TITLE: ANTAARES AUTOMATIC BEAM ALIGNMENT SYSTEM

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Antares Automatic Beam Alignment System
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Abstract

Antares is a 24-beam-line CO₂ laser system for controlled fusion research, under construction at Los Alamos Scientific Laboratory (LASL). Rapid automatic alignment of this system is required prior to each experiment shot. The alignment requirements, operational constraints, and a developed prototype system are discussed.

A visible-wavelength alignment technique is employed that uses a telescopic-TV system to view point light sources appropriately located down the beamline. Auto-alignment is accomplished by means of a visible centroid tracker, which determines the off-axis error of the point sources. Error is nullled by computer-driven, movable mirrors in a closed-loop system. The light sources are fiber-optic terminations located at key points in the optics path, primarily at the center of large copper mirrors, and remotely illuminated to reduce heating effects.

There are 2 power amplifiers, each containing 12 beams. One telescope-TV camera is needed per amplifier. The driver amplifier, power amplifier, and target system optics are collimated to the telescope-TV camera optical axes. The final alignment to the target is accomplished with the use of a special fixture.

The use of visible light for alignment, rather than infrared, requires less expensive components, gives a smaller diffraction blur, and permits more accurate pointing. The dispersion between 10.6-μm and visible light due to the NaCl windows is measured and compensated by the control system.

Introduction

Antares is a high-power (80-100 MW), high-energy (35-40 kJ), pulsed CO₂ laser system for the investigation of inertial confinement fusion. The system consists of three major optical sections: the front end, the power amplifier, and the target chamber system (Fig. 1).

The front-end system (Fig. 2) consists of those components necessary to generate two separate laser beams that are fed into two main power amplifiers. The front-end system contains a multicystronic, line-selectable oscillator (0.25 μs, 1 ns, four rotational lines in the 10.6-μm band), switch-out and conditioning optics, preamplifiers and spatial filters, beam splitters and relay optics for coarse temporal synchronization of the propagation paths of the two power-amplifier beam lines. The two driver amplifiers (90 J, 1 ns, annular shaped beam) have saturable gas cells for additional contrast enhancement (10⁷ contrast ratio) and parasitic oscillation control.

There are two main power amplifiers (Fig. 3). Internal to each power amplifier the annular beam from the front-end system driver amplifier is spatially split into 12 sectors. After passing through a spatial filter, each of the sector beams makes two passes through the gain medium. Each power amplifier has 12 trapezoidal-shaped output beams (0.5 ns, 1400 J, 40-cm chord dimension), which fit into an annular array. The 24 beams originating from the power amplifiers are independently controlled beams and must be spatially aligned through the system and independently centered and focused upon the target.

The 12 output sector beams of each of the 2 power amplifiers are relayed in the turning chambers in an annular array and then further relayed to the target chamber (Fig. 4). The final optical elements in the target chamber (f/6 off-axis parabolas) can independently center and focus the energy of each sector in a focal spot less than 200-μm in diameter.

The cost-effective beam-alignment technique employed to align the 72-beam system is shown in Fig. 5. The system consists of variable-focus telescope-TV cameras (operating in the visible wavelength spectrum) to view borealight light sources appropriately located down the beam. The detection errors of a point source are determined by a video centroid tracker and the error is nullled by a computer-controlled, closed-loop, mirror actuator system. The light sources are fiber-optic terminations located at key points in the optic path, primarily at the center of large copper mirrors, and remotely illuminated to reduce heating effects. The optical axis of the telescope is main collinear with the front end drive amplifier and, therefore, the output is collinear with the borealight line through the system optical network.

Work performed under the auspices of the U.S. Department of Energy
Antares Beam Line Physical and Operational Constraints

The automatic beam-alignment system must manage a number of various shaped beam sizes in a number of environments. The front-end driver-amplifier output beam (angular 9-cm i.d., 15-cm o.d.) is directed along a 15-m temperature-controlled atmospheric path to the power-amplifier vacuum input window. In this 9- to 15-m (10-5 torr) input section of the power amplifier the angular beam is divided into 12 trapezoidal-section beams (3 cm by 4 cm) and directed 7 m along relay and focusing mirrors and through spatial filters to the input window of the 1600-torr CO2/N2 pressure vessel. Each of the 12 sectors is double passed through the four discharge regions, expanded, and shaped to a 32-cm by 41-cm trapezoidal cross section. The discharge-induced electric and magnetic fields are very high (750 kV/m, 5 kA/m) at the various mirror positions. Additionally, components are subjected to x-rays generated by the half-million volt, 150-kV, discharge gain gas regions. The slightly converging trapezoidal beams next exit through 46-cm-diameter NaCl window and are relayed along a 20-m path (10-6 torr vacuum) and focused on the target. The electrical components in the target chamber will be subjected to large EMF and other target implosion-generated radiation.

The optical support structures have been designed to maximize the natural resonance frequency and minimize the response to the pressure and vacuum states of various sections. A worst-case analysis of pressure- and vacuum-induced movements of components indicates a 450-rad beam-pointing offset between the amplifier and target chamber. The power amplifier and target system structural designs were tailored to provide structural lowest-resonance mode frequency above 40 Hz. The corresponding structural modes, which are induced rotations, are less than 1 rad at 40 Hz. The closed-loop beam alignment servo-system bandwidth is determined strictly by operational requirements.

The general operational constraints are governed by both total system and subsystem requirements. They are: (1) The power amplifier and target system should initially be aligned independently from the driver system and interfaced prior to a shot. (2) Each beam line, an individual power amplifier within its non-functioning target system optical network, should be independently aligned. (3) The entire Antares system, the automatic alignment system, should not be configured within a half-hour period for target shots. (4) The automatic alignment system control system and steps in the beam path are not allowed to interfere with the mecha-electrical distribution network. (5) The alignment system is the only method of ensuring that the beam enters, traverses, and exits the power amplifier whose corresponding target system relay optics without vignetting, and with final centering and focusing of the beam on target. Locating the two alignment stations between the driver and power amplifiers allows constraints (1) and (2) to be met.

General Requirements

The previously listed physical and operational constraints initially provide information for the optical network. An optical sensitivity analysis was made of the Antares optical beam line. The sensitivity involves both geometrical and diffraction analysis to determine the beam parameters to within 1 μm (Fig. 6, Tables 1, 2, and 3). The total analysis includes the effects of all geometrical beam aberrations, vignetting, diffraction losses, beam decenteration and angle errors due to still mirror motions, and the beam focusing characteristics at the target plate.

The primary Antares system requirement is to deliver 90% of the power amplifier output energy into a 12-cm-diameter spot at the focal plane. A diffraction analysis of the overall optical train performance was carried out in which the performance degradation results from individual tilt, orientation, deflection changes, and measured mirror errors of the optical elements were included. Degradation due to diffraction loss is not included. The power amplifier beam, after the 5-m-long average beam path, is 50 mm in diameter (Fig. 7) for the degraded case without any final alignment. A conservative final beam spot size of 2.5 mm is adequate. Table 2 shows the power requirement for the final centering and pointing required for the target alignment system. As indicated in this table, the majority of alignment errors must be constrained in order to meet the target alignment requirements. Additionally, the error sources are, in general, mutually independent, so that the error in the beam can be approximated by the square root of the sum of the squares (RSS).

Working back from the target alignment requirements, a number of system requirements are established throughout the remainder of the optical network. The details of elements, field of view, error budgets, and requirements for the remainder of the optical network is presented in Table 3 and reconsidered in Fig. 6. The error budgets contain the possible vibrations, and thermally induced offsets in beam centering, control system deadbands, and computer error actuations, plus-driven interface offset errors. These errors are RSS'd or coherently added where appropriate. The motor controlled elements are shown in Fig. 5. The other elements are mis-aligned or manually adjusted. The alignment as to which mirror position should be nominal controlled is determined by a sensitivity analysis and from practical engineering considerations like accessibility, susceptibility to environmentally induced strains, and the particular system environments. For example, the back-reflector mirror, element 14 (Fig. 5), is subjected to a pressure change (-3 psi) from the electrical discharge in the gun region at the absorber window, element 13, is present. In this case the back reflector, which directs the beam down to the target system, would not likely be misaligned and in need of a remote adjustment.
Table 1. Calculated Energies and Intensities

<table>
<thead>
<tr>
<th>Station</th>
<th>Energy (J)</th>
<th>Pct. Loss</th>
<th>Imax (J/cm²)</th>
<th>Imax/IA0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Splitter</td>
<td>6.35</td>
<td>5.1</td>
<td>1.1</td>
<td>—</td>
</tr>
<tr>
<td>Spatial Filter</td>
<td>5.20</td>
<td>13.7</td>
<td>2750</td>
<td>—</td>
</tr>
<tr>
<td>Gas In</td>
<td>4.54</td>
<td>4.4</td>
<td>0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Gas Out</td>
<td>1573</td>
<td>0.4</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Turn</td>
<td>1439</td>
<td>1.6</td>
<td>3.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Fold</td>
<td>1415</td>
<td>1.0</td>
<td>4.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Focus</td>
<td>1400</td>
<td>0.0</td>
<td>4.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Target</td>
<td>1400</td>
<td>—</td>
<td>2.3 x 10⁻³</td>
<td>—</td>
</tr>
</tbody>
</table>

*Loss prior to gain portion of first pass
(primarily loss in cold CO₂)
**Obscuration and window loss

The major task in the system alignment is most often that of centering the beam on the various optical elements as seen in Table 3. The exceptions are:

1. The collinearization of the telescope axes with the detector alignment path, see Fig. 8.
2. The polychromatite elements of the optical system, where the errors at the polychromatite mirror are magnified by a factor of 10 at the back reflection. Hence, it is necessary that the polychromatite mirror be aligned with respect to the pupil stop.
3. The range of pointing angles to the target system, which is determined with a path interferometer to minimize alignment-induced aberrations, and the target site, which is set using focusing adjustments on the parabola.

The Antares optical cone is designed to eliminate stray radiation paths. As a consequence, the range of sources on the face of the mirrors is limited to the use of a single beam in the system, which is accomplished through the use of integrated and window optics as illustrated in Fig. 5. With those few exceptions, the system was designed and tested which is functionally reliable and cost effective, and it demonstrated the total Antares optical network.

Alignment System Description

The visible-wavelength alignment technique uses a path interferometer to view pointing and centering errors at key positions in the optics path. Automatic alignment is accomplished by measuring the deviation from the reference image. Pointing and centering misalignments are registered as displacements on the interferogram as illustrated in Fig. 8. These displacements are quantified by the tracking scan, which is then used to control the appropriate motorized mirror to null the misalignment. The TV camera is a standard 525-line CBC system using a silicon image sensor.

Figure 5, a schematic diagram showing all of the key alignment devices, includes the alignment scheme into Antares. The key items are: the front-end alignment station, primary assembly, polychromatite alignment device, back reflector from point light source, mirror with integral light sources, and the target alignment fixture. All misaligned primary mirror and steered motion driven so that positions can be retained in computer memory.

The heart of the alignment system is the front-end alignment system, as shown in detail in Fig. 3. This station is physically located in the front-end room where the laser beams are generated. The laser pulses are generated there and are directed to the telescope. This telescope views the point light source via the motorized mirror pair, which is used to move the beam just up-beam from the telescope. This enables the telescope to either forward light toward the target or back towards the front-end laser amplifier. A third station is the laser alignment after alignment is complete, the beam from the front-end laser can pass between the motorized mirror pair and up the beam tube toward the power amplifier.

Visible and CO₂ alignment lasers are also on the front-end alignment station. The visible alignment laser (500-mW Krypton-Ion) is an aid in initial setup, where alignment is critical, and the CO₂ alignment laser provides 10.6-μm radiation for initial alignment, which is used to align visible and 10.6-μm alignment due to dispersion caused by the path interferometer. Both of these laser beams are spatially filtered by the spatial-filter device, which is also a part of the front-end alignment station.
Table 3. Element Field of Views, Acquisition Ranges, Decenter and 1st Residual Errors

<table>
<thead>
<tr>
<th>Element and No.</th>
<th>Instantaneous Field of View</th>
<th>Required Acquisition Range</th>
<th>Allowed Error</th>
<th>Predicted Error</th>
<th>Limiting Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle at Power Amp. Driver Spatial Filter Input</td>
<td>#3 mrad</td>
<td>#20 mm</td>
<td>#0.7 m</td>
<td>#0.1 m</td>
<td>#0.4 m at EL No. 3</td>
</tr>
<tr>
<td>Translation at Power Amp. Driver Output</td>
<td>—</td>
<td>350°</td>
<td>#1 m</td>
<td>#0.3 mrad</td>
<td>#0.4 mm decenter at EL No. 14</td>
</tr>
<tr>
<td>Angle of Periscope Index</td>
<td>—</td>
<td>—</td>
<td>#0.6 m</td>
<td>#0.1 m</td>
<td>#0.4 mm decenter at EL No. 14</td>
</tr>
<tr>
<td>Translation of Periscope Index</td>
<td>—</td>
<td>—</td>
<td>#0.6 m</td>
<td>#0.1 m</td>
<td>#0.4 mm decenter at EL No. 14</td>
</tr>
<tr>
<td>Angle at Polyhedron, No. 3</td>
<td>#0.6 mrad</td>
<td>#2 m</td>
<td>#1 mrad</td>
<td>#0.1 m</td>
<td>#0.4 mm at target El No. 21</td>
</tr>
<tr>
<td>Translation at Polyhedron, No. 3</td>
<td>#12 m</td>
<td>#30 m</td>
<td>#0.2 m</td>
<td>#0.1 m</td>
<td>#0.4 mm decenter at EL No. 14</td>
</tr>
<tr>
<td>Translation at Spatial Filter Input</td>
<td>#3 m</td>
<td>#13 m</td>
<td>#0.2 m</td>
<td>#0.1 m</td>
<td>#0.4 mm less than 0.5 mrad</td>
</tr>
<tr>
<td>Translation at Box Reflector, No. 14</td>
<td>#40 m</td>
<td>#12 m</td>
<td>#0.2 m</td>
<td>#0.1 m</td>
<td>#0.4 mm less than 0.5 mrad</td>
</tr>
<tr>
<td>Translation at NaCl Window, No. 15</td>
<td>#31 m</td>
<td>#12 m</td>
<td>#0.2 m</td>
<td>#0.1 m</td>
<td>#0.4 mm less than 0.5 mrad</td>
</tr>
<tr>
<td>Angle of Rotary Wedge</td>
<td>—</td>
<td>360°</td>
<td>#750 m</td>
<td>#150 m</td>
<td>#1 mm at EL No. 14</td>
</tr>
<tr>
<td>Translation at Rotary Wedge</td>
<td>#117 m</td>
<td>#3 m</td>
<td>#0.2 m</td>
<td>#0.1 m</td>
<td>#0.4 mm at EL No. 14</td>
</tr>
<tr>
<td>Translation at Turn on Chamber Mirror, El No. 19</td>
<td>#17 m</td>
<td>#10 m</td>
<td>#0.2 m</td>
<td>#0.1 m</td>
<td>#0.4 mm at EL No. 14</td>
</tr>
<tr>
<td>Translation at Fold Mirror, El No. 19</td>
<td>#95 m</td>
<td>#61 m</td>
<td>#1 m</td>
<td>#1 m</td>
<td>#0.4 mm at EL No. 14</td>
</tr>
<tr>
<td>Angle at Focus Mirror, El No. 20</td>
<td>#1 m</td>
<td>#1 m</td>
<td>#0.5 m</td>
<td>#0.5 m</td>
<td>#0.4 mm at EL No. 14</td>
</tr>
<tr>
<td>Translation at Focus Mirror, El No. 20</td>
<td>#62 m</td>
<td>#76 m</td>
<td>#1 m</td>
<td>#1 m</td>
<td>#0.4 mm at EL No. 14</td>
</tr>
<tr>
<td>Pointing Angle at Target El No. 21</td>
<td>#0.5 m</td>
<td>#0.5 m</td>
<td>#0.5 m</td>
<td>#0.5 m</td>
<td>#0.4 mm at EL No. 14</td>
</tr>
</tbody>
</table>

*Limited positioning angle includes errors from target and all the spatial filter components.*

The beam expander/spatial filter device uses zinc-selenide input and output lenses, which are mounted on stepper-motor driven slides so that they can accommodate both the vertical and horizontal tilt. For this reason, the devices change the focus position of the input lens to enable the alignment lasers to be focused on the target's location of interest throughout the telescope optical system.

After the alignment beam exits the beam expander/spatial filter, it passes through the beam expander, which directs the beam exiting from the front end driver amplifiers to an annular zone (60 x 5 µm) in a vacuum chamber.
The polyhedron alignment device is located in the power amplifier and aligned to the polyhedron mirror. The polyhedron mirror, which has a hole in its center, accepts the annular beam generated by the front-end and splits it into 12 trapezoidal shaped beam sectors, each of which follows its own path to the target. The polyhedron alignment device consists of a lens that is illuminated with a point light source at its focal point. The telescope/TV camera is able to view this light source through the hole in the polyhedron mirror. By viewing the front-end centerline through the hole in the polyhedron mirror with the telescope/TV camera at infinity, the point-light source in the polyhedron alignment device can be viewed and angular distortions/misalignments nullified by the appropriate mirror. By changing the telescope/TV camera focus to the polyhedron alignment device, it is possible to achieve a centering alignment to the polyhedron mirror, Fig. 8.

For alignment further into the system, it is necessary to sight off each of the 12 faces of the polyhedron mirror. To achieve this, the periscope/carousel is inserted into the beam path prior to the polyhedron mirror. This device consists of two parallel mirrors that are rotated around the center of the wing path of the annular beam path. These mirrors have the proper offset so that the telescope/TV camera views one of the 12 faces of the polyhedron mirror. By automatically indexing the periscope mirror panel, it is possible to sequentially view (with the telescope/TV camera) through each of the 12 individual beam sectors in each plane of the mirror.

The back reflector "flip-in" light source is located just before the annular reflector in the wing amplifier. It consists of a fiber-optic light source mounted on an arm which can be moved to the correct position in front of the mirror. At this location, this "flip-in" light source is directed onto a mirror mounted in the mirror in order to view the risk of parasitic oscillations in the beam amplifier.

The rotary wedge device (Fig. 5) is located after the output NaCl window. The slit window is a light wedge built into it for diagnostic purposes. Therefore, it was necessary to align, correct for angular distortion between the wing and the side radiations, and correct for remaining angular to the wing of the mirror using the side radiations. The alignment is done with the periscope/carousel. Also mounted on the rotary wedge in a fiber-optic light source serves as a target for the telescope/TV/trackers.

Next, alignment is done at the turning chamber, target chamber, and flat parabola mirrors. Alignment at each of these locations is similar since each is an off-axis parabola mirror. The fiber-optic light source is installed in a hole in the center of the mirror.

Final alignment to the target is accomplished using an illuminated target-alignment fixture. The fixture is accurately located at the target position so that it is aligned using a beam sensor, a pair of orthogonal reflectors, or internally reflective surfaces and aperture arrays located at positions on the target chamber. The fixture is mounted in a single, large fiber-optic light source, Coupled to a telescope/TV/trackers then aligns to the light exiting the aperture in the target alignment fixture.

A typical computer-controlled automatic alignment operation is to first scan the alignment fixture by viewing the hole in the turning chamber and then view the point sources on the front-end alignment system. The alignment program aligns the pointing alignment system to the polyhedron alignment system. The program then aligns the appropriate back reflector flip-in light source to a mirror on the back reflector. At this time, the flip-in light source is redirected, the two mirror Flips sequentially are aligned to the target, and alignment is accomplished. The flip-in light source is then to the focus parabola in the target chamber. Next, the lens system in the lamphead is illuminated and final alignment to the target is performed. Finally, the amplifier is moved into position and alignment is accomplished at the target chamber. After alignment, the spatial filters device inserts a pair of filters into the test beam to test the point source position to the filter aperture. This completes the alignment process. The periscope/carousel is then used to the next alignment fixture. The periscope/Carousel is used to correct and position the amplifier. The beam path and the beam path length are all corrected out of the beam path and the rotary wedge in the front end is removed. Next, the beam path is passed through the beam path and the beam path is passed through the beam path and the beam path. The target-alignment fixture is replaced by the target and the system is realigned.

Correction is based upon values obtained in a calibration procedure and applied, which may corrects between the individual 12 beam paths. The calibration values are obtained using a 1006-um alignment laser to locate the position of the alignment beam. The distance between the lamp pulses is then used as an alignment source. These positions are compared to the beam position at the target position, and an error is calculated. The errors are added to the desired beam position, and the resulting error is resolved, the path correction is calculated, the errors are corrected, and the desired beam point and the path point with a spatially filtered alignment is resolved. The beam path is corrected, the resulting fringe pattern that shows off-axis, lateral misalignment, and the beam path is corrected. The beam path is corrected by tilting and translating the beam path to the desired beam point with the preceding two flat mirrors.
Performance Analysis

The driving requirement from the standpoint of resolution/accuracy is the 1 mm centering on the 3.1 m mirror in the target chamber. A light source at this mirror is imaged by the laser optics at 23,000 mm from the telescope. The laser optics also have a linear/lateral magnification of 0.14. At this mirror a decentering of 1 mm translates to 40.14 mm at 23,000 mm or, equivalently, 6.11 mrad. This latter figure for this image is the polyhedron beam splitter, which produces a diffraction angle of about 35 mrad. Thus, the 0.1 mrad resolution requirement can readily be achieved by resolving the diffraction spot to better than 1 part in 3, assuming that the source size does not significantly enlarge the diffraction spot.

Making the light source 1 mm in diameter adds 6 mrad to the diffraction spot size, yielding a 6.11 mrad image. This image requires a resolution of about 1 part in 4, but at the same time keeps the source brightness requirement reasonable.

The required source brightness (lumens/ft²) is given by

\[ B = \frac{H(A_{\text{spot}}/A_{\text{source}})T}{\Omega} \]

where

\[ H = 0.1 \text{ lumens/ft}^2 \text{ of 2835K tungsten light (required silicon vidicon illumination for good results)} \]

\[ \Omega = 8 \times 10^{-2} \text{ steradian} \] - maximum collecting solid angle (limited by polyhedron aperture size).

\[ A_{\text{spot}} = \text{Area of source image on vidicon.} \]

\[ A_{\text{source}} = \text{Area of source at fold mirror.} \]

\[ T = \text{Total transmittance of all optics between source and vidicon.} \]

In order to obtain 43.5 mrad of resolution (40.14 mm at the target), which allows for other sources, the telescope magnification for this source must be 0.34. This result is based on using a system of 525 TV-line, 1-mg vidicon, and the numerical analysis 9.4 m-35 resolution limit. Thus, for a 1 mm source, \( A_{\text{source}} = 0.021 \text{ m}^2 \) for a 21 mrad source. The transmittance of the optical train for a source at the fold mirror (Fig. 4) is approximately 0.07 at 633 m. For a 1 mg-millimeter source brightness, a calculated from the formula, must be 5 x 10^6 lumens/ft². This allows for fiber-optic connector losses plus adjustment of \( A_{\text{spot}} \) to obtain more resolution if needed.

The 0.34 magnification factor implies a telescope focal length of the order of 50 m. With similar sources at infinity, such as the target, resolution is not the driving requirement and the long focal length results in a system with marginal field of view at the target and requires a bright source. Thus, the required requirement on the telescope design is a shorter focal length (smaller magnification for infinite objects and a longer focal length (larger magnification) for 23,000 mm objects.

The target alignment total error budget is 49 mrad at the telescope. This includes a 1.6 mm focal length, focus parabola and 7.44 angular magnification in the Antares laser optics, and an angular error of 0.45 mrad at the target. A reasonable source size (in a "jack-o-lantern" type target) alignment fixture is 50 m, which is 23.5 mrad at the telescope. The total source angular subtense is then 310 mrad, as seen by the telescope, requiring resolution 5.8 part in 4. A 5000 m focal-length telescope would give a spot diameter of 1.74 mrad on the vidicon requiring a source brightness of 4.7 x 10^4 lumens/ft² (\( \Omega = 4.85 \times 10^{-2} \) steradian). This brightness is difficult to achieve from a "jack-o-lantern" type alignment fixture without resorting to high pressure lasers for illumination. A telescope focal length of 50 m would require less brightness, 1.4 x 10^4 lumens/ft². The field of view at the target is 0.4 m with the 0.03 m focal length, increasing with the 2500 m focal length, the field of view is 0.8 m, which allows more error in target location without resorting to search modes.

A telescope that provides a magnification of 0.34 for 50 m objects and a 2700 m focal length for infinite objects has been designed with off-the-shelf components, and is presently being fabricated. This design, however, does not provide for viewing objects within 1 mm (front-end requirements) or other objects that focus to within 11 m (to also allow imaging front-end pit mirrors) are currently being evaluated.

Tests

Tests were performed using a mock-up of an Antares head-line section, which essentially verified the performance predictions of the above analysis. The mock line mock-up used actual focus mirrors and most of the components and was complete except for Antares salt window.
The following questions had to be answered:
1. Will the Antares beam line allow good visibility using visible light sources at the focal flat and at the target?
2. Will the reflectance of the copper mirrors allow for adequate system transmissivity?
3. Will pressure-induced bowing of the salt windows affect the optical characteristics of the system?
4. Will salt-window surface damage, due to high CO2 flux and water vapor, degrade the system's performance noticeably?

The telescope used for the tests was a 7-in.-diameter Questar set-up with a focal length of 697 in. Fig. 11 shows the tracker error maximum/minimum outputs vs movement of a 1-mm-diameter source at the focal flat. This data shows the resolution to be approximately 0.1 m.

The light spot covered 6 TV scan lines compared to a predicted 5 TV lines using a 3-by-4 aspect-ratio raster, 3/8 in. high by 1/2 in. wide, 480 scan lines. The effective magnification for the Questor TV was 0.34, which allowed the object to be viewed at a magnification of 0.22. A telescope with a magnification of 0.34 for the focal flat source will provide even better resolution.

Figure 12 shows the same type of data for the target. In this case, resolution is about 80 μm. The spot size in this case covered about 90 TV scan lines, whereas one would predict about 80 TV scan lines. This was due to aberrations resulting from deliberately inaccurate placement of the alignment mirror, simulate worst-case component alignment, and also from atmospheric scintillation since the beam sector was not enclosed.

Initially, there was concern that the diamond-turned mirrors might spread the image of the point sources. These fears were dispelled by earlier MTF measurements and by the tests just mentioned. The data is shown in Fig. 13. The beam line contains 7 diamond-turned copper mirrors and 1 polished copper mirrors between the alignment telescope and the target. The worst-case contrast transfer for seven diamond-turned mirrors is 0.91. The target at the equivalent resolution bar size corresponds to the spot size of 230 μm.

Reflectance measurements made on diamond-turned and polished-copper mirrors in the visible spectrum (0.63 μm) showed the diamond-turned mirrors to be consistently better than 0.9% reflectance. These reflectance values included both absorption and scattering. The reflectance of polished copper mirrors varied considerably, depending on the supplier (0.33 to 0.95). The polished copper mirrors used in the mirrors box were specified to have a reflectance higher than 0.85 at 0.33 μm. Since the mirror reflectances were not high as expected, the actual source brightness requirements were met with the predicted requirements.

Early in the program, there was concern about the effects of the large 0.8% output window size caused by the 0.800-torr pressure differential across the window faces. Tests made on an Antares prototype window to measure the defocusing of a beam passing through the window for various pressure differentials and orientations. It was found that at 830 torr the window experienced a very slight monostatic location of the size of 10-3 μm at 633 nm, which corresponds to an equivalent focal length of 3.58 x 10-2 m and a maximum sag of 1.2 x 10-4 m at 633 nm.

Concern was also expressed as to a possible reduction of the alignment telescope and image contrast due to the degradation of the salt window faces from dust and a haze formation that would affect surface absorption of water. Tests were made of the point source contrast ratio as the polished salt windows were added into the Antares single-sector test bed. The windows were more effective than the polished salt windows in reducing these effects, and the results indicated that even in this worst-case measurement, the contrast ratio was maintained at a high level. This result is not surprising, since the silicon dioxide array TV camera tubes used in these experiments are well suited for 0.8 to 0.1-μm band where the forward scattering function of haze surfaces fall off sharply.

The main effect of any possible haze in the Antares system is to reduce the transmission slightly, with angle scatter from the haze would have to pass through the typical salt solid angles, a 30° V view to the telescope/TV camera system.

Summary

The automatic alignment system for the Antares CO2 fusion laser is described. The use of wave-front alignment techniques meets the Antares beam alignment requirements in a very cost-effective manner. The technique employed uses a telescope/TV system to view point light sources at any point in the optics path. Automatic alignment is accomplished by means of a video control system, which helps to correct for errors with a computer-controlled, closed-loop mirror actuator system.

System analysis shows the technique to be well suited for automatically correcting point light sources at any point in the laser beam path. A small size mock-up of the Antares beam-line sector has been setup to test mirror and component alignment techniques and is complete from the front end to the target. This alignment technique is currently being refined using this mock-up, and hardware is being prepared for installation in an actual Antares power amplifier later this year.
References


Fig. 1. Antares facility schematic.
Fig. 2. Antares front-end optical schematic.

Fig. 3. Antares power amplifier (1 of 6).
Fig. 4. Antares target system optical schematic.

Fig. 5. Antares automatic alignment system schematic.

Fig. 6. Antares power amplifier optical train.

Fig. 7. Encircled energy at target.
Fig. 6. Alignment concept.

Fig. 9. CCTV/Tracker alignment station.

Fig. 10. Front-end alignment station.

Fig. 11. Fold flat source movement vs. tracker error signal.

Fig. 12. Target source movement vs. tracker error signal.
Fig. 13. Contrast transfer of diamond-turned copper mirrors for 18" diameter elliptical mirrors (1977 Vintage) and 4" diameter mirrors (1979 Vintage).