LA-UR -83-1668

LA-UR--83-1668

CONF-830425--25

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DE83 014180

TITLE: ANTARES BEAM-ALIGNMENT-SYSTEM PERFORMANCE

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

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Antares Beam-Alignment-System Performance

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Abstract

The beam alignment system for the 24-beam-sector Antares CO_2 fusion laser automatically aligns more than 200 optical elements. A visible-wavelength alignment technique is employed which uses a telescope/TV system to view point-light sources appropriately located down the beamline. The centroids of the light spots are determined by a video tracker, which generates error signals used by the computer control system to move appropriate mirrors in a closed-loop system. Final touch-up alignment is accomplished by projecting a CO_2 alignment laser beam through the system and sensing its position at the target location.

The techniques and control algorithms employed have resulted in alignment accuracies exceeding design requirements. By employing video processing to determine the centroids of diffraction images and by averaging over multiple TV frames, we achieve alignment accuracies better than 0.1 times system diffraction limits in the presence of air turbulence.

Introduction

Beam alignment concepts currently employed in the Antares laser readily meet the requirements for establishing and maintaining alignment of a large optical system. Controlability has been demonstrated to be adequate and accuracies exceed the requirements.

During operation of the laser, the power amplifier, with its optical components, is subjected to high level shocks (13 g) from the pulsed power pumping which has necessitated realignment after each shot. The alignment system has been instrumental in locating faulty optical mounts which move beyond acceptable limits after laser operation.

In a benign environment, the optical stability permits satisfactory alignment to be maintained for several hours at most before realignment is again necessary.

System overview - general alignment subsystem requirements

Fundamental system requirements imposed upon the Antares alignment system[1] are the result of operational performance needs of laser users as well as the specific laser optical design. Operationally, the Antares CO_2 laser is to deliver 2-4 shots on target per day. The nominal alignment requirement is to place 80 percent of the laser energy contained in 24 distinct channels within a 280-μm-diameter sphere coincident with target centers. In addition, each of the 24 energy channels must be independently focused and pointed to any point in space within 5 mm radial from target center.

Configuration of the laser shown in Figure 4 requires that two 15-cm annular beams (9 cm ID) output fom separate driver amplifiers be transported approximatly 28 m in air to two locomotive-size power amplifiers. At this point, in each power amplifier, the annular beam is separated into 12 energy channels or sectors by a multifaceted annular mirror (polyhedron). The energy in each sector propogates radially outward from the polyhedron in a 3-cm-diameter, trapezoidally-shaped footprint. Independently controlled mirrors then direct each sector's energy to focus mirros which provide a focal plane for spatial filtering. After spatial filtering, the energy is double passed through a 1500-torr CO_2 gain media for a combined path length of nearly 16 m. The twelve sector annular array output from each power amplifier contains 20 kJ in the now expanded (40-cm diameter) trapezoidal footprints. Propogation down each sector is then independently directed via periscope and turning mirrors along a 70-m vacuum path to the target chamber. At the target chamber, final target pointing and beam focusing are accomplished with 24 F/6 off-axis parabolas.

Thus, due to the laser design and operational constraints, the alignment system must align the mirrors to transport laser energy over a total path length of 114 m while traversing three distinct pressure zones (each of which are separated by salt windows). Additionally, the system must provide for angular alignment and/or beam centering to prevent vignetting from element to element. Finally, the system must permit each sector to point the focused laser energy to any arbitrary coordinates within a 1-cm sphere located at target center.

Alignment system hardware configuration

The alignment system for the Antares laser employs both visible and infrared (10 μm) alignment techniques. As developed, the bulk of the alignment task is carried out at visible wavelengths with final touch-up alignment at the target occurring at 10 μm.

Hardware items which are key to the visible alignment task are depicted schematically in Figure 1. Fundamentally, alignment errors are detemined by viewing point-light sources located at critical alignment positions beginning at the polyhedron and continuing down each sector to the target position. These sources are the terminations of fiber optic cables which are illuminated by 0.7×10^6 footcandles 3000°K projector lamps. An alignment telescope (described in these proceedings)[2] looking down a given sector images these sources onto a silicon vidicon whose raster is stabilized to 0.25 TVRL. The video output from this camera is then processed by a video centroid tracker. Centroid coordinates of the imaged point source are calculated by the tracker at the TV frame rates (1/30 sec), this data is sent to a computer which averages a specified number of centroid coordinates. By comparing the calculated average of the spot centroid with values stored in a data base, the computer determines whether the system is aligned up to the source position. Should the system be unacceptably misaligned, commands are sent by the computer via a stepper motor driver to null the error by adjusting tip/tilt of appropriate mirrors. Typical angular resolution of the larger mirrors in the system is 4 μr/step. The process of calculating a centroid attempting to null the error and then calculating and comparing a new centroid is repeated with appropriate limits until the source is aligned.

Alignment along a given sector continues in the described fashion until the target position is reached. At the target location a special alignment fixture shown in figure 2.0, places a point light source at the desired beam focus coordinate for the sector being aligned. Alignment again takes place as in figure 1.0. The fixture referred to as the Alignment Gimbal Positioner (AGP) is a two-axis gimbal which is mounted on a three-axis set of linear translation stages. These five axes permit the AGP to serve as an alignment reference for all 24 sectors. Positioning accuracy of this device, using encoder feedback, is ±15 μm.

Located on the inner gimbal of the AGP is an assembly consisting of a 100-μm pinhole, 3-mm-diameter beam splitter, fiber-optic illuminator and pyroelectric (10 μm λ) detector. The integrated assembly serves both as a 10-μm detector and as a visible source (DVS).

When alignment to the visible source on the DVS is complete, a 7-watt CO_2 alignment laser is injected into the beam path at the output of the driver amplifier. This aignment laser is collinear with the driver output and propogates down the visibly aligned sector to the target chamber where it is brought to a focus on the DVS. The energy through the pinhole, as seen through the germanium beamsplitter by the pyroelectric detector, is then optimized by perturbations of the last fold mirror. This final correction eliminates dispersion errors between visible and 10-μm wavelengths arising chiefly from wedged salt windows.

The described alignment scheme is performed, in turn, on each of the 24 sectors. Independent and simultaneous alignment occurs on the two power amplifier beamlines from the driver amplifiers up to the target location. At the target location alignment must be done serially since the DVS can serve only one beamline and sector at a time. If the DVS is in use by one beamline and sector, the independent nature of the alignment procedures allows the other beamline to align all 12 sectors in the visible up to the DVS.

Alignment control algorithms

Analogous to the alignment system hardware, the alignment control algorithms were developed to meet both operational and hardware specific requirements. Operational time constraints require that the alignment functions be automated as much as possible. Automated operations must then make use of feedback available from the alignment hardware to provide proper closed-loop control. In addition, the structuring of the software and algorithms must support system integration and trouble shooting.

The techniques developed for visible alignment are generalizations of a simple concept tailored for a specific task such as angular alignment, beam centering, or field of view search. This approach is fundamentally one of calibration of a linear system performed by imaging a reference light source onto the vidicon, taking a centroid reading, moving a particular mirror an appropriate number of steps, and then taking another tracker reading. The difference in the tracker readings divided by the number of motor steps activiating the mirror tip/tilt defines a sensitivity coefficient. In general, movement of a single mirror axis will produce source displacement in both vertical and horizontal on the vidicon raster. Thus, two coefficients will typically be calculated for each of the two mirror axes.

Performing the mirror perturbations in both axes about the nominal alignment position provides the necessary data to describe source displacement with a linear system of equations. Written in matrix form the movement of an alignment source is described in terms of mirror parameters as in equation (1).

$$\begin{bmatrix} \alpha & \alpha_1 \\ \beta_1 & \beta \end{bmatrix} \begin{bmatrix} M_x \\ M_y \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \qquad (1)$$

where the elements of the 2x2 matrix are sensitivity coefficients associated with motor steps in the x and y axes. The source displacement resulting from M_x and M_y motor movements are then given by Δx and Δy.

When an alignment is to be performed, desired Δx and Δy displacements are obtained by differencing a source tracker reading with reference coordinates stored in a data base. By taking the product of the inverted senstivity matrix with the displacement matrix one obtains the motor steps, M_x and M_y, required to null the error in both axes. Inversion of the sensitivity matrix need occur only once and storage of the inverted coefficients in a data base permits rapid alignment via simple matrix multiplication. Note that no assumption has been made concerining orthogonality of mirror movements and the iterative capability provided by computer control minimizes the importance of actuator backlash and nonlinearities in general.

The actual alignment function performed by the algorithm depends on the light source being viewed. Nulling the error of a light sorce viewed at infinity will correct an angular error while correcting the position of a source at a finite object distance provides for beam centering. At certain points within the beamline it is desirable to establish both beam centering and angular alignment at the element. This may be accomplished by using two mirrors in conjunction with the two types of reference light sources. Extending the generality of the matrix concept to perform simultaneous angle correction and beam centering one may construct the matrix as shown in equation (2).

$$\begin{array}{c} \\ \infty \\ \\ S_0 \end{array} \begin{bmatrix} \alpha & \alpha_1 & \alpha_2 & \alpha_{21} \\ \beta_1 & \beta & \beta_{21} & \beta_2 \\ \hline \alpha' & \alpha'_1 & \alpha'_2 & \alpha'_{21} \\ \beta'_1 & \beta' & \beta'_{21} & \beta'_2 \end{bmatrix} \begin{bmatrix} M_{x1} \\ M_{y1} \\ M_{x2} \\ M_{y2} \end{bmatrix} = \begin{bmatrix} \Delta x_1 \\ \Delta y_1 \\ \Delta x_2 \\ \Delta y_2 \end{bmatrix} \qquad (2)$$

(columns 1–2: Mirror 1; columns 3–4: Mirror 2)

Here the 4x4 sensitivity matrix has been generated in a fashion analogous to the previous 2x2 matrix, perturbations of two mirrors have taken place twice; once for each of the reference light sources.

Simultaneous correction of both angular alignment and beam centering requires that the error displacement be calculated for both sources before any mirror rotations are initiated. This involves time-consuming changes of telescope focus (~10 sec), which may be of little importance for a perfectly linear system. However, experience has shown that several iterations are required to null the error of both sources, thus increasing both alignment time and mechanical wear of the telescope drive. An alternative approach is to decouple the procedure by iterating on a single source, for instance until it is completely aligned. Of course such a procedure must not disturb the position of the source not being directly aligned, S_0. Inspection of equation (2) shows that this is possible defining the error (Δx and Δy) of S_0 as being equal to zero. When the initial source, ∞, has been aligned, the telescope focus may be changed to view S_0. In turn the position error of the initial source, ∞, will be defined as zero corresponding to its aligned state. As alignment of source S_0 proceeds, the established alignment of source ∞ will remain undisturbed within the nonlinearities of the sensitivity matrix.

The chief advantage of the second approach is that the decoupling of the alignment task permits a software structure which may be independently executed. Independent execution allows alignment procedures which are unwarranted on a shot-to-shot basis to be eliminated.

When alignment has been so severely disturbed that sources are no longer in the video field of view, search procedures are required. Typical structured search patterns involve a conical scan of the field of view (FOV) about a nominal look position. Equation (1) (single mirror single source) readily provides the motor steps required to displace the FOV in whole or fractional increments in a given direction. For instance, defining Δy as 500 TVL and Δx as zero, one obtains motor steps to displace the FOV one FOV height in the y axis only. Similar calculations can be made for the x axis, thereby providing the necessary constants (m r steps) needed to conduct a "square" spiral search pattern.

Analogous calculation may be performed using equation (2) for coupled search (two mirrors and two sources). In a coupled mirror set one may be faced with the situation where one source is in the FOV and has been aligned but the complimentary source is out of the FOV. This requirement is very similar to the function performed during decoupled alignment outlined above. Thus, by defining appropriate displacement errors as being zero, constant motor step values for the square spiral search of a given light source are generated.

Alignment system performance

System performance using the hardware and visible control techniques outlined earlier have been demonstrated in the system through the power amplifier on six sectors and to the actual target location on a single sector. To date, testing of the CO_2 alignment technique has been limited to evaluation on a full-scale beamline mock-up in the laboratory.

Visible alignment

While alignment errors due to overnight system drift and pressure changes in the power amplifier are observed and must be corrected, the most dynamic effects occur when the laser is fired. Typical errors observed in the system alignment after a laser shot are shown in Table 1. The data in this table are based upon centroid averages obtained from 100 successive video frames presented to the tracker, typical 1 σ values are approximately 1/2 to 3/4 TVL depending on the signal-to-noise ratio of the source being tracked.

The column labeled "Decoupled Iterations" refers to the total number of tracker readings and motor movements required to null the error of the indicated source. Since each source of a coupled set is independently aligned, the complimentary source must be checked to see if its alignment has been disturbed. The number of times this must be done before closed-loop centering and angular alignment is obtained is indicated under "Coupled Iterations." Residual alignment errors are then indicated along with the required alignment accuracy. While the indicated error residuals are substantially better than those required by the error budget, it is done so at the cost of alignment time. Generally speaking, an operator can manually align the system from the front end through the power amplifier on a single sector in 30-40 minutes. Making full use of the error budget, the computer should accomplish this task in less than ten minutes.

Utilization of the two types of alignment sources in a coupled alignment has permitted the identification of faulty optical mounting techniques in the relay optics support structure located in the power amplifier. Alignment errors for ∞ and S_0 are plotted in figure 4 for the back reflector alignment procedure, these errors are those resulting from firing of the laser. Examination of the errors at the back reflector flip-in (S_0) and the spatial filter (∞), shows a marked inconsistency, i.e. errors at S_0 indicate that much larger errors should appear at ∞. Since the errors at ∞ are small, all preceding mirrors are relatively stable. Referring to Figure A, one is then led to suspect that the mechanical placement of source S_0 is unreliable or that movement of the relay mirrors occurs. Since repeatability tests are regularly conducted on the alignment insertion devices to insure their accurate placement, movement of the relay mirrors was the primary suspect. An investigation was conducted that revealed proper assembly techniques had not been followed. After reassembly, subsequent laser firings showed the error had been reduced by an order of magnitude well within acceptable limits of the alignment system.

CO_2 alignment

Evaluation of the CO_2 alignment approach in a mock-up beamline has been chiefly concerned with verifying the sensitivity of the detector system to incremental step changes of the target chamber fold mirrors. The error budget allocation for pointing the beam to the DVS is 26 μm. Single step movement of the fold mirror results in an approximate beam displacement of 13 μm in the focal plane. Alignment using the fold mirror must then be accurate to ±2 steps. Plotted in Figure 5 is the detector voltage as a function of fold mirror step movement about the nominal alignment position. The CO_2 laser used was attenuated to provide less than 100 μm at the focal plane detector corresponding to the anticipated value after propogation through saturable absorber gas and the CO_2 lasing media. Each point plotted on the graph is the average of 100 samples taken at the 30-Hz rate established by a chopper wheel required by the pyroelectric detector. As evidenced by the plot, sufficient sensitivity to mirror movement is exhibited to permit beam pointing at the DVS to approximately half the error budget.

Once verification of the system fundamental sensitivity had been established, an algorithm was developed to perform closed-loop alignment using an LSI-11 computer. It was found that reliable alignment operation could be expected with initial misalignments of approximately 180 μm. Verification of the alignment was accomplished by keeping track of motor steps once the particular mirror used exhibited no backlash (cf. forward and reverse overlap shown in Figure 5). Additional verification was provided by taking tracker readings of the back illuminated pinhole at the aligned position, disturbing the alignment, exercising the algorithm and then comparing the final tracker reading with the initial. Alignment times were generally on the order of 5-7 minutes with initial alignment errors of 180 μm. Improvements in the algorithm and fundamental differences in the Antares motor driver are expected to lower the alignment time to approximately 50 seconds per sector.

Summary

The Antares CO_2 laser system is reviewed and the critical alignment system hardware and control techniques are described. Fundamentally, a dual alignment approach using both visible and 10 μm wavelengths is employed. Initial alignment of the entire optical system takes place at visible wavelengths permitting the use of standard optical tooling during assembly and maintenance. Techniques for angular alignment, beam centering, and field-of-view search have been developed which are special cases of a general calibrated matrix algorithm. Use of the calibrated matrix concept is amenable to data base driven computer control and readily supports a software structure providing independent alignment of any given segment in the beamline. The hardware and control techniques provide demonstrated system capabilities exceeding the design requirements. Final touch-up alignment at 10 μm eliminates dispersion errors associated with propogation through wedged salt windows. This final alignment is accomplished by maximizing the energy of a 10-μm alignment laser to a pinhole detector at the target location with movement of the target chamber fold mirror. The combined detector sensitivity and maximization techniques have demonstrated pointing accuracies to approximately half the required error budget.

References

1. Q. Appert, T. Swann, W. Sweatt, A. Saxman, "Antares Automatic Beam Alignment System," SPIE 24th Annual Technical Symposium, San Diego, California, July 28-August 1, 1980.
2. Q. Appert, T. Swann, "Alignment Telescope for Antares," Los Alamos Conference on Optics '83, Santa Fe, New Mexico, April 11-15, 1983.

Table 1. Typical After-Shot Alignment Errors and Corrections

Location	After Shot Error, TV Lines (Angle Position)	Decoupled Iterations	Coupled Iterations	Final Error, TV Lines(μm) (Angle Position)	Error Budget, TV lines(μr) (Angle Position)
Polyhedron (Coupled)	θ ΔX=1.88(14μr) ΔY=-2.25(17μr)	3	2	θ ΔX=0.01(<1.0μr) ΔY=-0.17(1.3μr)	θ ΔY=8.4(64μr) ΔY=8.4(64μr)
	S_0 ΔX=-1.76(79μm) ΔS_0=9.68(430μm)	2		S_0 ΔX=0.29(13μm) ΔY=-0.89(40μm)	S_0 ΔX=31.5(1.4mm) ΔY=31.5(1.4mm)
Back Reflector (Coupled)	θ ΔX=-6.05(46μr) ΔY=1.63(12μr)	6	3	θ ΔX=0.00 ΔY=0.61(4.6μr)	θ ΔX=14.3(109μr) ΔY=14.3(109μr)
	S_0 ΔX=-7.76(4.2mm) ΔY=-85.7(46mm)	4		S_0 ΔX=0.21(113μm) ΔY=0.17(91μm)	S_0 ΔX=6.6(3.5mm) ΔY=6.6(3.5mm)

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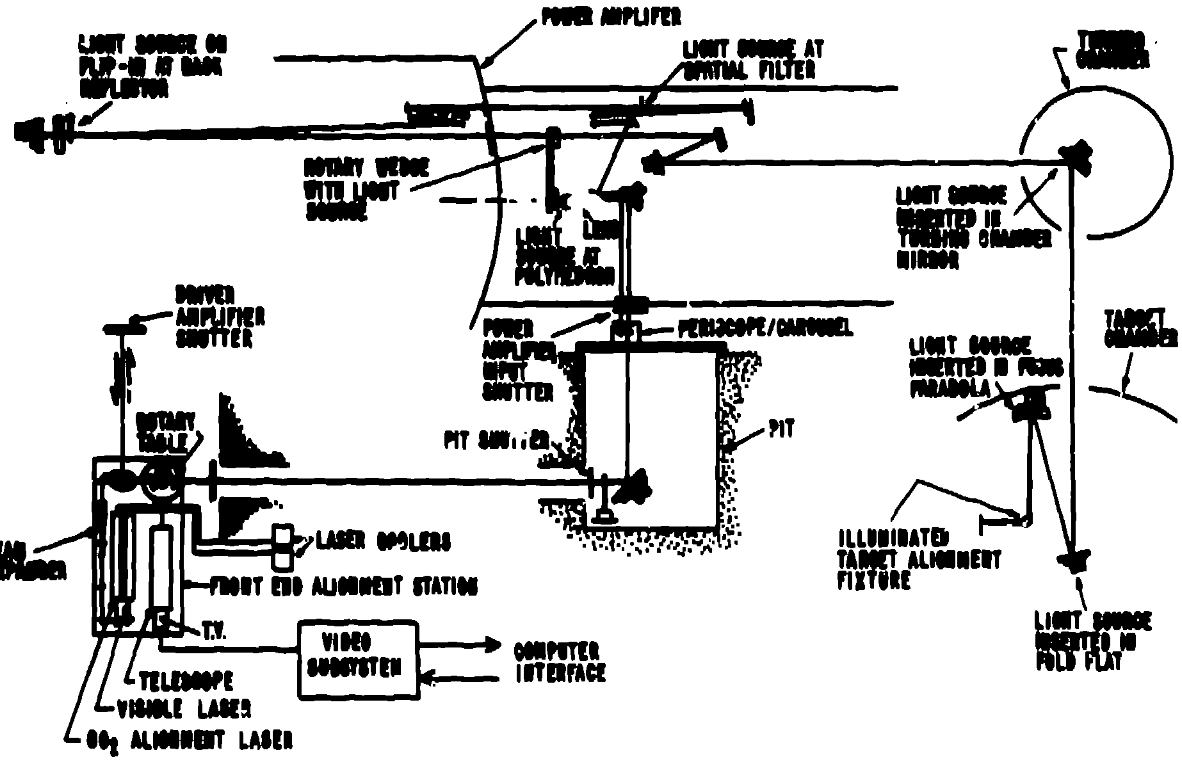

Fig. 1. Antares Automatic Alignment System Schematic.

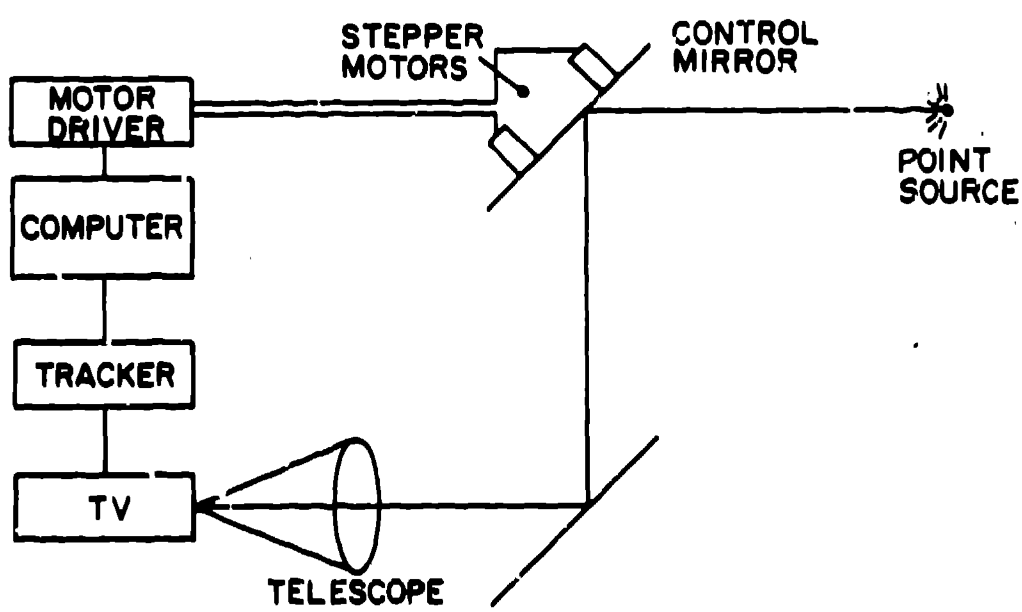

Fig. 2. Alignment Hardware Schematic.

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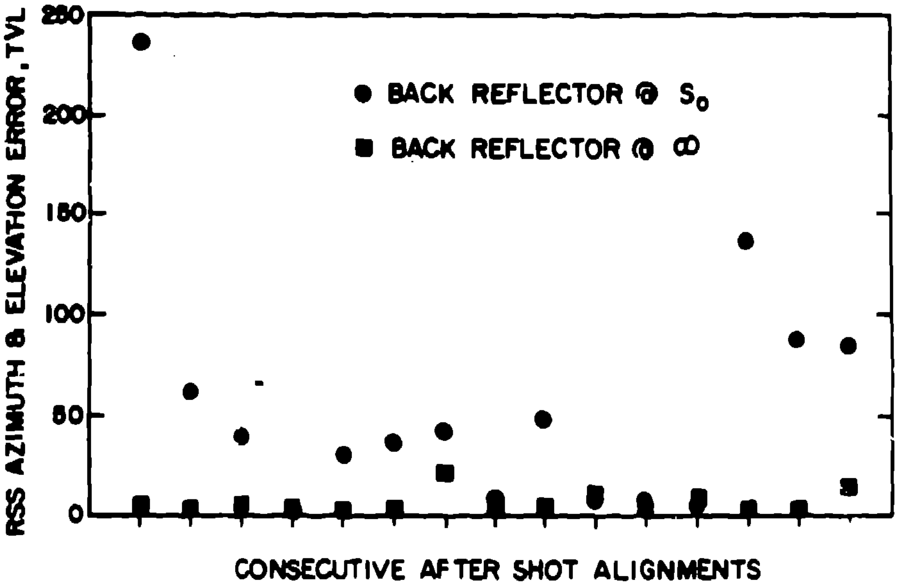

Fig. 3. Back Reclector Centering.

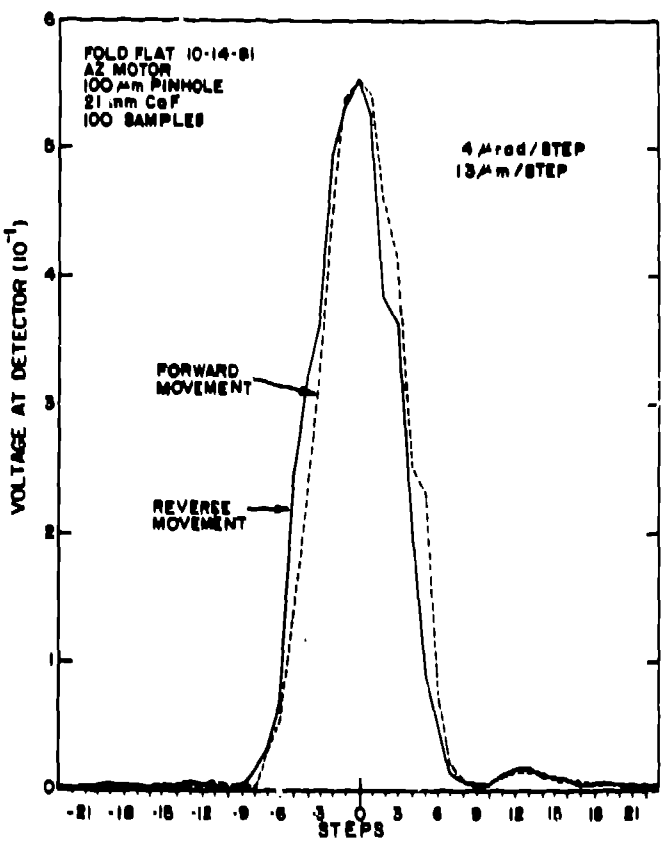

Fig. 4. OEL Target Chambe~ Deam Profile.