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A Constellation of Satellites for Shared Missile Launch Surveillance

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Increasing Nuclear Stability

On January 16, 1961 a US fighter jet sat on the tarmac prepared to defend the continental United States against a possible Soviet nuclear-armed bomber attack. As part of its arsenal, this jet carried a 1.7 kiloton nuclear tipped air-to-air missile as it waited on quick reaction alert. While many jets had sat on such quick reaction alerts before, this day was different. During a routine "engine run up," the underwing fuel tank accidentally dropped off; the resulting leaking fuel caught fire, badly scorching and blistering the nuclear warhead. This was far from the only accident involving on-alert nuclear weapons in the United States. A year before a long-range nuclear tipped cruise missile had been destroyed by fire while on alert. That time, the nuclear warhead was completely destroyed and the plutonium pit melted. Unfortunately the history of deployed US nuclear weapons has many other examples where a nuclear weapon might have detonated causing widespread destruction.

Figure 1 US fighter jet with genie air-to-air missile similar to the one involved in the 1961 fire.

Why didn't that happen? Certainly a large part of the answer has to do with what is called "one-point safety," design features that prevent any single failure from causing a nuclear detonation. For instance, an electrical short might cause one of the high explosive lenses--shaped charges that compress the plutonium "pit" until a nuclear chain reaction starts, inevitably causing a nuclear explosion--surrounding the weapon's plutonium to detonate. A design that is one-point safe would stop such a short from causing more of the surrounding lenses to fire, thereby preventing the necessary uniform compression of the pit. Both the United States and Russia have devoted a considerable number of their nuclear tests to developing such designs. In fact the United States devoted 32 of its first 280 tests to understanding how to make nuclear weapons one-point safe. (It is highly likely that the United States continued to devote a large portion of its nuclear tests to one-point safe designs and that the actual total is significantly greater but the purposes of the later tests remain classified.) The number the US has devoted to one-point safety in just the beginning of its nuclear program is many more than the total number of tests that India or Pakistan have performed and rivals the total number of tests China has performed. We can only conclude that neither country's nuclear weapons are one-point safe.

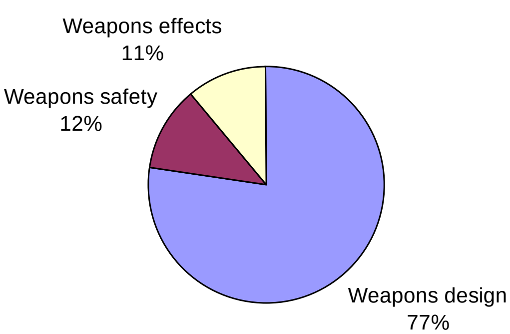


Figure 2 Fraction of the first 281 nuclear tests devoted to one-point-safety.

Of course, the safest way of storing nuclear weapons is to store their individual components separately; many analysts believe both India and Pakistan currently do this. However, in a period of increased political tensions between the two countries, it's likely that both countries would start to assemble and perhaps actually deploy their nuclear stockpiles. In that case, the chances of a nuclear accident are greatly increased. Not only has neither country had the opportunity of developing one-point safe weapons, but also their militaries have not had day-to-day experience handling armed nuclear weapons.

Suppose such a period of heightened tensions actually arose. Let us further suppose that through one of the many possible mistakes that could be made—an airplane being refueled catches fire, a missile detonates on its launch pad—a tragic nuclear accident occurs at one of Pakistan's nuclear depots. What would happen next? All witnesses to the accident have of course been obliterated. Would the government of Pakistan realize that a nuclear accident had occurred? Or would it jumped to the conclusion that been attacked in a preemptive war? Sadly, the most likely outcome is that they would conclude that they had been attacked and would "retaliate" with nuclear weapons. Again, we know this from the experience of near nuclear wars between the US and the Soviet Union.

The whole world knows about the Cuban missile crisis and how close the world came to nuclear annihilation. Four other incidents where the world was almost engulfed in a nuclear conflagration are a lot less well knew. In all four incidents, a benign event almost triggered one side or the other to launch what it considered to be retaliatory nuclear strike. And in three of these instances, the government that felt it was threatened was able to consult the data from space-based sensors to reassure itself that no attack had actually been launched. (In the fourth example, a Soviet early warning satellite actually caused the incident by giving a false indication of a US missile launch.)

The so-called "training tape incident" on 9 November 1979 is illustrative of the others. Early that morning, the night shift at the US NORAD command center-- an underground bunker that houses the headquarters responsible for launching America's nuclear forces-- decided to run a training exercise. In preparation for that exercise, they inserted a computer tape that would cause the screens above the operator's heads to display all the signs of a massive nuclear strike from the Soviet Union. However, the night shift ended before they could run the simulation. Unfortunately, no one thought to remove the computer tape or tell the morning shift that the tape was inserted. The result was that shortly after 8 a.m. the new operators saw every indication that the United States was being attacked by a massive first right from the Soviet Union. A National Threat Assessment Conference was called to decide on what response should be taken. Minutemen crews inside their buried bunkers throughout the western United States were put on high alert. A number of veterans of this incident have reported that they thought the United States was very close to nuclear war. However, the participants of the National Threat Assessment Conference were able to look at the raw data from the US early warning satellites that would show the plumes from any missiles launched in the Soviet Union. Because of that, they were able to reassure themselves that no attack had been launched regardless of what was shown on the computer screens at NORAD.

Figure 3 NORAD command center

If the National Threat Assessment Conference had not been able to look at the raw data from US space sensors, it is quite possible that the world would have been engulfed in a nuclear fireball because some operator at the end of a sleepless night had forgot to remove a computer tape.

India should be concerned that Pakistan's nuclear weapon designs, even if they came from China as many analysts believe, are not one-point safe. An accidental detonation of one of Pakistan's nuclear weapons, a tragic event in itself, might escalate into a global catastrophe by triggering a nuclear “retaliatory” strike. Undoubtedly, Pakistan feels the same worry about India’s nuclear weapons.

What can the world do to lessen the probability of such a disaster? Some might suggest that the United States or Russia share one-point safe technology with both India and Pakistan. However, making a bomb safe against accidental nuclear detonations requires a specific analysis of each bomb design with custom-made improvements. Ignoring the nonproliferation issues associated which such assistance, would India really feel comfortable with the United States “improving” Pakistan's bomb design? Wouldn't Pakistan object if the United States contributed to India's? Such meddling might actually increase tensions and not improve the situation.

Fortunately, there is another way to prevent the tragic accidental detonation of a nuclear weapon causing a nuclear war. The international community could establish a constellation of satellites designed to detect the launch of a ballistic missile whose data would be shared among the countries of the world. Both India and Pakistan would have access to the data and could in fact participate in the satellite’s construction. If there was one day such an accidental nuclear detonation, the country that suffered the calamity could use the information from the satellites to reassure itself that no missiles had actually been launched. At that point they could step back from the brink of catastrophe and let cooler heads prevail. Even before such a tragic event, Indian and Pakistani participation in such a global endeavor would be a significant confidence building measure between the two nuclear armed states.

Detecting missile plumes from space

As with any detector, three variables must be considered when deciding sensors to detect missile plumes. First, the signal strength: how bright the missile plan is and what wavelengths is it right us. Second, what contributes to possible backgrounds and how can they be reduced. Third, the sensor sensitivity: what sensors can maximize the signal strength and minimize the background.

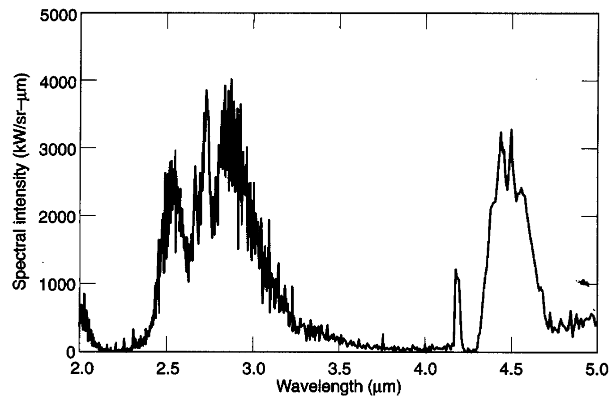


Fig. 5.3. Spectra of Titan IIIB at 18 km and viewing aspect of 48 deg.

Figure 4 Spectrum from Titan IIIB missile at 18 km altitude

Most of the combustion associated with the missile plan takes place inside the combustion chamber. As a consequence, the radiation from the plume results not an optical light-- which would require electronic transitions in highly excited atomic species-- the rather infrared emissions associate with vibrational states of the combustion products. This is illustrated in figure 1, which shows the infrared spectrum of a Titan 3B (at an altitude of 18 km). The broadband between roughly 2.4 and 3.5 µ is associated with vibrational states of water, a major component of the combustion products from most liquid propellant engines. By comparison, figure 2 shows the same plume (close to the Earth's surface) in visible light. Just exiting the nozzle, the exhaust appears almost transparent. And in fact the major source of visible light is where the streams from the two nozzles interact and cause a shock wave heating.

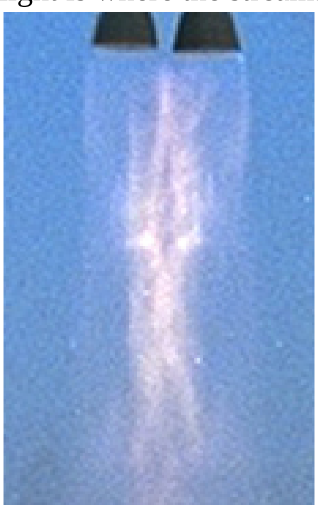


Figure 5 Visible light from the twin engines of a Titan IIIB close to the Earth's surface

Solid propellant missiles have a slightly different phenomenology associate with their plumes. While again, almost all the combustion happens with inside them is body, the combustion chamber, the exhaust from solid propellant missile has a considerable amount of solid as such is aluminum particles associated with it. This results in considerable blackbody radiation within the visible range. Figure 3 shows an example of this difference in visible light for solid and liquid propellant engines by examining the light from both types of boosters in the US by shuttle launch. Nevertheless, solid propellant missiles also radiate considerably in the infrared from exactly the same processes as mentioned in the liquid propellant model. This is shown in figure 4 which compares a solid propellant source and liquid propellant source.

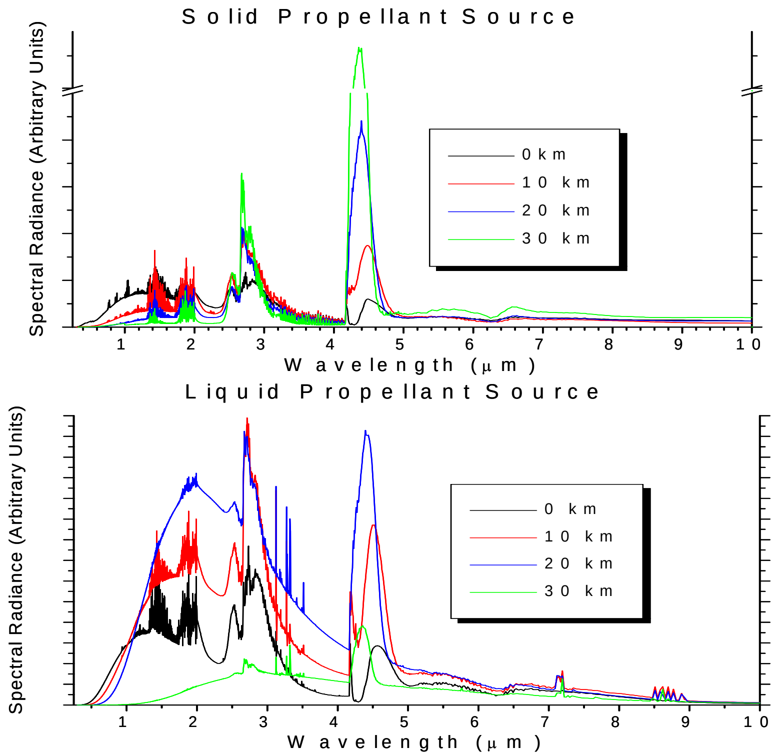


Figure 6 Spectra from generic solid and liquid propellant missiles

Figure 7 Space Shuttle showing the visible light from both solid (the bright white plumes) and the liquid (faint blue).

Returning for a moment to figure 1, the spectra that Titan 3B, consider the total amount of light radiated around the wide peak at 2.7 µ. If our detector is a geostationary orbit directly above the missile, it might subtend an area of 9.7 x10^{-15} sr. If filters only permitted light from a .2 µ region around the peak, the total energy received by the detector would be roughly 6x10^{-9} watts. This, of course, needs to be compared to possible backgrounds.

The backgrounds to detecting missile plumes come primarily from sunlight reflected off clouds or possibly snowed fields on the earth or radiated from the earth itself. This is shown in figure 5, which is a spectrum of light reflected from the Sun in infrared light generated by the earth itself. It is fortunate that the bands we most interested in looking at, there is corresponding to light originating from vibration of water molecules and having a wavelengths of roughly 2.7 µ, correspond to the minimum of these two backgrounds. However, they still represent a significant problem. After all, the Sun is very bright and the detector will be integrating over large areas on the surface of the earth. As will be discussed in later sections, each pixel of the image, as seen from geostationary orbit, corresponds to a square roughly 3 km on a side.

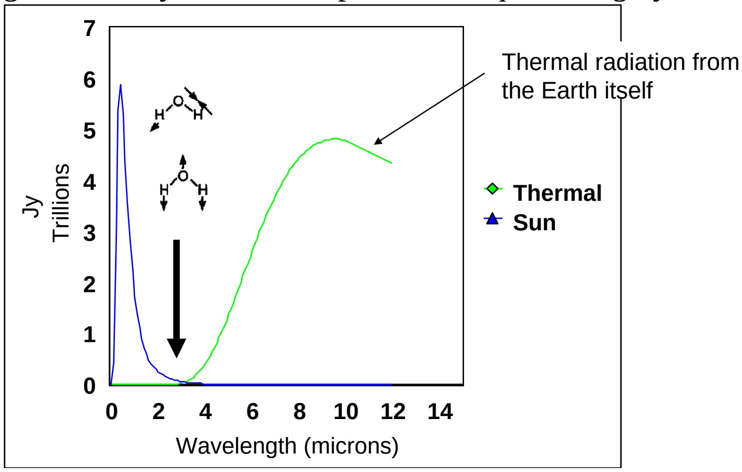


Figure 8 The background spectra from the Earth and Sun.

In the narrow band of light that we are considering, between 2.6 to 2 .8 μ, each square meter of cloud surface reflects 14 Watts of sunlight. Thus, on a cloudy day, each three kilometer by 3 km square will reflect 7.8×10^{-7} Watts in to the geostationary sensor. Thus approximately 130 times the signal strength from a large ICBM. It is clear that this background must be reduced even further.

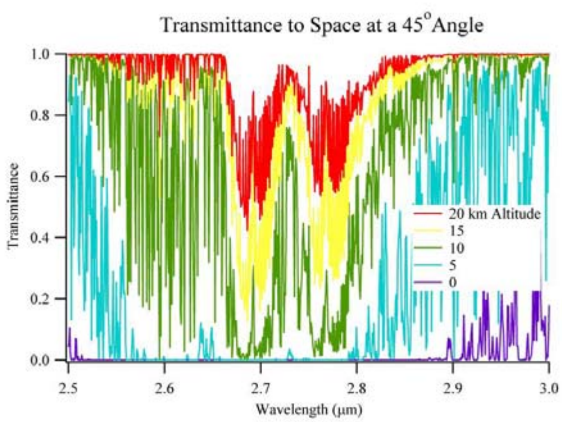
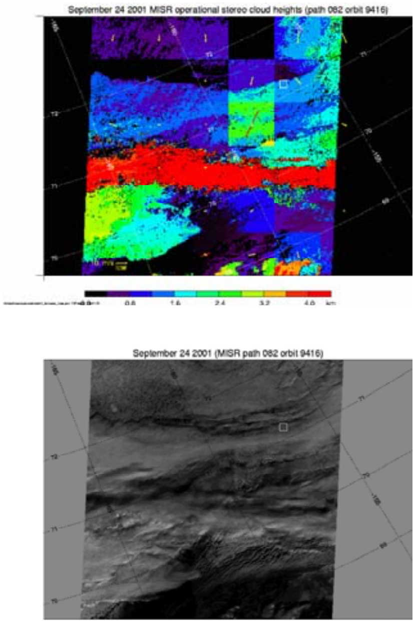


Figure 9 Atmospheric transmittance as a function of wavelength for various altitudes.

Fortunately, there is once again a natural reduction in most backgrounds from looking at the missile plumes in the water bands. This is illustrated in figure 6, which illustrates the absorbance of light from a missile plume to outer space as a function of wavelength for various missile heights. While this absorption reduces the plume's signal, it reduces the solar background even more: sunlight must pass twice through the atmosphere, once before it is reflected from the cloud surface and once after. Thus for a missile and cloud at the same altitude, for instance at 10 km, the cloud brightness relative to the missile plume appears to be 5% what it would be without atmospheric absorption. And clouds at

10 km are much less common than lower level clouds, a fact that further reduces the average background. (They are, however, far from unknown. Such high altitude clouds have, in the past, presented false signals with the best known case causing a nuclear alert in 1985.) Typical cloud heights are illustrated in figure 7 which shows the view of clouds from the MISR (Multi-angle Imaging Spectro-Radiometer) satellite and the cloud's reconstructed height. Reflections from clouds at these more typical altitudes are suppressed with respect to a missile plume at the same altitude by a factor of greater than 100.



wavelength=0.67 micron (red light)

Figure 10 The top illustration shows the reconstructed cloud height (red corresponds to the maximum cloud height of about 4 km) of the scene shown in the lower photograph.

Satellite Constellations for Missile Launch Surveillance

To date, only the United States and the Soviet Union (now the Russian Federation) have fielded operational constellations of satellites dedicated to the detection of missile launches from outer space. The United States has relied solely on satellites placed in geostationary orbit, while the Soviet Union placed most of its emphasis on satellites in highly eccentric orbits at large inclinations commonly referred to as Molnyia orbits. While most of the Soviet early warning satellites were placed on these Molnyia orbits, they also placed a significant number in on geostationary orbits as well. While it is an interesting academic question to ask why the Soviets placed so many satellites in Molnyia orbits (some analysts believe that this reflects a technological limitation of Russia's industrial base[1]) it is clear that missile launch warning satellites have not been placed in low earth orbit. The reason for this is also clear. Requiring global coverage

[1] See, for instance, G. Forden, *Russia's Early Warning System: Which Came First, Technology or Doctrine?*, Breakthroughs, Vol. X, no. 1, Spring 2001, pp. 9-16.

from low earth orbit, which inherently means smaller fields of view of the earth's surface, requires many more satellites than geostationary constellations.

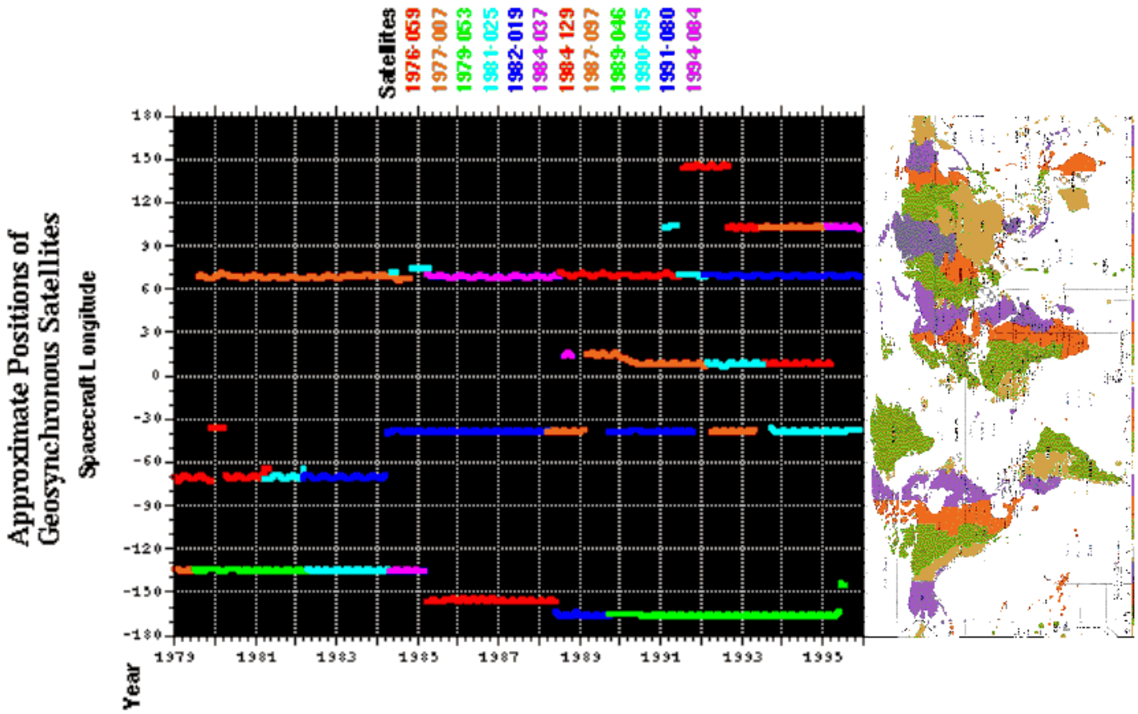


Figure 11 History of longitudnal positioning of US geostationary early warning satellites

The constellation proposed in this paper has, at full complement, five geostationary satellites. The positioning of the satellites is illustrated in figure 12, which not only shows the positions of the satellites into geostationary station orbit with respect to the earth but also their projected fields of view, shown as cones in this illustration. Figure 13 shows the fields of view projected on the earth's surface, which in turn is rolled out in a Mercator projection to illustrate the overlap of these fields of view. The five satellite constellation, most areas of the earth's surface that are a concern for missile launches can be covered by at least two satellites and in some cases three. Absent by multiple satellites is important, not because of reliability issues with the satellites, but because viewing a launch from multiple directions can allow the three-dimensional reconstruction of a missiles track more easily than with a single satellite[2].

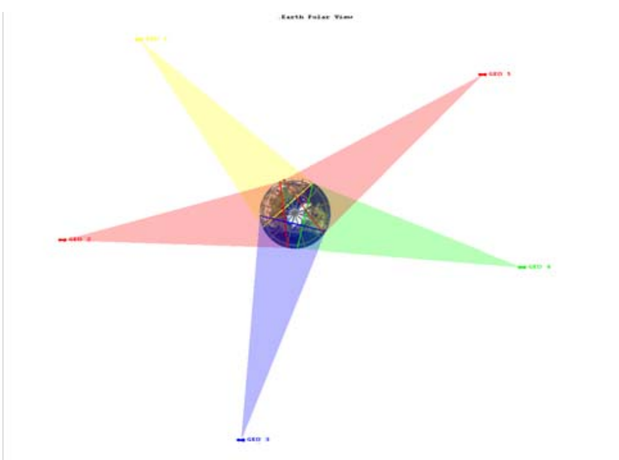


Figure 12 The five geostationary satellite constellation

[2] Some mechanisms have been proposed for detecting the height of a missile in the earth's atmosphere from a single satellite by using the varying atmospheric absorption of the light from the missile's plan. However, such techniques still only hypothetical have yet to be demonstrated even in a test case.

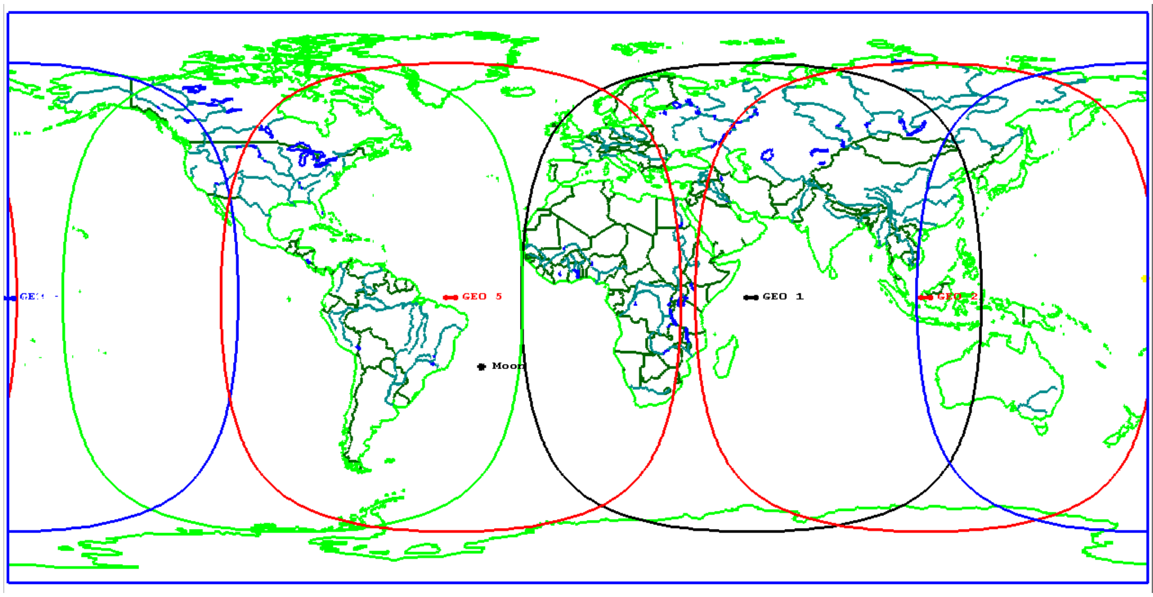


Figure 13 The coverage, projected onto the Earth's surface of the five satellite constellation shown in Fig. X

We have estimated, based on a study by the US Congressional Budget Office[3], that a single satellite as we will describe a suitable for the proposed mission should cost approximately $250 million. Assuming the geostationary orbit launch services are purchased using a Russian launch vehicle, we estimate that each satellite would have an additional $75 million associated with placing an orbit. Thus the optimal five satellite constellation would cost approximately $2 billion while the bare minimum three satellite constellation would come in at about $1.4 billion.

Optics and Sensors

There are two requirements placed on these detection systems. First, the sensors must detect a missile within seconds of its launch. Second, it must provide a reasonable track of the powered portion of the missile's flight. While these are not mutually exclusive, it does represent a significant difficulty to try to accomplish both at once. Detection could be accomplished by having a fairly coarse sensor looking down at essentially the entire earth's surface. In that case, the pixel size, translated into square kilometers of coverage per pixel, could be determined solely by the signal-to-noise requirement for detecting the missile. This requirement prevents the individual pixel coverage from getting too large; even the bright missile plume could be overwhelmed by reflected sunlight off of high altitude clouds. Sizing coverage solely by a signal to noise ratio requirement implies each pixel could correspond to a square several tens of kilometers on a side, once various noise reduction techniques have been employed. Tracking, on the other hand, could benefit from having pixels corresponding to half a kilometer on a side. However, given the finite size of most sensor arrays, this has implications for the field of view of the camera and in consequence the time between revisits to a particular site.

[3] US Congressional Budget Office Letter to Senator Tom Daschle, “Improving Russia’s Access to Early Warning Information: Preliminary Results”, 3 September 1998, available on the web at http://cbo.gov/

There are two ways we could handle this trade-off. First, we can have a satellite with a single large square array of sensitive pixels. The optical axis of the camera can be shifted, by a small steering mirror, along a preset pattern to cover the visible surface of the earth. Since approximately one quarter of a second must be allowed for the camera to come to rest after each movement, this limits the speed with which a scene may be revisited. For instance, if the field of view of the focal plane array corresponds to one quarter of the earth then it would take at least one second for the camera system to scan the entire earth's surface. Of course, a smaller, higher resolution array, would take proportionately longer. An array corresponds 1/16 of the Earth's visible surface would result in revisit time of once every four seconds.

Cartridges at times imply that the missile would travel further between pictures, degrading tracking. For instance, an ICBM with a speed of roughly 7 km per second near the end of its powered flight would travel 28 climbers between pictures taken every four seconds. Even more importantly, the determination of the final speed, and hence range of the missile, would suffer dramatically as the revisit time increases.

Alternatively, we could have a satellite with two cameras; one a wide field camera that covered essentially the entire surface of the earth and the other a narrow field camera with high resolution that was directed to a point of interest. These two options are shown in figure 14. However, there are political implications for these two satellites that we must consider, and in particular for the two camera satellite. Since the narrow field camera must be directed to a point of interest on the earth's surface some, algorithm must be agreed to by all participating countries that would direct the movement of the narrow field camera. It is possible that after enough confidence in the system and in the international partnership has been built-up of such an algorithm could be agreed upon. However, we will assume for purposes of this conceptual study that a single camera satellite design has been picked.

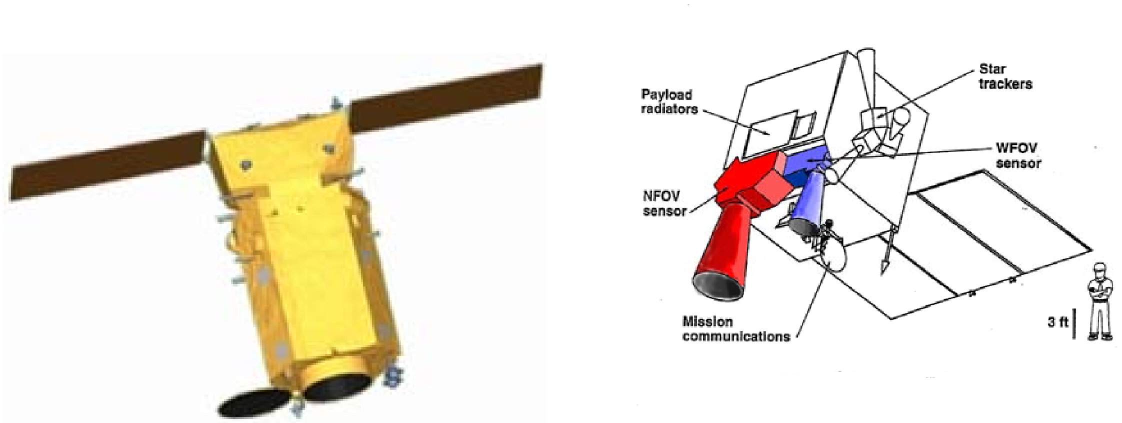


Figure 14 The two options for camera sizings; the left is a single camera satellite and on the right is it to camera satellite.

The details of such a telescopic system will depend on the details of the focal plane array—the detector that acts as the cameras “film.” Fortunately, the technology of focal plane arrays has improved considerably in recent years. For this conceptual study, we will assume that the technology is similar to the Rockwell HAWAII-2RG focal plane array, shown in figure below. This cadmium-mercury-telluride array has over 4 million pixels (2048 x 2048) and in terms of geometry is nearly ideal for our application. Unfortunately, its spectral response is not ideal for detecting missiles since its quantum efficiency falls off rapidly in the region of 2.5 μ that we are interested in for detecting missile launches, see figure 15.

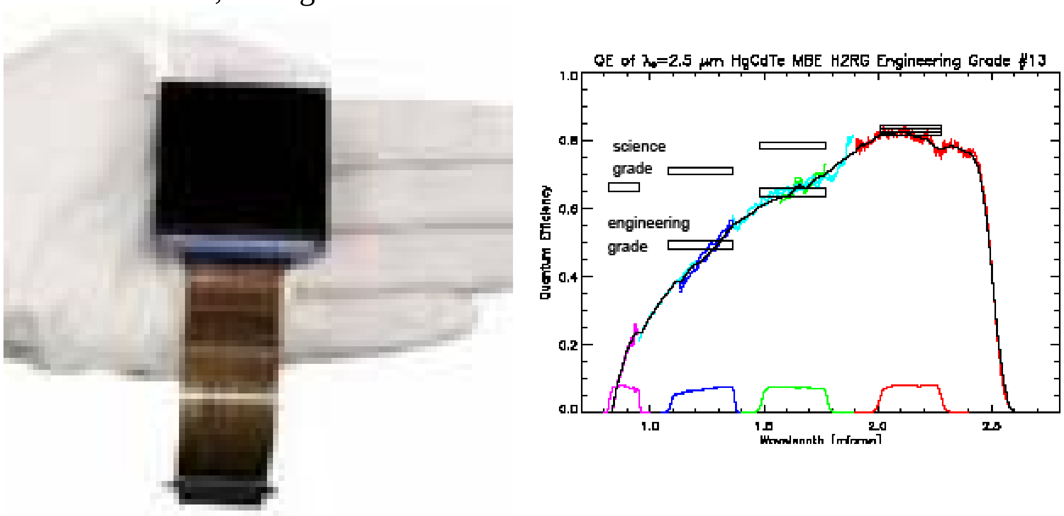


Figure 15 HAWAII-2RG focal plane array (on left) and its spectral response.

It is possible other versions of this array could be extended somewhat to improve this response around the water absorption line. If that is not possible, it still must be remembered that we will be using a fairly narrow pass filter sensitive to the water absorption line to for the remove background from reflected sunlight. Of course, in all likelihood the international collaboration building the system will prefer to use a focal plane array produced by a country other than the United States such as France, which also has an active and very capable industry. In that case, an equivalent focal plane array might need to be developed as opposed to being purchased off-the-shelf.

Assuming these characteristics for the focal plane array, what would the rest of the telescope look like? If we require a revisit time equal to one second, the visible surface of the earth being viewed in four steps shown in figure 16, then we could use a mirror diameter of 11 cm, a focal length of half a meter, and each pixel would correspond to just over 3 km on a side. If on the other hand, we want a higher resolution say of 1.6 km, then we need a mirror with a one-meter focal length (the mirror still has a diameter of 11 cm), a revisit time of four seconds, and the pixel corresponding to 1.6 km outside. These results are summarized in Table 1, which also shows the same parameters assuming the focal plane array is a composite of four HAWAII-2RG-like wafers. An example of these expanded focal plane arrays is shown in figure 17.

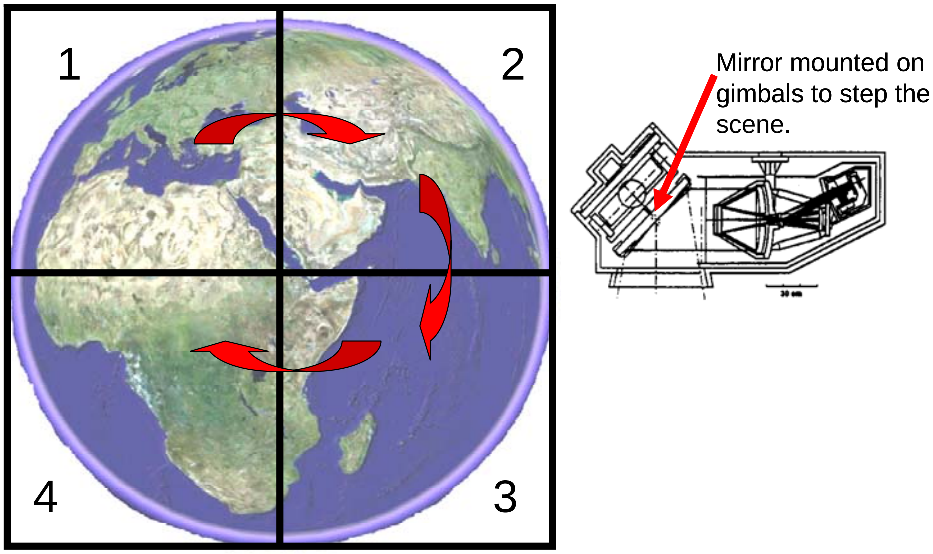
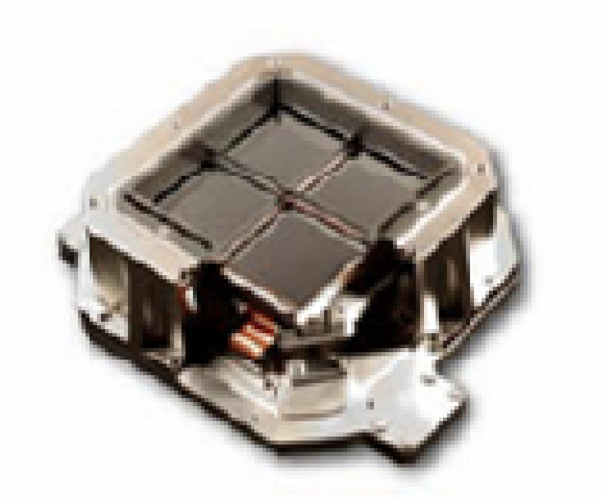


Figure 16 A four-step pattern for viewing the Earth is shown on the left. As shown, the focal plane array is currently viewing the first quadrant, as indicated by the small grid pattern representing pixels. On the right, the folded optics for a telescope showing the steering mirror.

Table 1 Telescope parameters for various options

	One HAWAII-2RG		2 X 2 HAWAII-2RG	
Number of steps to view complete Earth	4	16	1	4
Earth surface equivalent pixel size (km on a side)	3.11	1.6	3.11	1.6
Revisit time (seconds)	1	4	"revisit time" = integration time ~ milliseconds	1
Telescope focal length (meters)	0.5	1	0.5	1
Mirror diameter (meters)	0.11	0.11	1	1



The 4096 x 4096 FPA uses standard H2RG multiplexer FPAs in a 2 x 2 mosaic.

Figure 17

Other Sensors

So far we've only considered infrared detectors suitable for observing the plume of the missile during powered flight. There are of course, other detectors that if mounted on the satellites might contribute to increasing nuclear stability around the world. An obvious example of such a additional sensor is this so-called Bhang meter. The sensor utilizes the double flash of visible light associated with nuclear atmospheric explosions to determine the yield of the weapon. This double flash consists of a very fast initial peak and observe radiation associated with the bomb material (the bomb case, the unexploded fissile material, etc.) and the surrounding one or two meters or so of atmosphere being heated up to approximately 1,000,000° Kelvin in the first microsecond.

This extremely hot material radiates off an enormous amount of light, producing the first peak observed by the Bhang meter. The shock wave caused by this initial fireball expands and absorbs the surrounding cold air, forming an opaque barrier to the visible light of the fireball. The net result is that the light visible from space decreases as this initial shock wave expands. However, as a shock wave expands and cools off, it becomes less opaque to the light of the inner fireball until eventually the observed intensity starts to increase again. The fireball continues to expand during this process increasing its surface area and amount of light effectively radiated off into space. Eventually there comes a point when the expansion of the fireball cools off sufficiently to decrease the net observed light. This second drop off a causes the second peak observed by the Bhang meter. The difference in time between these two peaks is a function of the yield of the weapon. This is shown in figure 18.

How would such a sensor increase nuclear stability? We have postulated a scenario whereby an accidental detonation of a nuclear weapon-- albeit one that takes place during a period of heightened political tension-- could cause an escalation to an actual if inadvertent nuclear war. One of the contributing factors to this scenario is our belief that completely effective “one-point safe” nuclear weapons have not been developed by a number of new nuclear powers. However, it is possible that partially effective one points to safe designs have been implemented. Thus it's possible that if an accidental nuclear explosion takes place it could be in the hundreds of tons as opposed to the tens of kilotons range. (It is doubtful that the survivors would realize the difference.) A Bhang meter observing such an accidental detonation would add further credibility to the belief that it was truly accidental because its yield would be below an effective nuclear explosion.

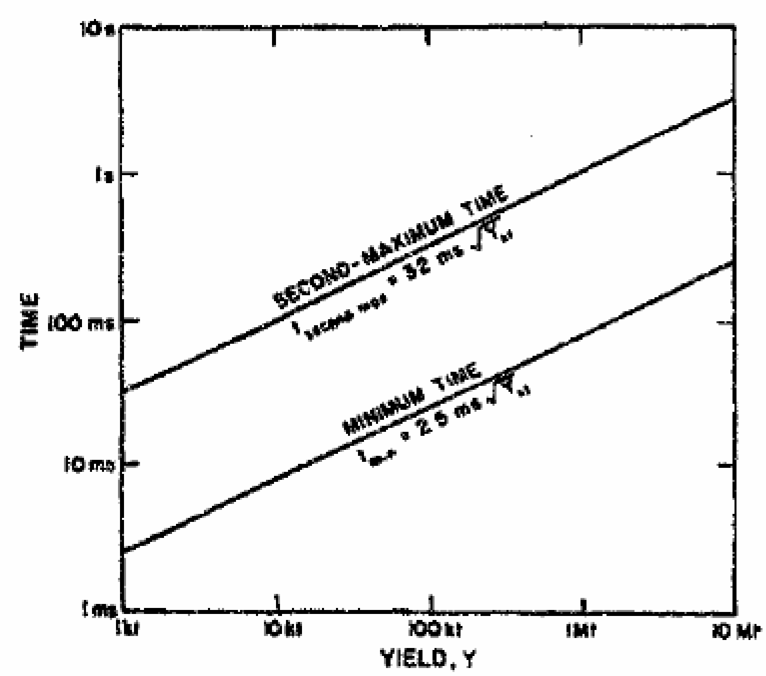


Figure 18 The time between the first and second peaks characteristic of nuclear atmospheric explosions can be used to determine yield.

Communications and Control

The satellite system must both be controlled (a matter of maneuvering the satellite to keep it on station even as small perturbations like asymmetries in the earth's gravitational field or the pull of the moon or Sun try to move it away) and it must broadcast its collected data to all partnering countries. These are two very different requirements. The control of the system of satellites is achieved by a small number of earth stations that will both determine the position of the satellite and send up control commands. As such, there must be a control station in line-of-sight of each satellite though there could certainly be different control stations for different satellites. One possibility for controlling the constellation of missile launch surveillance satellites is to use the European Space Agency's system of ground control stations known as ESTRACK[4]. As such, they allow all the satellites in the five satellite constellation to be control, as shown in figure 19. ESA normally provide the service of controlling a satellite but it could be worked out that the international partnership of countries simply utilizes their antennas

[4] ESA ground control stations are in Sweden, French Guiana, Australia, Belgium, and Spain.

and sets up a control room staffed by multinationals selected from the various anticipating countries if the politics makes that preferable.

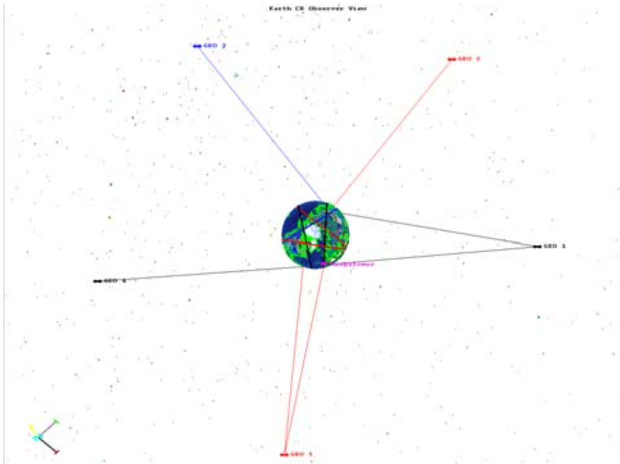


Figure 19 Line of sight lines between each of the satellites in the 5-satellite constellation and ESTRACK stations.

In terms of providing each country with all the data recorded by the system, there are several more choices to be made, some of which will be affected by the technical capabilities of the system. In the beginning, it will certainly be preferable that all countries receive all raw data taken: that there be as little on board data processing as possible. If we imagine the telescope using the single 2048 by 2,048 focal plane array and having a digitization with an eight bit analog-to-digital converter then we can imagine each satellite beaming down 134 Mb per second (equal to 4 X 8 X 2048 X 2048, where the fact of four derives from the one frame every quarter of a second needed because of the time it takes to settle the optics down after each step).

A number of radio bands allocated to satellites are capable of broadcasting this rate of data. For instance, the X7 and broadcast between 7.3 and 7.45 GHz with a maximum bandwidth of 150 Mb/s. However, these bands are not capable of broadcasting a factor of five times that expected from a single satellite. That means that the full raw data from a single satellite can be beamed down directly to those portions of the earth visible from that satellite and either a processed image (with a greatly reduced bandwidth requirement) from each of the other four satellites—distributed to each satellite by satellite to satellite indication links—can be broadcast. Or the other four satellites data can be accumulated on tape and distributed to partner countries later. Once an algorithm for data processing has been agreed upon by all partner countries, the communications requirements will be considerably reduced.

Another requirement on the communications systems that some analysts believe might be required by the political situation, is introducing a preset delay between the time a scene is observed and when it is broadcast to earth. This delay could act as a buffer to prevent the system from being used to trigger retaliatory nuclear attacks. For instance, by including a modest data storage capacity on each satellite it could be possible to record five minutes of data and then start beaming down the signals with this delay built into it. Such a five-minute delay would prevent the system from inadvertently escalating a situation in the India Pakistan relationship, for instance, without affecting its utility for improving Russia's Russia's access to early warning information with regards the United States. On the other hand, some analysts feel that this delay is not necessary. The partnership of countries should decide these sorts of questions for itself.

Appendix: US and Soviet/Russian Early Warning Satellites

Both sides of the cold war sought reliable, long-range early-warning systems as they raced for intercontinental ballistic missiles. Previous to the missile age, the Soviet Union's air defense radars, with ranges of around 550 km, provided sufficient warning of the relatively slow moving strategic bombers deployed by both sides in the 1950s. Those radars were capable of several hours of warning for bombers but only one or two minutes warning against an incoming ballistic missile. The next decades saw both countries make rapid improvements in the range and resolution of radars together with expensive programs to increase their numbers. But ultimately, both the United States and the Soviet Union turned to space-based sensors to give the maximum amount of warning time.

Once in space, however, the systems diverged to a remarkable degree. They differ to such an extent that Western analysts have struggled to understand their underlying logic. This is the basic difference: U.S. early-warning satellites give essentially global coverage 24-hours a day from their three positions in geostationary orbits. Soviet Satellites, on the other hand, require ten satellites to give 24-hour coverage of only a very limited region of the continental United States.

Russian scientists familiar with the history of their country's early-warning satellites have argued that this is all that was needed: their nuclear doctrine was based on the belief that the United States would never launch anything but a massive nuclear strike. Assuming that this truly was—and perhaps—remains—their doctrine, a number of interesting questions arise. Did this doctrine shape the development of their early-warning system? Or did technological difficulties impose the doctrine as the only viable strategy?

<u>Soviet Early-Warning Radars.</u>

The West first became aware of the Soviet Union's efforts at long rang radar in 1957 when a U2 spy plane photographed the Sary Shagan missile test range in Kazakhstan.[5] The radar facility photographed on that flight was the prototype for the 6000-kilometer range "Hen House" radar. (The West referred to this system as Hen House because the long buildings that supported the antennas were reminiscent of chicken coops.) Seven years later, in 1964, the Soviet Union had added four more Hen House radars, two looking toward China and the Pacific, and two scanning the attack corridors of U.S.

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[5] Steven J. Zaloga, <u>Soviet Air Defense Missiles: Design, Development, and Tactics</u>, (Jane's Information Group, London, 1989.) p. 125

ICBMs and submarine launched SLBMs. Those systems could spot SLBMs soon after launch, but would have to wait until the warhead from an ICBM appeared to rise above the horizon. This could take anywhere from 10 to 15 minutes, vital decision-making time either country lost when using that type of radar from with in its own boarders. (In 1960, the United States started positioning its Ballistic Missile Early Warning Radar Systems in Canada, Greenland, and England, an option not available to the Soviet Union.)

Both sides launched high priority research and development projects to try to increase this warning time. One avenue for extending the range of radars is to use special radio frequencies that bend around the Earth's surface.[6] This type of radar is know as "Over-the-horizon" radar. The Soviet Union started operating its first over-the-horizon radar in 1971 with a facility in Belarus—the western portion of the Soviet Union—aimed at the U.S. ICBM fields. Such radars sacrifice their ability to measure distances accurately and also are more prone than regular radars to atmospheric disturbances such as the Northern Lights. The Soviets constructed a second over-the-horizon radar on the eastern edge of their country in 1973 to try to compensate for these deficiencies. They obviously hoped that one or the other could always look around the electronic noise associated the polar region. However, this system proved inadequate and the Soviet Union abandoned over-the-horizon radar for long-range missile surveillance by 1990.

As discussed below, the Soviet Union started to move its warning systems into outer space. However, they still had a use for powerful strategic radars, only by 1978 they were more interested in the resolving power of the radars and were willing to sacrifice distance for improved tracking ability. In that year, they started to replace the aging Hen House radars with a newer design. Those high-resolution tracking radars became known in the West as Pechora-type radars, after the Russian town near which the first one appeared.

Pechora-type radars operate in a range of the radio spectrum optimized for detecting, and tracking, incoming warheads. An unintended consequence of this choice of radio frequency is that the radars are unusually susceptible to being blinded by nuclear bombs exploded high in the upper atmosphere—the "precursor" attack that must have been a principle concern during the Norwegian rocket incident in 1995. But the improved tracking capabilities of these radars, which the Soviet Union intended to install in a ring around their country, has two important applications. First, it can be used for ballistic missile defense. In fact, the United States protested vigorously when the Soviet Union started to construct a Pechora-type radar in the Krasnoyarsk province. The Krasnoyarsk site was situated a considerable distance inside Soviet borders—a clear violation of the 1972 Anti-Ballistic Missile Treaty. The other nine Pechora-type radars were constructed on the periphery of the Soviet Union and were permissible under the ABM treaty. The original planned arrangement of the Soviet Union's Pechora-type radar coverage, with the actual coverage today is shown in Figure 20.

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[6] Matthew Partan, Soviet Assessments of U.S. Early-Warning Technology Programs, (Center for International Studies, MIT, Research Report No. 86-1, 1986)

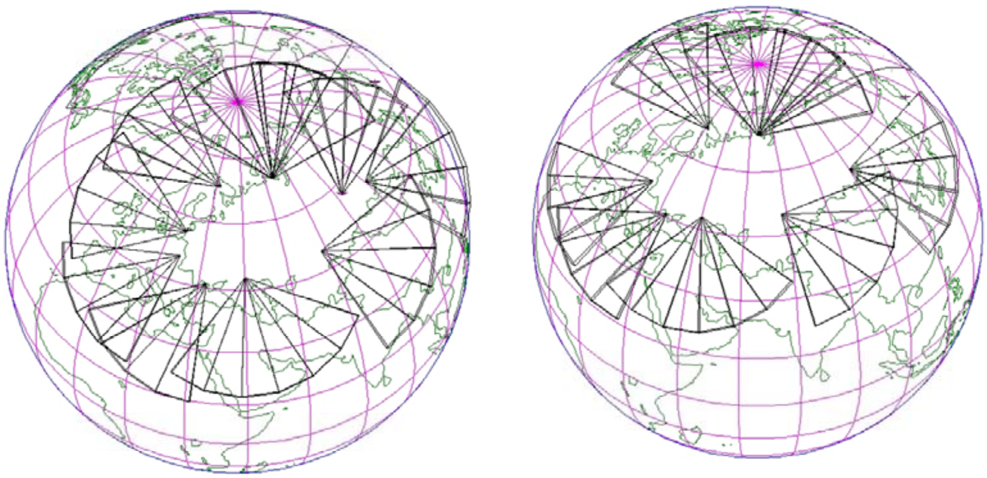

Figure 20 The overlapping radar fans, or regions of coverage for the Soviet Unions Pechora-type radar stations is shown on the left while the actual coverage today is shown on the right.

Second, the improved tracking capabilities of the Pechora-type radars gave the Soviets the ability to assess an actual attack. This assessment involves projecting the paths of the incoming warheads toward their intended targets as well as backtracking their flight to their launch silo. Projecting ahead allows military commanders to know which of their own nuclear missiles are in danger from the first wave of incoming warheads. Backtracking the incoming warheads could, in principle, allow the Soviets to re-aim warheads previously aimed at empty U.S. silos. Thus the Soviets could avoid wasting missiles on empty silos. However, even Pechora-type radars would not be very accurate at backtracking the warheads because of uncertainties in missile maneuvers below the radar's horizon.

The Soviet's chain of Pechora-type radars was never completed. Protests by the United States had the effect of halting the construction of the Krasnoyarsk radar. In fact, after the fall of communism, Russian leaders have admitted that its construction was a violation of the ABM treaty.

Adding to Russia's early-warning problems, several of the Pechora-type radars that were constructed on the periphery of the Soviet Union now are situated in the newly independent states. This has been a source of conflict been the Russian Federation and these new nations. In fact, Latvia dynamited the early-warning radar facilities on its territory on September 1, 1998, creating a second large gap in Russia's radar fence. Russia must worry that this gap could function as a new attack corridor for Trident II missiles. This too contributes to the imperatives to respond quickly to perceived threats.

Early-Warning Systems Move into Space.

The atmospheric difficulties encountered by the over-the-horizon radars helped drive both countries to investigate space-based systems. For instance, the United States abandoned its over-the-horizon radar efforts when it started to deploy geostationary early-warning satellites in 1970. Those so-called Defense Support Program (DSP) satellites were actually the second generation of U.S. space-based missile detection systems. The United States first attempted to orbit an infrared-sensitive missile launch detection satellite in 1960, named the Missile Detection and Alarm System (MIDAS). Those low orbit satellites reportedly used an infrared sensitive television-type of camera. However, they had very serious difficulties distinguishing actual missile launches from naturally occurring phenomena that also gave very bright signatures and the program was abandoned in 1962.

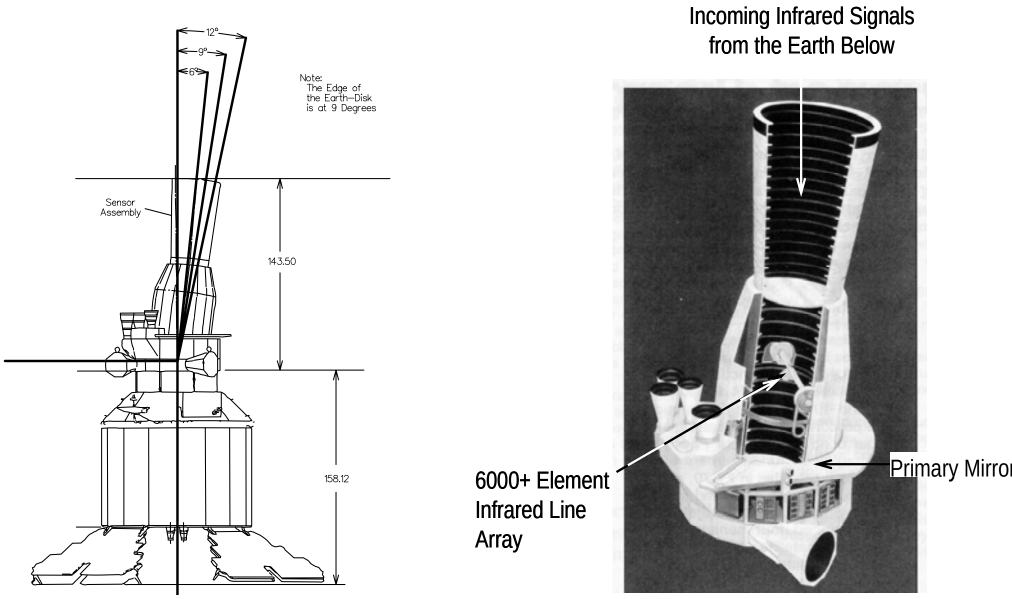

Figure 21 A line drawing of a DSP satellite (on the left) and a cut away of one showing the main mirror and line array.

The Soviet Union also started research into space-based early-warning satellites in the 1970s. Their initial efforts were split between television-type cameras similar to the failed MIDAS satellites and primitive solid-state detectors along the lines of those used in the DSP program. However, the Soviet's television-style detectors were abandoned before the system was operationally deployed. But producing space-qualified solid-state detectors requires a number of well-developed hi-tech industries such as producers of high purity silicon wafers, high precision photolithography, and proficient micro-assembly industries. At the time, the Soviet Union was struggling with all these procedures. Russian expatriates familiar with the Soviet early-warning satellite programs have stated that the solid-state sensors tested on these early flights were about 50 pixels long. By contrast, some experts believe that the first DSP satellites had infrared sensors nearly 1000 pixels long.

Those relative detector sizes have had an extraordinary effect on how each country has used its satellites and on their ultimate capabilities. With detectors one thousand pixels long, the United States was able to scan the Earth's entire visible surface from geostationary orbit and segment it into squares 1 kilometer on a side. Thus, the system only had to distinguish the light of a missile's plume from the light reflected from clouds or ice or snow in one square kilometer. If the Soviets tried to view the entire surface of the Earth, they would have to distinguish the missile's plume from light reflected from over 14,000 square kilometers of clouds—clearly a more difficult problem.

Faced with this problem, the Soviet Union traded global coverage, but with a high chance of false alarms, for very limited coverage of highly sensitive areas—the U.S. continental missile fields—with significantly reduced chances of false alarms. (Of course, the Autumn Equinox incident discussed above showed that they still had some unexpected occurrences.) To accomplish this, they positioned their satellites in so-called Molnyia orbits so that they viewed the areas they were interested in at a glancing angle. Thus, a U.S. missile would appear to be silhouetted against the black background of space.

Pioneered by the Soviets, the Molnyia orbit is a highly elongated trajectory with a point closest to the Earth, just 2000 kilometers, over the southern hemisphere. But it is the early-warning satellite's Molnyia orbit with its highest point, over 36,000 kilometers, above Northern Europe that distinguishes it from communication satellites. A satellite spends most of its time at this high point. Soviet communication satellites had their highest points over the Soviet Union to facilitate ground-to-satellite-to-ground communications. Early-warning satellites had this high point shifted to above Northern Europe.

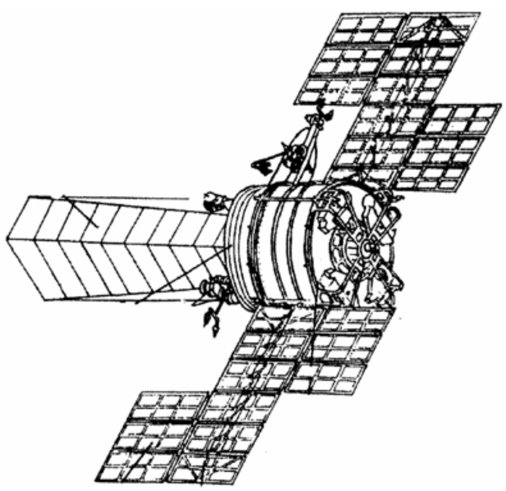

Figure 22 A Soviet 1st generation Oko satellite such as were put in Molnyia orbits.