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High-Energy Hydrogen Fluoride/Deuterium Fluoride Laser Beam Correction: History and Issues

David Johannsen* **and Lorraine Ryan**
The Aerospace Corporation, P.O. Box 92957, Los Angeles, California 90009

and

John Albertine
Consultant, 109 Kingswood Road, Annapolis, Maryland 21401

We begin with a discussion of the history of attempts to correct combustion-driven high-energy laser (HEL) beams; these attempts have not tended to be as successful as hoped. After discussing beam control tests on MIRACL, a megawatt-class deuterium fluoride (DF) laser, we consider the conclusions of a Beam Control Maturity Assessment Panel (BCMAP)—convened by the now-terminated Space Based Laser Integrated Flight Experiment program—concerning the history of HEL beam control. We then discuss the results of the Alpha LAMP Integration (ALI) tests and what was and was not learned from those tests. Next we evaluate what was known from the wavefront sensor available as part of the Alpha Laser diagnostics suite and from high-frequency subaperture intensity data available from a mode beating experiment performed with Alpha. Taken together, these sources defined the need for a high-bandwidth measurement of Alpha subaperture intensity and tilt behavior, the defining requirements for the MHz Intensity and Tilt Sensor (MITS).

KEYWORDS: Deuterium fluoride laser, High-energy laser, Hydrogen fluoride laser, Laser beam control, Laser beam correction

1. Introduction

Development of very high power (100-kW-class and beyond) lasers was spurred by their potential as long-range, nearly immediate kill weapons. To be effective in this role, however, the quality of the output beam (relative to a diffraction-limited beam) needed to be good enough to be well focused on a target. Although a fairly poor-quality beam can be propagated over a few kilometers and still be focused onto the target, propagation at ranges of hundreds of kilometers or more requires a beam to be near the diffraction limit if a useful amount of power is to be focused on the target. The challenge, however, is that pushing lasers to produce the maximum power from a device of a given size has always resulted in degradation of the beam quality. To escape from this compromise between maximizing device power and retaining high beam quality, it has long been desired to reduce optical

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*Corresponding author; e-mail: david.johannsen@aero.org.

aberrations on the beam external to the lasing medium, either by measuring the phase errors on the beam and correcting them in the beam train or by using nonlinear materials to phase conjugate the beam. This paper discusses the former approach: its history, the implications of that history for plans to use hydrogen fluoride (HF) lasers in space, and the motivation for the MHz Intensity and Tilt Sensor (MITS) used to measure beam properties on the megawatt-class Alpha Laser.

2. Tests on MIRACL

The Mid Infrared Advanced Chemical Laser (MIRACL) was the first megawatt-class laser developed in this country, and it remains the highest-average-power laser yet demonstrated. A combustion-driven deuterium fluoride (DF) laser, it was originally developed by the Navy for short-range fleet defense, and its intrinsic beam quality, while mediocre, was adequate for the mission. In its role as a testbed, however, it was used to develop beam control technologies intended to improve the performance of chemical laser systems.

In 1986–1987, a local loop control system was tested as part of a larger program called SkyLite. It employed a cooled, 69-actuator deformable mirror (DM) known as HICLAS to correct the high-power beam. Wavefront sensing initially employed a pinhole filter, a point detector, and an uncooled 69-channel mirror to modulate a low-power sample of the beam in a multidither fashion and later used a 69-channel Hartmann wavefront sensor. This was an improved version of a system that had been developed in 1977 to correct gas dynamic CO_2 lasers.

SkyLite used a hybrid servo system developed to permit use of the HICLAS DM for both tilt and higher-order correction. This was an expedient decision, as there was no room on the bench for a separate fast-steering mirror (FSM). Extensive laboratory characterization was conducted prior to field testing with an electric discharge laser with static MIRACL-like irradiance and phase and applied beam jitter. Diffraction-limited performance was achieved (Fig. 1).

High-power tests were preceded by 15 "piggyback" tests with the corrector in a low-power sample of the MIRACL beam. These tests were used to explore parameter settings. Up to a 2.3-fold increase in peak irradiance and some decrease in the 63% flux area were achieved. Similar performance was obtained with only the $P_2(8)$ or $P_1(9)$ line being sensed through a pinhole as with all the lines. Six tests with the HICLAS DM in high-power beam were performed. In these tests, only power from $P_2(8)$ line was sensed. The tilt control system was integrated with the MIRACL alignment system. A factor-of-two reduction in tilt PSD out to 300 Hz was achieved. The higher-order wavefront correction resulted in a twofold increase in peak intensity, but there was no change in the 63% flux area (Fig. 2).

From 1993 to 1995, another series of SkyLite tests was performed with a 32 × 32 subaperture Hartmann wavefront sensor. High-power correction (tilt and wavefront) used the same 69-actuator HICLAS DM. Reference gradients, obtained with a low-power chemical laser (LPCL) alignment laser beam, were subtracted from the MIRACL gradients before reconstruction. This removed most of the noncommon path errors, assuming that the LPCL had flat phase. Difference gradients were ramped to zero for low-intensity regions. A digital phase gradient reconstructor provided a 17 × 17 phase map, and a programmable spatial filter was used to generate drives for the 9 × 9 DM. The wavefront control bandwidth was limited to 0–15 Hz by the low (40%)-charge transfer efficiency of IR charge-coupled device detector.

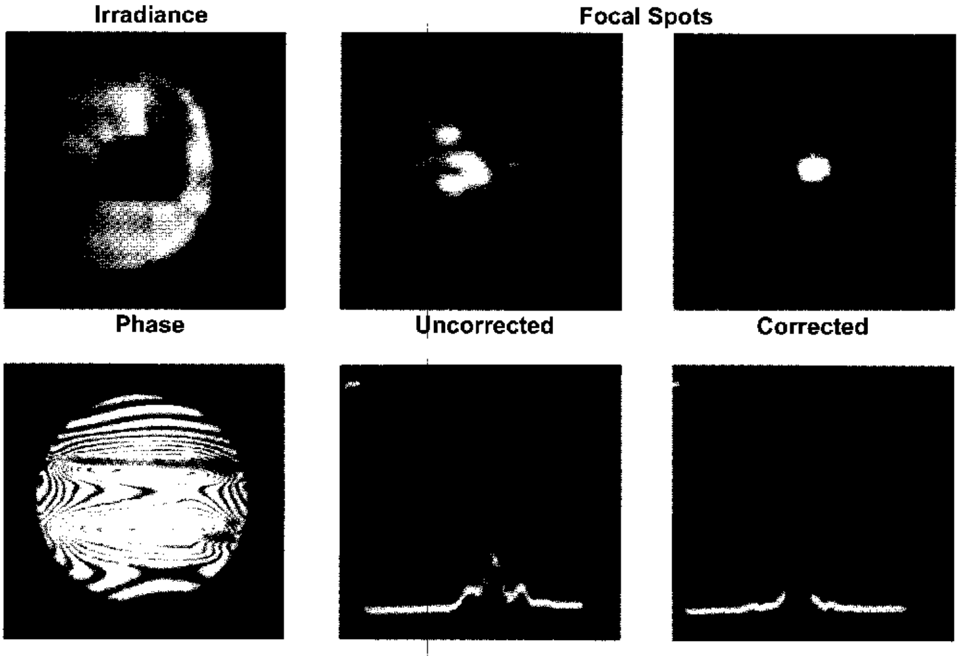

Fig. 1. SkyLite performance on an electric discharge laser with static, MIRACL-like irradiance and phase and applied beam jitter.

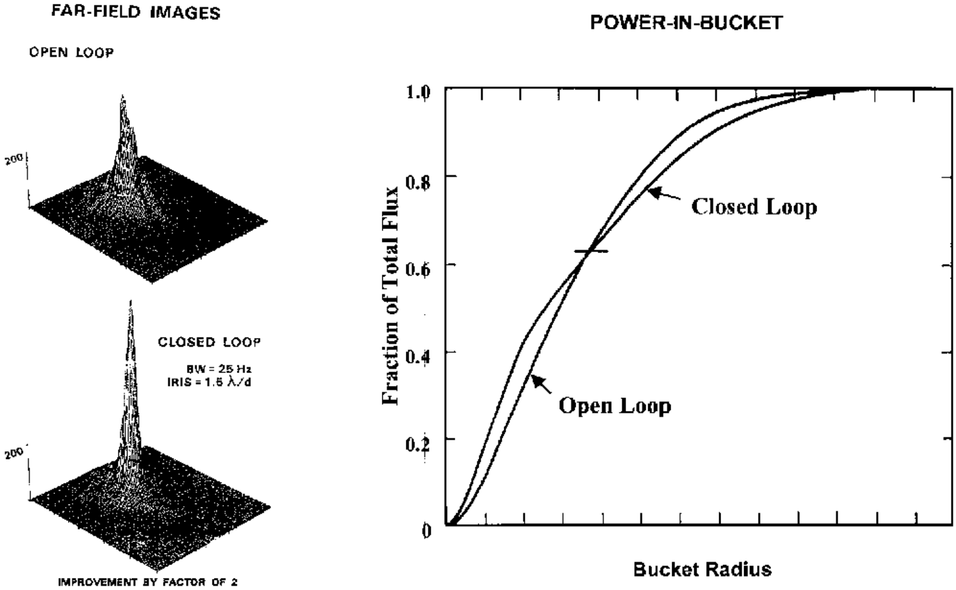

Fig. 2. SkyLite performance on the MIRACL beam.

This system participated in eight MIRACL tests, three taking passive (open-loop) data only and the others with ~8 s for loop closures at the end of each test. The wavefront sensor used only the $P_2(8)$ line except for the last test, which was done on all lines.

Consistent jitter correction out to 300 Hz was achieved with a 2.5-fold reduction in rms azimuth and elevation. Wavefront correction was a mixed success. In test 1 a 2.5-fold increase in peak irradiance was observed when the loops first closed, but the correction degraded with time. This was attributed to poor control of the actuators in the low-intensity regions. In test 2 a gradient processor modified for better edge control resulted in stable loop closure, but no far-field data were obtained due to a camera failure. In test 3 the use of a 3 × 3 spatial filter provided a 1.25-fold improvement in peak irradiance and a 25% decrease in the 50% flux area. In test 4 the sensor was improved, but no improvement was seen with the loop closure. Posttest computer propagation with the phase measured by the closed-loop Hartmann sensor predicted that a fivefold increase in peak irradiance should have been seen. This points to the need for an independent sensor to score performance!

3. Beam Control Maturity Assessment Panel

In 1999 the Space Based Laser (SBL) Program Office at the Air Force Space and Missile Systems Center, which was managing the (since canceled) SBL Integrated Flight Experiment (IFX) for the Ballistic Missile Defense Organization (BMDO), chartered an expert panel to assess the readiness of high-energy-laser-beam-control technology to support the IFX program. This Beam Control Maturity Assessment Panel (BCMAP) was chaired by John Albertine and included members from the Department of Defense, Federally Funded Research and Development Centers (FFRDCs), and industrial contractors. Although the panel considered all aspects of laser beam control, we will discuss only its findings regarding beam correction.

In evaluating the tests performed with MIRACL, the BCMAP concluded, "Multidither and Hartmann sensor local-loop systems provided near diffraction-limited corrections with multi-line electric-discharge lasers, but modest improvements with combustion-driven high-power lasers." As "Plausible Explanation[s]" they offered "System corrected low spatial and temporal frequency errors, perhaps mirror heating and some aero effects in laser medium" and "Higher spatial frequencies have higher temporal frequencies, so no benefit in increasing bandwidth without increasing actuators."

In assessing what was unknown about correcting high-power chemical lasers, the BCMAP concluded as follows:

- What is the spatial and temporal spectrum of wavefront errors?
  - Are there significant variations from line to line at higher frequencies?
- Will subaperture power fluctuations limit ability to accurately sense wavefront errors at the (high) frame rates needed for correction?
  - How coherent is the wavefront?
- Is it sufficient to justify investment in expensive correction system?
- How will the measurement of high-spatial-frequency wavefront errors be affected by instrument limitations (dark current, read noise, accuracy and stability of slope calibration, threshold settings) and the overall magnitude, gradients, and temporal variations in the in-band background?
- Note: Resonator codes and system optical quality codes have not been reliable enough to provide this information

- In the absence of such information, previous systems have been built with the best available technology, constrained by budget, schedule, and interface considerations (space, electrical power, thermal control, etc.).

Recommendations for future local loop systems were as follows:

- More diagnostics on laser needed before designing system.
  - Spatial and temporal spectrum of tilt and wavefront errors.
  - Power spectrum of subaperture intensity fluctuations.
  - Phase coherence over aperture (two-pinhole experiment).
  - All of above: single lines and all-lines, and over power range of interest
- Best choice, based on current understanding:
  - Design Hartmann sensor, with at least 6 × 6 pixels per subaperture.
  - Design bandwidth and N_{sa} based on laser diagnostics.
  - Sense all laser lines to minimize effects of single-line fluctuations.
  - Use separate high-power FSM and DM.
  - Use independent jitter sensor and far-field camera for scoring.
  - Use near-field irradiance monitor in low-bandwidth loop to select edge actuator control and select best reconstruction matrix.
- Big payoff in characterizing system in laboratory:
  - Tailor irradiance distribution to look like high-energy laser (HEL) distribution.
  - Introduce irradiance fluctuations, wideband tilt and higher-order aberrations simultaneously.
- Conduct HEL test in stages:
  - Open-loop characterization prior to closed-loop tests.
  - Plan on enough tests to understand and optimize performance.

4. Alpha Lamp Integration

Following the cancellation of the Zenith Star SBL flight demonstration in the late 1980s, the Strategic Defense Initiative Organization (SDIO) decided to integrate the megawatt-class Alpha HF laser (which was designed for space vacuum operation), the beam control technologies developed under the Large Optics Demonstration Experiment (LODE), and the 4-m-diameter primary mirror built under the Large Advanced Mirror Program (LAMP) into a functional ground demonstration of SBL beam control. This was known as the Alpha LAMP Integration (ALI) program.

Figure 3 shows the LAMP mirror in its ALI configuration (the Griff Telescope) as a beam director. With the closeout of the Alpha, ALI, and IFX efforts, the LAMP mirror is being transferred to the Air Force Academy, where it will become an astronomical and space surveillance telescope. This is also shown in Fig. 3.

The ALI system used 202 holographic optical elements (HOEs) on the LAMP mirror to pick off a small amount of the power in the HF $P_1(7)$ line and direct it through a hole in the center of the secondary and onto a Hartmann wavefront sensor (Fig. 4).

Four high-power tests were conducted. Test HL410 was a short test of system safety. HL420 closed the jitter control loop. HL430 closed the beam correction loop with a water-cooled DM. The final test, HL440, closed the correction loop with a new, uncooled DM.

Unfortunately, some of the 202 subapertures were obscured (by support struts and the feedback hole), and many others were usable only part of the time due to varying subaperture signal-to-noise ratios. The Alpha laser was originally designed to have 5 m of gain, but for

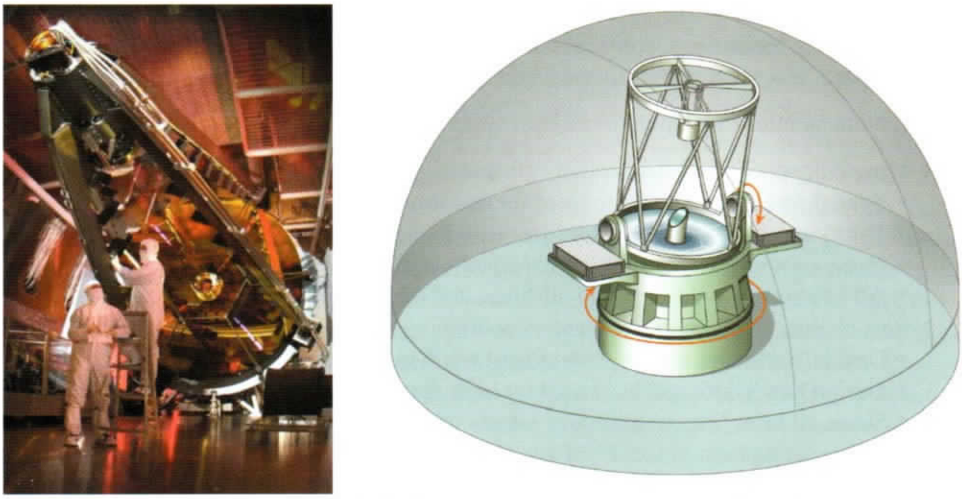

Fig. 3. Left: ALI beam director (Griff Telescope) employing the 4-m LAMP mirror. Right: U.S. Air Force Academy design for reusing the LAMP mirror in an astronomical and space surveillance telescope.

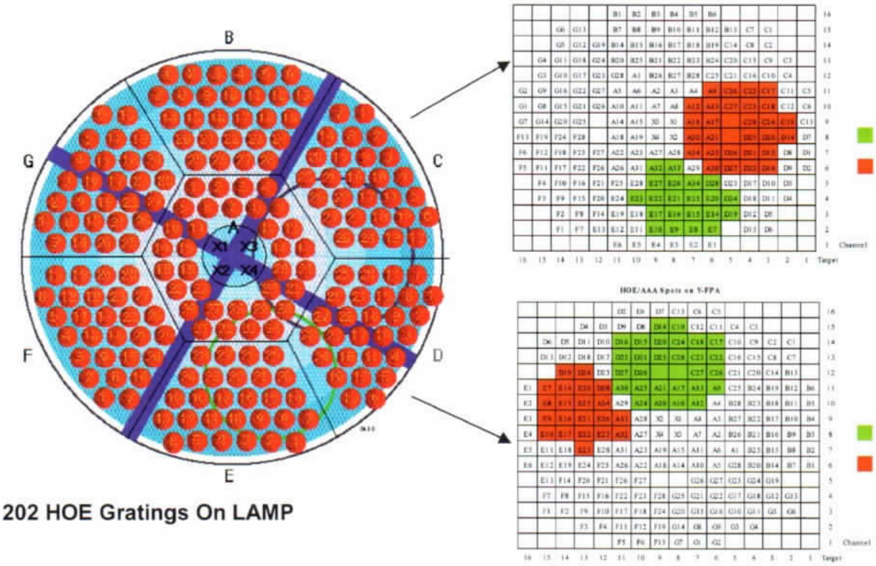

Fig. 4. HOE map on the LAMP mirror and on the wavefront sensor.

cost reasons was built with 2 m of gain. The result of this was a reduction in saturation, which led not only to a factor-of-three reduction in total power but also to a less uniform beam, both spatially and temporally. Figure 5 shows the near-field intensity pattern from the HL910 test adjusted to the beam orientation on the LAMP mirror as well as the HL410 beam as scattered from the LAMP surface. (HL410 was the first high-power beam placed on LAMP. HL910 did not propagate the beam to LAMP, but the near-field intensity pattern is

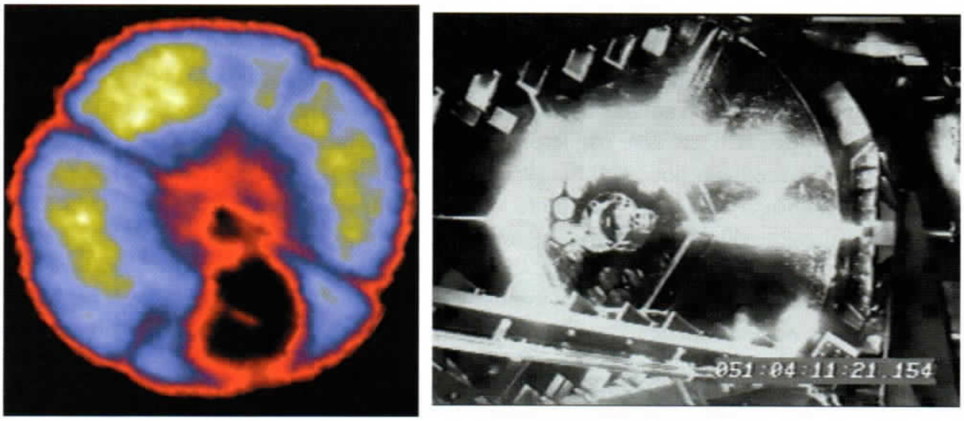

Fig. 5. Left: Alpha near-field intensity pattern as projected on LAMP. (The HL910 image is used for illustration, although HL910 did not propagate the beam onto LAMP.) Right: Infrared image of HL410 beam on LAMP (March 20, 1997).

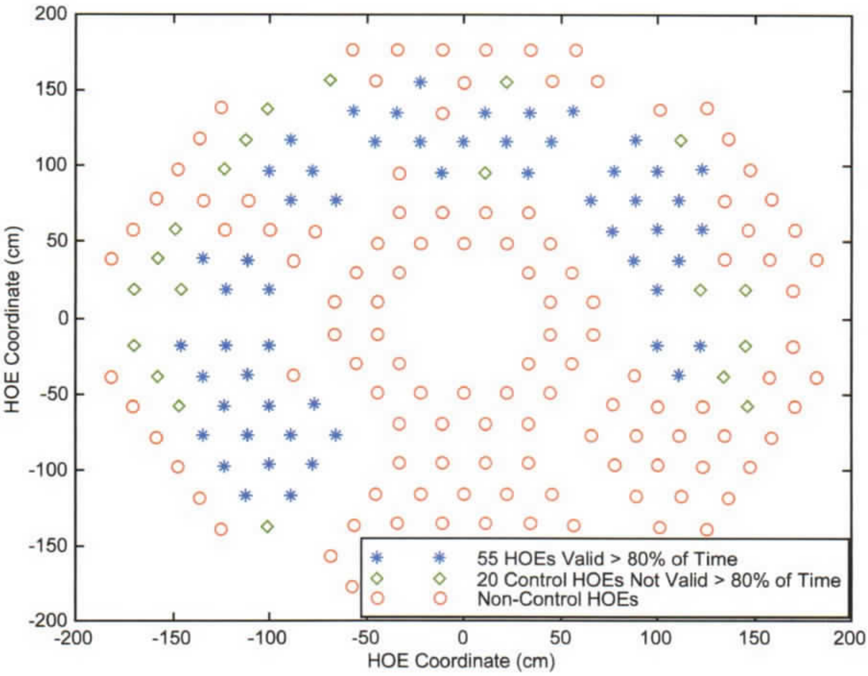

Fig. 6. Map of control HOEs.

representative of the Alpha beam.) Of 175 unobscured HOEs, only 55 had sufficient signal to use more than 80% of the time, with another 20 usable less than 80% of the time. Figure 6 shows the map of these HOEs.

The reported results showed correction to within 15% of the program goal. (The specific goal was classified.) This result must be taken cautiously, however. The wavefront control sensor was used for scoring, and there was no independent truth sensor. This meant that any actual wavefront errors that, for whatever reason, could not be measured by this sensor would not be seen as residual error by the scoring system. The same would have been true of errors induced on the beam due to imperfections in the wavefront control sensor itself or due to its misalignment relative to the primary mirror (and, hence, the HOEs). What was ultimately measured was how well the system corrected perceived wavefront error, not the final beam quality. It also was based on reconstructing the wavefront from a limited subset of subapertures, as discussed above. As a result, we are not certain how well the system actually performed. While it appears that the quality of the beam was improved, the lack of a full (4-m) aperture truth sensor made it impossible to accurately quantify the resulting beam quality. There was an independent wavefront sensor measurement of a 1.5-m subaperture of the beam, and the result was similar to that seen in the same subaperture in the control wavefront sensor. Both subaperture results, however, showed worse corrected-beam quality in the subaperture compared to what the control wavefront sensor measured over the full aperture, and so it is difficult to draw conclusions about the full-aperture-beam quality.

5. Measurement on the Alpha Beam

Over the years various measurements were made on the Alpha beam to try and understand its correctability. It is important to note that low temporal and spatial frequency aberrations should be relatively easy to correct, so that ultimate performance is determined by the high-temporal and high-spatial-frequency components of the beam.

Alpha output beam wavefront errors were measured with a rotating grating wavefront sensor. This device was originally designed to drive a low-bandwidth correction loop and was never intended to provide a comprehensive measurement of the Alpha beam. Although it sampled the wavefront at 6 kHz, data from this wavefront sensor seem to show a noise floor between 200 and 300 Hz, depending on the signal. Because there is device- and facility induced structure on the beam out to 100 Hz or so, these data are only able to hint at a $1/f^2$ roll-off in the subaperture slope PSD and in the reconstructed wavefront error at high frequency. An example from HL912 is shown in Fig. 7.

Higher frequency measurements of subaperture intensity were made. As far as is known, slope and intensity variation arise from the same underlying sources and so are expected to have the same roll-off at high frequency. A high-bandwidth-intensity detector was installed to measure an intracavity subaperture. When the feedback for the unstable resonator was fed back in to the laser, it was expanded off of a conical optic. To avoid placing power on the tip of the cone, a 1-cm piece of the beam was cored from the feedback. Of this, a 1-mm sample was measured with the intensity detector. There is no reason to believe that the behavior of this part of the beam was any different from that of the outcoupled beam. The original purpose was to observe the beating of the longitudinal modes at 6-MHz intervals out to about 30 MHz and to confirm that multiple transverse modes were not present. The electronics were later upgraded to allow sampling at 1 GHz, which produced a PSD useful to about 250 MHz. Data storage capacity limited the sample to 30 μs; therefore the data are valid only for high frequencies.

The results were somewhat ambiguous. There is possible structure in the few-megahertz regime, but there is also a lot of noise in this regime. The mode beating is obvious and dominant where it is expected. For higher frequencies the roll-off actually appears to be faster than $1/f^2$. One fit put it at $1/f^{2.8}$. See Fig. 8.

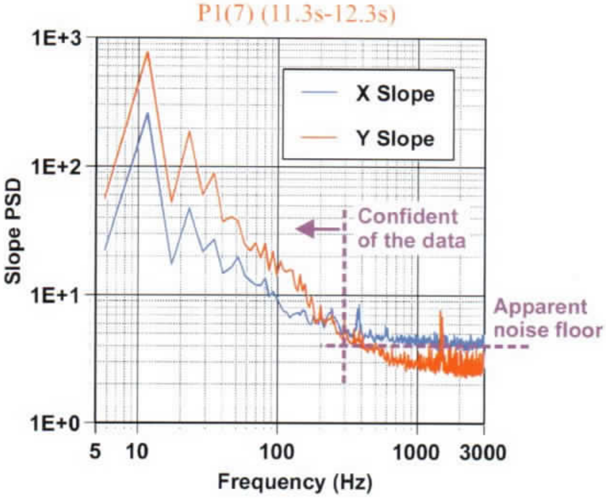

Fig. 7. Example of an Alpha (HL912) tilt PSD from the diagnostic wavefront sensor, showing the apparent noise floor beyond ~300 Hz.

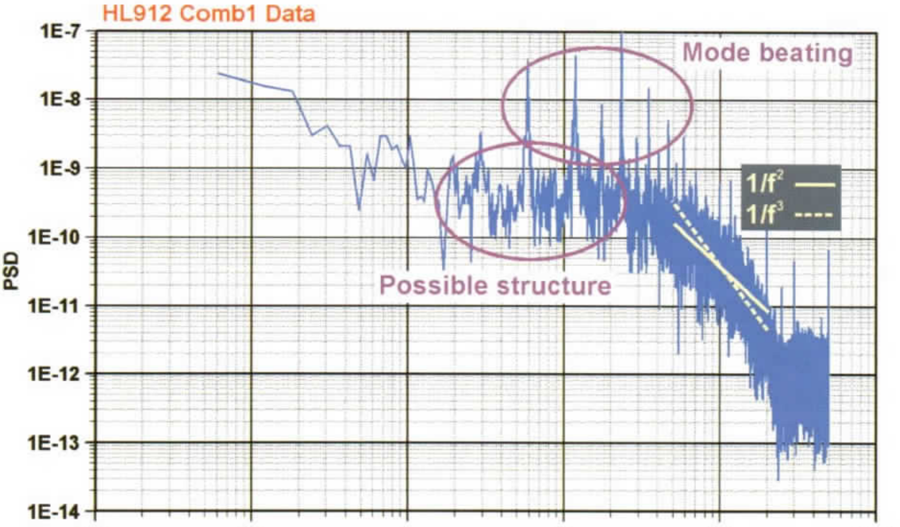

Fig. 8. Annotated intracavity subaperture intensity PSD (HL912) showing mode beating, possible structure at megahertz frequencies, and roll-off at high frequency.

6. Why Understanding the High-Frequency Behavior Is Important

In principle, the aberrations on a laser beam could have content at all spatial and temporal frequencies, but physical size and timescales associated with the generation and propagation of the beam result in a rapid roll-off for high frequencies. A wavefront sensor will have the

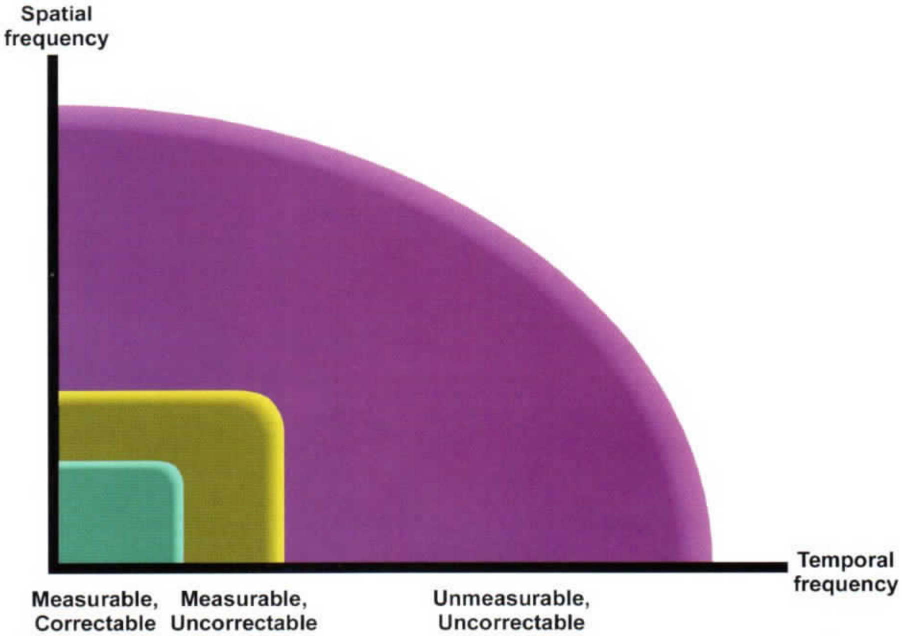

Fig. 9. Only part of the WFE on a laser beam is measurable, and of that only part is correctable.

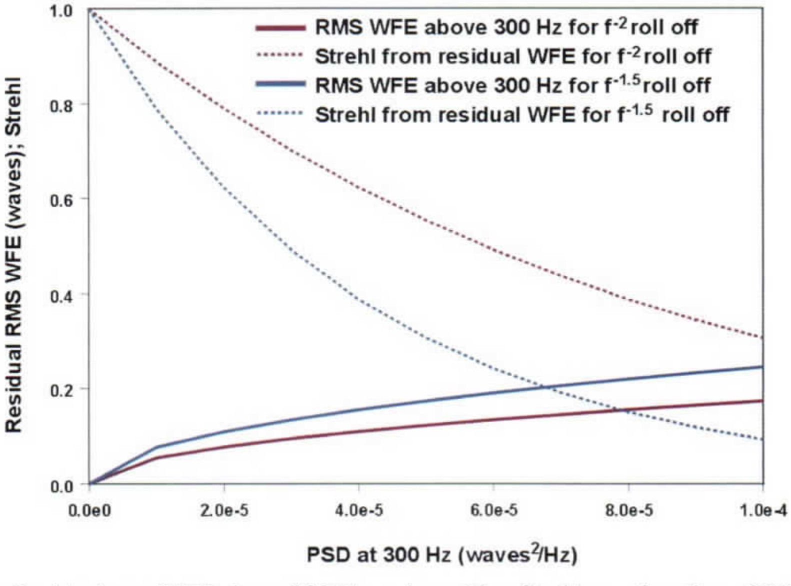

Fig. 10. Residual rms WFE above 300 Hz and resulting Strehl as a function of WFE PSD at 300 Hz.

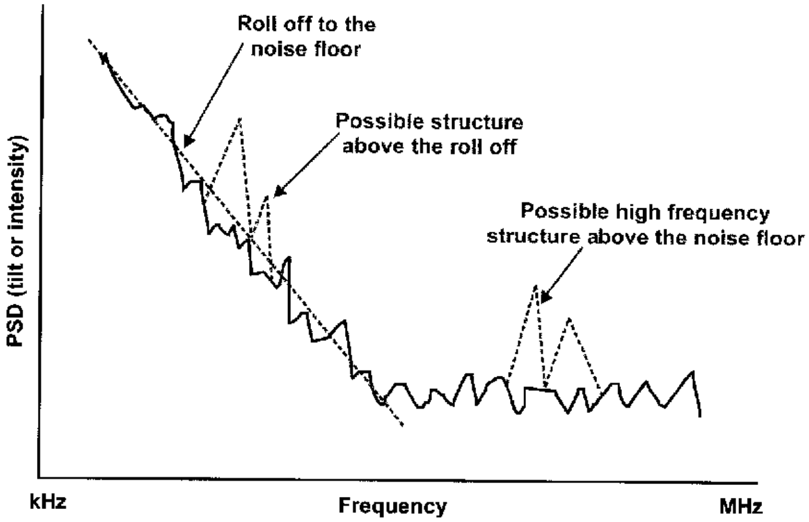

Fig. 11. What MITS was developed to look for.

ability to measure the aberrations up to some spatial and temporal frequency limits based on its design and construction, and a beam correction system will be able to correct the errors up to some lesser spatial and temporal frequencies. The resulting corrected wavefront error (WFE) on the beam is a combination of the residual error after correction of the nominally correctable part, the measurable but uncorrectable part, and the unmeasurable (at least by a wavefront sensor) part. Because the last of these terms is unmeasurable, it must be inferred to allow for an estimate of the total residual error after correction. (The effects of all sources are, of course, evident but not very separable in far-field measurements.) Figure 9 shows the regions pictorially.

Understanding the roll-off in both spatial and temporal frequencies is necessary to assess the uncorrected residual from a beam correction system. Measuring the high-spatial-frequency content requires either wavefront sensors with very many subapertures or inference from behavior in various sizes of subaperture. Although the IFX program was beginning to address this at its termination, we will concentrate on the high-temporal-frequency behavior. While physical dimensions and mechanical frequencies are likely to limit the high-spatial-frequency content of the WFE, high-temporal-frequency effects involving reactions within the supersonic flow of the lasing medium and optical mode interactions have been postulated as possible sources for high-temporal-frequency content.

If the roll-off has the form $\mathrm{PSD} = cf^{-a}$ where f is frequency and a and c are constants, the integrated residual rms WFE from a frequency f_0 to infinity is $[cf_0^{-a+1}/(a-1)]^{0.5}$. This can be converted to a Strehl (from this error only) by the Marechal approximation. Figure 10 shows an example for $a = 2$ and 1.5 with $f_0 = 300$ Hz and the rms WFE at 300 Hz varied parametrically from 0 to 1×10^{-4} waves^2/Hz. Clearly the residual high-frequency error can limit corrected beam quality.

7. MITS

To address the issue of high-temporal-frequency behavior of a combustion-driven HF laser beam, the IFX program created the MITS. The goal was to explore the subaperture

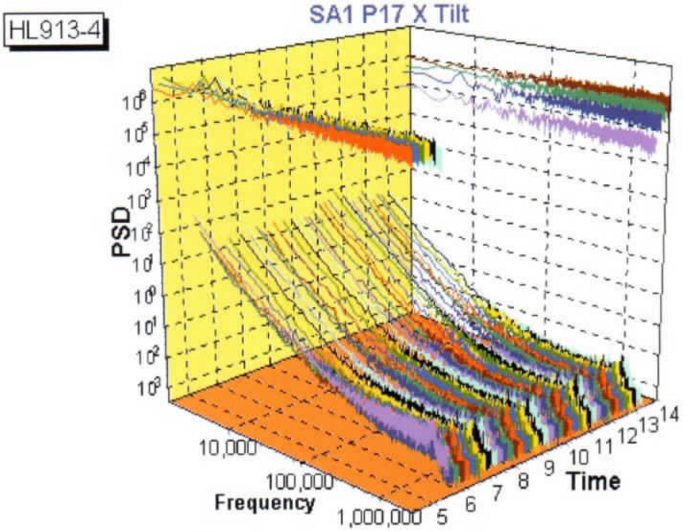

Fig. 12. Sample MITS PSD.

intensity and tilt behavior of the Alpha laser beam, looking to observe the roll-off to higher frequency, to identify possible structure above the roll-off, and to identify higher-frequency structure rising above the noise floor of the sensor (Fig. 11).

An Alpha test, HL913, was performed to obtain MITS data. As hoped, the data showed a $1/f^2$ roll-off of subaperture tilt and intensity with no evidence of high-frequency structure. It also showed good correlation between lines. Although this suggests that the beam would have been highly correctable, more data would have been useful to characterize correctability limits. Figure 12 shows a sample PSD.[1]

8. Conclusions

Historical attempts to correct high-energy-laser beams have not tended to be as successful as hoped. In particular, the results of beam control tests on MIRACL, a megawatt-class DF laser, generated concerns about the general correctability of beams from combustion-driven HF and DF lasers. The SBL IFX program chartered a Beam Control Maturity Assessment Panel (BCMAP) to consider this and other beam control issues. The panel identified a number of issues that needed to be addressed and recommended approaches to addressing them. The results of the Alpha LAMP Integration (ALI) tests, combined with results from the Alpha laser diagnostic wavefront sensor and from high-frequency subaperture intensity data from an Alpha mode beating experiment, provided some insight into HF laser behavior. It also raised questions. Taken together, these sources defined the need for a high-bandwidth measurement of Alpha subaperture intensity and tilt behavior—the defining requirements for the MHz Intensity and Tilt Sensor (MITS). It was the team's hope that the measurements made with MITS would help define the optimum approach to wavefront correction of a combustion-driven HF laser as well as the practical limits of correctability. Although only one test was completed with MITS, the data from that test increased confidence that combustion-driven, high-energy-laser beams are correctable to near the diffraction limit.

Reference

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The Authors

Mr. John Albertine has his B.S. and M.S. in Physics from Rose Polytechnic Institute and Johns Hopkins University, respectively. Prior to working for the Navy, he was a senior staff physicist in the Space Division of the Johns Hopkins Applied Physics Laboratory. From 1976 through 1997, he worked in the Navy's High Energy Laser (HEL) Program Office, directing the Navy's technology development for the past 15 years. During that time, he led the development and test of the first megawatt-class HEL system in the free world. He retired from civil service in 1997 and now consults for OSD, the Air Force, ONR, the Navy HEL program office, and Penn State in the Directed Energy field. Mr. Albertine is also a member of the Air Force Science Advisory Board and served as Executive Vice President and a member of the Board of Directors of the Directed Energy Professional Society.

Dr. David Johannsen has a B.S. in Physics from the California Institute of Technology and an M.S. and a Ph.D. in Physics from the University of California, Riverside. After teaching at Loyola Marymount University and working at Hughes Aircraft Company, Allied Corporation, and Northrop Corporation, he joined The Aerospace Corporation in 1987. In addition to Space Based Laser (SBL), he has supported a variety of Missile Defense and Air Force space programs. Since the demise of SBL he has been a Senior Project Leader supporting MDA's Space Tracking and Surveillance System.

Ms. Lorraine E. Ryan has a B.S., Chemistry, from Loyola Marymount University at Los Angeles and was enrolled in the Materials Engineering Masters Program, UCLA, 1971–1973. Ms. Ryan is currently a Senior Project Leader at The Aerospace Corporation in the Missile Defense Space Systems Space Based Surveillance Division. Her past employment was with NGST's Systems Engineering Center as the Airborne Laser (ABL) Laser Segment Systems engineering manager. This engineering management assignment included the incremental evaluation and upgrading of requirements and the management of the technical work of 52 systems, technology, and laser engineers working on Block 04–Block 08 ABL activities. Her past assignment at NGST was as a Sr. Technical Specialist with the Laser and Sensor Products Center. Ms. Ryan managed the Alpha Laser Program. This Air Force Program was the centerpiece testbed for the Space Based Laser Integrated Flight Experiment Program. This High Energy Laser Program conducted the tests that anchor the predictive models for the SBL IFX flight payload design.