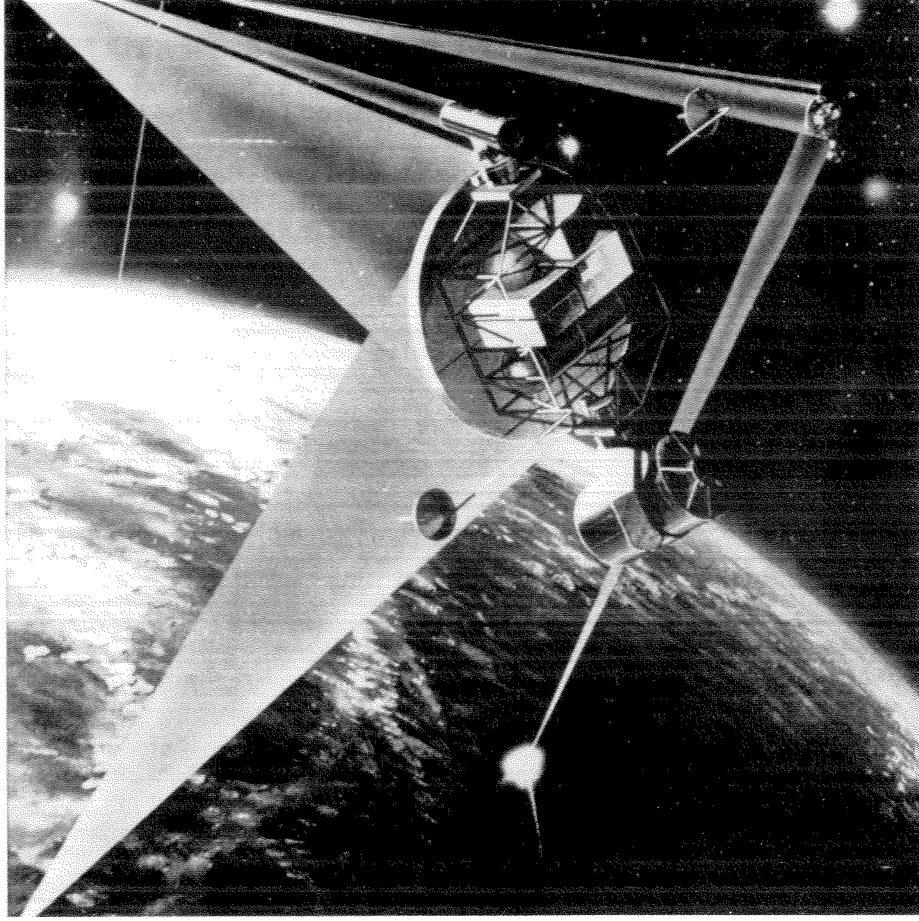
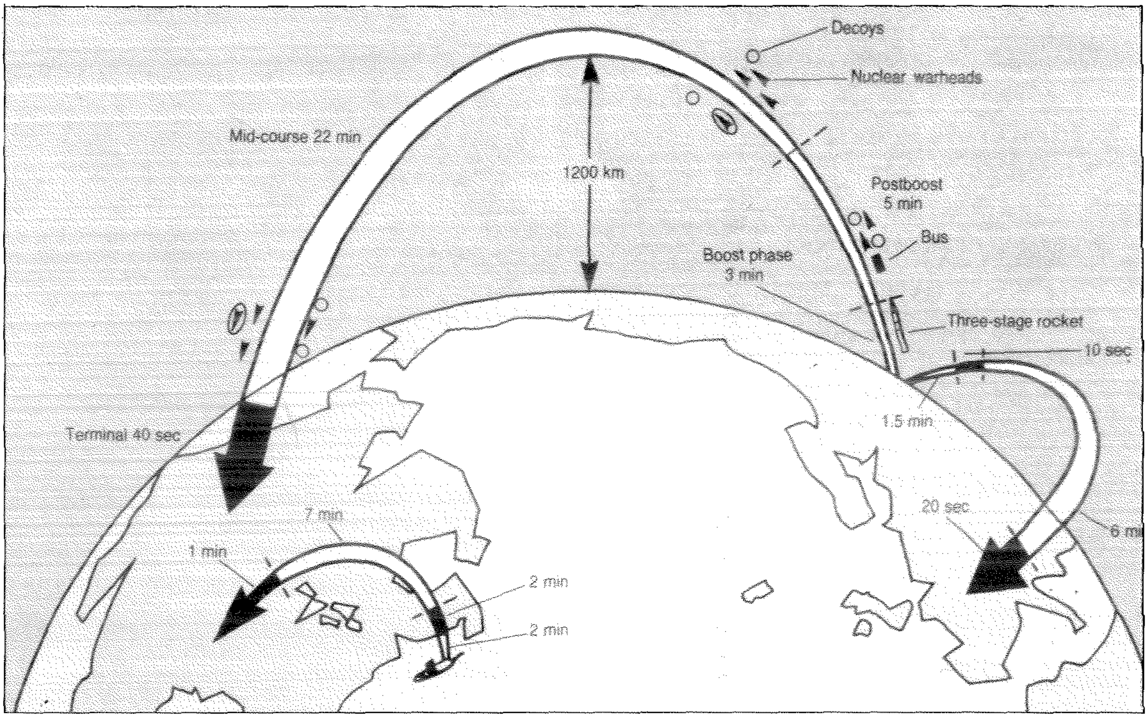


Star Wars Technology: Will It Work?

by *Amnon Yariv*

On March 23, 1983 President Reagan called upon the American people, and especially the technological community, to undertake a research and development effort with the goal of finding an alternative to the current policy of assuring national security through the threat of nuclear retaliation. The new defense system, which was meant to "render nuclear weapons obsolete," was organized under the control of the Strategic Defense Initiative Office (SDIO) whose mission was to accelerate and expand research in antiballistic missile defense. This organization and the program have come to be known popularly as Star Wars. Almost immediately following Reagan's speech an intense debate ensued, centered on ethical, political, and philosophical issues. What was missing, however, was an in-depth technological analysis of the feasibility of the proposed defense system.

So in November 1984 the American Physical Society constituted a committee



Of the three stages of an ICBM's trajectory, the missile is most vulnerable during the boost phase. Intercepting it during the post-boost phase may still be possible, but in mid-course it becomes immensely more difficult to stop.

of engineers, physicists, and chemists, whose charter was to study the technological aspects of Star Wars and report on them to the membership. The 17 members of the committee came from industry, academia, and the national government laboratories. Its funding came from private foundations, and it enjoyed the full cooperation of SDIO, as well as access to classified information. I was a member of that committee. But before I summarize the committee's findings, I'd like to set forth a primer on intercontinental ballistic missile (ICBM) technology and the defense strategies, mainly lasers, envisaged under Star Wars.

A missile under way from, say, the Soviet Union to the United States goes through three phases on its journey to re-entry. The first of these, the boost phase, takes the missile from rocket blast-off to an altitude of about 200 kilometers and lasts about three to four minutes. The burned-out stages of the rockets have been dropped by the end of this phase, and what is left in the post-boost phase is a big container called the bus, which is now moving at close to the orbital velocity of approximately seven kilometers per second.

The bus contains up to 10 warheads (MIRVs—multiple independently targeted re-entry vehicles), which it unloads during the post-boost phase one at a time, aiming each one at its specific target. At the same time the bus may also unload lightweight decoys. This stage lasts about five minutes. The independent warheads and the decoys make up the third and longest phase, the mid-course stage, which lasts about 20-22 minutes. The terminal stage, when these warheads re-enter the earth's atmosphere over the intended target, is very quick.

The missile is most vulnerable during the boost phase. During this phase the missile still includes the booster rockets, so the whole thing is very large—about 30 meters tall and close to 200 tons in weight. Because it's so large, it cannot be armored and is therefore relatively soft. It's also very hot, making it relatively easy to detect with infrared sensors. During the post-boost stage the bus is still relatively vulnerable but much less so than during the initial phase. Because it's no longer firing, it's much colder. In the third phase, however, intercepting the missile is immensely more difficult, because now in addition to the warheads there might be as many as 100,000 decoys moving with the speed of the warheads and, using currently available means, indistinguishable from them.

It is generally agreed that for a ballistic missile defense system to be most effective, it has to operate on the vulnerable boost phase and knock out the great majority of the missiles during that stage. Failing that, the missile could still be attacked with appreciably greater difficulty during the bus phase, when it is still a single target containing all the warheads. After that we may have to handle as many as 100,000 targets.

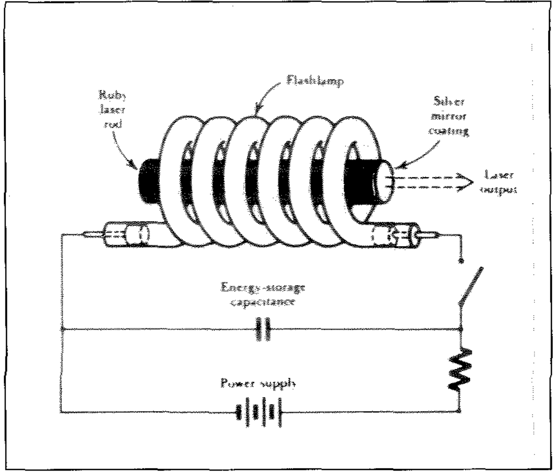
Today the Soviet arsenal consists mostly of SS-18 and SS-19 ICBMs. Altogether we assume that the Soviets have something like 1,400 missiles, each one capable of carrying six to eight MIRVs. So we are dealing with a total number of about 10,000 warheads potentially aimed at various targets in the United States or elsewhere.

Since we only have three or four minutes to destroy even the current Soviet missiles, which are relatively slow, during the boost phase, we need a weapon that can strike quickly. Nothing moves faster than light, so the main weapon proposed under Star Wars is the laser.

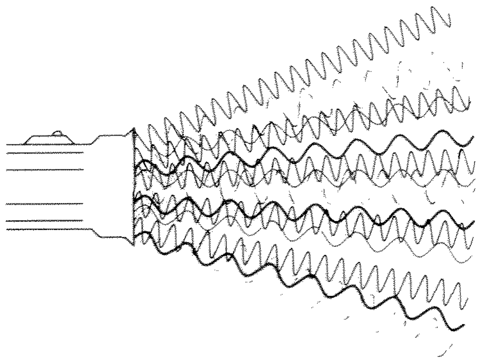
Other interesting approaches considered include charged and neutral atomic beams that move at close to the speed of light. These technologies are still very far behind the laser and are not effective in the atmosphere. We considered them less viable, although we still looked at them in great detail. The main reason for the choice of the laser, in addition to the speed of light, is the coherent nature of its light output, which in principle makes it possible to deliver the requisite level of light intensity across intercontinental distances and in many cases to penetrate the atmosphere.

The first laser was designed in 1961 by Ted Maiman at the Hughes Research Labs in Malibu and is shown schematically at right. It consisted of a helical flash lamp wound around a synthetic ruby rod, which is just aluminum oxide containing chromium ions. The end faces of the rod were polished and served as mirrors. These chromium ions are pumped by the surrounding helical flash lamp to excited states. A photon of the proper ruby frequency starts traveling between the mirrors and stimulates an excited chromium ion to make a downward transition. Now you have two photons of the same frequency. Another transition and you have three photons, and so on. So the light builds up and becomes more intense as it travels. When it hits the mirror, it turns around and comes back. In the meantime the atoms have been re-excited back to the upper state and the process continues. You end up with a very intense light beam bouncing back and forth between the two mirrors, and that's all a laser really is. What makes laser light different from the light from an ordinary light bulb is that, as the photons are forced back and forth by the mirrors, they organize themselves like soldiers marching in step. This gives a very tight wave and a single, pure color at a single wavelength, in contrast to a light bulb, which puts out light in all directions at different angles and different wavelengths. It spreads out, whereas the laser beam stays almost parallel and doesn't spread. But it turns out that the laser beam does spread just a very little bit, and this spreading limits what you can do with it in some cases.

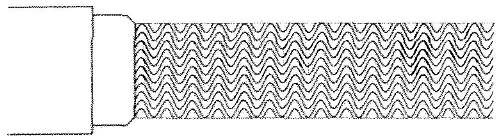
How much laser energy do we actually need for damaging a missile? We know how much power we can get from lasers, so the basic physics is very simple. The skin of a Soviet missile is usually made of aluminum, and it might have some ablative surface on it that would take more energy to burn through.



The first laser consisted of a helical flash lamp wound around a synthetic ruby rod containing chromium ions. Mirrors at the ends of the rod bounce photons (from the excited ions) back and forth, building up to an intense beam of light.

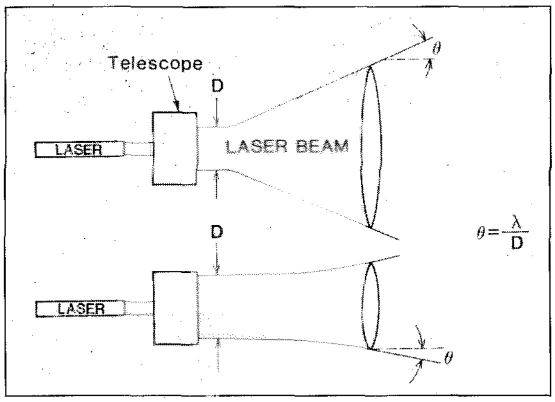


INCOHERENT LIGHT FROM A FLASHLIGHT

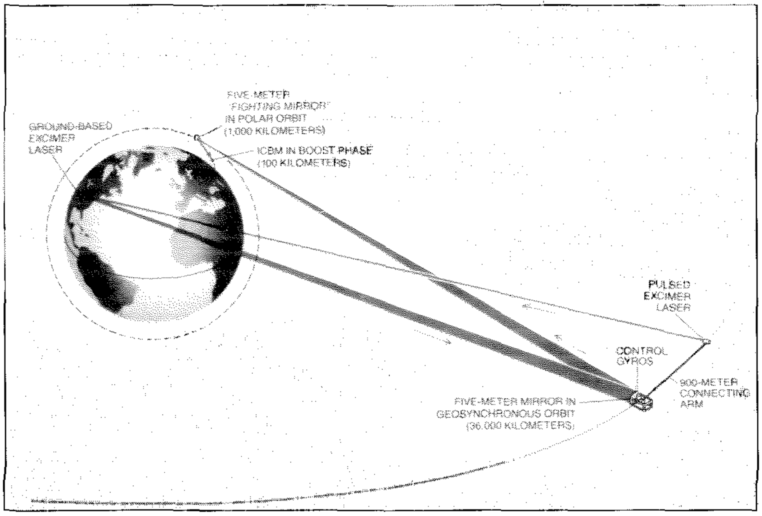


COHERENT LIGHT FROM A LASER

An ordinary flashlight produces light at different wavelengths and different angles spreading in all directions. Laser light is a tight, coherent beam at a single wavelength.



Diffraction of the laser beam can be decreased by a telescope. Because the spread angle is given by the wavelength over the diameter of the telescope mirror, the larger the mirror, the smaller the spread.



To decrease diffraction over long distances, a ground-based excimer laser (which produces an intense beam of ultraviolet radiation at a wavelength of .3 micrometers) could be beamed to a large mirror in geosynchronous orbit around the earth, and from there to a fighting mirror at lower orbit, which would focus it on the missile.

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All we have to do is go to the lab and find out how much laser energy it will take to burn a hole in missile skin. This has, of course, been done, and it turns out to be roughly 30,000 watts per square centimeter of the target during an exposure of one second. But if you want to deliver concentrated light energy over long distances, you can't just point the laser at the target. Although a laser beam spreads very little in comparison to ordinary light, over 40,000 miles it spreads too much to be effective for burning a hole in anything. The requisite power of the laser for damaging a missile is given by

$$P_{laser} = \left(I_{lethal}\right)\pi R^2\left(\frac{\lambda}{D}\right)^2$$

In this formula I_{lethal} stands for the intensity (watts/cm^2) necessary to burn through or seriously weaken the skin of the missile, assuming approximately a one-second exposure. R is the effective range from the laser to a relay mirror (to be discussed later), and D is the diameter of the laser telescope aperture, that is, the final (large) diameter of the launched laser beam. The factor $R\lambda/D$ is the theoretical radius of the laser beam at a distance R. λ is the wavelength of the laser.

From the formula you can see that if we try to compensate for the spread (diffraction) of the beam by using more laser power to start with, the amount we need becomes exorbitantly large. But since the spread angle is given by the ratio (λ/D) of the wavelength of the radiation to the diameter D, you can decrease the spread by increasing the diameter. You do this with a telescope. Unfortunately, to get the required laser power, we will need a telescope with a mirror about 10 meters in diameter. This is pretty big for a telescope. In fact, it's the size of the Keck Telescope, which is currently under construction, and which, when finished, will be the largest in the world. So, in addition, we will need a sizable structure to aim and control the laser. Like the Keck Telescope, Star Wars mirrors will probably have to be constructed out of segments that will be carefully adjusted relative to each other to achieve a perfect surface.

And where are we going to put these huge, expensive, delicately adjusted mirrors? If we want to get a laser beam from, let's say, Wyoming to Irkutsk, we can't go in a straight line because of the curvature of the earth and the atmosphere. So the current scenario is to put these mirrors in geosynchronous orbits—about 36,000 kilometers above the earth and stationary relative to a point on the earth. Somewhere over the Soviet Union other 10-meter mirrors, called fighting mirrors, would be positioned at much lower orbits, say 1,000 kilometers above the earth. The laser would be beamed from the earth to one of about 100 geosynchronous-orbit mirrors and then relayed to the fighting mirror, which would aim and focus it down on the ICBMs as they climb during the boost phase.

What kind of power do we need to do this? We know it will take 30 kilowatts for one second to burn through the skin of the missile. The formula tells us how light diffracts as it propagates through the atmosphere, so it's just simple bookkeeping. If we were to use radiation of one micron we will need a laser of roughly 30 megawatts. If this laser is going to be based on earth, so that we have to propagate through the atmosphere to the geosynchronous mirror and down to the fighting mirror, we will need as much as one gigawatt of power to achieve the requisite power density on the Russian missile in order to burn through its skin. One gigawatt is, for example, roughly the power output from one of the nuclear units in the San Onofre power plant. The difference, of course, is that this kind of power has to be available only during the engagement period of one to three minutes. The table at right shows some of the typical power levels that result from the above considerations.

The x-ray laser, the most exotic entry in the laser weapon field, doesn't need mirrors for the simple reason that no mirror has yet been made that can withstand x-ray radiation, and its operation is not based on feedback as in our example above but, rather, on one-pass amplification of spontaneously emitted x-rays. Since most of the information on x-ray lasers is classified, a small group from our committee who had the top Department of Energy clearance was able to go to Lawrence Livermore Labs to be briefed on them. I was not one of that group, so what I am going to say about x-ray lasers comes not from our committee deliberations but from the open literature. An x-ray laser is essentially an efficient nuclear bomb surrounded by a bunch of metal or plastic rods. When the bomb is exploded, most of its output consists of x-rays. In the billionth of a second before all the rest of the junk reaches the rods, the x-rays get there first and excite the atoms in the rods. Here you are just replacing the helical flash lamp around the ruby rod in Ted Maiman's laser with a nuclear bomb. When the x-rays excite the atoms in the rods, they lase along the rod axis. It's a rather crude laser in the sense that it isn't very collimated, or tight, and you can't concentrate the power on one small spot, but that's just what you might want in this case. The x-ray laser doesn't have to be pointed very accurately because it splashes a great deal of energy all over the place. The amount of energy envisaged is large enough that it can burn and disable objects over quite a broad area, so x-ray lasers just need to be pointed at the general vicinity of the target.

It would work like this: say the Soviets launch some ICBMs. Radar and other satellite-based sensors detect them, and the information is relayed to a U.S. submarine a few thousand kilometers off shore, which launches an extremely fast rocket. The x-ray laser is very light in comparison to any other laser considered. It does not have enormous mirrors (all it consists of is a nuclear bomb, which is a relatively light device, and a few rods), so you can achieve fast acceleration from the submarine to a line-of-sight position relative to the climbing enemy missile. Then the nuclear explosion is triggered, and x-rays are beamed at the vicinity of the target. One of the main problems with the system is that x-rays don't penetrate the atmosphere, so that you have to wait until the Soviet missile has risen above most of the atmosphere.

LASERS

Desired Power Output

To kill a nominal booster: with no losses and $D \sim 10M$

$\lambda = 1\mu m$	$P \approx 30MW$
$\lambda = 0.3\mu m$	$P \approx 3MW$
$\lambda = 3\mu m$	$P \approx 300MW$

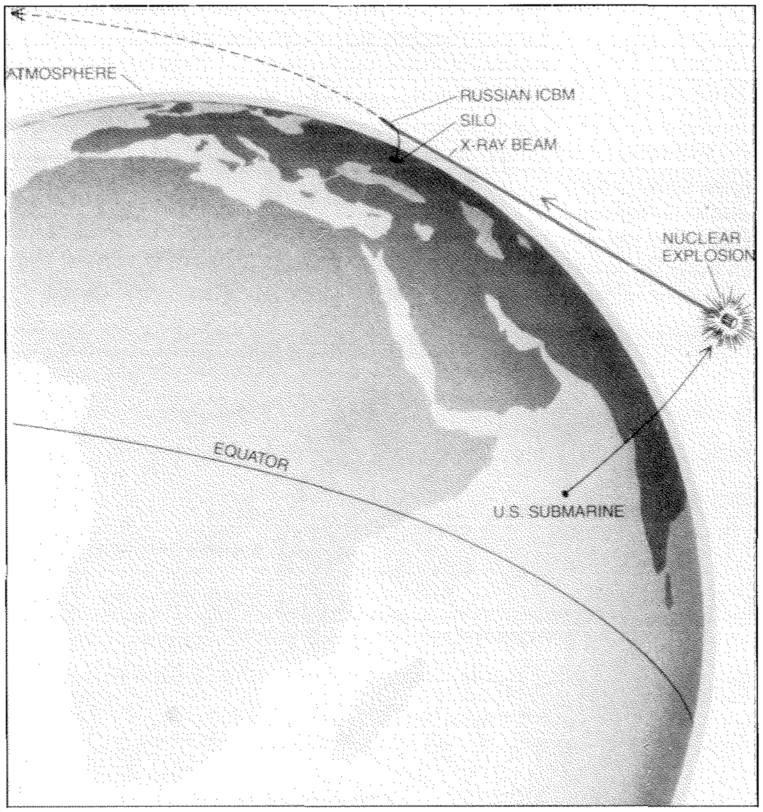
With inclusion of losses and reasonably hard targets

Space based lasers (HF,DF): $P \geq 100$'sMW

Ground based FEL ($1\mu m$): $P \geq 1GW$

Ground based excimer ($0.3\mu m$): $P \geq 100MJ$

Bouncing an effective ground-based laser off a 10-meter mirror in space to an orbiting fighting mirror demands various power outputs depending on the laser's wavelength.



Because it's very light, an x-ray laser could be launched and accelerated quickly from a submarine to a line-of-sight position relative to the missile. A nuclear explosion triggers the laser.

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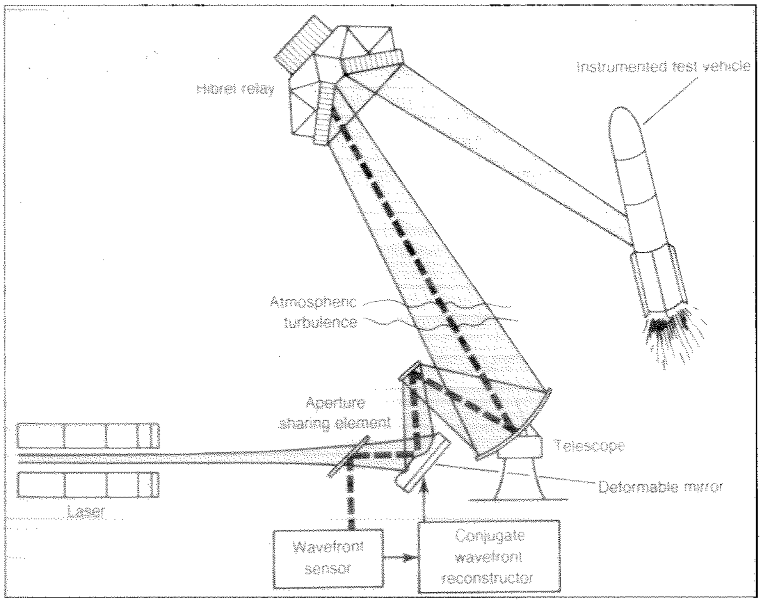
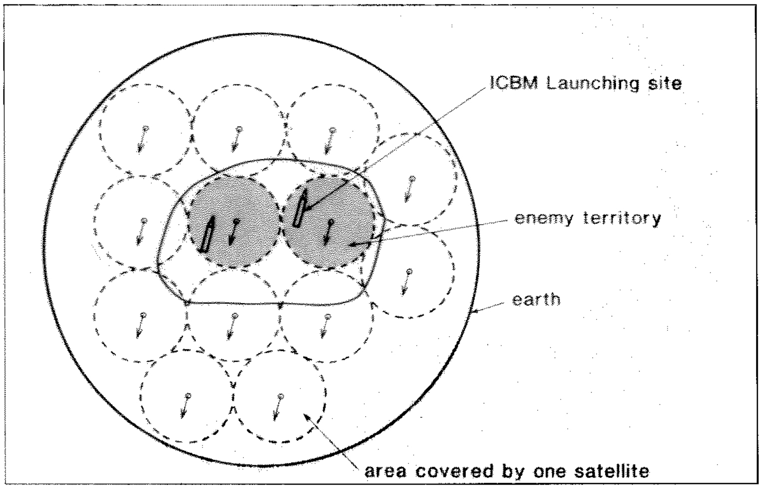


Using phase conjugate optics, a weak laser sent from a mirror in space would carry an "image" of the atmospheric turbulence in its own diffraction. This could be interpreted by a wavefront sensor and used to deform the mirror that launches the actual laser weapon, so that the distortion of the outgoing laser would cancel the effect of the atmospheric turbulence.

The atmosphere also bothers optical lasers. An ideal laser beam stays very tight and will propagate with a very small angle of dispersion. But an optical beam launched from an earth-based laser has to move through the atmosphere, and air turbulence makes the atmosphere an uncongenial medium for optical propagation. Instead of remaining narrow and tight, the beam breaks up and spreads over an angle that might be thousands of times larger than the ideal angle—with a concomitant loss in laser power on target. The intensity loss is so large that by the time the power reaches its target the intensity is too low to do any real damage. One of the major thrusts of current Star Wars research is dealing with this problem.

In one of the proposed solutions the large mirror assembly in geosynchronous orbit (36,000 kilometers above the earth) will house a small laser that shoots a beam down to the earth-based laser station. This weak beam probes the atmosphere, and when it arrives, its own distortion (spread) contains information about the atmospheric turbulence. A wavefront sensor extracts this information, which is then used to deform a mirror. The actual weapon laser beam is now reflected from this mirror and in the process gets distorted in exactly the complementary distortion necessary to balance the distortion caused by the atmospheric turbulence. The two distortions cancel each other, producing a diffraction-limited (collimated) beam. A deformable mirror would have to have as many as 100,000 little actuators that can push from below and deform the mirror locally.

Because of the earth's rotation, the number of fighting mirrors actually necessary to cover a launch site has to be exceeded by a factor of five.



Caltech has played an important role, conceptually and experimentally, in demonstrating many of the basic ideas that are involved in this technology, which goes under the name of phase conjugate optics. About 30 years ago Caltech astronomer Horace Babcock used techniques of this sort to compensate for scintillation in order to resolve astronomical objects better. In my own group we have been working for the last 10 years on phase conjugate optics and have developed, unrelated to Star Wars, nonlinear optical techniques that are relevant to correcting atmospheric distortions. The technique has many other applications, including photographing through clouds and transmitting images through fibers.

So we now know, at least theoretically, how to generate light, how to launch it, and how to compensate for distortion. What happens when the weapon beam is actually over the target? Two or three fighting mirrors at an altitude of 1,000-2,000 kilometers can cover the whole of the Soviet Union. But two or three mirrors don't have enough time during the one to four minutes or so of the boost phase to take care of all the Soviet missiles that are climbing. The Soviets can launch as many as 1,500 missiles at one time, so for an anticipated worst-case boost phase of one minute we will need some 12 mirrors, assuming half a second per kill. But these 12 mirrors can't be planted over the U.S.S.R. They will have to be orbiting all the time, and since we don't know when the missiles will be launched, because of the earth's rotation we will have to cover the whole earth with a blanket of orbiting mirrors. The factor by which you have to exceed the 12 or so that you actually need during engagement is referred to as the "absentee ratio," which turns out to be about five. So we will need about 60 orbiting fighting mirror platforms, each one 10 meters in diameter. We will also need one relay mirror in a geosynchronous orbit for each of the 12 or so fighting mirrors.

Even if we figure out how to do all this and make it work, it will take 10 to 15 years before this system is deployed, and the Soviets, of course, are not going to be sitting still during that time. They will be improving their own technology, especially in view of the fact that we are developing a ballistic missile defense system. They have many possible responses: they can attack the 60 orbiting platforms, each containing mirrors, electronics, radars, sensors, and power supplies. These platforms that we are going to hang up there are enormously complicated and expensive things, and they are relatively soft targets; that is, it will be far easier, I'd say by a factor of at least a thousand, to destroy them than for them to destroy the missiles. The Soviets would only need to explode a nuclear bomb above the atmosphere just before launching the missiles. This would disable everything we had within range and make it easier for their blind missiles to sneak through.

Our mirror platforms could also be destroyed by lasers, lasers much weaker than the ones I've discussed here, because our mirrors, electronics, solar cells, and antennas are a softer target than missiles. If the Soviets do undertake a Star Wars-type program but are unsuccessful in developing strong enough lasers to defend against our missiles, the ones they develop will very likely possess sufficient power to disable our weapon platforms with all our mirrors and electronics. We really have no clear idea how we are going to protect our assets in space. It's like buying a Cadillac and parking it in a high-crime area every night for 10 years.

Other fairly simple options for the Soviets that will make things more difficult for us include:

- Proliferation—increasing the number of targets by building more missiles.
- Booster rotation—rotating the missile as it rises so that the laser beam can't dwell on the same spot long enough to burn through. This simple move would increase the laser power requirement by a factor of approximately three—a huge factor when gigawatts are already involved.
- Ablation—using protective material that will require more power to burn a hole through.
- Fast-burn boosters—making booster rockets that will burn in one minute instead of four to five. This is possible even now and means that the critical time during the boost phase would be shortened by a factor of five. Almost every requirement would then be upped by that factor; we would need five to six times more power and so on. In addition, the boost phase would be completed at 80 kilometers or so, which is still within the atmosphere. This would reduce the effectiveness of the x-ray weapon considerably, because it can't penetrate through very much of the atmosphere. And because the nuclear bomb that triggers the x-rays has to be launched from a submarine and now would have much less time to get to its line-of-sight position relative to the target, new problems would be presented. The post-boost vehicle could also be redesigned to discharge its warheads and decoys faster, thereby spending less time in this vulnerable stage.
- Decoys and penetration aids—packing the post-boost vehicle, the bus, with 200-300 lightweight decoys. The decoys would be launched from the bus above the atmosphere and would move with the same velocity and have the same trajectory as the re-entry vehicle. They could also be shaped to look alike and to have similar responses to radar. By today's mostly passive means there would be no way of discriminating between them, with the result that, instead of concentrating on one warhead, you would have to deal with 200-300 objects that look the same. So, even if we were successful in destroying 90 percent of the launched Soviet missiles in the boost phase, so that instead of 10,000 warheads you would have only 1,000, we might still have some 100,000 decoys to deal with.

But forgetting possible Soviet countermeasures for a moment, where are we with Star Wars technologies right now and how far do we have to go? Demonstrations of correcting for atmospheric turbulence are short by a factor of 100 of what needs to be done. Chemical lasers' effectiveness has to be increased by a factor of 100 to get to the range where they can even theoretically be used. To do the job, excimer lasers need to be four orders of magnitude, or 10,000 times, more powerful than what we have today. X-ray lasers still have enormous problems.

Other exotic possibilities include free-electron lasers and particle beams. A free-electron laser uses a beam of electrons that have been accelerated to as much as 100 million volts to change the polarity of a magnetic

STATUS OF VARIOUS DEW TECHNOLOGIES

TECHNOLOGY	STATUS (ORDERS OF MAGNITUDE SHORTFALL)	
	BOOSTER KILL	DISCRIMINATION
LASERS		
Chemical Lasers (HF & DF)	P_{av} : >2	
Excimer Lasers	P_{pulse} : >4	
Free Electron Lasers	P_{av} : >6	
X-Ray Lasers	MANY	MANY
PARTICLE BEAMS		
Neutral Particle Beams	P_{av} : >2	P_{av} : >2
Charged Particle Beams	P_{av} : >3	P_{av} : >2

field in a regular fashion. This forces the electrons to undulate as they move along, and the wiggly motion forces the electrons to radiate, that is, give up energy in the form of photons. Electron-beam lasers would need to be improved by six orders of magnitude, and much of the basic physics isn't understood yet. Particle beams—beams of electrons, protons, or atoms, which can be accelerated to velocities nearly that of light—are still only a suggestion and are even further behind than lasers.

We don't know how to discriminate among warheads and decoys; only preliminary ideas have been proposed, and much work needs to be done just to establish their feasibility. We haven't yet built 10-meter mirrors, much less figured out how to put them in space and point them fast and accurately.

And system issues have yet to be addressed. We are going to have the most complicated system ever designed operating in a hostile environment of laser beams and exploding nuclear bombs. Vast amounts of information will have to be processed, including locations, decoy discrimination data, and kill verification. This information will have to be transferred and shared as the defense focus moves with the surviving missiles from one phase to the next. All the components of the system have to communicate perfectly, and we don't know how to do that. This problem is so difficult that I don't think people even know where to start. We considered this the most difficult part of the Star Wars challenge.

The degree of shortfall between other needed performance levels and present-day achievement is demonstrated in the table at left. As one can see, we need improvements of from two to six orders of magnitude in the basic technologies.

Our committee came to the following conclusion: "Although substantial progress has been made in many of the technologies of directed-energy weapons over the last two decades, the study group finds significant gaps in the scientific and engineering understanding of many issues associated with the development of these technologies. We estimate that even in the best of circumstances, a decade or more of intensive research would be required to provide the technical knowledge needed to make an informed decision about the potential effectiveness and survivability of directed-energy weapons."

It is important for us to have a sound understanding of the performance limitations of a directed-energy weapon defense system. For one thing, the system will be very expensive. Just shooting wildly from the hip I would guess thousands of billions of dollars, with tens of billions for annual upkeep and repair. Embarking on such an endeavor before we possess the basic technology and an understanding of the phenomena involved will almost surely lead to failure. And a failure of that magnitude will be a national catastrophe.

But there are already political pressures, which are increasing, to proceed with these untested ideas and technologies. This is probably due to the reluctance of Congress to shell out a few billion dollars every year for a basic research program in developing technologies. The pressure is to show results, and that pressure can force us to commit ourselves to premature technologies that are certain to fail. We hope that our report will make it easier to resist such pressures.

I want to reiterate in closing that our committee was not "for" or "against" the Strategic Defense Initiative. We concentrated on the technological and scientific issues. I personally would like one day to see an effective missile defense system developed strictly for defensive purposes, because the list of nations possessing nuclear weapons will increase and some of these nations may not be quite "reasonable." But our committee concluded that, based on present-day technology and understanding, the job cannot be done. What we need is at least 10 years of intensive research and development simply in order to find out if it *can* be done. □