Advances in verification technology

The alleged limits of verification techniques have been used to justify lack of action at the negotiating table, but advances in computer science and optics should help dispel doubts about the verifiability of treaties.

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ARMS CONTROL agreements rely on more than trust. The overlap between various technical means of verification and human intelligence and diplomacy affords considerable means to verify arms control treaties. These means are synergistic: when used together, they enhance our ability to know what the other side is doing. Treaties between the United States and the Soviet Union, which state that "each party undertakes not to interfere with the national technical means of verification of the other party," spell out the "right" to determine compliance.

The depth and complexity of the SALT treaties have re3ulted primarily from the perception of the "adequacy" of the technical means. In 1979 former Secretary of State Cyrus Vance defined "adequate" for the Senate: "Although the possibility of some undetected cheating in certain areas exists, such cheating would not alter the strategic balance in view of U.S. programs. Any cheating on a scale large enough to alter the strategic balance would be discovered in time to make an appropriate response."

The technical means of verification need not be totally reliable in order to deter a nation from cheating. If the number of missile launchers was incorrect by 10, this would not be a threat to either superpower's security since there are over 1,000 land-based launchers on each side. An error of 100 launchers would be somewhat more significant, but it also would be much more detectable by present means of verification. Since it takes several years to develop and deploy a new missile system, a delay in discovering its initial phases is not extremely critical to our national security.

Nevertheless, confidence in the degree of adequacy of means of verification has affected the writing of treaties. For example, James Timbe, chief of the Strategic Affairs Division of the Arms Control and Disarmament Agency stated in 1979: "We have a basically adversarial relationship with [the Soviets], and our ability to verify their compliance with an agreement is critical. The design of SALT II has been based on what could be verified and what couldn't.'"

The technical means of observing and verifying foreign military endeavors is crucial to arms control for two fundamental reasons:

- If Soviet or American military planners are convinced that there is a reasonable chance that any violation of a treaty would be discovered, they might act more cautiously since they would not wish to encourage an opponent to increase its armaments or respond drastically in other arenas.
- For an arms control treaty to be negotiated successfully by the executive branch and ratified by the Senate, these bodies must believe that the technical and nontechnical means of verification are adequate. That is, they must be confident that the United States would have "timely warning" to protect its national security against Soviet cheating by a "break-out" from a treaty with new weapons.

The high-quality data obtained from today's reconnaissance satellites, seismographs and other technical means tend to stabilize the arms race. Since both sides now can identify, count and monitor ICBM launchers and tests, nuclear explosions, troop movements and so forth, both should, in principle, be less prone to the "worst case analyses" which cause them to build additional systems to counter feared "missile gaps." Because of the national technical means of verification, most observers felt that the SALT treaties could be adequately verified to ensure Soviet compliance. On balance, reconnaissance satellites are much more stabilizing than destabilizing to world peace; in 1967 President Johnson commented that the $35 to 40 billion for space programs had been well spent because, "I know how many missiles the enemy has."

The intelligence community, in gathering data on the strategic balance, now focuses on supporting computer scientists in McLean, Virginia rather than on "our man in Minsk." The vast majority of the U.S. intelligence budget (about $15 billion per year) is spent to gather and analyze data from technical means rather than from espionage sources. And the volume of this data is such that it can only be handled by an array of large computers that sift through and interpret it.

VERIFICATION can be done by monitoring either objects, such as silos and missiles, or activities, such as missile and warhead tests. To monitor objects, we must be able to measure sizes and shapes so that we can identify the differences among and enumerate the various classes of launchers. This type of data is obtained from reconnaissance satellites, radar and human intelligence. For example, the "Big-Bird" satellite's massive weight-11 tons—allows it to carry a huge camera, whose high-resolution film is periodically ejected in reentry canisters that land near Hawaii. In addition, Big Bird carries television equipment which can scan black-and-white, color and multispectral photographs. These pictures allow observers to identify and count the number of Soviet silos or to monitor the movement of mobile SS-20 missiles. Its infrared pictures can also be used to measure the thermal output of warm bodies in underground silos or buildings. The multispectral monitors can detect camouflage since they can easily distinguish live vegetation from paint of the same color. Of course, these satellites cannot see through walls to determine activities inside buildings.

To monitor activities such as nuclear weapon or missile tests, the deployment of weapons and troop movements, the detector must be time-sensitive. For example, a missile launching can be observed by a satellite and then monitored during its flight by radar and optical systems located on land, sea and air. The Cobra Dane radar system is useful for following the trajectories of the various MIRVed warheads since it can simultaneously track 100 objects the size of a basketball at a distance of 3,000 kilometers. The communication signals from the missile to its ground crews (the telemetry) can be monitored by receivers based on land, sea, air and space. Nuclear weapons testing can be monitored by seismographs located outside the Soviet Union and by untended seismic stations located in the Soviet Union which can detect nuclear explosions in rock down to about one or two kilotons. Since nuclear weapons typically have an explosive yield greater than 10 kilotons, the United States should be able to verify compliance with a comprehensive test ban with a high degree of confidence.

The list of words and acronyms for technical means of verification is long: ELINT, SIGINT, Cobra Dane/Cobra Judy, digital image processing, charge-coupled devices, RECOVER, Rhyolite and so on. Rather than broadly describing this potpourri of many available verification systems, a summary of their properties is presented in the accompanying table. A few technologies that are on the verge of improving our capabilities of photographic reconnaissance are then described below.

THE TECHNOLOGY of reconnaissance satellites often has been said to be of such high quality that it is possible to read an automobile's license plate (if held horizontally). Thus, Drew Middleton, a military affairs reporter, wrote in the *New York Times* of September 11, 1983:

> The United States and NATO specialists said satellite pictures were the mainstay of visual intelligence. Pictures taken from satellites flying at 100 or more miles altitude after magnification have in one instance shown the bolts on the deck of a Soviet cruiser. In another picture, a man reading a newspaper on the street of a north Russian town was seen in the picture to be perusing Pravda. It is known to be Pravda, they note, because the nameplate is clearly visible in the satellite photograph.

Let us consider these speculations by looking at some of the facts that have appeared in science and technology journals. For example, G. Kaplan in 1982 had this to say about the resolution of satellite photography:

> How effective are the spy satellites? Of key importance is the resolution of the image obtained by a sensor. Although the exact resolution of a spaceborne close-look camera is classified, recent improvements in optics and film quality facilitate ground resolution of anywhere between 5 and 15 centimeters (2-6 inches) from a relatively low orbit, depending on the weather, pollution, and such factors as the alignment, stability, and vibration of the sensor, as well as the movement of the target.[2]

To provide a more graphic idea of what a resolution of two to six inches is, I have taken some photographs of an automobile. First, a good picture was defocused, or blurred, by adding an external lens (Figure 1). In order to obtain an estimate for the resolution of the blurred photograph, I placed circles of two, four and six inches in diameter on the auto. These circles indicate that at the rear of the blurred auto the resolution is about four inches—not good enough to read the license plate, but we can identify the car as a Volkswagen Beetle. This resolution is also not sufficient to read the name of a newspaper, but it might be sufficient to count, with the aid of computer processing, the letters needed to distinguish *Pravda* from the other common Soviet newspaper, *Izvestia.*

Since photographs of reconnaissance satellites are classified, judgment of the quality of verification will have to be based on considerations of the maiden flight of the space shuttle *Columbia* in April 1981. After the launch, the crew observed that several thermal tiles were missing from the upper portion of *Columbia.* A photograph, taken by the television monitor on the shuttle, shows the tiles, which are about three inches across (Figure 2). There was a great deal of concern that many other tiles could have been lost during the launching and that the lives of the crew might be endangered during re-entry into the atmosphere without the heat shield. Unfortunately, the monitor could not observe the bottom of the craft. The question was answered fairly quickly by the Department of Defense, which used some specialized photographic techniques with land-based cameras, to determine that no tiles were missing from the underside.' The "angular resolution" from this measurement of a three-inch tile at a distance of 100 kilometers is consistent with the earlier statement here of a two- to six-inch resolution.

IN THE AUTOMOBILE example, the image of the car was blurred by adding an extra lens to the camera. Scientists have devised methods to reverse this process to recover some of the precision of the image of the auto by using the data of the blurred image.' Figure 3 exemplifies this enhancement process with the image of a freeway system degraded by cloud cover; digital image processing (DIP) techniques have then been used to enhance the contrast in the photograph to reveal more details.[5] Since digital computers can deal only with numbers, it is necessary either to use electronic devices that automatically give numbers or to read and convert the film darkness (density) in small regions (pixels) into numbers.

Photographic systems tend to blur straight lines and edges into a gray region of transition from light to dark. This blurring can be caused by the optical system, fluctuations in the air or motion. DIP methods can restore lines and edges by searching for the shortest distance through the gray transition region in the same way that we could search out the steepest and shortest path down a mountain. After a number of these steepest paths have been discovered, the computer can then determine the location of the edge or line. Once the computer has found the line, it restores the image by removing some of the data from the foothills and returning it to the mountain top.

An over-exposed photo lacks sharpness because it has too much information; the picture is obscured in haze or noise. Rather than dealing with just a region of the photo as in edge restoration, it now is desirable to use all of the picture's information to remove the noise. Since the object being looked for, such as an SS-20, will be much larger than the individual photographic grains, or pixels, we can analyze the picture in terms of the sums of waves of various frequencies. By removing the high-frequency noise (short-wavelength) from the picture, we will have enhanced the remaining low-frequency (long-wavelength) information describing the SS-20.

The past decade has seen a tremendous growth in the sophistication of DIP; with the advent of the very large-scale integrated circuits (VLSIC) on very tiny semiconductor chips, DIP technology will become more powerful and compact, so that it will be possible to incorporate DIP directly into reconnaissance satellites. If the shapes of several objects are already known, computers can identify the observed pattern from the patterns in its memory. A considerable amount of time can be saved with pattern recognition routines in which the shape of a mobile SS-20, for example, can be stored in a computer's memory and then compared directly with the digital image of the unknown object.

THE USE OF FILM in reconnaissance satellites causes some difficulties: the film must be read either by a television camera or by a fiber optics reader, both of which blur the resolution of very good film. To retain good resolution, the film can be sent to the earth in a film canister to be developed. This, however, is time-consuming and can only be done occasionally since the film supply is limited. The film, in spite of its excellent resolution, has other drawbacks. It is "nonlinear": the darkness of the image on the negative saturates; whereas, if the exposure time is doubled, there is less than twice the darkening effect. The film also has a very low quantum efficiency (the conversion of light into activated film grains) and a relatively narrow dynamic range (the ratio of white to black).

A charge-coupled device (CCD) is a semiconducting device that is sensitive to light; it stores a charge in the individual regions (or pixels) that is proportional to the intensity of light.[6] After the exposure of the picture ends, the circuitry of the CCD measures the charge at each pixel. This process is very similar to putting many buckets in a field during a rainstorm and then weighing the rain in each bucket.

The development of CCDs has solved most of the problems of films. The CCDs are read directly by computers, eliminating the awkward process of dropping film canisters from satellites and converting the images to digital data. Furthermore, the CCDs are about 70 times more efficient than film:

- they are linear: the charge stored is proportional to the time of the exposure;
- they are sensitive to a broader range of frequencies into the infrared; and
- they have a much greater dynamic range between white and black.

As a further bonus, the CCDs are reliable, have a very small mass compared to a year's supply of film and do not need the high voltage supply that television requires. The resolution available with the large CCDs of 1,000 by 1,000 pixels is better than that obtainable by television, and it is presently approaching that of average-quality film (100 lines per millimeter).

THE SIMILARITIES between astronomers and those who need to verify arms control agreements are vastly greater than their differences.' The combination of the use of large arrays of CCDs and the power of DIP enhanced by VLSIC is going to permit the verifier to carry out directly in the satellite some aspects of identifying objects. Turbulence in air tends to blur photographs of stars. However, since the objects observed by a satellite looking downward are much less subject to the turbulence than the observation of stars, the resolutions obtained by the space telescope orbiting above the air should be quite comparable to what reconnaissance satellites will be able to do. Thus, we should examine carefully the progress in space-based astronomy; what astronomers are capable of doing will be a guide to what verifiers will be able to do.

The technical specifications for the space telescope which is under construction and scheduled for launch in 1986 (Figure 4) are impressive and include very high resolution cameras. This telescope will be confined to measurements in the visible region of the electromagnetic spectrum. The infrared region is presently being studied by a collaboration of American, Dutch and British scientists which launched the Infrared Astronomy Satellite (IRAS) in January 1983. The IRAS group for the first time observed planetary matter in orbit around another star, Vega, which is 26 light years away. The IRAS technology includes an infrared array of 62 detectors that must be cooled to near absolute zero by 475 liters of liquid helium. Since the helium slowly evaporates, IRAS had a finite lifespan of about 340 days—comparable to that of the American satellites and considerably longer than that of most of the Soviet Cosmos series.

These impressive results and plans for satellite and shuttle telescopes using charge-coupled devices, very large-scale integrated circuits and digital image processing are, indeed, a technological tour de force which future verification schemes cannot neglect. While advances in science and technology have often exacerbated international relations and accelerated the arms race, it is encouraging that these technological achievements could help stabilize them. Since it appears that the quality of verification technologies is one of the main conditions limiting the reach of arms control treaties, these advances could be useful in helping to break the political impasse in the control of nuclear weapons. ❑

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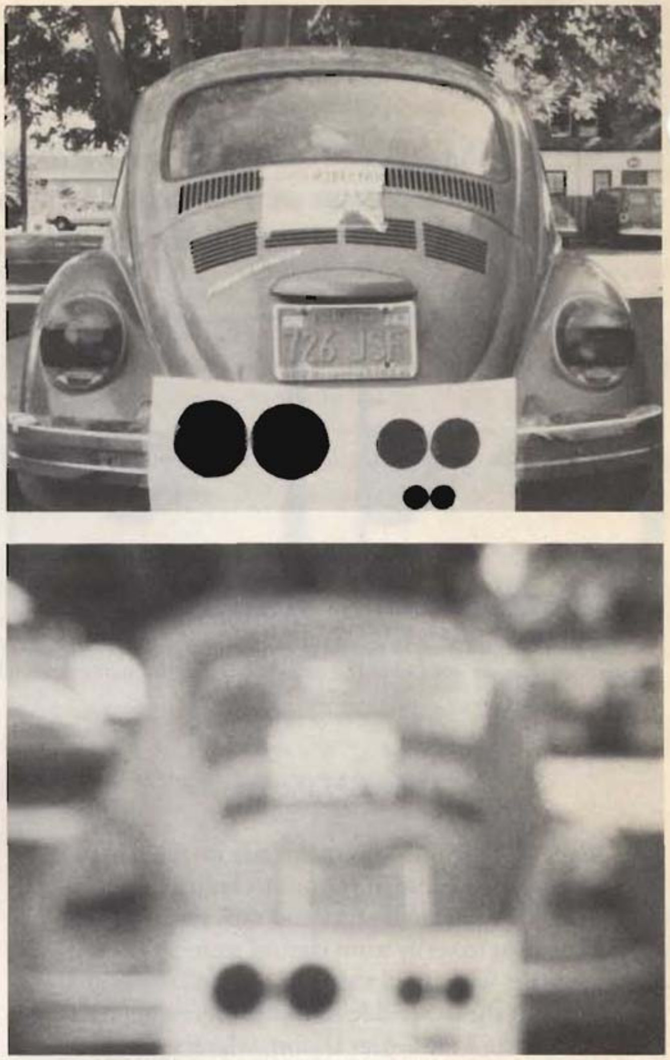
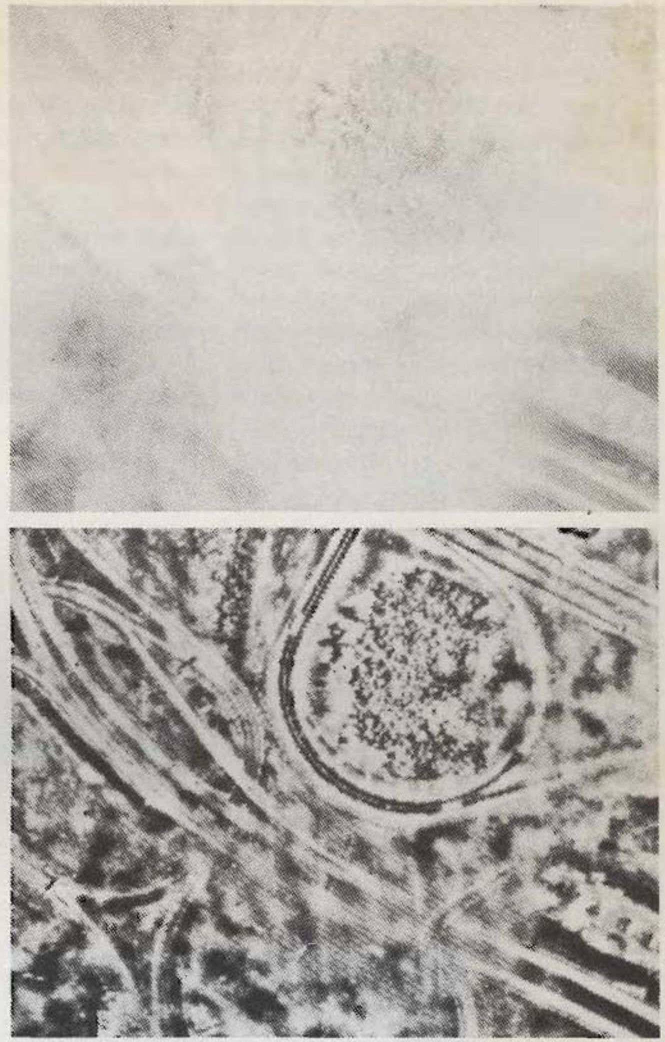


Figure 1. The lower photograph was taken with an extra lens to simulate a resolution of about three inches, similar to the cameras used for verification. Neither the license plate nor the Izvestia logo are legible, but the car can be identified as a Volkswagen "Beetle."

Figure 2. This photograph of the space shuttle *Columbia*'s upper side reveals missing tiles (dark patches in upper central area). Courtesy NASA.



Courtesy Jae Lim.

Figure 3. An example of contrast enhancement, the lower photograph of a freeway interchange shows the results of computer calculations of light and shadow under the clouds which obscure the upper photo.

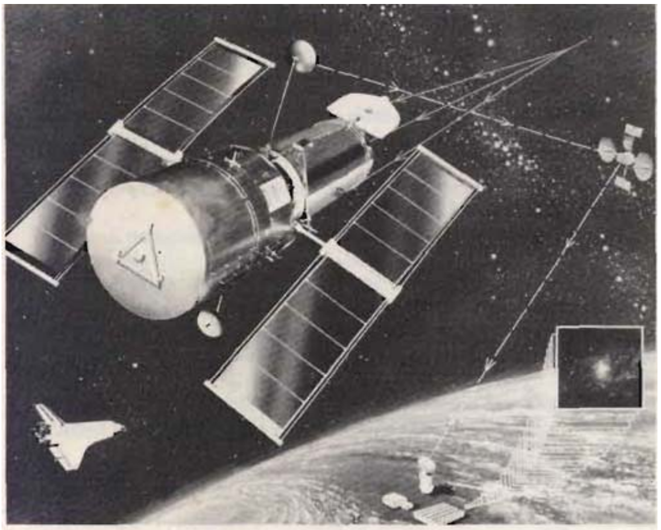
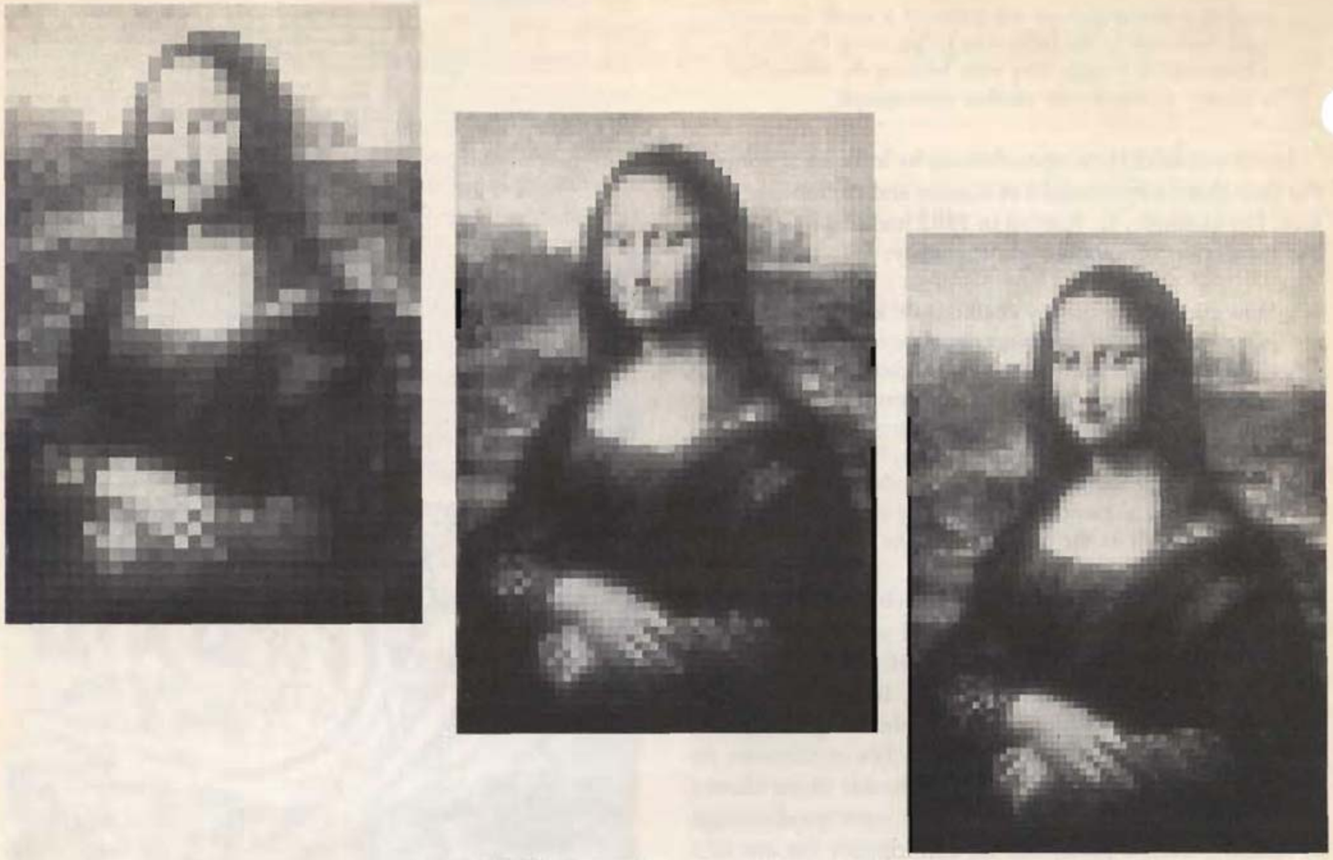


Figure 4. The space telescope, to be delivered and serviced by the space shuttle. Starlight strikes a mirror inside the telescope. The light is reflected to a secondary mirror, then "bounces" back through a hole in the primary mirror to the "focal plane" in the telescope. A photographic image results, which the disk atop the telescope relays to the tracking satellite at right. The image is then transmitted to Goddard Space Flight Center in Greenbelt, Maryland, which corrects the image data and sends the result to the Space Telescope Science Institute. *Courtesy NASA.*



The Mona Lisa undergoes digital image processing via MODULENS™. A photograph of the painting is converted to square pixels. Each pixel assumes the color, or gray tone, dominant in its area of the picture. The photo at right has four times as many pixels as the image at upper left, thus providing greater detail and higher resolution. MODULENS™ is a patented process of Goldsholl Associates, Inc., Northfield, Illinois. *Photographs courtesy Goldsholl.*

Technical verification systems'

Imaging reconnaissance satellites

KH-11: operates at 250-500 kilometers, with resolution of two to three meters. Two are in orbit at all times. Multispectral. Provides real-time data by a scanning mirror which projects the image onto an electronic plane.[3,4]
Big-Bird: operates at 160-280 kilometers, with resolution of approximately 25 centimeters. Sends film to earth in a pod; for lower resolution, film is scanned with a television camera in the satellite.[2]3
Close-Look: operates at 130-300 kilometers, with resolution of about 5-15 centimeters. Sends film back to earth.[2,3] *Space shuttle:* uses multispectral infrared radiometer and cryogenic infrared radiance instrument. Department of Defense plans to use 25 of 72 shuttle flights scheduled through September 1987. *Landsat:* operates at 800 kilometers, with resolution of 20-30 meters. Multispectral, using television-type transmission.

Electronic reconnaissance satellites

Rhyolite and chalet: operates in geosynchronous 36,000-kilometer orbit. Collects telemetric information about Soviet missiles during their flights. Aquacade to be used after 1985.[4,5] *Ferret:* operates at 600 kilometers. Collects information about Soviet launches and radars.[4']5

Radar and optical detectors

Seasat: operates at 800 kilometers, with resolution of 25 meters and two to five centimeter altimeter accuracy. Chirp radar.[4'6] *Cobra Dane and Cobra Judy:* phased-array radars located, respectively, on land and on ships for detection of re-entry vehicles above 35 kilometers. Other phased-array radars in Florida and Massachusetts can determine the size, shape and configuration of objects in space up to 5,000 kilometers distant.
Ballistic missile early warning system: radars in Alaska, Greenland and Britain for tracking missile tests.[5]
Altar: Can track 14 reentry vehicles up to 2,500 kilometers with an uncertainty of five meters in range, 250 microradians in angle and 0.1 meter per second velocity. Located on Kwajalein Atoll in the Pacific.[5]
Tradex: Can track six reentry vehicles at a distance of 1,400 kilometers with accuracy of three meters in range, 150 micro-radians in angle and 0.01 meters per second velocity.[5] *RC-137* (converted Boeing 707 airplane): air-based radars. *Over-the-horizon radar:* not restricted in its range by the curvature of the earth.[5]
Recording automatic digital optical tracker: Long-focal-length (6.1 meters) telescopes that can discriminate among reentry vehicle types at ranges in excess of 3,000 kilometers.[5]
Fourier optics: Interferometric technique used to determine dilute gaseous impurities at a great distance.?

Nuclear explosion detection

Vela: satellites at 100,000 kilometers; gamma ray, x-ray, electromagnetic pulse and infrared detectors. Early-warning detection of ICBM launchings and nuclear explosions above ground.[8] *Global positioning satellites:* 18 located at 18,000 kilometers.
Optical, electromagnetic pulse and x-ray sensors as well as navigational systems that give accurate positions of nuclear explosions.[4]
Seismic arrays: located in Montana, Norway and elsewhere in a world-wide network. Capable of detecting explosions as low as one to two kilotons in hard rock.[9]
In-country seismic sensors: tamper-proof instruments to be buried in an opponent's soil to send back seismic, acoustic and magnetic data by satellite.

Airplanes

U-2, SR-71: operates at maximum height of 28 kilometers, using cameras and other electronic surveillance.[4]
Airborne warning and control system (AWACS): operates at nine kilometers, with resolution of 0.5 meter. Comprehensive surveillance to a range of 370 kilometers. Can identify aircraft using radar wavelengths of about one to 30 centimeters.")

Submarine verification

Photographic reconnaissance satellites monitor Soviet shipyards to count submarines.
Sound surveillance system: passive system of hydrophones permanently fixed on the continental shelf of the United States and some allies. Can locate a Soviet submarine within a radius of about 100 kilometers."
Surveillance towed array sensor system: about 18 arrays of hydrophones towed by slow-moving boats.'"
Rapidly deployable sensor system: buoys with passive sensors that are deployed by aircraft, helicopters and ships."
Seasat: radar and infrared data from the Seasat satellite can compute the oceans' background noise so that it can be partially removed from the data of passive and active detection systems.[6].[11] *Laser photography:* blue-green lasers positioned in satellites to obtain photographs of some aspects of the ocean."

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1. The characteristics in this table are taken from the sources indicated. There may be errors-even major ones- but that appears unavoidable because of the classification of the data.
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