Bush's GPALS limits more than defense

An in-depth study of the administration's new strategic defense program, prepared by 21st Century Science and Technology *magazine.*

Once again the nation's Strategic Defense Initiative (SDI) is in for an overhaul. President Bush announced in his January 29, 1991, State of the Union address that he has directed the SDI Organization (SDIO) to shift its emphasis from providing the U.S. with a shield against a large-scale Soviet missile attack to providing "protection from limited ballistic missile strikes whatever their source" and whatever their target. The system is to protect every region of the world from a limited strike by any country.

The name given to this version of a ballistic missile defense (BMD) is GPALS, an acronym that stands for Global Protection Against Limited Strikes.

As outlined by Pentagon officials in recent months, the GPALS system would consist primarily of ground- and space-based antiballistic missiles (ABMs). From 750 to 1,000 ground-based interceptor missiles would be scattered in approximately a dozen sites inside the United States; about 1,000 space-based interceptors, widely known as "Brilliant Pebbles" (BPs), would be placed in low-Earth orbit; and an array of space-based satellite sensors and ground-based radars would round out the system, providing the means to detect and track the hostile missiles. Early experimental versions of all three components have been tested repeatedly, many with outstanding successes.

The Brilliant Pebbles aspect of the GPALS missile defense system has been greatly reduced from the earlier SDI scheme to defend the U.S. from a massive Soviet strategic attack, which envisioned a force of about 4,500 such space-based interceptors.

In addition, Bush's initiative suggests that the Pentagon will be given the go-ahead to proceed with major new research on a new generation of a Patriot-style missile system to intercept short-range ballistic missiles (SRBMs). This new missile system would undoubtedly be an element of GPALS. The Patriot intercepted dozens of short-range Scud missiles fired against Israel and Saudi Arabia. The Pentagon has spent millions in recent years to develop such weapons. Bush's initiative effectively curtails indefinitely any fast track development and deployment of "exotic" new anti-missile systems such as lasers and particle beams.

Let us forgo for the moment an evaluation of the dramatic policy shift from an SDI system to defend the U.S. against a Soviet first strike to a GPALS system. Let us first discuss how a GPALS might work, and then evaluate its potential military effectiveness and economic viability.

GPALS and the Patriot anti-missile systems

The mission of a GPALS system would be similar to the mission of the Patriot ABM system used in the Persian Gulf—to neutralize ballistic missiles launched from Third World (or other) nations before they reach their target. The difference between GPALS and the Patriot is that GPALS is a combined space- and ground-based system whereas the Patriot is a strictly ground-based system. Current information concerning GPALS seems to suggest that the ground-based component is a Patriot-like antiballistic missile (ABM) system with sufficient capability to intercept the high-speed 6 kilometer per second reentry vehicles of intercontinental ballistic missiles, and the easier 2 km per second reentry vehicles of SRBMs. The SDI Organization used to call this system ERIS; the new name is E^2I for Endo/Exoatmospheric Interceptor. The ABMs are to be based at roughly a dozen sites in the United States. If the ABMs are transportable, as the Patriot is, they could also be temporarily based in any country that asked for their protection, but only if the U.S. deemed this to be in its own interest. Even if a country did not want to be protected from another nation's ballistic missiles, the space-based component of GPALS would nonetheless be available to provide this protection. While the available information on GPALS suggests that the space-based interceptors are much like the Brilliant Pebbles that have been under study for the past two years, the GPALS Brilliant Pebbles are probably faster, so they can travel from their orbits and intercept the low-flying trajectories of short-range ballistic missiles, such as Scuds, before the SRBMs are much beyond the halfway point to their targets. Since SRBMs rarely leave the atmosphere (their maximum altitudes range from 50-100 km and are achieved when the missile has traveled halfway to its target), the GPALS Brilliant Pebbles will also have to withstand and operate through any atmospheric heating.

Is a missile-based GPALS a militarily sound and cost-effective defense against a limited number of ballistic missiles? We have long advocated the thesis that *any* U.S. ballistic missile defense system must be based on new physical principles if it is to be militarily and economically viable. A system based solely on ABMs—using missiles to shoot down missiles—is a bad idea. The proof can be given at two levels. At the more fundamental level, it amounts to showing that the defense sector of the economy is a net benefit to the entire economy, rather than a net loss, when it spins off fundamentally new technologies at sufficient rates to ensure an overall increasing rate of real productivity in the economy. Such would be the case, in our view, if the Strategic Defense Initiative were organized, similar to the Manhattan Project, as a crash program to master the science and technology of visible and X-ray lasers, neutral particle beams, and radio-frequency weapons. An SDI committed primarily to achieving marginal performance gains in a technology as old as missiles, which is its current mission, is a net loss to the economy, rather than a benefit.

At a less fundamental level, the viability of any BMD system can be approximated by computing its cost exchange ratio. This is the ratio of the production cost of the BMD system to the production cost of the opposing missile force. Research and development costs are neglected in this calculation because it is only the cost to field each element of the two forces that determines whether or not a combatant can afford to do battle.

A cost exchange ratio much less than one would indicate that the BMD system is viable. In our experience, this only happens if the BMD is premised on weapons employing new physical principles—visible and X-ray lasers, neutral particle beams, nuclear lasers, and radio-frequency weapons.

Cost exchange and the issue of new technology

Justifying ballistic missile defense with a cost exchange argument is a tricky business, especially when the costs for new technology weapons are involved. Most economists and military planners vastly overestimate the cost of new technology weapons in such an exercise, primarily because they neglect to factor in the productivity payback to the economy that the development of the new technology weapon brings about, such as what is involved in the concept of maximum technological attrition.

Granted, the initial investment to develop the new technology may be high, but if thevelopment is properly carried out and the technology is of a fundamental sort (specifically a technology of greater energy density than present technologies), the initial investment will always yield a positive return (a healthier economy able to support more people at a higher standard of living), implying that the true cost of developing the technology is essentially zero, in that it pays for itself and then some. The "labor cost" of a weapon premised on the new technology may be relatively high immediately after the technology is developed, but within a decade or two, after the technology has permeated the economy, the "labor cost" of this weapon is dramatically reduced.

Consider by way of example the fission bomb. The initial investment was tremendously high (the cost of the Manhattan Project) and the production cost of the first 100 bombs was in the neighborhood of 1,000 man-years. Fifty years later, after nuclear technologies have permeated the power industry and many fields of physics, biology, and medicine, the production cost of those same fission bombs is roughly 10 man-years. This great reduction in labor cost is not due exclusively to the assimilation of nuclear technologies into the economy, but nonetheless a certain portion is, which illustrates the point being made.

We are on much safer ground with cost exchange ratios, if the items being costed employ old or current technologies. This avoids the problem of predicting the cost of new technologies.

There is a second issue with respect to cost exchange that deserves discussion, which relates to its definition. We must be clear on the "exchange" being costed if the term is to have any meaning.

There are three basic ways cost exchange can be defined:

1) Cost exchange between forces: This is a balance-of-power concept which compares the total production cost of two opposing forces. For example, the ratio of the production cost of all U.S. tanks, ships, aircraft, etc. to the production cost of the Soviet arsenal would fit this definition. Arguments for and against SDI have sometimes used the ratio of the production cost of an SDI system to the production cost of the Soviets' strategic missile force, including its countermeasures to SDI. This cost exchange is the least meaningful of the three under consideration, as will become apparent, and will not be considered further.

2) Cost exchange at the margin: This is also a balance-of-power concept. It begins with two opposing, balanced forces and compares the cost to one side to counter a marginal improvement in the other side. This is the cost exchange test which Congress has imposed on SDI, and was originally put forward by Paul Nitze. An SDI will only be deployed if is cost-effective at the margin. Consider the system of 4,500 Brilliant Pebbles that SDIO has been studying, as an example. It is well known that, for each new ICBM the Soviets deploy, 10 additional Brilliant Pebbles must be put into orbit to maintain the BP system's boost-phase kill effectiveness. If the Soviet ICBM costs $10 million, the cost of a single Brilliant Pebble, including putting it into orbit, must be under $1 million for the system to meet the "cost-effective at the margin" test.

3) Cost exchange under combat: Even though it has its flaws, this is perhaps the best cost test for a military system. It is the only cost exchange definition of the three which addresses the issue of "defense in depth." The true test of any military force is *not* if it can indefinitely deter war by maintaining a balance of power, but rather if it can *win* the war once deterrence fails. The key issues here are the cost and speed of replacing assets lost in battle, as well as how quickly total military capability can be expanded. Consider again a simplified SDI example consisting of an exchange between an SDI Brilliant Pebbles system and a ballistic missile force. Suppose two BPs are required to destroy a single ICBM. If the cost to replace the two BPs is less than the cost to replace the ICBM, the Brilliant Pebble system wins the cost exchange under combat. When comparing two different SDI system concepts, the one which can replenish itself the most rapidly and at the lowest cost is the better system.

This brings us to our principal topic under discussion—the viability of a ballistic missile defense based on Brilliant Pebbles and advanced Patriot missile system technology. Since the idea of GPALS is to defend against ballistic missiles by using antiballistic missiles, and both groups of missiles (the defensive and offensive) are envisioned to employ old and current technologies, a cost exchange analysis is a fairly safe way to determine the military and economic viability of an ABM-style GPALS system.

A cost exchange analysis begins with a simulated missile engagement. In keeping with the times, suppose Iraq had launched a single Scud attack against Israel. Let us consider the ability of the space-based components of GPALS, the Brilliant Pebbles, to defend Israel. The 1,000 BPs are in low-Earth orbits passing over the North and South Poles. They therefore travel roughly north and south over every country in the world. To guarantee that a single orbiting GPALS BP is always over the Persian Gulf and in position to intercept a Scud, roughly 100 of them must be placed in orbit.

We computed this 100:1 BP "absentee ratio" by making use of three facts: 1) roughly 10 BPs must be placed in orbit if one of these BPs is to have a chance to intercept a Soviet-launched ICBM during its boost phase (see *EIR*, April 19, 1990); 2) the duration of an ICBM's boost phase is roughly equal to the total flight time of a short-range ballistic missile; and 3) the Soviet land-area containing ICBM launch complexes is roughly 10 times larger than the land-area of Iraq. From these facts, it follows that roughly 100 BPs must be placed in orbit if one of them is to have a chance to intercept an Iraqi-launched SRBM. The number is probably greater than 100, because the absentee ratio increases, as the distance of the launch site to the Equator decreases—Iraq is south of the Soviet Union; for the sake of consistency, we will neglect this effect. Therefore, for each Scud the Iraqis have, 100 BPs must be placed in orbit.

To compute the cost exchange ratio, we must now estimate the cost of a BP and a Scud. As **Table 1** shows, the specific cost (cost per unit weight) of a missile varies over a considerable range, depending primarily on the size (or total weight) of the missile and the method and accuracy of its guidance system. The Pentagon's SDI Organization has established a $0.5 million cost goal and 50 kilogram weight goal for a Brilliant Pebble. We shall adopt both without modification. Note that the cost goal of a Brilliant Pebble is about equal to the cost of a Patriot missile, but that its $10,000 per kg specific cost is roughly 20 times the specific cost of a Patriot. Apparently most of a Brilliant Pebble's cost comes from its miniaturized guidance and sensor systems, rather than its propulsion system.

Estimating the cost of a Scud SRBM

To estimate the cost of an Iraqi Scud, which is a modified Soviet Scud B, we note two facts from Table 1 and **Table 2:** 1) The specific cost of a Soviet space launch system (Proton) is about one-quarter that of a similar class U.S. space launch system (Titan IV); and 2) a Soviet Scud B and a U.S. Pershing IA are similar class missiles. Therefore, assuming that the factor of four cost difference in large missiles also holds for smaller missiles, the cost of a Soviet Scud B can be estimated to be about one-quarter the cost of a Pershing IA, or $0.6 million. The Iraqi Scuds launched toward Israel are not Scud Bs, but either of two modified Scud Bs, called the Al-Hussein, which is 1.1 times longer and heavier than a Scud B, and the Al-Abbas, which is 1.2 times longer and heavier than a Scud B. The Al-Abbas has twice the range and roughly the same throw weight of a Scud B. It is doubtful that the cost of modifying a Scud B to create an Al-Abbas is greater than the purchase price of the Scud B. Therefore, a price of $1 million appears to be a safe upper limit for the cost of an Iraqi Scud.

Using the SDI Organization's goal of $0.5 million for the cost of a Brilliant Pebble and an upper limit of $1 million for the cost of an Iraqi Scud will yield the best possible cost exchange ratio for SDIO's proposed space-based, ABM-style GPALS system. Recalling that 100 Brilliant Pebbles must be placed in orbit for each Iraqi Scud that is to be intercepted, and assuming a single Brilliant Pebble is sufficient to neutralize a single Scud, the "cost exchange at the margin" is 50 to 1 in favor of the Scud. By its own established criteria, Congress should not approve a BP-style GPALS since it is not cost effective at the margin.

Some may argue that the 100 to 1 BP absentee ratio should not be included in the cost exchange calculation above; or in other words, that cost effectiveness at the margin is not an appropriate test for a GPALS system. Although 100 BPs must be deployed to defend against a single Scud in Iraq, these same 100 are also defending against 99 other potential Scuds based anywhere else on the globe. And if a Brilliant Pebble neutralizes a single Scud somewhere, only a single BP must be launched into orbit to replace the one fired at the Scud. Therefore, the "cost exchange under combat" is perhaps a better criterion. If the Scud costs $1 million and the Brilliant Pebble costs $0.5 million, and the cost to put a BP into orbit is $0.5 million (we neglected this cost earlier, which is roughly $11,000 per kg for systems such as the Titan IV), then the GPALS BP system achieves an even cost exchange as the cost exchange ratio is 1 to 1. This ratio assumes Brilliant Pebbles with a 100% probability of kill and no countermeasures employed by the Scud, a 25-year-old system. If the Scud were an extremely "high value" target (perhaps it carries a nuclear warhead), then it would be prudent to attempt to intercept it with at least 2 or 3 Brilliant

TABLE 1

Sample comparative missile costs used to compute cost exchange ratios

	Guidance method	Circular error probability (m)	Launch weight (kg)	First unit cost (thousands of 1990 $)	Cost/unit ($ per kg)
U.S. missiles					
Titan IV[1]	Inertial	NA	860,000	170,000	198
Titan IV solid rocket motor	None	NA	316,000	17,000	54
MX Peacekeeper	Inertial	40	88,000	65,000	739
Pershing II	Inertial	40	4,600	5,000	1,087
Pershing IA	Inertial	400	4,600	2,300	500
Patriot	RDH[2]	1	1,000	530	530
Copperhead	LDH[3]	1	64	41	641
ADAT/FAAD	LBR[4]	1	51	100	1,961
Hellfire	LDH[3]	1	43	36	837
Hawk	RDH[2]	1	627	300	489
U.S.S.R. missiles					
Proton (SL-13)[5]	Inertial	NA	670,000	36,000,000	54
Energia (SL-W)[5]	Inertial	NA	2,000,000	71,000,000	36

1. The Titan IV main stages use liquid engines; the two solid motors are strap-ons.
2. Radar Designator Homing.
3. Laser Designator Homing.
4. Laser Beam Riding.
5. These missiles use liquid propulsion.

Sources: *Aviation Week, Janes Weapon Systems,* and *Nuclear Weapons Databook.*

TABLE 2

How the Soviet Scud B tactical missile compares to the Patriot and Pershing IA

	Patriot	Pershing IA	Scud B
First deployed (year)	1984	1971	1965
Range (km)	90	160-840	165-300
Launch weight (kg)	1,000	4,600	6,400
Maximum throw weight (kg)[1]	70	360	500
Circular error probability(m)	<1	400	900
Number of warheads	1	1	1
Warhead yield (kt)	NA	60-400	<1,000
Propulsion	Solid, 1 stage	Solid, 2 stages	Liquid sustainer
Length x diameter (m)	5.3 x .41	10.5 x 1.0	11 x .85
Guidance principle	Radio commanded/homing	Inertial	Simplified inertial
Guidance method	Fins	Fins	Tail fins
First unit cost (1990 $)	$500,000[2]	$2,000,000[2]	$600,000

1. Weight of post-boost vehicle, including bus, warhead, guidance, penetration aids.
2. 1990 first unit production cost of a fully assembled missile, based on a highly reliable source.

Sources: *Jane's Weapon Systems* and *Nuclear Weapons Databook;* Scud B throw weight and first unit cost is an estimate by *21st Century* staff.

Pebbles. (Currently, Army tactics call for firing at least 2 Patriots at each Scud.) For this scenario, GPALS loses the "cost exchange under combat."

Perhaps instead of using the GPALS' space-based BPs to intercept Scuds, it makes more sense to use the GPALS' ground-based ABMs by transporting them to the target area, exactly in the way the Patriots were used. Does this improve the GPALS cost exchange? In other words, is the cost exchange for the Patriot-style ABMs any better than the cost exchange for the Brilliant Pebble-style ABMs? The answer is "no" for the cost exchange under combat and "yes" for the cost exchange at the margin. Because there is no absentee ratio for ground-based point defense systems such as the Patriot, the cost exchange under combat and cost exchange at the margin are equivalent for these ABM systems. Since the costs of the Patriot-style and BP-style ABMs are roughly equivalent, about $0.5 million, a ground-based ABM-style ballistic missile defense has a roughly equal cost exchange at the margin and cost exchange under combat against a $1 million Scud, assuming two ABMs are required to shoot down a Scud with high confidence, as was being done in the Persian Gulf.

Since ABMs must always be more agile (greater lateral acceleration capability) than their targets to effect an intercept, they are also generally smaller and more technologically advanced than their targets. Note that the technology of a Patriot is greater than that of a Scud, but a Scud is a more massive missile (see Table 2). Given the methods by which contractors establish a cost for a missile, a military analyst would be hard pressed not to assume that the costs of an offensive missile and the ABM designed to intercept it are roughly equal. In light of this, an ABM-style GPALS may in some instances have an even cost exchange under combat with offensive missiles, but it can never win this cost exchange outright. Since the cost exchange at the margin is always worse than or equal to the cost exchange under combat (due to the effect of the absentee ratio), an ABM-style GPALS can never win this cost exchange either.

Before leaving our evaluation of the ABM-style GPALS system, let us draw attention to one more fact. We noticed earlier that for every Scud the Iraqis launched, at least 100 BPs must be in orbit to guarantee that at least one Brilliant Pebble is in position to intercept the Scud. The SDI Organization has said that the GPALS BP constellation will consist of only about 1,000 Brilliant Pebbles. Putting these two facts together, it appears that the GPALS BP system will be capable of interdicting only 10 nearly simultaneously launched Scuds! Calling GPALS a *limited* strike ballistic missile defense system is no exaggeration.

Getting out of the BMD Stone Age

Let us suppose that the U.S. is committed to the policy of a GPALS system. Is there a more militarily sound and cost-effective approach than the ABM system currently being proposed? Is there a GPALS concept that wins the cost exchange test by a wide margin? The answer is yes, which is easily demonstrated.

For the sake of comparison, consider a space-based laser (SBL) GPALS which meets the same mission requirements proposed for the ABM GPALS: 1) the ability to intercept 10 Scuds simultaneously launched from Iraq; and 2) the ability to defend any targeted country from a limited ballistic missile attack. Placing sufficient SBLs in orbit to ensure global coverage, as is done for the BP system, and designing each space-based laser so that the total number over the Persian Gulf at any one time can shoot down at least 10 simultaneously launched Iraqi Scuds, will meet both requirements. Therefore, this will be our approach.

There are a host of laser concepts from which to choose for an SBL (see **Table 3**). Perhaps the most promising and most militarily (and industrially) useful is the free electron laser (FEL), primarily because it is tunable (laser beams can be produced at short wavelengths where the atmosphere is nearly transparent, that is wavelengths which range from 0.3 to 2 microns), has high overall efficiencies (20 to 50%), and is promising for ultrahigh-power applications (100 megawatt average power for a wavelength of 1 micron). The basic components of a space-based FEL are an electric power source, an electron accelerator or gun, a "wiggler" or "undulator" where electron kinetic energy is converted to laser energy, and the output optics.

Setting a maximum SBL-to-target range essentially determines the number of space-based lasers required in orbit. For a maximum SBL-to-target range of about 2,200 km, 50 SBLs in circular orbits passing over the North and South Poles at an altitude of 600 km ensures that any missile launched from anywhere in the world will be within range of at least one space-based laser. If the missile is launched in the vicinity of the Equator, only one SBL will be within range; if it is launched near the North or South Pole ten SBLs will be within range. For launch locations between these two extremes, the number of SBLs in range will be between one and ten. Missiles launched from Iraq would have to evade roughly 1.2 space-based lasers. In other words, at least one SBL is always within range of Iraq, and 20% of the time two SBLs are within range of Iraq.

The amount of power required in each SBL's laser beam is a function of the diameter of the beam at the target, the amount of time the beam illuminates the target, and the amount of energy per unit area that must be deposited on the target to destroy it. The continuous-wave (constant power level) energy per unit area required to destroy military targets ranges from 1 kilojoule per square centimeter for soft targets to 100 kJ per square centimeter for hard targets. The kill is accomplished by heating the structure which subsequently causes structural failure. Generally speaking, about 10 kJ per square centimeter is sufficient to destroy a missile during powered flight. A more efficient kill mechanism—impulse kill—is available with pulsed lasers such as free electron lasers. Here the laser beam couples with the plasma produced at the target's surface and is therefore relatively insensitive to the surface material. The plasma leaves the surface at high velocity, delivering an impulse to the target. Only 5 kJ per square centimeter of pulsed laser energy may be necessary to break apart any target, hard or soft. At this point in our analysis, we shall be extremely conservative and use a value of 100 kJ per square centimeter as the lethality requirement.

By requiring that the laser beam destroy its target and re-aim in the shortest possible time, we maximize the space-based laser's firing rate and minimize the countermeasures available to the target. A dwell time of 1 second and slew time of 0.1 seconds per target have been advocated by SDIO in the past and will be adopted here. This gives the SBL the ability to shoot down 1 short-range ballistic missile every 1.1 seconds. Since about 200 seconds of an SRBM's total flight time is the time-span over which it is vulnerable to a space-

TABLE 3

How the Global Protection Against Limited Strikes works: a summary

GPALS system	Kills of colocated simultaneously launched Scuds	Cost exchange at the margin	Cost exchange under combat
Space-based ABM (BP)	10	50:1	1:1
Ground-based ABM	500	1:1	1:1
38 MW CW SBL/SBM	230	133:1	**1:5 to 0**
38 MW CW GBL/SBM	230	133:1	**1:50,000 to 0**
38 MW Space-based FEL/SBM	4,600	7:1	**1:100 to 0**
38 MW Ground-based FEL/SBM	4,600	7:1	**1:1,000,000 to 0**
1 GW Space-based FEL/SBM	129,000	**1:4**	**1:100 to 0**
1 GW Ground-based FEL/SBM	129,000	**1:4**	**1:1,000,000 to 0**

The numbers in boldface show cost exchanges that are favorable to Global Protection Against Limited Strikes, such that the smaller the fraction, the more cost effective the system. The cost exchange goes to zero, that is a laser shot is free, if the laser fuel is recycled via solar energy.

All laser systems assume 10 meter optics and 0.5 micron wavelength.

The lethality requirement for continuous wave (CW) lasers is 100 kilojoules per square centimeter; for free electron lasers (FEL) it is 5 kilojoules per square centimeter.

based laser (above 15 km in altitude—atmospheric transmittance of visible light at 15 km is close to 100%, but at 0 km it is only about 50%), it follows that one of our SBLs can destroy roughly 190 SRBMs simultaneously launched from the same area. Since Iraq is covered by 1.2 SBLs on the average, roughly 228 simultaneously launched Iraqi Scuds can be destroyed by our SBL GPALS. The firing rate we have adopted yields an space-based laser system that greatly exceeds the requirement to destroy only 10 simultaneously launched Iraqi Scuds, but let us continue on to see how this over-designed SBL system fares in a cost exchange.

To deposit 100 kJ per square centimeter of energy on a Scud in 1 second requires a laser beam flux of 100 kilowatt per square centimeter. Assuming a near diffraction limited laser beam, the diameter of the laser beam at the target is proportional to the product of the SBL-to-target range and the laser wavelength divided by the diameter of the final optical aperture or beam director. For a SBL-to-target range of 2,200 km, a laser wavelength of 0.5 microns (visible light) and an aperture diameter of 10 meters (the aperture of the Hubble Space Telescope is 2.4 meters), the diameter of the laser beam at the target is 22 cm, which is less than the 85 cm diameter of a Scud, thus ensuring that none of the energy in the beam is wasted when it is centered on the target. The power required in the laser beam is simply 100 kW per square centimeter times the area of a 22 cm diameter circle, or 38 MW.

While the space-based laser mirror is 4 times the diameter (16 times the area) of the 15-year-old Hubble mirror, new methods of mirror manufacture have yielded a factor of 10 to 20 improvement in the weight per unit area of large mirrors. These new mirrors are very thin and made of several independent segments. Two mirror materials that have been investigated are silicon and molybdenum. The primary and secondary mirrors must be cooled when the laser is firing to remove absorbed laser energy. Cooled silicon mirrors using silicon heat exchangers have been used at incident power densities of the order of 10 MW per square centimeter. (Our laser system's power density at the target is 100 kW per square centimeter; the power density on the mirror surfaces would generally be less than this.) Actuators attached to the backside of each mirror segment provide active shape control and also compensate for beam distortions due to turbulence in the atmosphere.

The laser beam can be pointed by either gimbaling the large 10 meter mirror, or by holding the 10 meter mirror stationary and gimbaling a small mirror in the optical train. This latter approach is preferred, but it requires the optics to have a large field of view and trackers that look through the optical system. This requires high-power aperture-sharing elements, which are conceptually possible but have yet to be built and tested.

To summarize, a possible SBL-style GPALS would consist of 50 space-based lasers, each with a 10 meter aperture and 38 MW of beam power. Each visible light laser "shot" lasts 1 second and delivers 38 MJ of energy. The firing ratio is one shot every 1.1 seconds which permits 190 co-located, simultaneously launched missiles to be killed if they are vulnerable (above 15 km in altitude) for 200 seconds. For a single space-based laser to destroy a total of 190 missiles, its power system must provide 7,220 MJ of total beam energy. A power system consisting of a combustion turbine burning liquid hydrogen and oxygen coupled to an electric generator could easily meet the required power and energy requirements. The total weight of each SBL, including the power system fuel (H_2+O_2 reactions yield 121 MJ per kilogram in the form of heat), the power system itself, the electron gun, the wiggler and the 10 meter optics would be in the range of 50,000 to 100,000 kg. This is roughly the weight of 5 to 10 Hubble Space Telescopes.

The above space-based laser system is very similar to those considered in the American Physical Society's (APS) 1987 report evaluating the status of the science and technology of directed energy weapons. The APS stated that virtually every technology required for these SBLs has been demonstrated and is in some state of development. The question is whether these technologies can be scaled up to the required performance levels. The APS provided no answer to this question, believing the existing data is insufficient to provide an answer.

Before attempting to estimate the cost exchange for our SBL system, an alternate laser concept is worth considering. The SDI Organization in the past and the APS in its report have considered laser systems in which the lasers and their associated power systems are based on the ground, and only mirrors are placed in orbit. Rather than having 50 SBLs in orbit, 50 space-based mirrors (SBMs), essentially the 10 meter optics of the SBL, could be placed in orbit. These SBMs would direct the 38 MW (after traversing the atmosphere) laser beams provided by several ground-based lasers (GBLs) to the targets. Several ground-based lasers at appropriately scattered sites are required to get around the problem of having clouds obscure the uplink to the mirrors. To achieve the maximum possible firing rate, one unobscured ground-based laser must exist for each space-based mirror that is engaged in battle. While the atmosphere must be traversed twice in this arrangement and a system must be devised to coordinate the transfer of laser light between mirrors, the system has the favorable feature that the weight of the space-based components is considerably reduced to roughly equal the weight of two Hubble Space Telescopes. This combination ground- and space-based system would undoubtedly be much less expensive than a completely space-based system. For comparison, we will carry along both the SBL concept and the GBL/SBM concept in the analysis to follow.

Space-based target tracking and surveillance

We have yet to address the issue of a surveillance system to track the laser targets. The same space-based system envisioned for the ABM-style GPALS could be used, but a much better system would be available virtually free of charge with any laser system. The large mirrors which focus and direct the laser beam can be designed to double as telescopes when the laser is not firing. The resolution of these 10 meter telescopes would be about four times better than the resolution of the Hubble. Objects the size of a few centimeters could be seen from a range of 1,000 km. This would undoubtedly be a far better peacetime surveillance capability than the one currently being considered for GPALS, and probably also much better than the current U.S. spy satellite capability.

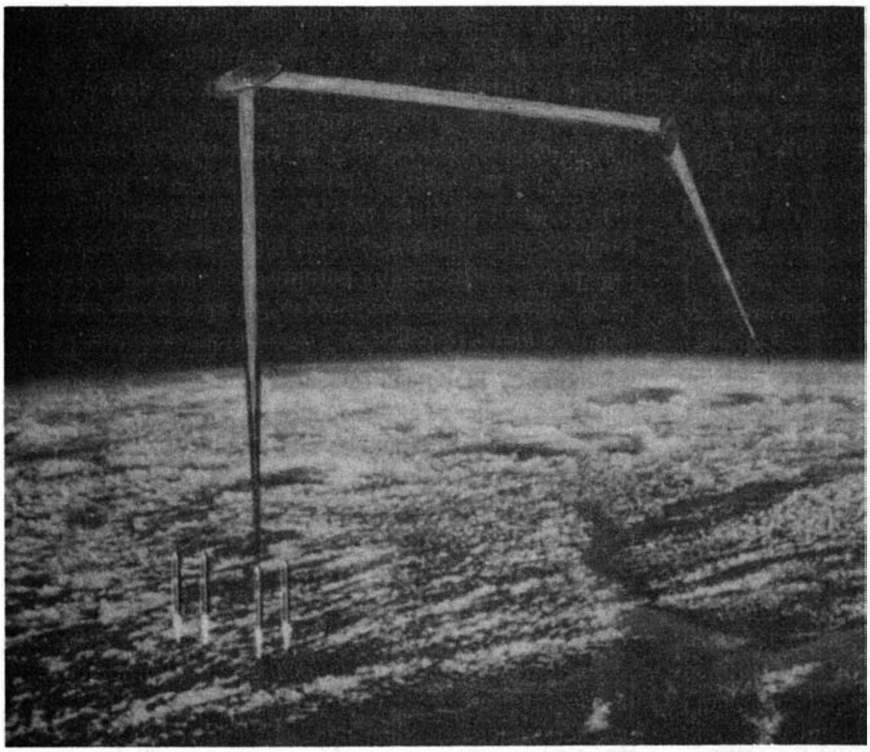
Whether the mirrors can be shared for target tracking and beam delivery during laser firing has been studied and is considered conceptually possible. One concept calls for rapid switching back and forth between the two tasks; another calls for performing the two tasks simultaneously by tracking the targets at a longer wavelength than the laser light so the laser light can be filtered out. If a shared tracker/laser optical system can be developed, additional surveillance satellites will not have to be deployed to support the laser system.

Consider now the cost exchange between a laser-style GPALS and SRBMs. As before, let us compute the "cost exchange at the margin" and the "cost exchange under combat," beginning with the former. Our two laser-style GPALS systems are designed to destroy about 228 Scuds launched nearly simultaneously from Iraq. If the threat is increased to 229 Scuds, how many additional laser components must be deployed and how much would this cost?

Consider our GBL/SBM laser system first: Recall that the power of each ground-based laser and the slew rate and mirror area of each space-based mirror is sized such that a single SBM can destroy 190 Scuds in 200 seconds. Since the constellation of 50 SBMs results in an average of 1.2 SBMs over Iraq at any instant, the total number of Scuds that can be destroyed is 1.2 times 190 or 228. To achieve its full firing rate, each space-based mirror involved in battle must be continuously linked to a ground-based laser, so at least 2 GBLs are involved in the 200-second battle. The total GBL firing time is 1.2 times 200 seconds or 240 seconds.

It should be clear that one of the techniques available for destroying more than 228 Scuds in 200 seconds is to increase the average number of space-based mirrors flying over Iraq. If 1.205 SBMs fly over Iraq instead o200, the number of Scuds that can be destroyed is 1.205 times 190 or 229, rather than 228. Again, at least 2 ground-based lasers are active during the 200-second battle. The total required GBL firing time is 1.205 times 200 seconds or 241 seconds. Clearly, to kill one additional Scud requires no increase in the number of ground-based lasers, only an increase in the number of space-based mirrors, so that on average 1.205 SBMs fly over Iraq instead of 1.200 SBMs. Since 50 SBMs in polar orbits yield 1.200 SBMs over Iraq, it follows that 50.219 SBMs in polar orbits will yield 1.205 SBMs over Iraq. This is equivalent to adding roughly two-ninths of an SBM to the original 50 for each additional Scud to be destroyed, a 2:9 "weapon exchange at the margin." Obviously, adding a fraction of an SBM to the original constellation can not be done in practice, but this is theoretically what is required to kill one additional Scud. Adding two whole space-based mirrors to the original 50 results in the ability to kill 9 additional Scuds, which is perhaps a more practical interpretation of the 2:9 weapon exchange ratio.

A review of the calculations required to compute the weapon exchange at the margin shows that it is simply the product of the absentee ratio (the ratio of the total number of



Artist's conception of a ballistic missile defense, deploying a ground-based laser and two space-based mirrors, the first as a relay mirror and the second as the mission mirror, which strikes the ballistic target in the boost phase.

SBMs in orbit to the number involved in battle) and the kill ratio (the ratio of 1 SBM to the number of targets destroyed by 1 SBM). For our scenario, the absentee ratio is 50:1.2 and the SBM to Scud kill ratio is 1:190. Therefore the weapon exchange at the margin is (50/1.2)×(1/190) or roughly 2:9.

Our 2:9 weapon exchange ratio presumes the orbits of the SBMs added to the original constellation to offset an increase in the number of deployed Scuds are similar to the orbits comprising the original constellation. In other words, the weapon exchange ratio presumes the added space-based mirrors increase the SBM coverage uniformly, on average, over the entire globe. But suppose we do not wish, or need, to increase the coverage at the higher latitudes. Since the original constellation of 50 SBMs results in 10 SBMs in range of the North and South Poles at any instant, but only 1.2 SBMs in the range of Iraq (33° latitude), can we augment the SBM constellation in such a way as to only improve the coverage in the lower latitudes? If this is possible, fewer mirrors will have to be placed in orbit to counter additional deployments of Iraqi Scuds (i.e., the constellation has a smaller absentee ratio).

As it turns out, two orthogonal rings of space-based mirrors at 600 km altitude with 10 SBMs per ring, and the rings inclined to the Equator so the SBMs never travel farther north or south than roughly 40° latitude, results in an SBM over Iraq 80% of the time. Thus, since the 50-mirror global coverage constellation provides an average of 1.2 SBMs over Iraq and the 20 SBM lower-latitude coverage constellation provides an average of 0.8 SBMs over Iraq, the total combined coverage over Iraq for these two constellations is 2 space-based mirrors.

If space-based mirrors are added to the original 50 in this way, the battle absentee ratio for the weapon exchange is 20/0.8 rather than 50/1.2, and the weapon exchange at the margin becomes (20/0.8)×(1/190) or roughly 2:15 rather than 2:9. Thus 60% fewer space-based mirrors are required to offset each additional Scud when the SBMs are deployed in lower latitude coverage orbits as compared to global coverage orbits. We shall use the 2 to 15 ratio for the calculations which follow.*

Now suppose our laser system consists of SBLs rather than GBLs and SBMs. Does anything change? The answer is no, because whether our laser system has lasers on the ground and only mirrors in space, or the entire system is space-based, we need only add 2 SBMs to our system to handle 15 additional Scuds, not 2 entire GBLs. In other words, just as is done for the ground-based laser/space-based mirror system, 15 additional SBL "shots" can be brought into the battle area simply by "turning on" existing SBLs not in use (e.g., those just out of range of Iraq) and directing their laser beams to the battle area, where the added SBMs can direct the laser beams to the Scuds. The two added SBMs

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*Our earlier calculation for the number of additional Brilliant Pebbles that must be placed in orbit to offset an increase in the number of Scuds was also optimized for the coverage of Iraq, but not in such an explicit way as done here for the SBMs. For the BP calculation we considered a constellation optimized for coverage of the Soviet Union and shrank the Soviet Union to the size of Iraq. This technique yields the smallest theoretical BP absentee ratio over Iraq, or equivalently the maximum number of BPs that can be over Iraq, on average, for a fixed number of total BPs in orbit.

increase the average coverage of Iraq from 1.200 to 1.280 SBLs/SBMs, giving the system the ability to kill 15 additional Scuds. Thus, to compute the cost exchange at the margin for both laser systems—the SBL/SBM system and the GBL/SBM system—we need to compute the ratio only for the cost of 2 SBMs to the cost of 15 Scuds.

To now compute the cost exchange at the margin, we must estimate the cost of a single SBM.

Costing out the space-based mirrors

Today's cost of the 15-year-old technology Hubble Space Telescope, including its cost overruns due to delays, is about $2 billion. Taking into account new technologies, economies of scale and mass production (recurring cost versus one-of-a-kind cost), the order of magnitude cost of a 10 meter space-based mirror unit can be reasonably set at $1 billion, including the cost to put it into orbit. Using as before $1 million for the cost of a Scud, the cost exchange at the margin between a laser-style GPALS and an Iraqi Scud force is simply the product of the weapon exchange at the margin (2:15) and the ratio of the cost of a SBM to that of a Scud ($1 billion to $1 million), or 133:1, in favor of the Scud force. (Recall that the space-based ABM to Scud cost exchange at the margin was 50:1 in favor of the Scud and the ground-based ABM to Scud cost exchange at the margin was a draw.) This result looks rather bleak for the laser system, but there are two factors still to be considered: 1) the payback to the economy a massive investment in laser technology will provide; and 2) the very amazing influence of the initial capabilities assumed for the laser system on the marginal cost exchange.

Let us address the second issue first.

Recall that we were very conservative in specifying the amount of laser energy that has to be deposited on a target to kill it. We assumed a value of 100 kJ per square centimeter, although recent research suggests only 5 kJ per square centimeter may be required for a pulsed laser such as a free electron laser. If this is the case, then the time required to kill 1 Scud is reduced by a factor of 20 and our laser system firing rate is increased by a factor of 20. Consequently, our laser system can destroy 20 times as many simultaneously launched Iraqi Scuds as we originally assumed. In other words, the laser to Scud kill ratio is now 1:3,800 rather than 1:190, meaning roughly 4,600 Scuds can be destroyed for 1.2 laser coverage over Iraq. We have reduced the time for the mirrors to re-aim by a factor of 10 for this calculation, since very little re-aiming is required with so many missiles coming from the same small area. For this laser system the weapon exchange at the margin, which is a product of the SBM absentee ratio and kill ratio is (20/0.8)×(1/3,800) or roughly 1:150; the earlier value was 2:15.

The cost exchange at the margin is now (1/150) × ($1 billion/$1 million) or 20:3 in favor of the Scud, which is roughly *eight times better* than the cost exchange at the margin for the space-based ABM-style GPALS, but still about 7 times worse than the 1:1 cost exchange at the margin for the ground-based ABM-style GPALS. However, it should be clear that by keeping the SBM absentee ratio and cost fixed (this implies keeping the design of the 10-meter mirror fixed and improving the kill ratio of the laser system in other ways—e.g., increasing the beam power or decreasing the wavelength), a laser system can be designed that *wins* the laser to Scud cost exchange at the margin outright.** The margin of victory depends on the final performance numbers selected for the laser system. For the highest performance, near-ultraviolet lasers under consideration by SDIO and reviewed by the APS, the laser to Scud cost exchange at the margin is roughly 1:4 in favor of the laser. Thus, the laser system is potentially more cost effective at the margin than the proposed ABM GPALS concepts, and also appears to offer the only chance of achieving the congressional GPALS to Scud cost exchange criteria. The laser system should, therefore, be the nation's concept of choice for any ballistic missile defense system.

A summary: laser versus antiballistic missile

To summarize at this point, we have demonstrated that both a ground-based ABM-style GPALS and a laser-style GPALS can achieve a roughly even current dollar cost exchange at the margin against Iraqi Scuds, although only the laser system GPALS has the potential for eventually winning the cost exchange. The proposed GPALS space-based ABM system has by far the worst cost exchange at the margin—roughly 50:1 in favor of the Scud. In addition, the proposed GPALS space-based ABM system can kill only 10 simultaneously launched Iraqi Scuds; the proposed GPALS ground-based ABM system can kill 300 to 500 Scuds if all the 1,000 ABMs are based in the Scud target area; our proposed GPALS laser system can kill over 4,500 simultaneously launched Iraqi Scuds.

The proposed GPALS ABM system cannot defend the U.S. against an all-out Soviet attack; our proposed GPALS laser system can do so with ease (the Soviets have a total of about 3,000 missiles of all types: intercontinental, intermediate-range, short-range, and submarine-launched ballistic missiles. The GPALS ABM system requires a surveillance support system, as does the GPALS laser system, but the GPALS laser system has a portion of this surveillance system provided for "free," as its mirrors can be used for the surveillance system telescopes. The resolving power of these mirrors is probably 5 to 10 times better than that proposed for the ABM surveillance support system.

**Increasing beam power or decreasing wavelength may require alterations in the mirror design. For example, higher beam powers require a smoother mirror surface. The percentage change in the cost of the mirror is expected to be much less than the percentage change in beam power or wavelength. For example, mirror cooling for power densities 100 times greater than that of our laser system have been demonstrated. Incorporating this cooling capacity in our mirror design would not substantially change its $1 billion cost.

The ABM system adds very little new technology to the U.S. economy; the laser system adds high-energy free electron laser technology to the U.S. economy and mass-produced, large-scale optics. Together these technologies can fundamentally transform our nation's economy in areas as diverse as basic physics and astronomy, medicine, industrial processes, biology and chemistry—they all stand to gain in countless ways. In this sense, a laser-based ballistic missile defense system is cost free, as it can vastly improve the standard of living and quality of life in the years ahead. Developing an ABM-style ballistic missile defense that is based on old and current technology has the opposite effect—it only makes us poorer. If the payback of laser systems alone to the economy is factored into their cost exchange at the margin ratios, they outperform ABM systems by powers of 10; in fact, the cost exchange may not be just extremely small, it could be negative!

The fact that only the laser-style GPALS has the potential to win the congressional test of being cost effective at the margin (even taking no account of the economic payback factor) and the fact that it is so superior to the proposed ABM GPALS system in so many other ways demonstrate in the starkest possible terms the incompetence of the policymakers in Washington. Considering the laser system's cost exchange under combat confirms this even further.

Lasers cost exchange under combat

We said earlier that if a cost exchange criteria has to be used, the "cost exchange under combat" is the best to use since it measures to some degree the "defense in depth" of a nation relative to its adversaries. Essentially, the cost exchange under combat is the ratio of the cost to replace each side's expended firepower or "ammunition." The "ammunition" of a BMD may be an ABM or a pulse of energy converted to laser light; the "ammunition" of an offensive missile force is its missiles. Recall that the ABM-style GPALS versus the Iraqi Scud cost exchange under combat is roughly a draw (1:1). Is this also the case for a laser-style ballistic missile defense?

The cost exchange under combat for a laser-style BMD against a Scud force is simply the cost of one or two laser shots in order kill a single Scud divided by the cost of a Scud. The energy in a single laser shot is roughly 5 kJ per square centimeter times the cross-sectional area of the beam at the target (a 22 cm diameter circle), or about 2 MJ. The efficiency of transforming prime electrical power to free electron laser beam power is conservatively estimated to be on the order of 10%, so 20 MJ of electrical input energy is required to kill one Scud. If the lasers are based on the ground, the electrical input energy can be supplied by commercial power plants. The cost of electricity in the U.S. is on the order of 3¢ per megajoule. Therefore, a ground-based laser-style BMD can kill a $1 million Scud with a pulse of electrical energy costing about 60¢! In other words, the GBL-style GPALS versus Iraqi Scud cost exchange under combat is on the order of 1:1 million in favor of the ground-based lasers. Even order of magnitude errors in our GBL system assumptions can not alter the clear message here.

If the lasers are based in space, the electrical input energy can be supplied by a space-based combustion turbine-generator system burning hydrogen and oxygen. Assuming conservatively a 20% heat-to-electricity conversion efficiency, 1 kg of fuel can supply 20 MJ of electrical energy, which is the electrical input energy required to kill one Scud. If the exhaust water of the combustion turbine is not recycled (collected and electrolyzed back to hydrogen and oxygen using solar energy), the cost to replenish 1 kg of fuel is dominated by the cost to lift it into orbit, which is roughly $11,000. Thus a space-based laser-style ballistic missile defense can kill a $1 million Scud with a pulse of electricity costing about $10,000. The SBL-style GPALS versus the Iraqi Scud cost exchange under combat is therefore on the order of 1:100, again in favor of the laser system GPALS. If the battle scenario permits expended fuel to be replenished over an extended period of time, the combustion turbine exhaust water can be collected and electrolyzed back to hydrogen and oxygen using solar energy. The cost to replenish expended fuel is now essentially free, and the SBL-style GPALS versus the Iraqi Scud cost exchange under combat is now essentially zero, meaning Scuds can be killed free of charge! (This argument can also be made for the ground-based laser system.)

We have demonstrated that the cost exchange between a laser-style GPALS and Iraqi Scud force is either comparable to, or at least a million times better than, the cost exchange between an ABM-style GPALS and the Iraqi Scud force, depending on the definition of cost exchange that is used. The laser-style GPALS also offers greater future gains in the cost exchange as the requisite technologies evolve; ABM systems are already near the point of diminishing returns. It is also generally well known that the new technologies represented by high-energy lasers can totally transform the U.S. economy for the better, just as the internal combustion engine and electricity transformed previous U.S. economies. Given the clear superiority of lasers over antiballistic missiles for ballistic missile defense, we return to the question we implied at the outset of this analysis, "Why has President Bush adopted a BMD policy that advocates ABMs over systems based on new physical principles such as lasers, a total reversal of SDI's original intent?"

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