LASER IGNITION OF OIL SPILLS: TELESCOPE ASSEMBLY AND TESTING

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ABSTRACT

A technique for using two coupled lasers to heat and ignite oil spills has been described previously.[3-6] Outdoor demonstrations have proven the ability to ignite cold crude oil in a simulated Arctic environment, and an engineering design has shown the viability of mounting the needed equipment in a helicopter. We have now assembled the telescope required to focus the pulsed "igniter" laser from a helicopter hovering at an altitude of 20m. Ignition has been demonstrated at slant ranges between 20 and 30m, with the lasers directed outward from the platform at angles between 0 and 49 degrees from the vertical. In addition, two techniques for automatically focusing the telescope were studied.

RÉSUMÉ

L'utilisation de deux lasers jumelés pour chauffer et porter jusqu'au point d'ignition des nappes de pétrole a déjà été décrite.[3-6] Effectués à l'extérieurs des essais en milieu arctique simulé ont démontré qu'il était possible de mettre feu à une nappe de pétrole. De plus, une étude d'ingénierie a déterminé qu'il était faisable d'installer l'équipement requis sur un hélicoptère. À la suite de quoi, un hélicoptère a été doté d'un télescope servant à focaliser les faisceaux lasers impulsionnels ?allumeurs/ en vol stationnaire à 20 mètres d'altitude. Des essais d'ignition ont été réussis à des distances comprises entre 20 et 30 mètres (en diagonale), le laser étant dirigé vers l'extérieur de l'appareil, avec un angle de visée variant entre 0 et 49 degrés par rapport à la verticale. De plus, deux techniques de mise au point automatique du télescope ont été étudiées.

1. INTRODUCTION

In the event of an Arctic oil spill, either from a shipwreck or maritime well blowout, it is envisioned that oil reaching the surface of an ice field melting during springtime will form tens of thousands of pools, each having typical dimensions of a few tens of meters.[1] The technique of choice for removing these pools before the ice melts allowing the oil to escape is to set each afire within a few days of its appearance. Due to the remote location of the potential accident, ignition of the oil must be accomplished from an airborne vehicle. To date, only pyrotechnic ignitors[2] have been able to achieve this task. Unfortunately, these devices have shelf lives of only about 5 years, and production of sufficient stock to clean up one major spill could require a recurrent cost of several million dollars. The logistics of manufacturing and transporting the thousands of devices to the spill site have been found to be quite difficult.

During the past four years, a novel dual-laser approach to starting pool fires has been developed. In Phase I,[4] the technique was developed theoretically and laboratory tested, Phase II[5] showed that the technique worked outdoors in conditions simulating an Arctic environment, and in Phase III[6] an engineering design for mounting the system on a helicopter was completed. Testing of certain critical aspects of the optical components within that design was completed in the last 6 months and has proven successful.

2. BACKGROUND

The laser ignition process may be summarized as follows: A continuous-wave (CW) carbon dioxide laser is used to heat a portion of the surface of an oil pool to its flashpoint temperature and simultaneously establish a thermal field within the oil which will support the growth of a nascent flame. A focused, pulsed laser beam then provides energy which creates a momentary "spark" above the oil surface to ignite a fire. The technical advances that led to the success of the technique were: (1) learning the requirements to start a small diffusion flame which is able to both sustain itself and spread over a large pool of cold oil; and (2) determining how to satisfy these requirements using lasers.

A schematic illustration of a one-dimensional diffusion flame is presented in Figure 1. At the surface of the cold liquid is a relatively hot layer from which fuel evaporates and mixes with the air above. Combustion occurs in a very narrow layer located a small distance above the surface of the fuel, and combustion products such as hot soot and gases rise above this zone. As the fire burns, combustion energy is radiated and conducted through the air back to the oil pool, thus providing the power required to continue vaporization of new fuel and sustain the burning. If this power is insufficient to overcome the heat flux transported to the bulk liquid by conduction and convection, the surface cools to a temperature below that at which sufficient vapor is produced, i.e., below the flashpoint, and the fire extinguishes itself. Thus, the liquid will burn only after several criteria are satisfied: 1) The surface of the liquid must be hot enough to provide a vapor above the surface which, when mixed with ambient air, is combustible; 2) This vapor/air mixture must be raised briefly to a temperature sufficiently high to initiate combustion; and 3) The liquid fuel must establish temperature and flow fields which transport less power into the liquid's volume than a nascent flame is capable of supplying back to the liquid surface.

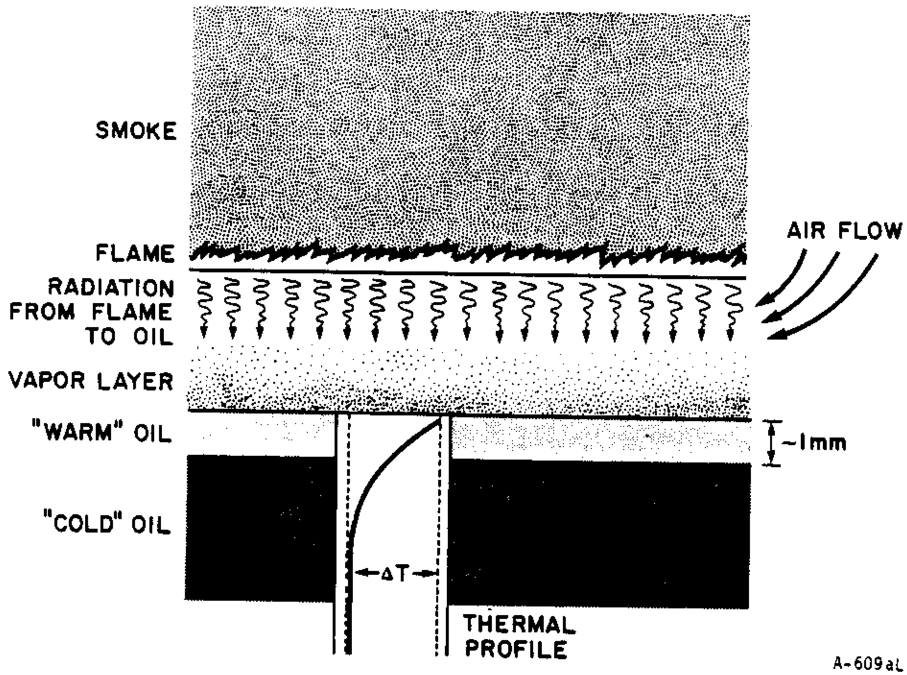

Figure 1. Salient Features of a One-Dimensional Diffusion Flame

Cold, aged crude oils fail to inherently satisfy any of these criteria. To generate a combustible vapor mixture, the surface of the liquid must be heated to its flashpoint temperature, typically as high as 100 C. To ignite the vapor mixture, it must be exposed to a heat source of 700 C or more. The third criteria requires that the liquid absorb a certain amount of energy before the fire is ignited.

Laser beams, which act as remote infrared energy sources, are used to satisfy each of these requirements in the Laser Ignition of Oil Spills (LIOS) technique. By selecting appropriate combinations of laser power, intensity (power/unit area), and irradiation time, ignition of sustained, spreading fires on the surfaces of cold, aged oil pools is accomplished. The powers and intensities delivered by the laser beams are controlled by the choice of lasers and the use of focusing or defocusing optical components. Two lasers are used in tandem as illustrated by Figure 2: A moderate power (< 1000W) CW

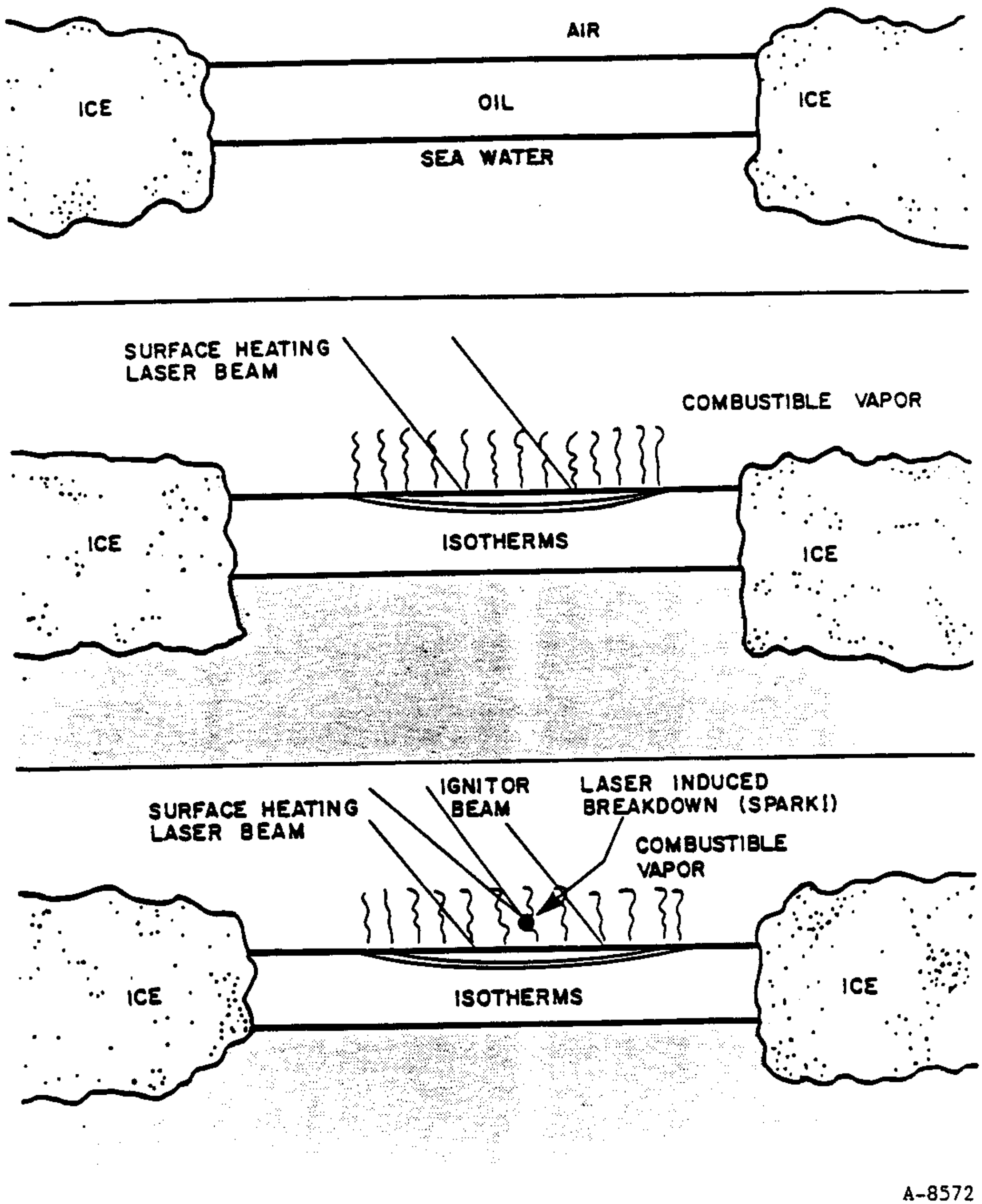

Figure 2. Laser Ignition of Oil Spills Concept and Sequence

laser continuously irradiates or "preheats" a small portion of the oil surface thereby establishing the thermal and flow fields required for vapor production and flame survival, satisfying criteria 1 and 3. Concurrently a high power (7 MW) short-pulsed (2 μs duration) focused laser fires once per second. By focusing this pulsed laser beam to provide a fluence (energy/unit area) exceeding 10 J/cm^2 at the surface of the pool, its energy is absorbed in the vapor above the oil thereby generating temperatures high enough to initiate the combustion reaction, satisfying criterion 2. When conditions are ripe, the vapor mixture ignites and initiates a self-sustaining fire. Carbon-dioxide (CO_2) lasers have been used exclusively in this technique because of their advanced state of development, energy conversion efficiency, availability and cost. These lasers radiate at a wavelength of 10.6 μm, in the far-infrared.

To utilize this technique for ignition of oil from an airborne platform in an Arctic environment, focusing of the pulsed laser must be accomplished from a distance. In addition, the pulsed laser must be pointed colinearly with the (unfocused) CW laser. As a portion of the Phase III program, PSI designed an optical system in which the pulsed laser beam is focused to the required fluence by a variable focal length reverse Cassegrainian telescope and directed along with the CW laser beam onto a mirror which subsequently directs both beams onto the oil pool.

The helicopter-deployable version of the LIOS system has been designed with the following features:

1. Can be installed in a Sikorsky S61 or comparable helicopter without affecting airworthiness or safety;
2. Incorporates a CW CO_2 laser producing up to 1000W of power and irradiates the oil pool with the required preheating intensity of 5 to 10 W/cm^2;
3. Incorporates a pulsed laser which is focused to provide sufficient fluence to ignite, from a distance, fires on preheated oil pools;

4. Holds the laser beams on target despite helicopter movements and vibrations;

5. Provides sufficient power and cooling capability to operate all of the system components; and

6. Can be operated by an aircraft maintenance technician.

Assuring that the pulsed laser beam is focused at the surface of the oil pool to a fluence which is sufficient to ignite the preheated oil is clearly critical to the success of the system - no spark, no fire. It was determined in Phase I that ignition of a properly preheated oil spill by a single firing of the pulsed laser requires focusing the laser beam to provide a fluence exceeding 10 J/cm^2 on the surface of the pool. Lower fluences yield a decreased probability of ignition on each pulse; fluences below 7 J/cm^2 are unusable.

Throughout the experimental development process, the required fluence was achieved by focusing the pulsed laser beam with short-focal-length mirrors located within one or two meters of the oil surface. It had not been shown, except by calculation, that sufficient fluence could be provided from a hovering helicopter. This uncertainty has now been resolved, as reported herein. The telescope required to focus the pulsed 'igniter' laser has been assembled, tested, and proven successful. In addition to meeting the minimum fluence requirement, the optical system design satisfies certain economic constraints as well as limitations imposed by the CW laser[6] which force the system to operate from a helicopter hovering at a fixed altitude of about 20m above ground level and allow ignition of individual oil pools elevation angles between 0 and 49 degrees, corresponding to slant ranges between 20 and 30m as illustrated in Figure 3. Oil ignition was demonstrated with the telescope at these slant ranges and angles. Also, two methods of passively or semi-passively focusing the telescope were investigated.

3. OPTICAL SYSTEM

3.1 Design and Layout

The pulsed laser currently used as the igniter is a Lumonics Model TEA-103 operated in an unstable resonator optical configuration. This laser is nominally capable of yielding 4 J of focusable energy per pulse. To provide a fluence well in excess of the requisite 10 J/cm^2 at the oil surface, the beam is focused to a diameter of less than 0.4 cm using a two-element reverse Cassegrainian telescope as illustrated in Figure 4. The laser beam is first expanded by a -35.5 cm focal length, 2.5 cm diameter concave lens, and then focused by an 208 cm focal length, 25 cm diameter concave mirror. The two elements are nominally separated by 190 cm. The distance from the concave mirror at which the beam achieves its minimum diameter is the effective telescope focal distance. This focal distance can be varied within the range of 20 to 30 m simply by moving the concave mirror relative to the lens by a distance of about 8 cm.

The components are all mounted on a single table. The pulsed laser beam is directed into the telescope by small flat mirrors (indicated as components #1 & 2 in Figure 4). The beam passes through component #3, the anti-reflection (AR) coated germanium diverging lens and thence passes unaffected through a germanium flat, component #4, also coated so as to be non-reflective at the laser wavelength. The beam then impinges on the focusing mirror (#5) after expanding to a diameter of about 20 cm. The now slightly-converging beam is reflected back along its original path, and exits the telescope.

The concave mirror is mounted on a linear translation stage to facilitate focusing. The accuracy with which it must be positioned is determined by the depth-of-field of the focused beam, defined as the range of distances away from the focal point over which the fluence remains sufficiently high to

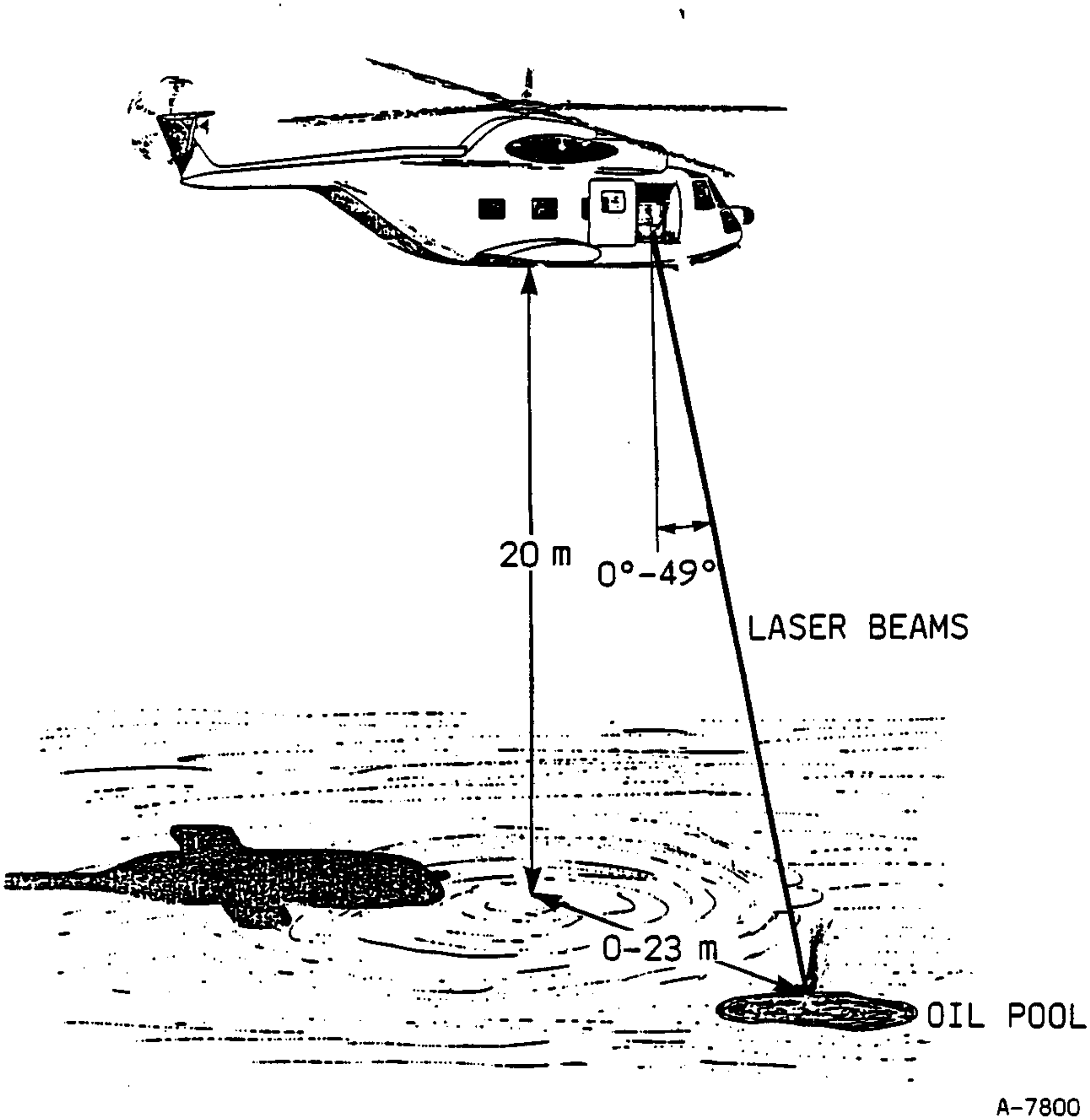

Figure 3. Operational Scenario for Airborne LIOS System. Not to scale. (Adapted from Ref. 6.)

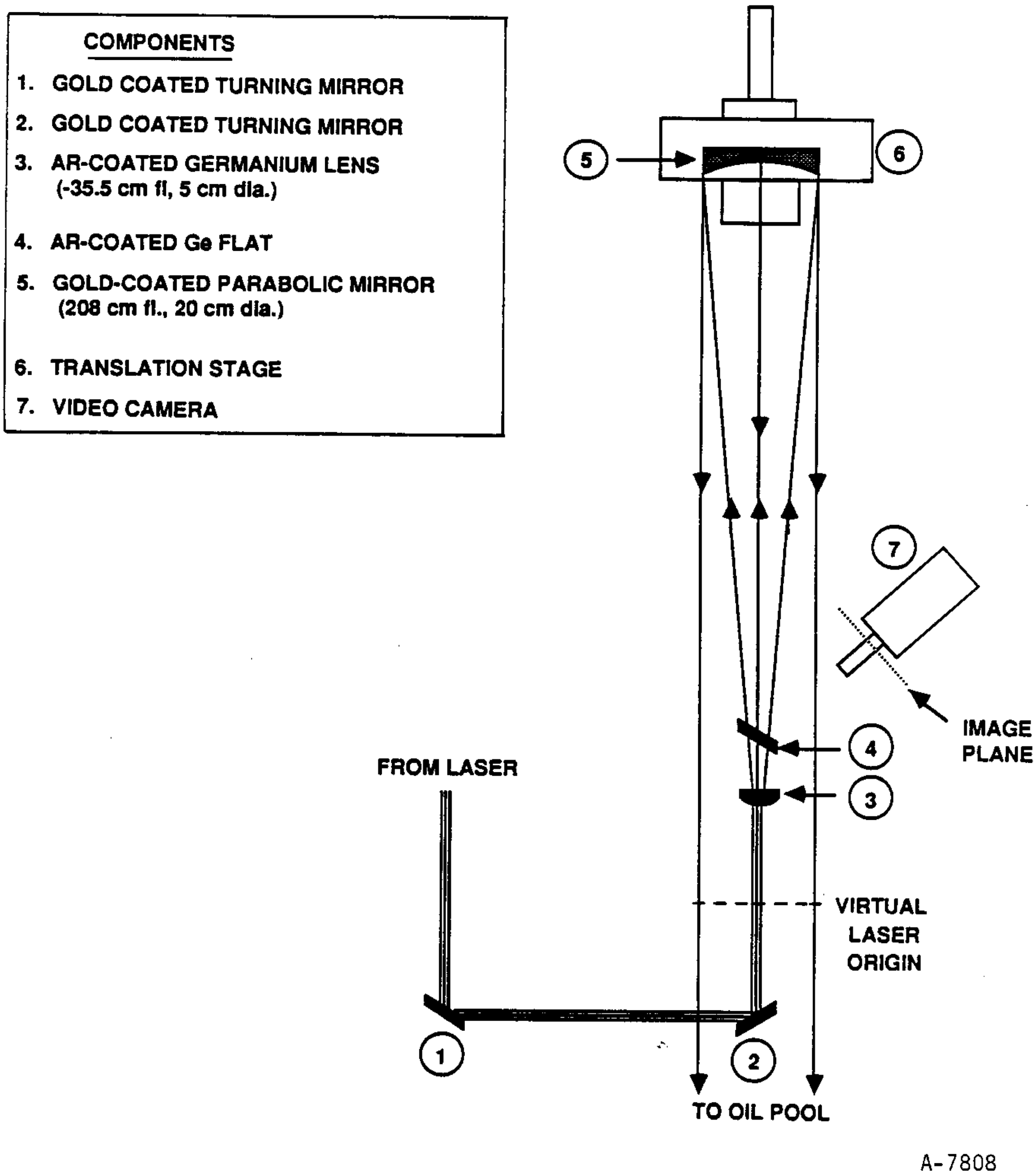

Figure 4. Laser-Focusing Telescope Configuration

assure ignition. The telescope is designed to produce, at its maximum range, a focal spot having a diameter which is roughly 1/2 that which is required. (At shorter ranges the focal spot is smaller, i.e., the fluence is higher.) As a result the theoretical depth of field is about 1m, indicating that the mirror must be positioned with an accuracy of about ±8 mm.

3.2 Oil Ignition Results

To test the ability of the focused laser to ignite fires over the entire 20 to 30m range the laser beam was aimed at an oil-filled petri dish located at a measured distance from the telescope's concave mirror. To achieve the required slant ranges and angles, a turning mirror was used to direct the laser irradiation onto the oil pool, as shown in Figure 5. In a helicopter-based system, larger flat mirrors at the telescope exit will serve the same function.

Focusing of the telescope and measurement of the depth-of-field was accomplished by the following procedure: The concave telescope mirror was first positioned such that the oil located at the selected range would not ignite. The mirror was then moved along the translation stage until oil would ignite with each laser pulse. (Ignition was defined as a brief flash of flame. Since the oil temperature was below the flashpoint, fires could not be sustained.) The mirror was then translated further in the same direction until ignition ceased. These two points are the outer limits of the depth-of-field. The position halfway between these limits was called the focus. Figure 6 is a plot of the focal distance as a function of mirror position. The sizes of the error bars correspond to the measured depth-of-field. The line is a theoretical calculation. Clearly, the agreement between the design and actual operation is nearly perfect.

Oil ignition at incident angles of 0 and 49 deg from vertical was verified at 20, 25, and 30m from the concave mirror. The depth-of-field at these three ranges is given in the following table:

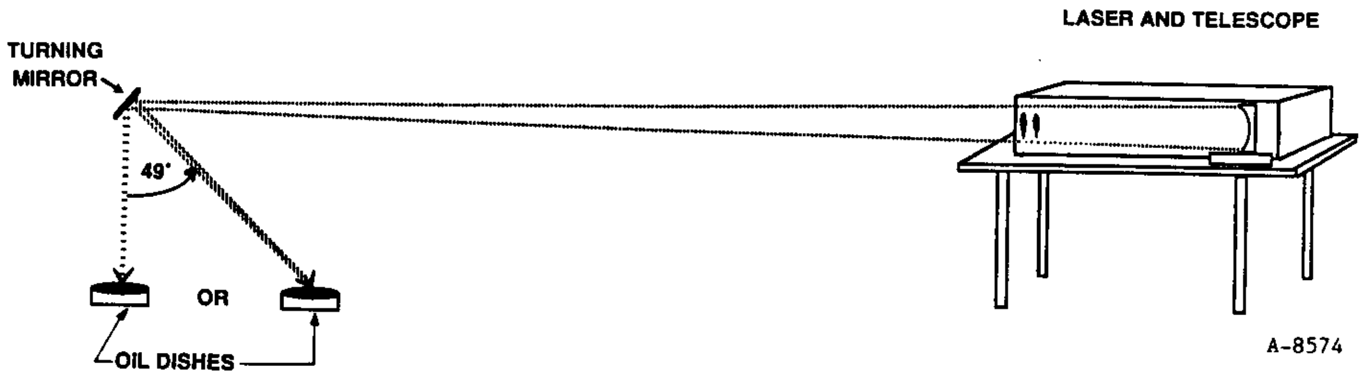

Figure 5. Setup Used to Test Oil Ignition at Required Slant Ranges and Angles

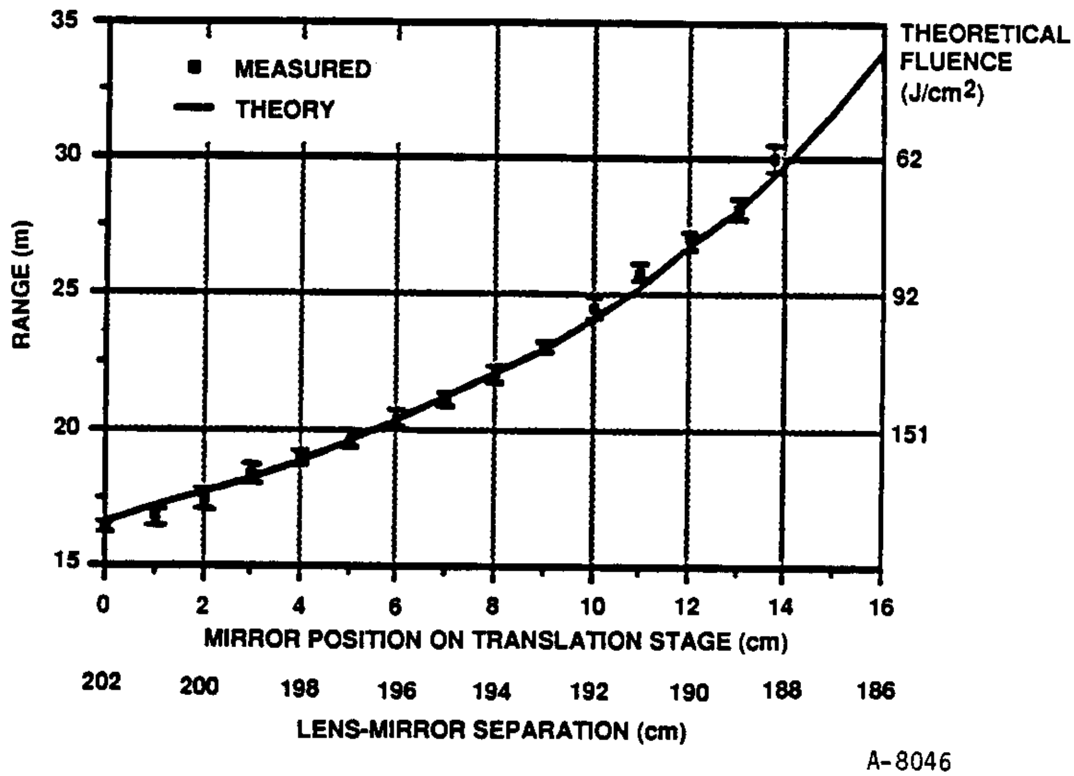

Figure 6. Slant Range from Telescope to Oil Pool as a Function of Relative Mirror Position

Distance	Depth of Field	Required Mirror Positioning Accuracy
20m	0.80m	1.0 cm
25m	0.98m	0.8 cm
30m	0.89m	0.3 cm

Note that these values are close to the theoretical depth of field calculated previously.

3.3 Focusing

There are several possible methods for automatically focusing the telescope. In previous work,[6] we had described two techniques, termed passive and active. The passive method observes an image of the oil pool through the telescope and varies the position of the concave mirror until the image is in focus, while the active method employs a direct measure of the distance between the telescope and the oil pool to calculate the appropriate mirror position. Active rangefinders are commercially available, but at a cost of about $20,000 for an instrument which might (or might not) be suitable for the LIOS application. During this phase, we explored the feasibility of developing a low-cost passive focusing system for use in a helicopter-borne LIOS system. We also considered a third, semi-passive technique which appears to hold the greatest promise for field use.

3.3.1 Passive Focusing Technique

Passive focusing works as follows: The diverging lens (component #3 in Figure 4) causes the pulsed laser beam to effectively originate on a plane located one focal length (35.5 cm) behind the lens. The telescope images this plane onto the oil pool. By symmetry, an image of the oil pool is formed by the concave mirror at the effective laser origin. This image is comprised of radiation from scattered sunlight and infrared energy emitted in response to heating by the lasers. It therefore has a fairly broad spectral distribution containing energy at wavelengths ranging from the visible to the far-infrared. Much of this energy is split from the laser beam's optical path by the germanium flat #4, which, although coated to transmit energy at 10.6 μm without reflection, is highly reflective for wavelengths shorter than about 5 μm. Thus, a visible/near-infrared image of the oil pool is located at the image plane shown in Figure 4. Focusing the telescope can therefore be a simple matter of adjusting the concave mirror position until the image of the oil pool is brought into sharp focus.

This technique makes manual focusing a simple matter of observing an image on a TV screen and turning a knob until the image is sharp, but a helicopter-deployable system requires high-speed automated focusing. We automated the passive focusing process by using a computerized image analyzer to determine when the image is at its best focus and employing that information to drive a motorized position controller which moves the concave mirror. In this technique, images are captured and digitized with a Data Translation Model 2851 Frame Grabber operating within a Compaq 286 personal computer. The frame-grabber generates a two-dimensional array of data corresponding to the brightness or intensity of the image at each of 512 x 512 pixels. These data are processed numerically to calculate intensity gradients along a set of intersecting lines, as shown in Figure 7. The position of best focus is defined as that position where the intensity gradient observed along a line within the image is maximized. One of the lines, that which has the largest gradients and thus contains the features having the highest contrast, is selected for the focus analysis.

To find the optimum mirror position, the telescope mirror is translated along its entire length of travel and the maximum intensity gradient along the selected line calculated as a function of mirror position. Typical results are plotted in Figure 8. The mirror is then returned to the position corresponding to the peak value of this curve, which is the position of best focus. The error bars in Figure 8 corresponds to the variation in the maximum

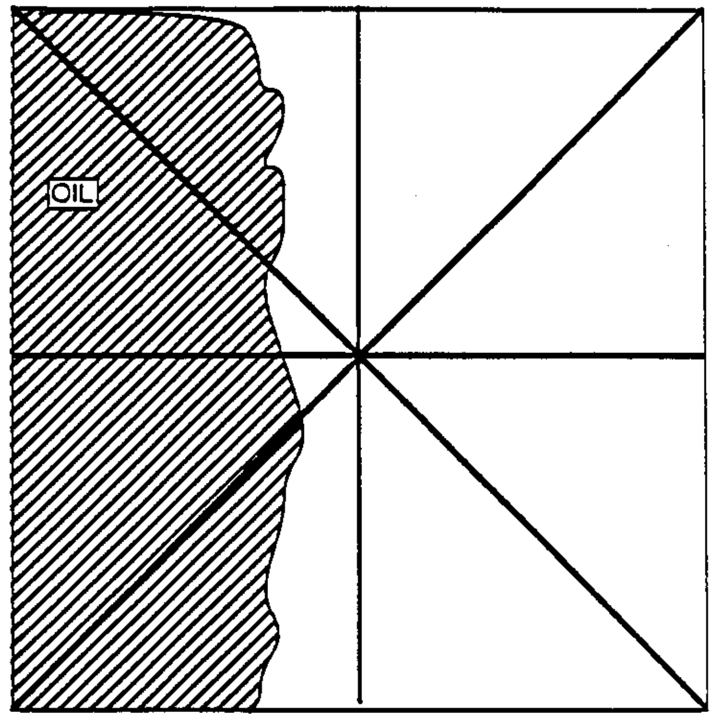

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Figure 7. Illustration of Method Used to Maximize Image Contrast. Intensity Gradients are Calculated Along the Indicated Lines

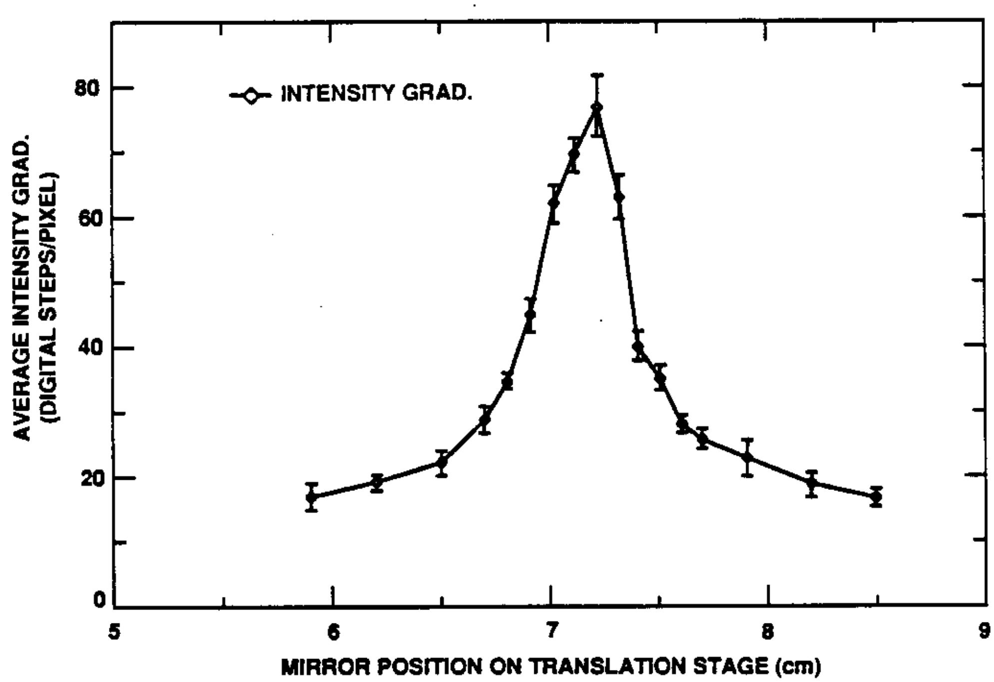

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Figure 8. Average Intensity Gradient Along a Line of Image Versus Mirror Position

intensity gradient measured over 10 trials. This variation limits the system's resolution to about ±1 mm. Tests have confirmed that, by using this algorithm, the mirror is positioned within ±1 mm of the position which would be calculated from a direct measurement of the distance to the oil pool surface, i.e., the position indicated by Figure 6. Figure 9 compares the calculated mirror positions with those determined using the passive focusing technique.

Passive focusing clearly provides excellent accuracy but only at the expense of speed and cost. It requires a dedicated computer with associated image acquisition and processing hardware and software. The equipment utilized in this program was borrowed, and has a value of about $10,000. Furthermore, analysis of the image is time-consuming and, if the oil pool moves out of focus, refocusing requires repetition of the entire algorithm. It is unlikely that the technique will operate fast enough to be useful in an airborne ignition scenario. An alternate technique, potentially capable of high speed operation and requiring only low cost materials is discussed next.

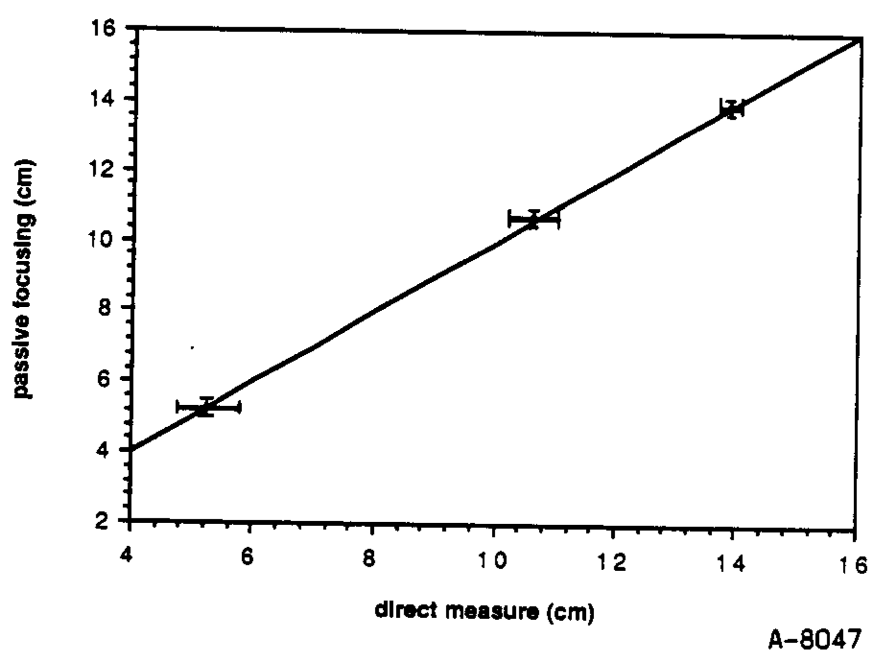
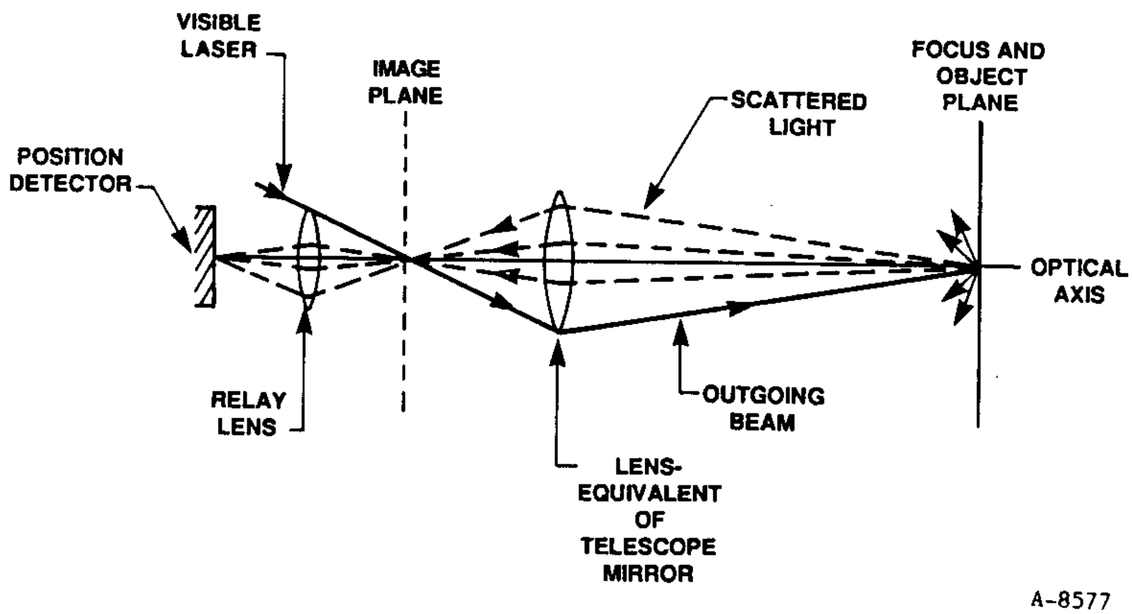


Figure 9. Position of Concave Mirror Determined by Passive Focusing Versus Position Determined by Direct Measurement of Effective Focal Length

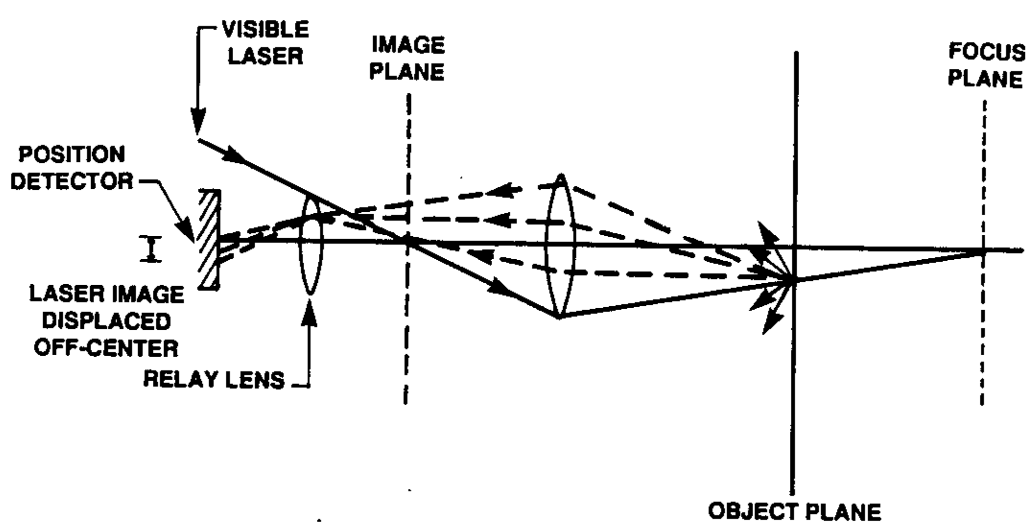
3.3.2 Semi Passive Point Triangulation Focusing Technique

The second focusing method investigated is a variation of the range-finding technique known in the robotics community as point triangulation. In this semi-passive approach, an auxiliary laser beam is directed through the telescope and onto the oilpool as illustrated in Figure 10a. A portion of the laser light which is scattered from the oil surface is collected by the telescope and used to determine the proper focusing, as follows: First, we define the "center" of any plane within the laser's path as the intersection of that plane with the telescope's optical axis. As described previously, when the telescope is properly focused a sharp image of the oilpool is formed in the image plane, i.e., the plane of the virtual laser origin. The implication of this is that, when the telescope is focused onto an oilpool or any other object, any light ray which passes outwards through the center of the image plane and thence through the telescope subsequently passes through the center of the object plane. The converse is also true. The outgoing laser beam can be thought of as one such ray, while the incoming laser light scattered by the object comprises many such rays. Thus, when the outgoing laser beam is set up to pass through the center of the image plane, it illuminates the center of the object. The light scattered by the object is collected by the telescope and imaged onto the center of the image plane.

To use this concept for auto-focusing, it is necessary that some readily measured change in the image of the scattered light occur when the telescope is out of focus. This is accomplished by directing the outgoing laser beam so that, though it passes through the center of the image plane, it also is reflected from the extreme edge of the telescope's focusing mirror. Then, as illustrated in Figure 10b, when the telescope is out of focus, the laser beam strikes the object off center. The scattered light then collected by the telescope is not perfectly imaged in the image plane, but forms a blurred circle having a centroid which is positioned off center. The position of the centroid is determined by the distance and direction by which the telescope is



(a) Telescope Properly Focused



(b) Telescope out of Focus

Figure 10. Point Triangulation Method

misfocused. By simply locating in the image plane the centroid of the scattered light, it is possible to determine exactly how far and in what direction the telescope mirror should be moved to focus properly! As a result, this technique offers the potential for high-speed focusing.

Attempts to implement this technique have so far met with limited success. The method was tested using a 2 mW He-Ne as the auxiliary laser, and a United Detector Technology Model SC-25D position sensing photodiode as the centroid detector. Since the He-Ne laser beam had to pass through the image plane, the detector could not also be located in that plane. Therefore, the scattered light was reimaged onto a secondary image plane using the relay lens shown in Figure 10.

The position sensing photodiode used was selected because of its immediate availability in our laboratory. It is a silicon-based detector having dimensions of roughly 19 mm square. The photo-generated charge is collected through four electrodes located near each of the outer edges of the electrically-resistive sensor surface. The difference in charge passing through the electrodes located on opposing sides of the detector is proportional to the displacement of the centroid of illumination from the center of the line joining the electrodes, while the sum of the charges is proportional to the total incident illumination. Thus the position of the centroid is determined by the difference/sum ratio.

Unfortunately, the detector and amplifier available to us were too noisy for the technique to function as well as desired. When the 2 mW laser is scattered from a perfectly reflecting but diffuse surface (as approximated by a piece of white paper), only about 1/100,000 of the laser power, or about 2×10^{-8} W is reimaged by the telescope. The noise equivalent power (NEP) of the detector is 10^{-11} W/Hz$^{1/2}$. Assuming negligible amplifier noise, this means that the detector must be filtered to a bandwidth of ~1 MHz, or the response time of the detector limited to about 1 μs, to achieve a signal-to-noise ratio of unity. Through this would seem adequate for our needs, the situation is confounded when the telescope observes scattering from an oil surface. In this case, the surface is not perfectly reflecting or diffuse, but is highly absorbing and quite specular. Thus, most of the incident laser power is either specularly reflected away from the telescope or absorbed by the oil. We have measured the backscatter from the oil surface, and found it to be 4×10^{-4} of that from a piece of white paper, or about 4×10^{-9} of the incident power. To observe this signal with the position sensing photodiode would limit the response time to about 6 seconds, clearly impractical for our needs.

Since this detector could not be used to focus on an oilpool, we attempted to test the technique by focusing on a piece of paper. Unfortunately, we found that 60 Hz noise in the amplifier completely obscured the signal. Rather than attempt to limit the amplifier noise (which would have required more effort than available resources allowed), we chose to increase the signal by specularly reflecting the laser beam back towards the telescope with a flat mirror, as shown in Figure 11. The reflected beam is equivalent to one ray of the scattered light returned from the object. Assuming that it does not reflect directly back onto the outgoing ray, the reflected ray is displaced in the image plane when the telescope is out of focus as described above. It therefore was useful for testing the speed at which the telescope can respond to changes in the object's (i.e., flat mirror's) position. Using this technique, we successfully demonstrated an ability to focus from one extreme of the telescope's range to the other in approximately one second.

This test demonstrated that the point triangulation method is able to focus fast enough for the LIOS application. However, to utilize it for focusing on oil pools, it is clearly necessary to increase the signal-to-noise ratio. Preferably, this would be done at low cost, implying the use of simple optical components. The signal can be increased by a factor of five simply by replacing the 2 mW He-Ne laser with one producing 10 mW, at a cost of US$1050.

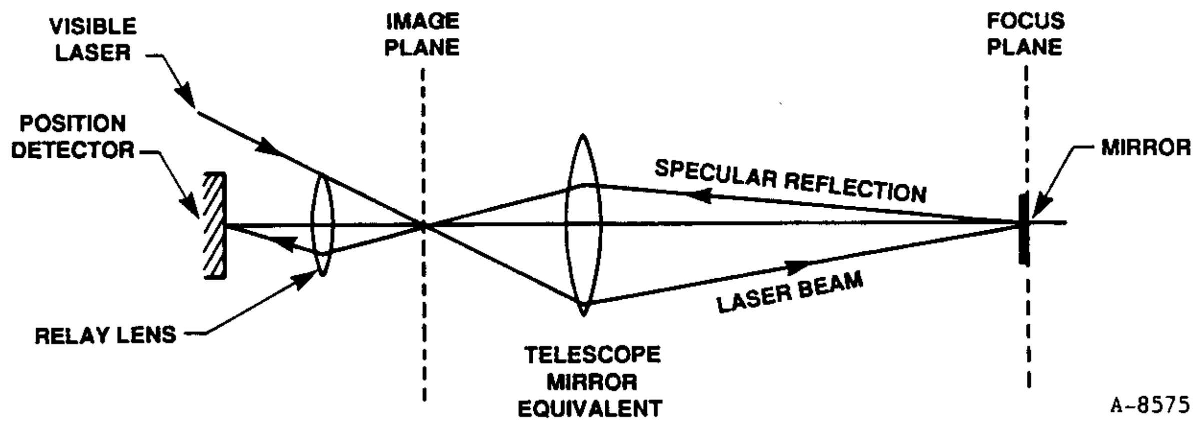


Figure 11. Telescope in Focus. Specularly Reflected Beam Used to Increase Signal

The noise can be reduced by using a small bi-cell photodiode rather than the position sensitive diode. The bi-cell simply provides an error signal which tells whether the centroid of the scattered light is to the left or the right of the detector's center. With careful analysis, limited position information can be achieved but is not necessary for this application. The NEP of such a detector is better than 10^{-13} W/Hz$^{-½}$, yielding a theoretical signal-to-noise ratio of at least 40 when used with the 10 mW laser and 25 Hz bandwidth. The cost of the components for the detector is about $300, though care must be taken during assembly to isolate the amplifiers from extraneous noise and to shield the optics from external light. Temporal modulation (i.e., chopping) of the laser beam may help distinguish it from the background and would allow the use of a lock-in amplifier or a fixed-frequency low bandwidth amplifier for good signal detection. We believe that this approach holds the most promise for high-speed, accurate, and low-cost auto-focusing. We hope to have the opportunity to test it in the future.

4. SUMMARY AND DISCUSSION

A laser focusing telescope suitable for igniting oil from a distance of 20 to 30m has been assembled and tested successfully. In addition, two techniques for focusing the telescope have been investigated. A passive focusing algorithm was automated by storing an intensity gradient function in computer memory and programming the computer to drive the mirror to the position of maximum intensity gradient. However, computation of the intensity gradients is rather time consuming, and it appears that this method would require several seconds to refocus the telescope after acquiring a new image. This period can potentially be reduced using custom-built analog electronics or a high-speed computer, but both alternatives may be expensive.

In contrast, the semi-passive technique known as point triangulation appears to offer the potential for high-speed focusing at low cost. Unfortunately, due to exhaustion of available resources, we were unable to fully develop this promising technique. The utility of point-triangulation may be compromised by signal-to-noise limitations, in which case it would be necessary to resort to active focusing. An active system uses a laser rangefinder to continually measure the distance to the oil pool and instruct a controller to properly position the focusing mirror based on precalibrated knowledge of a positioning curve such as Figure 5. In future work, we hope to further explore semi-passive focusing before making a final selection of the focusing system.

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REFERENCES

1. Lewis, E.L., Oil in Sea Ice, (Unpublished Manuscript), Pacific Marine Science Report 76-12, Institute of Ocean Sciences, Victoria B.C., June 1976.

2. Ross Environmental Research Ltd., Igniter Requirements for a Major Oil Spill from a Vessel in the Canadian Arctic, Environmental Emergencies Technology Division Report EE-56, Environment Canada, November 1984.

3. Frish, M.B., Simons, G.A., DeFaccio, M.A., and Nebosine, P.E., Laser Ignition of Oil Spills; Phase I: Concept Development, Final Technical Report, Physical Sciences Inc., Andover, MA, April 1985.

4. Frish, M.B., DeFaccio, M.A., Nebolsine, P.E., and Simons, G.A., "Laser Ignition of Arctic Marine Oil Spills", Oil & Chemical Pollution, 3, 355 (1987).

5. Frish, M.B., DeFaccio, M.A., Nebolsine, P.E., Nawwar, A., and Howard, D., Laser Ignition of Oil Spills; Phase II: Outdoor Demonstration, Final Technical Report, Physical Sciences Inc., Andover, MA and Arctec Canada Ltd., Kanata, Ontario, May 1985.

6. Kung, W.L., Frish, M.B., DeFaccio, M.A., Wong, J., Scholaert, H.S.B., and Nebolsine, P.E., Laser Ignition of Oil Spills Engineering Design, Report No. 3016, Aass Aerospace Inc., Downsview, Ontario, 1986.