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Laser Brightness Verification

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Limits on the brightness of ground-based lasers appear to be straightforward to define and, at high power and with cooperation, to monitor for verification of possible arms-control treaties. We suggest using potential brightness defined as (beam power)·(beam diameter)^2/π·(wavelength)^2 as the appropriate parameter to limit. Actual brightness is quite dependent on atmospheric conditions. The complexities of on-site monitoring and space-based lasers are discussed.

ONE CLASS of directed-energy weapon under development for attacking strategic missiles and military satellites in flight involves bright lasers beamed from earth to space or space to space. As is the case for other directed-energy weapons, lasers designed to intercept missiles or warheads can be used in principle during any phase of trajectory: boost, coasting, or re-entry. Ground-based lasers can be used directly for the terminal phase and indirectly, with space-based mirrors, to reach earlier portions of the launch trajectory. In both cases, the beam would have to be directed through part of the earth's atmosphere, which would result in significant and variable attenuation and defocusing. Although space-based lasers would not suffer such atmospheric losses, the development of these systems could involve some testing in or through the atmosphere.

Proposals have been made for a treaty to curtail development and testing of bright lasers above some threshold power below the brightness required for ballistic-missile defenses (BMD) and antisatellite (ASAT) uses.[1] In order to

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assess technological and procedural capabilities for verification of laser brightness, we first define brightness and then examine the factors that affect its role as a measure of laser-weapon capabilities. We discuss the characteristics of sources of laser light and evaluate the technology and the complexities associated with the monitoring of laser beams.

It is assumed for the purposes of this analysis that quantitative limits on laser-beam brightness could be negotiated, that in-country monitoring supplemented by on-site inspection could be utilized for verification, and that other information from national technical means (NTM) and perhaps prelaunch satellite inspection would be available. We assume, however, that inspection of large lasers closely enough to fully disclose details of their technology would be considered unacceptably intrusive.

We believe that, in the near term, space-based surveillance and other NTM and human intelligence sources are not sufficient by themselves to give confidence in threshold limits. For example, satellite optical surveillance of test sites could be blocked by clouds. Although clouds would also complicate tests of phase-compensation schemes and of general problems of beam transport, useful tests could be carried out below cloud level, where most of the transport problems occur.

In order to minimize the number of facilities that would be subject to continuous monitoring, certain protocols would have to be developed in a treaty. We assume that all facilities that could produce laser beams above a high-level power threshold averaged over 1 second would be banned. Military research and development facilities that have laser power levels above a negotiated lower threshold would have monitoring stations installed nearby.

There would also have to be provision for challenge inspection of undeclared facilities that are large enough to contain high-powered lasers. In some cases, if it were impossible to agree on a thorough internal inspection of the facility, monitoring stations could be put in place around it at the request of the inspecting party.

LASER BRIGHTNESS

We believe the key variable for control of lasers as weapons is brightness B, which in this article is defined to be $PD^2/(\pi\lambda^2)$ where P is the power of a laser, D is the diameter of the beam at or near the source, and λ is the wavelength of the emitted radiation.* We will use SI units, in which case brightness is in watts per steradian. As will be made clear later, B is potential brightness rather than actual brightness. The latter can vary from point to point across a beam and is greatly complicated by effects of the atmosphere.

Potential brightness could best be monitored by permanent stations placed within about 1 kilometer of sites where large lasers are tested in the atmosphere. As will be seen below, brightness limits of the order of 10^{21} watts per steradian would prevent applications to long-range (> 1,000 kilometers) destruction of missiles. Much more restrictive limits would be needed to prevent their threatening satellites.

A conceivable drawback to using potential brightness as a limit is the possibility that some peaceful application of powerful lasers might be developed that did not require complete coherence. In this fairly remote circumstance it might be desirable to negotiate an exemption.

Damage Caused by Laser Beams

Lasers are of interest for ballistic-missile defenses (BMD) primarily because they offer the possibility of producing beams of electromagnetic radiation with enough power density to be damaging to missiles 1,000 kilometers or more from the source.

Damage is dependent on the energy density that can be delivered in a short time Δt. Tens of seconds will work. One tenth of a second is roughly the optimum: longer times permit significant cooling hence require more energy (but less power); shorter times would require extreme power densities, which might degrade the beam propagation or damage the laser.[2] The integrated energy fluence F in J m^{-2} that can be produced by a laser of power P, using a

* It has been pointed out to us by R.L. Garwin that this formula would lead to an underestimate of the fluence in the important central area of the spot in the focal plane by a factor of $\pi^2/4$ in cases of ideal propagation. We agree with Garwin, but in view of the fact that the APS report has become a standard reference and that this formula gives an approximate *average* brightness out to the first diffraction-limited null, we think that the APS definition is an acceptable (if arbitrary) basis for a treaty definition of potential brightness. See *APS Study* (reference 2).

mirror of diameter D to focus radiation on a target a distance R_T away, is limited by diffraction to approximately[3]

$$F = \frac{P \Delta t D^2}{\pi R_T^2 \lambda^2} \qquad (1)$$

Using the expression for brightness given earlier, we see

$$F = \frac{\Delta t}{R_T^2} B \qquad (2)$$

Since Δt and R_T^2 are usually constrained by the target, B becomes the most important free parameter determining a laser's ability to inflict damage. For concreteness, if $\Delta t = 0.1$ seconds, and we take the fluence necessary to destroy hardened targets to be 10–1,000 MJ m^{-2}* and the target distance to be 1,000 kilometers, we get B to be 10^{20}–10^{22} watts per steradian.

It should be noted that $B\Delta t$ would be a reasonable quantity to limit. It is probably what would be measured by a monitor in any case, since Δt is a relatively easy quantity to measure. The distinction is not great.

The wavelength of the laser is also important. Atmospheric transmission (see figure 1) probably limits it to greater than 0.4 microns for ground-based lasers. The difficulty of finding suitable reflectors probably limits it to greater than 0.2 microns even in space. Since the spot size goes as λ^2/D^2, the difficulty of deploying very large mirrors limits the largest wavelengths that could be considered. Thus 20 microns appears to be about the upper limit.[4]

For our purposes we will take the diameter D to be that of the beam at the point where it starts upward. There could be circumstances where the diameter of the space mirror is more important, but for the rough calculations we are doing the difference is not of major significance.

* For illustration, 100 MJ m^{-2} will melt a 1-millimeter aluminum plate even if it reflects 99 percent of the incident radiation, provided that the radiation is delivered in less than 1 second. See the APS study (reference 2).

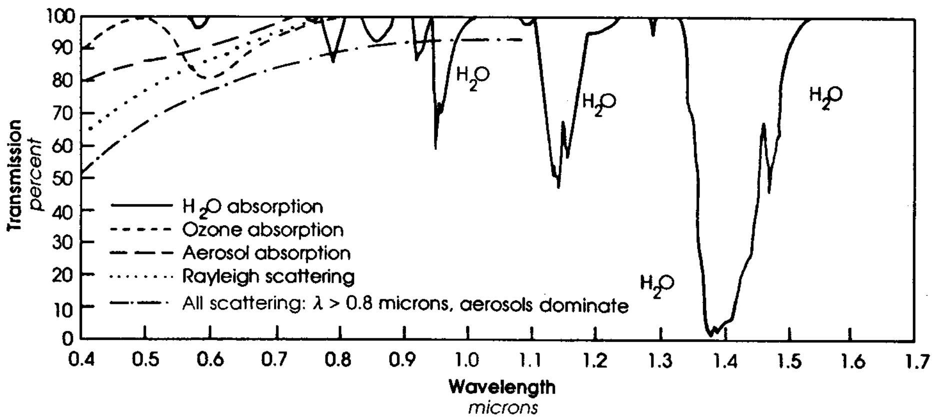

Figure 1: Atmospheric transmission under typical clear conditions of constituents as a function of wavelength

Source: APS Study Group, *Reviews of Modern Physics*, **59**, p.S1 (1987)

Brightness Limits

From the above calculations it appears that a brightness cap of around 10^{21} watts per steradian would constrain use of ground-based lasers for damaging hardened missiles at distances greater than 1,000 kilometers in a time of 0.1 seconds. If it were decided to limit the use of lasers for discrimination between decoys and warheads, a level lower by at least 100 times would probably be necessary, since the ablation needed for discrimination by recoil is much smaller than that necessary to produce damage.

Satellites are more vulnerable than ballistic missiles, however, and could be attacked from the ground at distances as low as 150 kilometers. The hardness of satellites is probably at least a factor of 10 lower than that of missiles.* If we take a hardness of 10 MJ m^{-2}, then the maximum allowed brightness would be roughly 10^{18} watts per steradian for pulsed ground-based lasers. Another ASAT strategy is long (100 seconds) irradiation at lower power that could overheat the whole satellite. Such long irradiations might be

* Satellites may have special vulnerabilities. We do not believe, however, that they are easy to blind by beams directed along their optical axes, because these axes are not very easy to observe and are unpredictable.

practical because satellite trajectories are highly predictable and the satellites are far apart. To limit this option an upper bound of 10^{16} watts per steradian for the brightness would be needed for continuous-wave (CW) lasers and 10^{18} watts per steradian for pulsed lasers. For space-based lasers no meaningful limits can be set, unless these lasers could somehow be prohibited from arbitrarily close approaches to satellites.

The parameters entering in the calculations of the limits we have suggested are poorly defined in the published literature. This is particularly true for hardness. Our limits are therefore very approximate. We have, however, tried to make our suggestions for monitoring robust enough to tolerate large variance in such limits.

Phase Compensation

The atmosphere can be a poor transport medium for coherent light beams.[5] To be of practical size, ground-based lasers designed to attack objects in space would probably need adaptive optics, which have been developed in the last 10 years for phase compensation. The details are complex, but for our purposes the important facts are the following: to compensate for phase distortions in the atmosphere, a probe beam is needed that traces the beam path backwards through the atmosphere every few milliseconds and determines the effect of atmosphere distortions on the beam phase. The source of this probe beam could be something as simple as reflections of a sodium laser beam off the layer of very-low-pressure sodium vapor in the upper atmosphere[6] or as complex as a satellite-based laser near one of the battle mirrors. As a result of these adjustments to the beam at its source on the ground, the killing beam would have a very complex phase structure. From point to point in a plane normal to the beam the relative phase will not be uniform but will vary by a significant fraction of a radian about every 10 centimeters and about every 10 milliseconds. It is clear that the higher the power of the laser, the more likely it is to use phase compensation—because of thermal blooming,[7] which rises with fluence as an important source of atmospheric irregularity, and because the cost of a compensation system would be a small fraction of the total cost of a high-power laser facility.

Laser Power Requirements

We have estimated the required brightness of a BMD laser as 10^{20}–10^{22} watts per steradian for an illumination time of 0.1 seconds. If the opposing side made minimal efforts to harden its most vulnerable missiles, this range might become 10^{21}–10^{22} watts per steradian. Taking $3{\cdot}10^{21}$ for illustrative purposes, and assuming λ is 1 micron and D is 3 meters, we find a power requirement for a phase-compensated laser of 10^9 watts and an energy requirement of 10^8 joules. For comparison, the large Nova lasers at the Lawrence Livermore Laboratory, used for inertial confinement fusion experiments, produced about 10^4 joules. The power and energy requirements for BMD lasers are considerably beyond the capabilities of any machines of which we are aware, and will in all probability require physically large lasers with large energy-storage capability that would occupy several thousand cubic meters in a building, and for BMD test purposes would need an access to the sky more than 10 square meters in area.

From the history of laser development we conclude that lasers of the capability just mentioned can probably be developed within a few years. The most interesting type perhaps is the free-electron laser (FEL), because it promises high efficiency and a beam of controllable wavelength. It is not clear, however, whether it would be practicable to put a high-power FEL in a space vehicle.

MONITORING LASER BEAMS

Ground-Based BMD Lasers

We believe the most practical method of ground-station monitoring of open beams is to look at the beam radiation scattered by the aerosols normally present in the atmosphere. The scattered radiation would reveal the power in the beam and, if necessary, give the beam diameter and the wavelength. The potential brightness is easily calculated from these parameters. The alternative—direct sampling of the beam—would pose problems of intrusiveness, safety, and sampling accuracy. Inspection of the laser itself might be too intrusive.

We will assume that a monitor can be placed within a kilometer or so of

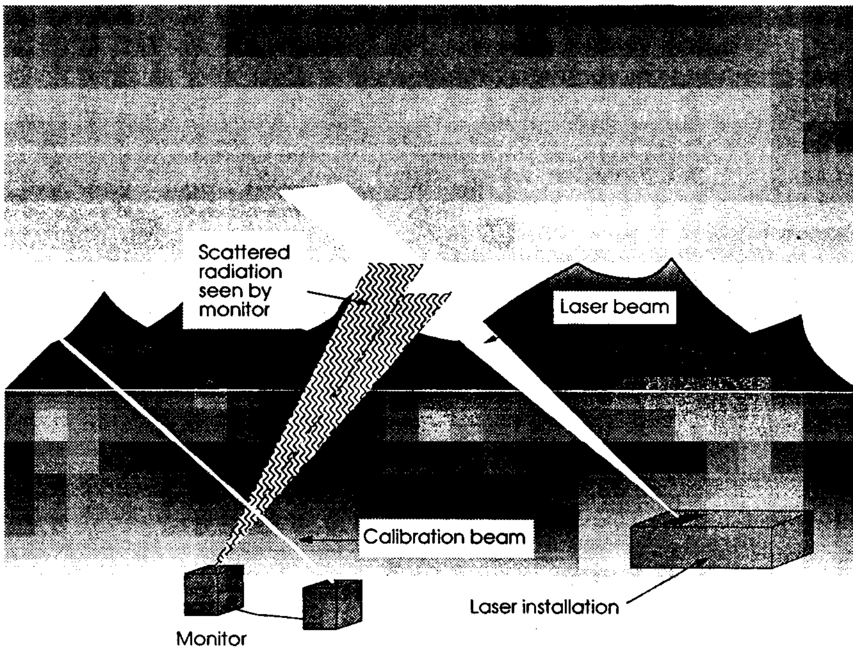

Figure 2: Sketch of a possible monitoring arrangement near a large laser facility

the beam and can observe it against some reasonable background such as the sky (figure 2). The angle of observation is not very important, but should probably be between 55° and 180° to the beam. It will be assumed that the wavelength, direction, and time of operation are not disclosed by the facility operator. This is a worst-case assumption and somewhat implausible given the assumption that the host country is cooperative enough to allow a permanent, probably manned, monitoring station near its large laser facility. However, as shown below, the costs of not knowing the wavelength or exact beam direction and width are not terribly high.

We believe it is straightforward but not trivial to measure the power of the beam by measuring the light scattered, largely from aerosols as the beam travels through air. To show that this is quantitatively reasonable we first take as an example the beam from the laser mentioned above. That laser had a brightness of $3{\cdot}10^{21}$ watts per steradian, a power of 10^9 watts, and an energy of 10^8 joules. Call S the fraction of the energy of the beam that is scattered into 1 steradian in passing through 1 meter of air. This fraction is dependent on the scattering angle, but within the range we are considering, 55° to 180°, the variation is generally less than a factor of two, and for simplicity in this calculation of feasibility we will treat it as constant.[8] The power density of the scattered radiation from this meter of beam length at the monitor position thus becomes

$$I_{MB} = \frac{P_B S}{R^2} \qquad (3)$$

where P_B is the power in the laser beam and R is the distance from the laser beam to the monitor. A reasonable minimum estimate[9] of S is 10^{-7}. Taking the area of the monitor lens as 10^{-3} square meters, one would then get a signal of 10^{-7} watts at 1 kilometer from the beam, or $6 \cdot 10^{11}$ photons per second of 1-micron wavelength. This is an easily detectable amount if the background is low.

What is the background? The biggest potential source is scattered sunlight. We approximate the scattering of sunlight by assuming S to be the same as that of the laser beam. Then the scattered sunlight per cubic meter of air is $I_N S$, where I_N is the power density of sunlight in W m^{-2}. The amount reaching the position of the monitor would then be $I_N S/r^2$ where r is the distance from the cubic meter of air to the monitor. The background then will be given by integrating this through a cone of solid angle Ω with apex at the monitor and extending to the top of the atmosphere. The appropriate Ω is the angle subtended at the monitor by the beam, of width w, taking the length as 1 meter since this whole calculation is done for 1 meter of beam length. Thus $\Omega = w/R^2$. Since the integration through the actual atmosphere of varying density gets rather messy it is useful and conservative (because scattering per gram of air generally decreases with altitude) to use an equal-mass constant-density atmosphere model. We then get for the power density of the scattered sunlight at the monitor position

$$I_{MS} = I_N S \Omega L = \frac{I_N S w L}{R^2} \tag{4}$$

Here L is the distance along the line of sight of the monitor to the top of the atmosphere. If the monitor were looking straight up, L would be 8 kilometers. A more reasonable guess at the angle, 20° above horizontal, would give an L of 23 kilometers. The ratio of the signal from the beam and that from the scattered sunlight is then

$$\frac{I_{MB}}{I_{MS}} = \frac{P_B}{I_N w L} \tag{5}$$

For the reference laser w = 3 meters, and taking I_N as 1,300 W m^{-2}, the ratio for L = 23 kilometers is 11—which seems ample. However there are, of course, several complications. First we have implicitly assumed that the sunlight is scattered at more than 45°. If one is looking more directly at the sun the background could rise considerably. Also there could be brightly lit clouds in the background. Most important, we are interested in monitoring lasers of much less power than 10^9 watts. Therefore we discuss in the following sections methods of enhancing signal-to-background ratio.

The worst-case situation for monitoring purposes would be an ASAT laser, because of the relatively lower power required for this mission. We consider the cases of both a pulsed laser and a continuous laser.

Pulsed Lasers

Assume in this case that neither the wavelength nor the beam direction is known, and the ASAT laser's brightness and power are about 10^{-3} of those considered for the BMD laser. Here it will be necessary that the detector be a two-dimensional array of roughly 200 × 200 sensitive elements. One direction will be used to scan the region of the beam for about 50w meters. The other direction will be a scan in wavelength achieved by a dispersing element, perhaps simply a prism. The wavelength range covered should be as narrow as it can be and still be sure to encompass the laser wavelength, in order to maximize dispersion. If there is literally nothing known of the wavelength, several arrays may be needed: it is undesirable to cover more than a 2-to-1 ratio of wavelengths in one array, as this will adversely affect the signal-to-background ratio.

The signal associated with detection of a laser pulse consists of high output from the elements that span the width of the beam in the row corresponding to the laser wavelength. The background is given automatically by the adjacent elements at nearby wavelengths. For this one could take sets of elements at the same place in the position scan as the laser signal but at a wavelength on each side of the laser's wavelength, and interpolate to the laser wavelength (figure 3). The combination of dispersal in wavelength and careful background subtraction should enhance the signal-to-background by a factor of thousands—enough to offset the factor of 10^{-3} reduction in signal intensity going from a BMD-capable to an ASAT-capable laser. The apparatus required to do the electronic analysis is fairly similar to existing optical multichannel analyzers.[10]

Continuous Lasers

As noted above, in ASAT mode, a possible tactic is to use a laser of lower power than is needed for a pulsed irradiation and keep it on the target for 10 seconds or more. This tactic is available because even a low-altitude satellite would be in sight for that length of time, and there would probably be no competing targets. In this case, flux rather than fluence is the appropriate parameter, and we estimate a flux equal to the black-body radiation from a surface at the melting point of aluminum (about 200 kW m^{-2}) would be a possible limit. This would correspond to a brightness of 10^{16} watts per steradian, a power of 100 kilowatts (assuming a 3-meter mirror and 10-micron wavelength),* and a satellite distance of 200 kilometers. Using the methods given above, this would in turn give a scattered beam in clear air (100-kilometer visibility) of $3{\cdot}10^{-3}$ W m^{-2} scattered radiation. The infrared background from the ground at 10 microns (the worst case) would be about 10 W

* This assumes that the spot can be held to about 1 meter (or 1 arcsecond pointing accuracy) on the satellite. This is not a trivial task but is within atmospheric turbulence limits.

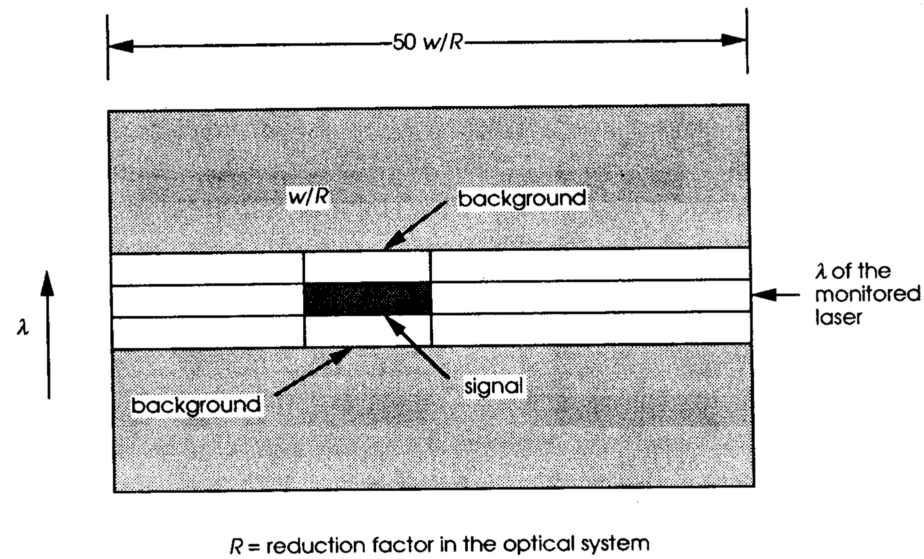

Figure 3: System for enhancing signal-to-background ratio for measurements on medium-power lasers

m^{-2} for a 10-micron band. Clearly a very narrow wavelength selection would be needed to detect the scattered laser light, and the monitor should not look at the ground. Radiation from clouds, however, can be comparable, and they may be hard to avoid (although heavy cloud cover is apt to discourage operations of the monitored laser).

If the wavelength were known within a few percent, the two-dimensional scan of figure 3 combined with a high-resolution dispersing instrument—a grating, for example—that matched the display might permit detection but this is not guaranteed. Another tactic that might be useful would be to take advantage of the long time of operation to use very-high-resolution Fourier-transform spectroscopy.[11] This could give wavelength resolution as high as 1 part in 10^5, with corresponding background suppression. The background is given accurately by this technique also, and can be subtracted to exhibit the signal. There will probably be a loss of position discrimination however, and this will cost a factor of the order of 30 in signal-to-background ratio.

While the two suggested techniques have been available for some time, we are proposing uses that will very possibly be near their limits. It would obviously be necessary to have tests in realistic situations to demonstrate their feasibility.

In intermediate cases, less heroic measures should do. For example, if one knows the wavelength of the laser to be monitored, a custom-made interference filter with a transmission band width of 10^{-3} microns may suffice. Such filters are considerably cheaper and simpler to use than the other apparatus we have discussed in this section.

Another advantageous relaxation of our worst-case assumptions would be to station the monitor about 50 meters from the laser's directing mirror so that it would look along the beam at an angle of say 175° to the beam. This would gain in two ways: first, the signal-to-background ratio would be much better, and second, the calibration beam could be shone along a path in nearly the same air as the monitored beam. Also, for monitoring CW lasers, we may have considerably underestimated the hardness of satellites, especially those yet to be put into orbit. For example, the long irradiation periods we have been discussing allow time for the satellite to react, turning its least vulnerable side to the laser.

Calibration of the Monitors

Since scattering is essentially all due to aerosols, which vary highly from hour to hour, it would be necessary to calibrate this scattering near the time of observation of the beam. This can be done by observing the scattering from a low-power (about 1 watt) laser beam a meter or two away from the detector and directed at the same angle to the monitor's line of sight as the beam from the large laser. To detect this modest scattered radiation from a low-power laser, the laser must be run for perhaps a minute, and to suppress background a narrow filter must be used. This is simple because the wavelength of the calibrating laser is known well. The measurement will be useful even if the wavelength is different from that of the large laser being monitored, because aerosol scattering is not strongly wavelength dependent in general.[12] (There are, however, regions [for example, around 10 microns] where there is a strong dependence, and serious efforts must be made to match the wavelength within 1 percent or so to get even 10-percent accuracy.)

It will be necessary to know or measure the width w of the beam being monitored and to know its distance from the monitor. We assume the latter will be obvious from the installation of the monitor. The angular width of the beam can be measured by the monitor, but it requires at least a one-dimensional scan—which could well be necessary anyway. The angular width and the distance, of course, determine w. It is also straightforward to measure the pulse duration in simple cases. In the worst case, in which there is a pulsed, moderate-powered laser, as discussed above, there would be complications if the time of firing were not announced. This would require the stored data from the array to be erased approximately every 0.01 seconds if no laser pulse were detected. If one was, the next $0.01n$ seconds of data from the portion of the array near the laser signal would have to be stored, and the pulse length measured this way. None of this is a heavy strain on modern data handling methods, but it is an expense and must be considered.

Since the calibration beam is assumed to be as much as a kilometer away from the monitored beam, it would be desirable to check the relative scattering in the relevant volumes of air with a lidar (radar using light instead of radio waves) beam. Again, this is nearly an off-the-shelf technology, but its use would represent an increase in cost and complexity. The use of lidar would probably be required only if the monitoring had to be done during a moderate dust storm. (A severe storm would very probably shut down the monitored laser.)

A possible complication in this scheme is that a high-power laser might cause some of the scattering aerosols to evaporate, thus giving less scattering than a low-power beam. This point should be studied. If it proves significant, one remedy might be to focus the calibrating beam to a sharp point and look at the scattering from there. A 1-watt laser can give a power density at its focal point of 100 GW m^{-2}. By changing the focus, one could adjust the laser to match the beam of the monitored laser in power density. Pulse length might also have to be matched. This whole problem may not be very important in the low-humidity weather at desert sites that would be favored for ground-based laser weapons, because the aerosols would presumably not be volatile.

Monitor Installation and Operation

The in-country monitoring equipment need not be placed just next to a laser facility, but it should be within a few kilometers. It should operate in a "staring" mode, that is always sensitive to laser bursts, and it should not be limited to being only directed towards declared facilities. It will need a small calibrating beam within a few meters of the monitor. The equipment needed for the complete station consists essentially of off-the-shelf items. No major development program is needed.

Conceivably such a station could be unattended, operating passively with satellite link-up to transmit data to all treaty parties.[13] Supplementary verification could be achieved by on-site inspection during maintenance visits to the monitoring station. Here is a case where the host country might be willing to contribute to the cost of on-site monitoring in order to carry out legitimate laser tests that fall between treaty-limited brightness levels and a lower threshold that requires no monitoring. However, unattended stations might be vulnerable to simple forms of cheating such as smoke screens and other methods of interrupting the path from the beam to the monitoring station. NTM might not serve to deter these forms of deception because some tests could be conducted under cloud cover. Supplementary instruments and procedures need to be considered to counter deception scenarios of significance.

As a confidence-building measure, the verification potential of ground-based laser brightness measurements could be evaluated in demonstration experiments with off-the-shelf equipment.

Space-based Lasers

Space-based lasers clearly pose very difficult monitoring problems. The most severe is that one must have a space vehicle that can get within a few kilometers of the laser to be monitored. Given that, there is a possibility that one could monitor the laser.

We will take the situation at 200 kilometers altitude for illustration. Here the number of molecules per cubic meter N_m is $7.1 \cdot 10^{15}$ and the scattering

Table 1: High-energy lasers in the open literature

Developer	Brightness *watts per steradian*	Power *megawatts*	Type	Date operated
USAF Kirtland AFB[1]		~0.2	CO_2	~1972
Avco Everett Research Laboratory[1,2]		0.04	CO_2	1975
Rocketdyne (Rockwell International)[1]		0.1	Rocketdyne Advanced Chemical Laser (RACHL)	1977
USN and TRW[1]		0.4	deuterium fluoride (Mid Infrared Advanced Chemical Laser—MIRACL)	1978
USN and Hughes Aircraft[1,2]			Navy ARPA Chemical Laser (NACL)	~1978
USAF Airborne Laser Laboratory[1,3]	10^{15}		CO_2 (gasdynamic)	1981
USN and DARPA[4,3]	10^{13}		submarine communication: XeCl, HgBr	1983
SDIO and TRW[1,5,3]	10^{17}	2.2	deuterium fluoride (MIRACL)	1986
DoE (Lawrence Livermore)[6]	15kJ 2 ns pulse		Nova (inertial confinement fusion) neodymium glass	1986
DARPA and TRW[3,7]	10^{18} (planned)	5	Alpha-HF	1989
USAF Kirtland AFB[8]		0.010	COIL (chemical oxygen iodine), 1.35 microns; upshifted to 0.657 microns in a lithium iodate crystal	1989
DoE, Los Alamos[9]	1.3 kJ in ~5 ns		KrF (inertial confinement fusion) 1.05 microns	1989
SDIO, Boeing, Los Alamos[10]		0.002 average 10 peak	Free electron laser (FEL)	1990

Table 1 *continued*

Developer	Brightness *watts per steradian*	Power *megawatts*	Type	Date operated
USSR (Sary Shagan)[11]		0.02	CO_2	~1982
USSR (Dushanbe)[3]	~10^{17}?			?
USSR (Kurchatov Institute, Troisk)[12]		1	CO_2 (inertial confinement fusion)	1989

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cross section is roughly $3 \cdot 10^{-32}$ square meters per molecule.* A laser pulse of 10^8 joules would give about $2 \cdot 10^{14}$ scattered photons per kilometer of track. To an observer at 3 kilometers with a 1-square-meter detector this would give $2 \cdot 10^6$ photons. A 10-meter × 1-kilometer track would occupy 10^{-3} steradians, and the starlight in such a solid angle arriving at 1 square meter would be roughly 10^{10} photons in 0.1 seconds. This would clearly require a filter giving a discrimination of about 10^4 against any wavelength but the laser's. So if both the wavelength and the beam direction were known, one would have a reasonable chance of measuring brightness with useful accuracy.

The severe requirements of this measurement, plus the fact that at perhaps another 50 kilometers of altitude the measurement becomes nearly impossible, make this altogether an unattractive option. Inspection of the launch package on the ground is a possible method of controlling sizes and weights of space lasers, but given the rapid changes in technology it would be necessary to leave a considerable margin for error in setting such limits. One could, for example, set quite small limits, say 100 kilograms for weight, and take up the cases individually if someone comes up with an important peaceful application requiring a larger laser. We are not aware of any such application.

Other Constraints on ASAT-mode Lasers

Control of antisatellite weapons by prohibition of tests of these weapons in space has been proposed by Durch and Garwin.[14] We agree that development of laser ASAT and BMD weapons would be discouraged, if not stopped, by prohibition of testing that involved directing a beam of significant power at a satellite from a ground-based laser or indeed from a space-based laser. Such testing could, in principle, be monitored by detecting the scattering of the beam off the satellite. This monitoring could well have a seriously inhibiting effect on such tests because it would be very hard to be sure the opposing side did not have a satellite in position to observe the scattered pulse. Old-fashioned intelligence methods might provide cues as to where and when to look.

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* The scattering cross section may be obtained by setting the index of refraction n equal to $1 + (0.159\ \lambda^2 N_m b)$, where b is the scattering amplitude, $2\pi b^2$ is the scattering cross section and the index of refraction at 1 micron at ground level is known to be $n = 1 + 2.67 \cdot 10^{-4}$.

Tests at very-low-brightness levels with a cooperative satellite could probably be concealed, but there would be serious questions as to how realistic they were. It would be hard to be sure the focal properties of the laser system would not be affected by a change of a factor of 10^6 or more in beam power.

Another constraint on ASAT (or BMD) use of lasers is to restrict the construction of large lasers to regions with more than average cloud cover. No rational government would make such an investment in weapons that could be useless for weeks at arbitrary times.[15]

CONCLUSIONS

High-intensity lasers beamed through the atmosphere from known locations constitute a technology that could be subject to agreed limitation. Our purpose has been to explore the verifiability of such limitations, primarily by in-country monitoring. Although the actual brightness would be difficult to measure directly, we can determine with ground-based equipment the potential brightness. Since this represents an upper bound to the energy density deliverable by the laser, it would be an appropriate quantity to limit.

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