A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

MASTER

CONF-830425--21

TITLE: FUNCTIONAL ALIGNMENTS AND SELF-TESTS FOR TILTED AND
DECENTERED OPTICS

AUTHOR(S): W. Bauke, P-5 (NJ)
E. W. Cross, P-5

SUBMITTED TO: Los Alamos Conference on Optics '83
Sweeney Convention Center
Santa Fe, New Mexico
April 11-15, 1983

NOTICE**PORTIONS OF THIS REPORT ARE ILLEGIBLE.**

It has been reproduced from the best
available copy to permit the broadest
possible availability.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the substance form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Functional alignments and self-tests for tilted and decentered optics

W. Bauke and E. W. Cross

University of California, Los Alamos National Laboratory
 P.O. Box 1663, MS E523
 Los Alamos, New Mexico 87545

Abstract

The alignment of tilted and decentered optics is ordinarily difficult, because such optics have neither simple alignment points amenable to ordinary boresight methods, nor a simple alignment theory.

Several different alignment examples which provide insight into a practical universal approach to all such systems are explored. The examples detailed are segments of the Antares Laser Fusion Project's optical train.

Introduction

In very large optical systems the size, nature, and spatial separation of optical elements makes direct alignment and boresighting exceedingly difficult. The Antares Laser presents a unique example of such a system. It is designed to amplify, transport, and focus 24 beams of light at the wavelength of $10.6 \mu\text{m}$, over a pathlength of approximately 100 meters, onto an inertial fusion target which is typically less than 1 mm in diameter. This optical system consists of two distinctly different sections:

- a. An open bench-type "Front-End".
- b. A closed-shell "power amplifier" and "target" system.

The front-end system is located in a large room, with most elements necessary to generate the annular seed beams located on open optical benches. The multicavity, line-selectable oscillator, switchout and conditioning optics, preamps, filters, and relay optics are mounted on separate optical tables with easy access and sufficient space between tables to insert alignment devices.

The remainder of the optical system is enclosed in steel shells of varying size and complexity, and physical access is restricted or impossible after assembly. The optical beam enters a section of the power amplifiers which contains the 12-faceted polyhedron and turning mirrors, corner cubes, focusing elements, and other associated optical elements, all in vacuum. After amplification, the high power beams, of 2 trillion watts or more, travel through vacuum beam tubes to the target system. The tubular or circular steel shells range in diameter from 1.8-7 meters, and the environmental conditions vary from 1800 Torr of CO_2 N_2 gas in the pressure vessel to a vacuum of 10^{-6} in the beam tubes and target chamber.

The Antares optical schematic (Fig. 1) shows that there are numerous points where the beams are being split, folded, or enter and exit the different media through NaCl windows. The general design parameters and automatic alignment systems are discussed in detail in Ref. 1. However, before the entire optical train can be automatically aligned and boresighted to the target, a major task is to prealign single elements or a combination of elements in the form of subassemblies by the use of optical tooling techniques, visible lasers, or autocollimation methods. The physical size of some of these subassemblies, which range in weight up to 13 tons, their complexity, and the requirement for cleanliness dictates special handling procedures in controlled environmental conditions, i.e. clean-room facilities.

Most Antares optical elements are mounted off center, but concentric to the system centerline and mostly with specific tilt angles to the system centerline converging toward the center axis. The primary task of the manual prealignment is then to separate the optical train into discrete segments, transfer main theoretical fiducial references to support frames and shells and into separate facilities, and then the alignment of all tilted and decentered optics to such fiducials which represent the main optical reference lines.

The closed-shell optical system

The closed shell which is being referred to consists of two power amplifiers, optical transfer spools, and a vacuum system which connects to the target chamber. While the

power amplifiers are pressurized with gas, the remainder of the system is at vacuum. In any case, there is minimal or no physical access after assembly.

The power amplifiers are about 3.5 meters in dia. and 15 meters in length and connected to the optical transfer spools of about 3 meters dia. and 2 meters in length, which then connect to stainless steel beam tubes of 2 meters dia. which terminate at the target chamber. The beam tube path length exceeds 50 meters, and is folded at the optical turning chambers. The optical design evolves around a "primary centerline", or PCL. Ideally, all major mechanical equipment is set to this theoretical reference line so that the mechanical centerline becomes coincident with the optical system centerline. The power amplifiers are set to the global coordinate grid such that the mechanical center line is in elevation at the target level of $z = 0$, and is inclined to the east-west target plane Y at an angle of $83^{\circ}36'21''$. The amplifiers were assembled out of segmented rings within a tolerance field of 1 mm, and the shell assemblies were set to the primary center line, or PCL with a pointing error of about 1 arc sec (Ref 2). As these accuracies fall within the correction capabilities of the automatic alignment system, we can consider the mechanical center line to be coincident with the optical system centerline, and therefore, use the mechanical center as a direct alignment reference.

The power amplifiers and optical transfer spools are assembled as single units and contain the majority of the optical elements (Fig. 2). The input beam is of annular shape, 15 cm OD and 9 cm ID and enters the closed shell from below, pointing vertically up, through a NaCl window, and is folded by a turning mirror 45° to be now oriented concentric to the PCL and to point to the 12-faceted polyhedron. This element splits the ring into 12 quasi-trapezoidal light beams, each of which is projected to its own beam path and is being independently handled and transported to the target. Consequently, it is evident that we can work directly to the system centerline only to the polyhedron. From this point on the optical elements are mounted too far from the center, often in major subassemblies with no direct visual access to the center, and suitable references have to be established. The alignment task requires the identification and reproduction of the PCL and the secondary references throughout the system, and the orientation of mechanical and optical components relative to these references.

The alignment theory

Under discussion is an optical system with numerous elements which are to be aligned to form an optical path that terminates at a real target in the form of a microsphere. The obvious technique appears to be direct boresighting, which in effect is being used by the automatic alignment system in its final stage. The previously described system size and complexity however, makes it necessary to perform intermediate alignment steps, as direct target acquisition from the front-end is not possible during the construction phase.

The basic theory applied is that of self or quasi-self alignment: the alignment optical path duplicates or closely approximates the optical path of the operational device, over the range of the system segment to be aligned. Standard optical tooling instruments are being used to simulate the input beam to the sectors under consideration and auxiliary targets or reflectors are introduced to facilitate the techniques being applied: boresighting or autocollimation. The solution is to simply identify direct optical path segments and to align these, using the self-alignment principle, by adding modified optical tooling and/or testing techniques. We will describe in detail a practical application of the autocollimation and boresight technique.

Periscope mirror alignment using autocollimation

The periscope mirrors are located at the point where the amplified beams leave the power amplifier. Their purpose is to fold and steer the beams toward the target system. The mirrors are identified in (Fig. 2) and in the central area of (Fig. 3). Each beam line requires a set of two mirrors, and there are a total of 12 sets and 24 mirrors in each assembly. They are arranged symmetrically around the system centerline in a circular array with a diameter of approximately 1.5 and 2 meters, as visible in Fig. 4.

Alignment requires that the mirrors be precisely positioned laterally as well as in angle in relation to the system centerline. This can be achieved by projecting a reference beam to the mirror surface at the optical center of the mirror and adjusting the position and tilt angle as required. The beams, however, do not run parallel to the system centerline. Each beam is inclined toward the center at an angle of $11^{\circ}17'$ as it hits the first periscope mirror. Therefore, gravity can not be used as a direct reference to set an alignment telescope or autocollimator. In situ alignment would require setting a theodolite at a compound angle, which is different for each of the 12 beams, at an elevation of up to 5 meters above floor level, making alignment extremely time consuming and difficult.

During assembly of the mirrors, the shell is located in a clean room with its axis turned 90° . If alignment is done at this time, the optical system under consideration can be reduced to the one shown in (Fig. 3). There are 12 beams spaced symmetrically around a vertical center line. They enter at an angle of $11'17''$ from vertical, reflect off a first mirror's face to a second mirror, and exit parallel to the geometric center. If a gravity oriented mirror is introduced as terminal reflector, the beam will be autocollimated back through the system to the observing telescope. Any errors introduced by its mislocation due to tolerance buildup is being compensated by the movable second mirror.

The instrumentation used to perform the alignment is shown in Fig. 5. The shell is positioned with the centerline exactly vertical, on leveling jacks. Plumbing can be achieved by sighting with a vertical transit up through two centering targets such as a Brunson optical tooling spider (Fig. 6). As this is being centered to the optical support structure, note that the shell is still standing up, but the center can be set also in the horizontal position. An instrumentation bridge is then placed over the upper flanges. In this case, a modified three-meter Brunson tooling bar was used, with elongated holes cut in the center to permit direct projection of the line-of-sight to the mirrors below. The tooling bar carries two instrumentation carriages with a jig transit mounted on each. One transit has a cross-axis telescope to permit viewing in a direction of 90° to the line-of-sight. The other transit has been modified to carry a sine bar with a mirror over its cross axis. By setting the sine bar to the desired offset of $11'17''$, we now have a reference reflector which is offset to the line of site by the desired angle.

The two jig transits are now related to each other, and one will be used as working transit while the other one is the control instrument. By correctly leveling and orienting the transit scope, we obtain an optical reference grid which runs parallel to the system center and through the center of two opposing periscope mirrors. The periscope no. 1 centerpoints are defined by centering masks made of frames with piano-wire crosshairs. Now the working transit will be tilted until the cross scope autocollimates off the tilted reference mirror, which in effect sets the working line of sight to the desired angle of $11'17''$.

The tilted reference scope is now being moved laterally until the line-of-sight intersect a radial reference point provided by the center prism in the flying wedge. This device provides an illuminated reference point in space for alignment purpose, and can be rotated to be positioned at the center of any of the 12 beamlines during alignment and can be moved out of the beamlines during operation of the laser. Its detailed function is being described elsewhere (Ref. 3).

With the working transit fixed, the periscope mirror can be adjusted such that the incoming beam will aim within a specified tolerance field at the optical center, and the beam is correctly projected to the corresponding tolerance field of the second mirror. The angle of the second mirror can be adjusted with stepper motors in tip and tilt, until the beam reflects off the gravity-oriented terminal reflector. A good choice for this device is the surface of a mercury pool, but other devices are also acceptable.

After one periscope set is adjusted, the working transit is being plumbed so that its barrel points straight down and the reference mirror is offset. Now the second transit, which was originally the control scope, is tilted until the reference cross-scope autocollimates off the tilted reference mirror. We thereby reversed the function of the two jig transits by simply changing their tilt and now we can use the same procedure to set the opposite periscope mirror set, using the same instrument setup.

To complete the alignment of all 12 periscope sets, the tooling bar was rotated through six positions, each one straddling two sets of periscope mirrors.

Turning mirror alignment using boresight techniques

The turning mirrors are located in the input section of the power amplifier and identified in Fig. 2 as turning mirrors no. 2 and no. 4. The first one, mirror no. 2, is the primary turning mirror and folds the annular input beam to be incident on the polyhedron. The mirror can be seen in the center of Fig. 7. The annular beam is split by the polyhedron into 12 quasi-trapezoidal elements, each of which is reflected by a second turning mirror into its individual beam path. The array of 12 mirrors is arranged symmetrically around the system centerline, and two second turning mirrors can be seen on the outer periphery of Fig. 7.

Alignment specifications require that the first turning mirror and the polyhedron be oriented in closely controlled relationship to each other and the system centerline; that the polyhedron facets be aligned in angular orientation to the twelve beamlines; and that the second turning mirrors be set in angle to point each beam to the next control point

down the beamline, which is on the focus mirror.

As the polynedron is designed to split an annular beam which has a central void of 9 cm diameter, there are no active optical elements in its central region which can be used to directly align the polynedron to the system centerline. Therefore, auxiliary references were added in the form of a reflective flat surface and a collimated light source, which is positioned in the geometrical center of the element and is visible in Fig. 8. The light beam is set to project concentric with and at right angle to the polished reference flat, by using a large aperture autocollimator which is pointed to the flat as primary reference, and by steering the beam until it is visible as a star image in the center of the autocollimator. This star image is also designated as primary reference for the automatic alignment system, as it is concentric to the polynedron and therefore to the 12 beams, and it points backwards through the system to the front end, as visible in Fig. 1.

A further reference is required to identify the central points of each polynedron facet. This is only to be used during the initial optical tooling phase. A removable mask is inserted, which has scribe lines for locating, and holes for beam penetration, and is shown in Fig. 8 and Fig. 9.

If the alignment is done while the assembly is in the cleanroom and rotated 90° as described in the previous study, the optical system to be considered can be reduced to the one shown in Fig. 10. There are 12 beams being projected into an array concentric to the system centerline which is ultimately identified by the polynedron star image. The optical path of the operational device can be directly used to project a reference beam through the array of reflecting surfaces and beam steering is accomplished by moving the turning mirror to acquire the boresight target on the face of the focus mirror. A movable jig transit can be set level, using gravity as reference to simulate the input beam, and then be translated in horizontal and vertical direction to simulate each of the 12 beam centers.

The instrumental setup is shown in Fig. 11. The shell has been leveled as previously described, and a "Brunson" optical tooling transit has been set as working scope to aim through the center of the input window to the center of the polynedron. As control instrument a transit with cross-scope is positioned a short distance away. The working scope has been modified by adding a large axis reflector to accommodate the relatively large movement of the instrument during the alignment procedure, when we have to cover the centerpoints of all polynedron facets.

Prior to the alignment procedure the first turn mirror must be pointed to the input beam: it must be aligned to the vertical plane intersecting the center of the input window and be tilted 45° to the horizontal plane. A Wild T-2 theodolite was set in front of the mirror and was bucked in to the centers of the input window and mounting plate and then turned 45° from horizontal to point at the turn mirror face. Using the autocollimation eyepiece the instrument could be used as direct reference to tip and tilt the mirror correctly. The Wild T-2 is ideal for this purpose as we can reduce the focusing distance to less than 50 cm by using auxiliary objective lenses.

For the actual alignment, the working scope is set to the polynedron reference star image. The control scope is then locked to the axis reference mirror, and the working scope is translated to aim at a polynedron facet center. After each translation movement, the working scope must be checked for position. The control scope will tell any change in azimuth and tilt, and the coincidence level on the working scope will tell any error in level.

With the working scope positioned, one simply has to focus along the optical path to the face target on the focus mirror. By changing the angle of the second turn mirror in tip and tilt, the beam can be steered to bring the target in coincidence with the working scope cross hair.

After the basic setup is completed and the preparatory work is done, a full alignment of all 12 sectors can be completed rather routinely within a normal working day.

Summary

In very large optical systems, such as Antares, the initial beam alignment is difficult and it is an impossibility to boresight the system to the target during the construction phase. An alignment theory must be developed which is tailored to the specific system, but which in the interest of economy incorporates as many standard procedures and as much commercially available equipment as possible.

The most obvious solution is to have the alignment optical path duplicate or closely approximate the optical path of the operational device, and use a minimal amount of

secondary targets or beam identification devices coupled with optical tooling or precision surveying equipment. The use of autocollimation and boresight techniques on segments of the Antares optical path has been discussed.

References

1. A. Saxman, T. Swann, W. Sweatt, and Q. Appert, "Antares Beam Alignment System," Proceedings of the Los Alamos Conference on Optics '79, ed. D. H. Liebenberg, SPIE 190, pp. 207-217 (1979).
2. W. Bauke, A. Saxman, and N. O'key, "Optical Tooling for Antares," Proceedings of the Los Alamos Conference on Optics '81, ed. D. H. Liebenberg, SPIE 288 pp. 154-161 (1981).
3. T. Swann, C. Combs, and J. Witt, "Opto-Mechanical Devices for the Antares Automatic Beam Alignment System," Proceedings of the Los Alamos Conference on Optics '81, ed. D. H. Liebenberg, SPIE 288, pp. 484-492 (1981).
4. E. W. Cross, "Alignment and focusing tolerance influences on optical performance," Airborne Reconnaissance VI, Proc. SPIE 354, to be published (1983).
5. E. W. Cross, G. L. Woodfin, "Alignment tolerance as a figure of merit for optical design," Airborne Reconnaissance VII, Proc. SPIE 424, to be published (1983).

Fig. 1. Antares optical system schematic.

Fig. 2. Antares power amplifier optical system schematic.

Fig. 3. Schematic of alignment setup for power amplifier periscope mirrors.

Fig. 4. End view of optics spool with complete array of periscope mirrors.

Fig. 5. View of instrument setup for periscope mirror alignment.

Fig. 6. Setting center target inside optical support structure.

Fig. 7. South face of optics spool with first and second turning mirrors partially installed.

Fig. 8. Front view of polyhedron beamsplitter mirror with alignment mask installed.

Fig. 9. Polyhedron with alignment mask.

Fig. 10. Schematic of Optical setup for polyhedron and turn mirror alignment.

Fig. 11. View of instrument setup for polyhedron and turn mirror alignment.