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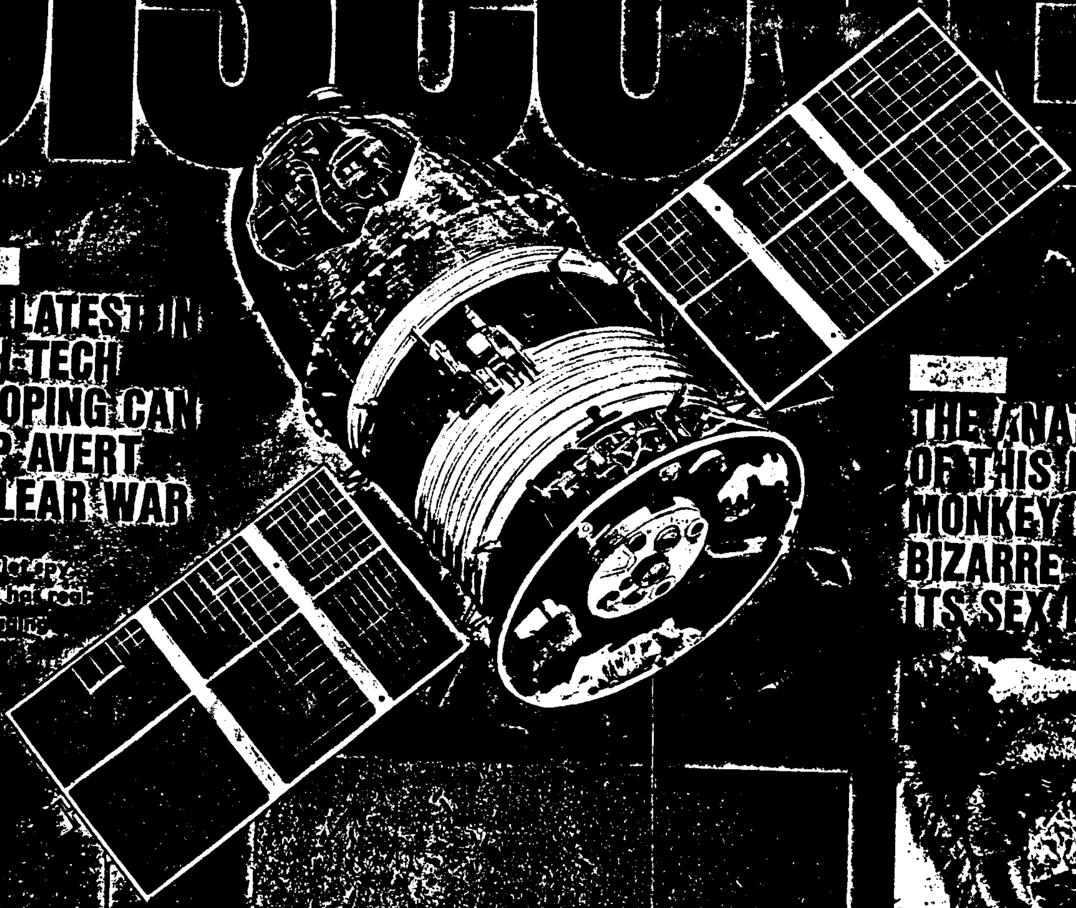


THE LATEST IN HIGH-TECH SNOOPING CAN HELP AVERT NUCLEAR WAR

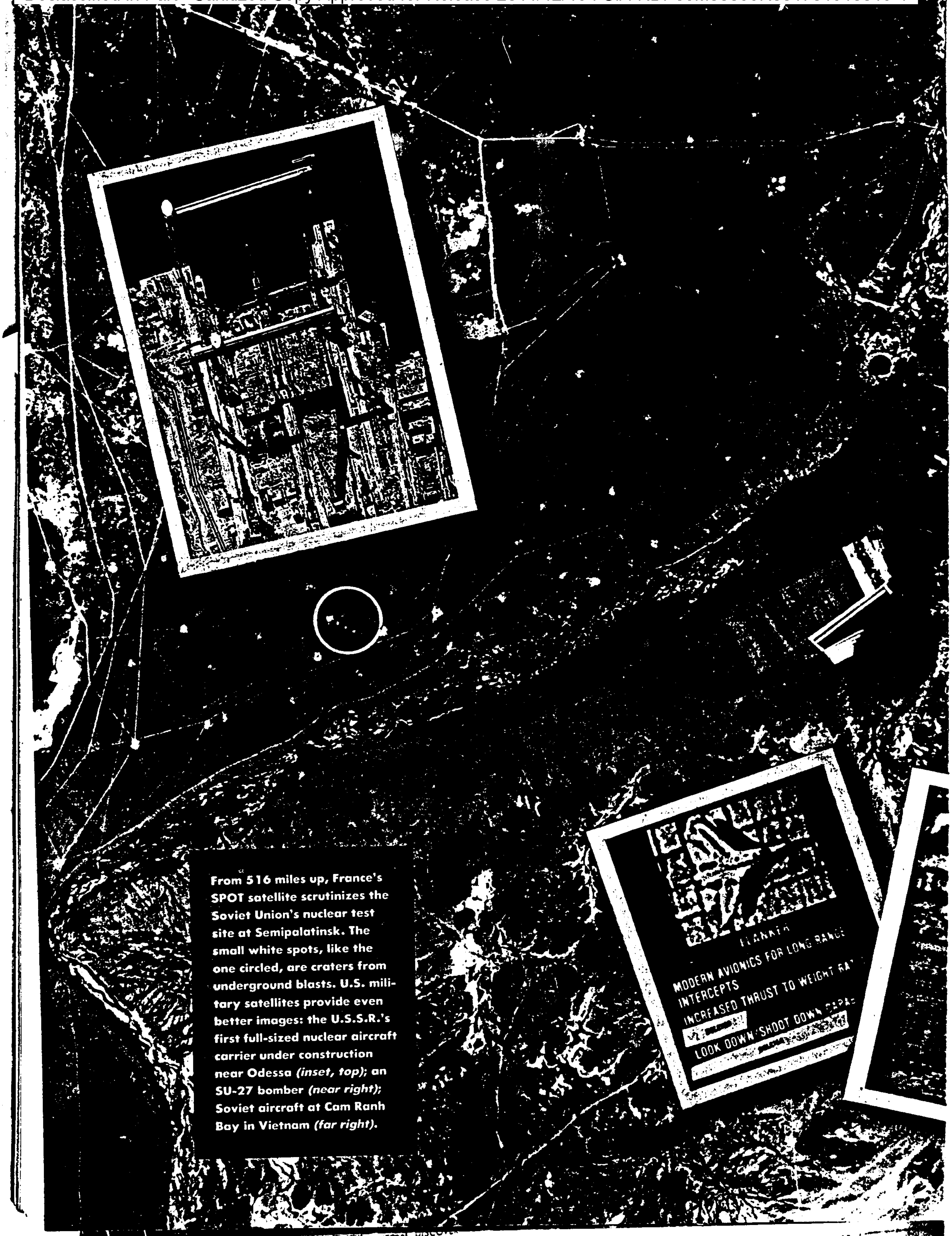
This Soviet spy satellite has real-time imaging

THE ANATOMY OF THIS RARE MONKEY IS BIZARRE—DITTO ITS SEX LIFE

NEW ATOM SMASHERS ARE COMING ON LINE, BUT WILL THEY REVEAL ANYTHING NEW?

THIS SCIENTIST IS LEARNING THE RULES THAT GOVERN HOW AN EGG BECOMES A HUMAN BEING

Mutant fruit flies like this one; they also reveal how complex animals evolved



From 516 miles up, France's SPOT satellite scrutinizes the Soviet Union's nuclear test site at Semipalatinsk. The small white spots, like the one circled, are craters from underground blasts. U.S. military satellites provide even better images: the U.S.S.R.'s first full-sized nuclear aircraft carrier under construction near Odessa *(inset, top)*; an SU-27 bomber *(near right)*; Soviet aircraft at Cam Ranh Bay in Vietnam *(far right)*.

ARMS CONTROL PACTS CAN BE VERIFIED

BY KOSTA TSIPIS

A dazzling collection of high-tech devices—from spy satellites to radars that look over the horizon—makes it all but impossible for cheating to go undetected

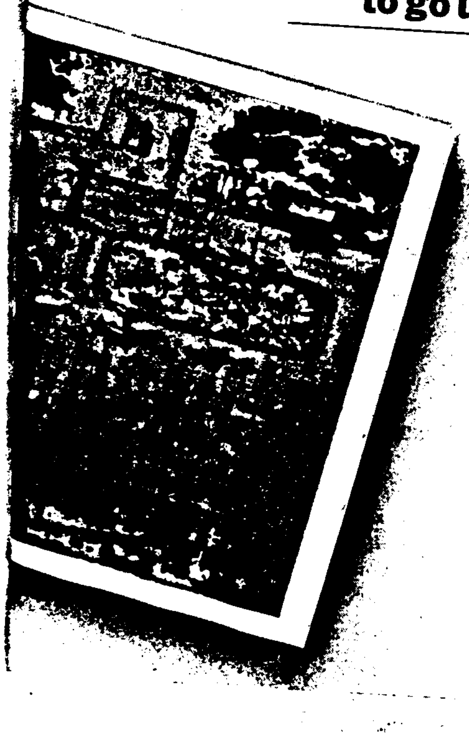
When fire broke out aboard a Soviet nuclear submarine east of Bermuda last October, its captain and crew weren't the only ones to hear the boat's alarms go off. The signals were also picked up loud and clear by secret American listening devices on the continental shelf several hundred miles away. Indeed, thanks to these underwater acoustic detectors, which can record the reverberations of an explosion halfway round the world, the Pentagon may well have known about this accident, which eventually led to the vessel's sinking, before the Kremlin did.

Strategically placed along the East, Gulf, and Pacific coasts, as well as in other militarily significant areas, such as the approaches used by Soviet subs into the North Atlantic above Norway and into the Pacific near the Kuriles, the automated listening posts are just one link in a vast network of high-tech snooping devices that keep a continual watch on Soviet military activities, not to mention Nicaragua, the Iran-Iraq frontier, and terrorist training camps in North Africa and the Middle East.

By far the greatest share of the U.S. intelligence budget (at least $15 billion a year) now goes for what those in the business call non-intrusive technical means of information-gathering, or TECHINT (technical intelligence), in contrast to HUMINT (human intelligence). These include giant hydrophones linked by cables on the ocean floor for monitoring the Soviet fleet of 375 submarines, reconnaissance satellites equipped with sharp-eyed cameras, radars on the perimeter of the Soviet Union looking out for missile launches, ELINT (electronic intelligence) listening posts in Turkey, Pakistan, and China, ships bristling with a variety of antennas, and large arrays of seismic detectors that pick up virtually every creak and groan of the earth, natural or man-made. Much of the information gathered by these electronic eyes and ears is screened, analyzed, and stored by computers that can process data at rates of billions of bits per second.

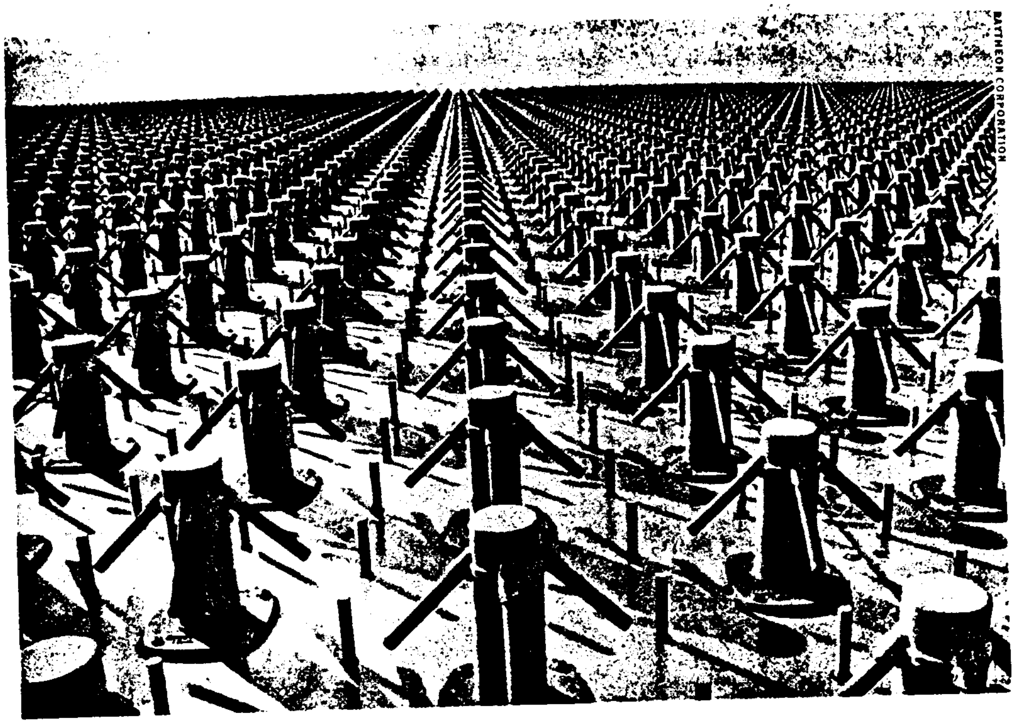
On balance the great investment in such sophisticated intelligence-gathering has been a force for peace. Nasty international incidents, like the crisis that ensued when Francis Gary Powers was

Kosta Tsipis, a physicist, is the director of MIT's Program in Science and Technology for International Security.



ILLUSTRATIONS BY JAMES A. BRYANT

shot down in his U-2 spy plane over the U.S.S.R. in 1960, are avoided.* Nor is one side likely to spring unpleasant surprises on the other. In 1967 President Johnson defended the billions spent for spy satellites by explaining that they told him "how many missiles the enemy has." Today they also provide clues to their quality and potential for destructiveness. Even before the Soviets test-fire new intercontinental ballistic missiles (ICBMs), the Pentagon usually has a good idea about such characteristics as "throw weight," number of warheads, even accuracy.



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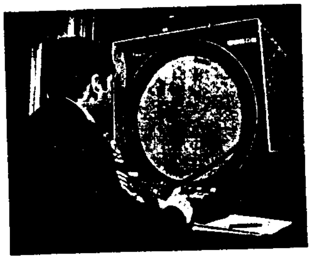

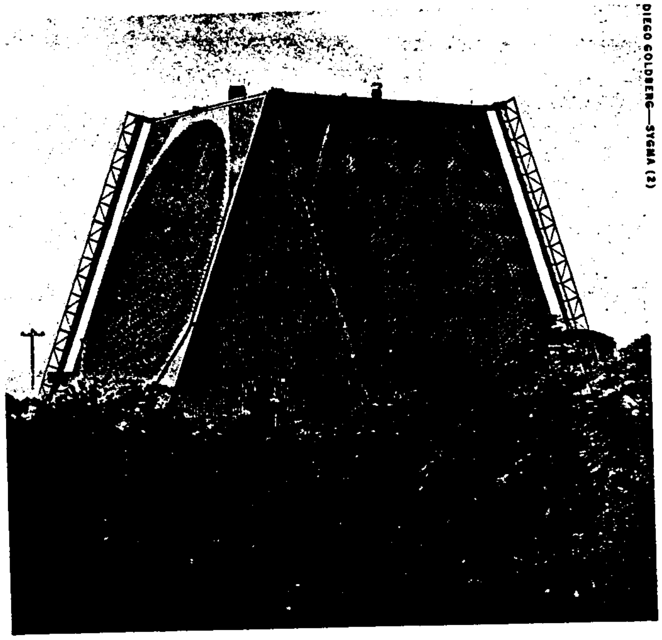

DIEGO GOLDBERG—SYGMA (2)

EARLY WARNING FROM A HIGH RISE

PAVE PAWS phased-array radar at Otis AFB in Massachusetts can observe planes or missiles 3,000 miles away with 1,800 transmitting and receiving elements *(top)* on a 10-story building *(right)*.

However, as useful as such equipment may be for collecting military intelligence, it has another important role that has yet to be fully exploited: it can monitor Soviet compliance with the terms of arms control agreements—or, in the shorthand of diplomacy, verification. At the moment, to be sure, there isn't much to verify. Only a handful of agreements exists to curb the arms race between the superpowers, notably the Limited Test Ban Treaty, which forbids nuclear testing everywhere but underground; SALT II, which limits the number of strategic missiles, warheads, and launchers, and forbids camouflaging launch sites (but which has never been ratified by the Senate, and was effectively broken by President Reagan in November when he ordered a 131st B-52 bomber with cruise missiles deployed; and the ABM (antiballistic missile) Treaty, which prohibits the introduction of exotic systems for intercepting ICBMs in flight, except to defend one mutually agreed upon site on each side. (The Soviets have chosen to defend Moscow; we've opted not to exercise the right, on the ground that any available defense would be easily penetrated.)

One reason for the lack of real progress in arms control is the widespread opinion that the Soviets will cheat on any agreement, and that undetected deception will give them the upper hand. The Reagan administration has used this argument to reject out of hand a proposal by the U.S.S.R. to halt all underground nuclear explosions. It insists—counter to the arguments of some U.S. seismologists that Soviet tests could be detected—that the U.S.S.R. could secretly continue to conduct such tests and leap ahead in weapons design. In any case, on Feb. 26 the Soviets ended their 18-month moratorium on testing by exploding a 20-kiloton nuclear bomb at Semipalatinsk. And

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*Although the Soviets originally considered satellite overflights a violation of their national sovereignty, as do many other nations, they stopped complaining once their own surveillance program got under way. However, the issue of where national sovereignty ends and space begins has never been satisfactorily resolved.

the U.S. is continuing to detonate nuclear bombs under the deserts of Nevada.

The Kremlin, which long opposed on-site inspection, seems willing to accept it now for the sake of getting an agreement on arms reduction. Moscow's change of heart has been signaled not only by the statements of high-level spokesmen, from General Secretary Mikhail Gorbachev on down, but also in such direct action as permitting the Natural Resources Defense Council, a private American environmental group, to place seismic equipment inside the Soviet Union that could pick up the vibrations of underground tests. On Feb. 28 the U.S.S.R. proposed the withdrawal of all Soviet and American medium-range missiles in Europe independent of an agreement on the Strategic Defense Initiative (SDI), a proposal quickly welcomed by President Reagan.

But, as Reagan stressed, before we can sign an arms control deal with the Soviets, we must first ask ourselves how good our ability to detect violations is. Clearly, the same equipment that keeps tabs on Soviet military activities will have to be used to monitor the Kremlin's compliance with a pact. But after the initial intelligence collection, the two processes—military reconnaissance and treaty monitoring—diverge subtly. In the analysis of the data, verification must decide whether a suspicious activity—say, the construction of a new radar or a change in the throw weight of a new missile—violates the agreement or not. Often the decision may be clouded by ambiguity. The suspected violation may not have been observed in enough detail to show an undisputed transgression. Or even if it shows up clearly, the treaty provisions may be too murky for it to be declared a violation. Thus verification makes its own very special demands on intelligence analysts.

These demands are complex and interrelated. First and foremost, verification must enhance national security. We have to be able to tell whether the Soviet Union is doing anything forbidden by the terms of an arms control treaty that could damage us if undetected for any length of time.

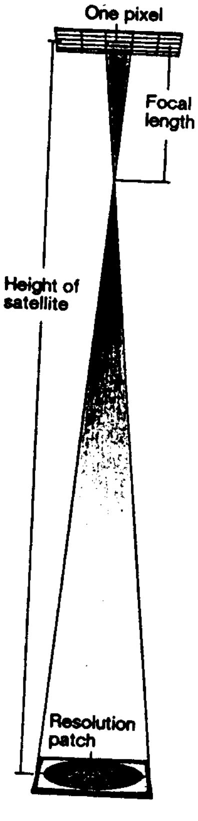
Second, verification must have a deterring effect: if the Soviet Union knows that cheating will be discovered, it won't attempt it.

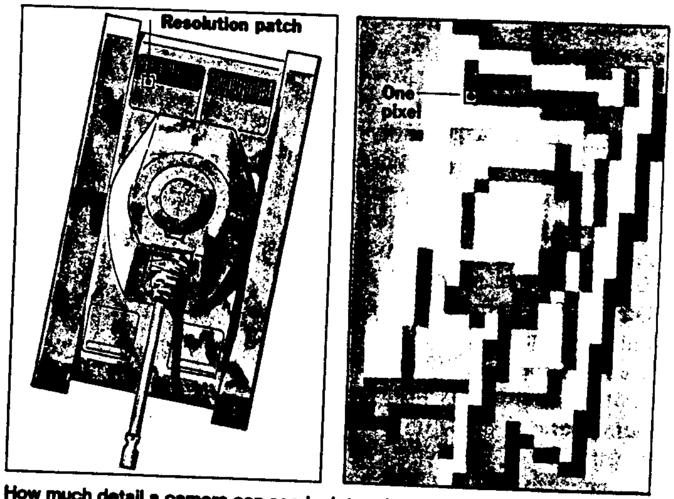
Third, verification should enhance stability, mutual trust, and confidence among the signatories of an arms control agreement. If we're convinced that the U.S.S.R. is abiding by the terms of the pact, we won't engage in the paranoia of "worst case" analyses, whereby even the suspicion of a violation leads us to declare bomber or missile "gaps" and begin expensive arms build-ups. Instead, there will be exchanges like those that occurred in 1973, a year after the signing of SALT I. U.S. satellites had spotted what looked like the excavation of silos for a powerful new ICBM in northern Siberia in violation of the new treaty, and the Nixon administration complained to the Soviets. Keep watching, they replied. Sure enough, as the work continued, satellite observations showed that the Soviets weren't digging missile silos. They were building underground command posts, which were in fact permitted by the treaty.

Finally, verification must satisfy domestic political requirements. No U.S. administration can hope for ratification of an arms control treaty by the Senate, to say nothing of acceptance by the public, unless it can convincingly show that it can monitor compliance.

Proponents of a comprehensive test ban claim that since the U.S. is able to detect an underground nuclear detonation with a yield of only a few hundred tons of TNT, our means of verification are adequate. The explosive power of some of the Soviet warheads is equivalent to millions of tons of TNT. Therefore a test of a single warhead of less than a kiloton, even if undetected, couldn't alter the strategic balance or threaten our national security. In other words, adequate verification is a function of the size of the arsenals, a relative, not an absolute, concept.

The argument goes something like this: If we agreed with the Soviets to allow 10,000 nuclear bombs each, our security couldn't be affected very much if they secretly increased their inventory to 10,100. But if we agreed to reduce our total arsenals to only 50 bombs each, it would matter a great deal if they secretly tripled their number to 150, even though the actual increase—100 bombs—is the same in





How much detail a camera can see is determined by:

$$\frac{\text{height (h)}}{\text{focal length (f)}} \times \text{diameter of a pixel (d)} = \text{diameter of resolution patch (s)}$$

IT'S ALL A MATTER OF RESOLUTION

Whether a satellite can identify a tank, say, depends on the diameter of the smallest detail, or resolution patch, it can see. This is determined by its height, the focal length of its optics, and the size of the picture elements (pixels) of its film or electronic detector. A resolution patch of the size shown on the tank would produce the image to the right of it.

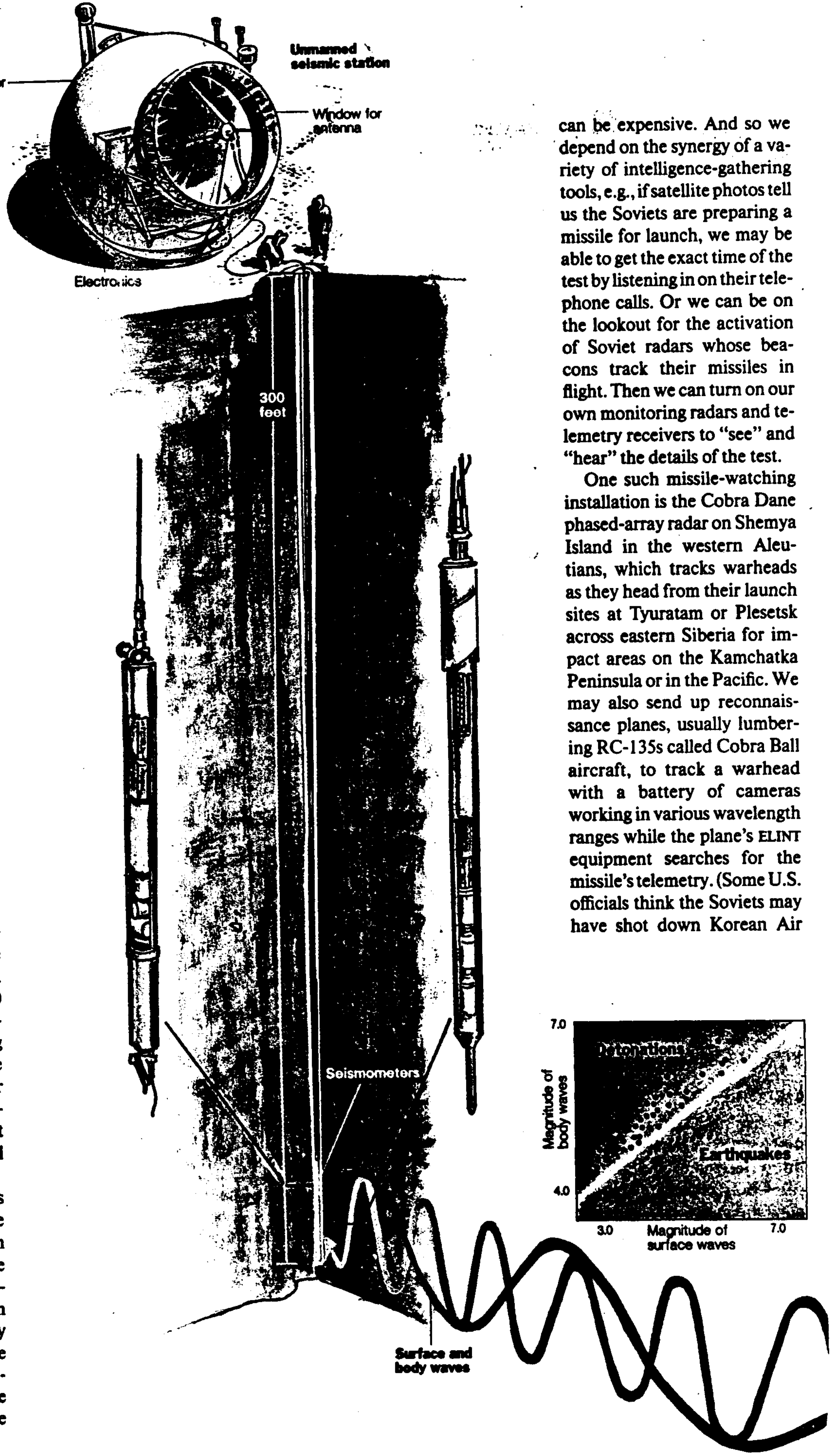
both instances. (The opponents of arms control agreements say that what matters, at least for now, isn't whether those 100 secret bombs pose a military threat but that we be able to verify that there's no cheating at all.)

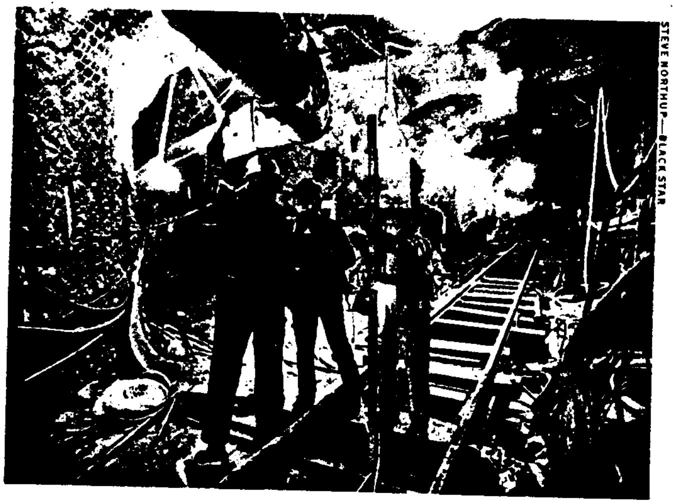
If we're to be assured that we can always monitor Soviet compliance with any arms control agreement, we should be able to determine whether an event has or hasn't happened, or is in the process of happening. There are two kinds of event: one, like the firing of a missile, changes the scene temporarily; the other, like the construction of a large radar or a missile silo in the middle of a forest, creates a permanent change.

Permanent changes, or even semi-permanent ones—for example, the slow movement of a division of troops or a wing of mobile missiles from one part of the country to another—are detected by before-and-after comparisons. Usually this is the task of photo reconnaissance satellites, which routinely photograph whatever comes into their field of view (it can also be done by high-flying planes like the U-2, whose ceiling is 90,000 feet, and the SR-71, or Blackbird, which can travel at Mach 4 at 125,000 feet, or by small remotely piloted vehicles). By comparing different images of the same scene, taken under similar lighting conditions over a period of time, we can detect changes—the laying of a keel for a nuclear submarine, say.

But such transient events as the flight test of a new missile or the underground detonation of a nuclear explosive must be observed while they're occurring. Therefore the detection systems (radars and telemetry receivers in the case of missile tests, seismographs for underground explosions) have to be on at all times. Such vigilance can be expensive. And so we depend on the synergy of a variety of intelligence-gathering tools, e.g., if satellite photos tell us the Soviets are preparing a missile for launch, we may be able to get the exact time of the test by listening in on their telephone calls. Or we can be on the lookout for the activation of Soviet radars whose beacons track their missiles in flight. Then we can turn on our own monitoring radars and telemetry receivers to "see" and "hear" the details of the test.

One such missile-watching installation is the Cobra Dane phased-array radar on Shemya Island in the western Aleutians, which tracks warheads as they head from their launch sites at Tyuratam or Plesetsk across eastern Siberia for impact areas on the Kamchatka Peninsula or in the Pacific. We may also send up reconnaissance planes, usually lumbering RC-135s called Cobra Ball aircraft, to track a warhead with a battery of cameras working in various wavelength ranges while the plane's ELINT equipment searches for the missile's telemetry. (Some U.S. officials think the Soviets may have shot down Korean Air





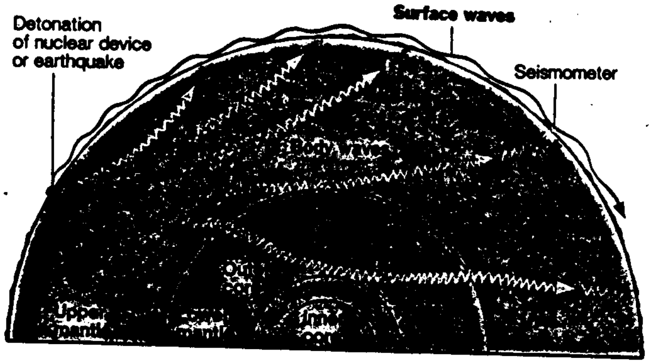
Workmen at the Nevada nuclear test site preparing the tunnel for the Feb. 3 underground detonation

STEVE NORTHUP—BLACK STAR

Lines Flight 007 because they mistook the Boeing 747 for an American spy plane on just such a mission.)

In the seas, the Navy's hydrophone network, known as SOSUS (sound surveillance system), can recognize the distinctive patterns of individual Soviet submarines from thousands of miles away. Each detector consists of a score or more of hydrophones sealed in large vats, said to be as big as oil storage tanks, and buried in the sea floor. Because the microphones are tuned to different frequencies, they can pick up different and distinctive sounds—engine noise, prop wash, the whirr of pumps—from a submarine. This cacophony is relayed by satellites in geosynchronous orbit to analysis centers, where computers sort and compare the signals with those in their memories. The objective is to form a sonic profile of each submarine in the Soviet armada, which can then be used to identify it wherever SOSUS may pick up its telltale sounds.

Because a single source of information—whether a radar, a camera, or a hydrophone—can rarely tell the whole story, the intelligence analyst must fit together myriad pieces of information from different sources, from real-time detectors like radars that observe events as they unfold and from off-line detectors like photo satellites that provide delayed but consecutive observations of the same scene, before he obtains a complete picture of a suspicious event.



THE LONG AND SHORT OF TEST DETECTION

An unmanned seismic station, opposite page, could help verify a test ban by picking up tremors—from a nuclear blast mostly high-frequency body waves that travel through the earth, from a quake mostly low-frequency surface waves—and relaying the data to a satellite. When the magnitudes of the waves are plotted on a graph *(left)*, their origin becomes readily apparent.

Of course, even without any agreements, simply as a matter of national prudence, we must be able to observe the development, testing, and deployment of Soviet nuclear weapons systems. We must be able to detect and measure the amount of energy released by underground nuclear explosions. We must also make sure that nuclear explosives aren't placed under water or in earth orbit, and we must be certain the Soviets aren't secretly exploding nuclear weapons in such exotic locales as behind the sun (a site physicist Edward Teller once suggested they might use).*

We also have to be able to count the number of Soviet ICBMs and bombers; know how many warheads each can carry; and tell whether new Soviet missiles vary from older ones by more than five per cent in any of a number of important performance characteristics (because this would be a violation of SALT II). If the types of sweeping arms control agreements discussed by Reagan and Gorbachev at Reykjavik are ever to be signed, we should also be able to count how many missiles have been destroyed, and to make sure their nuclear warheads are dismantled. We should determine that no intermediate-range ballistic or cruise missiles are deployed in European Russia, and we should have a way of finding out whether the Soviets are producing any more plutonium or weapons-grade uranium and other ingredients for nuclear explosives. Finally, we must be certain they aren't developing or testing ballistic missile defense systems beyond those allowed by the 1972 ABM Treaty, or anti-satellite (ASAT) weaponry that could knock out our unmanned orbital observatories.

Many technical experts working on arms control verification systems now think that such a task can be accomplished, thanks to recent advances in technology. Detection depends on the fact that all objects emit or reflect electromagnetic radiation of some sort (infrared or visible light or radio waves) and that almost all events involve the release of some energy in the form of electromagnetic or sound waves.

Consider the testing of a new missile. As it sits on the pad, the missile reflects sunlight, which allows the optical camera on a satellite to photograph it. As its engines start up and it lifts off, the exhaust plume of hot gases sends out large amounts of infrared and visible radiation, which can be detected by special infrared cameras that stare at the entire Soviet land-mass from a fixed position in geosynchronous orbit 22,300 miles above the earth. As the missile arcs across the sky, we can follow its motion in the minutest detail, spotting course deviations of much less than one degree, by illuminating it with giant radars directed toward the interior of the Soviet Union. And as the missile's sensors broadcast data about its performance in flight—telemetry signals—for Soviet engineers on the ground, antennas aboard our satellites and at our listening posts intercept them, decode them, and let us know how the missile behaves.

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*Even a test of this sort could probably be spotted by keeping watch on the moon for a faint flash of reflected light from the blast.

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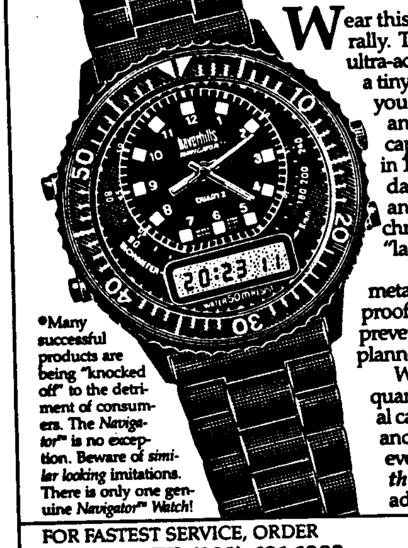

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The best known system for intercepting these electromagnetic waves is the satellite-borne photographic camera. The first successful photo reconnaissance satellite, a 300-pound package of miniaturized optics publicly called Discoverer to create the impression that it was purely for scientific purposes, though known privately in the intelligence community as Corona, was launched in 1960. Three years earlier the Soviets had orbited a similar machine, Sputnik 1, the earth's first artificial satellite, which astonished the world but could do little more than send out beeps. The cameras aboard Discoverer satellites and succeeding spies in the sky contained large rolls of film, which enabled them to record many sequential images of the terrain below. When a roll was completely exposed it was ejected inside a protective canister. As it entered the atmosphere a parachute opened to slow its descent and a plane equipped with special hooks snared it in mid-air. Once the film was developed, an analyst could see what the camera had seen.

Even the early photo reconnaissance satellites told us how many ICBMs and bombers the Soviets had, how many warships they were building, and how many submarines were in their pens. They could be raised or lowered through adjustments in their orbits, which allowed them to sweep down for a closer look at suspicious activity. But the satellites had disadvantages. First, they were wasteful. A single camera-satellite complex cost many hundreds of millions of dollars, only to become a piece of space junk once all its film was exposed, sometimes within only weeks or months. Second, additional time would elapse before the film was developed and analyzed. That was all right for monitoring events that proceeded slowly, like the construction of a missile silo, but not for more rapid developments, like the installation of mobile missiles and radars, or even a short conflict like the Six-Day War. Third, bad weather might keep large areas hidden under clouds for months at a stretch.

The first two drawbacks were overcome in the mid-'70s with a new technology called charge-coupled devices (CCDs). Using essentially the same technology as that in home video cameras, they take and transmit pictures electronically. Each CCD consists of an array of tiny sensors, or pixels (for picture elements), numbering in the thousands, arranged in a grid. As light waves fall on the array, each sensor stores a quantity of electrons proportional to the intensity of the light that has hit it. A counter tallies up the number of electrons each sensor has accumulated, and that number, as well as the location of the sensor in the grid, is transmitted to a receiving center on the ground. There a computer uses the information to construct on a TV-type screen an exact copy of the original image captured by the CCD. Meanwhile, aboard the satellite, as the electrons drain from the individual pixels the array becomes ready for another exposure. All this happens in milliseconds. No film has to be ejected, captured, and developed. Someone sitting at a console in Fort Belvoir, Va., the site of the CIA's satellite imagery center, can see in real time what the satellite is seeing in the Soviet Union. If something tweaks his curiosity, he can zoom the lens and take a more detailed picture on the next pass. And the CCD array can be used again and again, inexhaustibly.

How much the camera will see depends on its resolution, the size of the smallest object *s* it can distinguish. That depends on its distance from the scene, its focal length, and the size of the individual pixel. The smaller the pixel *d* and the longer the focal length *f*, the smaller *s* will be—that is, the better the resolution of the system. Let's say the satellite is at an altitude *h* of 100 kilometers, that the individual pixel size is 2 microns, and that the focal length of the camera is 4 meters. You quickly find out that the resolution on the ground of the hypothetical camera is 5 centimeters, which means it can detect objects as small as two inches from an altitude of about 60 miles above the earth.*

Although the capabilities of the satellite cameras are secret, stories circulate that we've been able to follow the pucks during ice hockey games at outdoor rinks in Moscow or see astonishing closeup details of Soviet submarines. Says one intelligence analyst, "You can tell if the guys on the bridge watch have their parka hoods up."

High resolution can be a mixed blessing, however. Say the camera takes a picture of a scene 100 x 100 meters on the ground. If the resolution is one meter, the picture will be composed of 100 x 100, or 10,000 pixels. But if it's 5 centimeters, the number of pixels increases to 2,000 x 2,000, or 4,000,000 pixels. As a result, 400 times as much information will be transmitted

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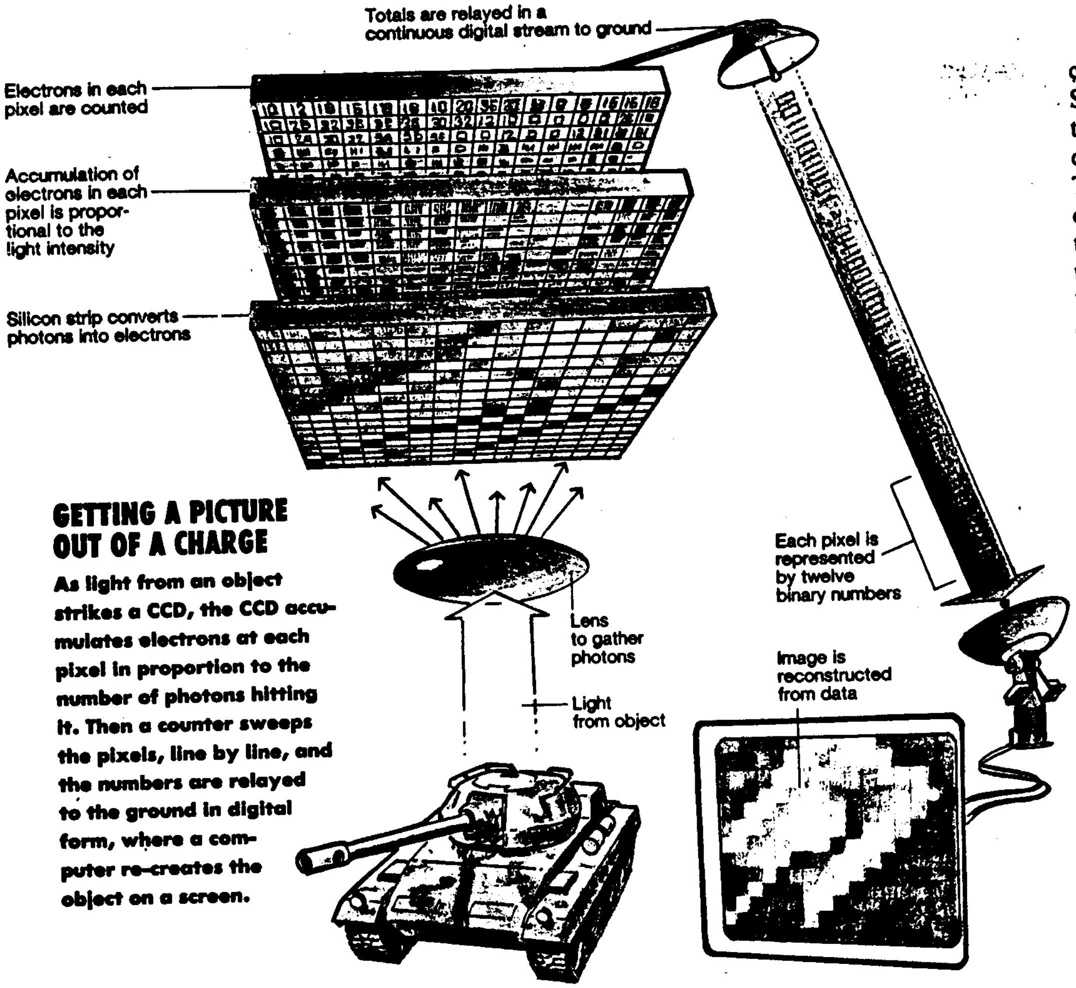
*The formula: $s = (h/f)d$.



GETTING A PICTURE OUT OF A CHARGE

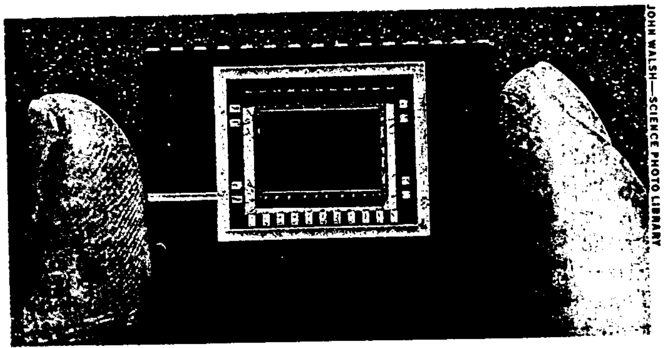
As light from an object strikes a CCD, the CCD accumulates electrons at each pixel in proportion to the number of photons hitting it. Then a counter sweeps the pixels, line by line, and the numbers are relayed to the ground in digital form, where a computer re-creates the object on a screen.

to the receiving station. This means the satellite must have a very large transmitting antenna (to handle the increased flow of data) and a lot of electrical power, which isn't always available from its solar cells. Ground controllers often order photo satellites to conserve their energy by taking pictures at lower resolution.

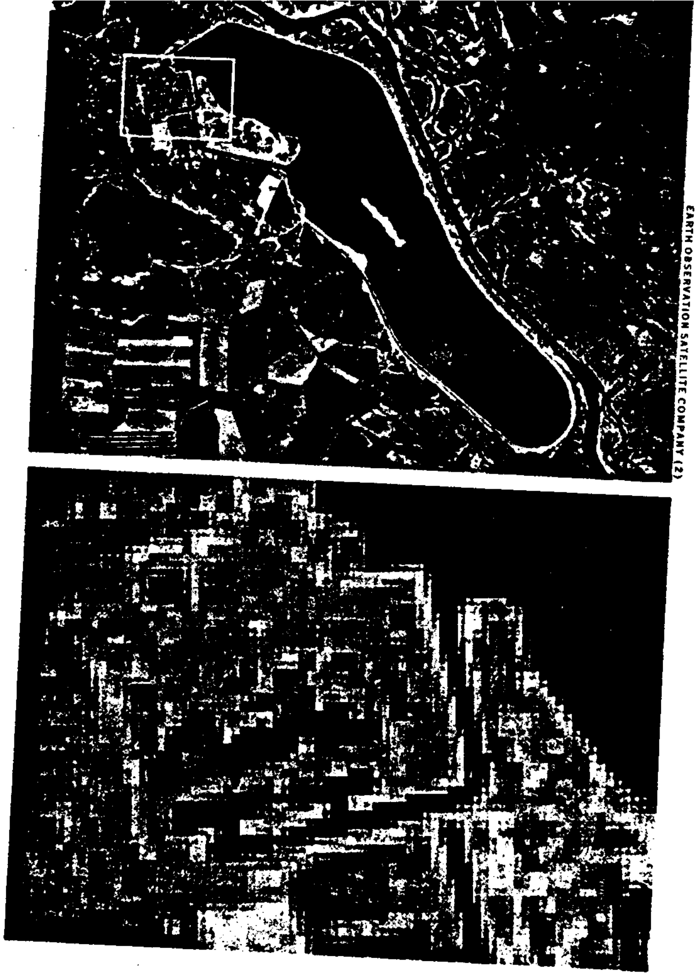
Also, the satellites may take too many pictures, overloading the analysts. Since new pictures are compared with earlier ones of the same scene, the process can be mechanized with the help of electro-optical scanners. A flesh-and-blood photo-interpreter would be needed only when the machine points out a change. Even so, the number of pictures would be overwhelming if the satellite camera took pictures of all the terrain it flew over. So the camera is turned off when it encounters clouds, or when it's over oceans or other areas where we would expect nothing to be happening, like the Sahara or the Soviet Arctic. But this practice can lead to oversights, such as the alleged installation of a nuclear explosives test facility by South Africa—which was discovered by a Soviet photo reconnaissance satellite—or the construction of a large early warning radar near Krasnoyarsk, in central Siberia, in apparent violation of the ABM Treaty, which was only noticed by one of our satellites two to three years after construction had begun. (The Soviets presumably have photographed our modernizations of the early-warning radars in Thule, Greenland, and Fylingdales Moor, England, which they claim are breaches of the treaty. We insist that they're "grandfathered" under the accord and therefore legitimately open to upgrading.)

Besides cameras, some satellites, like the Air Force's Big Bird, one of the KH (for Keyhole) series, carry sensitive listening devices that allow us to intercept radio and microwave telephone signals within the Soviet Union as well as transmissions from Soviet satellites. Such eavesdropping is supplemented by listening posts in Norway and elsewhere that can pick up the Russians' own ferret satellites (so named because they fly low enough to trigger tracking radars) as they download streams of intercepted American signals. This technology, which is of the same kind that enables us to receive and interpret signals from the eight-watt radio aboard the spacecraft Pioneer, now almost four billion miles away from earth, not only listens in on internal Soviet communications but also picks up the telemetry from Soviet missiles during testing. These signals establish a missile's rate of acceleration, fuel consumption, and temperatures and pressures at different points in the engine. Even though the Soviets encode some of these messages—in violation of SALT II say some experts, but not in my view—we can compensate fo the loss of a portion of this information through radar an satellite tracking.

These satellites monitor other activities as well. Whe American bombers attacke Libya last April, their targe were picked out with the help a photo reconnaissance sate lite and a signals intelligenc


JOHN WALSH—SCIENCE PHOTO LIBRARY

Tiny charge-coupled devices (CCDs), like those in home video cameras, have made real-time observations from space a snap.



EARTH OBSERVATION SATELLITE COMPANY (2)

The Landsat satellite observed Chernobyl from more than 400 miles up *(top)*. Reactor lies within rectangle, enlarged at bottom. Below, computer enhancement sharpens a blurry image.

LOS ALAMOS NATIONAL LABORATORY

satellite (SIGINT) whose orbit had been changed so that it passed over North Africa rather than Eastern Europe. Some satellites, like the Velas, orbiting in pairs at an altitude of 70,000 miles, nearly a third of the distance to the moon, carry a variety of sensors to detect nuclear explosions in the atmosphere. (The chores of the Velas are gradually being assumed by the new NAVSTAR global position system [GPS]; its primary function is as an extremely precise navigation aid, but its satellites also carry detectors for spotting detonations.) Other satellites are designed to ferret out the characteristics of Soviet radars and electronic jamming devices. Still others are equipped with special radars to obtain images at night or to penetrate cloud cover. These are known as synthetic aperture radars (SARs). Conventional radars, even when they send out beacons at very short wavelengths, can't provide very high-resolution images, because their resolution is limited by the ratio of the wavelength of their radiation to the diameter of the antenna. Even if the wavelength were one millimeter and the antenna ten meters long, the resolution of the radar flying 800 kilometers above the surface of the earth would still be only 80 meters (in contrast to my imagined camera's five-centimeter resolution).

But in the case of the SAR, after the radar's waves are bounced off the ground they're tricked electronically into "thinking" the satellite's receiving antenna is as long as the distance the spacecraft has traveled during that interval. A typical SAR with a ten-meter antenna, orbiting at 800 kilometers, will have a resolution of just five meters. (To achieve this resolution with an ordinary radar would require an antenna almost 20 kilometers long, or about twelve miles.) The size of the antenna can't be reduced to achieve higher resolution because the radar beam will be spread out and diffuse by the time it reaches the ground, thereby spoiling the image. But even with this limitation, satellite SARs can achieve resolutions approaching one meter and provide almost photographic images of the terrain they survey.

In radar systems of this sort the amplitude and arrival time of each reflected wave must be briefly stored. Then all the pulses returning from a given point on the earth must be added up electronically. In the past this information had to be transmitted to the ground and processed by computers before it could be viewed on a monitor. But now that computers have shrunk in size and their power requirements have been reduced, very complex computational capability can be carried on board the satellite, which makes it possible to send back pictures in real time. This is a significant advance, considering that large areas of the Soviet Union are blanketed by clouds for extended periods and that the northernmost regions are cloaked in the darkness of the polar night for several months a year.

Of course, such surveillance requires that we have at least one fully operational photo reconnaissance satellite in orbit—preferably more. The halt in space shuttle launches after the *Challenger* catastrophe and the loss of two Titan boosters and their satellite payloads, all in the past year and a half, have crippled our satellite-orbiting capability. Before the Air Force finally managed to loft a ferret satellite in February, our watchdog capacity had dwindled. For notable example, we were left with only a single KH-11, the workhorse of our reconnaissance program. This advanced satellite is equipped with a large optical telescope that has a primary mirror of 70 or 80 inches, high-resolution CCDs, and multispectral and infrared imagers. It will be replaced by a new super satellite, the KH-12, which will have not only extraordinary resolution—less than three inches, according to reports*—but also extraordinary night-seeing ability. However, it's so heavy it can only be carried into orbit by a shuttle or a modified Titan booster.

Large phased-array radars on the ground and on ships monitor the maneuverings of satellites (which are also observed with very large optical telescopes installed on Maui and in Florida), the testing of missiles and aircraft, and the trajectories of ballistic missile re-entry vehicles. Activities that take place too deep inside Soviet territory to be observed by radars on the periphery of the

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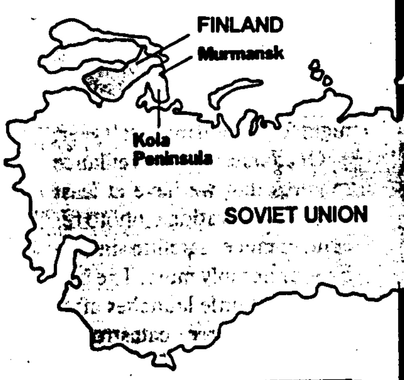
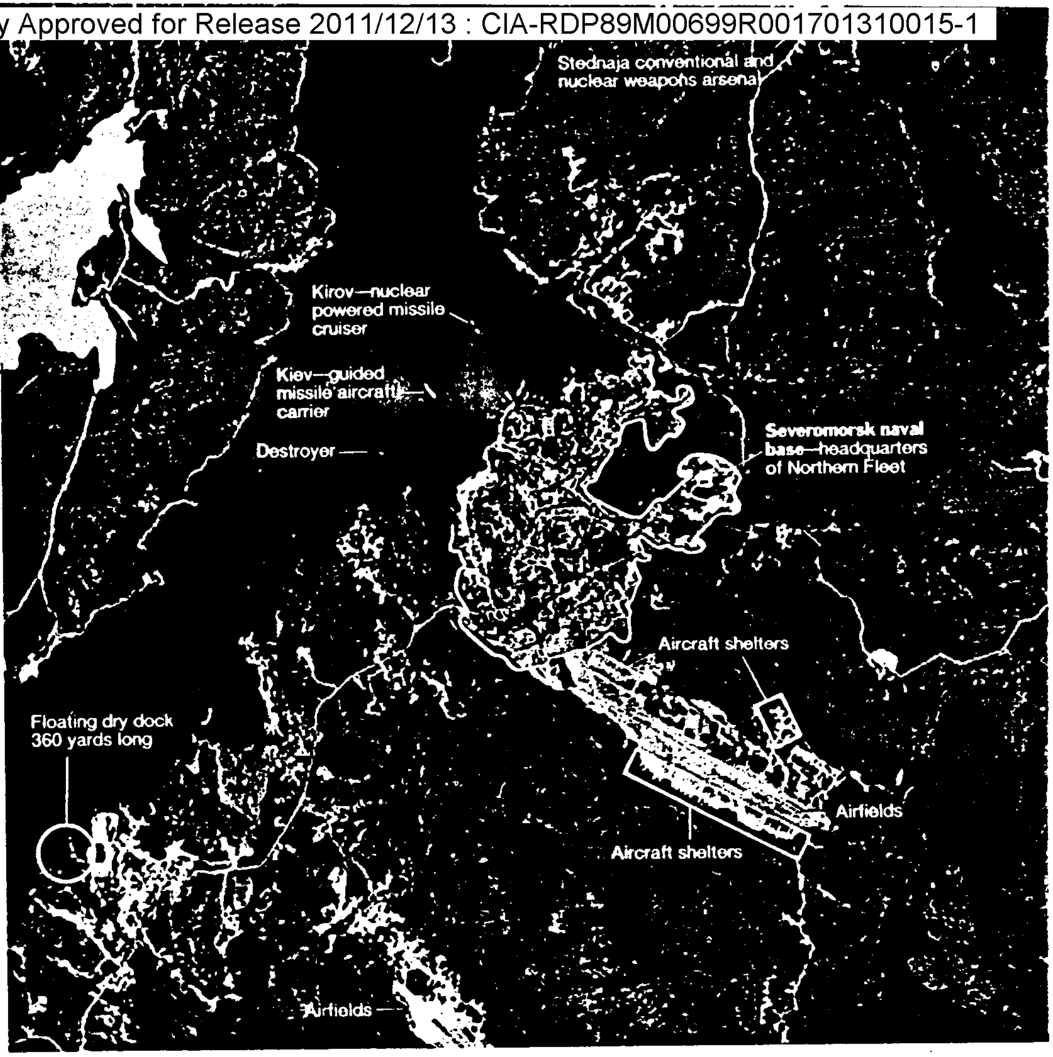
*This means you couldn't quite tell whether a man sitting in Gorky Park was reading *Izvestia* or *Pravda*, as it is often said you could. But as former CIA director William Colby once testified before Congress, "You can see the tanks, you see the artillery, [even if] you may not quite see the insignia on the fellow's uniform."



NASA; COLORING, JOHNNY SKORVE



EYE ON MURMANSK

The Soviet port of Murmansk is seen by Landsat from about 400 miles up. The smaller picture is an overview of the Murmansk fjord; the larger one, a closeup of the Severomorsk naval base, shows ships, piers, and airfields.

country are monitored by "over the horizon" radars that seem to defy the physical law that all radio waves travel in a straight line. They bounce powerful beams at small grazing angles off the surface of the sea. These are reflected off the ionosphere, flooding the interior of the Soviet Union with radar waves. If missiles or aircraft happen to pass through them, the waves are disturbed in characteristic ways, so that when they're eventually recaptured by receivers at the other end of the continent—by listening posts in the Aleutians, say—they can provide information about the performance of the vehicles that caused the disturbances.

Beginning with Eisenhower, every American president except Reagan has tried to limit or to ban nuclear testing. John Kennedy agreed with the Soviet Union to stop all tests except those conducted underground. During the Nixon years, Washington and Moscow agreed to stop detonating nuclear explosives with a yield greater than the equivalent of 150,000 tons of TNT. Although Congress had urged the U.S. to join in the U.S.S.R.'s moratorium, the administration continued its test program. If we could in fact get a comprehensive test ban treaty, as the Carter administration had hoped, could the U.S. confidently detect a small, clandestine Soviet nuclear explosion?

When a nuclear explosive detonates underground, it releases a portion of its energy as earthquake-type waves. In addition to pinpointing the test site with standard seismic techniques, seismologists can calculate the size of the explosion. They start by measuring the amplitude of the waves, which are proportional to the amount of energy released. They then take into account what type of rock the pulses have traveled through, since the terrain will affect how quickly they lose their strength. (In general, higher-frequency waves are attenuated more rapidly than those of lower frequencies.) From these two measurements they can estimate the size of weapon yields with an accuracy of 10 to 20 per cent, with the uncertainty reduced further as their knowledge of the geology of the test site increases. In any event, seismometers are now so sensitive that the U.S. and the U.S.S.R. both claim to have recorded unannounced tests by the other with yields as low as one kiloton.

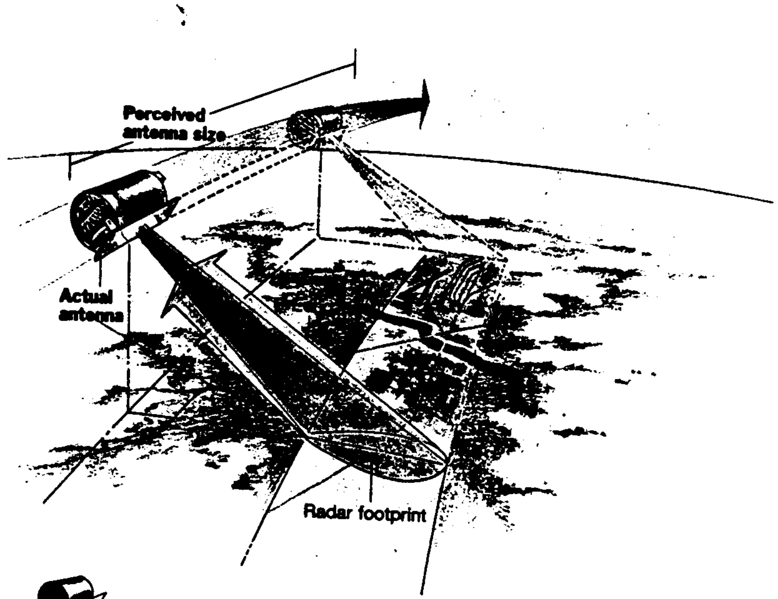
The detection technology consists of arrays of sensitive seismometers and the recording and computerized analysis of the signals they pick up. Such arrays are located in Norway, Montana, Turkey, and Japan, and two new ones may be operating now in China's Sinkiang province, only 300 miles from the U.S.S.R.'s underground test site at Semipalatinsk in Kazakhstan. To ensure that an underground test will be detected, the seismometers must be permanently on. Unfortunately for analysts, the earth's crust is a noisy place, shaken by numerous earthquakes, big and small, by the pounding of the oceans on shorelines, the rumbling of construction and mining oper-

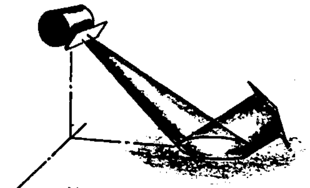
ations, even the swaying of skyscrapers and large trees buffeted by high winds. As a result, there's always a risk that the waves caused by a detonation will be drowned out by the earth's other tremors, or that a nuclear test will be mistaken for an earthquake.

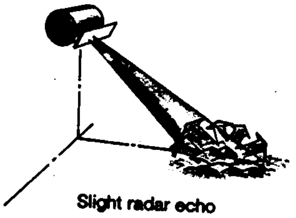
Nonetheless, seismologists have learned to discriminate between quakes and underground nuclear detonations. They've found that the relative magnitudes of the surface and body waves generated by a quake are distinct from those given off by an explosion. So when the needles of their seismographs come alive, they compare the size of the two types of waves that have been recorded. This tells them unambiguously whether they were generated by an earthquake or a nuclear test. Yet in spite of these advances, or perhaps because of them, the Defense Department has cut funding for the seismic research. Some scientists suspect the reason may be the Reagan administration's distaste for any test ban.

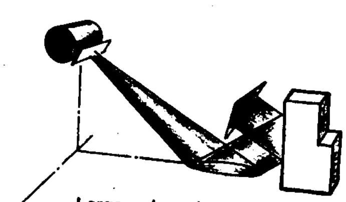
Test ban monitors might be duped in two ways. One, an underground nuclear test might be conducted at the very moment an earthquake is taking place in the area (the Soviet Union has many quake-prone regions). The waves from the quake might obscure the waves generated by the explosion. Two, a cavity hundreds of meters in diameter could be dug and a nuclear explosive detonated at its center. The waves from the blast would be very small, because the giant hole would have "decoupled" the explosion from the surrounding soil, and they might escape detection.

Both these possible ploys have been overcome by seismologists at the U.S. Geological Survey in Menlo Park, Calif., and the University at Colorado at Boulder, who can now detect very small detonations, even those under 1,000 tons of TNT and even if they occur during an earthquake or take place in a muffling underground cavity. The technique is based on the fact that a quake releases its energy over a large area, from a rupture in the earth that may be tens or hundreds of kilometers long, primarily in the form of long, low-frequency waves, whereas a nuclear blast is effectively a point source that emits predominantly short, high-frequency waves. Consequently, seismometers used to monitor test-ban violations are tuned to pick up higher-frequency seismic waves. So even if a quake is occurring at the same time as a test, the instruments will ignore the quake's low-frequency waves and "see" only the high-frequency signature of the explosion. This selective monitoring also works for tests conducted in decoupling cavities, since they attenuate the low-frequency waves but not the high-frequency ones.




No radar echo

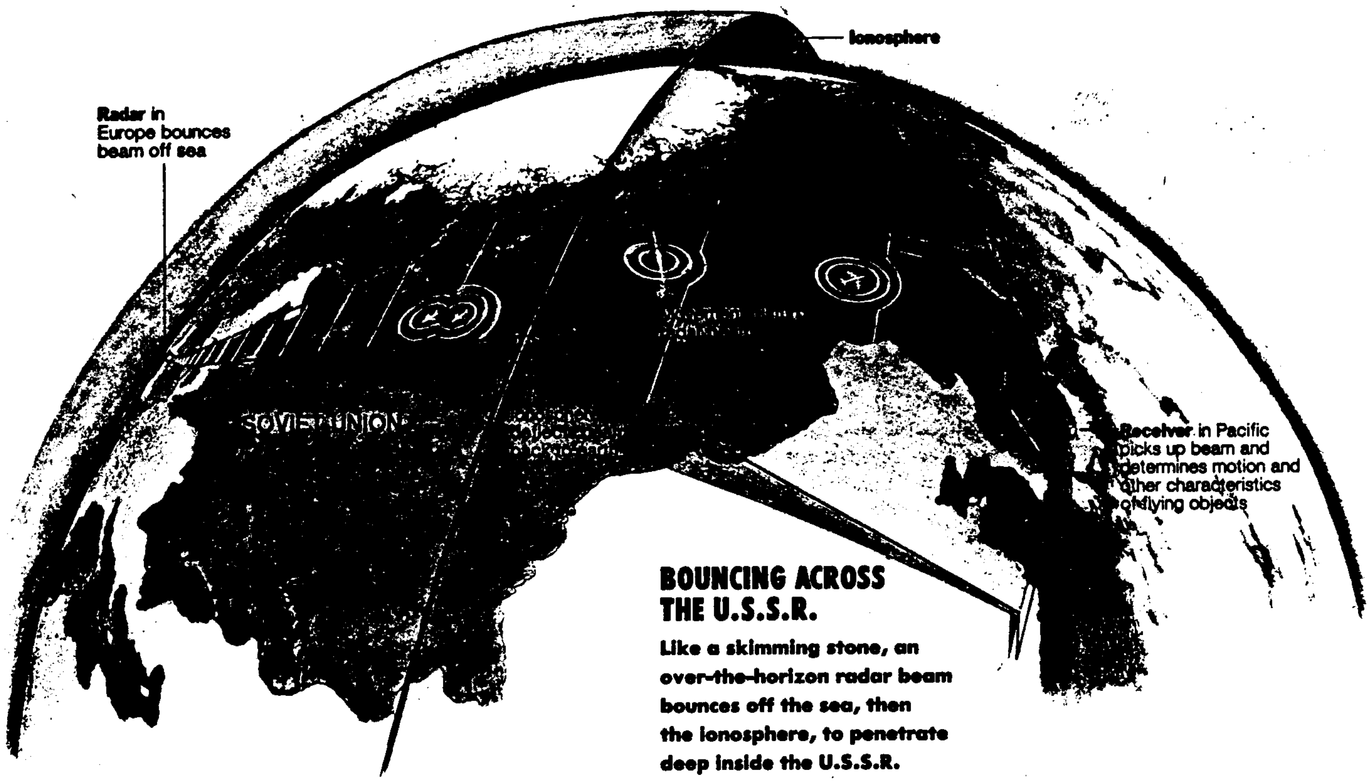

Slight radar echo


Large radar echo

TRICKS THAT TURN NIGHT INTO DAY

To pierce the night or clouds, spy satellites use synthetic aperture radar. It has much higher resolution than ordinary radar, thanks to electronic trickery that seems to increase the receiving antenna's size to the distance traveled in the time the signals echo from the ground.

However, there are limitations. High-frequency waves don't travel underground as far as low-frequency ones, so if we're to be confident of our detection procedures, we must place seismometers near the test sites. This creates a sticky political problem, because neither superpower likes the idea of foreign scientists snooping on—or under—its soil, particularly around test sites. Sandia National Laboratories in Albuquerque, N. Mex., may have provided a solution with the development of an unmanned, tamperproof seismic station. It can be installed inside the Soviet Union and monitored by a satellite, which relays the signals detected by the seismometer and alerts the controlling facility in the U.S. if anyone tries to tamper with the equipment. Several of these seismic stations are now in operation in the U.S. and Canada to test their sensitivity and tamperproof qualities. Although the Soviet Union had resisted the placement of these "black boxes" on its territory, it has now



BOUNCING ACROSS THE U.S.S.R.

Like a skimming stone, an over-the-horizon radar beam bounces off the sea, then the ionosphere, to penetrate deep inside the U.S.S.R.

agreed to accept them, so there no longer seems to be a technical barrier to monitoring compliance with a complete test ban agreement down to explosions of one kiloton or less.

As the new detection systems indicate, our intelligence gathering has achieved extraordinary levels of sophistication. These capabilities are even better than the government will admit in public. Given this rosy assessment, what kinds of arms control measures could be undertaken with the Soviet Union without threatening our national security?

A prime example would be a comprehensive test ban treaty, ending all explosions of nuclear weapons. With unmanned seismic monitoring stations inside the U.S.S.R., we should be able to detect even the sub-kiloton blasts. But political obstacles remain. When the Soviets said they would resume underground testing in response to the U.S. testing, they told visiting American seismologists to halt their studies of Soviet geology during the test period.

A second objective could be a ban on the testing of ballistic missiles, especially those with several warheads, or MIRVs (multiple independent re-entry vehicles). It could easily be verified because a multi-stage rocket lifting off is hard to miss even if you've got only a few radars and listening posts. Besides, new missiles require tens of tests, and honing their accuracy at least twenty more, so the probability that the Soviet Union can develop, test, and deploy an improved ICBM without our knowledge is virtually zero.

Missiles that can carry many warheads must be able to release them sequentially with great precision by performing delicate maneuvers in flight. Such maneuvers can readily be observed by radar. But they would be still easier to spot if the Soviets and we agreed to install a transponder on all test missiles. During flight it would broadcast a continuous stream of signals that would enable the other nation's detectors to spot changes in speed or direction, thereby providing a foolproof check on whether the missile had been MIRVed.

Another class of arms-control agreement that we could verify with confidence is the sort of drastic reduction in nuclear arms discussed at the Reykjavik summit. Photo reconnaissance satellites and other spaceborne intelligence-gathering devices can see and count the dismantling of ballistic missiles and their silos, fleets of bombers, and ballistic-missile-carrying submarines if the Soviets agree not to conceal them. However, they can't monitor the disassembly of nuclear warheads and the peaceful disposal of their radioactive materials, since this work has to be done indoors in special laboratories. The only workable check would be the presence on site of inspectors.

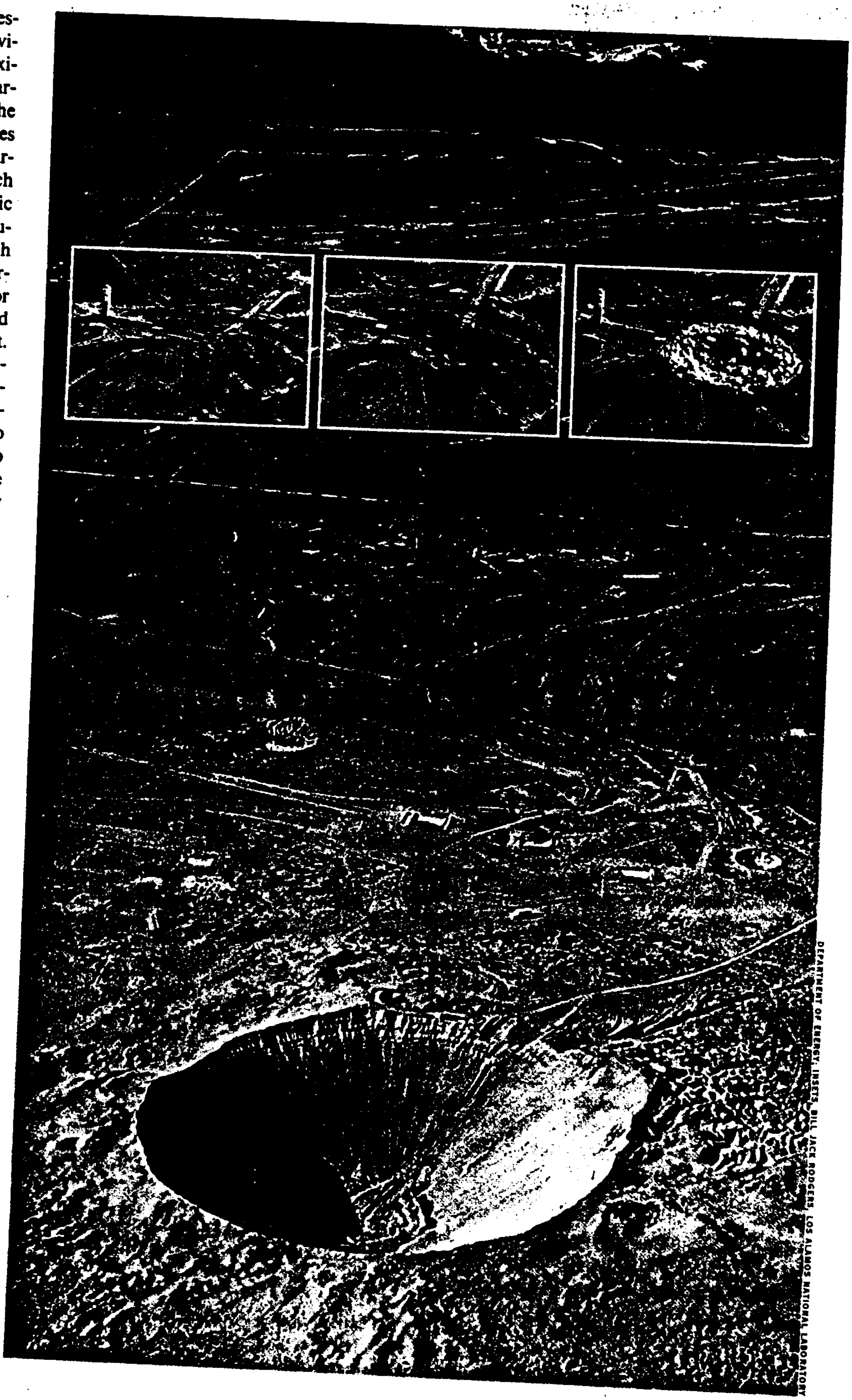
Cruise missiles pose a special verification problem. Tactical cruise missiles with conventional explosives and long-range ones with nuclear explosives look alike, so it would be very difficult to check compliance with an agreement limiting the number or means of deployment of these weapons unless both types were barred. This is a good example of a more general principle in arms control: it's easier to monitor a complete ban than a partial one, since the discovery of only a single event or a single proscribed weapon would be a clearcut tip-off to a violation.

In conjunction with any drastic reduction in the number of nuclear arms each country would be allowed, there would probably have to be a limitation on the production of plutonium, weapons-grade uranium, and large quantities of deuterium and tritium—all of them components of nuclear warheads. This ban could be monitored with existing technical means by making sure that nuclear reactors dedicated to the production of these materials were shut down, a relatively simple assignment for infrared sensors. Yet small quantities of fissile materials, enough perhaps to build a few tens of new warheads per year, could be produced clandestinely in small research reactors or reactors ordinarily used for power production. At present, with the U.S. and the Soviet Union each having approximately 25,000 nuclear warheads—enough to blow the planet to eternity many times over—a few additional warheads wouldn't make much difference in the strategic scheme of things. But in a future arms regime, when each side has slashed its nuclear arsenal by, say, 90 per cent or more, a handful of contraband warheads could be significant. To avoid such a situation, Soviet and American power reactors would have to be monitored by on-site inspectors to reassure one another that no weapons-grade materials were being diverted. The necessary monitoring technology exists, and all it would take is the political will to install it.

In recent years, because of the emergence of President Reagan's Strategic Defense Initiative to provide a shield against ballistic missiles and because of the administration's complaints that the Soviet Union has been violating the ABM Treaty, which bars certain practices related to land-based ballistic-missile defenses, considerable work has been done on devising technical methods to monitor the testing of systems that could be used in ballistic missile defenses. While laboratory tests of small SDI components could perhaps be conducted unobserved, there's little doubt that testing of full Star Wars systems in space—or even on the ground—can be monitored. One can't hide a laser or a particle accelerator the size of a factory or fire their beams into or from space without being caught. Nor can a nation conduct secret tests of the kinetic energy kill weapons or the radars needed for a defensive network.

If these assertions seem overly optimistic, consider the detail in which the U.S. has

A lunar-like crater, 320 feet deep and 1,280 across, was created in 1962 by a 100-kiloton underground nuclear explosion at the Nevada test site. The sequence at the top shows what happened within one second during a more recent blast.



DEPARTMENT OF ENERGY; INSETS, BILL JACK RODGERS, LOS ALAMOS NATIONAL LABORATORY

BY WILLIAM E. BURROWS

WE HAVE AN EDGE IN QUALITY, BUT THE SOVIETS OVERWHELM US IN QUANTITY

If U.S. reconnaissance satellites are the Rolls-Royces of space-based espionage, their Soviet counterparts are its Chevrolets. Both do their job more than adequately: the differences between them have to do with their degree of refinement and with sheer numbers.

Overseeing the design and operations of American spy satellites is the highly secret, CIA-dominated National Reconnaissance Office in the Pentagon. It prefers a relatively small number of hand-made, extremely sophisticated spacecraft that reflect the substantial American lead in optics and high-speed digital computers indispensable for the collection of intelligence from orbit.

The Soviets try to offset superior American technology by modifying their basic spacecraft—dependable workhorses like Vostok and Soyuz—on the assembly line to carry either cosmonauts or a wide array of hardware, much of it for reconnaissance. The technique is similar to the way aircraft manufacturers produce passenger and cargo versions of the same plane.

Although the types of Soviet reconnaissance satellites closely match those orbited by the U.S.—photographic intelligence (PHOTINT), electronic intelligence (ELINT), radar ferreting (SIGINT), and radar ocean reconnaissance (RORSAT)—the numerical difference is startling. Only two KH-11s carried the photo reconnaissance load for the U.S. in 1985, while the U.S.S.R. sent up 34 camera-carrying spacecraft, which was about average. Furthermore, 64 of the 98 satellites of all kinds launched that year by the Soviets were on some sort of reconnaissance or surveillance mission, often involving electronic snooping or ocean surveillance in addition to picture taking. The KH-11's orbital lifetime is about three years, that of its Soviet counterparts from days to about seven months, depending on how quickly their intelligence cache is needed.

Soyuz spacecraft, which are more than two decades old and whose latest version (named, in a bit of unintended humor, the model T) carried two cosmonauts back from a four-month space station mission last July, have been the mainstay of the Soviet photo reconnaissance program.

The basic Soyuz is made of three parts. As a manned satellite, it's composed of a cylindrical propulsion module, a bell-shaped descent module, and a spherical orbital module through which its occupants crawl when the ship is linked up to another spacecraft. The Soyuz's photo reconnaissance version uses the descent module for its tiny maneuvering rockets and their fuel, the orbital module to hold film canisters and batteries for operating the cameras, and the cylindrical segment to store the high-, medium-, or low-resolution cameras (depending on the mission). The craft, a little more than 23 feet long, is seven feet in diameter, and weighs about seven tons (the KH-11 is 50 feet long, 15 feet wide, and weighs about 29,000 pounds).

When its mission is completed, the orbital module, containing cameras and exposed film, is separated from the other two sections and fired back down toward the Soviet Union, landing under a billowing parachute. Most of the expensive cameras are no doubt reused. The Soviets have also developed their own electro-optical real-time system, using a variant of the Soyuz without the jettisonable sphere *(see diagram)*. This new breed can remain in orbit for seven months or more, uses charge-coupled devices, and can probably produce images similar to those from the KH-11. Any limitations would come from inferior computers on the ground, not from the quality of its telescope.

The pictures returned by the Soyuz and Vostok satellites (which fly under the generic name Cosmos) are thought to be slightly inferior to those sent down by U.S. spacecraft. Still, they would easily be equal to the task of supplying high-quality technical intelligence and ensuring adequate monitoring of the various arms control agreements, including SALT II's prohibition on changing the size of ICBMs by more than five per cent. Five per cent of Minuteman's 5.6-foot width is a shade over three inches. This implies that in 1979 the Soviets were sufficiently confident in the resolving power of their spaceborne cameras to sign the treaty, knowing that even so slight a change would be spotted from orbit.

But useful photographic intelligence depends upon a great deal more than resolution. It also means getting the data quickly and then being able to manipulate them for analysis. Moscow's new near-real-time capability is overcoming the first shortcoming, but imagery enhancement, which requires very high speed digital computing and enormous data banks, is another matter. Although Soviet satellites have for many years carried the same kind of infrared and multispectral scanners used on Keyhole spacecraft, Soviet computer enhancement techniques are probably very crude by U.S. standards, and that would limit the amount of intelligence the imagery could be made to yield. A technique known as electro-optical subtraction, for example, uses data banks to show U.S. analysts what has changed in a given scene over a period of time by automatically filtering out everything that remains the same from the time a previous picture of the area was taken. What's new is made to stand out, for closer scrutiny. This system has been used by the CIA for years, but is almost surely well beyond Soviet capability.

Quantity is another matter. While it takes months to plan and launch

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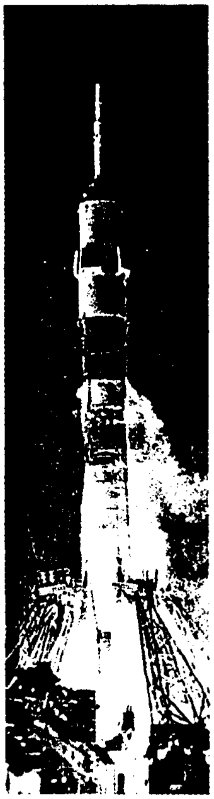
William Burrows, director of the science and environmental reporting program at New York University, is the author of the new book Deep Black: Space Espionage and National Security.



A Soyuz spacecraft lifts off from Tyuratam on Feb. 6.

V. KUZMIN—SOVFOTO

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complained of Soviet violations of the ABM Treaty. The charges themselves are proof of how well we watch Soviet activities relating to ballistic defenses deep inside their territory. In my view, an agreement to ban the testing and deployment of both antiballistic missiles and anti-satellite weapons appears verifiable.

Together, verification and arms control create a bootstrap process: advances in verification make arms control agreements possible, and the confidence and trust these agreements breed make more cooperative verification approaches acceptable. Until very recently, verification was based exclusively on non-intrusive, unilateral national technical means. Now the Soviets are showing a refreshing willingness to use advances in technology in a more cooperative manner, viz., their acceptance of a Keyhole, the Soviets can send up a Cosmos in hours, the assembly lines in effect extending to the launch pad. Several Cosmos reconnaissance craft are mounted on their boosters and kept on flatcars in sheds to be rolled out, erected, fueled and fired when a mission is ordered up. Since 1975 the U.S.S.R. has orbited an average of three reconnaissance satellites a month; it sent up a record six photo reconnaissance satellites and four ocean reconnaissance types during one seven-day period in September 1985.

The high launch rate allows the Soviets to cover virtually the whole world at all times. But they can't keep their snooping very secret. Their satellites are tracked by the North American Aerospace Defense Command (NORAD) radar network: their mission "envelopes"—apogees, perigees, inclinations, periods, orbital eccentricity, and a great deal more—are fed into the computers soon after a launch has been observed. Since there's an optimal flight envelope for every kind of mission, and since classes of satellites follow characteristic envelopes, the mission of a particular Cosmos quickly becomes apparent. Cosmos 1603, launched in 1984, initially threw NORAD into confusion bordering on panic because its flight fitted no established envelope. It performed three major maneuvers and changed its orbital inclination (its angle relative to the earth's poles) twice, in addition to changing altitude from 200 kilometers to 850. It was finally calculated to be a heavy intelligence satellite. A new envelope had been established.

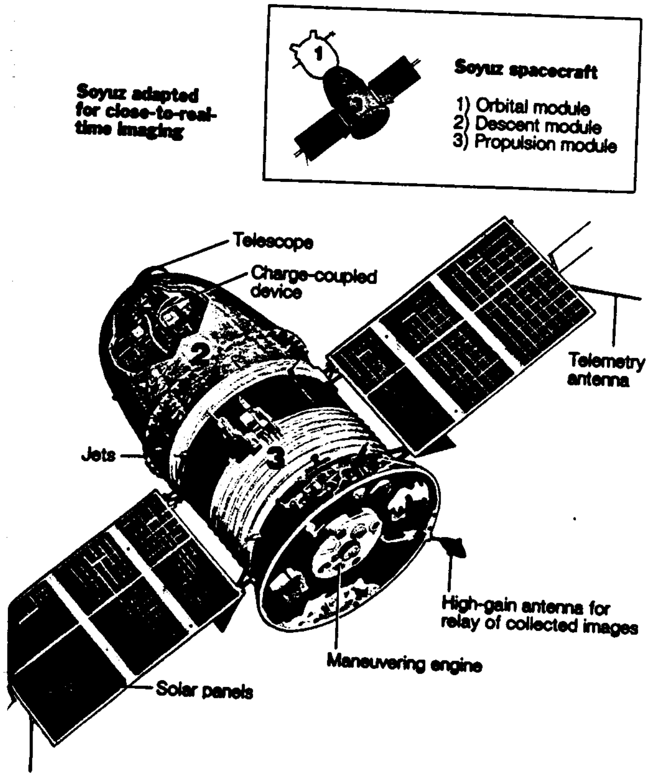
Soviet reconnaissance satellites are also monitored when they maneuver to change orbit, as frequently happens when a political or military event occurs that the Kremlin's intelligence directorate wants to appraise from overhead. In January 1985, for example, Cosmos 1616 was maneuvered to provide coverage of eastern Afghanistan and western Pakistan, possibly to search for arms shipments going to the Afghan rebels. Two months later, with the "War of the Cities" between Iran and Iraq boiling over, Cosmos 1630, which had been launched on Feb. 27 to relieve Cosmos 1616, was directed out of its normal orbit into one that placed it over the battle area. And Cosmos 1647, sent up on April 19 to replace Cosmos 1630, spent 20 days on normal surveillance before being maneuvered to pass over the Bekaa Valley in Lebanon while Israeli troops were withdrawing. The short duration of most Soviet photo reconnaissance missions means that valuable space aboard the satellites can be allocated to sensors rather than to all the fuel needed for long-term, extensive maneuvering.

And the large number of spacecraft, combined with quick-launch capability, brings a far more important potential advantage. Were a war to break out in which it was considered necessary to blind the opponent's reconnaissance satellites as a prelude to an all-out onslaught, the U.S.S.R. would have a distinct edge by the sheer size of its flotilla of spacecraft. (This advantage, however, doesn't take into account hardening, decoys, spoofing—taking command of an enemy's satellite with your own signals—and other means of protecting space "assets.") It's conceivable that the relatively few Rolls-Royces would be picked off during the first hour or so; the fleet of Chevys, on the other hand, might well keep coming for as long as their launch complexes remained undamaged.

Soviet reconnaissance satellites have their share of problems, including some spectacular failures. The two most widely publicized involved RORSATS, powered by small nuclear reactors and designed to work closely with electronic ocean reconnaissance satellites (EORSATS) to follow NATO surface vessels in real time. When one of them, Cosmos 954, came tumbling out of the sky in January 1978, its highly radioactive fuel survived re-entry and plowed into the Great Slave Lake area of the Canadian tundra, leaving a trail of hot debris and a lingering black eye on Soviet intelligence activity (only partly compensated for by a $3 million payment to the Canadians). A similar accident happened five years later to Cosmos 1402, whose reactor sailed out of orbit and plunged into the Indian Ocean.

Nor have photo reconnaissance satellites been spared. The Soviets have destroyed several that experienced control problems in orbit rather than have them hit a populated area or fall into the hands of U.S. intelligence. Since the ball that carries the cameras and film must survive a fiery descent through the atmosphere before its chute can open, it's extensively shielded and could land anywhere in one piece. In the latest such occurrence, on Jan. 29, Cosmos 1813, which had been launched two weeks earlier, was blown up after it failed to descend as ordered. NORAD recorded the explosion and tracked more than 100 fragments, some of which went into higher orbit, as the doomed spacecraft passed over the northeastern U.S.S.R.

This fifth-generation Soviet spy satellite has been stripped of the usual Soyuz orbital module *(boxed)* and crammed with electro-optics that provide virtually real-time imaging.



seismic stations on their soil. If the sweeping reductions of nuclear arsenals so grandly envisioned by Reagan and Gorbachev at Reykjavik are to be implemented, verification will have to move into its third and final stage: the bilateral, cooperative use of technical means and human observers to monitor agreements that preserve a common security for both the U.S. and the U.S.S.R., and for the rest of the world. ■