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Plan For A

LASER WEAPON VERIFICATION RESEARCH PROGRAM

T. J. Karr

1 March 1990
(Revised)

Lawrence Livermore National Laboratory

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PLAN FOR A

LASER WEAPON VERIFICATION RESEARCH PROGRAM

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1 March 1990
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PLAN FOR A LASER WEAPON VERIFICATION RESEARCH PROGRAM

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Lawrence Livermore National Laboratory
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SUMMARY

Future treaties governing laser weapons may include limitations on total laser power, energy or brightness. Verification of such limitations presents many technical challenges. Although verification may rely heavily on national technical means, it would benefit greatly from cooperative monitoring on the territory of the parties. Our preliminary analysis suggests that it is feasible to build a laser monitor which detects all optical and infrared lasers, with sensitivity sufficient to verify weapon-level laser power and energy at long range by direct line-of-sight scattering from the air or the target and probably also at very long range by over-the-horizon scattering.

We recommend a three-year research program to resolve the technical uncertainties of cooperative laser verification. In year 1 a first-generation laser sensor package will be designed and built. Demonstration of this sensor will be a major milestone of year 1, and continuation of the program will be contingent on its success. In year 2 this sensor will be field tested for an extended period, to demonstrate that it can detect weapon-level laser power/energy and can discriminate laser events from natural background and man-made non-laser events. There will be time to conduct some field testing on foreign territory in year 2; such testing would be very valuable if it can be arranged. Also in year 2 a second-generation sensor package will be built, with improvements in technology. In year 3 the second-generation sensor will be field tested. Each year the utility of cooperative laser verification will be evaluated in the light of our technical progress and in the context of other arms limitations and other means of verification. Test results and evaluations will be reported unclassified to the maximum extent possible. If the field demonstrations are successful, at the end of year 3 the laser weapon verification technology would be ready for engineering into a monitoring system for actual treaty verification, should this be required. The cost of this program is approximately \$2 million in the first year and \$8 million over three years.

We recommend this research program be conducted through the National Laboratories, with the work to be shared as follows. The program divides naturally into three tasks: (1) sensor modeling, development, operation and data analysis, (2) extended field testing, and (3) Red Team/Blue Team assessment and evaluation of cooperative monitoring. Lawrence

Livermore National Laboratory would take the lead in sensor modeling, design, assembly, characterization, signal processing, field testing and data analysis, i.e. would manage tasks (1) and (2). Other laboratories with innovative concepts and relevant experience in this area would collaborate with Livermore. Sandia National Laboratory, working outside this program, would participate significantly in the extended field tests of task (2) through their ongoing C-LAMP program. A National Laboratory other than Livermore would manage the intelligence assessment and the Red Team/Blue Team analysis of task (3), while drawing on appropriate expertise in all the Laboratories. This division of responsibilities takes maximum advantage of the capabilities and prior experience of the laboratories with minimum duplication of effort.

INTRODUCTION

Currently there is great interest in the question of how, or even whether, a treaty limiting the development and deployment of laser weapons could be verified. The concept of cooperative laser weapon verification is that each party would place monitoring stations near the other party's declared or suspect laser weapon facilities. The monitoring stations would measure the "primary laser observables" such as power or energy, either directly or by collecting laser radiation scattered from the air or the target, and would verify that the laser is operated within treaty limits. This concept is modeled along the lines of the seismic network recently activated in the USSR as a joint project of the United States Geologic Survey and the Soviet Academy of Sciences. The seismic data, gathered cooperatively, can be used by each party as it wishes, including to support verification of future nuclear test ban treaties. For laser weapon verification the monitoring stations are envisioned as ground-based, and would verify treaty limitations on ground-based laser anti-satellite (ASAT) weapons and on the ground-based development of other laser weapons. They would also contribute to verification of limitations on air-, sea- and space-based laser weapons, and the technology developed for cooperative verification could also be used in national technical means of verification.

Laser weapons have several technical characteristics that make treaty verification quite challenging. A single laser weapon facility, ground- or space-based, which is known to work, provides a significant military capability. Even a single research and development facility which is known to work at damaging power/energy levels provides a military capability. [In this case "known to work" may mean there has been a single successful live-fire test against a target; it also may mean that, although the weapon has never destroyed a target, the capability to do so is inferred from various other low- and high-power tests.] This is because a single functioning laser weapon can be fired many times and can, over time, destroy many satellites. The infrastructure and hardware required to fire once can be used to fire again with little or no additional development or construction. This is unlike the case of ballistic missiles. A single successful flight test of one missile does not make a significant new military threat; the military threat requires deployment of many missiles and takes some time longer to achieve. Furthermore, laser weapons developed and tested for one application can quickly be converted to other applications. For example, a ship-defense laser weapon that can shoot down supersonic cruise missiles could be used, with little modification, as an ASAT weapon. Therefore laser weapon verification may be required to guarantee a negligible probability of even a single violation escaping detection. This probably would require redundant and overlapping verification systems.

No cooperative ground-based system of monitors is guaranteed to see all treaty-controlled activity. Effective verification of treaty limitations on laser weapons will involve combining *all* the data from cooperative means and national technical means. "Secondary laser observables" such as thermal signatures of laser operation, electromagnetic emanations, effluents, acoustic signatures, etc. can corroborate primary observations and provide a backup if the primary observation system fails. Limited on-site inspection also can strengthen laser verification. The value of cooperative monitoring of primary laser observables should be judged by what it contributes to the overall verification system. Given the difficulty of watching everything everywhere all the time, cooperative laser monitoring which put some facilities under reliable continuous surveillance would definitely make a positive contribution to verification. We believe it may be technically feasible to do cooperative monitoring with a high probability of laser detection and low false alarm rate, which would make a substantial contribution to effective verification.

PHYSICAL BASIS OF LASER MONITORING

The large-scale damage induced by a laser depends mainly on the power density and energy density absorbed by the target. The power density or irradiance I_a absorbed by a distant target is related to the laser and target characteristics by

$$I_a = (B/R^2)\,a \qquad (1)$$

where the radiant intensity B in Watts/steradian is a characteristic of the laser system, R is the range from the laser to the target and a is the target absorption. [In photometry brightness has units of lumens/cm^2/steradian and is something different from radiant intensity, but the term "brightness" often is used incorrectly to mean radiant intensity. In deference to this very popular usage, henceforth we refer to radiant intensity as "brightness".] For each laser and transmitter there is an upper limit to the brightness, known as the "potential brightness":

$$B < PA / \lambda^2 = \text{potential brightness} \qquad (2)$$

where P is the laser power transmitted, A is the area of the beam at the transmitter and λ is the wavelength. Absorbed energy density obeys the same relations (with the brightness given in energy units). Therefore it is likely that any treaty restricting laser ASAT weapons would limit the average laser power and/or total energy that could be transmitted through the air or space, and would limit the laser brightness.

Brightness can be directly measured, in principle, by observing the laser radiation scattered by a target at long range, for example from a target satellite in a live-fire weapon test. The laser power P_c collected by the sensor is related to the brightness B by

$$P_c = (B/R^2)(d\sigma_t/d\Omega)\Delta\Omega_c T_s \qquad (3)$$

where $d\sigma_t/d\Omega$ is the target differential scattering cross section, $\Delta\Omega_c$ is the solid angle subtended by the sensor and T_s is the atmospheric transmission of scattered radiation from the target to the sensor.

Transmitted laser power or energy can be measured, in principle, by observing the laser radiation scattered by the atmosphere. Potential brightness can then be deduced from power and wavelength if the beam area at the transmitter is known by on-site inspection or national technical means. The laser power collected by the sensor is related to the transmitted power by

$$P_c = (P/A)(d\sigma_a/d\Omega)\Delta\Omega_c T_a T_s = P\,\beta\,\Delta L\,\Delta\Omega_c T_a T_s \qquad (4)$$

where $d\sigma_a/d\Omega$ is the atmosphere differential scattering cross section, β is the atmospheric scattering per unit solid angle (for single scattering), T_a is the atmospheric transmission from the weapon transmitter to the scattering point in the air and ΔL is the atmospheric path length viewed by the sensor.

For treaty verification purposes a laser monitor should measure laser power, energy and brightness by observing laser scattering from the atmosphere or the target and inverting equations (3) or (4). It is very difficult to measure the scattered laser power in the natural environment without also knowing or measuring the laser wavelength, as is discussed below. Therefore, at a minimum, the laser monitor should measure the "primary laser observables" of average power, integrated energy, and wavelength. Another primary observable, pulse duration, is helpful in assessing a laser's lethal potential.

Inverting equations (3) and (4) to get power or brightness from collected scattered power requires that one know the scattering differential cross sections or scattering coefficients and the path transmissions. These characteristics of the atmosphere or the target may vary over several orders of magnitude, so a local and current scattering calibration is required for any laser monitor. Some uncertainty or imprecision in this calibration seems unavoidable and translates into uncertainty in the treaty-limited variables one is trying to measure. Consider the uncertainties of atmospheric calibration. The atmospheric scattering coefficient depends on the wavelength of light, the scattering angle and the composition and size distribution of aerosol particles in the air. The scattering coefficient could be measured in situ at one wavelength and angle by propagating a lidar laser beam to the air volume of interest and measuring the backscattered power returned to the laser monitor, but the scattering at the weapon laser wavelength and angle would still be unknown. An atmospheric model could be used to extrapolate from the lidar to the weapon laser, but with a significant margin of error to account for atmospheric variability. In practice the laser monitor may only be capable of assigning a *probable range* of power, energy and brightness to the weapon laser. This should not prevent effective verification, since the gap between treaty-limited power and lethal power can be made much larger than the uncertainty of measurements.

REQUIREMENTS*

Physical destruction or "hard kill" of a satellite by a laser weapon would occur by melting, ablating or puncturing through the envelope of the spacecraft. The power or energy required to do this depends strongly on the laser wavelength and transmitted beam area and the target range, and weakly on the laser pulse format. A power density of about 5 Watts/cm^2 absorbed for about 100 seconds, or an energy density of about 500 Joules/cm^2 absorbed in a few pulses, will destroy a satellite with a 1mm-thick aluminum shell. The total power needed for hard kill by continuous-wave (CW) ground-based lasers under typical conditions is shown in Tables 1 and 2; the power needed by space-based lasers is similar to Table 2. Low altitude satellites are vulnerable to hard kill by CW lasers with average powers between about 100 kilowatts to a few megawatts, depending on the laser wavelength. But satellites have many sensitive components which can be damaged at power levels far below that of hard kill. The satellite "sure-safe" power density probably is comparable to the solar illumination of 0.13 Watts/cm^2 (which the satellite is designed to routinely survive), and therefore the "sure-safe" laser power is 10 to 100 times smaller than Tables 1 and 2. We assume that a treaty would limit transmitted laser average power and total energy to "sure-safe"

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* Data and predictions in this section are developed entirely from unclassified sources. Use of classified data may change some numerical requirements, but the general conclusions would not change.

levels, so *we have the goal of detecting lasers in the atmosphere and space at power levels of 1-50 kilowatts or integrated energies of 0.1-5 megajoules, depending on wavelength.*

The variety of potential laser weapon threats is very broad. High energy and high power lasers are scientifically feasible at all wavelengths from 0.2 microns to 10 microns and longer. The free-electron laser, for example, could operate in principle at any wavelength. Laser pulse durations vary from 10^{-11} seconds (radio frequency free-electron laser) to 10^{-8} seconds (some CO_2 lasers) to 10^{-6} seconds (excimer lasers) to 10^{-3} seconds (some atomic lasers) to continuous (chemical lasers). Some lasers radiate on a single frequency, others radiate on many frequencies and the distribution of energy among frequencies can be varied. Even if the type of laser is known, for example CO_2, the laser frequencies can be changed by altering the isotopic composition of the laser material.

If the characteristics of the laser are precisely known then detection of laser radiation is feasible even at extremely low power and energy. For example, if the laser frequency is known within a narrow bandwidth then heterodyne methods can be used to detect a single photon; this sensitivity means a sensor in geosynchronous orbit could detect atmospheric scattering of a low-power laser. If the laser pulse duration and frequency is known then a sensor with bandwidth matched to this pulse duration and Fourier analyzed at this frequency can directly detect this laser even at low average power and energy. In this sense the technical feasibility of measuring primary laser observables by detecting radiation scattered from the air or targets is certain beyond doubt. Atmospheric remote sensing by lidar works by detecting scattering, and is routinely done with low-power lasers in the field at ranges of many kilometers. If the characteristics of the laser weapon under observation are known, then the problem of laser verification is technically trivial, and the only issue is the engineering for remote secure operation. However, such a simple laser monitor is easily spoofed by letting it watch a low-power "Potemkin" laser with known characteristics while the real weapon laser, with unknown characteristics, operates undetected.

We have taken a broader definition of the problem. We believe the goal should be to develop technology that can detect the primary observables of *any* optical and infrared laser that exceeds the sure-safe level of power/energy, without regard to its characteristics, so that the monitor is *omni-laser*. The maximum range at which a weapon laser could be detected should depend on the wavelength, the atmospheric conditions, and the operating principles of the sensor, but not on the characteristics of the (possibly unrevealed) laser. We further believe that the goal should be to develop technology with a long detection range, so that the laser monitor has *area coverage*. At this time one cannot know how many monitoring stations would be permitted by a treaty. If each party is limited to only a few monitoring stations, then there is a high payoff for even modest area coverage.

An omni-laser monitor simply measures the average laser power or integrated laser energy scattered into it from the atmosphere or target. It works by direct incoherent detection and is broadband, so it detects lasers of any wavelength. It has a long integration time, so it responds to lasers in any pulse format.

The minimum transmitted laser power which can be directly detected with current state-of-the-art detectors (which are near-ideal)† is shown for single atmospheric scattering in Table 3 and for target scattering in Table 4. Nothing has been assumed about the laser. A one second integration time was assumed for the signal processing, so the minimum detectable laser energy (in Joules) is the same as the power (in Watts). The target reflectivities in Table 4 represent typical satellite structural materials and thermal coverings. The atmospheric scattering coefficients in Table 3 are about the lowest values observed at most sites, i.e. they represent very clear air. Under typical conditions the aerosol scattering is at least 10 times greater, and the minimum detectable laser power is at least 10 times lower (or can be detected at least 10 times further away). Multiple scattering, although weaker, under some conditions (such as when broken cloud decks are present) could produce a detectable signal at much greater range and permit over-the-horizon laser monitoring. In the infrared the radiation is assumed to be filtered or dispersed so that the detector sees only a narrow spectral range; this is required to reduce the bright/warm daytime sky background. These spectral resolutions are low-to-moderate by the standards of infrared astronomy.

Several conclusions are evident from Tables 3 and 4. First, all the thresholds of detectable power are in the "sure-safe" class, i.e. they imply (with transmitter area of a few square meters) power densities on target comparable to the solar illumination of 0.13 Watts/cm^2 or less, even for this very clear atmosphere. Therefore, it is feasible for an omni-laser sensor to verify sure-safe laser brightness from atmospheric scattering at short range. Second, even low-power lasers can be observed and verified by target scattering. Although not every laser weapon test will involve a target, the sensor should always look for target scattering because it provides such a strong signal. Third, infrared lasers are the most difficult to detect, because the atmospheric background noise and clutter is very large and the atmospheric scattering is weakest in the infrared. Some spectral dispersion or filtering is required to detect infrared atmospheric scattering.

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† These predictions are derived from the manufacturers' published performance data for commercially available detectors. Detectors available only to Government agencies may exceed these predictions.

A laser monitor that looks for both target and atmospheric scattering has several advantages. Target scattering is the only way to directly measure true laser system brightness. Target scattering can be seen even if the laser is far over the horizon and the atmospheric scattering path is too weak or is blocked, so it has more area coverage. Target scattering (and the related "port scattering" of the laser itself) is the only way to directly observe a space-based laser. It is desirable to conduct complex tests of a laser weapon over one's own territory, for better control and diagnostic observation. A few ground-based cooperative monitors on Soviet territory looking at target scattering would deter Soviet testing of a space based laser over large parts of the USSR, and would reduce the volume of space that must be watched by national technical means.

But the main approach of the laser monitor must be detection of atmospheric scattering, because cloud cover would prevent seeing targets, and significant ground-based weapon tests could be done without targets. The range of the laser monitor would be set by its sensitivity to atmospheric scattering.

LASER MONITOR CONCEPT

Our ideal laser monitor has the following characteristics. It stares at a large portion of the sky, looking for laser atmospheric scattering. It also stares at a large portion of the sky (possible a different portion) looking for laser target scattering from high-altitude aircraft, balloons or satellites. It is multi-spectral--with a separate detection system optimized for each of four or five spectral bands (corresponding to the bands in Tables 3 and 4), it looks simultaneously at all wavelengths that are transmitted through the atmosphere from ultraviolet (UV) through visible to infrared (IR). In each spectral band it has energy-integrating photon detectors, so it is omni-laser. It has a spectrometer for each band, possibly a coarse one in the visible and near-IR but a more complete one in the mid- and long-IR. It also images the scattered laser light, to identify the location of the laser transmitter and/or the target. This multispectral imagery also foils many attempts at spoofing and interference. It operates unattended for several months at a time. In contains an atmospheric lidar system, which it uses periodically to calibrate the atmospheric scattering. The laser monitor is built entirely from commercially available and exportable technology. The monitoring station is completely contained in a small trailer van. There are at least three such monitoring stations at each cooperative site; observations from two stations provide the direction of the laser beam through the atmosphere, and the third station provides redundancy.

The monitor must identify the scattered radiation as *laser* radiation. The primary defining characteristic of laser light is its spatial coherence, but this coherence is lost after atmospheric scattering. The laser radiation now has nothing to distinguish it from natural or man-made incoherent radiation. The problem of identifying laser light is part of the larger problem of avoiding false alarms. The laser monitor is essentially a set of very sensitive optical and IR detectors staring at the outside world. It is flooded with radiation, most of it not from lasers. It is so sensitive that it registers the passage of cosmic ray particles. It also has electronic and thermal noise. The monitor relies on some design features and on signal processing to discriminate laser radiation from all other events.

Cosmic ray and other non-optical/IR events are rejected by having two independent detectors look at each location and requiring that the signals correlate. This guarantees that only true optical/IR radiation events are considered further.

Laser radiation is discriminated by its spectrum. A laser instantaneously has narrow spectral width. Natural and man-made non-laser light is not narrow-band, and furthermore each non-laser source has a unique spectral distribution at the monitor. The laser monitor measures the spectrum in each wavelength band. The detectors in each instrument double-sample each resolution element, to get a two-detector correlation. Laser sources are discriminated by their narrow linewidth. The non-laser background sources are identified by signal processing which compares the spectrum to a data base of events accumulated over a period of field trials. This background identification insures that the monitor is not being flooded with man-made light such as flares as a method of spoofing. With these techniques of spectral double sampling, two-sensor correlation and background identification the laser monitor should achieve a detection probability greater than 99.5% with less than 1 false alarm in 30 years.

The laser monitor can measure the spectrum with three different types of sensors. First, the monitor can have an imager which simultaneously makes two (or more) images, one in narrow spectral lines typical of certain lasers and the other in broadband light. The spectrum is measured by the image intensities; broad non-laser sources will give image intensities in the ratio of the narrow to the broad spectral bandwidths, but laser sources will give images with radically different intensity ratios (whether the laser falls within the narrow lines or outside them). This imager also gives a crude measurement of laser wavelength. Second, the monitor can have a spectrometer for each wavelength band which continuously observes the spectral distribution of radiation; laser sources will appear with an excess of energy in one spectral bin over a non-laser background. The spectrometer also measures the laser wavelength. For added confidence two spectrometers can be used in each band, with different dispersions; narrow-width laser signals will be the same in both spectrometers, but broad non-laser signals will be in the same ratio as the spectral bin widths. Third, the previous instruments can be combined into an imaging spectrometer.

The multi-linewidth imagers can be used to observe target scattering in each spectral band from UV to thermal-IR, and to observe atmospheric scattering in the UV, visible, and near-IR bands. A spectrometer is used to observe atmospheric scattering in the mid- and long-IR, to overcome the sky background. These spectrometers also image at least a one-dimensional slit across the sky.

The spectral resolution required for laser discrimination and background identification is low-to-moderate compared to the state-of-the-art, so these instruments will not be expensive. Narrow linewidth for the imagers can be achieved by interference filters. Adequate dispersion in the spectrometers can be achieved by grisms in the visible to mid-IR bands, and by low-resolution eschelles in the thermal-IR. For good laser discrimination the signal processing is at least as important as the configuration of optics and detectors.

The architecture of the laser monitor is as follows. The monitor has separate systems for each spectral band. Each band has several sensor packages. Each sensor package is dedicated to a portion of the sky. A sensor package has an optical system, an imager or spectrometer, detectors and signal processing electronics.

Each sensor package has wide-field-of-view (WFOV) optics, with a field of view of 1-3 steradians and an aperture of 10-30 centimeters. This is similar to the WFOV systems already demonstrated at Livermore. Three or four such apertures for each broad spectral band will cover most of the sky. One aperture is inclined for optimum satellite coverage and is dedicated to target scattering. The other apertures are at lower elevation angles and look for atmospheric scattering from all directions.

The focal plane in such WFOV optics covers a large area, many square centimeters, so it would seem that the sensor must contain a very large number of pixels (much larger than a typical array), with corresponding high cost for detectors and electronics. But this is not the case. The signal-to-noise ratio (SNR) of laser-atmospheric scattering is essentially independent of the resolution element size (both the signal and the noise are proportional to pixel area$^{1/2}$), and the SNR of laser-target scattering is so high that resolution element size is not critical. The laser monitor does not need high spatial resolution, so it divides the focal plane into a relatively small number of large pixels. Each pixel is undersampled by an optical fiber bundle, and the fibers channel the light into a typical-sized detector array. This gives broad area coverage with a small number of detector elements at high SNR. High-transmission optical fibers are commercially available for all the spectral bands required in a laser monitoring sensor (silicate in the visible, zinc fluoride in the mid-IR and chalcogenides or Ge in the thermal-IR). The fiber bundle can divide the light, sending some to the image detector array and the rest to the spectrometer. The imager and spectrometer can be combined into one imaging spectrometer instrument as follows. The fibers from the entire focal plane are rearranged into a linear bundle and the radiation piped into the spectrometer. In the spectrometer focal plane is a two-dimensional array detector; one dimension is the wavelength spectrum, and the other direction is spatial and is rearranged back into an image by signal processing.

A single sensor package, with WFOV optics and imaging spectrometer, is shown in Figure 1.

The imager and the spectrometer do not need high resolution, so as separate instruments they do not need large detector arrays. The imager has about 10^3 pixels in a two-dimensional array, and the spectrometer has about 10^3-10^4 pixels in several linear arrays (only a slit across the atmosphere with a few spatial resolution elements in the image plane needs to be spectrally analyzed). If they are combined into an imaging spectrometer, one could spectrally analyze every image point with a 1024 x 1024 array. This full spatial/spectral decomposition is not absolutely necessary, but is highly desirable. Arrays this size are commercially available for wavelengths from 0.3 microns to 1.1 microns. Mid- and thermal-IR arrays this large cannot be exported today, but a large array could be built up from available 256^2 arrays.

Ideally the detectors are operated in photoconductive mode, and the integrated charge transfer is sampled non-destructively at high bandwidth during a long integration time. This readout method, which has been demonstrated in IR astronomy for faint-object imaging, virtually eliminates readout noise with redundant samples and achieves true background-limited performance from the detector. The high-bandwidth time samples also measure the laser pulse duration and repetition rate.

The ideal laser monitor uses cooled detectors in the IR. The best detector performance is obtained by cooling to 20 degrees Kelvin or less, but the closed-cycle coolers may not be sufficiently reliable at this temperature for unattended long-term operation. Therefore we have assumed that the laser monitor only uses detectors at 77 degrees Kelvin, which should be possible for long duration.

Scattering calibration is required for any laser monitor. Atmospheric calibration is done at an eye-safe wavelength with a small lidar system built into the monitor. Atmospheric sensing by lidar is an established technology, and lidar systems are available commercially. Sensing could be done in several spectral bands, for more accurate calibration of the atmospheric models. Weather-satellite measurements of albedo also are used for calibration. Target calibration is done from observations of target thermal-IR emission and reflected sunlight. One can conceive of specially-designed "spoofing" targets which quickly change their scattering just for a laser weapon test, but this is not trivial. The laser monitor observes the target in many spectral bands, so it is difficult to disguise such spoofing. If detected, a spoofing target is highly suspicious.

This design concept is optimized for the mission of cooperative laser monitoring. It should perform much better than other laser sensors built and tested in other programs, and its performance should approach ideal. Other laser sensors have been designed primarily for threat warning or for covert applications. Threat warning sensors must be small (to fit into existing platforms) and very cheap (to deploy in the thousands). Covert sensors must be small and lightweight, for portability and concealment. Performance must be sacrificed to meet these other design constraints. But our ideal laser verification monitor does not have these constraints; it can be large and bulky, if this gives better performance, and it is intended to be deployed in only modest numbers for a long-term high-value mission, so it can contain better technology with higher value per copy.

This design concept for a cooperative laser monitor meets all the goals we have set. All its technology is commercially available and exportable today, except possibly the large two-dimensional array IR detectors which are available to the government today and are expected on the commercial market in a few years.

DEMONSTRATION SENSOR CONCEPT

Our demonstration sensor concept is intended to validate all the key design innovations discussed above for the laser monitor. Since the detection process is most difficult in the mid- to long-IR, and also since the IR laser threat may be nearer-term, the demonstration sensor is built for the mid- and long-IR bands. It can be upgraded to also cover the visible and near-IR in the second demonstration cycle. To reduce cost and inessential complexity it uses somewhat smaller detector arrays than may be ultimately required in the laser monitor, and therefore it has somewhat smaller spatial FOV and spectral bandwidth. It retains all the essential features of the laser sensor.

Specifically, we propose that the demonstration sensor include the following elements.

Separate systems for the 4μm and 10μm bands

Wide FOV optics, 0.5 steradian goal

Two apertures for each band, one optimized for target sensing and the other for atmospheric sensing

Low resolution imaging spectrometer, fiber-coupled to the WFOV focal plane

256^2 or 128^2 detector arrays (approximately), PtSi or InSb in the 4μm band, Si:As or HgCdTe in the 10μm band, double sampled for correlation-discrimination

Nondestructive charge-integrating readout electronics, so that the sensor measures integrated energy or average power

Closed-cycle cooling to 77 degrees Kelvin

Full signal processing for natural background identification and laser discrimination

Commercial lidar system for atmospheric scattering calibration

All sensor systems installed in a trailer van for easy transportation to field test sites, but signal processing done off-line and not in real time.

Continuous operation

The demonstration sensor is not intended for unattended remote operation, or for operation in a hostile environment. It operates remotely, but with frequent operator inspection and intervention.

We believe that the demonstration sensor can be assembled and operating in one year, as it uses mainly off-the-shelf technology.

RECOMMENDED PROGRAM

The utility of the cooperative laser monitor depends on technical performance in three areas: (i) the sensor sensitivity and area coverage that can be reliably achieved in the field, (ii) the ability of the sensor and signal processing to correctly discriminate lasers from natural background events, and (iii) the resistance of the monitor to tampering and spoofing and the ability to correctly identify such interference. Technical achievement to-date in (i) has fallen far short of the best feasible, but the sensors were not developed specifically for this verification role. The fundamental limits to detection are well beyond the reported performance. We believe that much better performance can be achieved with innovative optical designs and better engineering in a dedicated verification sensor. Area (iii) has not been studied in detail for laser monitoring but has been studied for seismic and INF verification. The most serious technical problems are in area (ii). Previous generations of sensors have failed to consistently discriminate laser events from natural optical background events because of fundamental design flaws. Our concept of double sampling by all sensors, event correlation among several sensors and spectral measurement of all events should overcome this problem. The need for a very low false alarm rate is so important in verification, and the variability of natural background and man-made radiation events is so great, that adequate laser discrimination can be demonstrated only by extended field testing. *Therefore the research program should proceed to field tests of a sensor at the earliest feasible date.*

The sensor and signal processing fielded in early tests will not be optimized. Also, the field tests will undoubtedly reveal problems that could not be foreseen in the design phase. Therefore the appropriate research program builds a demonstration laser sensor and field tests it, then iterates that cycle several times until either the "bugs" are worked out or a fundamental shortcoming is discovered. A robust program would design and build several competing sensor concepts and evaluate all of them in comparative field tests, and then would iterate with improved versions of the best sensors. A higher-risk but lower-cost program would make an early selection of the most promising sensor concept, build that sensor and field test it, then iterate with improved technology or a new concept. To reduce cost, we recommend a minimum viable technical program with the latter approach, and accept the increased technical risk.

We recommend a three-year research program to resolve the technical uncertainties of cooperative laser verification. The work, by year, is as follows.

Year 1: A first-generation demonstration laser sensor package will be designed and built. *Demonstration of this sensor will be a major milestone, and continuation of the program beyond the first year will be contingent on its success.*

Year 2: This sensor will be field tested for an extended period, to demonstrate that it can detect weapon-level laser power/energy and can discriminate laser events from natural background and man-made non-laser events. There will be time to conduct some field testing on foreign territory in year 2; such testing would be very valuable if it can be arranged.

Also, the demonstration sensor package will be upgraded. The upgrades may be additional apertures for increased sky coverage, improved or larger detector arrays, visible and near-IR sensors, or other new technology.

Year 3: The upgraded sensor will be field tested.

All years: The utility of cooperative laser verification will be evaluated in the light of our technical progress and in the context of other arms limitations and other means of verification. This evaluation will include the susceptibility to tampering and spoofing and possible countermeasures, and the requirements and methods for physical and communication security and data authentication.

If the field demonstrations are successful, at the end of year 3 the laser weapon verification technology would be ready for engineering into a monitoring system for actual treaty verification, should this be required. The cost of this minimum viable program is approximately $2 million in the first year and a total of $8 million over three years.

The program plan and schedule are summarized in Figure 2.

The critical element of this program is the demonstration sensor package(s) designed and built in the first year. This paces the rest of the program. In the minimum viable program there are only enough funds to build one sensor concept. To reduce risk and avoid duplication of effort, the organization(s) responsible for the sensor should have full access to the results of all other sensor development and test programs, both prior and ongoing projects, from all sponsors. The prior sensor designs and test results should be reviewed to insure that the laser verification research program does not repeat the mistakes of others. This may require access to SCI data, so the responsible organization(s) should have appropriately cleared personnel and facilities, and should receive the cooperation of the appropriate sponsoring agencies.

Since the intent of this program is to research and develop technology for cooperative treaty verification, the sensors built under this program and the test results should be classified at the *lowest* level consistent with national security, and if possible be unclassified. Good security awareness and practice will guarantee that highly sensitive data is not compromised. To facilitate full and open discussion of laser weapon verification most reports in this program should be unclassified, with a classified annex for highly sensitive results which must be protected.

The program divides naturally into three tasks: (1) modeling, design, assembly and characterization of the laser sensor(s) and signal processing, which establishes the sensor performance in the field, (2) extended field testing of the sensor(s), which validates the signal processing and establishes the discrimination of laser events among natural backgrounds, and (3) Red Team/Blue Team assessment of design concepts, test results, tampering/spoofing methods and countermeasures, which evaluates the utility of cooperative monitoring combined with all other means of verification. The three tasks of the program also naturally involve three distinct areas of expertise: (a) laser propagation and detection, for the sensor modeling, design, hardware integration, signal processing, field testing and data analysis, (b) field test operations, for the coordination of sensors, lasers and atmospheric diagnostics in long-duration tests, and (c) intelligence assessment and general verification technology and practice, for the analysis of spoofing and security and the evaluation of laser monitoring in the context of other observables and systems. These areas are well-matched to the expertise of the National Laboratories, as detailed below.

Therefore, we recommend this research program be conducted through the National Laboratories, with the work to be shared as follows. Lawrence Livermore National Laboratory would take the lead in sensor modeling, design, assembly, characterization, signal processing, field testing and data analysis, i.e. would manage tasks (1) and (2). Other laboratories, such as Argonne National Laboratory, with innovative concepts and relevant experience in this area would collaborate with Livermore on major subtasks. Sandia National Laboratory, working outside this program, would participate significantly in the extended field tests of task (2) through their ongoing C-LAMP program. A National Laboratory other than Livermore would manage the intelligence assessment and the Red Team/Blue Team analysis of task (3), while drawing on appropriate expertise in all the Laboratories. Argonne National Laboratory, which originated the cooperative laser monitoring concept in 1989, would participate significantly in this task. In this task Sandia National Laboratory would have responsibility for evaluation of physical and communication security and data authentication. This division of responsibilities takes maximum advantage of the capabilities and prior experience of these laboratories with minimum duplication of effort. We estimate that task 1 will be approximately 60% of the total program effort, task 2 about 30% and task 3 about 10%.

CAPABILITIES AND EXPERIENCE

The concept of cooperative laser weapon verification has been studied for more than one year by an unofficial group of scientists drawn together by their interest and expertise in the problem. This group, informally dubbed the "Santa Cruz Group" for the location of several meetings, includes a number of well-known scientists from federal laboratories as well as academic scientists. Lawrence Livermore National Laboratory (LLNL) has participated fully in the Santa Cruz Group and done a major share of the technical analysis for the Group. Among the national laboratories, LLNL has made the largest commitment of effort and has the greatest technical involvement in the Santa Cruz Group.

Lawrence Livermore National Laboratory has nationally-recognized capabilities and experience in all the areas of the laser weapon verification research program. Some of the relevant capabilities in the Laser Programs at LLNL are as follows.

LLNL has the largest active research group in the U.S. on high energy laser propagation in the atmosphere. This group conducts extensive computer modeling and experimentation on propagation for strategic and tactical defense applications, and provides the propagation modeling and research for laser projects at other national laboratories. This knowledge, modeling capability and laboratory experience in laser propagation are critical to the sensor design and data analysis in tasks (1) and (2). This group also analyzes Soviet developments in laser, optics and propagation technology, which is relevant to sensor design and also to the utility analysis in task (3).

LLNL is developing novel methods of high-resolution imaging for the Department of Defense (DoD). Under this program LLNL has developed and fielded several quantum-limited state-of-the-art cameras at DoD observatories to image satellites, most recently at AMOS on Maui. The camera and signal processing technologies are directly relevant to laser verification.

LLNL is developing imaging and detection technology for DoD strategic defense applications. This project already has developed and fielded several generations of ultraviolet, visible and infrared cameras to image ballistic missiles and space vehicles in flight. These instruments have been deployed on telescopes at the AMOS facility in Maui, flown on the Kuiper Airborne Observatory and on high-altitude balloons. The sponsor considers the data from these cameras to be the best, radiometrically most reliable data ever obtained on missile plumes, hardbodies and re-entering spacecraft. This hardware development and field test experience are directly applicable to laser verification. This project also has extensive capabilities in signal and image processing relevant to laser verification.

LLNL is conducting research on advanced methods of signal processing to extract weak signals from noisy imagery. The success of these methods has been demonstrated in synthetic aperture radar processing and in speckle imaging. This project is relevant to extending the sensitive range of a laser monitor.

The Special Studies Group at LLNL is developing wide-field-of-view optics for various DoD applications including broad area surveillance and satellite tracking. These optical systems can have a field-of-view exceeding 1 steradian in a single aperture, and can be cheaply fabricated at wavelengths from ultraviolet to long-wave infrared. This performance matches the requirements of a laser verification monitor. Visible-wavelength wide-field-of-view cameras have been operational for several years at LLNL, and infrared versions are in advanced development.

The Atmospheric Sciences Program at LLNL developed and maintains the state-of-the-art atmospheric radiation transport models. These models are under continuous refinement for the Department of Energy (DoE)-sponsored study of nuclear winter. These model are directly applicable to the study of multiple laser scattering off aerosols and clouds for over-the-horizon laser monitoring at long range.

LLNL has extensive experience in verification technology and other classified programs. Traditionally LLNL has been the DoE resource on national technical means of verification from ground-, air- and sea-based locations. We have developed technology for the control, processing and authentication of data from remote sensor networks. LLNL is a participant in the CCMP and C-LAMP programs, with data relevant to this program.

Sandia National Laboratory manages the C-LAMP program; its responsibilities include coordination of laser tests, which is relevant to the laser verification research program. Sandia also has developed technology for secure unattended operation of verification systems on foreign territory. This experience is relevant to task (3).

Los Alamos National Laboratory has traditionally been the DoE resource on national technical means of verification other than ground-, air- and sea-based. This expertise is relevant under task (3) to integrating cooperative laser verification with all other means, and to analyzing the role of secondary observables.

TABLE 1
Ground-based laser power for 5 W/cm² absorbed (no atmospheric compensation)

Wavelength (μm)	target absorptivity [(1)]	r_0 (cm)	Range (km) 300	1000	10,000	36,000
			power (MW)			
0.4	.3	3.3	3.9	44	4.4×10^3	5.7×10^4
1	.16	10	4.0	44	4.4×10^3	5.7×10^4
4	.76	53	.54	6	6×10^2	7.8×10^3
10	.76	160	.38	4.2	4.2×10^2	5.4×10^3

(1) From: The Infrared Handbook p. 15-77, data for typical spacecraft materials and coatings

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TABLE 2

Ground-based laser power for 5 W/cm² absorbed (with atmospheric compensation)

wave-length (μm)	target[1] absorptivity	r_0 (cm)	Strehl ratio	Range (km): 300 / Beam dia (m): 1.8	1000 / 1.8	10,000 / 3.5	36,000 / 3.5
				power (MW)			
0.4	.3	3.3	0.25	5.4×10^{-3}	.06	1.6	21
1	.16	10	0.25	.049	.55	14	1.9×10^{2}
4	.76	53	0.25	.19	2.1	55	7.1×10^{2}
10	.76	160	0.25	1.2	13	3.4×10^{2}	4.4×10^{3}

(1) From: The Infrared Handbook p. 15-77, data for typical spacecraft materials and coatings

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TABLE 3

With commercially available detectors (which approach ideal), *atmospheric-laser* scattering can be directly detected *at short range*

wavelength μm	detector	linewidth μm	scattering cm^{-1} sr^{-1}	NEP[1] W	Min detectable transmitted power[2] at 1 km
0.4	PIN diode	.25	5×10^{-8}	5×10^{-16}	50 W (noise & clutter)
1	PIN diode	.5	2×10^{-9}	3×10^{-16}	200 W (clutter)
2	PbS(193°K)[4]	1	10^{-11}	6×10^{-17}	400 W (noise)
4	PtSi(77°K)[3]	10^{-2}	3×10^{-11}	4×10^{-17}	500 W (noise)
10.6	HgCdTe(77°K)[3]	10^{-3}	10^{-11}	10^{-16}	6 kW (clutter)

(1) 1 Hz bandwidth, and pixel size = $\lambda f\#$
(2) 30 cm Ø; detection at 10^{-2} of daylight background and SNR = 10
(3) Stirling cycle cooler, MTTF > 4000 hrs
(4) Thermoelectric cooler, MTTF > 5 yrs

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TABLE 4

With commercially available detectors (which approach ideal), *target-laser* scattering can be directly detected *at long range*

wavelength μm	detector	linewidth μm	reflectivity	NEP(1) W	Min detectable transmitted power(2) at 1000 km
0.4	PIN diode	.25	0.7	10^{-15}	3 W (clutter)
1	PIN diode	.5	0.84	10^{-15}	10 W (clutter)
2	PbS(193°K)(4)	1	0.7	7×10^{-17}	0.1 W (clutter)
4	PtSi(77°K)(3)	10^{-2}	0.24	4×10^{-17}	0.2 W (clutter & noise)
10.6	HgCdTe(77°K)(3)	10^{-3}	0.24	10^{-16}	2 W (clutter)

(1) 1 Hz bandwidth,and pixel size
(2) 30 cm Ø; detection at 10^{-2} of daylight background and SNR = 10
(3) Stirling cycle cooler, MTTF > 4000 hrs
(4) Thermoelectric cooler, MTTG > 5 yrs

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FIGURE 1
Typical sensor package for the laser monitor

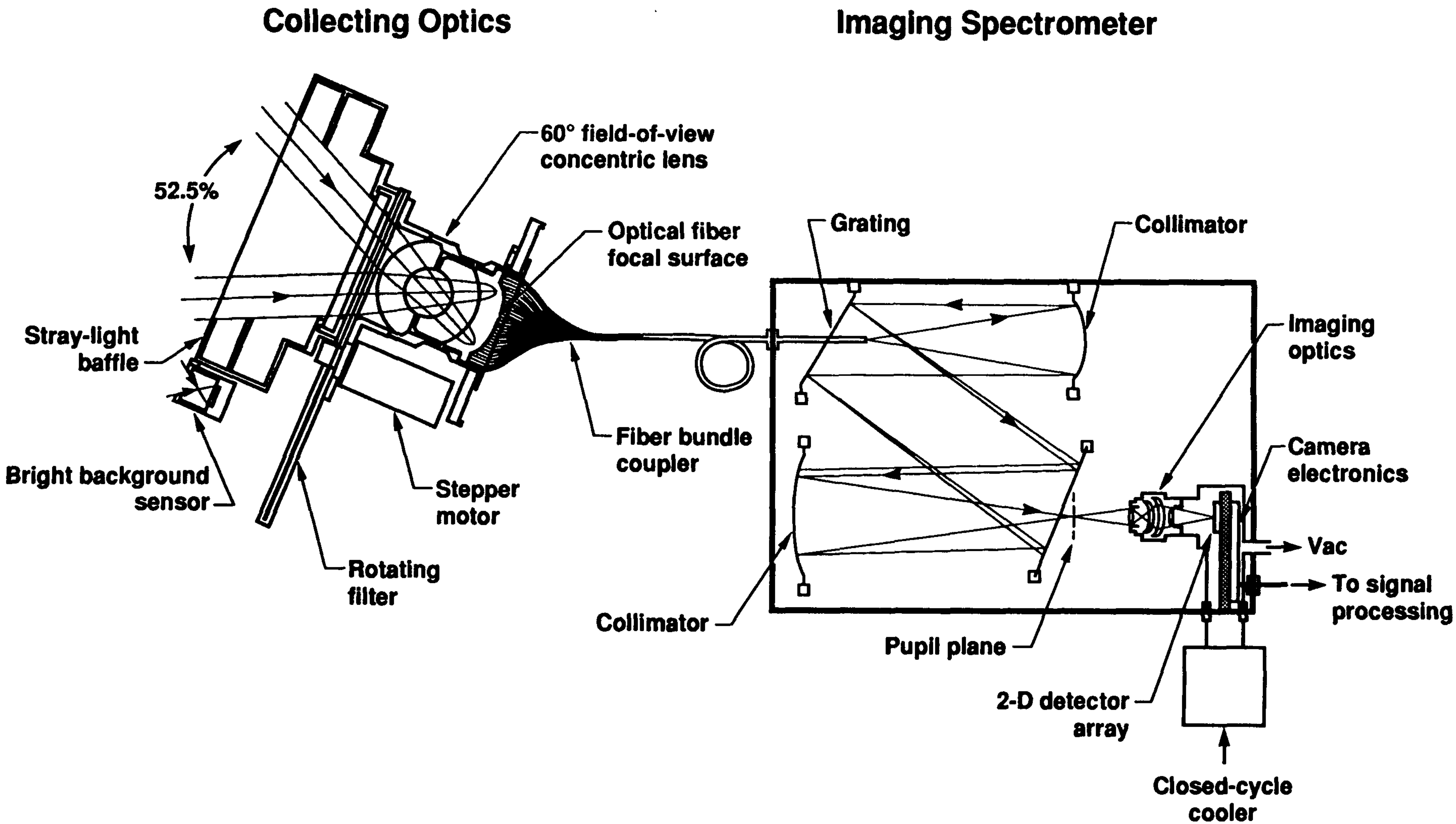

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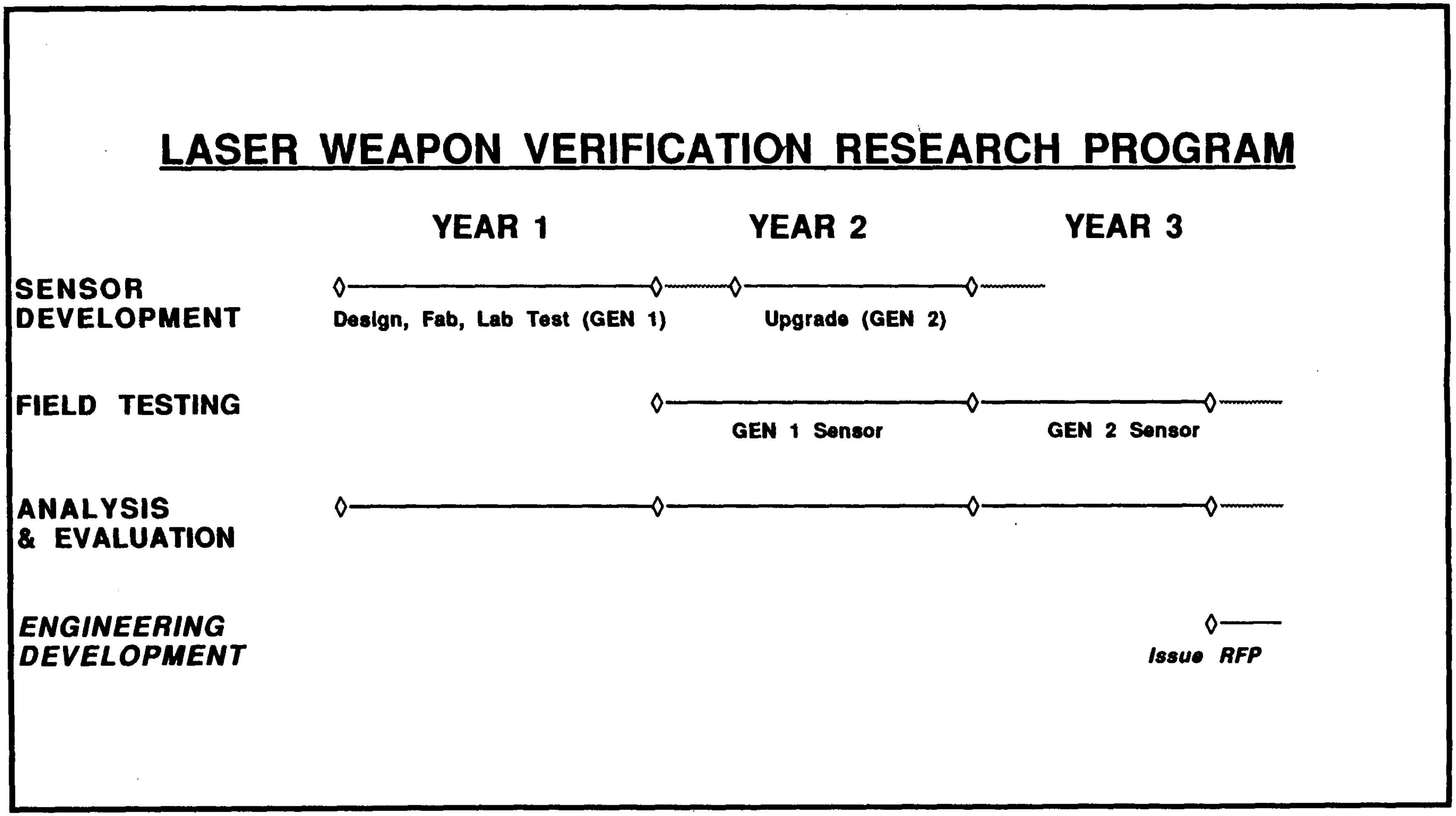
FIGURE 2



LASER WEAPON VERIFICATION RESEARCH PROGRAM
YEAR 1
YEAR 2
YEAR 3
SENSOR DEVELOPMENT
Design, Fab, Lab Test (GEN 1)
Upgrade (GEN 2)
FIELD TESTING
GEN 1 Sensor
GEN 2 Sensor
ANALYSIS & EVALUATION
ENGINEERING DEVELOPMENT
Issue RFP