Linear Phase Conjugation for Atmospheric Aberration Compensation

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Abstract

Northrop Grumman reports on a program utilizing Linear Phase Conjugation to compensate for atmospheric induced aberrations that severely limit laser performance. In a program to improve both the beam quality and laser energy delivered to the target, Northrop Grumman has developed a novel aberration compensation technique. This technique, hereafter referred to as Active Tracking System, utilizes a silicon Spatial Light Modulator as a dynamic wavefront reversing element to undo aberrations induced by the atmosphere, platform motion, or both. Northrop Grumman's aberration compensation technique results in a high fidelity, near-diffraction limited laser beam delivered to the target.

Introduction

Atmospheric induced aberrations can seriously degrade laser performance, greatly affecting the beam that finally reaches the target. This is especially true for propagation over long distances in the atmosphere. Lasers propagated over any distance in the atmosphere suffer from a significant decrease in fluence at the target due to atmospheric aberrations. This is primarily due to fluctuations in the atmosphere over the propagation path, and from the motion of the platform relative to the intended aimpoint. Also, delivery of high fluence to the target typically requires a low divergence beam, thus, atmospheric turbulence or platform motion results in a lack of fine aimpoint control to effectively keep the beam directed at the target. Northrop Grumman's Active Tracking System (ATS) continually tracks the target as well as compensates for atmospheric and platform motion induced aberrations. This results in a high fidelity, near-diffraction limited beam delivered to the target.

Energy deposited on target depends upon several factors including atmospheric turbulence strength, signal-to-noise ratio, and system latency time. With ATS, gains of one to several orders of magnitude increase in laser fluence at the target have been demonstrated. Additionally, a multitude of operational wavelengths may be addressed due to the linear system architecture, and powers well in excess of 1 kW can be routinely handled with the use of silicon-based SLMs. With ATS, as a result of the aberration compensation and target tracking capability, lasers operating with a very low divergence may be utilized. In this manner, a greater amount of laser energy is able to be delivered to the target. Some areas that can benefit from ATS include IRCM, EOCM, laser radar, and sensor damage countermeasures.

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Aberration Compensation Concept

The ATS concept is illustrated in Figure 1; its operation consists of two discrete steps. In the acquisition step, a low power illumination laser transmits a highly diverging beam to the target. Ideally, the divergence of this acquisition beam is matched to the uncertainty of the target direction. An OA return is received. This return is collected and interfered with a reference beam from the local oscillator (LO) on an integrating detector array (CCD) to form an electronic hologram. The hologram is read from the CCD array, processed, and written to the spatial light modulator (SLM).

In the engagement step, a beam from an engagement laser is reflected off the SLM. The SLM acts as a phase modulator and the reflected energy is contained in a beam that is the phase-conjugate of the target return. Now, this beam, which is the conjugate of the original beam, retraces the path to the target. During this time, any wavefront distortions are undone, thus resulting in near-diffraction limited energy delivered to the target. By continually repeating the acquisition and engagement steps, moving targets can be tracked (whether the target is moving relative to the platform or the platform is moving relative to the target) and compensation performed for time varying aberrations in the atmosphere.

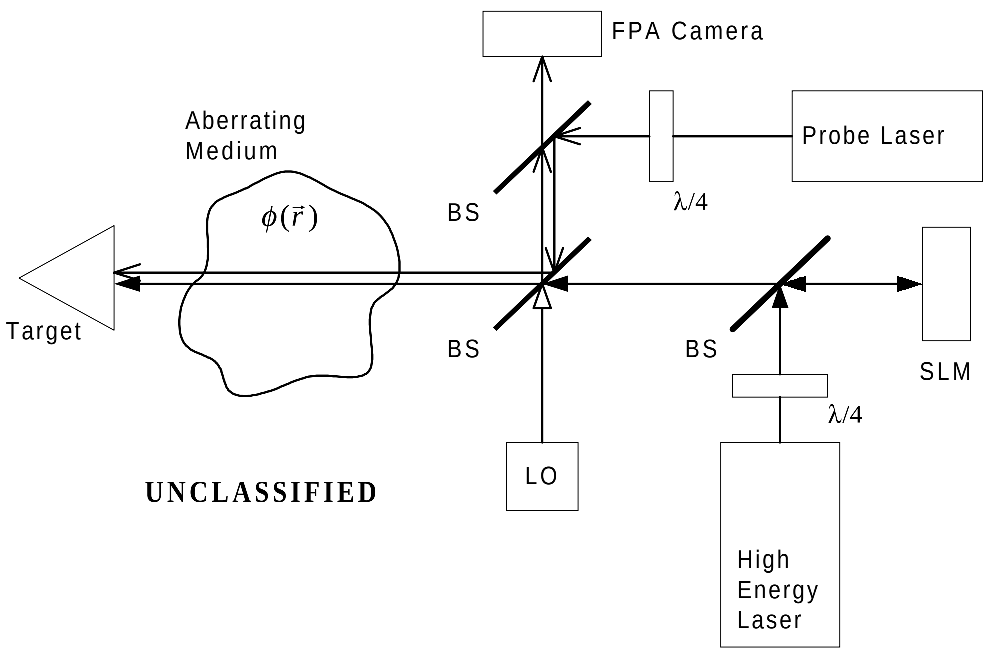

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Figure 1. Northrop Grumman’s aberration compensation concept

The maximum energy-on-target enhancement factor for the engagement laser is equal to the number of SLM pixels multiplied by the hologram efficiency. Thus, for 64 x 64 devices, and with a 0.4 hologram efficiency (the maximum efficiency for a plane, binary phase hologram) the enhancement factor is about 1640. Hence, the greater the number of SLM pixels, the greater the performance improvement that will be realized. Energy deposited on target depends upon several factors including, atmospheric turbulence strength, signal-to-noise ratio, and system latency time, but gains of one to several orders of magnitude can be expected

ATS provides automatic target acquisition within its field-of-view, as well as atmospheric aberration compensation. When compared to conventional adaptive optical schemes, there are no wavefront reconstruction algorithms required. Additionally, when compared to all-optical phase conjugation schemes that require very high optical amplification factors, up to 10^{15}, optical amplification of the target return is not required. The energy of the propagated beam is limited only by the engagement laser maximum energy and the SLM damage limit.

The homodyne process utilized in ATS exhibits the high gain of a coherent detection process without the field-of-view limitations characteristic of the heterodyne process. If desired, even greater sensitivity may be attained using a multiple-step "bootstrapping" process, whereby targets with a signal-to-noise ratio of much less than unity can be detected. It allows target acquisition with low initial photon counts. Bootstrapping is an iterative process that utilizes a sequence of pulses, each pulse corrected by the return from the preceding pulse. Here, the illumination laser is reflected off the SLM; even very noisy holograms will slightly increase the illumination energy on the target, resulting in a higher signal-to-noise ratio in the subsequent hologram. This iterative process typically converges to a maximum energy-on-target in three to four pulses. The bootstrapping process is depicted in Figure 2.

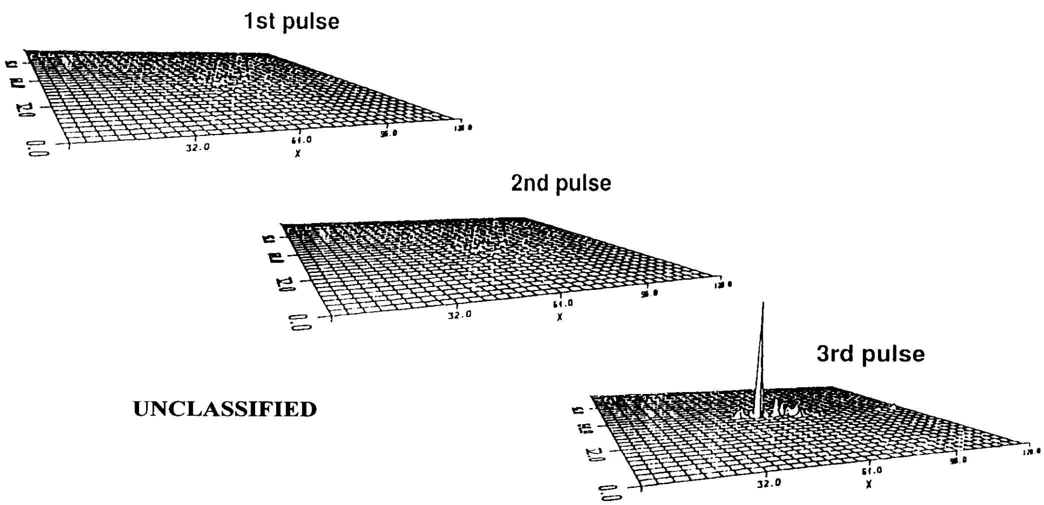

Figure 2. Bootstrapping Process

An advantage of ATS, when compared to all-optical phase conjugation techniques, is that the hologram that contains information about the target and the intervening medium is available in electronic form. This information can be stored in computer memory and processed to extract information about the target. With the very high processor speeds available, this may be performed very quickly. As an example, by computing the Fourier transform of the hologram, target direction relative to the optical axis is obtained. In cases where multiple targets are present, targets can be removed in the Fourier domain, thus allowing sequential target engagement.

Spatial Light Modulator and Electronics Subsystem

Northrop Grumman has developed a novel silicon SLM capable of displaying the phase information required for atmospheric correction. This SLM behaves as a dynamic wavefront reversing element to undo aberrations induced by the atmosphere, platform motion, or both. A hologram formed on a CCD array camera is transferred, pixel-by-pixel, to the SLM. This hologram, the conjugate of that formed on the CCD, contains both intensity and phase information about the intervening medium between the SLM and the target. Due to their close interaction, the CCD array, hologram processor, and SLM form a single subsystem. Their interrelationship is shown in Figure 3.

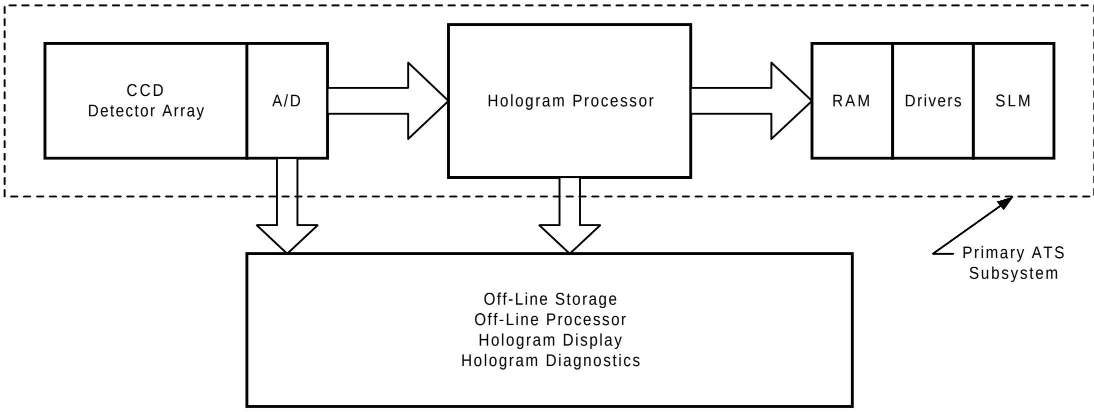

Figure 3. CCD Camera, Hologram Processor, SLM Subsystem

The SLM is fabricated by Northrop Grumman using silicon micromachining techniques. Figure 4 shows a diagram of the SLM constructed of a movable (deformable) diaphragm and a backplate to which an interconnect board and driver electronics are connected. The diaphragm is subdivided into N by N pixel elements; each element is supported from the backplate by an oxide grid. Individual pixel elements are etched with a flexure region, thus deflecting in a piston-like motion. In practice, the entire pixelated SLM behaves in much the same manner as a phased array antenna. The backplate, constructed from a flat, thick piece of silicon, serves as a support for the pixelated diaphragm and a structural surface to maintain device rigidity. Electrostatic attraction between the conductive silicon diaphragm (ground potential) and a deflection electrode requires a modest voltage ($\approx$ 20 volts) to achieve deflection. The electrical connection from a deflection electrode to the X-Y addressable electronics through the interconnect passes through a via under each element. Additionally, this via serves as a vent for critical (fluid) damping of the diaphragm.

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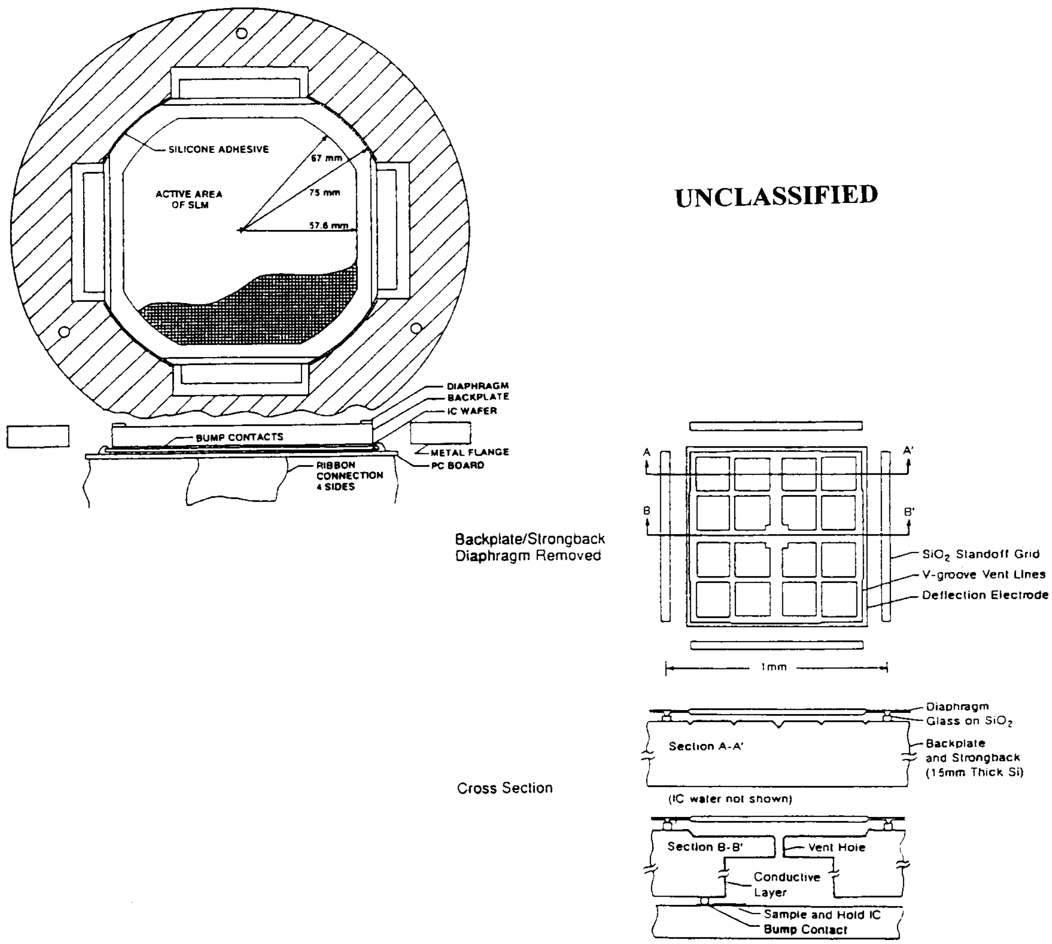

Figure 4. Design for N by N Pixel Silicon SLM

The N rows of the CCD FPA are read-out in parallel, converted from analog to digital signals, and written to the SLM. The detected hologram (digital FPA output) and the processed hologram (array written to the SLM) are stored electronically for post-processing, if desired. Mathematically, an expression for the intensity forming the hologram pattern is given by:

$$H(i,j) \sim \left|R(i,j)\right|^2 + o(i,j)R(i,j)^* + o(i,j)^* R(i,j) + \left|o(i,j)\right|^2 \qquad \text{Eq. 1}$$

where $R(i,j)$ and $o(i,j)$ are the complex electric fields of the reference beam and the object beam at pixel (i,j). The reference beam profile, the first term on the right, must be nearly uniform across the FPA array while the object intensity, the fourth term on the right, must be small compared to the reference intensity. The second and third terms contain information about the target and the intervening medium.

The homodyne detection SNR is given by the expression:

$$SNR = \frac{2n_R n_{o,rms}(T_o / T_R)}{n_R + n_{o,rms} + n_B + n_D + n_j^2} \qquad \text{Eq. 2}$$

where n_R, $n_{o,rms}$, n_b, n_D, and n_j are the number of photoelectrons due to the reference beam, the object beam, the background, the detector dark-current, and the Johnson/readout noise, respectively. T_R and T_o are the pulse width of the reference beam pulse and the object beam pulse, respectively. Ideally, these two pulse widths would be equal, but, in practice, $T_R > T_o$ in order to reduce the required accuracy of the target-return arrival time.

The primary function of the hologram processor is to subtract the reference intensity term as shown in Equation 1. This term represents the bias and can be subtracted since it does not contain any useful information. However, since its value is considerably larger than that of the information containing terms, this subtraction must be performed with a high degree of accuracy.

The dynamic range of the CCD array and, hence, the number of bits in the analog-to-digital (A/D) converter is dictated primarily by the requirement to keep the object beam, which acts as a noise term, small when compared to the other terms in the hologram expression. The magnitude of this term varies both spatially and temporally because of atmospheric scintillation. Analysis indicates that the minimum number of bits is about eight, with higher numbers desirable to improve performance and reduce the accuracy to which the target range must be known. The minimum CCD bucket size is primarily determined by the requirement that the Shot noise count due to the reference beam be greater than the noise count due to the other noise sources.

Performance

ATS presents several distinct advantages as compared to a conventional approach: 1) since most targets are found using OA, bootstrapping can permit a system utilizing this concept to lock onto targets incorporating significant cross section reducing CCM; 2) ATS acquisition beam may be several times wider than with a system not utilizing this technique, thus reducing pointing accuracy requirements with regard to the search beam; 3) there is a significant increase in the energy-on-target, thus minimizing engagement laser energy requirements (delivering a high fidelity, near-diffraction limited beam over the laser propagation path is essential to laser damage applications); 4) the automatic, vibration-insensitive, pointing capability eliminates the necessity for complex and expensive gimbals used in conventional pointing systems, and; 5) provision for sequential engagement of multiple targets within its field-of-view. Therefore, the output energy of the engagement laser may be significantly reduced, or, for a given engagement laser energy, the energy-on-target can be increased and the engagement range extended.

Figure 5 and Figure 6 show the fraction of energy-on-target without ATS and with ATS, respectively, for various degrees of atmospheric turbulence, C_n^2. Here, the transmit aperture is 10 cm and the target has a 5 cm receive aperture; the wavelength selected is 0.85 μm. Notice in Figure 5, the non-compensated case, that the energy-on-target decreases rapidly as the C_n^2 increases. Thus, for a C_n^2 of 10^{-13} at a 3 kM range, the energy-on-target would be 0.004 of that from the engagement laser. Now, for the compensated case, Figure 6, and identical conditions for a C_n^2 of 10^{-13} at a 3 KM range, the energy-on-target would be 0.2 of that from the engagement laser. Therefore, if 1 mJ of energy is required on target, the non-ATS case would require a 250 mJ engagement laser, while the compensated case would require only a 5 mJ engagement laser; fifty times more engagement laser energy would be required for non-compensated laser case. Indeed, this would have a significant impact on system performance and cost, especially if greater energy or range performance is required.

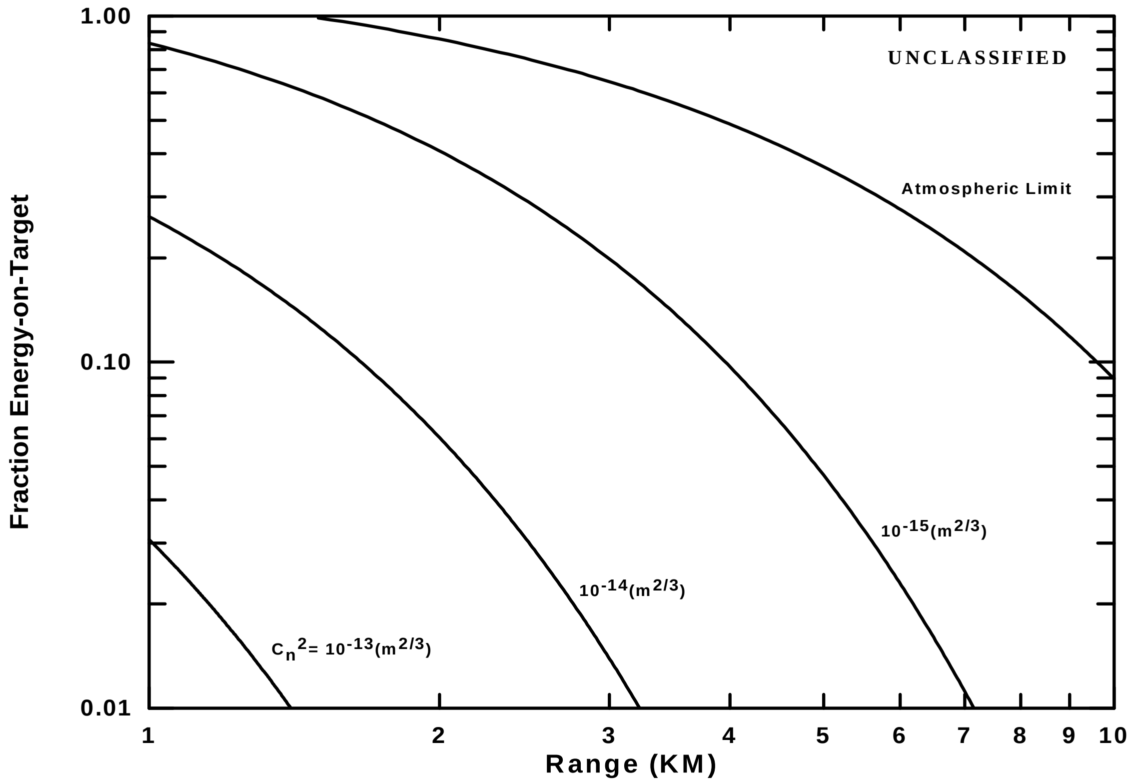

Figure 5. Typical Performance Without Aberration Compensation

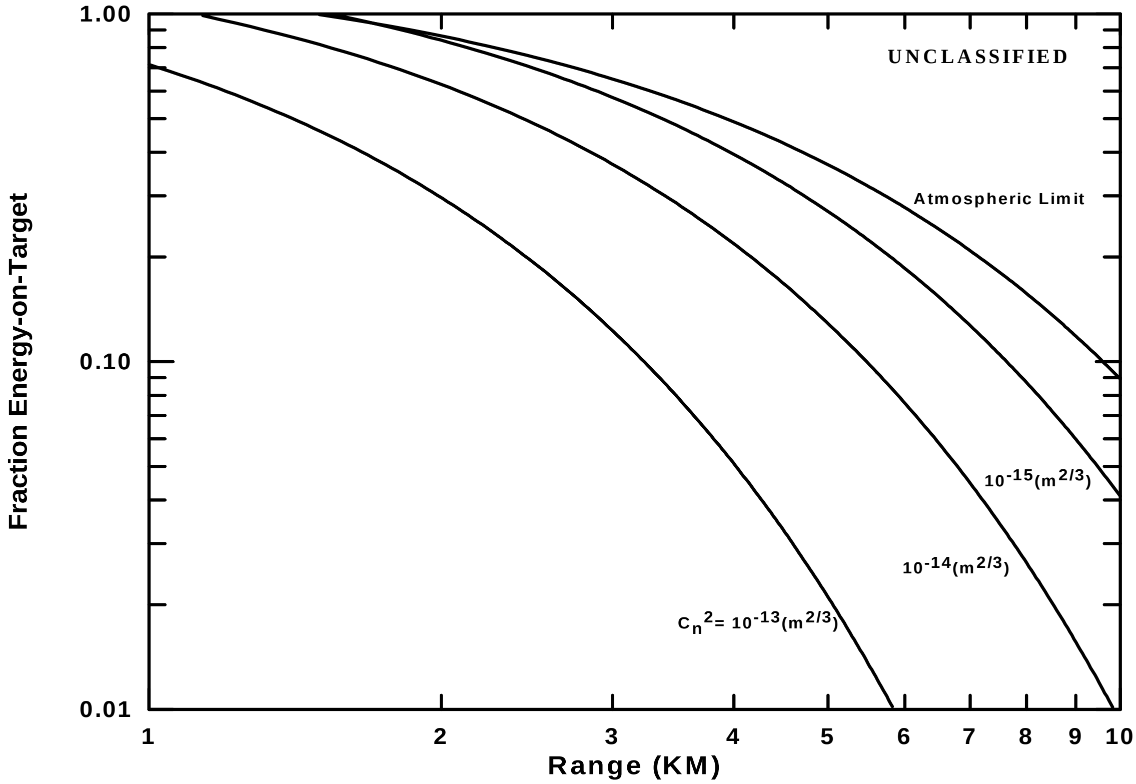

Figure 6. Typical Performance Without Aberration Compensation

Test Results

Analytical, simulated, and experimental results of Strehl ratio (peak intensity to diffraction limited peak intensity) as a function of SNR is shown in Figure 7. Here, excellent agreement was obtained between theory and experiment, even at SNRs as low as 0.1. The difference between the analytical results and the computer simulations is due to the statistical nature of the noise. Figures 8 and 9 show computer simulations and experimental data, respectively, for bootstrapped operation. The top row in each figure shows the hologram written to the SLM and the bottom row shows the resulting intensity distribution at the target plane. Experimental results are shown as an intensity profile through the peak intensity.

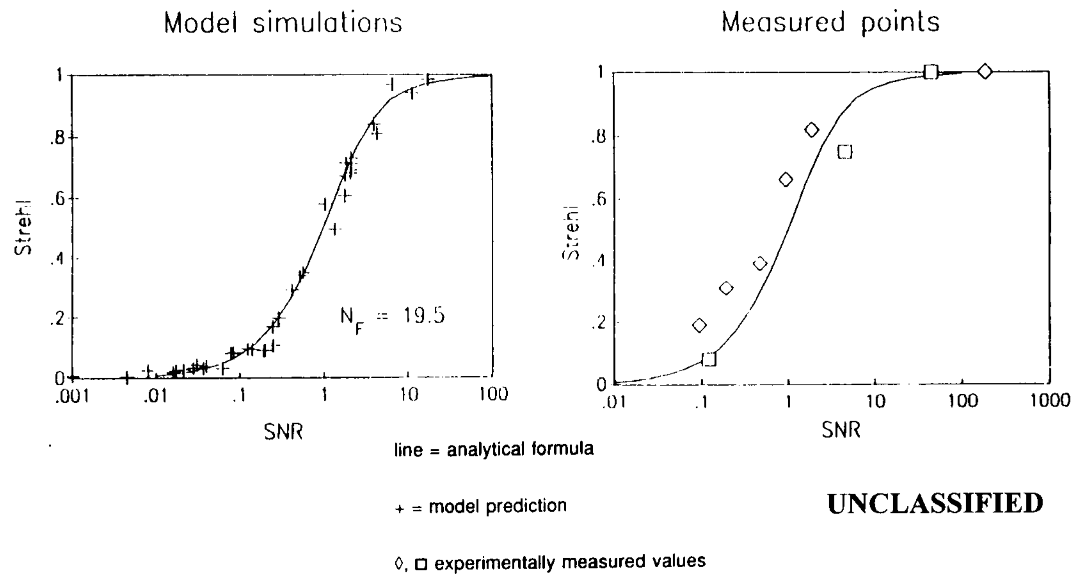

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Figure 7. Simulated and Measured Target Intensity versus SNR

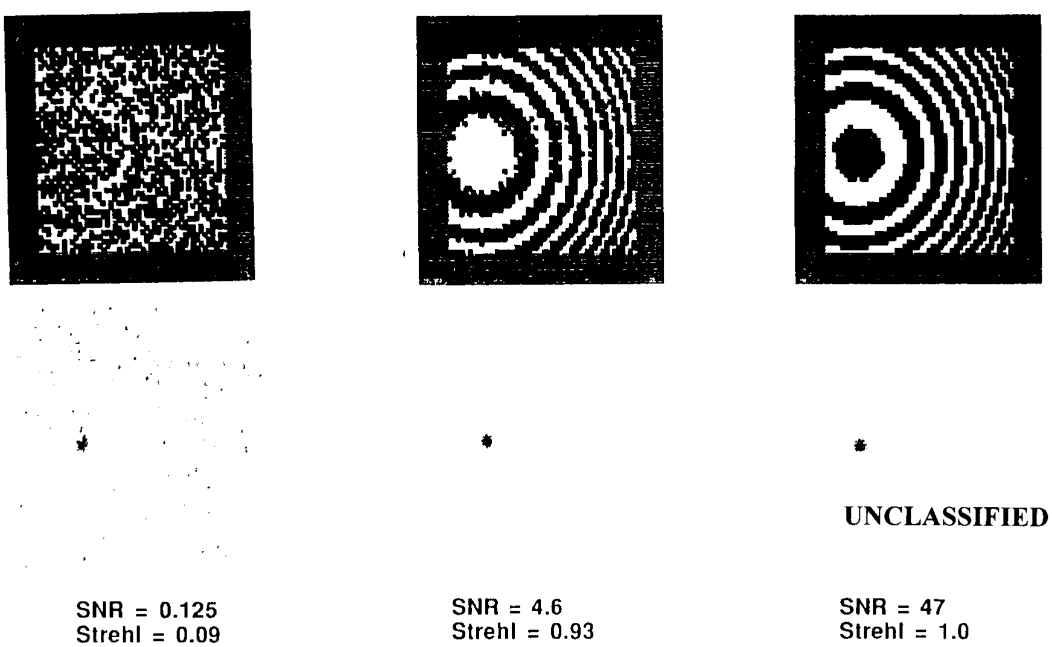

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Figure 8. Bootstrapped Operation Model Predictions

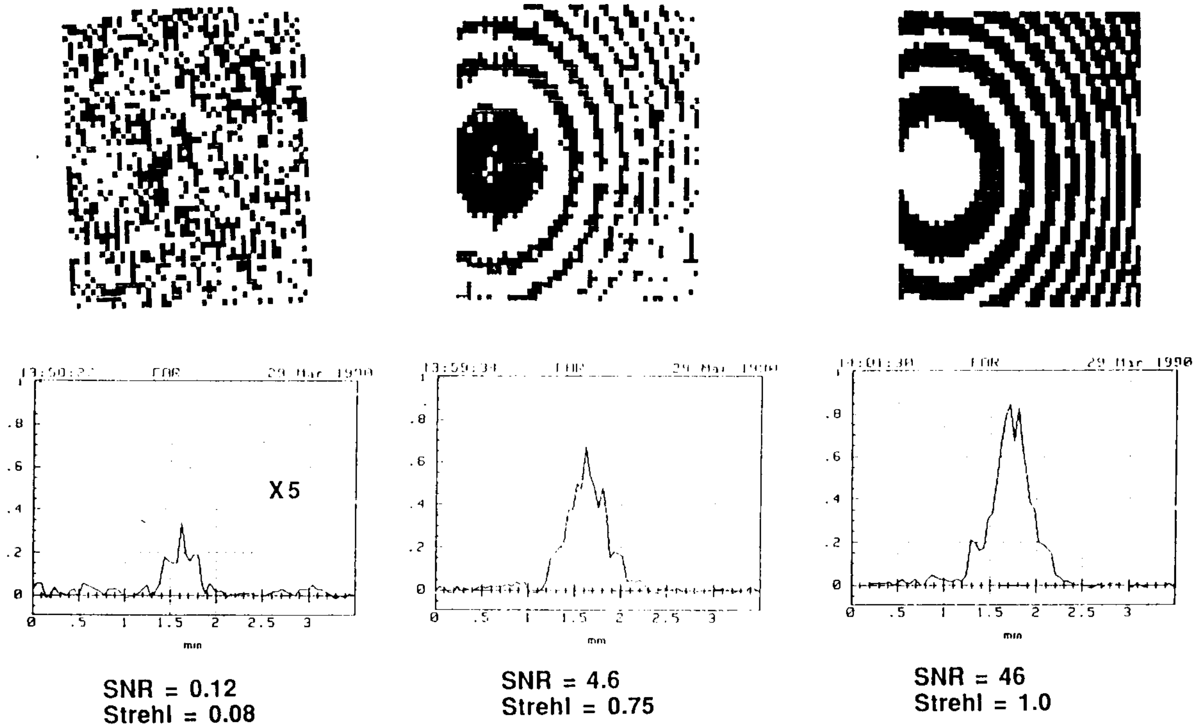

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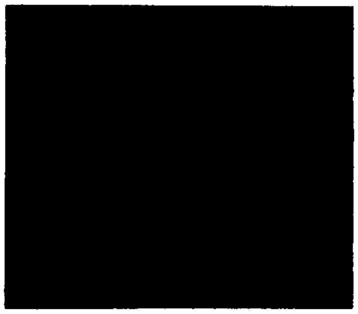
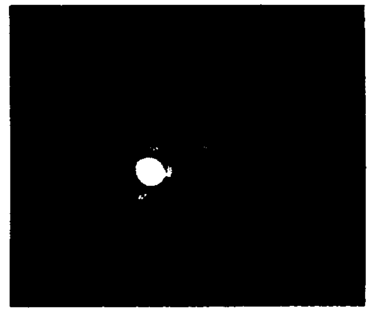
Figure 9. Bootstrapped Operation Experimental Results

Performance tests were carried out both during the daytime and at night to a range of 3 km; target acquisition tests were performed to a range of 5 km. Test objectives were to compare the performance of ATS with the performance of a non-ATS system, without aberration compensation. The goal was to demonstrate a five-fold increase in energy-on-target as compared to the non-ATS system. In actuality, more than ten-fold increase in energy-on-target was demonstrated. Figure 10a shows the variance in energy-on-target without ATS. It is important to notice how distorted the beam appears over the 3 km path. Figure 10b shows the improvement realized with ATS. Here, the near diffraction limited beam is clearly observed.



10a. Aberrated Farfield Image



10b. Improvement with ATS

Figure 10. Performance Improvement Realized with ATS

Summary

It is quite apparent that ATS can provide tremendous gains in increasing the laser energy delivered to a target. When coupled with a laser radar, IRCM, or EOCM system, a high fidelity, near diffraction limited beam is delivered to the target. In most cases, this translates into either an increase in energy on target for a given laser energy, or a reduction in laser energy required to deliver a specific amount of energy to the target. With ATS, laser size, weight, and cost may be reduced therefore making certain laser radar, IRCM, EOCM, and LIDAR applications feasible.