson cut funding for the Black Chamber cryptographic unit in 1929 with the comment that "*gentlemen do not read each other's mail.*" It is well known that some phone calls within the United States have been intercepted by the Soviets for at least a decade by using microwave intercept techniques and other methods. Computer codes search the phone messages for "key" words such as nuclear, MIRV, CEP, and so forth. It is generally assumed that the techniques used by the U.S. in the Soviet Union are more sophisticated than those used by the Soviets; this advantage is offset by the fact that the Soviets have much more access to information in the "open" society of the U.S. Both sides maintain radio antennae on satellites, airplanes, ships, and on land in order to ferret out useful information from radio messages. These intercepts obtained by technical means are supplemented by defectors and agents who "listen" for signs of political intention, troop movements, technical information, and so forth. Ex-President Nixon gave a glimpse into the process when he stated in 1984 that "*One of the reasons that the release of the Pentagon papers caused great concern in the CIA, was that one of the items in the papers could only have come from the fact that we had Brezhnev's car bugged.*" (3) In certain cases it is possible to assist the technical means of verification with "cooperative measures" in which one side reduces the difficulties of monitoring for the other side.

Because the purpose of this paper is to discuss the technical aspects of some of the means of verification and not its broader political context, we will not discuss such topics as the historical, political and legal aspects of verification; the criteria of the quality of verification ("adequate versus effective"); the question of the vulnerability to "break-outs" to arms control treaties; the international means of verification as by the International Atomic Energy Agency or the proposed International Satellite Monitoring Agency; the specific terms of arms control treaties; charges and countercharges over violations of arms control treaties; and so forth.

III. PHOTOGRAPHIC RESOLUTION

We can base part of our judgment on the quality of reconnaissance photographs by considering the maiden flight of the Space Shuttle Columbia on April 12, 1981. After the launch, the crew observed that several thermal tiles were missing from the upper portion of the Columbia. There was a great deal of concern that many other tiles might have been lost during the launching of the Columbia, and that the lives of the crew might be endangered during the re-entry into the earth's atmosphere without the protective covering of the heat shield. Unfortunately, it was not possible to determine directly if this fear was correct since the Columbia's TV monitors could not observe the bottom side of the craft. The question was answered quickly by the Department of Defense (4) which used some specialized photographic techniques with land-based cameras and with the KH-11 reconnaissance satellite in orbit. The DoD determined that no tiles were missing from the underside of the Columbia, and that the crew had nothing to fear from this potential problem. From this measurement with land-based cameras, we conclude that the resolution at height of 100 miles must have been about 10-15 cm.

This same resolution can be achieved with orbiting cameras. Since the object distance ($o = 120$ km) is much larger than the focal length ($f = 6$ m), the image distance is the same as the focal length ($i = f$). Using film with 100 lines/mm ($r_i = 10\mu$), the object resolution would be

$$r_o = r_i (o/i) = (10^{-5} \text{ m})(1.2 \times 10^5 \text{ m}/6 \text{ m}) = 20 \text{ cm.} \quad (1)$$

If the diameter (D) of the lens was 1 m, the angular spread from the diffraction limit of the lens can be ignored since

$$\theta(\text{diff}) = 1.2\lambda/D = (1.2)(0.5 \times 10^{-6} \text{ m})/(1 \text{ m}) = 0.6 \mu\text{rad}, \quad (2)$$

which is much less than the angular uncertainty induced by the film with 100 lines/mm,

$$\theta(\text{film}) = r_i/i = (10^{-5} \text{ m})/(6 \text{ m}) = 1.7 \mu\text{rad.} \quad (3)$$

If the film quality were to be improved to 1000 lines/mm ($r_i = 1\mu$), the theoretical resolution obtained through Eq. 1 would not apply since the value of $\theta(\text{diff}) = 0.6 \mu\text{rad}$ would exceed the film resolution, $\theta(\text{film}) = 0.17 \mu\text{rad}$. Thus, we conclude that the real resolution might be somewhat between these two limits, or about 10 cm. Larger diameter mirrors, such as the space telescope's 2.4 m, have attained a resolution of $0.3 \mu\text{rad}$ (full-width at half-maximum in the laboratory), but this level of resolution often isn't necessary. A resolution of 10 cm is not sufficient to

read the masthead of a newspaper (as some have claimed), but it would distinguish a Volkswagen Bug from a Chevrolet Vega (on a clear day).

Turbulence of the air imposes another limit on the resolution obtainable with these types of cameras. Such turbulence blurs, for example, the images of stars for telescopes that look upwards through the atmosphere. Over times of the order of tens of milliseconds, the density of air in cells about 20 cm in size fluctuates and thus misdirects the rays of light from a star by angles of the order of a second of arc, or $5 \mu\text{rad}$. This would smear a photograph looking upwards at the shuttle by about 50 cm, which is much more than the size of an individual tile. This effect is much greater for telescopes on the ground pointing away from the earth than for reconnaissance cameras looking downwards towards the earth because the turbulence is much closer to the land-based telescope than it is to the satellites which are typically 150 km about the earth. An effective way to remove this smearing for land-based telescopes is to use the technique of "adaptive optics" which we will discuss below. Since adaptive optics and smooth tracking can effectively reduce the spacial resolution (looking upwards) at the altitude of the shuttle to, perhaps, 10 cm, it might be expected that reconnaissance satellites (looking downwards with a 1 m lens) could also obtain resolutions of the order of 10 cm, since the problem of atmospheric turbulence is considerably reduced looking downwards.

IV. VARIOUS IMPROVEMENTS IN OPTICS

The optical systems (5) for reconnaissance have improved considerably over the past decade in a variety of ways:

1. Commercial aerial survey films are now available with a high contrast capability of about 1000 line pairs per millimeter, or about one micron between lines (or better).

2. The design of very good lens systems are complicated because the various colors do not focus uniformly onto the plane of the film. Since digital computers can rapidly trace hundreds of optical rays, complex lens systems can be designed to minimize this problem.

3. Nonspherical lens can be machined with the aid of computers to take into account deviations in the physical and geometrical properties of the glass.

4. Stresses from temperature and pressure gradients can distort a lens system. By using improved lens mounting materials and improved thermal insulation materials, such as a blanket of 100 layers of metal coated mylar, these problems have been minimized.

5. The forward motion of a satellite will slightly blur a photograph. This smearing is removed by slightly moving the film relative to the lens with precise timing mechanisms and servo control systems.

6. Similar objects can reflect and emit differently in the visible and infrared wavelength regions. Multispectral cameras are used to record these differences in the colors by using a series of nearly identical lenses in combination with narrow-pass filters. Nine or more separate photographs are taken to record the different wavelength images, or special-layered multispectral films are used for one composite picture.

7. By using two views of the same terrain taken at different angles, one can obtain stereoscopic images which resolve the heights of objects. Such a cartographic camera in the Space Shuttle covered an area of 25,000 square kilometers in stereo with a resolution of about 10 meters with only a single pair of pictures.

8. Fourier transform infrared spectrum has enhanced resolution in the infrared by several orders of magnitude. Other advances which are enclosed, and described below, are:

9. Adaptive optics.
10. Digital image processing.
11. Charge-coupled devices.

Adaptive Optics

Adaptive optics (6) is the ingenious technology that was first used in astronomy to reduce the blurring of stars by atmospheric turbulence, or to correct for imperfections in the optics of the telescope. By using adaptive optics, it has been possible to improve the resolution of land-based telescopes to nearly the diffraction limit. The main use of adaptive optics for verification so far has been to obtain high-resolution images of satellites from land-based telescopes. Adaptive optics is not as important for images obtained by satellite cameras because the "seeing" problem caused by atmospheric turbulence is considerably smaller for the case of satellites looking downwards through the atmosphere.

Adaptive optics systems use deformable mirrors, wavefront sensors, and wavefront processors. Part of the light from the object being observed is diverted into the wavefront processor which uses an array of detectors to measure the intensity at different locations of the wavefront. The light is chopped at the same instant in order to obtain the time displacement and the spatial slope of the wavefront. This information is processed in the wavefront processor which then directs the electro-mechanical actuators to move the segments of the deformable mirror in order to remove the phase shifts introduced into sections of the wavefront by turbulence. It is necessary to be able to compensate for the rapidly changing turbulence by moving the deformable mirrors by about the wavelength of light (0.5μ). This must be done to within a small fraction of a wavelength of light (about 1% of 0.5μ , or 10 nm) in order to obtain good imaging. After this processing, the output image is reconstructed in such a way as to remove the effects of the atmospheric turbulence.

Digital Image Processing.

The computer revolution has spawned great improvements in the ability to enhance (7) photographic images. The first textbooks on digital image processing (DIP) were written in the late 1960s; now there are more than a dozen textbooks, and universities have developed considerable curricula to teach the art of DIP. The information content of a photograph can be digitized by measuring the film density (or grey level) in

very small regions called pixels. However, the use of film can be avoided altogether if electro-optical devices, such as charge-coupled devices, are used to directly measure the optical intensity at each pixel location and directly transfer the data into the memory of a computer. In either case, by devising computational algorithms as well as specialized hardware systems consisting of 10,000 or more processing elements, it is possible to perform a variety of manipulations which enhance the digitized image.

Images contain straight lines and edges that are blurred into a gray transition region, going from light to dark. This blurring can be caused by the optical system, by turbulence in the air, and by motion. DIP methods can restore lines and edges by searching for the shortest distance through the gray transition region in the same way that a mountain climber might search out the steepest and shortest path down a mountain. Once the computer has found the line or edge, it can restore the image by shifting some of the data from the light "foothills" and returning it to the dark "mountain tops." Other techniques can be used to remove the noise from over-exposed photos, to enhance contrasts, or to search even for various patterns such as circular missile silos. The advent of very large scale integrated circuits (VLSIC) is increasing our capabilities to do some of this processing directly in the satellites before transmitting the image information to the earth. By comparing two images of the same object that were taken at different times, one can look for small changes in the environment that might have military significance.

The blurring of an image can be described mathematically by a point spread-function (h_c). By estimating this function it is possible to remove some of the effects of blurring and enhance the image. The basic equation for the formation of an image is

$$g(x,y) = \iint_{-\infty}^{\infty} h_c(x_1-x, y_1-y) s(x_1, y_1) dx_1 dy_1 + n(x,y) \quad (4)$$

where s is the direct and indirect flux at the sensor, and n is the noise. One way to determine the point-spread is to Fourier transform the image to obtain the image as a two-dimensional frequency distribution. By ignoring the noise term in Eq. 4, one obtains

$$G(u,v) = H(u,v) S(u,v) \quad (5)$$

where u and v are the spatial frequencies, and G , H , and S are the Fourier transforms of g , h , and s .

Charge-Coupled Devices (CCD)

The use of film in a real-time mode in reconnaissance satellites causes some difficulties; the film must be read either by a television camera or a fiber optics reader; both of these methods blur the resolution of very good film. In order to retain the good resolution of high quality films, the film can be sent to the earth in a film canister for analysis. However, this process is time consuming and can only be done occasionally since the film supply is limited. In addition, film, in spite of its excellent resolution, has other drawbacks; it is "non-linear" in the sense that the darkness of the image on the negative saturates; if the exposure time is doubled, one gets less than twice the darkening effect. Also, film has a very low quantum efficiency (the con-

version of light into developed silver grains), and it has a relatively narrow dynamic range (white to black ratio). On the other hand, the size of a pixel in a charge-coupled device (CCD) (8) is about a factor of 10 larger than the grain size of film that we quoted above ($13\ \mu$ for the CCD vs. about $1\ \mu$ for film). In addition, the conversion for resolution from pixels and grain size adds another factor of 2 to 3; the CCDs might, therefore, only have a resolution from low earth orbit of about 50 cm with a 6 m focal length. However, by using longer focal length lens systems with CCD sensors, it would be possible to obtain the same ground resolution as film. Because of the greater data handling capacity of CCD sensors, as compared to film canisters retrieved from satellites, CCDs will become very important in the field of reconnaissance verification. In the near term, CCDs will be used with long focal length systems or by sacrificing resolution, or a combination of both; in the long term, CCDs will be improved by shrinking the pixel size and by using CCDs directly with computer processing devices.

The development of CCDs has solved most of the problems of films, plus several more. The CCDs are read directly by computers; this real-time use negates the tortuous and limiting process of ejecting film canisters from satellites and laboriously converting the images to digital data. In addition, the CCDs are about 50 times more efficient than film; they are linear in that the stored charge is proportional to the time of the exposure; they are sensitive to a broader range of colors and infrared; and they have a much greater dynamic range between white and black. As a further bonus, the CCDs are very reliable, have a very small mass compared to a year's supply of film, and they don't need a high voltage supply that TV requires. The CCDs presently being installed on the space telescope consist of an array of 2.5 million pixels (1600×1600).

Infrared

Reconnaissance photos can also be taken during the day or the night with infrared detectors which are sensitive to heat. Arrays of infrared sensors (9) like CCDs, are available and are used in space astronomy and on guidance systems for some battlefield weapons. These infrared detectors provide data which can be used to determine the nature of the heat source. For example, thermal mappings of the atmosphere are taken by IR sensors on weather satellites, and the speed and altitude of aircraft may be determined by more sensitive IR sensors. Infrared detection technology currently lags behind radar and optical sensors in scale and scope of usage, but applications are constantly growing. One major advantage of infrared and optical sensors over radar systems is that they do not broadcast radiation; thus, they do not give away their presence or location as do "active sensors." This "passive" quality is of great value in many surveillance and reconnaissance applications.

There are two "windows" in the atmosphere which will transmit ir, between $3\text{--}5\ \mu$ and $8\text{--}14\ \mu$. The best possible resolution in the $10\ \mu$ region (with folded optical systems) will be about an order of magnitude worse (about $20\ \mu\text{rad}$) than for the visible region since the ir wavelength is 20 times the wavelength in the visible region. This result is consistent with the resolutions obtained in recent astronomical ir measurements: The IRAS satellite has obtained dramatic photographs of astronomical bodies in the infrared, as well as locating a ring of solid material at an angle of $50\ \mu\text{rad}$ from the star Vega, Mt. Polomar has obtained $4\ \mu\text{rad}$

in the ir, and the 4 m Kitt Peak telescope observed a "planet" 5 μ rad from the star VB-8. A resolution of

$$\theta(\text{diff}) = 1.2\lambda/D = (1.2)(14 \mu)/(1 \text{ m}) = 20 \mu\text{rad} \quad (6)$$

from low earth orbit would give a ground resolution of about 2-3 m. The ir devices measure the accumulated charge at a pixel due to the thermal intensity. The best available temperature sensitivity is about 0.01 K from a body at 300 K, which requires a voltage measurement accurate to

$$\Delta(\sigma T^4)/(\sigma T^4) = (4)(\Delta T/T) = (4)(0.01/300) = 0.01\%. \quad (7)$$

The achievable accuracy from a satellite will be diminished by the atmosphere and it will depend on the sweep speed of the device as well as other parameters.

There are still many significant technological issues to be solved before satellites can exploit the full potential of infrared for treaty verification. Current ir systems use smaller arrays of about 20,000 detectors as compared to optical CCDs with arrays of 3 million detectors or phased-array radars with 35,000 radiating elements. The Landsat, Tiros, and Nimbus series of ir remote sensors provide dramatic examples of the uses of ir sensing to acquire data on crops, to locate petroleum and minerals, and to observe the weather.

V. RADAR

Synthetic aperture radar (SAR) systems (10) mounted in satellites are presently used to obtain maps of features on the earth and the planets as well as to monitor military activities. Resolution from SAR is not as good as the resolution obtained with optical systems, but it can be used during the night and when the objects are covered with clouds, rain or foliage. To obtain high resolution radar images of the earth from a satellite with a "single exposure" would require an antenna several kilometers long. To circumvent this problem, the motion of the satellite is used to increase the effective size of the antenna. The SAR systems are used by both satellites and reconnaissance airplanes. The SEASAT satellite at an orbit height of 800 km has a resolution of about 20 m. The resolution could be improved to about 8 meters by using a higher carrier frequency. Considerably better resolutions of 1 to 3 meters are possible if the higher frequency of 10 GHz were used at lower altitudes. For example, consider the case of a radar operating at 6 GHz ($\lambda = 0.05 \text{ m}$) at a slant range of $R = 200 \text{ km}$. To obtain a resolution (ΔR) of 5 m, the angular resolution would have to be

$$\theta = \Delta R/R = 25 \mu\text{rad} = \lambda/2D. \quad (8)$$

(The synthesized antenna produces an effective beam width from an antenna which is twice the synthetic antenna length.) This gives a synthetic aperture with a diameter of 1 km. Since the orbital velocity for a low earth orbit is about 8 km/s, the processing time for the SAR would have to be about 0.1 second. Longer processing times would improve resolution in the tracking direction, parallel to the velocity of the satellite, but it can never be better than 1/2 of the length of the actual antenna. As in the case of optical systems, the best achievable resolutions would be limited by atmospheric inhomogeneities and radar stability. Three-dimen-

sional surface maps can be obtained by either placing two antennas on a satellite or airplane, or by recording images during two successive passes over the region and correlating these images.

Ground-based radars can be used to monitor re-entry vehicles and satellites. An inverse synthetic aperture radar (ISAR) is effectively created as the re-entry vehicle approaches the radar. As the RV rotates, it is possible to determine some aspects of its shape by using the motion of the RV to increase the effective size of the antenna as in the case of SAR. These techniques can be used to determine sizes to determine if "new classes" of missiles are being tested.

The SALT II treaty places a limit on the number of RVs that are tested on each type of missile. Such testing can be monitored by large phased array radars (PAR), like the Cobra Dane radar that use an array of 34,769 small radiating and detecting elements to track simultaneously up to 100 objects, the size of a grapefruit, at a distance of the order of 2000 km. By varying the phases between the individual radiators and detectors, the radar beam can be steered onto the target. Digital processing techniques similar to those used for photographs are used to enhance the resolution. The PAR Cobra Judy radar is mounted on the stern of the USNS Observation Island. It can move around on the ocean and monitor various properties of re-entry vehicles such as their mass and missile coefficient (a measure of its accuracy), as well as count the number of re-entry vehicles released by a single missile. PAR radars also can be used for early warning and space tracking, as well as for battle management of anti-satellite and ballistic missile defense systems.

VI. NUCLEAR WEAPONS TESTS

The Limited Test Ban Treaty (LTBT) of 1963 was the first major arms control treaty signed by the U.S., U.K. and the U.S.S.R. Since the LTBT forbids nuclear weapons tests in the atmosphere, in the sea, or in space it forces nuclear weapons tests to be held underground. It is an interesting fact of history that the U.S. Senate decisively ratified (88 to 19) the LTBT before launching the first VELA satellites which were needed to verify compliance with the treaty provisions against explosions above the atmosphere. (Seismographs and other equipment could verify explosions in and below the atmosphere.) For the verification of a Complete Test Ban Treaty (CTBT) a network of about 24 seismic stations located inside (and near) the U.S.S.R. could be used to identify nuclear weapons tests in a decoupling cavity having yields as low as 1 to 5 kilotons with 90% confidence. Improvements in seismic technology hold out the promise that test ban treaties will be more verifiable in the future than in the past.

Since the ratification of the Limited Test Ban Treaty in 1963, there has indeed been considerable progress on technical means of monitoring weapons tests:

1. Seismic signals at frequencies of about 30 Hertz can considerably improve the ability to detect and identify explosions that might be hidden by detonating in large cavities (decoupling);
2. Seismic stations appropriate for unattended use in remote places of foreign countries have been tested and are in use; and

3. Vela satellites are being joined by 18 Navstar Global Positioning Satellites (GPS), which will make nuclear testing in and above the atmosphere more readily identifiable.

High Frequency Discrimination

Estimates of the desirability of nuclear test ban treaties have been greatly influenced by the fear of undetectable underground cheating. By exploding a nuclear weapon in a large cavity in the earth, the explosion can be partially decoupled from the earth, reducing the amplitudes of the wave by a factor as large as about 200 at lower frequencies (perhaps by 60-75 in practice). The frequency spectra of both nuclear explosions and earthquakes are relatively flat, or unchanging, up to their "corner frequency" beyond which the amplitude decreases with increasing frequency. This can be seen by considering the frequency spectrum $U(\omega)$ which was obtained (11) by Fourier transforming the elastic displacement produced by a step pressure P at a distance r :

$$U(\omega) = (a^3 P_0 v) / (c r) (v^2 - 0.075 a^2 \omega^2 + i v a \omega) \quad (9)$$

where the compressional velocity $v = 4$ km/s, the elastic pressure limit of the media is P_0 (440 bars for salt), a is the size of the cavity for elastic behavior, and c is a constant. The low frequency limit ($\omega \ll v/a$) does not depend on ω while the high frequency limit is proportional to ω^{-2} . The corner frequency of an explosion occurs at higher frequencies than that of an earthquake of equivalent low frequency p-wave amplitudes because the explosion takes place more quickly and in a smaller volume. The decoupling of an explosion in a cavity shifts the "corner frequency" (Figure 1) to higher frequencies, resulting in greatly reduced decoupling at the higher frequencies. Thus, a decoupled explosion might have its amplitude reduced by about a factor of up to 200 at low frequencies below the corner frequency, but by only a factor of about 8 above the corner frequency. Figure 1 shows that the amplitude of earthquakes falls off more rapidly with frequency than is the case for explosions, so that at higher frequencies, in the region above 30 Hertz, the earthquake amplitudes are less important. These data show that the reductions of the amplitudes of the decoupled explosions are relatively less at the higher frequencies. The high frequency components can be used to detect and identify decoupled explosions down to about less than 1 kiloton (11), or 3-10 kilotons (12) without the high frequencies with about 90% confidence.

Unattended In-Country Seismic Stations

In order to provide the required capabilities to verify a CTBT, each side must be able to observe seismic signals on the soil of the other country. The Pugwash Conference in 1962, proposed building automatic seismic stations that were "sealed in such a way that they cannot be tampered with." Starting in the mid-1960s, the Sandia National Laboratories (13) has built and tested unattended stations, and now uses them in a network in the U.S. and Canada, as well as at the small-aperture NORSAR array in Norway. The unattended stations are powered by thermoelectric generators, with batteries as back-up power in case of a failure in the generator system. The seismic data is sent by satellite link unencrypted to whatever collection points are desired, so that the data can be available to all those who wish to receive it. Procedures and equipment have

Figure 1

Decoupled Nuclear Explosions. The frequency spectrum of an underground nuclear explosion is "flat" or unchanging up to its "corner frequency" where the amplitude drops at higher frequencies. If the explosion takes place in a large cavity in the earth, the amplitudes of the lower frequencies can drop by as much as a factor of 50 to 200. However, the decoupled explosion's high frequency spectrum does not change as dramatically. The corner frequency is shifted to higher frequencies so that the amplitudes are decreased by only a factor of about eight. The higher frequency region above 30 Hertz is a promising region for these kinds of measurements because the amplitudes from earthquakes and the micro-seismic noise are reduced at higher frequencies.

(Data courtesy of J. Evernden)

been incorporated directly into the system design of the seismic stations to prevent the undetected introduction of false information into the data stream.

Nuclear Explosions in the Atmosphere and Space

The capability to observe nuclear explosions in and above the atmosphere are excellent. This has been done by the Vela satellites which have been improved considerably over the years. Initially the Velas were estimated to have a lifetime of only 9 months, but they have typically lasted more than 13 years. The Velas were launched in pairs and placed

Figure 2

An optical bhangmeter records the signal from a 19 kiloton atmospheric nuclear test. The shape of the double phase is used to determine the yield of the explosion.

(Data courtesy of Los Alamos National Laboratory)

180° apart in 115,000 km radius orbits, providing constant observation at all times of almost the entire earth. Above the ground explosions generate large amounts of x-rays, gamma-rays and neutrons, which, when released in the atmosphere, cause large optical and electromagnetic signals. The Vela satellites detect both the primary and secondary signals. The Panofsky Panel in 1959 pointed out the difficulty of concealing these effects. For example, a one-megaton explosion above the atmosphere will deposit more than a billion 10-keV x-rays in a one square cm detector located in a Navstar satellite 25,000 km from the explosion. Thus, explosions of less than a kiloton are readily observable even when exploded beyond the geosynchronous orbits of the earth. Smaller, but still readily observable, fluxes of gamma rays and neutrons are also produced.

After the last Vela launch in 1970, the Air Force placed large multi-purpose satellites in geosynchronous orbit, and, in 1983 a new series of satellites, the NAVSTAR Global Positioning Satellites (GPS), were initially deployed. The GPS satellites will have a dual purpose because they will monitor possible nuclear explosions as well as to be used for navigation and guidance of missiles. In all, there will be 18 satellites located at an orbital radius of 26,000 km in nongeosynchronous orbits; any spot on earth can be observed at all times by 4 to 8 of the GPS satellites. The accurate clock system of the GPS satellites will allow the determination of the position of a nuclear explosion with great accuracy. Had these instruments been functioning in 1979, they would, most likely, have removed the ambiguity from the Vela data of the "event" over the South Atlantic. (In 1980, the Ruina Panel of the Presidential Office of Science and Technology Policy reported that the light signals recorded

by a Vela satellite over the South Atlantic were probably not from a nuclear explosion.)

A nuclear explosion in the atmosphere gives a unique double-peaked optical pulse. The initial burst of x-rays lasts less than 1 μ s; these x-rays are absorbed in the first few meters of air, and their energy then "diffuses" to create a fireball by heating the air to about 10^6 K. Shortly afterwards, a shockwave carries the energy beyond the fireball. Since this high-temperature shocked gas is ionized, it is opaque to the optical radiation from the fireball behind it, thus reducing the luminosity of the fireball. After the shocked gas has expanded and cooled, it again becomes transparent to light, and the intensity of the fireball again rises. This very distinctive light curve is measured with a photometer known as a "bangmeter" which measures the light intensity as a function of time. The time between the pulses can be used to determine the magnitude of the explosion (a value of 19 kilotons can be derived for the explosion shown in Figure 2). Since the earth is a very bright object, it is necessary to use the fast rise time of the optical signal (of the order of milliseconds) to distinguish the characteristic double optical pulse from the background light signals. Nuclear weapon explosions also develop a very large voltage pulse called an electromagnetic pulse, or EMP. An explosion can be identified even more credibly by observing the timing between the EMP pulse with respect to the optical bangmeter signal.

VII. CONCLUSIONS

We have described some of the impressive newer technologies that are being used to monitor the military technologies and weapons systems for the verification of arms control treaties. Once the data have been obtained from these instruments, analysts and politicians will make the decisions as to whether or not there has been compliance with the provisions of arms control treaties. It is true that advances in science and technology have often exacerbated the relations between nations and accelerated the arms race; it is encouraging to see that technological advances can also help stabilize the arms race. Since it appears that the quality of the verification technologies is one of the main limiting conditions on expanding the reach of arms control treaties, these technical advances could be helpful in breaking the political impasse on potential future arms control treaties.

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