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14 MARCH 1975

LASER FUSION SYSTEM DESIGN STUDY

FINAL REPORT

Prepared For: **UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY
LIVERMORE, CALIFORNIA 94550**

CONTRACT NO. P.O.5379305

**AEROJET
ELECTROSYSTEMS
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FOREWORD

This final report on the Laser Fusion System Design Study has been prepared by the Electro-Optical Sensors Group of Aerojet ElectroSystems Company and is submitted in accordance with Statement of Work No. CSL 74-172.

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Section 1

INTRODUCTION

Interaction between a laser beam and a nuclear target can produce output energy levels significantly greater than the laser irradiation level. This premise makes laser fusion a viable potential source of energy. A key factor in achieving the required reaction is the development of a successful laser beam pointing and control system. Aerojet ElectroSystems Company (AESC) has just concluded a study to define and configure such a system, suitable for use in the Lawrence Livermore Laboratory (LL³) Laser Fusion Experiment. This study has yielded a laser beam pointing and control system design which is sufficiently detailed to permit experimental hardware development. In addition to being compatible with the current SHIVA laser baseline, its modular configuration will lend itself to future SHIVA growth configurations, while also being compatible with the Argus and Janus lasers.

In performing the study, AESC addressed itself to three principal tasks considered most critical to the conception and design of the laser beam pointing and control system. These are:

- a. The synthesis of a pointing/control system compatible with existing and advanced laser opto-mechanical configurations.
- b. Attainment of the required pointing angle, longitudinal focus, and differential pathlength accuracies.
- c. Maximum modularization of the sensor and gimbal assemblies to provide the required accuracies at minimum cost.

Achievement of these objectives entailed rigorous analyses of:

- Beam alignment methods up to the target chamber (including structural rigidity effects), optical folding configurations, optimum control-point concepts, optimum pointing error-sensor locations, focusing, centering, and optical pathlength adjustment of the laser.

- Beam alignment accuracy with respect to the surrogate target as a function of structural stability, sensing and control accuracy, and type of control system (manual, semi-automatic, and automatic).
- Cost impact of the various alignment and control concepts.
- Derivation of a recommended control configuration for a 20-path SHIVA system.

Aerojet was successful in formulating a highly promising design based on the results obtained from these tradeoffs.

Various proven control and optical concepts were reviewed and evaluated in terms of modularity, cost, and predicted performance. The result of these tradeoffs is a scientifically feasible, cost effective optomechanical laser beam pointing and control system.

The study established a theoretical performance baseline and determined that such performance was within the limits defined by the overall SHIVA system requirements. Rough order of magnitude system-implementation costs were determined, and an overall program schedule for design, fabrication, installation, and testing of the SHIVA pointing and control system was established.

Section 2

SUMMARY AND CONCLUSIONS

The AESC study served to formulate the following prime requisites to the design of the required pointing and control system. First, the laser beam must be pointed at the target with an accuracy of approximately 2 micrometers; the position of focus would have to be controlled with an accuracy of 7 micrometers; the accuracy of the differential pathlengths between the several laser beams must ensure the pulse time of arrival dispersion at less than 10 picoseconds. In addition, the beam must be centered within the laser amplifiers to an accuracy of approximately 2 mm; and finally, the oscillator must be pointed and centered with such accuracy as to maintain proper operation of each of the laser channels.

The AESC-designed alignment and control system will meet these performance requirements to within the following predicted accuracies and control ranges, and as required for SHIVA:

	Accuracy*		Range of Adjustment	
	Spec.	Capability	Spec.	Capability
Pointing on 1 mm sphere diameter	$\pm 2 \mu\text{m}$	$\pm 2 \mu\text{m}$	4 mrad	$\pm 2 \text{ mrad}$
Centering on final lens	$\pm 2 \text{ mm}$	$\pm 1 \text{ mm}$	$\pm 1 \text{ cm}$	$> \pm 10 \text{ cm}$
Focus	$\pm 7 \mu\text{m}$	$\pm 7 \mu\text{m}$	4 mm	12 mm
OPL Adjustment	$\pm 3 \text{ mm}$	$\pm 3 \text{ mm}$	6 cm	10 cm

* Values are $\pm 2\sigma$

All accuracies predicted for the AESC baseline system exceed the requirements, and the ranges of adjustment will be equal to or greater than those specified. Moreover, accuracy requirements become less stringent with increasing target size. The 300-micrometer deuterium-tritium target diameter used for accuracy calculations is a worst-case value and will usually be larger. Thus, the accuracy calculations are conservative.

In deriving this baseline, a number of sensor, gimbal and servo configurations which could potentially accomplish the four basic functions of pointing, centering, focus and optical path length (OPL) adjustment were synthesized and evaluated. The study also reviewed optical folding, beam expansion and pointing techniques which would minimize the effects of structural deflections upon pointing and focus positions. This report contains a brief discussion of the alternate techniques considered, and a review of their relative merits.

The baseline system proposed will make it possible to fulfill all system requirements with minimum risk and at minimum cost. For example, a space-stabilized pointing system could have provided better than required pointing accuracies, virtually independent of structural rigidity, but at considerably greater cost. Instead, the improvement of structural rigidity made such a system unnecessary and will permit the use of a less expensive, non-stabilized system. At the same time, the capability for adapting to the space-stabilized system has been retained in the baseline designs, should it be needed at a later date.

Versatility was underscored in the baseline pointing and control system design to ensure compatibility with different optical configurations since, at the conclusion of the AESC study, SHIVA is still in a state of evolution. Although the sensors and gimbals were specifically designed to fit the present SHIVA baseline they will also accommodate certain predictable variations in that baseline, involving different number of laser paths and different optical configurations. For example, the pointing and control system is readily adaptable to different spatial filter configurations, as well as

different polarizer and gimbal locations in the system. By this modular design concept, the sensors and gimbals may also be used in different laser systems, such as Argus, Janus, and others having a smaller number of laser beam amplifier paths.

Considerable attention was given to minimizing the cost of the pointing and control system by appropriate design techniques. For example, the system will make use of common sensor packages for centering, target pointing, and focus. Time-shared electronics will be used wherever feasible in the system. Simple, commercial gimbals will be used for beam pointing wherever their availability and performance permits. ROM program costs for the baseline system were generated during the study and have been transmitted to L³ under separate cover.

The AESC baseline design which satisfies these criteria is outlined in Section 3.0. Sections 4.0 through 7.0 contain detailed descriptions of the sensors, servos and electrical components, respectively. Section 8.0 describes the schedule for the proposed hardware development program, while Appendix A is a compilation of manufacturer's data sheets for components which would be used in the system. Supporting information included in Appendix B includes resumes of the key personnel and facilities which would be dedicated to the hardware program.

The entire program, including design study, prototype fabrication, and production fabrication, can be accomplished within program requirements. As discussed in Section 8.0, the proposed three-phase program will permit completion of integration and testing of the system in mid-1977. This schedule is based on presumption of award of a design study contract by 1 July 1975.

In Summary:

- The baseline design satisfies the design criteria.
- The baseline configurations are compatible with the present SHIVA baseline optical system and are adaptable to new configurations.
- The designs can be implemented now.

- The costs are reasonable.
- The program schedule is compatible with L³ objectives.
- The program risk is minimal.

Section 3

LASER BEAM POINTING AND CONTROL

The basic functions of the pointing and control system will entail:

- Pointing and centering of the master and test oscillators
- Centering of the laser beam
- Pointing of the laser beam at surrogate and real targets
- Beam focusing, sensing and adjusting, and
- Sensing and adjusting differential optical pathlengths.

The AESC design developed as a means of implementing these functions is summarized in the following sections.

3.1 BASELINE SYSTEM CONCEPT

The proposed configuration of the 20-beam pointing and control system is illustrated in Figure 3-1. A model of a candidate SHIVA laser with which this pointing and control system could be used is shown in Figure 3-2.

The output of the oscillator assembly, located at the base of the unit, will be divided into 20 beams by a beam splitter assembly. Each beam will pass through its corresponding amplifier system into the target chamber area where it will be folded by two mirrors. The beam will then be focused on a 1 mm surrogate target by the final focusing lens system. The surrogate target will be replaced with a 300-micrometer deuterium-tritium target just before firing.

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3-2

FIGURE 3-1 LASER BEAM POINTING/CONTROL CONFIGURATION

FIGURE 3-2 SHIVA LASER MODEL

3.1.1 Oscillator Assembly

Figure 3-3 is a schematic representation of the baseline alignment/control system. Located in the oscillator assembly is a test oscillator, consisting of a 1-watt CW YAG laser. This test oscillator is used for most of the alignment and control functions. A pocket cell will select the master oscillator and disable the test oscillator at the time of master oscillator firing. Two four-axis centering and positioning gimbals within the oscillator assembly will center and position the oscillators within the apodized apertures, and allow boresighting of the master oscillator to the test oscillator. An oscillator centering sensor located within the oscillator assembly will monitor the centering of the oscillator output beam. At the same time a pointing sensor (also a centering device) located on one apodized aperture will sense the position of the beam within that apodized aperture. Operating in conjunction with the four-axis gimbals, these sensors will permit the centering and pointing of the beams within the apodized apertures of the 20 laser paths.

3.1.2 OPL/Centering Gimbal Assembly

After the oscillator output has been divided into 20 beams by means of a beamsplitter assembly, adapted commercial five-axis gimbals will permit optical pathlength adjustment. This will result in manual centering of each beam within its respective apodized aperture and automatic centering of the beams within their respective laser amplifiers. Since the gimbal system uses a retro cube mirror configuration, longitudinal adjustment of the gimbal along the output laser beam axis will provide a means of controlling the differential pathlength between channels. Manual translation of the gimbal on two mutually orthogonal axes will permit manual beam-position adjustment within the apodized apertures. A precision gimbal drive system operating in conjunction with the beam centering sensors will center the beam in the laser amplifiers and within the final focusing lens.

3.1.3 Centering System

Centering of each beam within its respective amplifier chain will be detected by means of a beam centering sensor, one for each amplifier chain, located at the target-chamber end of the structure. This beam centering sensor will act in conjunction with the beam centering gimbal located at the

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3-5

FIGURE 3-3 BASELINE ALIGNMENT/CONTROL SYSTEM

oscillator end of the structure to ensure centering of the beam within the final amplifiers.

As illustrated in Figure 3-3 a polarizer, normally used for laser system isolations, will be used to pick off energy for the centering sensor. This technique precludes use of a flip-in flip-out beam splitter, and permits the centering sensor to also be used for pointing and for focus, thus reducing system cost. As the energy from the test oscillator and that reflected from the target leave the polarizer with orthogonal polarization planes, a rotating polarizer in the centering sensor can select the viewing direction of this sensor.

A silicon quadrant detector is used in the centering sensor to derive centering error. This technique provides satisfactory operation at low cost with no moving parts.

3.1.4 Pointing Systems

The operation of the pointing system will depend on the return energy reflected from a specular 1-mm radius surrogate target. By centering the return beam reflected from the surrogate target, using the same sensor as used for centering the incident beam, pointing at the center of the surrogate target will be extremely accurate. Moreover, such pointing may be achieved with considerably simpler and less expensive sensors than would be used in conventional angle-pointing systems.

3.1.5 Focusing System

The operation of the focusing system will also depend on detecting the energy reflected from the specular surrogate target. By viewing the diameter of the beam at the focus sensor, and adjusting the position of the final focusing lens to establish a minimum beam diameter at this point, the position of focus of the beam at the surrogate target may be established to the required accuracy. This method uses a considerably simpler and less expensive focusing sensor than would be otherwise required by conventional re-imaging focus techniques. Further, tolerances imposed upon other system parameters are significantly relaxed by this baseline technique.

3.1.6 Optical Pathlength Equalization (OPL) System

The optical pathlength sensor system will make use of existing streak cameras, otherwise required for diagnostic purposes. These cameras will view a diffusely reflective 1-mm radius surrogate target, which is substituted in place of the specular target normally used for pointing and centering purposes. By adjusting pairs of channels to a known differential optical time-delay using the optical pathlength retro mirror assembly, the required differential optical pathlength accuracy of 3 mm is easily attained at minimum cost.

3.2 BASELINE OPTICAL CONFIGURATION

The AESC baseline configuration is derived from the January 1975 L³ optical baseline illustrated schematically in Figure 3-4. A slightly divergent output from the test and master oscillators passes through a relatively tight spatial filter, located in the oscillator assembly, which cleans up the beam and provides a collimated, 5-cm diameter output. This collimated beam then passes through the beamsplitter assembly, the OPL adjust and manual centering gimbal, and then to the apodized aperture. The apodized aperture provides quadratic intensity shaping of the beam defined by the equation:

$$I = I_0 \left[1 - \left(\frac{R_{cm}}{1.25} \right)^2 \right] \quad (3-1)$$

Thus, the nominal apodized aperture output beam diameter is 2.5 cm, with an effective transmission loss of approximately a factor of 4. For purposes of these calculations, the collimated incident beam intensity variation has been assumed as:

$$I = I_0 e^{-\left(\frac{R_{cm}}{1.25} \right)^2} \quad (3-2)$$

The apodized aperture clearly has a transfer function which is the ratio of Equations (3-1) and (3-2).

Energy diverges from the apodized aperture at an angle of 5 mrad, until it reaches the final Faraday rotator, which is configured as a weak positive lens. At this final rotator, the 25-cm diameter beam is collimated. After a nominal distance (approximately 10 meters) the beam is passed through two beam-directing mirrors, one of which is gimballed to provide target pointing. The energy is then focused onto the target by means of an $f/2$ aspheric final focusing lens (0.5 meter focal length).

With this optical configuration, the 100-ft long space frame provides mounting for optical elements of each chain from the apodizer through the last C amplifier (and associated spatial filter). The Faraday rotator and its succeeding polarizer must be mounted in the target chamber room, unless beam expansion is accomplished in the last spatial filter.

In Figure 3-3, the centering, pointing, and focus sensor units are shown mounted just prior to the C amplifiers. This is a point in the system where the beam diameter is approximately 15 cm, an optical distance of 20 meters behind the Faraday rotator lens. (This sensor system may be relocated to various other points in the chain without significant penalty in system performance.) The key in locating the sensor is the position of a suitable polarizer which may be used as a bidirectional pickoff for the sensor. Such use precludes insertion of a beam-splitter in the high-power laser beam, significantly simplifies system design, and provides a highly effective technique for sensing centering, pointing, and focusing using both the incident and reflected beams, at minimum sensor complexity and cost.

3.3 BASELINE CONTROL CONFIGURATION

Figure 3-5 is a block diagram of the control/alignment system used in the synthesis of the baseline system. In effect, the alignment and control system is one very large multiple loop control system consisting of four fully automatic control loops, and two semi-automatic loops. The control loops of concern in the baseline system are:

FIGURE 3-5 POINTING/CONTROL SYSTEM FLOW DIAGRAM

- a. The oscillator centering loop, in which a centering sensor, located in the oscillator package, controls via the centering servo, either the test oscillator pointing and centering gimbal or the master oscillator pointing and centering gimbal.
- b. The oscillator pointing sensor (located on one apodized aperture) which controls via the oscillator pointing servo either the test oscillator pointing gimbal or the master oscillator pointing gimbal located within the oscillator assembly.
- c. The beam centering servos (one per laser channel) which control via the centering servo the position of the two-axis centering gimbals located at the oscillator end of the space frame.
- d. The target pointing system, which senses errors by means of a sensor that is time shared with the centering sensor, and which drives a two-axis gimballed mirror to point the beam incident upon the final focusing lens.
- e. The semi-automatic focus system whereby the operator uses the displayed output from a focused sensor to manually drive the focus lens system into a position which results in minimum image diameter at a prescribed point on the surrogate target.
- f. The optical pathlength control loop, in which an operator observes the outputs of streak cameras, and based on these results electrically drives the optical pathlength adjustment gimbal system.

This report describes the design of the error sensors for each of the loops, the servo systems and associated electronic components, the gimbal designs, the electronic units, the cabling, and the control consoles. Each of these areas is treated in detail.

The alignment and control system is designed for a combination of automatic and semi-automatic integration within the SHIVA laser system. Under normal conditions, the pointing and centering loops operate as automatic control systems, however, the capability is present for manual operation, under conditions wherein failure of a servo loop may occur. Additionally, it is intended that the entire alignment and control system will be shut down by computer command just prior to laser firing. In the event of a malfunction, however, the shut-down command and firing operation of the system, so far as the alignment and control system is concerned, can be accomplished manually. As will be discussed, the system is designed to provide feedback to the operator indicating readiness for firing. Indicators are provided which show when all servos and controls are nulled, or which indicate those elements of the system which are not yet ready for firing.

The alignment and control system is designed to compensate for long-term pointing and centering errors. This mode of operation results from the presumption, based on Livermore direction, that the structural stability will limit high frequency (greater than 1 Hz) structural perturbations to levels which are insignificant compared to system tolerances. This decision minimizes control system costs, by permitting time-shared operation of the servo systems, and by permitting simplification of gimbals. The system design, however, provides the capability for ultimate retrofit for a higher stability system, using stabilized mirrors, etc., should long-term laser growth require such improvements. From a design point of view, the stipulation of structural stability implies relatively low sampling-rate servo systems, optimized to the extent required to achieve the desired servo accuracies against long-term perturbations. Such operation dictates low-frequency response servo mechanisms, of the order of 10 Hz for the pointing servos, and of less than 0.1 Hz for the centering systems.

3.4 SURROGATE TARGET

The baseline alignment and control system illustrated in Figure 3-3 was designed for use against a spherical surrogate target which is accurately placed in the location of the real target. A large (1 cm radius) surrogate

target will be used for initial target acquisition in the preliminary system setup; a 1-mm radius reflective surrogate target will be used for beam centering, beam pointing and for focus, whereas a 1-mm frosted target will be used for optical pathlength adjustment. These techniques provide accuracies which are well within system requirements, yet permit the use of a relatively simple surrogate target which may be quickly interchanged with the real target just prior to firing.

Section 4

SUBSYSTEM AND SENSOR DESIGN AND PERFORMANCE

This section describes the design and performance of each of the alignment/control subsystems, concentrating on the design and operation of each of the baseline sensors. Alternate system designs, considered during the study, are also presented along with the reasons for the choice of the baseline.

4.1 OSCILLATOR POINTING AND CENTERING

4.1.1 Concept

The purpose of the oscillator pointing and centering system is to:

- a. Center the oscillator output beam in each of the apodized apertures to an accuracy of approximately 0.25 mm.
- b. Provide a suitable test oscillator, other than the pulsed master oscillator, for operation of the focus, target pointing and beam-centering system.
- c. Boresight the master oscillator and test oscillator.

These results are achievable in the AESC baseline system by means of the oscillator beamsplitter configuration shown in Figure 4.1-1. A 1-watt cw YAG laser output beam is injected into the output beam of the master oscillator, using a polarizer and Pockel cell existing in the baseline SHIVA optical system. By injecting the test oscillator at Brewster's angle to the polarizer, only vertically polarized (with respect to the figure) components are reflected from the polarizing mirror, while the polarizer assembly passes only horizontally polarized components from the master oscillator. Since polarizers are located in each rod amplifier assembly, triggering of the Pockel cell following the polarizer will shut off energy from the test oscillator and allow energy from the master oscillator to be transmitted. This switching action is the result of the Pockel cell rotating the plane of polarization through an angle of 90° when triggered at the time the master oscillator fires. This allows the master oscillator energy to pass while rejecting the energy from the test oscillator. Clearly, it will be desired to deactivate the test oscillator at the time of pulse laser firing, however, this technique of switching precludes the use of "flip-in flip-out" beamsplitters, and provides a fail safe mode of operation.

Located immediately between the polarizer and test oscillator is a mechanical chopper, whose function is to chop the test oscillator at a frequency of approximately 1 KHz to permit a-c operation of the centering and

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FIGURE 4.1-1 OSCILLATOR/BEAM SPLITTER CONFIGURATION

pointing sensors. A variable iris assembly following the chopper provides the ability to restrict the beam diameter from the test oscillator, thus permitting the pointing system to track the surrogate target under defocused conditions.

Also shown in Figure 4.1-1 are two four-axis gimbals. The function of these gimbals is to center and point both the master oscillator and the test oscillator. The "Oscillator Centering/Positioning" gimbal centers and points the entire oscillator assembly; the "Master Oscillator Centering/Positioning" (MOC/P) gimbal acts to boresight the master oscillator and test oscillator. The location of the MOC/P gimbal between the two oscillators simplifies the removal and replacement of the master oscillator and its realignment with the remainder of the system.

The pointing and centering system operates as follows. At initial system alignment, the master beam of the system (the beam having the oscillator pointing sensor^a at its apodized aperture) is placed roughly within the apodized aperture, and the error signals from this sensor and from the centering sensor are fed into the four axes (two rotational and two translation) of the "Oscillator Centering/Positioning" (OC/P) gimbal. This four-axis servo system thus maintains centering and pointing alignment between the test oscillator and the apodized aperture of the master chain. A second oscillator pointing sensor is then temporarily located at each of the other apodized apertures, in turn, and manual adjustments to place the beam in accurate alignment to these secondary apodized apertures are made by appropriate translation of their respective centering gimbals, locking of the translation axes, and removal of the adjustment handles to prevent tampering. Next, the test oscillator is de-energized, and the master oscillator is triggered with the centering sensor and master channel oscillator pointing sensor connected to the MOC/P gimbal. The OC/P gimbal is de-energized and locked in its original position. The action of the servo centers and points the master oscillator in

^a Only one sensor is required due to the rigidity of the space frame and the relatively loose alignment tolerances at the apodized apertures.

the same way as the test oscillator; thus, the master oscillator and test oscillator become boresighted using the MOC/P gimbal.

The beamsplitter configuration of Figure 4.1-1 consists of an oscillator package mounted half way up in the space frame assembly. In this configuration, the output beam from the oscillator assembly is split into four major beams, two each for four amplifier channels, and two each for six amplifier channels. The beams are subsequently split into the six outside channels and four inside channels depicted in the space frame assembly of Figure 3-1.

The beamsplitter assembly is readily reconfigured for a low-level oscillator mount, merely by changing the configuration and relative reflectance/transmission characteristics of the beamsplitters. From a control system point of view, there is little difference between the two configurations.

Five mirrors are used in each path, after leaving the oscillator package, to achieve beamsplitting, optical pathlength adjustment, beam centering, etc. This five-mirror configuration represents a compromise with prior system designs, to achieve a system which is adequate from the point of view of performance, but which minimizes system cost. The five mirrors used in this system comprise: a mirror for directing the oscillator package output into a vertical plane; a beamsplitting mirror for selecting the output for the desired channel, and retro cube assembly used in conjunction with the Optical Path Length (OPL) manual centering/beam centering gimbal.

The initial system design used eight mirrors to accomplish this function. Pairs of mirrors were mounted in rhomboid structures, such that motion of these mirror pair assemblies with respect to other portions of the structure did not generate beam angle rotations. As a result, the eight-mirror structure provided extremely high stability, independent of stability of the mechanical space frame structure.

The five-mirror structure is adequately stable, however, due to the high mechanical stability of the present space frame design. Late in the study, a four-mirror configuration was considered which used a roof mirror assembly at the OPL gimbal. This design was superseded by the five-mirror assembly because of slightly greater stability achieved by using the retro cube in place of the roof mirror, with only a minor change in cost.

Two centering sensors are used for alignment of the oscillator assembly. In both cases, these centering sensors consist of an array of four separate silicon detectors, which sample the energy around the periphery of the beam, and provides error signals indicating the location of the centroid of the beam relative to the mid point of the detector array. Clearly, these centering sensors must be capable of working both in a cw and in a pulse mode of operation, as it is necessary to energize both the cw test oscillator and the master oscillator to accomplish the required centering and pointing functions. In addition, these centering sensors operate only when the beam is at its full diameter, and are inoperative when the test oscillator iris is used. However, the relative angular stability of the oscillator assembly is high, having an estimated stability time of the order of several days. Thus, intermittent de-energizing of the oscillator centering and pointing servos should have little effect on accuracy of this portion of the system.

4.1.2 Accuracy

The oscillator pointing accuracy within the apodized apertures is principally dependent on the mechanical alignment between the apodized apertures. With realizable mechanical tolerances and misalignments between the several apodized apertures, an alignment accuracy well within requirements is achieved. As Table 4.1-1 shows, a pointing accuracy of considerably better than 0.25 mm at the apodized aperture is achieved by the pointing servo itself. The principal servo error is caused by gain unbalance between the amplifiers amplifying the respective outputs of opposing detectors; a 2% gain accuracy is assumed in the table. The sensor noise is insignificant at this point, due to the proximity between the detectors and the oscillator.

TABLE 4.1-1 OSCILLATOR POINTING AND CENTERING ACCURACY

Pointing		
Factor	Accuracy at Element (1σ)	Accuracy at Apodized Aperture (10 m from Gimbal)
Sensor offset	0.12 mm	0.12 mm
Sensor noise	0.05 mm	0.05 mm
Error quantizing	0.03 μ rad	0.0003
Mirror driver quantizing	0.03 μ rad	0.0003
Servo noise and limit cycle	0.2 μ rad	<u>0.002</u>
Accuracy = 0.12 mm (1σ)		
Centering		
Factor	Centering Accuracy	
Sensor offset	0.12 mm	
Sensor noise	0.05 mm	
Error quantizing	0.0025 mm	
Mirror driver quantizing	0.0025 mm	
Servo noise and limit cycle	<u>0.005 mm</u>	
Accuracy = 0.12 mm (1σ)

Similar accuracies are achieved by the centering servos. Again, the limiting error is that of sensor amplifier gain unbalance.

4.1.3 OPL Adjustment

The components associated with the oscillator pointing assembly also provide the capability for adjusting of differential optical path lengths (OPL) between channels to the required tolerance of 3 mm. The technique for sensing and accomplishing this task is discussed in Section 4.5 of this report. However, the typical positions of the optical pathlength gimbal assembly required to achieve pathlength compensation are shown in Table 4.1-2. For each of the 20 channels, this table lists typical oscillator-to-apodized aperture pathlengths, including a variable term whose value is determined by the longitudinal position of the OPL adjusting gimbal. The third column in this table shows C amplifier output-to-target typical distances derived from L³ Drawing AA74-114543-00. The fourth column of the table shows the total path (less the distance from the apodized aperture to the C amplifier, assumed equal for all channels). The fifth column shows that value of longitudinal position of the OPL gimbal required to accomplish path length equalization. The point of this table is that path length equalization can be reasonably achieved by appropriate longitudinal positioning of the OPL adjusting gimbals, and that for this example a maximum differential longitudinal position of approximately 4.5 meters is required. Clearly, the gimbals need move only by small amounts around these nominal positions, to effect final vernier adjustment of the differential optical pathlength.

TABLE 4.1-2 OPTICAL PATH LENGTH COMPENSATION

Channel	OSC to Apodized Aperture ^a	Camp Output to Target ^a	Total Path (Less AA to C) ^a	1/2 Rn ^a
1	11.3 + ΔL_1	15.8	27.1 + ΔL_1	2.2
2	9.75 + ΔL_2	12.5	22.3 + ΔL_2	4.6
3	9.75 + ΔL_3	14.0	23.8 + ΔL_3	4.0
4	10.7 + ΔL_4	14.0	24.7 + ΔL_4	3.4
5	8.5 + ΔL_5	13.1	21.6 + ΔL_5	5.0
6	10.7 + ΔL_6	17.1	27.8 + ΔL_6	1.9
7	11.3 + ΔL_7	19.2	30.5 + ΔL_7	0.5
8	10.7 + ΔL_8	17.1	27.8 + ΔL_8	1.9
9	10.7 + ΔL_9	14.0	24.7 + ΔL_9	3.4
10	9.75 + ΔL_{10}	13.1	22.9 + ΔL_{10}	4.3
11	9.75 + ΔL_{11}	14.0	23.8 + ΔL_{11}	3.9
12	8.5 + ΔL_{12}	14.0	22.5 + ΔL_{12}	4.5
13	7.0 + ΔL_{13}	15.8	22.8 + ΔL_{13}	4.4
14	8.5 + ΔL_{14}	14.0	22.5 + ΔL_{14}	4.5
15	7.9 + ΔL_{15}	14.0	21.9 + ΔL_{15}	4.8
16	7.9 + ΔL_{16}	17.1	25.0 + ΔL_{16}	3.3
17	7.0 + ΔL_{17}	19.2	26.2 + ΔL_{17}	2.7
18	7.9 + ΔL_{18}	17.1	25.0 + ΔL_{18}	3.3
19	7.9 + ΔL_{19}	14.0	21.9 + ΔL_{19}	4.8
20	8.5 + ΔL_{20}	17.4	25.9 + ΔL_{20}	2.8

* Distances in meters.

4.2 BEAM CENTERING SYSTEM

The beam centering system has the purpose of centering the beam in the final focusing lens to an accuracy of ± 2 mm (1.4 σ). The baseline system achieves an accuracy of 1 mm using quadrant silicon detectors.

This section discusses the baseline centering sensor which is also used for pointing and for focus, the effects of signal-to-noise ratio and gain unbalance on centering accuracies, and the different centering detector schemes which have been evaluated during this study.

4.2.1 Concept

Figure 4.2-1 shows the baseline optical configuration used for the centering, pointing, and focus sensor. The sensor is located at a position in the 5 mrad divergent beam where the beam diameter is approximately 15 cm. Only a small variation in accuracy results from moving the sensor to a smaller diameter portion of the beam.

In the baseline, energy from the beamsplitters is reflected from the gimbal centering mirror, passes through the apodized aperture, and passes through and is reflected from one of the polarizers in the C amplifier assembly, adjacent to the sensor. This polarizer can be either a single transmission polarizer, or a double reflecting polarizer.

The polarizer is used as a beamsplitter in this application to preclude introduction of an auxiliary beamsplitter in the system. As shown, the polarizer reflects the vertically polarized component of the energy from the source and from the surrogate target. A phase retardation plate or polarizer rotates the polarization plane of the reflected source energy, causing horizontally polarized energy to pass through the polarizer to the sensor. A rotating polarizer in the sensor can thus separate between energy from the source and reflected energy from the target.

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FIGURE 4.2-1 BASELINE CENTERING/POINTING/FOCUS SYSTEM

The centering sensor optics re-image the 15-cm-dia laser beam at the polarizer onto a 1-cm-dia quadrant silicon detector, with a 15:1 demagnification. As the incident energy from the test laser is chopped at a frequency of approximately 1 KHz, a-c preamplification of each of the four detector outputs may be used. Using standard technology, the outputs of the four amplifiers are subtracted in an appropriate manner to derive both X and Y error, indicating beam position with respect to the center of the quadrant detector. A non-linear automatic gain control circuit operates in conjunction with the summed output from the four detectors to maintain a more uniform error signal scale factor, independent of source intensity. The output of the signal processing electronics is synchronously demodulated with respect to the oscillator chopper, and the error signals are provided for processing in the electronics units and for use with either the centering or pointing servos.

The quadrant detector system operates on the premise of symmetry of the laser beam. It provides an error signal proportional to the degree of unbalance of energy on opposing pairs of detectors. (Note that the quadrant detector system is an area balance system, rather than a strict centroid detection system. The use of a lateral photovoltaic detector would provide a null at the centroid of energy, however, the location of the area balance point and the centroid are obviously the same for a symmetrical beam.)

Figure 4.2-2 is a layout of the baseline centering, pointing, and focus sensor. This layout is configured for use with a single transmission polarizer, however, the configuration can be modularly adapted for use with a double reflecting polarizer. As the layout shows, the sensor includes a silicon quadrant detector, used for beam centering error detector, and for pointing error detection. A TV camera, using a silicon target vidicon, is used for focus sensing. Located ahead of the quadrant detector is a rotating polarizer, which rotates through 90° increments to select viewing of either the incident energy from the source, or the reflected energy from the surrogate target.

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4.2-4

FIGURE 4.2-2 BASELINE CENTERING/POINTING/FOCUS SENSOR

The optics used in this sensor are extremely simple, and need have only moderate image quality - typically 0.5-mrad imagery. The function of the optical system is merely to re-image a plane, perpendicular to the beam at the location of the polarizer, onto the quadrant detector, with a magnification of 1/15. Thus, a 1/15-cm beam diameter at the polarizer plane is imaged onto the quadrant detector as a 1-cm dfa beam. The re-imaging property of the optical system means that the quadrant detector senses beam diameter at the polarizer plane, independent of the deviation angle of the main laser beam. Clearly, this re-imaging plane has a slightly different location for incident and reflected energy, however, due to the nature of the operation of the system, this change in location of the image plane has no effect on system operation.

The baseline concept also includes a folding mirror, a phase retardation plate or polarizer, and two shutters. These elements at the top of the sensor permit energy to be viewed from either the source or the surrogate target, as previously described. A polarizer may be used in place of the retardation plate, at lower cost but with a factor of four transmission reduction.

Figure 4.2-3 shows an alternate centering/locus sensor, which is set up to view energy only in one direction. The main difference between this sensor and that shown in Figure 4.2-2 is elimination of the quarter-wave plate, the mirror, and the upper shutter. The TV camera may also be eliminated if the sensor is not used for focusing.

In both concepts, shutters have been included adjacent to the sensor. These shutters are made of an absorbent material which absorbs energy scattered into the system at the time of laser firing. One shutter also blocks off energy from the quarter-wave plate and mirror assembly. This upper shutter not only provides a damage prevention mechanism, but also is useful in certain polarizer pickoff configurations to enhance the energy ratio between incident energy from the source and energy reflected from the target.

175-1666

4.2-6

FIGURE 4.2-3 ALTERNATE CENTERING/FOCUS SENSOR

In Figures 4.2-2 and 4.2-3, the system polarizer is shown as an integral portion of the sensor. In final designs, however, the system polarizer housing would be a sealed unit, containing thin windows on both ends of the unit, and windows on both the top and bottom. This construction would maintain extreme cleanliness around the system polarizer, as needed to preclude the initiation of damage mechanisms. This polarizer assembly would be provided by L³, & J AESC would provide the sensor modular packages which bolt onto flanges on the side of the polarizer housing.

4.2.2 Polarizer Pickoff System

As discussed, one of the system polarizers is used as a beam-splitter to pick off a portion of the energy from the test oscillator and from the signal reflected from the surrogate target for the purpose of determining beam centering, target pointing, and focus. The use of this technique considerably simplifies the design of the sensor, as it precludes using a removable beamsplitter in the system, with its concurrent problems of removal before firing, and of proper angular alignment.

The specific sensor/polarizer configuration is dependent operating conditions of the polarizer chosen. Figure 4.2-4 shows the different pickoff configurations, which vary with the relative planes of polarization of the incident and reflected beams. This figure depicts the configurations for a single transmission polarizer assembly, while Figure 4.2-5 shows sensor/polarizer configurations for a dual reflective polarizer assembly. In both cases, relative cost tradeoffs are shown between two alternate sensor configurations, one employing a single sensor, a mirror, and a shutter or phase retardation plate, while the other uses only two sensors. In both figures, the relative transmission of the system from the source intensity (S) is shown, as well as the transmission of the system to reflected energy from the surrogate target (T). In Figure 4.2-4, the ratios of source to target (S/T), and target to source (T/S) intensities are given when looking at the source and target, respectively.

FIGURE 4.2-4 SINGLE POLARIZER PICKOFF CONFIGURATIONS

175-1255

FIGURE 4.2-5 REFLECTIVE POLARIZERS PICKOFF CONFIGURATIONS

As these figures show, virtually any polarization configuration may be successfully used, with reflective or refractive polarizers. Figures 4.2-6 and 4.2-7 show sensor configurations for double reflecting polarizers. The variations to accommodate these different polarization plane configurations merely involve the use of quarter-wave plates or shutters, as appropriate. Generally, those configurations using a single sensor and a mirror, together with a shutter and/or quarter-wave plate, provide acceptable performance at minimum cost. Those configurations using two sensors provide generally higher performance, however, the cost is also somewhat greater due to the dual sensor configuration.

Some caution should be used in this cost comparison, however, as it is based on a cost of approximately \$500 per quarter-wave plate. Current information indicates the availability of thin film phase retardation plates at this price; testing has not confirmed their suitability, however. Should it be necessary to resort to crystalline quartz quarter-wave plates, for example, the price of the single sensor configuration could increase to a level which well exceeds that of the dual sensor approach.

As an alternate, however, a polarizer, oriented at 45° to the plane of the figure, could be used in lieu of the phase retardation plate, with a loss of a factor of four in transmission, as previously discussed. Such an approach may provide a lower cost alternative to the phase retardation plate.

During the detail design phase, it will be necessary to investigate achievable polarization precision available in the polarizers and phase retardation plates, as this precision affects the accuracy of the centering and pointing systems. Clearly, inaccuracies in the polarizers and phase retardation plates can be compensated by appropriate adjustment of the reflecting mirror and of the sensor housing. However, a significant variation in polarization angle or phase retardation could create an apparent asymmetry in beam intensity profile which would cause the apparent centroid to be shifted away from the actual beam centroid location.

375-1252

FIGURE 4.2-6 SINGLE SENSOR CONFIGURATION - REFLECTIVE POLARIZER

375-1256

FIGURE 4.2-7 DUAL SENSOR CONFIGURATION, REFLECTIVE POLARIZER

As Figures 4.2-4 and 4.2-5 show, modular sensors may be configured in such a way to satisfactorily perform with either the transmission or reflected polarizer configurations, and different configurations are readily available which can perform with almost any polarization plane configuration.

4.2.3 Performance

4.2.3.1 Accuracy

Beam centering accuracy requirements are derived from the system intensity uniformity requirements. The criteria is an illumination uniformity of better than 5%, under conditions of an $f/2$ final focusing lens, a 300 micrometer diameter target, and a quadratic profile beam. To achieve this, the system is defocused by 250 micrometers behind the center of the real target, to create a spot diameter of approximately 200 micrometers on the target surface.

Table 4.2-1 shows the alignment and mechanical systems error budget derived by L^3 , based on these constraints. As shown, the 5% illumination tolerance has been broken down into components attributable to pointing, focus, and centering errors. The values shown in this table represent 1.4 standard deviations. For centering, a 2% illumination variation allowance has been allocated, implying a tolerance of 3 mm at the final focusing lens, of which 2 mm is attributable to the alignment system.

Table 4.2-2 shows the alignment system requirements for centering, as well as for other parameters of the system. The table also indicates L^3 estimates of open loop stability; that is, the length of time required for the system to drift outside of the tolerance limits, under conditions of a deactivated control system. This open loop stability time will be used later in the report to set servo sampling rates.

The baseline system meets these centering accuracy requirements. As Table 4.2-3 shows, a standard deviation of 0.76 mm is calculated at the position of the final focusing lens of the system. These calculations presume a sensor located at a position where the beam diameter is approximately 15 cm.

TABLE 4.2-1 ALIGNMENT AND MECHANICAL SYSTEMS ERROR BUDGET*

	Illumination Variation Allowance	Implied Tolerance	Oscillator Drift	Optical Component Drift	Target Chamber Drift	Target Drift	Alignment System Error
Pointing	3%	4 μ m	0	2 μ m	2 μ m	2 μ m	2 μ m
Focus	4%	8 μ m	0	2 μ m	2 μ m	2 μ m	7 μ m
Centering	2%	3 mm	2 mm	1 mm	0	0	2 mm
Synchronism	0%	3 mm	0	0	0	0	3 mm
Total	5%						
* f/2, 300 μ m target, quadratic profile.							

4.2-14

TABLE 4.2-2 ALIGNMENT SYSTEM REQUIREMENTS

	Beam Accuracy $\Rightarrow$		* Alignment Mechanism Resolution	Beam Range $\Rightarrow$		** Alignment Mechanism Range	Alignment Mechanism Range per Resolution	Open-Loop Stability
	Position	Angle		Position	Angle			
Pointing	$\pm 2 \mu\text{m}$	$\pm 4 \mu\text{rad}$	1 μrad	$\pm 2 \text{ mm}$	$\pm 4 \text{ mrad}$	4 mrad	4000	100 sec
Focus	$\pm 7 \mu\text{m}$	--	3.5 μm	$\pm 7 \text{ mm}$	--	4 mm	4000	100 sec
Centering	$\pm 2 \text{ mm}$	$\pm 30 \mu\text{rad}$	7 μrad	$\pm 5 \text{ cm}$	$\pm 700 \mu\text{rad}$	700 μrad	100	1000 sec
Oscillator Beam Positioning	$\pm 8 \mu\text{m}$	$\pm 5 \mu\text{rad}$	4 μm 1 μrad	$\pm 4 \text{ mm}$	$\pm 2 \text{ mrad}$	8 mm 2 mrad	2000	10 days
Path Length	$\pm 3 \text{ mm}$	--	1 mm	$\pm 3 \text{ cm}$	--	6 cm	60	10 days
* Assumes gimbaled mirror before f/1000 rotator lens. ** Assumes gimbaled mirror after f/200 rotator lens.								

4.2-15

TABLE 4.2-3 CENTERING SYSTEM ACCURACY

	At Element	At Last Lens (σ)
Sensor Offset Error	0.4 mm rms (2%)	0.74 mm
Sensor Noise	0.1 mm rms	0.18 mm
Servo Limit Cycle	0.6 μ rad p-p	0.018 mm
Error Quantizing	0.12 μ rad p-p	0.0028 mm
Mirror Actuator Quantizing	0.12 μ rad p-p	0.0028 mm
$\sigma = 0.76$ mm		

The first column of Table 4.2-3 shows the actual error of the indicated element, while the second column normalizes this error to the location of the focusing lens. The 0.4-mm sensor offset results from a 2% assumed gain unbalance in the amplifier channels. Sensor noise results from the finite sensor S/N ratio. The servo is presumed to have a sinusoidal limit cycle whose peak-to-peak amplitude is two resolution elements of the mirror actuator system. As the error is equally likely to lie anywhere within the quantizing and mirror actuator quantizing peak limits, the standard deviation of error for each of these values is $0.2/\sqrt{12}$ mrad.

These angular values are normalized to linear dimensions using equations to be discussed later. The root sum of the square (RSS) of these linear error values results, as seen, in a standard deviation of 0.76 mm. This value, normalized to the 1.4 σ definition, is approximately one half the specified alignment system error for centering purposes.

Calculations have been made to determine the centering system accuracy, when the centering sensor is moved closer to the source to a location where the beam diameter is 7.5 cm. The results of this calculation are shown in Table 4.2-4. A small increase in centering error results from such movement of the centering system, however, the centering accuracy is again limited by sensor offset error, a value which may be improved. Practically, the sensor could be placed at either location.

The only significant equations used in calculating the centering accuracy relate the linear accuracy of the sensor and the angular accuracy of the gimbal centering mirror to linear error at the final focusing lens. The model for these computations is the configuration of Figure 4.2-1. The beam diameter at the final Faraday rotator is 25 cm, while that at the output of the apodized aperture is 2.5 cm. Thus, the equivalent optical distance between these two paths, with a 5-mrad beam divergence, is 45 meters. The distance between the Faraday rotator lens and the focusing lens is 10 meters.

TABLE 4.2-4 CENTERING ACCURACY - 7.5 CM DIA SENSOR POSITION

Parameter	At Element	At Las. Lens (σ)
Sensor Offset	0.2 mm (1σ)	0.92 mm
Sensor Noise	0.05 mm (1σ)	0.23 mm
Servo Limit Cycle	0.6 μ rad (p-p)	0.018 mm
Error Quantizing	0.12 μ rad (p-p)	0.003 mm
Driver Quantizing	0.12 μ rad (p-p)	0.003 mm
		<u>0.003 mm</u>
		$\sigma = 0.92$ mm

In the model, small motions of the gimbal centering mirror are assumed to create negligible beam translation at the apodized aperture.*

$$l_1 = \frac{D_1 - 2.5}{5 \times 10^{-3}} \times 10^{-2} \quad (4-1)$$

$$y_1 = l_1 \phi = 2l_1 \theta$$

$$y_2 = 45 \phi$$

$$y_3 = 45 \phi + 10 \left(\frac{\phi}{10} \right) = 46 \phi = 92 \theta$$

and

$$y_3 = \frac{92}{2l_1} y_1 = \frac{46}{l_1} y_1$$

where l_1 = distance between apodized aperture and sensor (m)

y_1 = linear error at sensor

D_1 = beam diameter at sensor (cm)

y_2 = linear error at last Faraday rotator lens

y_3 = linear error at focusing lens

ϕ = beam angle

θ = centering gimbal angle

Thus, for our model, the sensor errors are magnified by a factor of 1.84. With the sensor at the 7.5-cm diameter location, the magnification is 4.6.

* This approximation is not strictly true. Motion of the gaussian beam across the apodized aperture does cause a translation of the beam centroid to an extent dependent on the size of the incident gaussian beam, and on the precise beam profile created by the apodized aperture. For cases of fifth-power exponential beams, centroid translation values of one half the amount of the linear translation at the apodized aperture have been calculated.

4.2.3.2 Spatial Filter Effects

One or more spatial filters may be located between the centering sensor and the source (and between the centering sensor and the surrogate target). Figure 4.2-8 shows the effective transfer function of these spatial filters. The effect of the spatial filter is clearly a function of their magnification value. For example, with a magnification of unity, the spatial filter becomes approximately an inverting element. For other values of magnification, the spatial filter not only creates an inversion both in offset and in angle, but scales the magnitudes of these values in accordance with the inlet and outlet beam diameters of the spatial filter. One may conclude that the effect of the spatial filters on the system is nothing more than an effective mechanical foreshortening, with no serious optical effects, so far as the centering control dynamics are concerned.

On the other hand, the spatial filters cause significant difficulties, insofar as overall system mechanical stability is concerned, because translation and rotation of the spatial filters cause a translation and a rotation of the beam angles. Even at magnification values of unity, the negative magnification of the spatial filter causes the output beam to rotate at a rate which is twice the rotation angle of the spatial filter assembly. Similarly, beam translation occurs at a rate which is proportional to the total length of the spatial filter and to its rotational angle. Thus, structural implementation of the spatial filters and their location on the space frame must achieve a high degree of stability if overall system accuracies, particularly under dynamic conditions, are to be achieved.

The angular rotation and translation properties of the spatial filters may be used to provide spatial filter alignment during system operation. Using the centering sensors, the spatial filters may be aligned by finding those two translation and rotation positions of the spatial filter which result in centering of the beam and in 50% vignetting of the beam off the internal aperture of the spatial filters. This adjustment is made by simultaneously translating the spatial filters, and rotating them about their axes until the beam intensity drops by a factor of two. Noting the translational position

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$$m = \frac{f_2}{f_1}$$

$$h_2 = -m h_1 + \sigma f_1 (1 + m)$$

$$\phi = -\frac{\sigma}{m}$$

FIGURE 4.2-8 SPATIAL FILTER TRANSFER EQUATION

of the filter, the adjustment is again repeated, only on the other side of center of the beam. By these techniques, the translational position, which results in centering the beam within the spatial filter aperture, may be performed. After determining this translational position, the spatial filter angular position may again be aligned to achieve centering at the centering sensor. Calculations have indicated that spatial filter alignment sufficient to achieve required system centering accuracies may be performed using this technique.

4.2.3.3 Detector Signal-to-Noise Tradeoffs

The centering noise of the sensors results from the finite signal-to-noise ratio in the detector system. A number of different detector systems have been considered for possible implementation as centering detectors, each having slightly different characteristics. The properties of the quadrant silicon detector were investigated, as were the characteristics of a lateral photovoltaic silicon detector, which produces a differential current which is proportional to signal intensity and location of the centroid of the energy on the detectors. A four-detector array was considered, where four discrete detectors are placed around the edges of the beam, and the behavior of a rotating disk system was evaluated, wherein the center of the beam distribution is determined from the modulation of energy by a mechanically rotated disk within the optical assembly. Figure 4.2-9 shows the centering noise for these four detector configurations as a function of signal-to-noise ratio on the detectors, while Figure 4.2-10 shows the centering noise as a function of the total beam power on the detectors.

Both of these curves have been calculated using a quadratic intensity profile beam, and presuming operation of the sensor at a beam diameter of 15 cm. Performance of the quadrant detector array was predicated on use of a United Detector Technology Model PIN-SPOT/8D diffused silicon detector, having a noise equivalent power of 5×10^{-12} watts, and an active diameter of 1.1 cm.

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FIGURE 4.2-9 CENTERING DETECTOR S/N RATIO REQUIREMENTS

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FIGURE 4.2-10 CENTERING SENSOR ACCURACY

The centering noise was calculated as follows for the candidate detector configurations:

Quadrant Detector

Given a circularly symmetric image with intensity

$$I = I_0 \left\{ 1 - \left[\frac{R}{R_0} \right]^2 \right\} \quad (4-2)$$

on a quadrant detector array, with the center of the circle displaced ϵ from the center of the quadrant array. It may be shown that the incremental power change on each pair of detectors is:

$$\Delta P \approx \frac{4}{3} I_0 \epsilon R_0 \quad (4-3)$$

If the detector responsivity is K volts/watt, and opposing pairs of detectors are subtracted, the output voltage is:

$$\Delta E = 2K \Delta P \approx \frac{8}{3} \epsilon R_0 K I_0 \quad (4-4)$$

Since the total beam power is

$$P_T = \int_0^{R_0} 2\pi R I(R) dR = \frac{\pi}{2} R_0^2 I_0 \quad (4-5)$$

Substituting for I_0 ,

$$\Delta E = \frac{16}{3\pi} \left(\frac{\epsilon}{R_0} \right) P_T K \quad (4-6)$$

The noise voltage out of the electronics is:

$$\sigma_n = K (\text{NEP}) \sqrt{\Delta f} \quad (4-7)$$

where NEP is defined as the sensitivity of all four elements taken together. Thus, that error which is equivalent to the noise voltage is given by:

$$\Delta E = \sigma_n \text{ or } K(\text{NEP}) \sqrt{\Delta f} = \frac{16}{3\pi} \frac{\epsilon}{R_o} P_T K \quad (4-8)$$

Thus,

$$\epsilon = \frac{(\text{NEP}) \sqrt{\Delta f} R_o}{P_T} \frac{(3\pi)}{16} \quad (4-9)$$

For the detector used,

$$\text{NEP} = 5 \times 10^{-12} \text{ watt}$$

and

$$R_o = 7.5 \text{ cm}$$

and

$$\Delta f = 20 \text{ Hz (2 times servo noise bandwidth)}$$

Then

$$\epsilon = \frac{1.3 \times 10^{-11} R_o}{P_T}$$

P_T is the power incident on the detector, a value which is attenuated from the beam power at the polarizer by the following factors:

Polarizer pickoff transmission	0.05 (worst case)
Sensor optics transmission	0.80
Sensor polarizer transmission	0.40
Sensor beamsplitter efficiency	0.45
Total	0.007

In addition, the signal from the test oscillator is attenuated by the following factors:

10 polarizers $(2 \times 1.05)^{10}$	1.66×10^3
6 rods $(1.02)^{12}$	1.27
8 rotators $(1.02)^{16}$	1.37
4 spatial filter lenses $(1.02)^{16}$	1.37
1 apodized aperture 4	4
Beamsplitter 20	20
Glass, 150 cm @ $1\%/cm \left(\frac{1}{0.99}\right)$ 150	4.5
Total Attenuation	1.4×10^6

For this case, using a 1-watt laser source, the power at the detector is:

$$P_T = (1) (0.007) \left(\frac{1}{1.4 \times 10^6} \right) = 4.9 \times 10^{-9} \text{ watt}$$

The error is thus:

$$\epsilon = \frac{(5 \times 10^{-12}) (20)^{1/2} (7.5)}{4.9 \times 10^{-9}} \left(\frac{3\pi}{16} \right)$$

$$= 0.02 \text{ cm}$$

The value used in the noise analysis presumes a slightly higher polarizer pickoff transmission, and uses a value of $\epsilon = 0.01 \text{ cm}$.

Lateral Photovoltaic Effect Detector

Similarly, it may be shown that the transfer function for a lateral photovoltaic effect detector is:

$$\epsilon = \frac{\text{NEP} \sqrt{\Delta f} R_o}{1.6 P_T} = \frac{1.4 \times 10^{-11} R_o}{P_T} \quad (4-10)$$

for

$$\text{NEP} = 5 \times 10^{-12} \text{ watt}$$

and

$$\Delta f = 20 \text{ Hz}$$

Thus, the results are similar to the quadrant detector array.

Four Detector Array in Quadratic Beam

Using a system of four detectors spaced around the periphery of the beam, centering error may be derived by differencing the outputs of opposing detectors. For a quadratic beam, it may be shown that:

$$\epsilon = \frac{(\text{NEP}) \pi R_o^4 \sqrt{\Delta f}}{2 \sqrt{2} \omega P_T (2R + l)} \quad (4-11)$$

where NEP = the noise equivalent power of each detector at 1.06 microns

R_o = the beam radius

Δf = equivalent noise bandwidth

ω = width of each detector

l = length of each detector

R = distance from beam center to the inner edge of each detector

For:

$$\text{NEP} = 6.66 \times 10^{-12}$$

$$R_0 = 7.5 \text{ cm}$$

$$\Delta f = 20 \text{ Hz}$$

$$\omega = R = 1 \text{ cm}$$

$$R = 5 \text{ cm}$$

$$\epsilon = \frac{9.5 \times 10^{-9}}{P_T} \text{ cm}$$

This is almost 100 times less sensitive than either of the other two systems, for $R_0 = 7.5 \text{ cm}$. The net sensitivity decrease is not this poor, however, as there are no sensor optical system losses with this technique.

Four-Detector Array in Gaussian Beam

Highly satisfactory performance is achieved using the four detector array in the Gaussian beam at the oscillator and the apodized aperture.

For an array of four 1-cm long detectors, spaced 1.5 cm from the center of the beam at the apodized aperture,

$$\epsilon = \frac{3.2 \pi (\text{NEP}) \sqrt{\Delta f} R_0}{\omega P_T} \quad (4-12)$$

For:

$$\text{NEP} = 6.66 \times 10^{-12} \text{ watt}$$

$$\Delta f = 20 \text{ Hz}$$

$$R_0 = 2.5/\sqrt{2} \text{ cm}$$

$$\omega = 1 \text{ cm (detector width)}$$

$$\epsilon = \frac{5 \times 10^{-10}}{P_T} \text{ cm}$$

Since the attenuation is small, as these detectors are mounted right at the oscillators, the noise is insignificant. It may in fact be necessary to use much smaller detectors, or to attenuate the signal to the detectors.

4.2.4 Electronic Unbalance Effects

The dominant term in the centering error equations results from gain errors in the electronic system. Figure 4.2-11 shows the effect of gain unbalance per detector channel (1 σ values) in terms of centering error, with a quadratic 15-cm dia beam. This figure was prepared using the quadrant detector array previously described, and using a four detector system in which the 0.25-sq cm detectors are spaced around the periphery of the 15-cm dia beam.

A 2% gain unbalance per channel for the quadrant detectors provides a centering error of approximately 0.4 mm. Clearly, this centering error is the function of the beam diameter at the sensor location, and varies linearly with this diameter.

The four detector system provides considerably better accuracy for a given gain unbalance, however, its noise sensitivity is considerably poorer. Additionally, a variation in beam diameter causes significant difficulties in centering of a system using the four-detector array. Thus, this configuration is applicable only at locations such as the apodized aperture and in the oscillator centering area, where the beam diameter is relatively constant.

The gain unbalance value of 2% per detector channel was chosen as a relatively arbitrary value, and smaller gain unbalance values approaching 1% could be used with care in selection of the operational amplifiers used with this system, and with appropriate feedback resistors.

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4.2-51

CENTERING
ERROR M.M.

QUADRATIC BEAM 15 Cm DIAMETER

GAIN UNBALANCE / DETECTOR CHANNEL

FIGURE 4.2-11 CENTERING DETECTOR BALANCE

4.2.5 Alternate Centering Concepts

In the derivation of techniques for the centering sensor, four basic systems were considered. In all these systems, whose detector configurations are shown in Figure 4.2-10, centering was performed using some property of the beam related to its intensity characteristic. The quadrant detector was chosen as the baseline system, due to its simplicity and known performance characteristics. This detector configuration tends to center the average value of the energy distribution at the center of the detector array. On the other hand, detectors are available which accomplish centering by other means.

4.2.5.1 Lateral Photovoltaic Detector

By placing four contacts around the periphery of a silicon PN junction, it is possible to obtain a potential across these contacts which is proportional to the displacement of the true centroid of energy on the detector from the center of the detector. Such a device is called a lateral photovoltaic detector. The differential voltage derived from this detector is proportional to the product of the centroid displacement and the total intensity upon the detector. Thus, the system requires an automatic gain control circuit to achieve a relatively uniform servo gain characteristic. However, the servo error curve is independent of the size of the spot on the detector, unlike the quadrant detector, and hence a relatively linear error characteristic is achieved across the diameter of the detector.

This detector configuration represents a close alternate to the quadrant detector, and as Figures 4.2-9 and 4.2-10 show, its signal-to-noise ratio and sensitivity behavior is closely comparable to the quadrant detector. The specific detector used in these calculations was a United Detector Technology Model PIN SC 10, having a noise equivalent power (at spectral peak) of 5×10^{-12} watt, a diameter of approximately 1 sq cm, and relative spectral responsivity at 1.06 microns of 0.2.

4.2.5.2 Four-Detector Array

A second alternative would be provided by the system selected for the oscillator centering and pointing system. This approach, which makes use of four detectors located around the beam edges, would yield slightly better signal-to-noise ratio performance than would the preceding units; however, its power sensitivity is considerably poorer since it makes use of detectors without optics. Concurrently, however, the design of such a system should be less expensive due to elimination of the optics. It must be stressed, however, that the utility of this system is dependent on maintaining relatively constant beam diameter. Highest sensitivity for the four detector array is achieved when the detectors are placed around the periphery of the beam. Clearly, a reduction in beam diameter, therefore, destroys the usefulness of the four-detector array for centering purposes.

4.2.5.3 Rotating Disk Sensor

One of the most accurate systems, from the point of view of stability and sensitivity, was a single silicon detector at the focal plane of an optical system, which collects the total energy from the beam. Ahead of the optical system, or in a collimated portion of the system ahead of the detector, is placed a rotating disk whose axis defines the reference position for the centering system. As the disk rotates, a varying intensity signal is obtained, whose amplitude is proportional to the displacement of the beam center from the rotational axis of the disk. Due to its design, the accuracy of this system is independent of all electronic gain and tolerance values, and the centering noise value is considerably lower, from a power point of view, than that of any other system used. Thus, for extremely high accuracy conditions, the rotating disk system represents perhaps a better choice than any of the other three detector arrays. However, for this system, the accuracy is not needed, and the mechanical implications of the rotating disk in the system, compared to the quiescent operation of the other three detector configurations, tend to weigh heavily against this design.

4.2.5.4 CCD Sensor System

The feasibility of replacing the focus sensor vidicon with a CCD array was discussed in Section 4.4.12. Were this to be done, the array might also be used in place of the quad detector for centering. This option should be reviewed at the time of the program design phase, in the light of then existing technology. At the present time, however, the NEP of the CCD arrays is comparable to the incident power on the detector. Thus, the S/N achieved by this method would not attain the required centering accuracies, at present.

4.3 BEAM POINTING SYSTEM

The beam pointing system design will align the principal ray from the final focusing lens along a diameter of the surrogate target to an angular accuracy of ± 4 microradian (1.4σ). The method used will achieve, according to predictions, a performance better than the 4 microrad required value, using a technique which centers the return beam centroid.

4.3.1 Concept

Figure 4.3-1 shows the baseline pointing system concept. Energy from the modulated test oscillator is passed through the apodized aperture, the A and B amplifiers and a spatial filter, and through the polarizer pickoff for the centering/pointing/focus sensor. It eventually reflects off the surrogate target and back again to the polarizer pickoff. When operating in the centering mode, the sensor system will provide error signals to center the incident beam at the plane of the polarizer. Now, operating in the pointing mode, this centering sensor looks forward toward the reflected energy from the surrogate target and provides error signals which indicate centering error of the return beam, reflected from the surrogate target. By moving the gimbaled pointing mirror in response to the pointing error signals, the return beam can be centered at the polarizer. As calculations in Section 4.3.2 show, centering of the return beam results in accurate beam pointing toward the center of the surrogate target. This type of pointing system accomplishes this objective with the same accuracy as other systems while requiring less precision than do other techniques, hence lower cost.

The ball-bearing surrogate target acts as a non-inverting retro-reflector. When energy is focused at the center of the ball, the diameter of the reflected energy beam is the same as the diameter of the incident energy beam. The reflected beam is merely translated from the incident beam, as the pointing error increases from zero.

When the focus position is displaced from the center of the surrogate target, the effects are as shown in Figure 4.3-2. A varying magnification of the return beam occurs as the focus point is moved from the center of the

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FIGURE 4.3-1 BASELINE CENTERING/POINTING/FOCUS SYSTEM

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CENTERS RETURN BEAM FROM TARGET

FIGURE 4.3-2 BASELINE POINTING SYSTEM

surrogate target. When the focal point occurs ahead of the center of the surrogate target, the beam diameter is smaller than that of the incident beam, reaching a point of minimum diameter when the focus point is one-half the surrogate target radius ahead of the center of the target. Conversely, when the image is moved behind the center, the target size is magnified. With an image at the back of the surrogate target, the return beam is magnified by a factor of three over the diameter of the incident beam, thus causing return beam vignetting unless the incident beam diameter is reduced.

With a full aperture incident beam, tracking can be performed when the image is ahead of the center of the surrogate target. By reducing the size of the incident beam, tracking may be accomplished when the image is behind the center of the surrogate target, at some loss in total beam power.

In both cases, the translation of the return beam bears a constant relationship to the pointing error, as motions through the surrogate target are small compared to the focal length of the final focus lens. The translation of the beam is approximately 1 mm, for a 1-mm radius ball, and a 1-micron pointing error, thus, substantial error signals may be generated for extremely small movements. Should higher system sensitivities be required, a smaller diameter surrogate target could be used; the 1-mm value appears to represent a compromise between ball size, tracking field of view, and scale factor. Thus, the baseline pointing system is capable of tracking the image from the test oscillator, under all reasonable conditions of focus and deliberate de-focus.

An additional advantage of the baseline pointing system is that the sensing system combines both centering and pointing errors, thus tending to center the image on the target surface better than would a straightforward angle pointing system. The centering of energy on the target surface is a major criteria in achieving uniformity of illumination around the real target. The pointing accuracy of the focused image is only one factor in determining centering of energy on the target surface; the other factor is accuracy of beam centering at the final focus lens.

In Figure 4.3-3, a relation is shown for the combined effect of pointing and centering errors, in decentering the target image on the surface of the surrogate target. This relation is calculated for a realistic baseline defocus situation. The effect of the pointing system is to combine these errors such that they partially cancel. For this case, with equal beam centering and beam pointing errors, the decentering error at the target surface is about 30% of either of the errors. For other cases, the errors cancel completely.

Thus, the baseline pointing system tends to satisfy overall pointing and centering system requirements, rather than merely addressing just the pointing problem.

4.3.2 Target Pointing Accuracy

Table 4.3-1 lists those factors which determine the accuracy of the system. The factors include the incident beam centering accuracy, the return beam centering accuracy, and the incident beam angle. The accuracy of initial centering of the incident beam was discussed in Section 4.2. Table 4.3-1 shows the accuracy to which the return beam is centered; from this information, and from beam incident angle assumptions, the pointing accuracy may be determined.

The factors shown in the table include sensor noise resulting from S/N ratio effects and noise within the sensor, and sensor offset resulting from gain errors in the quadrant detector array and its associated electronics. Comparison with Table 4.2-3 will show that these two factors are assumed identical in the two cases. Actually, the S/N ratio in the pointing sensor will be somewhat reduced due to the attenuation in the path between the sensor and the surrogate target.

The latter three factors of the table, consisting of mirror oscillation, error quantizing, and actuator quantizing, are performance parameters of the servo system. The mirror oscillation term represents an estimate of the likely limit-cycle amplitude of the servo system, while the error quantizing represents the effect of digitizing the error signal outputs, and the actuator quantizing value represents the amplitude of incremental steps of the stepping motor.

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$$\delta = -1.3 \times 10^{-3} \alpha + 10^{-3} \beta$$

FIGURE 4.3-3 POINTING CENTERS IMAGE ON TARGET SURFACE

TABLE 4.3-1 TARGET POINTING ACCURACY

- Pointing Servo Return Beam Centering

Accuracy Factors:

	<u>At Element (rms)</u>	<u>In 25 cm Beam</u>
Sensor Noise	0.1 mm	0.166 mm
Sensor Offset	0.4 mm	0.66 mm
Mirror Oscillation	0.7 μ rad	0.028 mm
Error Quantizing	0.7 μ rad	0.012 mm
Actuator Quantizing	0.3 μ rad	0.012 mm

$\sigma_p = 0.68$ mm
Centering Error

- Target Errors Combine Pointing, Centering & Angle Errors

$$\sigma_e^2 = (10^{-3} \sigma_p)^2 + (10^{-3} \sigma_c)^2 + (10^{-2} \sigma_\theta)^2$$

$$\sigma_e = 1 \text{ micrometer } (\sigma_c = 0.76 \text{ mm}, \sigma_p = 21 \mu\text{rad})$$

The various accuracy factors listed in the second column of Table 4.3-1 were converted to equivalent error at the centering sensor. The standard deviation of the centering error is the RSS of these values. As expected, this standard deviation value is comparable to the centering accuracy of 0.76 mm achieved for the incident beam.

At the bottom of the table, the pointing, centering and beam angle errors are combined to derive the beam pointing error at the target. The incident beam angle value of 30 microrad (1.4 σ) represents the ratio of the 2-mm maximum centering error at the final lens, and the distance from the final lens to the effective object point of somewhat over 60 meters. The precise value of incident beam angle is not significant, as this term is small compared to the linear error terms.

Figure 4.3-4 shows the centering accuracy of a defocused image on the surface of the real target. The various error factors, shown in Table 4.3-1, have been combined in a manner to be discussed in the following section. The accuracy of centering, 0.7 micrometers, is slightly better than the pointing accuracy, due to the error cancellation effects previously discussed.

4.3.3 Pointing Equations

This section will describe certain key relations for the pointing system beginning with the surrogate target equations, and then deriving return beam centering equations, error, and defocused target centering accuracy.

4.3.3.1 Surrogate Target Relations

Figure 4.3-5 shows the geometrical relations between the surrogate target and the final focusing lens. In this illustration, a section has been taken through a diameter of the sphere. With X_0 , y_0 , the intercept height on the target (with respect to target center):

$$X_0 = \frac{m(bm - a) + \left\{ R^2(1 + m^2) - (bm - a)^2 \right\}^{\frac{1}{2}}}{m^2 + 1} \quad (4-13)$$

$$m = \tan \theta,$$

$$y_0 = a + (X_0 - b)m,$$

and

$$\phi = \sin^{-1} \frac{y_0}{R}$$

The equation of the reflected ray, in sphere coordinates, is:

$$y = (X - X_0) \tan(2\phi - \theta) + y_0 \quad (4-14)$$

and

$$\phi \approx 2\phi - \theta \quad (4-15)$$

• **Pointing System Combines Target Centering and Pointing Errors**

$$\sigma_Y^2 = (10^{-3})^2 \left\{ (.2\sigma_c)^2 + \sigma_p^2 + (6\sigma_\theta)^2 \right\}^{\frac{1}{2}}$$

$$\sigma_Y = 0.7 \text{ Micrometer}$$

for: 0.4 mm Defocus with
300 μ Real Target

[0.25mm Defocus with 1mm
Surrogate]

FIGURE 4.3-4 DEFOCUSSED IMAGE CENTERING ACCURACY

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FIGURE 4.3-5 SURROGATE TARGET GEOMETRY

It may be shown, for moderate values of error, that the apparent object height is given by:

$$\epsilon \approx a \quad (4-16)$$

Thus, the apparent angular error of a reflected ray from the target back through the principal point of the lens is:

$$\delta = \frac{2\epsilon}{f} \quad (4-17)$$

The lateral shift of the collimated beam is calculated by first assuming that the principal ray of the lens constitutes the beam center. Then, with $\theta = 0$, it is readily shown that:

$$\phi = \frac{2a}{R} \quad (4-18)$$

and that the intercept height of the reflected principal ray at the lens is:

$$h = \frac{2af}{R} \quad (4-19)$$

for $f = 0.5 \text{ m}$, $R \approx 10^{-3} \text{ m}$, $h = 10^3 a$.

The reflected beam diameter is magnified to an extent which depends on the focal point location, b_o . By taking the approximation that m is small, and that $a = 0$, the reflected angle is

$$\phi = \theta \left[1 - \frac{2b}{R} \right] \quad (4-20)$$

Thus, for $b = 1/2 R$ (focus ahead of ball center), the return beam is collimated for $b = -R$ (focus at back of ball), the return beam diameter is magnified three times.

Other relations may be derived. For example, the apparent focus position varies slightly with pointing error as

$$\Delta f = \frac{2a^2}{R} \quad (4-21)$$

However, the effect is too small to be of concern, with the pointing accuracy values envisioned.

4.3.3.2 Centering Accuracy

The pointing system centers the reflected beam from the surrogate target to accomplish pointing. Using the model of Figure 4.3-6a, the relations are:

$$\left. \begin{aligned} a_2 &= a_1 + \theta_1 (l_1 + l_2) + \phi l_2 \\ \theta_2 &= \theta_1 + \phi \end{aligned} \right\} \text{ Incident beam} \quad (4-22)$$

and

$$\left. \begin{aligned} b_1 &= b_2 + \delta_2 (l_1 + l_2) + \phi l \\ \delta_1 &= \delta_2 + \phi \end{aligned} \right\} \text{ Reflected beam} \quad (4-23)$$

The subscript 1 refers to the viewing plane and the subscript 2 refers to the focusing lens plane.

These relations are combined by the equations:

$$b_2 = a_2 \left(1 + \frac{2b}{R} \right) + \frac{a_2 f^2}{R} \quad (4-24)$$

and

$$\delta_2 = -\theta_2$$

taken from derivations similar to those given in Section 4.3.3.1.

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a. RAY GEOMETRY

b. CONTROL GEOMETRY

FIGURE 4.3-6 RETURN BEAM CENTERING ERROR

The "servo" diagram of Figure 4.3-6b shows the control system relations, embodied in the equation:

$$b_o = b_2 + \delta_2 (l_1 + l_2) + \phi l_1 \quad (4-25)$$

As the values b_2 and δ_2 are "inputs," the centering accuracy is just the RSS of sensor offset and noise, together with linear mirror motion effects (ϕl_1).

4.3.3.3 Linear Tracking Error

Combining equations, we can solve for return beam centering error as a function of target error, incident centering error and incident angular error (θ_1).

$$b_1 = a_1 \left(1 + \frac{2b}{R} \right) + \epsilon \left(\frac{2f}{R} \right) \left(1 + \frac{b l_2}{f^2} \right) + \theta_o \left(\frac{2b l_1}{R} \right) \quad (4-26)$$

inverting,

$$c = \frac{b_1 - a_1 \left(1 + \frac{2b}{f} \right) - \theta_o \left(\frac{2b l_1}{R} \right)}{\frac{2f}{R} \left(1 + \frac{b l_2}{f^2} \right)} \quad (4-27)$$

for the case:

$$b = 2.5 \times 10^{-4} \text{ m (defocused 1/4 radius behind ball center)}$$

$$f = 0.5 \text{ m}$$

$$R = 10 \text{ m}$$

$$l_1 = 20 \text{ m}$$

$$l_2 = 10 \text{ m}$$

$$\begin{aligned}\epsilon &\approx \frac{R}{2f} \left\{ b_1 - a_1 - \theta_1 \left(\frac{2b\ell_1}{R} \right) \right\} \\ &= 10^{-3} \left\{ b_1 - a_1 - 10 \theta_1 \right\},\end{aligned}\quad (4-28)$$

$$\text{or} \quad \sigma_\epsilon = 10^{-3} \left\{ \sigma_{b_1}^2 + \sigma_{a_1}^2 + 100 \sigma_{\theta_1}^2 \right\}^{\frac{1}{2}}. \quad (4-29)$$

$$\text{With } \sigma_b \approx \sigma_a = 0.7 \text{ mrad, and } \sigma_{\theta_1} = \frac{30 \times 10^{-6}}{\sqrt{2}},$$

$$\begin{aligned}\sigma_\epsilon &= 10^{-3} \left\{ (0.7 \times 10^{-3})^2 \times 2 + 10^2 (21 \times 10^{-6})^2 \right\}^{\frac{1}{2}} \\ &= 1.0 \times 10^{-6} \text{ meters.}\end{aligned}$$

4.3.3.4 Defocused Spot Decentering

Suppose that we are really interested in the accuracy to which we can center a spot on the surface of a target, rather than just pointing the beam along the target diameter. The error is a function both of pointing error and decentering at the final lens.

With the spot at a distance (C) from the focus point, the decentering error is:

$$\begin{aligned}\gamma &= a_2 \left(\frac{C}{f} \right) + \theta_2 \\ &= a_1 \left(\frac{C}{f} \right) + \theta_1 \left(\frac{C\ell_1}{f} \right) + \epsilon \left[\frac{C\ell_2}{f^2} + 1 \right]\end{aligned}\quad (4-30)$$

$$\text{but} \quad \epsilon = \frac{b_1 - a_1 \left(1 - \frac{2b}{f} \right) - \theta_1 \left(\frac{2b\ell_1}{R} \right)}{\frac{2f}{R} \left(1 + \frac{b\ell_2}{f^2} \right)} \quad (4-31)$$

Thus:

$$Y = a_1 \left\{ \frac{c}{f} - \frac{\left(1 + \frac{2b}{f}\right) \left(1 + \frac{cl_2}{f^2}\right)}{\left(\frac{2f}{R}\right) \left(1 + \frac{bl_2}{f^2}\right)} \right\} + \frac{b_1 \left(1 + \frac{cl_2}{f^2}\right)}{\left(\frac{2f}{R}\right) \left(1 + \frac{bl_2}{f^2}\right)} + \theta_1 \left\{ \frac{cl_1}{f} - \frac{\left(\frac{2bl_1}{f}\right) \left(1 + \frac{cl_2}{f^2}\right)}{\left(\frac{2f}{R}\right) \left(1 + \frac{bl_2}{f^2}\right)} \right\} \quad (4-32)$$

$$Y \cong \frac{R}{2f} \left\{ a_1 \left(\frac{2c}{R} - 1 \right) + b_1 + \theta_1 \left(\frac{2l_1}{R} \right) (c - b) \right\} \quad (4-33)$$

and, for: $a = 4 \times 10^{-4}$ m (200 μ spot size on 300 μ diameter real target)

$$b = 2.5 \times 10^{-4} \text{ m}$$

$$f = 0.5 \text{ m}$$

$$R = 10^{-3} \text{ m}$$

$$l_1 = 20 \text{ m}$$

$$l_2 = 10 \text{ m}$$

$$\sigma_Y^2 = (2 \times 10^{-4})^2 \sigma_{a_1}^2 + (10^{-3})^2 \sigma_{b_1}^2 + (5 \times 10^{-3})^2 \sigma_{\theta_1}^2 \quad (4-34)$$

$$\sigma_Y = 0.72 \times 10^{-6} \text{ m, for } \sigma_a = \sigma_b = 0.7 \times 10^{-3} \text{ m and}$$

$$\sigma_{\theta_1} = 21 \times 10^{-6} \text{ rad}$$

Note that the defocused spot decentering error is smaller than the actual pointing error, because the pointing system tends to take into account both the effects of decentering at the final lens and the effect of pointing errors.

4.3.4 Alternate Tracking Systems

A number of alternate configurations were considered in the evolution of the baseline tracking system. One of these systems, a close candidate for baseline, is shown in Figure 4.3-7, and in layout form in Figure 4.3-8. This alternate pointing system combines a centering and focus system, as does the baseline, however, the pointing system operates by matching the angles of the incident and reflected beams. It may be readily shown from symmetry that such angular alignment of the beams only occurs when the beam is directly pointed along a diameter of the surrogate target.

Clearly, the angles to which such alignment must be performed are comparable to the angular alignment accuracies at the target, itself. The angles are magnified, however, by the inverse ratio of the beam diameter at the location of the sensor and at the final focus lens. Thus, it is necessary that the angles be matched to an accuracy of about 6 microrad, when the sensor is located at a 15-cm diameter point in the beam (25 cm final focus beam diameter) to achieve a pointing accuracy at the target of 4 mrad.

The sensor of Figure 4.3-7 achieves this accuracy by matching the two beams, rather than attempting to achieve absolute accuracy. In Figure 4.3-7, a high image-quality optical system, having imagery comparable to the quality of the prime laser optical system, re-images the target image on a sunburst FM reticle. The image is nutated on this reticle in such a manner as to generate an FM signal at the single detector. The deviation ratio of this signal will be proportional to the error and its sub-carrier phase angle, with respect to the skew plate reference, will indicate the direction of error. Experience at AESC has demonstrated the capability of such systems to generate error signals to the accuracies required for this system. Moreover, by using a time-shared system which alternately looks at the signal from the source then the signal from the target, and reads error values from the two directions, the pointing servo system merely moves the gimballed pointing mirror until the error values are matched, rather than attempting to drive the error signal to zero.

FIGURE 4.3-7 ALTERNATE POINTING AND FOCUS CENTERING SENSOR

175-1597

FIGURE 4.3-8 ALTERNATE CENTERING/POINTING/FOCUS SENSOR

The optical configuration shown permits the desired accuracies to be achieved independent of the orientation of the retro cube or dielectric polarizer in the system. Thus, alignment of this concept is relatively straight forward and highly stable. On the other hand, the fact that the target energy diverges from the source, and converges when reflected from the surrogate target, requires that means be employed to compensate for this apparent object distance change.

The alternate configuration (Figure 4.3-8) is considerably more complex than the baseline system, due to the addition of the FM angle pointing sensor optics and scanning system. In addition, a retro cube required for reflection of energy from the polarizer somewhat complicates system design and implementation. The retro cube is needed, however, to make system alignment accuracy independent of polarizer or reflecting mirror angles.

Table 4.3-2 tabulates tradeoffs between the baseline pointing system and the angle system concept. As shown, both systems provide satisfactory tracking accuracy, however, the angle sensor system would be significantly more complex due to the requirement for high resolution optics, extra detector and electronic units, and rotating scanner system of the FM tracker. In addition, the angle sensor system is more expensive due to the additional hardware required.

TABLE 4.3-2 ANGLE VS CENTERING SENSOR FOR POINTING

Factor	Centering Sensor	Angle Sensor
• Tracking Accuracy	Satisfactory	Satisfactory
• Complexity	Same Centering & Pointing Sensors--Low Res. Optics No Rotating Parts	High Res. Optics, Extra Pointing Detector & Electronics
• Cost	\$170K (20 Units)	\$235K (20 Units)
• Alignment Accuracy	0.5 mrad	0.5 mrad
• Tracking During Defocus	Yes (with Iris)	Yes (With Sensor Refocus)

The alignment accuracy of the angle sensor system is much less stringent than that of the baseline, however, baseline alignment requirements are well within long-term stability tolerances. Additionally, the baseline pointing system is readily capable of tracking during significant deliberate defocus; the angle tracking system can accomplish this task, however, it is necessary to refocus each of the tracking sensors at the time of defocus. Thus, the angle sensor is a tracking system candidate, however, the baseline system appears to provide a more cost effective solution.

During the course of the study, a number of other types of tracking sensors were considered. One of these (Figure 4.3-9) contained a single error sensor located in the vicinity of the master oscillator and time shared such that it would provide error signals from all the laser channels. The advantage of this configuration was that the error sensor was located in a position where sensor tolerances were relatively noncritical. Thus, relatively high accuracies could be easily achieved. Moreover, the use of a time-shared system reduced systems cost by having only one error sensor in the system. The major disadvantages of the system lay in the high path round-trip attenuation (approximately 10^{10}) caused by the polarizers operating without Faraday rotators, and the effect of beam splitter scattering. The energy ratio between incident energy from the test oscillator and return energy from the target was of the order of 100 dB. Thus, there was serious question as to whether or not the scattering coefficients on the beamsplitter could be held sufficiently low to provide the desired signal to background ratio in the error sensor. Moreover, the time-shared nature of this system significantly reduced the information rate, and hence servo bandwidth, of the pointing systems.

Interferometer pointing sensors were also considered; one is depicted in Figure 4.3-10. The return beam, reflected from the surrogate target, is combined with the incident beam from a cw source to obtain an interference fringe pattern. By observing the fringe frequency and direction, and ring concentricity, pointing error signals could be derived as could information concerning the focus of the system. This concept was deemed to have a low success probability, however, not only due to the high path attenuation

FIGURE 4.3-9 SINGLE SENSOR--GEOMETRICAL

974-1211

4.3-23

- MEASURE RING CONCENTRICITY
- MEASURE FRINGE FREQUENCY AND DIRECTION
- LOW SUCCESS PROBABILITY

FIGURE 4.3-10 INTERFEROMETER POINTING SENSOR

of the system, but also due to the multiplicity of optical elements in the path to and from the surrogate target and the resultant low probability of achieving a usable interference pattern.

During the study, one of the concerns was that of obtaining tracking information after removal of the surrogate target and emplacement of the real target. Such information is necessary with a relatively unstable mechanical structure, to compensate for structural motions which may occur after surrogate target removal. Consequently, the likelihood of real target tracking was examined. Calculations were performed to determine the feasibility of using a 10-micrometer infrared imaging sensor (FLIR) for target detection. These calculations, which assumed a frozen target at 4°K, with an emissivity of 0.001, an index of 1.1, and a visual reflectivity of 0.002, showed that a FLIR entrance aperture diameter of approximately 0.7 meter would be required to achieve 10 line resolution on the target. Serious questions were raised with regard to the feasibility of accurately tracking the target due to the varying emissivity of the walls of the target chamber, which would appear as background behind the target and hence as a false target.

The feasibility of tracking using an 8 to 13 micrometer wavelength point target tracker was analyzed, and calculations showed that 10-micrometer tracking accuracy could be achieved with a 18-cm aperture point-target tracker. Again, however the background problem is a real disadvantage.

Real target tracking, using the laser test oscillator, may present a feasible technique, however, the source intensity must be kept low to preclude target sublimation prior to actual firing. Also, the serious background problem caused by the low target-reflectivity and the variations in reflectivity of the target chamber walls create difficulties. Multiple path attenuation effects rule out the use of a common tracker system. The only technique which may provide a feasible answer uses very high sensitivity multiple tracking sensors, one in each channel.

A technique whereby the tracker is mounted on the target chamber may provide a better alternative than real target tracking. In such a technique, (Figure 4.3-11) an angle pointing sensor of the type shown in Figure 4.3-8, would be mounted physically on the target chamber viewing energy incident from the laser chain and energy reflected from the surrogate target. With the surrogate target in place, the sensor would compare incident and reflected angles, as would the FM angle sensing system (Figure 4.3-8). Upon removal of the surrogate target, the sensor would continue to null the source angle to the memorized angle of the surrogate target, thus providing a pointing capability which compensates for target chamber motions and structural motions after emplacement of the real target.

4.3.5 Surrogate Target Aberrations

One of the key elements in this system is the use of a surrogate target for system alignment. Investigations into the availability of ball bearings of sufficient accuracy to achieve the required alignment precision have shown that the state-of-the-art for commercial ball bearings is well within the requirements of this system. For example, 2-mm diameter ball bearings with a sphericity of 0.125 micrometer are available. Thus, the tolerance is within approximately $1/8$ wavelength at 1.06 micrometers, a value which will render the aberrations from ball surface irregularities insignificant compared to other system errors.

Ball bearing aberrations are likewise insignificant. Figure 4.3-12 shows the effective image quality of a 2-mm diameter ball bearing under conditions of defocus and pointing error of varying values. As shown, the magnitude of these errors is significantly smaller than the expected geometrical aberrations of the system, and providing the pointing error is kept within 30 micrometers, any aberrations in the ball bearing should be of no significance.

1174-1246

4.3-26

FIGURE 4.3-11 TARGET CHAMBER TRACKING SYSTEM

1174-1227

FIGURE 4.3-12 SURROGATE TARGET ABERRATIONS

4.4 FOCUS ERROR SYSTEM

4.4.1 System Requirement

The focus system must set the longitudinal position of best focus to the desired location with an accuracy of $5 \mu\text{m}$ (1σ). The best focus is defined as the position where the smallest geometric blur spot occurs. The focus system tolerance is such that the diameters of the defocused beams projected on the real target vary not more than 1.25% (1σ).

4.4.2 Concept

The basic concept of the focus system is illustrated by the focus sensitivity model, Figure 4.4-1. This optical schematic shows the final focusing lens and the surrogate target. The optical bundle is shown going into the final lens and striking the surrogate target about midway between the center and the front surface of the surrogate target at a point "X". When focused at this point, the return beam is a small pencil beam whose diameter is about 0.25 mm. The focus system concept moves the final focus lens to minimize the diameter of this pencil beam seen at the focus sensor. By precomputing the value "X", it is then possible to move the focus position to any other location.

The dynamic range of the system may be shown by changing X. Note that as X is increased from zero, the return-beam size is reduced from the incoming beam size, to zero at the focus lens, back to the incoming beam size again when X is equal to the radius of the surrogate target. As the geometrical focus point goes behind the center of the surrogate target, the return beam at the final lens becomes larger than the lens. If the entering beam diameter is reduced, it is apparent that the return beam can be made to not overfill the final lens. Therefore, by narrowing the incoming beam, it is possible to perform rough focus anywhere within ± 1 radius of the surrogate target center.

4.4.3 Focusing Schematic

The focus system shown in Figure 4.4-2 illustrates the laser chain elements. These include the test oscillator, beamsplitter, centering mirror, apodized aperture, Faraday rotator lens, pointing mirror, final lens, and

175-1023

FIGURE 4.4-1 FOCUS SENSITIVITY MODEL

175-1643

FIGURE 4.4-2 FOCUSING SCHEMATIC

surrogate target. The arrows indicate the flow of the main laser beam. The reflected beam off the surrogate target is transmitted back through the final focus lens, the pointing mirror, and the Faraday rotator lens and is reflected off a polarizer in the C amplifier. When the image is minimized at this polarizer plane, the focus lies at the point "X" of Figure 4.4-1.

The distance, X, may be calculated, knowing the ray height into the final lens, the focal length of the final lens, the focal length of the Faraday rotator, the divergence of the incidence beam striking the Faraday rotator, the distance between the Faraday rotator lens and the focus image plane, and the size of the surrogate target. The calculation is simple and the results are not critically dependent on any precise system tolerances.

The beam at the polarizer plane is relayed and demagnified by an afocal demagnifier with zoom capability. This demagnifier assembly reduces the beam size so that the resultant beam at its focal plane will be just smaller than the diameter of the vidicon placed there. This is necessary to ensure detectable image size changes as the focus lens is moved during rough focus and to ensure maximum sensitivity to change in focus during fine focus. The demagnifier will have a minimum demagnification of 2.5 and a maximum value of 15.

A variable neutral-density filter is placed in front of the vidicon to ensure that the vidicon will operate in a linear mode at a maximum signal-to-noise ratio. The neutral density filters will also protect the vidicon from being burned out by inadvertent imaging of small intense inputs. The transmission range of the filter will from unity to 10^{-6} and may be accomplished by polarizers, instead of conventional absorbers and reflector filters.

The vidicon will be a silicon target vidicon with a sensitivity of 2.4×10^{-10} w/cm² at a signal to noise ratio of 1. Saturation is 200 times minimum sensitivity giving a level of 4.7×10^{-8} w/cm² at the photocathode for a saturated output. It must be noted that the responsivity of the tube falls off at the edge of the tube by 30%. Therefore, it is necessary to center

the image at the center of the tube to adequately compare image sizes and maintain symmetrical shapes.

The video processor receives the signals from the vidicon and peak holds the peak video amplitude. This peak held signal is used as a reference for two threshold comparators which are set to change outputs when their inputs are near 50% of the peak signal. The two comparators are offset by the contrast ratio to be detected, i.e., 5% of the peak value. The output of the comparators are gated such that a binary "1" will exist any time the output of the vidicon is between the two thresholds. At all other times the signal shall be a binary zero. This gated output, when connected to the TV display, will show an annular white ring whose diameter is proportional to the size of the half-peak intensity level of the image.

The size of the image on the display may be determined in one of three ways. The operator can measure the size using a graticule; he can measure the area using a set of masks containing concentric rings; or he can measure the area by using an Integrator. The use of a graticule will be adequate during rough focus, however, to accurately measure slightly changing image sizes, it will be necessary to use masks which can resolve a small part of the ring width. For aberrated images giving non-circular images, it will then be necessary to go to an area measurement device, such as an electronic Integrator which integrates the video signal.

With image size information, the operator controls the final focus lens, adjusting the image diameter for the appropriate size while adjusting the neutral density filter and variable Iris to maintain maximum sensitivity.

4.4.4 Image Size as a Function of Defocus

Figure 4.4-3 shows the change in image diameter vs defocus from the final lens focal point. The curves show parametrically the effect of having different best focus image diameters. The curves were generated by taking the root of the sum of the squares (RSS) of the image diameter due to defocus and the best focus image size. The best focus image size is determined by the type and degree of aberrations of the final system.

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4.4-6

FIGURE 4.4-3 IMAGE DIAMETER VS DEFOCUS

Figure 4.4-4 shows the change in image diameter at the focus sensor as a function of defocus from the center of the surrogate target. Note that the focus point is displaced by approximately $450\text{ }\mu\text{m}$ for a 1-mm radius surrogate target. At a $500\text{ }\mu\text{m}$ displacement, the reflected beam refocuses 0.5 meter from the focus lens; the $50\text{ }\mu\text{m}$ difference moves this focal point to the plane of the focus sensor, and is a slowly varying function of optical system parameters, reliably calculated.

The plots of Figures 4.4-3 and 4.4-4 are identical, except for the scale of beam diameter and the offset from best focus. It can, therefore, be concluded that the return beam focus sensor has about the same focus accuracy potential as a system which directly (or indirectly) examines the actual image at the target.

4.4.5 Components Required by the Focus System

The components required by the focus system are listed in Table 4.4-1. The baseline focus system has a focus sensor for each leg of the system, as it will be necessary to refocus each time the target chamber is re-evacuated. The system requires a single TV monitor, processing circuit and control panel to permit adjustments to be made on the selected laser chain.

During initial rough focus, the beam from one chain may be reflected into another chain, confusing the operator. It is therefore necessary to locate 20 shutters in the system, one per chain, such that only one chain can be focused at one time during rough focus.

During final focus, all laser beams can be active, enabling all the shutters to be opened. To ensure that the shutters will be open during laser firing, the shutters will be designed as fail open devices, and at the time of final focus the operator can reconfirm their open condition. The focus control mechanism will move the focus lens longitudinally while maintaining the final lens normal to the optical axis. This normality must not change by more than $10\text{ }\mu\text{rad}$ to keep the focus error down, and must be held

175-1697

BEAM DIAMETER Cm

4.4-8

FIGURE 4.4-4 FOCUS BEAM SIZE VS DEFOCUS

TABLE 4.4-1 COMPONENTS REQUIRED BY BASELINE FOCUS SYSTEM

•	Diagnostic Equipment
-	Focus Sensor for Each Chain
-	TV Monitor and Focus Control
•	Laser Chain
-	Place for 20 Shutters
-	Focus Control of Final Lens
-	CW Laser Source
•	Target
-	Specular 1 mm Target

to <0.43 mrad to keep lens induced coma at or below the diffraction limit. In addition, the longitudinal position of the focus lens along the optical axis must be known to $1.2 \mu\text{m}$ to achieve the desired refocus accuracy.

4.4.6 Initial Setup of Focus System

During the set up of the laser chain, no accurate focusing measurements will be necessary since the individual components, such as the source, apodized aperture, Faraday rotator lens, and spatial filters, will have very long focal lengths (>10 meters), and hence their position has little effect on the computation of the distance "X" of Figure 4.4-1. Since the only real requirement of the laser chain is to maintain a 2.5% image size uniformity from chain to chain, the lens have to be placed within ± 25 cm of their theoretical positions, assuming six identical lenses at focal lengths of 50 meters.

The above is only true with respect to longitudinal positioning of the separate components; it is not true of the individual lenses of the spatial filters, nor of the lateral component position. However, the mechanical center line can be determined quite easily by using a narrow laser beam, i.e., HeNe laser, to better than 0.1 mm. The normal to the optical axis can be determined to a second of arc by the use of autocollimators.

At initial installation, a 1-cm radius surrogate target may be used to find focus and for initial pointing. Initial focus would be attained in this system by translating the lens assembly until a return beam diameter equal to the incident beam diameter is attained at the focus sensor indicating focus at the ball center. The 1-mm radius surrogate target can be used to obtain final focusing of the system.

4.4.7 The Fine Focus Adjustment Procedure

Table 4.4-2 shows the fine-focus procedure. After the 1-mm radius surrogate target is inserted, the iris at the oscillator will be stopped down so that the beam at the focus sensor is not vignetting. The neutral density filters must be adjusted to maximize contrast. Then the focusing lens must be moved to null the image size at the focus sensor.

TABLE 4.4-2 FOCUS SYSTEM ADJUSTMENT PROCEDURE

- Narrow beam at oscillator by stopping down on Iris so that image fits TV format.
- Adjust neutral density filter so that image has proper contrast.
- Adjust focus to minimize image.
- Adjust Iris, neutral density filter, focus to obtain minimum image.
- Move off best focus until image is the size of a predetermined circular mask placed over the TV. Note position of focus lens.
- Move through best focus by adjusting focus until the image size again is the same size as the mask. Note this focus position.
- Calculate proper focus position from the two numbers, target size, focal lengths, beam sizes.
- Reposition to the required defocus position.

The actual focus point at null is difficult to directly determine, due to the low rate of change of image size with defocus at best focus, caused by image aberrations. To improve the focus resolution, it is necessary to move

slightly off best focus, where the slope is higher. A good position is a defocus of $D_0 \cdot f/$, where D_0 is the nominal aberration diameter, and $f/$ is the final lens speed.

By matching the sizes of the image at two points of final lens defocus on either side of best focus ($\pm D_0 \cdot f/$) the best focus point may be obtained by interpolation between the two points. The matching between the two points is done using annular masks or by integrating the area within the CRT image.

As the location of the best focus point on the surrogate target has already been calculated from system parameters, the amount of desired defocus may now be set into the system.

4.4.8 Focus Error Budget

The focus error budget is listed in Table 4.4-3. The effects of the first three items, namely ball size, focal length of optical system, and height of beam, were obtained from an examination of the focus sensitivity model, Figure 4.4-1. The model shows a near-collimated-beam incident upon the final focus lens. This lens focuses the rays to a point about one-half the distance between the center and the front edge of the target. This distance is noted as "X".

In the baseline, the rays reflected from the surrogate target are slightly divergent to cause the energy to come to a focus at the focus sensor. Thus, X is slightly less than $R/2$. However, for the special case where the rays reflected off the target surface are collimated, one can easily determine the relationship between ray height (H), focal length of the focus lens, the target size, and the distance X as:

$$X = \frac{R \cdot P^{\frac{1}{2}}}{\left[1 + (P^{\frac{1}{2}} + a)^2\right]^{\frac{1}{2}}} \quad (4-35)$$

TABLE 4.4-3 BASELINE FOCUS ERROR BUDGET

	RMS Error Micrometers
Ball Size	1.5 μm
Focal Length of Optical System	0.0 μm
Height of Beam	0.2 μm
Contrast Ratio of TV [at Image Aberration 5x Diffraction]	3.7 μm
Line Resolution of TV	0.5 μm
Human Resolution Using Masks	1.8 μm
Focus Control Resolution	2.3 μm
Focus Optical System	0.9 μm
Focus Error	5 μm

where

X = focus offset from the center of the target

R = radius of the target

$P = 1 + a^2$

$a = f/H$

f = focal length of the lens

H = height of the incident ray

By taking partial derivatives it can be shown the

$$\frac{\partial X}{\partial R} \approx 0.5 \quad (4-36)$$

$$\frac{\partial X}{\partial H} \approx 5.8 \times 10^{-5} \quad (4-37)$$

$$\frac{\partial X}{\partial f} \approx 1.5 \times 10^{-5} \quad (4-38)$$

The radius of the surrogate target is measurable to $1.3 \mu\text{m}$ (50×10^{-6} in.) giving an error of $0.7 \mu\text{m}$. The ray height must be within 2.5% of the nominal height to meet the chain to chain beam diameter requirement. Therefore, the change in height is just 3.1 mm, or an error in X of $0.2 \mu\text{m}$. The uncertainty in the focal length of the lens is a function of the test instruments used to measure the focal length. If one assumes that the measurement is within $1/\sqrt{12}$ of the diffraction limited focus range, then

$$\Delta FL = \pm \frac{2 \times 2.44 \times \lambda \times f^2}{\sqrt{12} H} \quad (4-39)$$

$$\Delta FL = 2.5 \mu\text{m}$$

As stated in Section 4.4.6, the focus system is highly tolerant to variations in the optical parameters of the system. The key thesis in the focus system is that by positioning the final focus for minimum beam diameter at the focus sensor, the focal point of the incident beam will be situated at a known location on the surrogate target. This location is slightly different from the one-half radius point previously described.

Focusing one-half ball radius ahead of the target center results in the return beam being refocused at 0.5-meter ahead of the final focus lens--we desire that it refocus at the focus sensor some 20 meters ahead of the lens. The focus shift requires that the incident beam focus slightly closer to the surrogate target center than the half-radius point. This slight difference is a second-order function of the system optical parameters.

Using a simple optical model, consisting of a 5-mrad divergent beam into a collimating 25-cm dia Faraday rotator lens, followed by a 0.5-meter focal length focus lens, the focus differential was calculated for varying divergence angle and focus sensor position, assuming a 1-mm surrogate target radius. As indicated by the results shown in Table 4.4-4, relatively wide variations (values within normal optical tolerances) in focus sensor location and beam divergence angle are permissible.

TABLE 4.4-4 OPTICAL EFFECT ON FOCUS POSITION

Beam Divergence Angle, mrad	Relative Focus Sensor Position, Meters	Focus Shift From 1/2 Radius Point, Microns
6.25	20	61
5.0	20	48
4.16	20	41
3.57	20	37
5.0	15	36
5.0	17.5	41
5.0	20	48
5.0	22.5	55

4.4.9 Focus Readout Accuracy

The focus errors consist principally of the accuracy to which the best focus position can be determined, and the accuracy to which the lens position can be determined. This section treats these two error sources and their combined effect.

Figure 4.4-4 shows the variation in beam diameter with focus. If the beam diameter can be measured on the TV display at a given defocus point, the accuracy in determining focus is:

$$\sigma_f^2 = \frac{\sigma_D^2}{\left(\frac{\partial D}{\partial f}\right)^2} + \sigma_S^2 \quad (4-40)$$

where:

σ_f = focus accuracy

σ_D = diameter measurement accuracy

$\frac{\partial D}{\partial f}$ = slope of curve (Figure 4.4-4)

σ_S = accuracy of reading lens position

Suppose that we interpolate between two reading points, each equally on either side of best focus (equal $\frac{\partial D}{\partial f}$), interpolate by averaging the readings, then defocus by some arbitrary distance. Then, the defocused accuracy is:

$$\sigma_{f_D}^2 = \frac{1}{2} \left[\frac{\sigma_D^2}{\left(\frac{\partial D}{\partial f}\right)^2} + \sigma_S^2 \right] + \sigma_S^2 \quad (4-41)$$

Now, since $I = I_0 \left[1 - \left(\frac{R}{R_m} \right)^2 \right]$ (quadratic beam profile) (4-42)

$$\left. \frac{dI}{I} \right| = - \frac{dR}{R} = - \frac{d(D)}{D}$$

$$I/I_0 = 0.5$$

Therefore $\sigma_D = D\sigma_I$, as indicated in Figure 4.4-5. Assuming Gaussian beam characteristics,

$$D = \left[(Kf)^2 + D_o^2 \right]^{\frac{1}{2}} \quad (4-43)$$

$$\frac{\partial D}{\partial f} = K \left[1 - \left(\frac{D_o}{D} \right)^2 \right]^{\frac{1}{2}} \quad (4-44)$$

where

$K = 260$ in our case

$D_o =$ aberrated image size at target

Thus,

$$\sigma_{f_D}^2 = \frac{3}{2} \sigma_S^2 + \frac{D^2 \sigma_I^2}{2K^2 \left[1 - \left(\frac{D_o}{D} \right)^2 \right]} \quad (4-45)$$

175-1714

FIGURE 4.4-5 CONTRAST ERROR

This equation is plotted in Figure 4.4-6. It is readily shown that the second term is minimized for $D = \sqrt{2} D_0$. This implies that the interpolation measurement should be taken at focal positions spaced approximately $\pm D_0 f$ from the best focus position of the lens.

A number of other factors enter into the focus accuracy, namely: the TV line resolution of the camera, the ability of an operator to read image size, lens tilt in the focus mechanism, and vidicon sweep accuracy.

Using a 480-line TV camera (525 line nominal), whose sensor optics cover a beam diameter of 15 cm, and measuring focus at an offset at $D_0 f$, it may be shown that a change in image diameter of one TV line is equivalent to a focus shift of about 1.5 micrometers. As this error is uniformly distributed, its standard deviation is $1.5/\sqrt{12}$, or less than 0.5 micrometer. Clearly, the error can be reduced further by using zoom optics to cause the camera to cover a smaller field.

The human resolution using masks is determined by the ability to split the width of the contrast region. It is reasonable that the operator should be able to split the region by a factor of 4, giving an error of 1.8 micrometer.

The error created by offsetting the focus position to compensate for non-linear effects is composed of two components, the measurement instrument and the lateral offset of the focus lens from the optical axis. The measurement device has an accuracy and resolution of 1.2 micrometer. The change in tilt of the focus lens will be known to an angle of 10 microrad over the focus range.

Assuming a 15-cm distance to the center of the lens from the measurement axis, this corresponds to a $0.15 \text{ m} \times 10 \text{ ur} = 1.5 \text{ } \mu\text{m}$ focus error. The resultant combined focus of the focus control system is

$$\sqrt{(1.5 \text{ } \mu\text{m})^2 + 2 (1.2 \text{ } \mu\text{m})^2} = 2.3 \text{ } \mu\text{m}$$

175-1698

FIGURE 4.4-6 FOCUS ACCURACY

4.4.10 Focus Sensor Sensitivity

The focus sensor S/N ratio is calculated as follows:

Path attenuation to and from surrogate target:

13 polarizers	$(2 \times 1.05)^{13}$	1.54×10^4
6 rods	$(1.02)^{12}$	1.27
10 rotators	$(1.02)^{20}$	1.49
4 spatial filters	$(1.02)^{16}$	1.37
Apodized aperture	4	4
Beamsplitter	20	20
Glass 2 meters @ 1%/cm		
	$\left(\frac{1}{0.99}\right)^{200}$	7.5
	Total	2.4×10^7

Sensor Transmission 0.07

(from Section 4.2.3.3, with pickoff efficiency of 0.5)

Thus, total energy incident on the vidicon from the 1-watt source is $\frac{0.7}{2.4 \times 10^7} = 2.9 \times 10^{-9}$ watts.

Using an RCA 4532 silicon vidicon, the S/N is unity at 1000 electrons per resolution element. Since the quantum efficiency is about 0.15 at 1060 nm, 1000 electrons corresponds to:

$$\frac{1000}{\lambda} \times \frac{hc}{\lambda} = \frac{1000 \times 6.62 \times 10^{-34} \times 3 \times 10^8}{0.15 \times 1.06 \times 10^{-6}} = 1.25 \times 10^{-15} \text{ watts per resolution element}$$

Using the quadratic beam of

$$I = I_0 \left[1 - \frac{R}{R_0} \right]^2 \text{ W/cm}^2 \quad (4-46)$$

with the beam diameter ($2 R_0$) equal to 480 resolution elements in height, and setting the $S/N = 1$ at the 50% intensity point of the beam ($R = R_0/\sqrt{2}$), the required peak beam intensity is 2.5×10^{-15} W/resolution element, or $2.5 \times 10^{-15} / \left(\frac{R_0}{240} \right)^2$. As the total beam power

$$P_T = \frac{\pi}{2} R_0^2 I_0 \quad (4-47)$$

$P_T = 2.3 \times 10^{-10}$ W. Since 2.9×10^{-9} W are incident on the vidicon, the S/N ratio at the 50% beam intensity point is 12.8.

The S/N ratio achieved is adequate however, moderate pickoff efficiency was needed to achieve this value. More detailed attention in this area will be needed during the design phase.

4.4.11 Alternate Focus Methods

Besides the baseline focus system just discussed, three other focus schemes were examined. These involved interferometry, autocollimation back to the source system, and autocollimation in the middle of the optical system. Also, image measurement using MTF and knife-edge measurements was evaluated.

Interferometric techniques were rejected because of the difficulty in alignment and interpretation of results in such a system. Autocollimation back to the source system was rejected because of the difficulty of measuring the return signals in the presence of scattered signal from the transmitted beam.

Autocollimation in the center of the optical system reduced the back scatter problem, however, requires a precise adjustable large aperture autocollimator and accurate measurement of the incident beam divergence angle. This technique permits direct image examination (but includes aberrations in the path between the sensor and target). The cost and complexity made this technique less desirable than the baseline, however.

A number of methods were evaluated for best focus determination. Among them were techniques where the image MTF was measured, with the intent that the focus would be set for maximum MTF values. This technique required a spinning chopper and was marginal in accuracy unless interpolation was made between two points of equal MTF, on opposite sides of focus.

Knife-edge techniques also used a spinning chopper, and effectively measured image width. These techniques were somewhat deficient due to higher noise susceptibility, however, were workable using the interpolation techniques previously described.

4.4.12 Charge Coupled Device (CCD) Focus Sensor

Evolving solid state technology has developed solid state imaging sensors which have the potential of replacing the quad detector array and vidicon with a single unit. Such a technique would have the advantages of potential lower cost, as the sensors are less expensive than vidicons, and as only one electronic processing channel might be used both for centering and for focus.

On the other hand, existing devices (such as the Fairchild CCD 201) have about 20 times poorer sensitivity than vidicons (RCA 4532). For the CCD 201, the NEP is about 5×10^{-9} W total energy on the device (5×10^{-13} W per resolution element) at 1.06 micrometers and 60 fields/30 frames per second. Thus, the sensitivity may be marginal.

The resolution of the CCD units is poorer at present, however this is not necessarily a problem as the beam diameter can be optically zoomed to fully fill the sensor. Moreover, 244 by 190 resolution element devices will be available during the SHIVA design phase.

4.5 PATHLENGTH ERROR SYSTEM

4.5.1 Specification

The differential pathlength from laser chain to laser chain must be maintained at less than ± 3 mm or ± 10 ps to ensure equal pulse time of arrival.

4.5.2 Baseline System

The baseline system (Figure 4.5-1) consists of a shutter for each laser chain, an optical pathlength control for each laser chain, a diffuse surrogate target, three streak cameras (otherwise used for diagnostics), and a display.

The baseline system operates by viewing energy reflected by the diffuse surrogate target using the target chamber mounted streak cameras. The laser chains are measured, two at a time, by establishing a specific differential time delay on the streak camera, by deliberate offset of the optical pathlength (OPL) adjust gimbals. Following this adjustment, the offset channel is realigned by an amount equal to the known time differential (4 cm nominal value), and serves as the reference for the next channel. This process is continued around the 20 paths. By this method, the path lengths are adjusted using existing instrumentation.

4.5.3 Optical Path Length Adjustment Procedure

Before OPL adjustment, the entire system must be roughly focused and pointing alignment accomplished so that the target will be struck by all laser beams. The system shall then be locked in place by cutting off power to the controls, and the specular surrogate target replaced by the diffuse target.

A reference channel, in the field of view of two streak cameras, will be selected by opening its shutter and closing the shutters of all others. The reference then will be offset by two oscillator pulse lengths so that it can be assured that it will be displayed first when two samples are examined. The laser master oscillator source is then fired to synchronize the scan position of the reference beam in the streak camera. After the camera has

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4.5-2

FIGURE 4.5-1 BASELINE OPL SYSTEM

been synchronized, a second chain is enabled by opening its shutter. The M.O. is again fired, and the delay between the two pulses noted. The differential path length delay is adjusted to 4 cm by moving the OPL gimbal of the sample beam. After repeating the shot to confirm the delay, another sample beam is selected by closing the first sample shutter, and opening a second sample shutter. The process is repeated until all samples within the field of view of the one streak camera have been adjusted. The beams in the field of view of the second streak camera will then be checked.

After completing this task, only the beams opposite the reference beam will be untested. They are checked with the third streak camera by offsetting a second reference beam opposite the first reference beam, by checking its offset against the previous beams examined, and by testing all untested beams against this second reference. Finally, the reference beams will be corrected for their offset. In this manner, all beams will be checked and cross checked to ensure minimum error.

The baseline OPL error budget is shown in Table 4.5-1. The optical path-length control device will be accurate to better than 0.1 mm or 0.3 ps. The diffuse target is assumed to be 2.0 mm in diameter, indicating that the largest error possible is 1.0 mm or 3.3 ps. Since the OPL adjustment and target size are small inputs into the error budget, the accuracy of the streak camera and the ability of the operator to resolve the output defines the error of the system.

TABLE 4.5-1 BASELINE OPL ERROR BUDGET

	RMS Error	
	Distance mm	Time ps
• OPL Adjustment	0.1	0.3
• Ball Size	1.0	3.3
• Streak Camera		
- Linearity Calibrated to 1%	0.9	3.0
- Resolution	<u>2.7</u>	<u>9.0</u>
	3.0	10.0 ps

If a 1% streak linearity over a 300 ps period is assumed, the error would be 3 ps. It would be difficult to maintain absolute linearity to 1%, however, a scan calibrated to 1% is reasonable. It must be noted that as the pulse width is reduced, the problem can be made easier since the measurement over the pulse period is reduced. Ideally, it would be best to have a calibrated 10 ps pulse which could be used to measure the offset between pulses.

The position of a large pulse may be made using the leading edge, lagging edge, and/or center of a pulse. The combined operator and streak camera error must be less than 2.7 mm (9 ps) if the 10 ps differential path-length specification is to be met.

4.5.4 Alternate OPL Systems

There are a number of different systems which were evaluated. They are noted in Table 4.5-2. The half-frosted ball concept uses a clear hollow sphere with a diffuse hemispherical area. One streak camera normal to the diffuse hemispherical area would be able to examine all beams impinging the target. The target would have to be hollow to inhibit damage due to the focusing of the laser beam in the transparent medium. This method was not selected because of the possibility of multiple reflections within the target due to its concentric shell design and the difficulty of constructing the target. However, if there is a reason to limit the use of streak cameras it is still a viable candidate.

A method of measuring the path length difference of all beams simultaneously is the fiber optic ball concept. In this concept a surrogate target, having a fiber optics bundle as an integral part, is placed at the target position. One fiber assembly is installed for each laser chain, and the fibers are positioned to place one in the center of each laser beam image.

This method was rejected because of the time spread of the pulse as it passed through the fiber optic. This time spread is the result of angular divergence of the beam in the fiber optic bundle. It must be noted

TABLE 4.5-2 OPL SYSTEMS EVALUATED

Systems	Comments
Frosted ball	Easiest to implement, most accurate, requires 3 camera positions
1/2 frosted ball	Needs only one camera, cannot be focused in material, multiple reflections may be a problem
Fiber optic ball	Has to be positioned angularly, not too reliable because of fiber optics, requires communication through the chamber, needs only one camera
Streak camera at OSC	Back scatter problem, attenuation of closer chain elements
Interferometric	Accuracy not necessary, difficult to implement
Modulated carrier	Requires considerable hardware development, gives direct readout

that even with a collimated input into the fiber bundle, the resultant beam at the output is significantly divergent.

The distribution of the divergence angle indicates the spread of the optical path-length. For example, if a 1-meter fiber optic bundle has rays coming out at two angles, the delay time between the two rays is

$$\tau = \frac{nL}{c} \left(\frac{1}{\cos \theta_1} - \frac{1}{\cos \theta_2} \right) \quad (4-38)$$

ΔT = delta time between the two rays

n = index of refraction of the fiber optic

c = speed of light

θ_1 = average angle of first ray

θ_2 = average angle of second ray

If the two angles were 0° and 20° , the pulse would be stretched by 320 ps if the divergence angle went from 0° to 20° . Over the bends and length envisioned, this dispersion is *not* unreasonable, however, it results in disastrous time distortion of the pulse.

An offshoot of this concept is to place the individual fiber bundles in the center of each focus lens, outside the chamber. Alternately, the fibers would be placed at the edge of the focus lenses and, by defocusing the focusing lenses, a divergent beam can be detected off the specular surrogate target. The difficulty with this system is again the stretching of the pulse through long fiber optic bundles thereby losing resolution. Additionally, the energy collected by the fibers is small, due to their small collecting area, resulting in poor sensitivity.

During initial portions of the study effort it was attempted to measure the differential time delay of all of the beams back at the oscillator using a single streak camera. The scatter level off the beam splitter, together with round-trip signal attenuation, was again the problem, and this concept had to be abandoned.

Some consideration was given to interferometric techniques, however, the difficulty of alignment, the effects of multiple optical elements, and the cost quickly eliminated the concept. An interesting method of measuring path length, using phase detection of a modulated carrier, was examined. It was rejected because it could not be used with the optical elements within the system.

Section 5

GIMBAL AND MECHANICAL DESIGN

5.1 SYSTEM CONTROL CONFIGURATION

Throughout the study, such critical factors as the number and location of the optical chains, space frame construction, location of the master oscillator, and method of separating and folding the oscillator output have been under consideration by L³.

At the conclusion of the study, a configuration such as that shown in Figure 5.1-1, was considered the most promising by L³. With this configuration as a baseline, AESC has determined the points of beam control, which are shown on the figure.

The oscillator and first beam separation stages are shown at the rear of the structure just above the floor level. Four optical beams are shown leaving the assembly, two at each side. One beam on each side passes through the structure to the external side of the frame, is deflected vertically and is then split into six equal intensity beams with beamsplitters. The beams are directed to the rear of the structure and are retro-reflected down the center of the optical amplifiers. The beamsplitters are supported very close to the frame to provide maximum stability.

The parallel beam separation of the retro mirror assembly is then adjusted to accommodate the desired offset between the beamsplitter axes and the center of the amplifier chain. The retro assemblies are adjusted in a staggered pattern to provide equalization between the optical pathlengths of the laser chains.

FIGURE 5.1-1 SYSTEM CONTROL CONFIGURATION

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The beams are directed forward to the target room where each is folded twice before entering the target chamber. The first mirror is fixed, while the second provides beam pointing at the target. The optical energy is focused on the target by a single aspheric lens, remotely positioned for best focus.

This section presents baseline designs for the focus drive mechanism, beam pointing gimbal, the optical pathlength and beam centering gimbal, and the oscillator centering and pointing gimbals.

5.2 OSCILLATOR POINTING AND CENTERING GIMBALS

The precise function of the oscillator pointing and centering gimbals and the accuracy achievable is discussed in Section 4.1. Then servo control is discussed in Section 6. Two gimbal assemblies are employed, one to maintain alignment of the test oscillator with the apodized apertures, and the other to maintain boresight between the test oscillator and the master oscillator. Each must center and point the oscillators to within ± 0.1 mm of the center of the apodized apertures located near the end of the laser space frame. Horizontal and vertical linear and azimuth and elevation angular adjustments are provided for possible long-term drifts, both linear and angular, of the oscillator structure with respect to the main frame, and drifts in the oscillator output beam.

The four-axis gimbal assembly is presented in Figure 5.2-1. It consists of two linear servo controlled translation stages, a single two-axis gimbal assembly, and a fixed beam deflection mirror. The beam from the oscillator is reflected first to the gimballed mirror at a height of 16 cm above the base. It is reflected vertically to the fixed mirror, turned 90° , and leaves perpendicular to the incoming beam. The optical beam is 5 cm dia at this area, so 8-cm diameter circular mirrors are used to simplify installation and reduce costs.

The linear translation stages are arranged with their axes at 90° with respect to each other. Incremental linear motions of these stages provide translation of the output beam. The drives are d-c stepper motors, commercially available from Aerotech, Inc., Allison Park, Penn. The performance parameters are presented in Figure 5.2-2. The manufacturer's data is included in Appendix A.

Linear position accuracy and repeatability is achieved by using ultra-precise ground lead screws. The units are modular in that the mounting hole configuration permits stacking or ganging the individual units together.

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5.2-2

FIGURE 5.2-1 OSCILLATOR CENTERING AND POINTING GIMBALS

1. TRANSLATION STAGES

AccudexTM (Aerotech, Inc.) Model ATS 301H

Range	1 in.
Linear Resolution	0.0001 in./step
Lead Screw Pitch	50
Accuracy (Lead error accumulative)	0.0001 in.
Nominal Slew Rate	200 steps/sec.
Repeatability (uni-directional)	25 μ in.
Straightness of travel	0.0001 in./in.
Size	5" x 5" x 1-1/2"
Weight	$\approx$ 5.2 lb.

Drive Electronics

AccudexTM Model ASM 100-1 Stepping Motor Drive

Maximum Stepping Rate	300 steps/sec.
Available Controls	(slew-jog, forward-reverse, local-remote operation)
Readout	Digital with BCD output
Input	Manual five-digit indexer with parallel BCD input-provide compatibility with digital computers

DEFLECTION

2. TWO-AXIS GIMBAL ASSEMBLYMount - Source

Burleigh Instruments

Model

SG-201

Material

Stainless Steel

Axes

Two (orthogonal)

Gimbal Mount/Actuator Coupling

Magnetic

Actuator

Model PZ-500 (inchworm)

Two required

Total travel

25 mm

Linear Resolution

6 mm

Speed Range

0.33 to 5 mm/sec.

Gimbal Assembly

Total Angular Adjustment

> 6°

Angular Resolution

0.02 sec./step

Angular Slew Rate

0.02 to 1300 sec./sec.

0.01 in./step

0.01 in.
steps/sec.

0.01 in.

0.01 in./in.

5" x 1-1/2"

2 lb.

steps/sec.

se, local-

r with parallel
ibility with

2

FIGURE 5.2-2 TO & MO CENTERING AND POINTING GIMBALS

The 2-axis gimbal assembly consists of a commercially available SG series Star Gimbal mount, with Model PZ-500, PZT Inchworm translators from Burleigh Instruments. This assembly provides azimuth and elevation movements of the optical beam up to 6° from the nominal position, with resolution as fine as 0.02 arc sec/step. The angular slew rate can be adjusted between 0.02 and 1300 sec/sec, values limited by the internal operation of the actuators. Performance parameters of the components are presented in Figure 5.2-2 and detail data supplied by the manufacturer is included in Appendix A.

The SG Series gimbal mount is available in stainless steel or aluminum, and all components are constructed of the same material to prevent differential thermal expansion resulting angular drift. The mount is a true gimbal providing orthogonal angular adjustments. Magnetic coupling between gimbal and actuator is used to provide smooth operation of the gimbals. The Model SG-101 gimbal provides for installation of a mirror up to 50-mm diameter in the plane of the gimbal axes. As a mirror of about 80-mm dia is desired, an adapter will be used to couple the mirror to the gimbal. This will move the mirror surface ahead of the gimbal center, however, the resulting path-length change will be negligible over the small angular operating range of the gimbal.

The main frame of the gimbals has two clearance holes for the translators, a single large hole for the gimbal rings and a flange to carry the outer gimbal. Each gimbal ring has two flanges offset 180° , with the outer gimbal pivoting about a vertical axis inside the frame, and the inner gimbal ring pivoting about a horizontal axis inside the outer gimbal ring. The gimbal rings pivot in solid, oil-impregnated bronze bushings. Permanent magnets are mounted into the upper large flanges of the gimbal rings, and contact the frame-mounted translators.

The PZ-500 Inchworm provides a driving force of 5 lb over 25 mm of linear motion with resolution as fine as 0.006 μ m. Internal friction is about 8 oz. With magnetic coupling between the gimbals and actuators,

torsional loading springs on the gimbal axes are not necessary, and friction will adequately hold the mirror in position without power applies to the actuators.

The PZ-500 Inchworm is an electromechanical actuator about the size and configuration of a standard micrometer head. Mechanical and thermal stability is provided by a combination of Invar and alumino-silicate ceramic. The low expansion Invar spindle, keyed to prevent rotation, moves relative to the housing.

When operating with Inchworm controller, the spindle tip translates in discrete steps of 6 nm. The stepping rate is variable from one per second to 220,000 per sec, and is governed by the time required to clamp and unclamp the shaft. These stepping rates provide variable speed from 0.3 $\mu\text{m}/\text{min}$ to 20 mm/min.

The Inchworm Controller can be used to program the spindle to move forward or backwards, to take single steps, to move so long as a spring loaded switch is depressed, or run automatically until it reaches its limits of travel. At either end limit of its travel, an internal limit switch on the Inchworm is triggered and the Inchworm Controller automatically shuts down, and turns on an indicator light.

All functions can be controlled either from the Controller or from a remote programming source. Simple N.O./N.C. logic inputs to the Controller will govern direction, speed and single step motion.

All of the low voltage circuitry in the Inchworm Controller is digital, using TTL logic, simplifying interfacing with computers if the N.O./N.C. remote programming logic is not desired. Outputs are available to monitor all functions of the Controller.

The operation of the Inchworm can be described with the aid of Figure 5.2-3. A three element piezoelectric cylinder is fitted to a shaft. The fit between the first and third piezoelectric element is essentially zero.

375-1248

FIGURE 5.2-3 INCHWORM OPERATING SEQUENCE

The center piezoelectric element is a clearance fit on the shaft. When a voltage of approximately 500 volts is applied to the first piezoelectric element, its inner diameter decreases, causing it to grip the shaft. Then a variable rate staircase voltage is applied to the center piezoelectric electric element, causing it to move in discrete steps of 3 nm. The staircase takes 248 steps from its lower to its upper limit. The full range of the staircase voltage moves the third piezoelectric element with respect to the first approximately 0.6 μm .

At the 248th step, the Inchworm Controller logic commands a 500 volt signal to be applied to the third piezoelectric elements causing it to grip the shaft, then releases the voltage on the first piezoelectric element, thus loosening its grip on the shaft, then restarts the staircase downward through another 248 steps until it reaches its lower limit, at which point the first clamp is activated again, the third clamp released, the staircase started again and the process repeats over and over.

The stepping rate for the variable rate staircase is variable from approximately one step per second to approximately 220,000 steps per second. The total time duration for the clamps to switch is fixed at 2 ms, thus the maximum running speed is approximately 10 mm per minute and the minimum running speed is approximately 0.15 μm per minute. The Inchworm Controller can generate single steps on the staircase so that an operator can advance the Inchworm in 3 nm steps.

A further feature of the Inchworm is that its fit to the shaft can be controlled electronically. This feature is called Clearance Compensation. The fit change is achieved by applying a bias voltage to the minus inputs of the piezoelectric elements. This bias is variable with a rear panel control on the Inchworm Controller from -250 to +250 volts. This adjustment compensates for wear of the piezoelectric elements on the shaft or for changes in the fit due to gross temperature changes. It also helps to control the ability of the Inchworm to push heavy loads.

5.3 BEAM CENTERING AND OPL GIMBAL

Throughout the study, a number of optical beam folding arrangements were investigated to determine the optimum method of achieving long-term stability and to provide a means of optical pathlength adjustment for each chain.

Retro-reflecting mirror assemblies have been found to provide a method of obtaining high angular stability in the beam, while at the same time, a means of pathlength adjustment. Earlier in the study, a concept proposed by L³ included a separate space frame at the end of the laser room for the primary purpose of providing a degree of modularity to the laser system. This smaller space frame would carry the retro mirror assembly. If additional pathlength were required, the smaller frame could be moved rearward and another amplifier section added to the main frame. This space frame arrangement required a beam centering and pointing gimbal assembly to be located on the end of the main structure with the larger amplifiers. This was deemed necessary to preclude beam error due to possible dimensional stability between the two separate frames. Later in the study the baseline structure was modified, the smaller space frame was eliminated, and all components were placed on the main frame. This resulted in a more rigid assembly and a lesser number of beam folding mirrors. The baseline system selected for this study is based on this latest space frame configuration.

As illustrated in Figure 5.3-1, the functions of providing lateral and angular control of the beam axis down the length of each amplifier chain and the optical pathlength control can combine into a single three-mirror retro-reflecting assembly. This assembly is shown in Figure 5.3-2.

The assembly consists of three mirrors mounted to the same rigid structure and oriented to provide a retro-reflection of the beam. The incoming energy is reflected first at two stationary mirrors, and then to a third mirror which is mounted on a two-axis servo-controlled gimbal. The axis of this third mirror is coincident with the optical axis of the amplifier chain. The dimensions are tentative, and can readily be adjusted to accommodate

1. TRANSLATION STAGE

AccudexTM (Aerotech, Inc.) Model ATS 304(x)

Range	4.0 in.
Resolution	.001 in./step
Accuracy	.0001 in./in.
Slew Rate	2.0 in./sec.
Straightness of Travel	15 μ in./in.
Flatness of Travel	15 μ in./in.
Size	10" x 10" x 2-1/2"
Weight	45 lb.

Drive Electronics

Aerotech, Inc., Model ASM 100-1
5-1/2 digit readout, manual controls,
case and power supply

2. TRANSLATION STAGE

AccudexTM (Aerotech, Inc.) Model ATS-301

Range	1 in.
Resolution	1 μ in.

3. TWO-AXIS GIMBAL

Gimbal Mount

Actuator

Magnetic

Electronic

Model P

(Alter

Gimbal Ass

Angular

Angular

Minimum

Maximum

3. TWO-AXIS GIMBALGimbal Mount - Burleigh Instruments - Model SG-201

Actuators - PZ-500 (2 units)

Magnetic Coupling (2 units)

Electronic Controller

Model PZ-501 (single axis)

(Alternate PZ-502 - 3 Channel)

Gimbal AssemblyAngular Range Adjustment $>6^{\circ}$ each axisAngular Resolution $\approx .02 \text{ sec.}$ Minimum Slew Speed $.02 \text{ sec./sec.}$ Maximum Slew Speed $\approx 1300 \text{ sec./sec.}$

4.0 in.

.001 in./step

.0001 in./in.

2.0 in./sec.

15 μ in./in.15 μ in/in.

10" x 10" x 2-1/2"

45 lb.

=1

controls,

ATS-301

1 in.

1 μ in.

2

FIGURE 5.3-1 OPL CENTERING AND POINTING GIMBALS

375-1263

5.3-3

FIGURE 5.3-2 BEAM CENTERING AND OPTICAL PATHLENGTH GIMBAL ASSEMBLY

requirements dictated by the final design of the space frame, amplifiers, and beamsplitter arrangements. The retro-mirror assembly is shown with the input and output beams at the same height, therefore the mirrors are symmetrically positioned. Other mirror configurations can be provided as needed.

Vertical and lateral adjustments of the optical beam axis are made manually and locked into position. Two AccudexTM translation stages, Model ATS-301, are stacked together at 90° to provide the required degrees of motion. The performance parameters of these stages is summarized in Figure 5.3-1 and additional information is available in the data sheets in Appendix A.

Optical pathlength adjustments are made by moving the three-mirror assembly in the longitudinal direction. This is done with a d-c driven stepper motor stage, available as an off-the-shelf item from Aerotech, Inc., Model ATS-304(x). The performance parameters of this stage are presented in Figure 5.3-1 and in the data sheets of Appendix A. The two-axis mirror gimbal and drive are the SG-201 Star Gimbal Mount and PZ-500 inchworm actuator available commercially from Aerotech, Inc.

5.4 FOCUS DRIVE

5.4.1 Focus Drive Requirements

In establishing tradeoff parameters for a focus drive mechanism, a number of system requirements were considered. These were based on alignment and operating system requirements contained in the SHIVA Error Budget and technical interchanges between AESC and L³ personnel. The ground rules are as follows:

- a. Refocusing would be performed after each target chamber evacuation.
- b. A single focusing lens would be used which requires the mechanism to provide required accuracy when a one atmospheric pressure differential exists across the optical element.
- c. An absolute position of focus with respect to the target chamber would not be mandatory, but rather a focus position known at all times with respect to the target center.
- d. An overall beam position accuracy of $\pm 7 \mu\text{m}$ must be obtained along the optical axis. There are a number of error sources which contribute to overall system accuracy, and these are discussed in the Focus Error Budget in Section 4.4. A review of these sources establishes a requirement to provide a focus control resolution of $2.3 \mu\text{m}$.
- e. A focus range of $\pm 5 \text{ mm}$ about the center of the target to accommodate an adequate range of surrogate target sizes.
- f. The drive mechanism must provide suitable angular positional stability to the focusing lens while operating within the focus range. Preliminary calculations indicate this stability error must be less than $70 \mu\text{m}$, so the target is continuously within the angular tracking range of the tracking sensor.
- g. The focus drive must provide power-off stability for the focused beam better than $2 \mu\text{m}$. This open loop stability must be held for at least 100 sec.

There are several considerations which are important in arriving at an optimum focus drive baseline design.

- a. The lens and drive mechanism should consist of a single unit to permit easy removal from the chamber and so that the drive can be completely aligned and adjusted in the laboratory.
- b. Commercial hardware should be used where possible to minimize development and production costs, and improve reliability.
- c. Minimum chamber volume should be used by the lens and drive mechanism.
- d. Moving components, such as gears, bearings, and motor, should be external to the chamber if possible so adequate lubrication can be used, and breakaway torque held to a minimum so very small incremental movements can be efficiently made.
- e. Although weight is not critical to the operation of the system, a minimum volume and weight will assist in handling and adjusting the assembly.
- f. Angular and lateral adjustments should be provided in the assembly to permit coarse positioning relative to the chamber.

5.4.2 Focus Drive Mechanical Design

The baseline focus drive is shown in Figure 5.4-1. It is a single unit, including lens, sealing bellows, and drive and position readout components. The single unit construction permits easy removal from the target chamber and facilitates maintenance and replacement of components. The drive assembly, external to the chamber, is cylindrically shaped with a diameter of 46 cm, and extends approximately 18 cm from the chamber wall.

The lens is mounted at the end of a cylindrical cell and vacuum sealed. A bellows is then attached and vacuum sealed to the opposite end of the cell.

The lens cell is electrically driven in the axial direction by three ball screw assemblies equally spaced about the periphery of the cell. The ball nuts are mounted in the cell and the cell is advanced by rotating

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5.4-3

FIGURE 5.4-1 MULTIPLE BALL SCREW FOCUS DRIVE CONCEPT

the ball screws in synchronization by pinion gearing on each ball screw and an idler or indexing gear. The longitudinal and transverse position of the focusing lens is then determined by the accuracy with which each ball screw can be angularly rotated.

Provision is made for differential rotation of individual ball nuts. This motion will permit precision alignment of the focus lens system.

Pressure compensating springs are located around each ball screw to balance the effect of external pressure and to place a continuous preload force on the ball nut and screw and synchronizing gearing. This preloading removes gear backlash as a potential source of ball screw synchronizing inaccuracies and leaves only the index error which is of a cyclic nature.

As the lens system must operate with a pressure of one atmosphere across the lens element (21700 lb force), the drive mechanism must have either sufficient torque to drive against the force or the effect of pressure must be balanced. This is the function of the pressure compensating springs. The spring constant, total deflection to solid height and free length must be selected to statically balance the lens assembly when the chamber is evacuated and yet provide additional travel to permit a usable focusing range.

In operation, the system is statically balanced when the focus is approximately 8 mm short of the center of the chamber. When the focus is in the operating range of ± 6 mm from the target center, the drive torque need be sufficient to deflect the pressure compensating springs, and a preloading force is always exerted on the gearing system throughout the focusing range. This force will vary from 30 to 225 lb. As the ball screws are uniformly positioned about the lens cell, the system is symmetrical and thus the preloading on each ball screw can be made equal. This symmetry is an important parameter as the structure must resist the loads caused by the pressure difference, and deflections of the structure are uniformly distributed and thus have little effect in causing the focus to steer away from the target during the focusing operation. With the pressure compensating springs, the spring

constant of the bellows is inconsequential and need only withstand an external pressure of 30 to 40 psi.

A Slo-Syn stepping motor will drive a single ball screw pinion gear through a 14:1 reducer stage. The motor shaft advances 1.8° per step or 200 steps per revolution, and an overall gear reduction has been selected so that when coupled through the ball screw, ten incremental motor steps provide an axial movement of the focused beam of 3 μ m.

All the drive components outside the structure are mounted in a cylindrically shaped support consisting of two circular plates separated by load carrying members. This support is fastened together and dowelled prior to final machining so as to facilitate assembly. The ball screws extend between the end plates of the support and are mounted in ball bearings. These ball bearings are very important to the overall accuracy of the focus mechanism as their fit and run out can affect the ball screw synchronization accuracy. There is a variable thrust load exerted on the screws because of the pressure compensating springs, therefore, deep groove radial bearings are used to carry both thrust and axial loads. Radial play must also be eliminated. This can be accomplished by spring loading all bearings in the axial direction or with bearing pairs, manufactured to provide a specified ball clearance and maximum breakaway torque.

The axial position of focus will be determined by a high resolution incremental linear optical encoding system. The measurement is based on signals derived optically from a finely graduated glass scale which is attached rigidly to the fixed support. The read head, a small square assembly containing the optical and electronic elements, is fixed to the moving lens cell assembly. The head translates the linear motion into a pulse train that is counted to obtain an accurate measurement of the change in position between head and scale. The scale is positioned between the two end members of the support housing near the primary driven ball screw. The read head is attached to the flange at the rear of the lens cell. Reference signals can be provided at each end of the focusing range.

The linear-optical encoder system selected for the baseline focus drive is manufactured by Dynamic Research Corp. (DRC) as Model LMS-50. The hardware data sheet is included in Appendix A. The linear measurement system is based on signals derived optically from a finely graduated glass scale attached rigidly to the fixed frame. This type of encoder is preferred over a rotary encoder, as it is not subject to backlash and wear errors caused by translating the motion of a ball screw or rack and pinion to a direct measurement. The scale has thousands of finely divided vertical parallel lines vacuum deposited on transparent glass, using Inconel. The read head contains optical and electronic elements and translates linear motion into a pulse train that is counted to obtain the accurate measurement. The resolution and accuracy of the system depends directly on the number of lines per millimeter on the scale (62.5) which in turn determines the equivalent pulse count per millimeter. A bi-directional counter and display converts a dual channel 3.5-v square wave output of the encoder into a numerical indication of position.

In operation, a collimated light beam from one side of the head passes through a portion of the scale producing an image of light and dark stripes that is reflected by a right-angle corner prism into a lens system. The lens system inverts and magnifies the pattern slightly before it is double-reflected with a five-sided prism. The image is then projected through the scale again so that a superimposed pattern of lines falls on the photo cells. This has the effect of using two sets of scales sliding past one another resulting in an effect similar to a moire pattern in that, as the reading head moves with respect to the scale, moving interference bands are formed on the faces of four photo cells positioned on the same side of the scale as the illumination source. The cells are arranged in pairs connected so the interference patterns create two sinusoidal output signals that are out of phase by 90 degrees. If the relative motion of the encoder, with respect to the scale is reversed, the phase relationship shifts from leading to lagging, thus making the output bidirectional. The electronics to convert the low-level sinusoidal signals generated by the photo cells into square waves is located in the reading head. This close spacing of the photo cells and amplifiers make the system less immune to noise. Additional circuitry in

the display chassis differentiates the square waves and forms a pulse train in which each pulse represents the sequential zero crossing of each of the original sinusoidal wave forms. The output square wave signals are multiplied by external logic circuitry to provide a system resolution of 1 μ m.

The standard display is a Nixie readout-tube display which can be mounted on a chassis panel together with a set of thumbwheel switches. A numerical value can be preset into the counter memory by setting the thumbwheel switches and then count up or down from that preset value, or the counter can be zeroed at any position and count up or down from the floating zero.

Indexing marks can be placed on the glass scale at a position corresponding to the ends of the focusing range as a rapid means of locating target center for the operator. A mechanical or electrical counter which retains its information on power shut down can be placed in the console to also provide focus position information.

The baseline focus drive parameters are presented in Table 5.4-1 and data sheets have been included in Appendix A.

In the baseline drive, a preloading force is always exerted against the ball screw assembly and gear train. This effectively removes backlash from the system, and thus the indexing error (sometimes called angular-displacement error) will be a measure of the focus accuracy. The indexing error is the deviation from the theoretical linear relationship between input and output angles of rotation between gear meshes. Although backlash and indexing error are independent of each other, they often are a result of the same error source. In unidirectional systems, in which the driving and driven surfaces always remain in intimate contact, backlash does not contribute to the angular inaccuracy of the system. Indexing error on the other hand, is a cyclic factor and affects every revolution.

TABLE 5.4-1 BASELINE FOCUS DRIVE PARAMETERS

Drive Motor

Model MD62 Sio-Syn DC Stepping Motor

Degrees per step	1.8°
Nominal rated torque	65 oz-in.
Holding torque	100 oz-in.
Residual torque	8 oz-in.

Sealing Bellows (Nesting)

Internal diameter	12.0 in.
External diameter	13.5 in.
Stroke	2.0 in.
Free length	3.20 in.
Length in compression	1.2 in.
Spring rate	≈ 19 lb/in.
Design (stainless steel, nested, welded)	

Drive Screws

Number of screws	3
Screw thread diameter	0.625 in.
Lead	0.125 in.
Operating load (for 10 ⁶ inch travel)	203 lb
Static load capacity	2400 lb

Pressure Compensating Coil Springs

Quantity	3
Construction	Rectangular wire
Spring rate	≈ 400 lb/in.
Internal diameter	0.75 in.
Outside diameter	1.50 in.
Free length	4.00 in.
Fully compressed length	1.52 in.

Gearing (pinions)

Number pinion gears	3
Drive pinion pitch diameter	1.5

(continued)

TABLE 5.4-1 BASELINE FOCUS DRIVE PARAMETERS (CONT.)

<u>Gearing (pinions) (cont.)</u>	
Drive pinion pitch	48
Precision (AGMA)	Class 13
Material	Stainless steel (Rc45)
Gear width	0.25 in.
<u>Gearing (ring)</u>	
Number of gears	1
Pitch diameter	12.5 in.
Pitch	48
Precision (AGMA)	Class 11 or better
Material	Stainless steel
Gear width	0.25 in.
<u>Ring Gear Bearing</u>	
Kaydon KC Series Type X-4-point contact	KC 110 x P0
Bore	11.000 in.
Outside diameter	11.750 in.
Precision	Class 1 or better
<u>Linear Encoder</u>	
System	LMS-1M
Head assembly	L-50
Scale (Inconel on glass)	1/4" x 1-3/4" x $\approx$ 4 in.
Scale lines per inch	62.5 1/mm (further multiplied optically and electrically)
Resolution	1 μ m
Scale accuracy	1.25 μ m/25 cm
Head size	$\approx$ 2.8" x 3.0"
Temperature range	Resolution over 30-100°F
Electronic unit	Single-axis readout with preset function

Figure 5.4-2 and Table 5.4-2 investigate the factors which contribute to index errors in the baseline drive gear train, the permissible dimensional tolerances in the gears, bearings and mounts, and the resulting maximum angular index error. The indexing errors in the last column of each table are based on the gear meshing with a master gear.

TABLE 5.4-2 INDEXING GEAR TOLERANCES

Bearing - ABEC Precision 1
Gear - AGMA Quality No. 11, PA 20°

Factors	Maximum Permissible Tolerance	Maximum Index Error (min.)
1. Bearing to lens cell runout	0.001 in.	0.28
2. Bearing runout	0.0014 in.	0.39
3. Bearing to gear runout	0.001 in.	0.28
4. Gear pitch diameter runout	0.001 in.	0.55
5. Gear tooth thickness variation	0.0005 in.	0.14
6. Pitch variation error	± 0.0002 in.	0.11
7. Profile variation error	0.0003 in.	0.17
8. Lead angle error	0.0005/in.	0.28
9. Lateral runout	0.0005/in.-rad	0.14
RSS error =		0.88 min.

The probable angular positional error, e , of either of the follower ball screws can be estimated from the RSS error of the pinion and indexing gear errors. It can be approximately given by the following:

$$\text{error, } e_1 = [(e_1)^2 + (e_2)^2 + (ne_3)^2]^{1/2}$$

where

e_1 = RSS drive pinion error (1.96 min.)

e_2 = RSS follower gear error (1.96 min.)

e_3 = RSS index gear error (0.88 min.)

n = ratio of Index gear diameter to pinion gear dia $\left(\frac{12.5}{1.5} = 8.3\right)$

Probable error, σ , = 7.8 min. for the follower pinions. Assuming a lead screw pitch of 0.125 in./turn, 7.8 min. would result in a positional error of

$$\frac{0.125 \text{ in travel}}{360^\circ} \times \frac{1}{60 \text{ min.}} \times 7.8 \text{ min.} = 45 \text{ } \mu\text{in.}$$

If the two follower ball nuts were either lagging or leading the driver ball nut (which is assumed to have zero error as it is adjacent to the encoder), but in phase with each other (a worst case), the positional error between the center of the lens and the encoder would be $< 1 \text{ } \mu\text{m}$.

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Ball Screw Bearings - ABEC 7
Pinion Gear - AGMA Quality No. 13, PA 20⁰

<u>Factors</u>	<u>Maximum Permissible Tolerances</u>	<u>Maximum Indexing Error (min. of arc)</u>
1. Gear pitch diameter runout (2e)	0.00025 in.	1.14
2. Bearing runout (gear end)	0.0002 in.	0.46
3. Ball screw bearing to housing eccentricity	0.0002 in.	0.46
4. Ball screw bearing to shaft eccentricity	0.0002 in.	0.46
5. Pinion tooth thickness variation	0.0002 in.	0.46
6. Pitch variation error	+0.0001 in.	0.46
7. Tooth profile error	+0.0002 in.	0.92
8. Lead angle error	0.0005/in.	0.57
9. Lateral runout	0.0005/in.-rad	0.28
10. Pinion/index gear center to center variation	0.0003 in.	<u>0.50</u>
RSS =		1.96 min.

FIGURE 5.4-2 PINION GEAR TOLERANCES

5.4.3 Focus Drive Stepper Motor and Gear Train Selection

In establishing the focus drive stepper motor parameters, several requirements must be considered and design assumptions made:

a. Pressure compensating springs will be used to balance out the external pressure, so the motor need have sufficient torque only to further depress the compensating springs throughout the focusing range.

b. The stepper motor should have sufficient residual torque so that electrical power may be removed and the focus drive will remain in its adjusted position.

c. An overall gear ratio from stepper motor to lens cells should provide for 1 μ m linear incremental motion for each step of the motor.

d. The spring constant of the pressure compensating spring has been set at 400 lb/in. This value has been selected based on a consideration of the free length, amount of deflection desired in the springs when the chamber is evacuated and the additional force required to further deflect the spring to operate in the focusing range and consequently a need to always apply a preloading force on the ball nut and synchronizing gearing.

A Slo-Syn dc stepping motor series has been selected which will provide 1.8° rotation per stepping pulse. The size of the motor will be based on the nominal rated torque and on the residual torque, a value with neither winding energized.

The driving torque requirements can be based on a starting torque required to move the lens assembly when the focus is at the furthest distance in its operating range. If it is assumed the static focus position is 2 mm short of the target and a focusing range of 12 mm (0.5 in.) is desired, the total load on the three ball screws is $(3 \times 400 \text{ lb/in.}) \times 0.6 \text{ in.} = 720 \text{ lb.}$

The amount of torque, measured in lb-in., required to turn the ball screws can be given by:

$$T_d = \frac{P \times l}{2\pi \times e} \quad (5-1)$$

where P = load

l = screw lead (in./turn)

e = ball bearing screw efficiency (90%)

therefore

$$T_d = \frac{720 \times 0.125}{2\pi \times 0.9}$$

$$T_d = 15.9 \text{ lb-in.}$$

This torque is reflected to the stepper motor shaft by the gear ratio.

$$15.9 \text{ lb-in.} \times \frac{1}{15.6} = 1 \text{ in.-lb}$$

For normal design considerations, the operating torque capacity of the motor should be 10 x this value or 10 in.-lb. This compensates for striction, inertia loads, and breakaway torque in the motor.

If the power is removed at this position in the focus range, the residual torque of the motor should resist the back driving torque. This back driving torque (T_b) is the torque created at the lead screws by the applied load.

$$T_b = \frac{P \times l \times e}{2\pi} \quad (5-2)$$

where the units are equivalent to the direct driving torque.

Therefore

$$T_b = \frac{720 \times 0.125 \times 0.9}{2\pi}$$

$$T_b = 12.9 \text{ lb-in.}$$

The axial loads exerted by the pressure compensating springs also act on the bearings at the end of the ball screws and increase the striction or breakaway torque and there is additional loss at the gear in the system. An estimate of the magnitude of this resisting torque is 5 lb-in.

The backdriving torque, referred to the stepper motor, could be expected to be

$$\frac{(12.9 - 5.0)}{15.6} \text{ lb-in.} = 0.5 \text{ lb-in.} = 8 \text{ oz-in.}$$

The required value of the residual holding torque then becomes a criterion for the stepper motor selection. The Slo-Syn Basic Motor Series M062 will meet this requirement and has been selected for the baseline design. Its parameters are also indicated in Table 5.4-3.

TABLE 5.4-3 FOCUS DRIVE BASELINE MOTOR PARAMETERS

Model	Slo-Syn M062
Nominal rated torque	65 oz-in.
Holding torque	100 oz-in.
Residual torque	8 oz-in.
Weight	2.0 lb
Size	2.2 in. x 2.2 in. x 3 in. long

5.4.4 Alternate Focus Drive Concepts

Preliminary tradeoff investigations were performed during the study on several focus drive mechanisms. Two alternate concepts are shown in Figures 5.4-3 and -4.

These alternate drives use the same lens cell assembly, bellows, pressure compensating springs and incremental encoder that were described in Section 5.4.2 for the baseline drive.

Both of these concepts use linear ball bushing to support and guide the lens assembly. The two concepts differ, however, in the manner in which the lens is actuated. The lever drive system, Figure 5.4-3, utilizes a fork shaped actuating arm to provide a camming action between the movable lens cell and the stationary structure. This lever arrangement permits using a less precise linear actuator and most importantly an actuating force is applied symmetrically about the axis of the lens cell.

The single screw drive focus concept, depicted in Figure 5.4-4, would use a single ball screw and nut actuated by a stepper motor, similar to the baseline concept. The actuating force in this design would be applied at one location at the periphery of the lens cell. The precision and dimension stability of the system would be completely dependent upon the ball bushing and the stiffness of the structure supporting the lens cell.

Whether a high spring rate bellows or pressure compensating springs are used to balance the external force due to the pressure, or no springs are used and the ball screw assembly directly drives the lens against this force, there is a couple which must be resisted by the structure supporting the lens assembly. With the pressure compensating springs, this couple is directly proportional to the spring deflection and thus variable loads are exerted on the structure. The deflections in the structure can be made sufficiently small to eliminate focus steering which results, however, only at the expense of larger and heavier structures.

FIGURE 5.4-3 LEVER DRIVE FOCUS CONCEPT

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FIGURE 5.4-4 SINGLE SCREW DRIVE FOCUS CONCEPT

The ball bushing guides are an attractive method of guiding the lens cell, mainly because of the low breakaway friction which is very important to the success of a focusing device. Shake or lateral play can be eliminated by dimensioning the shaft for a line-to-line fit with the bearings, thus excellent positional stability can be expected.

A focus drive summary has been presented in Table 5.4-4 which compares the expected operational parameters of these two concepts and the baseline drive.

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TABLE 5.4-4 FOCUS DRIVE SUMMARY

<u>FACTOR</u>	<u>LEVER DRIVE</u>	<u>SINGLE SCREW</u>	<u>MULTIPLE SCREW</u>
CHAMBER VOLUME REQUIRED	Requires Structure for Focus Guide (Cell Diameter ≈ 36 cm)	Requires Structure for Focus Drive (Cell Diameter ≈ 36 cm)	Minimum Chamber Volume (Cell Diameter ≈ 29 cm)
COMPONENT LOCATION	Cell Support Guides Inside Chamber	Cell Support Guides Inside Chamber	All Components Outside Chamber
BEAM STABILITY DURING DEFOCUS	Minimum Beam Steering - $< 20 \mu\text{m}$	Some Drift Resulting From Variable Loading $50 \mu\text{m}$	Probable Random Steering $25 \mu\text{m}$
STABILITY DURING OPEN-LOOP OPERATION	Adequate	Adequate	Adequate
ESTIMATED AXIAL FOCUS DRIVE ERROR	$< 2 \mu\text{m}$	$> 10 \mu\text{m}$	$< 2 \mu\text{m}$
RELATIVE COST	100%	105%	125%

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5.5 POINTING MIRROR GIMBAL

5.5.1 Pointing Mirror Gimbal Requirements

Pointing mirror gimbal requirements have been established throughout the study and were based on a consideration of the stability and expected natural frequency of the structure and preliminary servo control response which is discussed in more detail in Section 6. The following requirements have been established:

- a. A servo controlled angular range of ± 2 mrad should be provided. The mirror assembly can be manually adjusted and aligned on the space frame to within 1 mrad.
- b. An angular resolution of 1 μ rad should be obtainable with the mirror drive.
- c. A maximum slewing rate of 20 μ rad/sec should be provided.
- d. An absolute mirror angular position is not needed.
- e. The mirror gimbal and support should be operable in any orientation.
- f. The mirror must retain its last commanded position when power to the drive is removed.

5.5.2 Pointing Mirror Gimbal Baseline Design

A baseline gimbal assembly was developed during the study which will meet the stated requirements. It is presented in Figure 5.5-1.

The design is a torsionally restrained system in that the gimbals are supported by high spring rate torsion bars which are deflected throughout the mirror working range. These rods provide a natural frequency of 20 Hz on each axis. The mirror is deflected by applying a force to the edge of the gimbal rings. This force is applied through low spring rate coil extension springs by a miniature ball screw assembly and dc stepper motor.

FIGURE 5.5-1 TORSIONALLY RESTRAINED GIMBAL

The gimbal assembly is shown in an elliptical configuration which is an optimum shape as it matches the optical beam at an incident angle of 45° . Some manufacturing costs might be saved if the mirror and gimbals were circular, however, this must be weighed against the larger mirror and its tendency to deflect a greater amount due to its own weight and the necessity of optically finishing a larger area. The gimbal baseline selected can be utilized, however, with both the circular and elliptical configuration and the final shape will be determined during the detail design program.

The two gimbal axes are orthogonal and pass through the center of mass of the mirror. The system will be statically balanced to eliminate oscillations externally induced. The torsion rods for the outer gimbal are restrained in a stiff, single piece structure which extends across the back of the mirror. This structure is mounted to the space frame with a three-point mount to provide the required coarse alignment between mirror and space frame. The mirror deflection drive will be initially set at 2 mrad, its nominal operating position. The complete gimbal assembly will then be adjusted using the three-point mount and locked into position.

One end of the gimbal actuating spring is attached to a small bracket at the edge of the gimbal ring, and the other end to a miniature ball nut assembly. The ball nut is restrained to move only in a linear, vertical direction when the ball screw is rotated. The screw is indexed in small incremental steps by a dc stepper motor through a gear reduction which provides 1 prad angular increments to the mirror for each ten steps of the motor. The ball screw has a 0.250 in. dia thread and 0.050 in. lead. The residual holding torque of the motor is sufficient to hold the mirror at its last commanded position when motor current is removed. A spring restoring force is always exerted on the screw assembly and all backlash is taken out.

Some servo damping of the gimbals will be provided and the consideration of system damping is discussed in greater detail in Section 6. The most suitable method of providing damping at very small angular movements incorporates an electrical signal feedback to the drive motor. The leading candidate is a dc tachometer located on each gimbal axis.

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The performance of the baseline gimbals has been based on the parameters of Table 5.5-1.

TABLE 5.5-1 BASELINE GIMBAL PARAMETERS

Mirror	Fused Quartz (Solid Construction)
Minor axis	30 cm
Major axis	42 cm
Thickness	7 cm
Weight	34 lb
Mass moment of inertia (minor axis)	0.82 in.-lb-sec ²
Mass moment of inertia (major axis)	1.56 in.-lb-sec ²
Inner gimbal ring	Stainless steel
Weight	19.5 lb
Inertia (minor axis)	1.07 in.-lb-sec ²
Inertia (major axis)	1.72 in.-lb-sec ²
Outer gimbal ring	Stainless steel
Weight	22.9 lb
Inertia (minor axis)	2.67 in.-lb-sec ²
Gimbal assembly	
Weight	76.4 lb
Inertia (inner gimbal)	1.89 in.-lb-sec ²
Inertia (outer gimbal)	5.95 in.-lb-sec ²

Inner Gimbal Design Parameters

The baseline parameters for the inner gimbal have been based on a natural frequency of 20 Hz. The torsional spring constant of the gimbal support shafts can be found from the following:

$$k = J \omega_n^2 \quad (5-3)$$

where k = torsion spring constant - in.-lb-rad⁻¹

J = mass moment of inertia - in.-lb-sec²

ω_n = natural frequency - rad/sec

therefore

$$k = 1.89 \times (125)^2$$

$$k = 29,530 \text{ in.-lb-rad}^{-1} \text{ or } 14,765 \text{ in.-lb-rad}^{-1} \text{ per shaft}$$

For the inner gimbal, the point of force application is 5.65 in. from the gimbal center, therefore, forces of 0.25, 10.4, and 20.8 lb are required to deflect the mirror 1 arc sec, 2 mrad, and 4 mrad, respectively.

An extension spring having a spring constant of 25 lb/in. was selected as it limits the travel of the spring to less than 1 in., and provides 1 arc sec of mirror rotation for each 0.001 in. travel of the ball screw. The total travel of the ball must then be ± 0.40 in. from the nominal operating position.

The approximate parameters of the extension spring can be determined from the following relationship:

$$y = \frac{8PD^3 N}{E_s d^4} \quad (5-4)$$

where y = deflection (in.)

P = load (lb)

D = diameter of the coil (in.)

N = number of active coils

E_s = torsional modulus of rigidity (lb/in.²)

d = diameter of the wire

If a 0.50 in. mean diameter spring having 35 active coils is assumed, the wire diameter, d , becomes 0.093 in. and the body length, B , equals 3.25 in.

The maximum stress in the wire occurs at maximum extension when the mirror has been deflected 2 mrad beyond the nominal operating position. The torsional stress, S_s , is given by the following relationship.

$$S_s = \frac{8Pd k}{d^3} \quad (5-5)$$

where k = Wahl stress correction factor, 1.28 and the remaining units are given above

$$S_s = \frac{8 \times 20.84 \times 0.5 \times 1.28}{(0.093)^3}$$

$$S_s = 42,200 \text{ psi}$$

The resulting stress is less than one-half the maximum allowable stress of 100,000 psi for either music-wire or stainless steel.

Inner Gimbal Torsional Shafts

The parameters of the inner gimbal torsional shafts can be determined by the following relationships. The active length of the shafts are selected at 1.50 in. to be compatible with the gimbal configuration shown in Figure 5.5-1.

$$J = \frac{k\ell}{E_s} \quad (5-6)$$

where k = shaft spring constant, 14,765 in.-lb-rad⁻¹

ℓ = shaft length, 1.5 in.

E_s = torsional modulus of elasticity, 12×10^6 psi

$J = 1.85 \times 10^{-3}$ in.⁴, which provides a shaft diameter of 0.37 in.

The stress in the shafts at maximum deflection of 4 mrad is as follows:

$$S_s = \frac{T C}{J} \quad (5-7)$$

where $T = K \theta$

$$T = 14,765 \times 0.004$$

$$T = 59.1 \text{ lb-in.}$$

$$C = 0.370/2 = 0.185 \text{ in.}$$

$$S_s = \frac{59.1 \times 0.185}{1.85 \times 10^{-3}}$$

$$S_s = 5920 \text{ lb/in.}^2$$

Outer Gimbal Parameters

Using the same relationship for the outer gimbal, the following parameters can be determined:

Total outer gimbal inertia	5.95 lb-in.-sec ²
Total torsional spring constant	92,970 in.-lb-rad ⁻¹
Point of force from gimbal center	9.77 in.
Force to deflect mirror 1 arc sec	0.046 lb
2 mrad	19.0 lb
4 mrad	38.0 lb
Extension spring parameters	
Spring constant	46 lb/in.
Mean coil diameter	0.50 in.
Number of active coils	30
Wire diameter	0.10 in.
Maximum stress (4 mrad mirror deflection)	56,500 psi

Outer Gimbal Shaft Parameters

Shaft length	1.5 in.
Shaft spring constant	46,500 in.-lb-rad ⁻¹
Shaft diameter	0.50 in.
Torsional stress (4 mrad deflection)	8000 psi

Section 6

SERVO

This section presents the mechanization and the expected performance of each of the control system concepts contained in the baseline system design description. As the mechanization concepts are presented, the guiding design factors are highlighted and discussed.

Both open loop and closed loop types of control are planned for the laser control system. Closed loop servos for target pointing and beam centering are automatic systems, while the open-loop, remotely actuated controls, such as the optical path-length adjustment and the focus control, will require operator participation.

6.1 TARGET POINTING SERVO

6.1.1 Disturbance Effects

The operational concept for the target pointing servo presented in Section 4.3 included the error budget for the servo system. Other design requirements are established by reviewing the intended operational scenario and by examining the basic physical restraints of the system approach. These requirements listed in Table 6.1-1 form the basis for the preliminary design. The requirements are discussed in subsequent paragraphs of this section.

The object of the control system is to maintain the laser line of sight to the desired accuracy in a dynamic environment subject to seismic motion and man-made disturbances.

To ensure an even concentration of illumination on the target, it is necessary to control the optical beam axis of the laser to within a few micrometers. The total tolerance allocated to the various sources was mentioned in the system design section. The 1×10^{-6} radian error allotted to the target pointing servo, although arbitrarily assigned, is based on experience in current technology and its capability.

TABLE 6.1-1 TARGET POINTING SERVO REQUIREMENTS

• Align all beams	<10 sec
• Structure and target stability	<100 sec
• Pointing mirror accuracy	1 μ rad
• Mechanism range	± 2 mrad
• Alignment maintained with power off	
• Structure in quiet seismic zone	
• System operable open loop	

In order to arrive at the pointing error allotment, the source of disturbance inputs which tend to modify the pointing line-of-sight were examined. The most likely source of disturbance was determined to be the seismic motion of the local terrain. This motion is attributable to nature as well as man, and is one of the factors considered in the design evaluation.

The disturbance effects were evaluated in conjunction with the relative rigidity of the optical mounting structure and the stability of the target chamber

Seismic activity can be represented as a disturbance amplitude band signifying limits expected at quiet and noisy locations. Figure 6.1-1 presents such a seismic curve in terms of acceleration.

FIGURE 6.1-1 TYPICAL SEISMIC INPUTS

The seismology data can be interpreted in terms of physical displacement as shown in Figure 6.1-2. The activity band illustrated represents the displacement expected vs frequency. The two curves represent the limits of the activity band. The upper curve is for a location with a level ten times the quiet environment represented by the lower curve.

Current L^3 data indicates that the locality can be classified quiet and therefore the expected motion is less than 1 micrometer on the average.

The seismology data shown is limited to periods less than 100 sec. For periods greater than 100 sec, other factors begin to dominate. The extent to which these disturbances influence the pointing system depends on the degree of coupling that they exert on the controlled elements. Factors such as thermal and wind loading on the building structure and surrounding terrain are minimized by designing the support foundation to extend deep into the earth. Decoupling these forces, on the roof and building walls, from the laser base can be easily accomplished.

Another potential source of terrestrial disturbance which would affect the accurate pointing of the laser beams is the amplification of man-made disturbance through excitation of base support resonances. Results of investigations by L^3 indicate that major vibrational type problems are not anticipated with the design presently planned. The L^3 analysis indicated that expected motions would be limited to a few tenths of a micrometer at several natural frequencies less than 20 cps. Man-made noises are expected to cause these higher frequency disturbances. This level of disturbance is expected in the laser room and a significantly lower amplitude level is expected in the chamber room since its foundation is far below ground level.

The current preliminary design of the target chamber and target pointing structure provides a high degree of stiffness and a high natural frequency greater than 25 Hz. Therefore, floor resonances should not couple into laser system resonances.

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FIGURE 6.1-2 SEISMOLOGICAL DISPLACEMENT SPECTRUM

From the foregoing discussion on seismic and man-made disturbances, it appears that the present structure and building design will not adversely affect the system alignment. Therefore the design is based on the assumption that the alignment can be maintained for a minimum of 100 sec. The stability period provides a key input to the control system design.

If the period of basic stability is 100 sec, the allotment of time to realign all beams should be some small percentage of this stable period. A period of approximately 10% (or 10 sec) is assumed. This system requirement, along with the base referenced gimbal approach and the error sensor configuration, shapes the control system design.

To ensure that each target servo may initially be aligned, the deliberate offsets could be introduced, and that the system could be operated in spite of a servo failure, an operational requirement was placed on the control system to ensure that the pointing mirror be controllable in an open loop configuration. This will permit the operator to precisely deviate the laser beam's line of sight without using the pointing error sensor.

6.1.2 Target Pointing Gimbal Selection

The operating features and potential performance of several gimbal approaches were evaluated during the preliminary design. The approach selected as the best, when all factors of cost, performance, and adaptability are considered, is a flexure gimbal approach.

This design is basically mechanized by securing the target chamber beam deviating mirror to a set of concentric gimbal rings supported by fixed torsional shafts in orthogonal transverse directions. The gimbals are torqued in two orthogonal directions about the center lines of the shafts. Precise angular motions can be achieved by stressing the fixed shafts. This type of gimbal is known as a flexure mount. The flexure gimbal provides excellent stability, controllability, and simple mechanization with standard control components.

The one significant disadvantage of the flexure mirror gimbal system is its resonance characteristic developed through the combination of mechanical characteristics of a spring-torqued flexed shaft, and the inertia of the pointing mirror. The resonance frequency is proportional to the square root of the ratio of the shaft spring constant to the mirror inertia. Since the flexure motions are small, very little natural damping is realized. This characteristic can result in an unstable servo response, unless appropriate damping techniques are used.

The laser beam size at the location of the pointing mirror is the most significant factor in determining mirror inertia. The mirror inertia varies as slightly more than the fourth power of mirror diameter. The spring constant of the supporting flexure mount must be high in value to ensure that any resonant natural frequency is not in the servo or the base passband. That is, the natural frequency of the mirror must not coincide with the disturbing frequencies expected from the mounting structure. This places the mirror flexure natural frequency at a value greater than 20 Hz.

To eliminate the undesirable response characteristic of an undamped mirror, an active damper is proposed in the baseline design. This active damper will be mechanized by placing a rate sensor on the mirror shaft to measure its angular rate. This signal is used to control the phase of the driving signal to ensure stable operation.

Figure 6.1-3 illustrates a basic servo control loop envisioned for the target pointing system when configured for using a flexure mount approach. The laser line-of-sight error is measured by an optical sensor which generates a signal proportional to the laser beam pointing error. Signal processing provides the appropriate coordinate transformations. Steering commands to each axis are therefore uncoupled regardless of gimbal orientation. The signal from each axis is processed by its stabilizing network which provides the drive signal for the stepper motor. The stepper motor drives the beam pointing mirror through a very soft spring, as explained in the mechanical design section. Large angular movements of the stepper motor result in very small angular motions of the turning mirror. The baseline design scale factor has a ratio

MECHANISM AND GIMBAL

$$TF = \frac{K}{P \left[\left(\frac{P}{\omega_n} \right)^2 + 1 \right] \left[P^2 \omega_s^2 + 2\zeta_s \frac{P}{\omega_s} + 1 \right]}$$

WHERE

ω_n = NATURAL FREQUENCY OF MIRROR AND FLUX SLOPE

ω_s = NATURAL FREQUENCY OF DRIVE SPRING

P = Laplace complex operator

FIGURE 6.1-3 TARGET POINTING CONTROL LOOP

of 10^{-7} rad/step. This allows precise control of the mirror during its tracking and pointing mode of operation.

The soft drive spring in the above mechanization is the source of a potential stability problem in the closed loop mechanization. The problem develops from the time delay characteristic of the spring. As the spring is a distributed parameter device, it behaves as a mechanical transmission line, rather than as a lumped parameter resonant device. An analogy which is useful in developing the time dependent characteristic of the spring is to model the spring as an electrical transmission line. The transmission line is assumed shorted at the receiving end in this analysis, as that condition results in the lowest natural frequency configuration, and is the analogy which most closely represents the mechanical condition.

The lowest natural frequency is

$$\omega_n = 2\sqrt{\frac{K}{M}} \quad (6-1)$$

where

K = force constant of the drive spring

M = drive spring mass

From the physical dimensions of the drive spring given in the mechanical section, the spring weight is estimated as 1/10 lb (45 gms). The spring constant is 20 lb/in. or 354 Kg/M.

Solving the above equation results in a frequency of $f_n = 90$ Hz.

The transient response and the stability characteristic of the closed loop system can be determined by including the spring characteristic as a lightly damped single second-order time constant located at the spring's lowest natural frequency. This assumption is sufficiently accurate for purposes of this study and permits straightforward linear analysis. Using this approximation, one finds that the small inherent internal dampening

(≈ 0.05) of the spring is sufficient to preclude oscillation at the spring natural frequency, and that the servo system is adequately stable.

6.1.3 Stabilizing the Pointing Mirror

Several methods of gimbal damping were examined during the study. The benefits of each were compared and the baseline was selected. The factors considered in the selection are discussed below.

The first method examined for dampening the mirror used a visco-elastic material such as natural rubber. The major shortcoming of this approach is the low per unit critical damping achieved by the rubber. Thus, additional damping is necessary if satisfactory performance is to be realized. One technique to provide the additional damping is the use of an electronic shaping network composed of complex zeros and poles. The network provides the additional phase compensation to stabilize the mirror. This approach, while technically feasible, is unreliable since any slight phase changes result in a highly undamped response. Any additional time delay, such as friction or hysteresis within the system, could cause the phase shift and hence the system instability. For this reason, other techniques were evaluated.

An active damper was the second approach evaluated. The damper consisted of a rate generator secured to one end of the mirror shaft, the output of which would be amplified and the signal applied to the input of a dedicated torque motor, mounted on the other end of the mirror shaft. This arrangement provides the necessary damping for the mirror assembly, however, at the expense of an additional torque motor and amplifier per gimbal axis. Amplifier signal gain to achieve 0.7 critical damping is 10^4 .

The baseline damping technique uses a rate generator, mounted on the mirror shaft, which drives the primary control motor through appropriate phase compensation networks. This damping technique is described in detail in the next section.

6.1.4 Inner Loop Servo Stabilization

Previous sections have presented the baseline control concept, control hardware mechanization, and the servo stabilization problem. This section presents the baseline servo stabilization techniques and the mechanization requirements. A simplified linear analysis is used in this preliminary design analysis.

Figure 6.1-4 illustrates the overall baseline control loop configuration in a block diagram form with associated transfer function equations. The inner loop dynamic equations were developed in the previous sections. The outer loop dynamics are presented for reference.

Referring to Figure 6.1-4, the first element in the outer loop represents the error measuring sensor. Its expected response form is combined with a stabilizing network and is presented in transfer function form. The factor (K_e) represents the scale factor relating motion of the laser line of sight to the output signal level for the axis of interest. The form and value of the outer loop stabilizing network will be evaluated later in the design.

The inner loop is characterized by three elements: the stabilizing network, the gimbal and drive spring, and the rate sensor. The factors determining stability are discussed next.

The gimbal represents the gimbal drive motor, lead screw, drive spring, mirror inertia, and shaft spring constant (see mechanical design description). The drive spring was developed in the previous section.

The dominant, time dependent characteristic is the mechanism's *mirror inertia and supporting shaft spring characteristic*. Zero dampening is assumed in this analysis, therefore the transfer characteristics of the load are a second order function with zero damping. The rate generator is shown located in the inner feedback loop, and is represented by a simple zero.

FIGURE 6.1-4 CONTROL LOOP TRANSFER FUNCTIONS

The root locus for the simplified inner loop is shown in Figure 6.1-5. The location of the stabilizing network poles and zeros causes the locus from the gimbal related complex poles to move toward the zeros of the stabilizing network. The lag portion of the stabilizing network has a locus which breaks away from the real axis and moves slightly toward the imaginary axis.

Figure 6.1-5 does not include the location of the poles caused by the soft drive spring since their value as determined by their natural frequency places them off the page. To include their effect, the phase lag caused by the complex poles pair is added into the root locus and is shown as a dashed line. (The solid line shows the loci without the drive spring.) As the phase lag due to the drive spring increases, the loci approach each other, eventually causing the mirror roots to move in to the right-hand plane.

The roots originating at the drive spring poles could result in a high frequency oscillation if the inherent internal damping of the spring is too small. For the gains selected, an internal spring per unit critical damping of less than 0.02 will result in a high frequency low amplitude oscillation. In most cases, the damping will be much higher than this value. However, appropriate loop compensation could be added in final design, if needed.

To ensure the type of response desired for the inner loop, a compensating network in the form of a double lead-lag is placed in the forward loop. The poles of this network are comparable to the mirror natural frequency.

The operating point was selected to place the roots of the inner loop at a location with a damping ratio of approximately 0.6. The loop gain required to place the operating point as shown is approximately 1/50.

For the operating point is as shown in the root locus diagram. The loop gain is distributed as follows:

FIGURE 6.1-5 INNER LOOP ROOT LOCUS

K_0 = compensation amplifier = 40 V/v

K_1 = nominal count rate 200 step/sec

K_R = rate generator amplifier gain = 25 V/rad/sec

These gains are within the capability of existing off the shelf hardware.

6.1.5 Outer Loop Stabilization

To provide preliminary design data the stability of the outer loop was established through a root locus evaluation of the dominate control loop response characteristics in form of transfer functions.

With the inner loop configured as described above, the outer loop can be characterized as an error sensor element with a stabilizing network, operating in series with the roots developed from the inner loop stabilization.

The root locus for the outer loop is shown in Figure 6.1-6. The pole developed from the rate generator moves horizontally along the real axis toward the lead zero, as the loop gain is increased. At very large loop gains, the root position coincides with the stabilizing network zero. The complex roots from the inner loop move toward the imaginary axis as shown, and with high enough gain will cross into the right half plane and provide unstable performance. An operating point was selected as indicated by the large crosses placed on the root locus plots. Component gains were established for the operating positions selected. The scale factor gain required for the line of sight error sensor was established for the root location shown. Its value is 2×10^3 volt/rad. The gain requirement for the error sensor appears reasonably easy to achieve with the type of sensor selected for the target pointing servo.

375-1250

FIGURE 6.1-6 TARGET POINT SERVO ROOT LOCUS PLOT

6.1.6 Target Pointing Servo Alternate

During the preliminary design phase, several alternate control system approaches for the target pointing servo were examined. Prior to the establishment of seismic levels and laser base natural frequencies, a control approach capable of providing a high degree of base isolation and pointing mirror stabilization was evaluated. One alternate design becomes a serious candidate in the advent that (1) seismic disturbances are larger than anticipated, or (2) the laser mounting structure is not as rigid as required.

The design evaluated was one in which both the turning and pointing mirrors at the target chamber are space stabilized. Other control loops are provided to space stabilize the target position and to space stabilize the laser beam line of sight. Neither the additional control systems for laser beam stabilizing or target stabilization were examined. The work on the space stabilized target pointing mirror will be discussed in the subsequent paragraphs.

The basic mechanization studied in the design is one where each mirror is supported in a 2-degree-of-freedom gimbal system. The gimbal would be mechanized by mounting the turning mirror in a precision mechanism that would use high-quality ball-bearing pairs preloaded to minimize ball and race eccentricity and maintain alignment. Gimbal movement would be controlled through the use of electrical torque motors to provide the smooth torque action required in a precision tracking system.

Space stabilizing signals would be generated by a high-quality integrating gyro. Positional referencing of each gimbal axis would be accomplished through the use of precision resolvers which would provide an electrical signal proportional to angular position. Each of the basic control components would be specifically selected for use in this application since the required accuracy for each of the components used in the control loop is greater than the average basic accuracy in components of this type. That is,

each component would have to be trimmed or selected to the best state-of-the-art quality.

An analysis of the control loop dynamic is necessary to establish required sensor sensitivities and characteristics for stable operation. This evaluation is most easily accomplished through examining the close loop system response as predicted through manipulation of system dynamic equation. The system transfer functions are illustrated in the block diagram shown in Figure 6.1-7. Symbols for the figure are shown in Table 6.1-2.

Motion of either the gimbal or the target causes the position sensor to generate an electrical error signal proportional to the displacement. This signal is processed by the control loop to reduce the error to zero, thus providing the closed loop tracking system.

All disturbances imposed upon the control system except base motion are represented by the input at the first summing junction of Figure 6.1-7. The magnitude of the disturbance is scaled to be proportional to its effect, whether its origin is amplifier noise, gyro drift, or whatever the cause.

The most significant disturbance to the system is represented by the laser base motion. This motion is coupled into the mirror position through the spring-like characteristic of the bearing. This bearing coupling is a disturbance and acts as a torque which tries to offset the line of sight.

Aerojet, in its work with precision tracking systems, has made laboratory measurements on effects of very small motions on the torques transmitted by high quality ball bearings. The origin of the spring coupling effect is the deformation of the bearing race due to the nonrolling action of the balls in the bearing.

Using the block diagram shown in Figure 6.1-7, and the transfer function indicated by the table, a simplified closed loop response equation is developed which can provide some insight into the performance.

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6.1-19

FIGURE 6.1-7 SIMPLIFIED TARGET POINTING SPACE STABILIZED SERVO

TABLE 6.1-2 SYMBOLS FOR FIGURE 6.1-7

θ_{to} = Target motion respect to space

θ_{go} = Gimbal motion respect to space

θ_{bo} = Base motion respect to space

θ_{do} = Equivalent angular disturbances

G_{os} = Optical sensor TF = $\frac{K_{os}}{1 + T_o P}$

K_{os} = gain

T_o = time constant

G_c = Gain and compensation $\frac{KA (1 + T_1 P)}{P}$

K_s = Gimbal spring coupling

G_j = Gimbal inertia = $\frac{1}{JP}$

H_g = Gyro TF = $\frac{K_g}{1 + T_g P}$

I = Integrates rate into position = $\frac{1}{p}$

P = Complex laplace operator

$$\frac{\theta_o}{\theta_{bo}} = \frac{\frac{1}{K_o K_a} P}{\frac{K_j}{K_o K_a K_s} p^2 + \frac{T_1}{K_s} p + 1} \quad (6-2)$$

where

$$\omega_n = \sqrt{\frac{K_o K_a K_s}{K_j}} \quad (6-31)$$

and maximum response

$$A_o = \frac{K_s}{K_D K_a T_1} \quad (6-4)$$

Examination of the control loop equation provides an insight to the design consideration required to ensure performance.

The transfer equation relating to the output gimbal motion vs base motion is shown in Equation (6-2). The peak amplitude of the gimbal motion, as a result of base motion, is given by Equation (6-4). The form of this equation shows that gimbal motion is proportional to the bearing spring constant and inversely proportional to the gain of the error sensor amplifier gain and stabilizing pole time constant.

6.2 BEAM CENTERING SERVO

As presented in the system analysis section, the centering of the laser beam in the disk amplifiers is necessary to ensure even illumination of the target during system operation. The control concept is to position the smaller reflective mirror located near the oscillator assembly in two orthogonal axis in accordance with the error signal derived at the centering sensor located in the latter section of the disk amplifier assembly. The accuracy and performance requirements for this control are less than those for the beam pointing servo.

The requirements are listed in Table 6.2-1 and the key items are the pointing accuracy of 7 μ rad with a stability period of 1000 sec. The angular pointing accuracy is developed by dividing the centering accuracy by the path length. The stability period is based on the type of construction for the laser support, and the stability of the foundation and support.

The beam centering servo design is mostly guided by the characteristics of the mechanical mechanism used to move the pointing mirror, and by the expected stability period.

TABLE 6.2-1 BEAM CENTERING REQUIREMENTS AND ASSUMPTIONS

• Align all beams	<50 seconds
• Structure stability	>1000 seconds
• Pointing accuracy	<7 μ radians
• Mechanical range	>700 μ radians
• Alignment maintained with power off	
• System operable in open loop	

The ± 0.7 mr range of movement, coupled with the small diametrical size of the laser beam at the control point, is a combination of requirements which are quite easily satisfied by a standard off-the-shelf mechanism developed by Burleigh Instruments. The mechanism uses several

piezoelectric crystals in tandem to provide precise incremental movements to the mechanism. These piezoelectric devices require special electronic circuits which are properly phase sequenced to provide the drive for the gimbal movement. These piezoelectric devices are actuated by electrical pulses. The format of the control signal to the centering gimbals is compatible with digital systems.

The control loop sampling rate is determined by the stability characteristic of the structure. That is, the minimum period between samples is determined by the centering tolerance and the structural stability. Figure 6.2-1 illustrates a single axis of a beam-centering servo in which the error signal, as developed by the sensor, is sampled and processed in digital format.

As discussed in Section 4.2, the sensor generates an electrical signal proportional to the linear centering error of the laser beam at the sensor. For servo analysis purposes, this may be treated as an angular error. The output of the sensor is processed by analog circuitry to derive two orthogonal error signals, in the coordinates of components in terms of the mirror mechanism. In the baseline design, the two axis coordinate conversion of each error sensor output is performed by a common central digital processing system. The error is converted to a digital count proportional to the error, and is then applied to a set of drive electronics that provides the proper number of motor steps to reduce the error to zero.

A sample of time sharing sampling is also shown in Figure 6.2-1.

The centering channels are sampled at an interval of 50 seconds, with 2.5 seconds per sample. During this 2.5 second sample period, the pointing servo is shut down and the centering sensor polarizer is rotated to look at the source. The error signal is continually sensed, and the centering servo is nulled. At the end of the 2.5 second period, the centering mirror driver and processing are converted to the next centering servo, the prior centering mirror is locked. The prior centering sensor reverts to the

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6.2-3

FIGURE 6.2-1 BEAM CENTERING SERVO

FIGURE 6.2-2 FUNCTIONAL SCHEMATIC CENTERING ELECTRONICS

pointing mode, and the pointing servo is reactivated. This configuration represents one of a number of possible sampling arrangements.

Figure 6.2-2 is a detailed functional schematic diagram of the time shared portion of the centering electronics. The drive electronics can be located in the control console or can be located at the oscillator end of the laser support structure. The benefit by remotely locating the drive electronics would be that the high voltage (520 volts) used to drive the piezoelectric crystal would not be in the control room.

It is anticipated that the response time of the Inchworm will be less than 1.0 sec of elapsed time. Based in the Inchworm response time and the sample rate stability problems with this control are not anticipated. Therefore, no special techniques for beam pointing are considered necessary.

A detail description of the theory of operation of the Inchworm is contained in the mechanical design section, Section 6.0.

6.3 FOCUS CONTROL SYSTEM

The focus control system is one of the more critical in performance, since the focus position must be precisely located for each of the beams, and a very precise focus offset must be made before each test. Its requirements are shown in Table 6.3-1.

The baseline control system, shown in Figure 6.3-1, operates as a semiautomatic open loop control system, as the operator must view the CRT display and read the lens encoder outputs to determine the position of best focus. The control system permits the operator to move the focus lens in small incremental motions in either direction to match the image diameter with a mask on the CRT display. It also permits him to command the system to move through large preset motions automatically to achieve the desired degree of focus offset.

The focus control system also includes a video preprocessor for the CRT display. This preprocessor causes the display to present an iso-intensity contour for the beam, at the point where the intensity level is about 50% of the peak value in the beam. Such a presentation eases the operator's task in determining apparent beam diameter.

TABLE 6.3-1 OPL AND FOCUS CONTROL REQUIREMENTS

• Use of CRT as control sensor• Focus requires precise offset capability• Maintain set point with power off• Focus position accuracy $<3.5 \mu\text{m}$• Focus range $\pm 7 \text{ mm}$• OPL accuracy $\pm 3 \text{ mm}$• OPL range 6.0 cm

175-1659

FIGURE 6.3-1 OPL & FOCUS FUNCTIONAL SCHEMATIC

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Section 7

ELECTRICAL DESIGN

7.1 CONTROL CONSOLE

The control console selected for the baseline is a desk-top type with three sloping panels arranged about the center of the operator. It is intended that most all control electronics be located within the desk with easy access to the circuitry through sliding drawers. Other electronics may be better situated near where the signal is developed or used. Two types of electronics are better located remotely: (a) the amplifier for the low level error signal from the sensors, and (b) any high power circuitry or high voltage not needed at the console.

The layouts for the three console panels are shown in Figures 7.1-1, -2, and -3. The center panel (Figure 7.1-1) contains the elements used in focusing each beam. Included in the center panel is a standard 525-line TV monitor which would be located in the panel as shown. Also on the panel is a set of selector switches which would be capable of selecting which function the CRT monitor would present to the operator. The CRT monitor would have available the normal TV controls for adjusting the quality of the picture. Located also on the focus panel is a rotary switch which is used to select the beam channel to be presented on the monitor. This switch would control a remote TV coaxial switch to commutate the proper camera to the monitor.

Selecting the channel to be monitored also presents the output of each incremental encoder which has had its position stored in a non-volatile memory. Interrogation of the channel presents the stored output on the digital display. Also located on the panel are the means for entering offsets or position commands for each of the beam paths. The system receiving the input command is determined by the position of the selector switch.

FIGURE 7.1-1 CONTROL CONSOLE FOCUS PANEL

FIGURE 7.1-2 CONTROL CONSOLE OPL/TARGET POINTING PANEL

175-508

7.1-4

FIGURE 7.1-3 CONTROL CONSOLE CENTERING PANEL

For the focus control system, three types of manual input commands are provided. The first is a preset counter which enters the amount of offset desired in each channel. The second type provides a variable input rate into the selected focus drive mechanism, and the third type permits individual steps to be inserted into the selected mechanism.

Three other functions are located on the focus panel. One is a manually actuated enable switch which, when activated, disables all controls and thereby freezes the system at the desired location. The second set of controls are the shutter controls for single beam isolation. Each of these switches operate a single shutter; these alternate action shutter switches have indicating lights to signify status. On/off and standby controls for the focus subsystems are contained on the panel.

The second panel (Figure 7.1-2) will contain the controls for the optical pathlength and the target pointing servo. The systems are different, in that the optical pathlength control is an open loop remotely operated mechanism, whereas the target pointing system is a closed loop servo which can be manually operated from the console when desired. The optical pathlength subsystem is operated in much the same way as the focus control subsystem. The focus CRT display indicates streak camera output. The target pointing servo controls are different in that they are closed loop servo systems capable of being operated manually.

To manually position the pointing mirrors the operator selects the channel he desires for manual control, and activates the manual mode switch on the panel. This switch sets a relay for that channel that opens the servo loop and allows manual control. In addition, the illuminated switch provides a visual indication of the open loop status of that beam to the operator. Closed loop control can be reinstated again by actuating the indicating switch. The three manual modes of control for the target pointing servo are the same as for the focus control, and are:

- a. Manual preset increment
- b. Variable rate offset
- c. A single step input

This panel also contains its individual on/off and standby controls for providing system power.

The third panel (Figure 7.1-3) contains the beam centering controls for both the disk amplifier as well as the controls for the test and master oscillator pointing and centering. The beam centering controls are closed loop servos that can be operated in an open loop manner upon selection by the operator. The same type of controls are provided in this system as in the others.

Master and test oscillator pointing controls are at the bottom of the panel and permit open or closed loop operation of these servos. In addition, the capability will be provided to select error signals from the sensors to either the master oscillator gimbal or the test oscillator gimbal, and to lock the unused gimbal.

7.2 TIME SHARING ELECTRONICS

The repetitive nature of the signal processing circuitry for each arm of the laser presents the opportunity for time sharing the electronics between the laser arms, thereby reducing the cost.

Table 4.2-1 is a trade table showing the relative cost of mechanizing the electronic circuitry for a 20-beam system for three levels of time sharing. Costs are shown for: (a) non-time shared (parallel processing); (b) fully time shared (serial processing); and (c) partially time shared. The costs are given for the target pointing and beam centering servos. The partially time shared system was based on the assumption that one driver amplifier was used in each channel, and that the processing electronics were commutated; clearly, commutating a certain number of driver amplifiers would result in a lower cost for this case.

The fully time shared system is the least expensive in both cases, although not as much so for the target pointing system, due to the lower driver amplifier cost. However, the fully time shared system drastically reduces servo sampling rates--a reduction undesired in the pointing system, but allowable in the centering system. Consequently, the baseline uses parallel processing for the target pointing system, and serial processing for the beam centering system with one driver per axis. This configuration provides a cost compromise, and satisfies performance requirements.

TABLE 7.2-1 TIME SHARING TRADES

	MUX	Proc	Decom	Driven	Total Cost (K)
Target Pointing					
Parallel	0	2.5	0	6.0	8.5
Series	2.5	2.0	2.0	0.5	7.0
Partial	2.5	0.8	0.2	6.0	9.5
Beam Centering					
Parallel	2.0	0.5	0	30.0	32.5
Series	2.5	0.2	6.0	1.5	10.2
Partial	2.5	0.2	2.0	30.0	34.7

Section 8

HARDWARE PROGRAM SCHEDULE

Figure 8-1 shows the schedule for the SHIVA alignment and control system hardware program. This program includes the phases of design study, prototype fabrication and test, and production of the multiple hardware units required. The schedule is predicated on the presumption of a 20-channel laser system; a change in the number of channels would likely have an impact on scheduling of the production phase of the program.

Based on a 1 July 1975 contract go-ahead date, a design study contract is envisioned whose output is a set of design drawings for the various components of the system. These drawings would be to commercial quality, however, their degree of detail and parts listing would be such that prototype fabrication could be initiated immediately in the next phase, without significant additional drawings.

System verification would be conducted during the first month of the design phase. Following this, detail design would be initiated, including electronic breadboarding of critical circuits, as necessary, to define circuit details and components. The concluding portion of this phase would consist of preparation of electronic and mechanical schematics, and packaging drawings for the various components of the system. Also included in this phase of the program (in addition to continuous informal interface between Aerojet and L³) would be a minimum of three formal program reviews to ensure design conformance with system requirements. The design phase would conclude with a proposal for the prototype and production phases of the program.

175-1709

FIGURE 8-1 SHIVA ALIGNMENT AND CONTROL SCHEDULE

After an appropriate period for contractor selection and for contracting, the prototype fabrication and test period would be initiated with immediate procurement of required components for the prototype system. In this phase, one each of all units required for the system would be fabricated. In cases where only one unit is required for the system, that hardware built under the prototype phase would constitute the final deliverable article.

The last two months of the prototype phase would include testing of a prototype system using a simulated optical configuration resembling the SHIVA optical configuration. These tests would verify the tracking accuracy and centering accuracies, as well as operation of the focus lens drive system, and various gimbals and servos of the system.

The schedule is constructed on the presumption of a fixed-price redeterminable contract for the prototype and production phases of the contract. Thus, it would be possible to move directly from prototype fabrication to production fabrication, subject only to final price negotiations for the production phase of the program. Long-lead items would be procured immediately upon initiation of this phase of the program, and deliveries of hardware would start on 1 March 1977, as shown in the schedule. Integration and testing of these deliverable units would be performed at L³ during the period ending 1 July 1977, with the option for further integration and test assistance during system testing being available to L³ as an option.

The maximum and minimum schedule variation limits are shown in the figure to indicate the range of accuracy of the schedule estimate. As shown, under favorable conditions the schedule length could decrease by as much as two months; under conditions of serious problems, a five-month slippage might result. Due to the low risk design employed in the SHIVA baseline, however, there is high confidence in Aerojet's ability to meet or exceed the nominal program schedule.

APPENDIX A

COMMERCIAL HARDWARE DATA SHEETS

This section contains pertinent portions of manufacturer's data sheets describing those key mechanical and electro-mechanical components used in the baseline design. Included are data on gimbal assemblies, Inchworm drive units, stepper motors, motor drive units, detectors, and other relevant components.

DETECTORS	TYPICAL RESPONSE
DEPHELD	4000/μ
SCHOTTKY	2000/μ
UV ENHANCED	2000/μ

DETECTORS	TYPICAL RESPONSE
DEPHELD	4000/μ
SCHOTTKY	2000/μ
UV ENHANCED	2000/μ

SHORT FORM CATALOGUE

U
UNITED
DETECTOR
TECHNOLOGY
INC

UNITED DETECTOR TECHNOLOGY, INC.

The detection and measurement of light in its many forms is United Detector Technology's only business. UDT has applied Schottky, Planar Diffused and Mesa technologies to meet a wide variety of electro optic device requirements. Offering over fifty standard devices in sensitivities and sizes to meet the majority of light sensing and laser applications are but part of the UDT story.

In addition to offering the widest variety of silicon photodiodes a major portion of our capability is directed at fabricating custom devices to meet the myriad of requirements in facsimile, OCR, optical alignment and process control.

SCHOTTKY SERIES

Schottky barrier silicon photodiodes are large area, high sensitivity, fast response detectors. The cold formed Schottky barrier produces low capacity, low noise devices. Larger single cell areas can be produced utilizing the Schottky technique than are available in planar diffused junction or Mesa type devices. The thin film gold contact offers better spectral response in the ultra violet and blue region. Unique Characteristics:

- Large areas - to 8cm² (Standard Series)
- Low capacity - to 25pF/cm² (LC Series)
- Long sensors - to 8 inch long (Long Line Series)
- High blue response
- High UV response - 30% at 3500Å
- Low dark current, Low noise
- Linear response, 10⁻¹² to 10⁻³ watts

Schottky Series						
	SPECTRAL RESPONSE	AREA (cm ²)	TO-18 DIAMETER (mm)	SENSITIVITY (A/W)	RESPONSE TIME (ns)	NOISE (pA/√Hz)
PIN-10	350-900 nm	0.5	5.0	100	100	1.0
PIN-15	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-20	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-25	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-30	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-35	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-40	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-45	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-50	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-55	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-60	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-65	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-70	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-75	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-80	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-85	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-90	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-95	1.000 cm ²	1.0	5.0	100	100	1.0
PIN-100	1.000 cm ²	1.0	5.0	100	100	1.0

LOW NOISE SERIES

PIN-020 (20 mil diameter) and PIN-040 (40 mil diameter) have unmatched low light level detection ability-to 5x10⁻¹⁵ watts. Mounted in TO-18 hermetic cans, the active element is completely isolated from and electrically shielded by the metal case.

Low Noise Series						
	SPECTRAL RESPONSE	AREA (cm ²)	TO-18 DIAMETER (mm)	SENSITIVITY (A/W)	RESPONSE TIME (ns)	NOISE (pA/√Hz)
PIN-020	350-900 nm	0.0001	0.5	100	100	1.0
PIN-040	350-900 nm	0.0004	0.5	100	100	1.0
PIN-060	350-900 nm	0.0009	0.5	100	100	1.0
PIN-080	350-900 nm	0.0016	0.5	100	100	1.0
PIN-100	350-900 nm	0.0025	0.5	100	100	1.0

DIFFUSED SERIES

Planar Diffused Detectors are low leakage, low noise, high impedance, wide spectral range devices.

The "D" series is optimized for a voltage biased mode of operation (photoconductive), which is required for fast response (less than 100ns). These devices are particularly suited for AC light signals.

The "DP" series is optimized for an unbiased mode of operation (photovoltaic). Because of their high zero bias impedance, these devices are ideally suited for coupling to an op amp in the current mode. In this photodiode/op amp mode, dc light level changes up to ten decades can be linearly detected and converted to an output voltage. These devices are particularly suited for DC light signals.

- Voltage Biased Operation (photoconductive)
- Fast Response Time
- Low Capacity
- Low Noise
- Low Dark Current
- Zero Voltage Bias Operation (photovoltaic)
- Optimized for op amp hook-up
- Ultra High Impedance
- Ultra Low 1/f noise
- Ten Decade Output Linearity with DC light inputs

Diffused Series						
	SPECTRAL RESPONSE	AREA (cm ²)	TO-18 DIAMETER (mm)	SENSITIVITY (A/W)	RESPONSE TIME (ns)	NOISE (pA/√Hz)
PIN-10	350-900 nm	0.5	5.0	100	100	1.0
PIN-15	350-900 nm	1.0	5.0	100	100	1.0
PIN-20	350-900 nm	1.0	5.0	100	100	1.0
PIN-25	350-900 nm	1.0	5.0	100	100	1.0
PIN-30	350-900 nm	1.0	5.0	100	100	1.0
PIN-35	350-900 nm	1.0	5.0	100	100	1.0
PIN-40	350-900 nm	1.0	5.0	100	100	1.0
PIN-45	350-900 nm	1.0	5.0	100	100	1.0
PIN-50	350-900 nm	1.0	5.0	100	100	1.0
PIN-55	350-900 nm	1.0	5.0	100	100	1.0
PIN-60	350-900 nm	1.0	5.0	100	100	1.0
PIN-65	350-900 nm	1.0	5.0	100	100	1.0
PIN-70	350-900 nm	1.0	5.0	100	100	1.0
PIN-75	350-900 nm	1.0	5.0	100	100	1.0
PIN-80	350-900 nm	1.0	5.0	100	100	1.0
PIN-85	350-900 nm	1.0	5.0	100	100	1.0
PIN-90	350-900 nm	1.0	5.0	100	100	1.0
PIN-95	350-900 nm	1.0	5.0	100	100	1.0
PIN-100	350-900 nm	1.0	5.0	100	100	1.0

"DP" Series						
	SPECTRAL RESPONSE	AREA (cm ²)	TO-18 DIAMETER (mm)	SENSITIVITY (A/W)	RESPONSE TIME (ns)	NOISE (pA/√Hz)
PIN-10	350-900 nm	0.5	5.0	100	100	1.0
PIN-15	350-900 nm	1.0	5.0	100	100	1.0
PIN-20	350-900 nm	1.0	5.0	100	100	1.0
PIN-25	350-900 nm	1.0	5.0	100	100	1.0
PIN-30	350-900 nm	1.0	5.0	100	100	1.0
PIN-35	350-900 nm	1.0	5.0	100	100	1.0
PIN-40	350-900 nm	1.0	5.0	100	100	1.0
PIN-45	350-900 nm	1.0	5.0	100	100	1.0
PIN-50	350-900 nm	1.0	5.0	100	100	1.0
PIN-55	350-900 nm	1.0	5.0	100	100	1.0
PIN-60	350-900 nm	1.0	5.0	100	100	1.0
PIN-65	350-900 nm	1.0	5.0	100	100	1.0
PIN-70	350-900 nm	1.0	5.0	100	100	1.0
PIN-75	350-900 nm	1.0	5.0	100	100	1.0
PIN-80	350-900 nm	1.0	5.0	100	100	1.0
PIN-85	350-900 nm	1.0	5.0	100	100	1.0
PIN-90	350-900 nm	1.0	5.0	100	100	1.0
PIN-95	350-900 nm	1.0	5.0	100	100	1.0
PIN-100	350-900 nm	1.0	5.0	100	100	1.0

POSITION SENSING

The position sensing series offers single axis or dual axis position sensing detectors. The spot series offers two and four element detectors for nulling position sensing.

Position Sensing Series					
	SPECTRAL RESPONSE	ACTIVE AREA (mm ²)	RES. (mm)	LINEARITY (% F.S.D.)	ACTIVE AREA (mm ²)
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-SPOT	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm

ARRAY SERIES

Single and Dual Axis arrays with center to center spacings from 0.002" to 0.500". Multiple chip or monolithic construction to 10" in length. A wide variety of mounting schemes are available.

Array Series					
	SPECTRAL RESPONSE	ACTIVE AREA (mm ²)	RES. (mm)	LINEARITY (% F.S.D.)	ACTIVE AREA (mm ²)
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-ARRAY	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm

CALIBRATED SERIES

Provides a fast, convenient, and accurate standard traceable to NBS for photometric and radiometric measurements. Calibration stability is better than 2 percent over a 6 month period.

Calibrated Series					
	SPECTRAL RESPONSE	ACTIVE AREA (mm ²)	RES. (mm)	LINEARITY (% F.S.D.)	ACTIVE AREA (mm ²)
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-CAL	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm

DETECTOR/FILTER COMBOS

These units feature a computer designed, spectrally matched detector / filter. The PIN-10DF has a flat spectral response from 4500A to 9500A. The PIN-10AP has a photopic "eye response." The PIN-10RP is spectrally matched to the photopic eye curve to 2% between 5800A and 7300A for LED measurement.

Photodiode/Filter Series					
	SPECTRAL RESPONSE	ACTIVE AREA (mm ²)	RES. (mm)	LINEARITY (% F.S.D.)	ACTIVE AREA (mm ²)
PIN-10DF	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10AP	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10RP	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10DF	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10AP	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10RP	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10DF	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10AP	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10RP	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
PIN-10DF	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm

PHOTOPS™

The PHOTOPS™ (Photodiode/Amplifier Combinations) are light to voltage converters. They combine a high reliability PIN Silicon Photodiode and a low noise current mode operational amplifier in the same package. The PHOTOPS™ Series utilizes FET technology and hybrid packaging to increase signal to noise ratio. The advantages of photomultipliers are now available in solid state device capable of detecting light over nine decades from 10⁻¹² watts/cm² to 10⁻³ watts/cm².

PHOTOPS™ are low impedance devices and may be used to directly drive analog meters, chart recorders or digital displays.

UDT PHOTOP™ 450 is a general purpose op/amp detector combination in a TO-5 package. The detector active area is .051CM².

UDT PHOTOP™ 500 is a large area 1CM² detector with a low noise operational amplifier. Sensitivity of this device is 10⁻³ watts to 10⁻¹² watts.

UDT PHOTOP™ 600 is a high speed detector/amplifier with a light response to 10 Megahertz. This is a high speed device in a TO-5 package.

Photodiode/Op Amp Series

	SPECTRAL RESPONSE	ACTIVE AREA (mm ²)	RES. (mm)	LINEARITY (% F.S.D.)	ACTIVE AREA (mm ²)
UDT-450	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-500	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-600	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-450	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-500	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-600	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-450	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-500	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-600	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm
UDT-450	Schottky	104	5 - 10 ⁻¹²	200	1" x 0.125 mm

SPECIALS

The Schottky and planar diffused technologies employed by United Detector Technology are very readily adaptable to new geometries and to modified characteristics. Geometries possible include lengths to 10", widths to 1", diameters to 2".

UNITED DETECTOR TECHNOLOGY, INC.
2644 30TH STREET, SANTA MONICA, CA 90405 • TELEPHONE (213) 386-3175 • TELEX 65-2413

LMS 50/100/250 SERIES

HIGH-PERFORMANCE LINEAR ENCODERS

DYNAMICS RESEARCH CORPORATION

GENERAL DESCRIPTION

The LMS 50/100/250 Series are high-resolution, high-precision, linear encoders with resolutions up to 50 micrometers and accuracies up to 50 $\mu\text{m}/\text{ft}$. Metric versions are also available with resolutions up to 1 micron. These encoders consist of a precision scale and a non-contacting optical/electronic reading head. The scale, up to 52 inches in length, is finely divided into thousands of vertical, parallel lines, which are vacuum-deposited Inconel on transparent glass — our exclusive Metrifilm™ process. The read head translates linear motion into TTL-compatible, quadrature square waves for bi-directional sensing.

Applications of this system include precision inspection and quality control equipment, PC board and microcircuit artwork generation, X-Y plotting tables, as well as closed-loop NC systems associated with precision metal-working machining centers.

OPERATION

The unique technique employed with the LMS 50/100/250 Series consists of using a collimated light source to optically superimpose one portion of scale rulings over another to produce an interference pattern which is detected by Silicon photocells. Since the imaged lines move in the opposite direction to the scale, the effect is to optically double the number of scale lines sensed. Additionally, this optical system makes the orientation of the scale to head virtually immune to pitch, and noncritical to gap variation — this results in easy alignment.

With the aid of external X4 logic, the ultimate count, in the case of the LMS-100 and LMS-250, is 8 times the number of scale lines sensed. In the case of the LMS-50, there is, in addition, a stage of electronic frequency doubling which produces an ultimate resolution of 16 times the number of scale lines sensed.

Sophisticated technology, equipment and facilities are key factors in producing the ultra high precision accuracy linear scales of superior quality for the LMS 50/100/250 Series. Masters are generated on a CNC designed, numerically controlled, linear ruling engine equipped with laser interferometer feed back. The transfer of these fine graduations from master to glass scale (our Metrifilm™ process) is accomplished via vacuum deposition using Inconel. Environmentally controlled, clean room facilities are used throughout in process and final inspection is performed with measuring equipment traceable to the National Bureau of Standards.

SELECTION CRITERIA

	Head Assy	Scale Density (Lines/mm)	Resolution (Cycles/mm)	Resolution (μ m)	Accuracy (μ m/25.4cm)
LMS-50	L-50	1250	5000	50	50
LMS-100	L-3	1250	2500	100	100
LMS-250	L-3	600	1000	250	250
		(Lines/mm)	(Cycles/mm)	(μ m)	(μ m/25.4cm)
LMS-1M	L-30	62.5	250	?	1.25
LMS-2M	L-3	62.5	125	?	2.5
LMS-5M	L-3	25.0	50	?	2.5

Note 1: Scales are provided as one-piece section, and reading lengths are selectable in increments of 1 inch up to 50 inches for English systems and in increments of 1 cm up to 127 cm for Metric systems. Add 2 inches to overall reading length requirement to accommodate encoder head sensing area.

Note 2: Indicated resolution is attained when encoder output is fed into external X4 logic circuitry.

SPECIFICATIONS**Electrical**

Signal: Two-Channel, Quadrature Waveform

Stow Rate: LMS-50 and LMS-100: 30 in./sec

LMS-250: 60 in./sec

Levels: Logic 0: 0.4 VDC max.

Logic 1: 3.5 VDC min.

Rise Time: 1 μ sec (10% to 90%)

Interchannel Phasing: 90 $\pm$ 45 electrical degrees

Excitation: $\pm$ 5.5 VDC $\pm$ 2% $\geq$ 250mA

5.5 VDC $\pm$ 2% @ 100mA

Output: LMS-50: IC pins with 51 ohm series
put impedance, short-circuit and
reverse voltage protection.

LMS-100 and LMS-250: IC pins
with 150 ohm output impedance,
short circuit protection.

ORDERING INFORMATION **DYNAMICS RESEARCH CORPORATION**

COMPONENTS DIVISION/50 CONCORD STREET, WILMINGTON, MASS. 01887
PHONE: (617) 658-6100 or (617) 438-3900/TWX (710) 347-0291

control thru measurement

STAR GIMBAL MOUNTS

burleigh

FEATURES:

- ☐ Stainless steel or aluminum construction
- ☐ Uniframe structure
- ☐ True orthogonal, gimbal motion
- ☐ No backlash, dual torsion spring coupling
- ☐ Large aperture at 45°
- ☐ Unique gimbal ring lock screws
- ☐ Superior thermal and mechanical stability
- ☐ Frame mounted micrometer heads
- ☐ Optical Erector Set components
- ☐ 360° mirror cup rotation
- ☐ PZT alignment accessories
- ☐ Multiple optical axis heights
- ☐ Smooth, shake-free motion

Burleigh's exclusive Star Gimbal is a new approach to laboratory mounting of optics and mirrors. We call it a Star Gimbal because the gimbal ring flanges resemble the points of a star, it's a functional design that results in many features not found in conventional mirror or gimbal mount designs.

For instance, All movable elements are mounted in one frame for superior mechanical stability. The new, dual balanced, torsion springs provide intimate mic head to gimbal ring contact. You get unique gimbal ring locks to prevent misalignment. And there are both micrometer and optional piezoelectric tilt adjusters.

Other features include true gimballed, orthogonal motion and stainless steel or aluminum models. All stainless steel is offered for critical tasks where thermal angular drift can't be tolerated.

Add the Star Gimbal mount to our Optical Erector Set. It offers you the advantage of your own model shop right in your laboratory cabinet. To construct many types of optical frameworks, just use the exclusive Rod Mounting Plates and the precision, centerless ground stainless steel or Invar Rods with our Star Gimbals and other components. Form laser cavities or laser amplifier systems, in seconds. The structure is rigid and stable.

Burleigh Instruments, Inc., 100 Despatch Drive, PO Box 388, East Rochester, New York 14445 / (716) 586-7930

SG SERIES STAR GIMBAL MOUNTS

The SG series mounts are available in stainless steel or aluminum. The all stainless steel model SG-201 includes stainless steel micrometers. A feature only we offer. This model has superior thermal performance. There are no dissimilar materials to cause differential thermal expansion with resultant angular drift. The stainless steel has excellent strength characteristics giving the unit its exceptional mechanical stability.

Both models offer the unique unit-frame construction. The gimbal rings and micrometers are held in one solid structure. This results in better mechanical stability than open frame construction.

All models are true gimbals with orthogonal angular adjustments. True gimbal mounts let you tilt your mirror without displacement of the mirror center.

The SG series uses our unique dual torsion spring coupling. These springs are specially balanced and located right at the axes of rotation. They provide solid, positive contact between the mic heads and gimbal rings. The torsion springs eliminate mic head thread backlash and allow 1 sec setability repeatedly and accurately. The mic heads contact chrome plated drive pads. The face of the drive pad is polished to a 10 micro-inch finish. This smooth interface allows the tip of the mic head to move easily over the face of the pad. The result is smooth motion and greater setability.

Optional PZT Pushers let you set to .01 sec or better. Nylon-tipped, spring loaded set screws assure intimate contact between the micrometers and the PZT Pushers. The spring loading and the torsion spring coupling can be combined to give the gimbal mounts superior stability. Our gimbals are the only ones to give you this double stabilizing feature. And we provide two non-misalignment features. The micrometers can be locked with their integral lock nuts. Or the set screws can be run-in until they bottom to lock the gimbal rings. Or if you want, use both.

Mounting is fast and safe. The optics are held in individual cups without distortion with a delrin retainer. The cups rotate 360° about the optical axis for added versatility. And the cups clamp firmly in the inner gimbal ring with our threaded clamp. Diameters up to 50.8mm can be mounted.

The compact profile of the Star gimbal means a full .75" usable aperture at 45°. And micrometer placement is above the optical axis. So you can make tilt adjustments safely and easily.

Use our SG-305 or SG-306 bases to set the SG series on your table or rail. Or use the 6-32 clearance holes in the Star Gimbal frame to mount to other components like our Erector Set Rod Plate.

The SG Series Star Gimbals directly accept our new PZT Aligner/Translators. Use the PZAT's for piezoelectric angular deflection or tilt-free translation of your optic.

HOW IT WORKS

The main frame of the Star Gimbal has two clearance holes for the micrometers, a large hole for the gimbal rings and a flange to carry the outer gimbal ring. The rectangular shape allows four orientations of the frame for four optical axis heights.

Each gimbal ring has two flanges offset 180°. The outer gimbal ring pivots about a vertical axis inside the frame. The inner gimbal ring pivots about a horizontal axis inside the outer gimbal ring. Point of intersection of the two axes is exactly at the center of the mirror surface for pure rotation about that point.

The upper (large) flanges of the gimbal rings hold chrome plated drive pads. The pads contact the frame mounted micrometers and are secured with retaining nuts. This holding scheme allows quick and easy removal. The shanks of the micrometer are threaded to allow retaining nuts to firmly hold the micrometers in the frame, and still offer removability. For super-sensitive adjustments, optional PZT Pushers replace the pads, and mount the same way.

The lower (shorter) flanges of the gimbal rings accept nylon-tipped, spring-loaded set screws. In normal operation with torsion spring coupling, the set screws are not needed. They can be used for superior antivibration resistance. Bottoming these screws will lock the gimbal rings in place.

Our exclusive dual balanced torsion spring coupling is unique. Located right at the axes of rotation, these springs provide positive contact between the gimbal rings and the mic heads. These springs eliminate backlash of the threads of the mic heads. Increase working life of the Star Gimbal. Enhance setability and stability.

The face of the drive pad in the gimbal rings is polished to a 10 micro-inch finish. This smooth interface allows the tip of the mic head to move easily over the face of the pad. The result is smooth motion and greater setability.

The gimbal rings pivot in solid, oil-impregnated bronze bushings. These bushings are important to achieving the smooth, shake-free and stable operation of the SG series gimbal mounts. The optics are mounted in a separate mirror cup to reduce the dangers of handling. Select stainless steel or aluminum to match the Star Gimbal. For distortionless holding in the cup, the optics are secured with a threaded delrin retainer. The cup inserts in the inner gimbal ring and is

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clamped with a threaded clamp ring. The mirror cup rotates 360° around the optical axis.

The rectangular frame holding the gimbal rings can be mounted in any of four orientations. Used alone you can have optical axis heights of 1½", 2", 2½", or 2¾". With the mounting base you get a height of 2¾". Use the mounting base for convenient mounting to your table or rail. The base hole pattern is four ¼-20 clearance holes on a 2" square hole pattern. Choose an aluminum or stainless mounting base to match the gimbal mount.

SG-101 or SG-201

SG-305 or SG-308

SPECIFICATIONS

STAR GIMBAL MOUNT		Model SG-101	Model SG-201
type		orthogonal, gimbal	orthogonal, gimbal
material		aluminum	stainless steel
adjustments	standard optional	steel mic heads piezoelectric plus steel micrometer heads	stainless steel mic heads piezoelectric plus stainless steel micrometer heads
total tilt	micrometers optional piezoelectric	12" up to 100 sec.	12" up to 100 sec.
optic mounting		individual aluminum mirror cups	individual stainless steel mirror cups
free aperture	normal 45°	43mm max. 18mm max.	43mm max. 18mm max.
gimbal locking	micrometers ring	lock nut set screws	lock nut set screws
mirror cup rotation		360°	360°
readouts	micrometers mirror cup	.001" 5"	.001" 5"
	PZT Pushers	voltage to 1 volt	voltage to 1 volt
resolution	micrometers PZT Pushers	1 sec. .01 sec.	1 sec. .01 sec.
optical axis	with base with frame	2½" 1½", 2", 2½", 2¾"	2½" 1½", 2", 2½", 2¾"
MIRROR MOUNT BASE		Model SG-305	Model SG-308
material		aluminum	stainless steel
mounting		four ¼-20 clearance holes on a 2" square hole pattern	four ¼-20 clearance holes on a 2" square hole pattern

OPTICAL ERECTOR KEY COMPONENTS

(See Optical Erector for data sheet or brief description on last page of this data sheet.)

PZT PUSHER		Model PZ-30	Model PZ-40
mounting		replaces drive pad in gimbal ring	replaces drive pad in gimbal ring
motion		5.5µm/1000 volts	15µm/1000 volts
(See PZT Pusher data sheet for complete details.)			
PZT ALIGNER/TRANSLATOR		Model PZ-81	Model PZ-81
motion sensitivity		.006µm/v	.0025µm/v
motion for 0-1250v		10µm	3µm
angular sensitivity		.1 arcsec/v	.062 arcsec/v

PRICE INFORMATION

Model No.	Description	Price
SG-101	Aluminum Star Gimbal including mirror cup and clamp ring.	
SG-201	Stainless Steel Gimbal including mirror cup and clamp ring.	
SG-305	Aluminum mounting base.	
SG-308	Stainless steel mounting base.	
SG-309	Rod Plate.	
SG-401	Aluminum Mirror Cup for 50.8mm diameter mirrors. No clamp ring.	
SG-402	Stainless steel Mirror Cup for 50.8mm dia. mirrors. No clamp ring.	
SG-403	Clamp Ring.	
SG-500-A	Aluminum adaptor for 25.4mm or 38.1mm diameter mirrors. Includes delrin retainer.	
SG-501-A	Stainless steel adaptors for 25.4mm or 38.1mm diameter mirrors. Includes delrin retainer. (Specify 25.4 or 38.1mm diameter by substituting for "A")	
SG-105	SG-101 Star Gimbal with two PZ-30's	
SG-108	SG-101 Star Gimbal with two PZ-40's	
SG-205	SG-201 Star Gimbal with two PZ-30's	
SG-208	SG-201 Star Gimbal with two PZ-40's	
PZ-30	PZT Pusher with connector and cable. 5.5 µm/1000v motion.	
PZ-40	PZT Pusher with connector and cable. 15µm/1000v motion.	
PZ-80	PZT Aligner/Translator. 10µm/1250v motion.	
PZ-81	PZT Aligner/Translator. 3µm/1250v motion.	
PZ-60	PZT Aligner/Translator. 10µm/1250v motion.	
PZ-91	PZT Aligner/Translator. 3µm/1250v motion.	
PZ-60-101	PZ-60 and SG-101	
PZ-81-101	PZ-81 and SG-101	
PZ-80-201	PZ-80 and SG-201	
PZ-81-201	PZ-81 and SG-201	
PZ-40-101	PZ-40 and SG-101	
PZ-91-101	PZ-91 and SG-101	
PZ-40-201	PZ-40 and SG-201	
PZ-91-201	PZ-91 and SG-201	

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INCHWORM**burleigh** **FEATURES:**

- ☐ 6nm resolution of travel anywhere within 25mm travel
- ☐ Backlash free
- ☐ All electronically controlled piezoelectric motion
- ☐ Computer interface compatibility
- ☐ Works over large temperature ranges
- ☐ Works in vacuum
- ☐ Easy to mount in $\frac{1}{4}$ " clearance hole
- ☐ Compact
- ☐ Pushes large loads
- ☐ 20mm/minute to .3 m/minute speed range
- ☐ Clearance compensation adjust
- ☐ No mechanical parts to wear
- ☐ No gears or threads

APPLICATIONS:

- ☐ Position optical elements
- ☐ Scan interferometers
- ☐ Drive translation stages
- ☐ Implant electrodes
- ☐ Position components in vacuum
- ☐ Scribe integrated circuits

Our PZ-500 Inchworm* gives you 25mm motion with resolution as fine as .006 μ m. Invar and Alumino-Silicate ceramic give mechanical and thermal stability. The Inchworm is backlash-free and pushes loads up to 5 lbs. Three PZT cylinders operate in a programmed manner, moving a precision honed shaft relative to the housing. Select speed from .3 μ m/minute to 20mm/minute. Mounts conveniently like any standard mic head.

The PZ-501 Inchworm Controller* drives one PZ-500, the PZ-503 drives up to three. Controllers have internal circuitry for manual or auto run modes. You can use either model to slave the Inchworm to a small computer to program your own motion.

Our Inchworm is ideal for high resolution travel over long distances. Use it to replace stepper motors in many applications. It operates over a wide temperature range. And in a vacuum.

*Patents Pending.

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INCHWORM

Our PZ-500 Inchworm is an electro-mechanical actuator. It's small and compact—about the size and configuration of a standard micrometer head. A low expansion invar-spindle, keyed to prevent rotation, moves relative to the housing. The motion is completely piezoelectric. So there are no threads or gears to worry about. The Inchworm is reliable, works anywhere in any number of tasks.

Total travel of the spindle is 25mm. When operating with our Inchworm Controller, the spindle tip translates in discrete steps of 6nm. Step rate is variable from one per second to 220,000 per second. The speed of our Inchworm is variable from 0.3mm/minute to 20mm/minute when you account for all the steps in a complete cycle.

The inchworm mounts in a $\frac{1}{8}$ " clearance hole. It can be used for many remote positioning and alignment applications. It's easy to align interferometers, implant electrodes or position elements in spacecraft or in vacuum chambers. The resolution of the Inchworm exceeds practically all known requirements and the speed is variable over more than five decades. Axial loads of up to five pounds can be pushed.

Operation of the Inchworm can be controlled either from the front panel of Burleigh's Inchworm Controllers or from a remote programming source. Simple N.O./N.C. logic inputs to the Controller will govern direction, speed and single step motion.

The Inchworm Controllers incorporate a clearance compensation adjustment. This allows a perfect fit between the PZT elements and the shaft. So you can easily compensate for wear, machining tolerances, dimensional changes due to large temperature changes or axial loads on the Inchworm.

FIGURE 1

HOW IT WORKS

The Inchworm is a compact and easy to use electromechanical actuator that'll give you ultra-precise resolution over large travel. You can expect 6nm resolution anywhere within a 25mm range. Use the Inchworm to replace stepper motors in many applications.

The Inchworm uses three coupled PZT cylinders as active elements. A precision honed PZT is fixed to a shaft. The fit between the first and third piezoelectric elements and the shaft is essentially zero. The center piezoelectric element is a clearance fit on the shaft. When a voltage of approximately 500 volts is applied to the first piezoelectric element, its ID decreases, causing it to grip the shaft. Then a variable rate staircase voltage available in our Inchworm Controller is applied to the center piezoelectric element, causing it to move in discrete steps of 6nm. The staircase takes 248 steps from its lower to its upper limit. The full range of the staircase voltage moves the third piezoelectric element with respect to the first approximately 0.6mm.

At the 248th step, the Inchworm Controller logic commands a 500-volt signal to be applied to the third piezoelectric element, causing it to grip the shaft, then releases the voltage on the first piezoelectric element, thus loosening its grip on the shaft, then restarts the staircase downward through another 248 steps until it reaches its lower limit, at which point the first clamp is activated again, the third clamp released, the staircase started again and the process repeats over and over (see figure 1).

The stepping rate for the variable rate staircase is approximately one step per second to approximately 220,000 steps per second. The total time duration for the clamps to switch is fixed at 2ms, thus the maximum running speed is approximately 20mm per minute and the minimum running speed is approximately .3um per minute. The Inchworm

Controller can generate single steps on the staircase so that an operator can advance the Inchworm in 6nm steps.

The fit of the PZT cylinder to the shaft can be controlled electronically with the Clearance Compensation feature. The fit change is achieved by applying a bias voltage to the minus input of the piezoelectric elements. This bias is variable with a rear panel control on the Inchworm Controller. This adjustment compensates for wear of the piezoelectric elements on the shaft or for changes in the fit due to gross temperature change. It also helps to control the ability of the Inchworm to push heavy loads.

When the Inchworm reaches either limit of its travel, two internal contacts are shorted. The Inchworm Controller senses the short and automatically shuts down the drive circuitry and turns on an indicator light. Monitoring of the operation of the Controller is simplified by three connectors on the rear panel which carry all-mounted versions of the two clamp voltages and of the variable rate staircase voltage.

MOTION ACCURACY

The Inchworm is designed to operate as smoothly as possible. Single step resolution is 6nm. Continuous motion characteristics are shown in figure 2

FIGURE 2

However, some discontinuities (see figure 3) in the motion may be observed in high resolution applications. When the clamps switch, some motion is imparted to the spindle. This discontinuity can be minimized by experimenting with the Clearance Compensation adjustment to select an optimum setting.

FIGURE 3

Between clamping times, the Inchworm motion is very smooth and resolutions of 6nm can easily be achieved. Because of the discontinuity characteristic, it may be necessary in some circumstances to go beyond a desired position and return to it from the other direction in order to realize the 6nm resolution in every position.

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MOUNTING

Using of the inchworm is straightforward. It mounts in a 1" diameter clearance hole (see Figure 4) with a retaining nut. The inner spindle can be programmed to move relative to the housing. The spindle is keyed to prevent rotation, and has a removable spherical tip. This tip is used when pushing against a spring load. With the tip off, elements can be mounted directly into the 6-32 threaded hole in the end of the spindle. A magnetic coupling can be used with the inner spindle and tip.

FIGURE 4

ENVIRONMENT

The inchworm is warranted for operation only in a normal laboratory environment. However, it is designed to operate in a vacuum and over a wide temperature range. Only low vapor pressure materials are used in the construction of the inchworm: driver, stainless steel, aluminum, ceramic, silver, PVC insulated wires and a low vapor pressure epoxy. Two small holes in the rear shell cover provide adequate ventilation to all internal parts. Provision for venting the cable and for electrical test must be made by the user.

The shell is made of a material with a coefficient of thermal expansion which matches that of the PZT cylinder, insuring a good fit over a wide temperature range. The Clearance Compensation feature can be used to correct for dimensional changes if the coefficients are not perfectly matched. A maximum operating temperature of 75°C is recommended at the user's risk.

INCHWORM CONTROLLERS

Burleigh PZ-501 and PZ-503 Inchworm Controllers are designed to drive Burleigh PZ-500 Inchworms. The PZ-501 Inchworm Controller will drive a single inchworm. The PZ-503 Inchworm Controller has three completely independent channels to drive three inchworms. Driving the inchworms with motion on the inchworm spindle tip of a total of one inch in increments of 6nm.

The inchworm Controller can be used

to program the spindle to move forward or backward, to take single 6nm steps, to move so long as a spring-loaded switch is depressed, or to run automatically until it reaches its limit of travel. At either end limit of its travel, an internal limit switch on the inchworm is triggered and the inchworm Controller automatically shuts down, and turns on an indicator light.

The speed of motion is variable from approximately 3nm per minute to 20nm per minute. All functions can be programmed either by front panel controls or by a remote source with simple N.O./N.C. logic.

The inchworm is actuated with three piezoelectric elements and the inchworm Controller provides a sequence of voltages to drive the inchworm. All of the low voltage circuitry in the inchworm Controller is digital, using TTL logic, simplifying interfacing with computers if the N.O./N.C. remote programming logic is not desired. Outputs are available to replicate all functions of the Controller.

LOCAL OPERATION

With the rear panel slide switch on the controller set to Local, all functions are controlled from the front panel. Flipping the Run switch to the Auto Run position causes the inchworm to run until the Run switch is flipped back or until the inchworm reaches either limit of its travel. When the Run switch is moved to the Manual Run position (which is spring loaded) the inchworm will run as long as the switch is depressed. Below this switch is found a single step switch, which is also spring loaded. Flipping this switch up causes the inchworm Controller to generate a single step on the staircase, thus causing the inchworm to take a 6nm step. Two controls on the top right govern the speed.

With the Speed Toggle switch in the Fast position, the speed can be varied from the top speed of approximately 20nm per minute to approximately 30nm per minute. In the slow position the speed varies from approximately 3nm per minute to 300 nm per minute. The toggle at the bottom of the control section marked Forward and Reverse governs the direction of running. Whenever the inchworm is running, the Run indicator light will be on. Whenever either limit is reached, the controller automatically shuts down and one of the limit indicator lights turns on.

REMOTE OPERATION

With the rear panel slide switch in the Remote position, all functions are controlled at the rear panel input connector with simple N.O./N.C. logic. When a contact is made at the

appropriate pins the inchworm can be made to run, to go in forward or reverse, to change speed or to take a single step. The speed can be varied from one of two settings. This is equivalent to flipping the front panel Speed Toggle switch from Fast to Slow. The two desired speeds of operation must be predetermined and set with the Speed Knob on the front panel. It is not possible to continuously vary the speed in the Remote operation configuration. Some users may wish to interface directly with the TTL logic in the inchworm Controller. This can be done by consulting the circuit diagrams in the test section. Output pins for the TTL logic are not provided at this time.

APPLICATIONS

The inchworm offers 25.4 (1 inch) of electronically controlled travel with 6nm (or equivalently, 0.01 μm or 0.24×10^{-3} inches) resolution. So it's an ideal positioning device: it's a wide range of applications. Never before has a piezoelectric device offered such long travel with so fine a resolution.

Use the inchworm to adjust transducer stages. Or position an element carried directly on the spindle. The unique mechanical construction lets you work at various temperatures and in different environments. And the remote control aspect of the inchworm makes it easy to work in tight, hard-to-get-at places. Or in inaccessible locations—like a vacuum chamber.

Several representative applications are listed below:

- ☐ Scan one mirror of a Michelson interferometer for Fourier transform spectroscopy.
- ☐ Implant electrodes in neurophysiological experiments, eliminating the master/slave hydraulic syringe systems.
- ☐ Position the focus of a lens to less than its resolution limit.
- ☐ Electronically control elements in vacuum chambers, eliminating mechanical lead-throughs.
- ☐ Remotely tune prisms and gratings in tunable lasers and grating spectrometers. Operate closed loop with a small computer.

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SPECIFICATIONS**Inchworm: PZ-500**

Travel	0-25mm
Resolution of Travel	6µm
Speed	0.3µm per minute to 20 mm per minute
Load	5 lbs.
Housing Material	Chrome Plated Stainless Steel
Spindle and Spindle Tip Material	Invar 36
Electrical Connector	Viking Thorcom II TKP07-102
Cable Length	6 feet
Size	(See below.)

Inchworm Controller: PZ-501 or PZ-505

Clamp Voltage No. 1	0 to approx. 550 volts
Clamp Voltage No. 2	0 to approx. 550 volts
Center Voltage	0 to approx. 480 volts in 248 discrete steps
Clamp Duration	When the staircase is running, or when the instrument is in the 'NO RUN' condition, one clamp is always clamped. When the staircase reaches either of its limits, the second clamp clamps in a 1µs period, and the first clamp then releases in a second 1µs period. Thus the total clamp switching time is 2µs. The staircase stepping rate is variable from 1Hz to 220Hz, thus the minimum time for taking 248 steps is approx. 7ms.
Clearance Compensation	Variable from -250v to +250v
Regulation on Staircase Voltage and Bias Voltages	1% for 10% line voltage change
Output Current for Center and Clamp Voltages	10ms, maximum
Limit Switch Common	Ground
Limit Switch Forward	+5 volts
Limit Switch Rear	+5 volts
Line Voltage Requirement	110v, 50/60Hz or 220v, 50/60Hz
Monitor Outputs:	
a. Clamp 1 + 100	100 to 1 attenuation of clamp No. 1 voltage, 0 to 5.5 volts
b. Center + 100	100 to 1 attenuation of variable rate staircase, 0 to 4.8 volts
c. Clamp 2 + 100	100 to 1 attenuation of clamp No. 2 voltage, 0 to 5.5 volts
Type	All solid state, push-pull drive circuitry with TTL low voltage logic
Ripple on center voltage and bias	500mv RMS typical

DELIVERY AND PRICES

Generally you can expect stock to four-week delivery. Consult the factory for exact delivery schedules.

Prices for the PZ-500 Inchworm and the PZ-501 Inchworm Controller are given in the Burleigh price list. Consult it for current costs.

WARRANTY

The Burleigh Inchworm and Inchworm Controllers are warranted against defects in material and workmanship for a period of one year after date of delivery and the return of Burleigh's warranty card. During the warranty period, Burleigh will repair or, at its option, replace parts which prove to be defective when the instrument is returned prepaid to Burleigh Instruments, Inc. The warranty will not apply if the instruments have been damaged by accident, misuse, or as a result of modifications by persons other than Burleigh personnel.

burleigh

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MINIATURE BALL SCREWS

The trend towards miniaturization of many kinds of mechanisms and systems has led Beaver into the development of extremely small, but accurate ball screws. Many of these units are so small that the total weight per assembly is but a few ounces. Lead accuracies, ball diameters, ball groove dimensions, etc., are so small that each unit is handled as a custom built assembly, to specifications even more stringent than are normally applied to ordinary sized ball screws. Hence the designation: "Miniature," used to set this group of ball screws apart from all others.

Beaver Miniature Ball Screws can be made from a variety of materials as needed for both normal and unusual environments, as outer space applications, electronic and magnetic fields and laboratory equipment. Ball return systems are confined within the outer diameter of the nut which is designed as a smooth cylinder to simplify mounting the ball screw assembly.

Load Life—Factors of load and life expectancy are especially critical for miniature ball screws. The adjacent chart can be helpful, as a guide, but it is recommended that Beaver Precision Products be consulted early in any new design to properly match the miniature ball screw to the job at hand.

.125	.031	.110	.015	50	31	300	.317	.312
	.031	.172	.015	50	41	272	.375	.375
.187	.050	.140	.020	50	55	402	.437	.502
	.052	.140	.020	50	56	402	.500	.610
.250	.031	.221	.015	50	50	370	.437	.502
	.050	.221	.020	50	74	440	.500	.502
	.063	.211	.020	50	110	440	.500	.502
	.100	.211	.030	50	110	440	.500	.730
.312	.031	.207	.015	50	57	456	.500	.502
	.050	.272	.020	50	132	805	.500	.750
	.063	.272	.020	50	134	805	.500	.750
	.100	.250	.027	50	150	1030	.700	.850

*Operating loads given for 1,000,000 revolutions.

ACCUDEXTM POSITIONING SYSTEMS

Featuring:

- Precision (x-y) tables
- Rotary tables
- Encoded DC-motor drives
- Hi-speed stepping motor drives
- Numerical tape controls

Introduction

Accudex™ constitutes the largest selection of ultra-precise NC positioning systems available. It is based on the concept that total system capability is an absolute prerequisite to economy and efficiency . . . and was made possible through Aerotech's unique blend of engineering and application experience. The versatile line includes production fabricated

tables, drives and numerical controls which are designed to permit expansion, in component fashion, from the most basic to extremely complex systems with little or no alteration.

This brochure describes the Accudex approach and discusses linear (x-y) and rotary tables, stepping motors and DC encoded servo drives and NC punched tape systems. Con-

venient cross-reference specification tables are provided for personalized customer-selected system building.

The need for reasonably-priced automatic positioning systems has been apparent for many years, and Accudex fills this need. Now, Aerotech is ready to help with your immediate or long-range applications.

ACCUDEX™ Positioning Tables

ATS301M Translation Stage

The Model ATS301M Linear Translation Stage offers quick and accurate positioning utilizing stepping motors. Linear position accuracy and repeatability is assured by employing an ultra-precise ground lead screw. Dynamic stability and excellent runout are controlled by high-quality linear roller bearings. Motors to drive this system may be selected from 200 or 2000 step-per-revolution models rang-

ing from 20 to 65 oz-in of torque. For maximum flexibility, the ATS301M is available in either an English or Metric version.

ATS301MR Rotary Translation Stage

The Model ATS301MR Rotary Translation Stage offers quick and accurate angular positioning utilizing stepping motors. Position accuracy and repeatability is assured by employing an ultra-precise worm drive mechanism. Dynamic stability and minimum wobble are maintained by a dual high-quality ball bearing support system. Motors to drive this unit are 200

step-per-revolution models ranging from 20 to 65 oz-in of torque. The ATS301MR Stage can be adapted to

any of the one- and two-inch linear models to complete a multi-axis automatic positioning system.

Hi-Speed (x-y) Tables

The Aerotech Hi-Speed (x-y) Linear Positioning Tables combine precise (x-y) positioning capability, with excellent dynamic performance and slewing speeds of up to 900 inches per minute.

These rugged, backlash-free systems utilize precision, low-friction, linear roller bearings and feature hard-mounted preloaded ball screw drive assemblies.

Accudex (x-y) tables may be driven

by a variety of stepping or DC torque motors and for maximum flexibility are available in either English or Metric versions, single- or double-axis configuration.

AT8312RM Heavy-Duty Rotary Table

The Aerotech Accudex AT8312RM Rotary Table offers the rotational capability for heavy-duty multi-axis positioning systems and is a valuable accessory for automated operations. Position accuracy and repeatability are assured by using an ultra-precision worm drive mechanism. Dynamic stability and minimum wobble are maintained by a dual high-quality ball bearing system. Motors to drive this table may be selected from a stepping

or DC variety ranging from 200 to 450 oz-in. of torque. The AT8312RM may be adapted to any of the Accudex Hi-Speed Linear Tables and can be operated in a vertical or horizontal position.

Specifications ACCUDEXTM Tables

MODEL (ATSI)	301M	302M	301N	302N	304 (x-y)	306 (x-y)	310 (x-y)	312 (x-y)
RANGE	1 inch	2 inches	360° Continuous	360° Continuous	4" x 4"	6" x 6"	10" x 10"	22" x 22"
RESOLUTION	200 Steps/Rev. 400 Steps/Rev. 2000 Steps/Rev. 4000 Steps/Rev.	0.001 inches/step .0005 inches/step 0.0001 inches/step Not Available	2 arc min/ 1/16 arc min 1 arc min/ 1/16 arc min	1 arc minute 1/16 arc minute	0.01 inches/step 0.001 inches/step 0.0005 inches/step	0.01 inches/step 0.001 inches/step 0.0005 inches/step	0.01 inches/step 0.001 inches/step 0.0005 inches/step	0.01 inches/step 0.001 inches/step 0.0005 inches/step
Minimum Lead Screw Pitch	50	50	50	50	50	50	50	50
Minimum Lead Screw Pitch	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm
Motor Range	25 mm	25 mm	25 mm	25 mm	18cm x 10cm	18cm x 10cm	25cm x 25cm	50cm x 50cm
Motor Resolution	500 Steps/Rev.	2 microns/step	2 microns/step	2 microns/step	2 microns/step	2 microns/step	2 microns/step	2 microns/step
Accuracy (load after accumulation)	0.001 inches	0.001 inches	3 arc minutes	3 arc minutes	0.001 inches	0.001 inches	0.001 inches	0.001 inches
Maximum Step Speed	2000 steps/second	2000 steps/second	2000 steps/second	2000 steps/second	800 inches/min	800 inches/min	800 inches/min	600 inches/min
Repeatability (unidirectional)	0.00025 inches	0.00025 inches	2 arc minutes	2 arc minutes	0.0005 inches	0.0005 inches	0.0005 inches	0.0005 inches
Stiffness of Travel	0.001 inch/inch	0.001 inch/inch	0.001 inch/inch	0.001 inch/inch	15 micro/inch	15 micro/inch	20 micro/inch	20 micro/inch
Flatness of Travel	0.001 inch/inch	0.001 inch/inch	0.001 inch/inch	0.001 inch/inch	15 micro/inch	15 micro/inch	20 micro/inch	20 micro/inch
X-Y Orthogonality	10 arc seconds	10 arc seconds	10 arc seconds	10 arc seconds	10 arc seconds	10 arc seconds	10 arc seconds	10 arc seconds
Table Top Diameter	4 inches	4 inches	12 inches	12 inches	10 inches	10 inches	10 inches	10 inches
Load Capacity	Horizontal 100 lbs.	Horizontal 20 lbs.	Vertical 25 lbs.	Vertical 25 lbs.	250 lbs.	600 lbs.	750 lbs.	1000 lbs.
Clear Through Aperture	2 in x 3 in (net)	1 1/2" (net)	1 1/2" (net)	1 1/2" (net)	8" x 8"	8" x 8"	14" x 14"	None
Grip	8" x 8" x 1 1/2"	8" x 8" x 1 1/2"	8" x 8" x 1 1/2"	8" x 8" x 1 1/2"	12" x 12" x 5"	12" x 12" x 5"	20" x 20" x 1 1/4"	34" x 34" x 1 1/4"
Weight (table only)	5 lbs.	5 lbs.	5 lbs.	5 lbs.	60 lbs.	65 lbs.	300 lbs.	1500 lbs.
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Finish	Black Anodize	Black Anodize	Black Anodize	Black Anodize	Black Anodize	Black Anodize	Black Anodize	Black Anodize
Vacuum Capability**	10-6 Torr	10-6 Torr	10-6 Torr	10-6 Torr	10-6 Torr	10-6 Torr	10-6 Torr	10-6 Torr
Drive System Compatibility	ASM100-1, ASM100-2, ASM100-3	ASM100-1, ASM100-2, ASM100-3	ASM100-1, ASM100-2, ASM100-3	ASM100-1, ASM100-2, ASM100-3	ASM100-2 or DCC-20K	ASM100-2 or DCC-20K	ASM100-2 or DCC-20K	ASM100-2 or DCC-20K

12 micro/inch optional **optional ***10 arc seconds optional

Linear Roller Bearing and Ball Screw Life

All Accudex Hi-Speed (x-y) Tables are designed to operate for 100 million inches of travel in excess of 15 inches per second.

C = Dynamic capacity (calculated for 10 million inches of travel)
P = Actual applied load

ACCUDEX™ Drive Systems

ASM100-1 Stepping Motor Drive

Offering the latest design in stepping motor drive systems, the Mod-1 ASM100-1 features self-contained logic for all local and remote controls. This controller, primarily designed to drive the lower speed (300 steps per second maximum) ATS301M and ATS301MR Translation Stages, can be used with any Sio-Syn SS-25 or equivalent stepping motor. For added flexibility, options for the ASM100-1 can be interfaced to a digital computer or tape reader programming system.

The ASM100-1 contains a translator card offering 1/2- and full-step control, power supply and terminal strip hook-up for motor and power leads. Local

controls (slew-jog, forward-reverse, local-remote and limit switches) can be wired to the board through the 12-pin connector provided with the system. The translator card is available separately for OEM applications. The system options include a ruggedly-designed aluminum housing with local controls and a full line of digital position readouts.

Three-axis control chassis with local controls and digital readout.

5 1/2-Digit Up-Down Counter Model ABC100

The Aerotech 5 1/2-digit Bi-directional Counter features buffer storage, magnitude, sign display and a 1014KHz counting range. The counter is de-

signed for use with the Accudex drives for OEM applications and is particularly suitable for accumulating pulses from bi-directional encoders. The ABC100's additional features include an overrange indicator, BCD output, lamp test input and a 1/2-stop accumulator.

ASM100-2 Hi-Speed Buffered Stepping Motor Drive

The ASM100-2 Hi-Speed Buffered Stepping Motor Drive System is a high-powered, all solid-state unit designed to run four- or eight-phase, 200 step-per-revolution stepping motors. It contains an adjustable ramping control card, power supply and power translator assembly that can be operated either in a 1/2- or full-step mode. This unit is housed in a standard 7-inch rack mount chassis. The ASM100-2 is compatible with ATS304-322 Series (x-y) Translation Tables and will drive them to speeds of from 2000 to 5000 steps per second.

OPTIONS

5-digit absolute/incremental (thumb-wheel) indexers
Digital position display
Local controls (slew-jog, forward-reverse and local-remote)
Homing circuit logic

DCC-20K Encoded DC Motor Drive

The DCC-20K Encoded DC Motor Drive System provides high-speed, ultra-smooth, resonance-free performance at any speed from 0 to 20,000 steps per second. Employed with the Aerotech Accudex (x-y) Positioning Tables, this high-performance controller is unequalled in stability and response.

The System consists of a DC torque motor, DC tachometer, optical encoder and all solid-state driver electronics which can operate in a 200 or 400 pulse-per-revolution mode. The DCC-20K is housed in a standard 7-inch high rack mount chassis. This unit is compatible with Accudex ATS304-322 Series (x-y) Translation Tables and will drive them to a maximum speed of 15,000 steps per second.

OPTIONS

5-digit absolute/incremental (thumb-wheel) indexers
Digital position display
Local controls (slew-jog, forward-reverse and local-remote)
Homing circuit logic

Specifications ACCUDEx™ Drives

Access Curve DCC-20K vs. ASM100-2 Drive

Shown is actual data taken from an Accudex ATS304 (x-y) Translation Stage using sequentially ASM100-2 and DCC-20K drives. Curve indicates total access time including settling.

MODEL	ASM100-1	ASM100-2	ASM100-3	DCC-20K	DCC-20K-1
Maximum Speed	300 steps/sec	5000 steps/sec	650 steps/sec	20,000 steps/sec	50,000 steps/sec
Step Selection/ Revolution	200 and 400			200 or 400	2000 or 4000
Drive Torque	40 in-oz	150 to 450 in-oz	80 in-oz	250 in-oz Peak	250 in-oz Peak
Step Size	1.8 or .9°/step				18 or .09°/step
Control Type	Open Loop			Closed Loop	
External Inputs	Clock (TTL Compatible, 10 micro second minimum pulse width) Direction Logic 1 = CW Logic 0 = CCW				
Outputs	Index Complete (TTL Logic 1)		Index Complete (TTL Logic 1)		
Internal Protection	Power Supply Current Limited with In-line Major Fuses				
Ramping Control	None	Adjustable to suit motor characteristics and loading	None	None	None
Accudex™ Table Compatibility	301M 302M 301RM	301M 304 (x-y) 302M 306 (x-y) 301RM 310 (x-y) 312R 322 (x-y)	301M 302M 301RM	312R 304 (x-y) 306 (x-y) 310 (x-y) 322 (x-y)	312R 304 (x-y) 306 (x-y) 310 (x-y) 322 (x-y)
Enclosures Available	Equipment Case or Optional Rack Mount		19" wide x 7" high x 18" deep Rack Mount Chassis		
Options	5-Digit Up-down Counter 5-Digit Absolute/Incremental (Thumbwheel) Indexer Linear Encoder Feed Back			Homing Circuits Local Controls (Slew-Jog, Fwd-Rev Local-Remote) Tape Reader and Computer Interface Home Offset (Thumbwheel) Control

NC100 Numerical Tape Controls

Standard Features:

- Advanced C/MOS-MSI circuitry
- Modular construction
- Provisions for remote control
- Absolute/incremental sign and magnitude dimensioning
- Local controls (slew-jog, forward-reverse and feed rate)
- 5-digit thumbwheel data entry
- One- to six-axis indexer control
- ASCII coding with variable block word address format
- 125 cps photoelectric tape reader with drop box
- Emergency shutdown switch with provisions for external interlock
- Deletion of leading or trailing zeros for minimum tape length
- Automatic homing
- Automatic rewind
- Step-only interlock
- Tape position or tape command display
- Axis enable/disable controls
- Secondary storage for tape command to maximize system speed
- Block-by-block or byte-by-byte operation for diagnostic purposes
- Odd or even parity check

Options:

- M function decoder and matrix (20 of 100) with relay closure outputs
- Programmable feed rate generator (20 discrete rates)
- Programmable position output pulse
- Block search
- Auto-start from "in position" signal in tape mode
- 300 character/sec tape readers
- EIA code converter
- Home position (thumbwheel) offset
- Dwelt timers
- Mirror image

HOME—In the Home mode, the axis will drive to a position preset by means of movable mechanical assemblies located on the X and Y axis.

MANUAL INDEX—In the Manual Index mode, axis movement is controlled by means of the X and Y thumbwheel control switches. The command set in the thumbwheel switches may be a position or increment.

MANUAL—In the Manual mode, the axis may be moved by means of the step and slew controls (see step and slew).

TAPE—In the Tape mode axis movement, absolute or incremental, is controlled by data on the paper tape.

BLOCK SEARCH—Will cause the tape to advance to the block number set into the three-digit thumbwheel switch located under the block number display. When the block search function is performed, the block of data selected will not be activated until the start command is given.

BLOCK DELETE—Causes the tape control to pass over any block of data that has the block delete code in it.

REWIND—The rewind function causes the paper tape to rewind to the beginning of the tape, then read and execute the first block of data.

START—The start switch will only function in the Manual Index and Tape modes. In the Manual Index mode, a start command will cause the axis to go to a position, or increment, as preset by the X and Y axis thumbwheel switches. In the Tape mode, the axis will execute the function in storage and advance the tape one block of data.

RESET—The reset switch, when energized, causes the point at which the "X" and "Y" axis are positioned, at the time the reset switch is energized to become the origin for the Cartesian coordinates over which the X and Y axis may be moved. The reset function also clears all storage and resets the drive packages.

STEP—When the tape control chassis is in the Manual mode, activating the step switch will cause the axis to move one-thousandth of an inch each time the switch is activated. The direction the axis moves is determined by the $\pm$ switch located in the proximity of the step and slew switches.

SLEW—Same as step except axis motion is continuous as long as the slew switch is energized at a rate set by the rate control pot.

RATE—The rate adjust potentiometer sets the rate of travel of both the X and Y axis in the Tape, Manual Index and Manual modes.

LAMP TEST—The lamp test switch causes all of the seven segment display tubes to read eight.

TAPE/POSITION—Readout mode switch in the Tape mode, the X and Y displays will display the position or increment in storage on the X and Y indexer boards. This stored information may be from the paper tape, in the Tape mode, or the thumbwheel switch command in the Manual Index mode. When the readout mode switch is in the position mode, the X and Y axis displays will show table position from a preset reference point designated zero.

ABSOLUTE—When the system is in the Absolute Sub mode, the axis position is as commanded by the thumbwheel switches or tape, the quadrant is determined by the $\pm$ command.

INCREMENTAL—In the Incremental Sub mode, axis position is the sum of the increments commanded by the axis thumbwheel switches or paper tape. The thumbwheel $\pm$ determines the direction of travel.

EMERGENCY STOP—Turns off system power and holds it off until the switch is reset (pulled out).

IN POSITION—Indicator lights when both the X and Y axis have completed a movement. The start function may not be initiated until this indicator is lit.

POWER ON—Turns system power on when the external interlocks are closed.

POWER OFF—Turns off system power.

"X" AXIS POWER—Activates the "X" and "Y" axis torquer. When de-energized, it causes the torquer to be dynamically braked.

X and Y DRIVE—Allows the rate and position command output train to go to the "X" and "Y" axis drive package.

REMOTE—Allows remote control of the axis select slew, step and start functions.

LOCAL—In local, all functions are controlled by the controls on the tape reader control chassis.

Typical NC100 Enclosure

The Aerotech NC100 Series Tape Controllers have been designed for easy check out and maintenance. Rear door and side panels lift off for easy access to all parts of enclosure.

CONTROL LOGIC CHASSIS—
TAPE READER
AND SPOOLER LOGIC—
SERVO DRIVE
AMPLIFIER PANELS—
SYSTEM AND LOGIC POWER
SUPPLIES AND
POWER TRANSFORMER—
RUGGED STEEL FRAME—

ACCUDEX™ Applications

Hi-speed optical scanning
Laser scribing and drilling
Laser semiconductor trimming
Step and repeat camera systems
Photo mask inspection
Photogrammetry
Automatic assembly and mfg.
General purpose (light duty) precise
machining and drilling
Automatic measurement and
inspection
Microdensitometers

PLUG-IN LOGIC BOARDS
C/MOS-MSI CIRCUITRY
UP TO 6 AXES OF CONTROL—
ACCESS THROUGH
REMOVED SIDE PANEL—
HINGED OPERATOR PANEL—
TAPE READER—

Typical ACCUDEX™ Systems

ATS301MD Linear Positioning System with Digital Readout

The ATS301MD Linear Positioning System consists of an ATS301 or 302 Translation Stage-Motor combination, complete with control package consisting of 1/2- and full-step translator drive electronics, micro controls and digital display with BCD output.

The 301MD operates simply by slewing the stage to an approximate position and then jogging to the exact location. Steps are accumulated by a

5 1/2-digit counter and displayed on a seven-segment digital readout accurate to ± 1 digit.

Controls included with this system are: slow-jog, forward-reverse, off-on, local-remote, counter reset and automatic limit switching. Maximum slew speeds exceeding 300 steps per second, as well as 1/2-step accumulator and metric digital readouts, are optional.

ATS304MD (x-y) Indexing System

The ATS304MD Indexing System is a point-to-point two-axis positioner ideal for straight-line milling, laser scribing, step and repeat cameras, resistor trimming and a variety of positioning and scanning applications.

The System consists of the ATS304 (4" x 4" travel) translation stage positioned by either stepping motor or DC motor drive systems.

Manual controls include slow-jog, forward-reverse and manual data entry via thumbwheel switches. Readouts for either the .001- or .0005-inch positioning resolution models are available. This System has a maximum slewing speed of 900 inches per minute.

Other Aerotech Products

- Manual, rotary and linear translation stages.
- Optical mounts and accessories
- Optical components and coatings
- Electronic measurement systems
- Rate tables and angular motion simulators

For further information on the AccuDEX systems, contact a local Aerotech representative or call us directly.

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Introduction

Aerotech optical component mounts and positioning accessories have been designed by engineers, utilizing their strong mechanical abilities combined with many, many years of practical experience in the electro-optical field. The result is the most versatile family of optical component positioners ever assembled. (A brash statement, perhaps, but one which can be substantiated.)

All the Aerotech devices described in this brochure employ patented coarse and fine positioning systems, enabling each to have the finest mechanical resolution available over the widest angular range. These units exhibit little or no creep, backlash or play and boast excellent

repeatability with good thermal characteristics.

In addition, the coarse/fine adjustment capability allows the operator to cover the total angular range quickly, while enjoying continuous fine resolution at any position. This feature significantly reduces alignment time and the possibility of error.

Each item in this line is generally available from stock, and all are warranted for a period of one year. We hope the information presented here will be useful to you and that you will contact Aerotech or an Aerotech representative for assistance in your immediate or future applications.

AOM110 Series Azimuth Elevation Gimbal Optical Mounts

The AOM110 Series Gimbal Optical Mounts are manufactured in frame sizes of 3, 6 and 12 inches and are available with adapters for intermediate size optics.

This series exhibits no cross talk, features hard-mounted ball bearing pivots and, with their narrow silhouettes, are ideal for beam splitter application. In addition, all 110 Series Optical Component Mounts can be fitted with rotary adapters adding a third axis of rotation.

SPECIFICATIONS

	110-3	110-6	110-12
Resolution	.1 arc sec	.05 arc sec	.025 arc sec
Range	12°	6°	5°
Gross Aperture	2.75"	5.62"	11.5"
Weight	1.5 lbs	9 lbs	40 lbs
Finish	Black anodize	Black anodize	Black epoxy paint

DIMENSIONS

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
AOM110-3	3.00	4.44	3.12	2.41	2.00	2.63	1.37	1.75	25	68	7.32	14.20	
AOM110-6	9.12	8.56	3.94	4.58	3.00	5.12	2.00	4.25	29	See M	9.32	No Hole	
AOM110-12	18.75	17.88	5.56	9.25	4.50	9.75	2.75	10.00	88	See M	9.32	No Hole	

AOM120 Series (Lo-Cost) Optical Mounts

The AOM120 Series Mounts are manufactured in frame sizes of 3 and 6 inches and are available with adapters for intermediate size optics.

The 120 Series is ideally suited for end mount application where no clear-through aperture is required.

SPECIFICATIONS

	120-3	120-6
Resolution	2 arc sec	.50 arc sec
Range	5°	4°
Gross Aperture	2.7"	5.5"
Weight	2 lbs	6 lbs
Finish	Black anodize	Black anodize

DIMENSIONS

Model	A	B	C	D	E	F	G	H	I	J	K
AOM120-3	3.50	4.25	3.04	2.50	2.00	3.00	1.00	2.75	9.32	14.20	
AOM120-6	7.00	7.73	4.06	4.25	3.00	5.00	1.50	5.00	9.32	No Hole

ATS300 Linear Translation Stage

The Model ATS300 Translation Stage provides precision linear motion over a half inch range with continuous one micro inch resolution.

By utilizing Aerotech's patented coarse/fine positioning mechanism, these stages provide quick linear travel while still having full range of the fine adjustment at any position. Multiple-

axis configurations, such as (XY) and (XYZ), are available using these stages, making them ideal for accurately positioning small optical components.

This high strength aluminum, black anodized unit is equipped with eight tapped holes to facilitate the mounting of various components and can be fastened to any flat base surface by means of four #6 socket head cap screws.

As an added feature, providing mechanical position readout, the ATS300 stages are available with linear scales (English or metric) with verniers as well as scored line adjustment barrels.

SPECIFICATIONS

Weight	1 1/2 lbs
Range	1/2"
Resolution	1 micro Inch
Material	Aluminum
Finish	Black anodize
Window	None
Load Carrying Capability	Horizontal 50 lbs Vertical 20 lbs

Linear Bearings Configurations	Crossed roller X, (XY), (XYZ)
Z Axis Adapter	None
Linear Scales and Vernier	Optional
Scored Barrels	Optional

ATS301, 302 and 303 Linear Translation Stages

The Models ATS301, 302 and 303 Translation Stages, providing one, two and three inches of travel respectively, use the Aerotech coarse/fine positioner allowing one micro inch continuous resolution over their complete travel. By utilizing precision preloaded linear roller bearings with a friction coefficient of less than .003 and a constant force spring mechanism,

these stages exhibit backlash and play-free operation making them ideal for attaining accurate, repeatable motion with minimum force.

All models are provided with convenient mounting holes for auxiliary equipment, are drilled and tapped for (XY) (fig.1) or (XYZ) (fig.2) configurations, and can be attached to any flat surface by means of two #10 socket head screws.

Models ATS301 and 302 are available with a 3 1/2" X 2" clear aperture designated by the suffix "W" on the part number.

SPECIFICATIONS

	301	302	303
Weight	4 lbs	4 lbs	4 lbs
Range	1"	2"	3"
Resolution	1 micro inch	1 micro inch	1 micro inch
Material	Aluminum	Aluminum	Aluminum
Finish	Black anodize	Black anodize	Black anodize
Window—add suffix "W"	3 1/2" x 2"	3 1/2" x 2"	None
Load Carrying Capability	Horizontal 100 lbs Vertical 20 lbs	Horizontal 100 lbs Vertical 20 lbs	Horizontal 100 lbs Vertical 20 lbs
Linear Bearings Configurations	Crossed roller X, (XY), (XYZ)	Crossed roller X, (XY), (XYZ)	Crossed roller X, (XY), (XYZ)
Z Axis Adapter	Light and heavy-duty	Light and heavy-duty	Light and heavy-duty
Linear Scales and Vernier	Optional	Optional	Optional
Scored Barrels	Optional	Optional	Optional

DIMENSIONS

Model	A	B
ATS301	.50	1.50
ATS302	1.00	1.87
ATS303	1.50	2.25

ATS301M, 302M and 301MM Motor-Driven Translation Stages

The Model ATS301M and 302M motor-driven linear translation stages (providing one and two inches of travel respectively) offer quick and accurate positioning utilizing 200-step-per-revolution stepping motors.

Linear position accuracy and repeatability are assured by employing an ultra-precise ground lead screw, while dynamic stability and excellent runout are controlled by high-quality cross-roller linear bearings. The 301M and 302M tables offer .0001 inch-per-step resolution while the 25mm travel model (ATS301MM) offers 1 micron-per-step resolution.

All models are provided with convenient threaded insert mounting holes for auxiliary equipment, are drilled

and tapped for (XY) and (XYZ) configurations and can be attached to any flat surface by means of two #10 socket head screws.

The ATS301M, 302M and 301MM are coated with an extra-hard (63 Rockwell) finish and are available on special order for 10^{-4} Torr vacuum operation.

SPECIFICATIONS

	301M	302M	301MM
Weight	6 lbs	6 lbs	6 lbs
Range	1"	2"	25mm
Finish	Hard black anodize	Hard black anodize	Hard black anodize
Resolution	200 steps/rev. 400 steps/rev.	.0001" .00005"	2 microns 1 micron
Load Carrying	Horizontal Vertical	Horizontal Vertical	Horizontal Vertical
Capacity	100 lbs 20 lbs	100 lbs 20 lbs	100 lbs 20 lbs
Repeatability (unidirectional)	.000025"	.000025"	.5 microns
Drive Mechanism	Precision lead screw	Precision lead screw	Precision lead screw
Maximum Step Speed	2000 steps/sec	2000 steps/sec	2000 steps/sec
Window—add suffix "W"	3 1/2" x 2"	3 1/2" x 2"	3 1/2" x 2"
Vacuum capability (optional)	10^{-4} Torr	10^{-4} Torr	10^{-4} Torr

DIMENSIONS

Model	A
ATS301M	1.00
ATS302M	2.00
ATS301MM	25mm

ATS301MR Motor-Driven Rotary Translation Stage

The Model ATS301MR Rotary Translation Stage offers quick, accurate and continuous 360° positioning utilizing 200-step-per-revolution stepping motors. Position accuracy and repeatability are assured by employing an ultra-precise

worm-drive mechanism, while dynamic stability and minimum wobble are maintained by a dual (high-quality) ball bearing support system.

The ATS301MR is available with a 1 1/2-inch clear aperture and two or one-half arc minute-per-step resolution. It is easily adaptable to any of the one- and two-inch linear models and can be fitted to operate in a 10^{-4} Torr vacuum.

SPECIFICATIONS

Weight	5 lbs
Range	360° continuous
Resolution	2 arc min 1/2 arc min (2 models) 400 steps/rev
Material	1 arc min 1/4 arc min Aluminum
Finish	Black anodize

Load Carrying	Horizontal	25 lbs
Capacity	Vertical	Dependent upon motor size
Repeatability (unidirectional)		.2 arc min
Table-top Diameter		4"
Maximum Step Speed		2000 steps/sec
Clear Aperture		1 1/2"
Optional Vacuum Capability		10^{-4} Torr
Accuracy (lead error accumulative)		3 arc min

KEENE
CORPORATION

KAYDON BEARING DIVISION

Catalog 300
REALI-SLIM
BALL AND ROLLER
BEARINGS

Kaydon REALI-SLIM Ball and Roller Bearings

TYPE X KAYDON REAL-SLIM BALL BEARINGS (CONTINUED)

KA SERIES												
Bearing Number		Dimensions in inches				Capacities (1)						Weight in Pounds
Current	Former	Bore	Outside Dia.	Land Dia. L ₁	Land Dia. L ₂	Rated in Lbs. Static	Thrust in Lbs. Static	Dynamic	Moment Static	Dynamic		
*KA020XP0	KA20XP	2.000	2.500	2.128	2.314	860	280	2,400	700	1,090	315	.10
*KA025XP0	KA25XP	2.500	3.000	2.696	2.814	1,175	320	2,940	800	1,620	440	.13
*KA030XP0	KA30XP	3.000	3.500	3.198	3.314	1,400	360	3,500	900	2,280	585	.16
*KA035XP0	KA35XP	3.500	4.000	3.696	3.814	1,600	390	4,000	990	3,000	730	.18
*KA040XP0	KA40XP	4.000	4.500	4.196	4.314	1,800	430	4,500	1,050	3,820	915	.19
KA042XP0	KA42XP	4.250	4.750	4.438	4.564	1,300	450	4,800	1,100	4,280	1,010	.20
*KA045XP0	KA45XP	4.500	5.000	4.696	4.814	2,000	480	5,050	1,150	4,750	1,090	.22
*KA047XP0	KA47XP	4.750	5.250	4.936	5.064	2,100	480	5,300	1,150	5,250	1,200	.23
*KA050XP0	KA50XP	5.000	5.500	5.196	5.314	2,200	490	5,600	1,200	5,780	1,290	.24
*KA055XP0	KA55XP	5.500	6.000	5.696	5.814	2,450	520	6,100	1,300	7,010	1,490	.26
*KA060XP0	KA60XP	6.000	6.500	6.196	6.314	2,650	550	6,650	1,350	8,280	1,720	.28
KA065XP0	KA65XP	6.500	7.000	6.696	6.814	2,850	580	7,200	1,450	9,620	1,950	.30
*KA070XP0	KA70XP	7.000	7.500	7.196	7.314	3,050	610	7,700	1,600	11,000	2,210	.31
KA075XP0	KA75XP	7.500	8.000	7.696	7.814	3,300	640	8,250	1,600	12,800	2,480	.34
KA080XP0	KA80XP	8.000	8.500	8.196	8.314	3,500	670	8,300	1,650	14,400	2,790	.38
KA090XP0	KA90XP	9.000	9.500	9.196	9.314	3,900	720	8,850	1,800	16,000	3,330	.44
KA100XP0	KA100XP	10.000	10.500	10.196	10.314	4,350	770	10,800	1,900	22,300	3,950	.50
KA110XP0	KA110XP	11.000	11.500	11.196	11.314	4,800	820	12,000	2,050	27,000	4,610	.52
KA120XP0	KA120XP	12.000	12.500	12.196	12.314	5,200	870	13,000	2,150	31,800	5,330	.56

NON-METALLIC
SNAPOVER
SEPARATOR
1/8" BALLS

② F = .025

KB SERIES												
Bearing Number		Dimensions in inches				Capacities (1)						Weight in Pounds
Current	Former	Bore	Outside Dia.	Land Dia. L ₁	Land Dia. L ₂	Rated in Lbs. Static	Thrust in Lbs. Static	Dynamic	Moment Static	Dynamic		
*KB020XP0	KB20XP	2.000	2.625	2.231	2.393	1,270	390	3,200	580	1,470	450	.16
*KB025XP0	KB25XP	2.500	3.125	2.731	2.893	1,550	450	3,875	1,120	2,180	630	.19
*KB030XP0	KB30XP	3.000	3.625	3.231	3.393	1,850	500	4,600	1,250	3,060	825	.24
*KB035XP0	KB35XP	3.500	4.125	3.731	3.893	2,050	540	5,150	1,350	3,910	1,030	.27
*KB040XP0	KB40XP	4.000	4.625	4.231	4.393	2,350	600	5,950	1,450	5,070	1,290	.30
*KB042XP0	KB42XP	4.250	4.875	4.481	4.643	2,500	610	6,250	1,500	5,700	1,390	.31
KB045XP0	KB45XP	4.500	5.125	4.731	4.893	2,650	640	6,650	1,600	6,380	1,540	.32
KB047XP0	KB47XP	4.750	5.375	4.981	5.143	2,750	660	6,950	1,650	6,960	1,670	.34
KB050XP0	KB50XP	5.000	5.625	5.231	5.393	2,900	680	7,350	1,700	7,710	1,810	.38
*KB055XP0	KB55XP	5.500	6.125	5.731	5.893	3,200	730	8,050	1,800	9,300	2,120	.41
*KB060XP0	KB60XP	6.000	6.625	6.231	6.393	3,500	770	8,750	1,900	11,000	2,430	.44
*KB065XP0	KB65XP	6.500	7.125	6.731	6.893	3,750	810	9,450	2,000	12,800	2,760	.47
KB070XP0	KB70XP	7.000	7.625	7.231	7.393	4,050	850	10,100	2,100	14,800	3,110	.50
KB075XP0	KB75XP	7.500	8.125	7.731	7.893	4,300	890	10,800	2,200	15,800	3,480	.53
*KB080XP0	KB80XP	8.000	8.625	8.231	8.393	4,600	920	11,600	2,300	19,100	3,820	.57
*KB090XP0	KB90XP	9.000	9.625	9.231	9.393	5,150	1,000	12,900	2,500	24,000	4,660	.66
KB100XP0	KB100XP	10.000	10.625	10.231	10.393	5,700	1,050	14,300	2,650	29,400	5,410	.73
KB110XP0	KB110XP	11.000	11.625	11.231	11.393	6,250	1,100	15,700	2,850	35,300	6,220	.75
KB120XP0	KB120XP	12.000	12.625	12.231	12.393	6,800	1,200	17,100	3,000	41,900	7,390	.83
KB140XP0	KB140XP	14.000	14.625	14.231	14.393	7,950	1,300	19,800	3,300	56,900	9,300	1.05
KB160XP0	KB160XP	16.000	16.625	16.231	16.393	9,050	1,450	22,600	3,600	73,800	11,800	1.20
KB180XP0	KB180XP	18.000	18.625	18.231	18.393	10,100	1,550	26,100	3,900	92,500	14,200	1.35
KB200XP0	KB200XP	20.000	20.625	20.231	20.393	11,200	1,650	28,200	4,200	113,700	16,500	1.50

② F = .040

• Available from stock - check for availability of other sizes.

(1) Capacities listed are not simultaneous. Moment capacity shown is in pound-inches. For combined loading see discussion of Bearing Selection and Load Analysis. Dynamic capacities are based upon 500 hours B₁₀ life @ 100 RPM (3.6 million revolutions).

② "F" is maximum shaft or housing fillet radius which bearing corners will clear.

TYPE X KAYDON REAL-SLIM BALL BEARINGS (CONTINUED)

KC SERIES												
Bearing Number		Dimensions in inches					Capacities (1)					Weight in Pounds
Current	Former	Bore Dia.	Outside Dia.	Land Dia. L ₁	Land Dia. L ₂	Radial in Lbs. Static	Thrust in Lbs. Static	Static Dyn.	Moment Static	Moment Dyn.		
*KC040XP	KCA4XP	4.000	4.750	4.277	4.473	2,800	750	7,000	1,850	8,120	1,840	.45
KC042XP	KCA2XP	4.250	5.00	4.527	4.723	2,950	780	7,400	1,950	8,820	1,800	.47
*KC045XP	KCA5XP	4.500	5.250	4.777	4.973	3,100	800	7,800	2,000	7,560	1,950	.48
KC047XP	KCA7XP	4.750	5.500	5.027	5.223	3,250	830	8,200	2,050	8,330	2,130	.50
*KC050XP	KC50XP	5.000	5.750	5.277	5.473	3,450	860	8,600	2,160	8,270	2,300	.58
*KC055XP	KC55XP	5.500	6.250	5.777	5.973	3,750	910	9,400	2,250	11,000	2,670	.59
*KC060XP	KC60XP	6.000	6.750	6.277	6.473	4,050	960	10,200	2,400	12,900	3,060	.63
*KC065XP	KC65XP	6.500	7.250	6.777	6.973	4,400	1,000	11,000	2,500	15,100	3,440	.68
*KC070XP	KC70XP	7.000	7.750	7.277	7.473	4,700	1,050	11,800	2,650	17,300	3,870	.73
*KC075XP	KC75XP	7.500	8.250	7.777	7.973	5,050	1,100	12,600	2,760	19,900	4,330	.78
*KC080XP	KC80XP	8.000	8.750	8.277	8.473	5,350	1,160	13,400	2,900	22,400	4,820	.84
*KC090XP	KC90XP	9.000	9.750	9.277	9.473	6,000	1,250	15,000	3,100	28,100	5,860	.94
*KC100XP	KC100XP	10.000	10.750	10.277	10.473	6,650	1,300	16,600	3,300	34,500	8,740	1.06
*KC110XP	KC110XP	11.000	11.750	11.277	11.473	7,300	1,400	18,200	3,550	41,500	7,960	1.16
*KC120XP	KC120XP	12.000	12.750	12.277	12.473	7,900	1,500	19,800	3,760	48,900	9,280	1.25
KC140XP	KC140XP	14.000	14.750	14.277	14.473	9,200	1,650	23,000	4,150	66,100	11,800	1.82
KC160XP	KC160XP	16.000	16.750	16.277	16.473	10,500	1,800	28,200	4,500	96,000	14,700	1.73
KC180XP	KC180XP	18.000	18.750	18.277	18.473	11,700	1,950	29,400	4,900	107,000	17,900	1.94
KC200XP	KC200XP	20.000	20.750	20.277	20.473	13,000	2,100	32,600	5,250	132,000	21,400	2.16
KC250XP	KC250XP	25.000	25.750	25.277	25.473	16,200	2,400	40,600	6,050	205,000	30,400	2.69
KC300XP	KC300XP	30.000	30.750	30.277	30.473	19,600	2,700	49,600	6,850	296,000	41,000	3.21

METALLIC
SNAPOVER
SEPARATOR
3/16" BALLS

③ F = .040

KD SERIES												
Bearing Number		Dimensions in inches					Capacities (1)					Height in Pounds
Current	Former	Bore Dia.	Outside Dia.	Land Dia. L ₁	Land Dia. L ₂	Radial in Lbs. Static	Thrust in Lbs. Static	Static Dyn.	Moment Static	Moment Dyn.		
*KD040XP	KD04XP	4.000	5.000	4.370	4.630	3,800	1,140	9,500	2,800	8,550	2,470	.78
*KD042XP	KD04XP	4.250	5.250	4.620	4.880	3,950	1,150	9,950	2,850	9,380	2,730	.82
*KD045XP	KD04XP	4.500	5.500	4.970	5.130	4,250	1,200	10,600	3,000	10,600	3,000	.88
KD047XP	KD04XP	4.750	5.750	5.140	5.380	4,400	1,200	11,000	3,050	11,500	3,150	.94
*KD050XP	KD05XP	5.000	6.000	5.370	5.630	4,700	1,250	11,700	3,200	12,900	3,440	1.00
*KD055XP	KD05XP	5.500	6.500	5.970	6.130	5,100	1,350	12,800	3,400	15,300	4,050	1.06
*KD060XP	KD06XP	6.000	7.000	6.370	6.630	5,550	1,400	13,800	3,550	18,000	4,550	1.16
*KD065XP	KD06XP	6.500	7.500	6.870	7.130	5,950	1,500	14,900	3,750	20,800	5,250	1.22
KD070XP	KD07XP	7.000	8.000	7.370	7.630	6,400	1,550	16,000	3,950	24,000	5,810	1.31
KD075XP	KD07XP	7.500	8.500	7.870	8.130	6,800	1,650	17,100	4,100	27,200	6,600	1.41
*KD080XP	KD08XP	8.000	9.000	8.370	8.630	7,250	1,700	18,100	4,260	30,800	7,220	1.53
*KD090XP	KD09XP	9.000	10.000	9.370	9.630	8,100	1,850	20,300	4,600	38,500	8,190	1.72
KD100XP	KD100XP	10.000	11.000	10.370	10.630	8,950	1,950	22,400	4,900	47,000	10,200	1.88
*KD110XP	KD110XP	11.000	12.000	11.370	11.630	9,800	2,100	24,500	5,250	56,300	12,100	2.06
*KD120XP	KD120XP	12.000	13.000	12.370	12.630	10,600	2,200	26,700	5,550	66,200	13,700	2.25
KD140XP	KD140XP	14.000	15.000	14.370	14.630	12,300	2,450	30,800	6,100	89,200	17,800	2.73
KD160XP	KD160XP	16.000	17.000	16.370	16.630	14,100	2,650	35,200	6,650	115,000	21,900	3.10
KD180XP	KD180XP	18.000	19.000	18.370	18.630	15,800	2,850	39,500	7,200	145,000	26,400	3.48
KD200XP	KD200XP	20.000	21.000	20.370	20.630	17,500	3,050	43,800	7,700	179,000	31,300	3.85
KD250XP	KD250XP	25.000	26.000	25.370	25.630	21,800	3,550	54,600	8,900	278,000	45,300	4.79
KD300XP	KD300XP	30.000	31.000	30.370	30.630	26,000	4,000	65,100	10,000	395,000	61,000	5.73

METALLIC
SNAPOVER
SEPARATOR
1/4" BALLS

③ F = .050

• Available from stock - check for availability of other sizes.

NOTE (1) Capacities listed are not simultaneous. Moment capacity shown is in pound-inches. For combined loading see discussion of Bearing Selection and Load Analysis. Dynamic capacities are based upon 500 hours B₁₀ life @ 100 RPM (12.6 million revolutions).

(2) "F" is maximum shaft or housing fillet radius which bearing corners will clear.

KAYDON Precision Tolerances and Recommended Fits For Real-Slim Ball Bearings in Normal Applications

Kaydon Real-Slim Ball Bearings

T Y P E X T Y P E A

PRECISION CLASS 1

Bearing size (Alt Series)	Bearing Diameters		Radial & Axial Runout		Rotating Shaft		Stationary Shaft				Bearing Diametral Clearance* (Type "X" only)		
	Bearing Bore	Bearing O.D.			Shaft Diameter	Housing Bore	Shaft Diameter	Housing Bore			Before Installation	Expected Minimum After Install.	
					Nominal +0.0000	Nominal +0.0000	Nominal	Nominal					
10	-.0004	-.0005	.0003	.0004	+0.004	+0.005	-.0004	-.0008	-.0005	-.0010	.0010	.0015	.0003
15	-.0005	-.0005	.0004	.0004	+0.005	+0.005	-.0005	-.0010	-.0005	-.0010	.0012	.0017	.0003
20	-.0006	-.0005	.0005	.0005	+0.006	+0.005	-.0006	-.0012	-.0005	-.0010	.0012	.0022	.0003
25	-.0005	-.0005	.0005	.0005	+0.006	+0.005	-.0006	-.0012	-.0005	-.0010	.0012	.0022	.0003
30	-.0006	-.0006	.0006	.0006	+0.006	+0.006	-.0006	-.0012	-.0006	-.0012	.0012	.0022	.0003
35	-.0008	-.0008	.0006	.0006	+0.008	+0.006	-.0008	-.0015	-.0006	-.0012	.0016	.0026	.0004
40	-.0008	-.0006	.0006	.0006	+0.008	+0.006	-.0008	-.0015	-.0006	-.0012	.0016	.0026	.0004
42	-.0008	-.0008	.0008	.0008	+0.008	+0.008	-.0008	-.0018	-.0008	-.0016	.0016	.0026	.0004
45	-.0008	-.0008	.0008	.0008	+0.008	+0.008	-.0008	-.0018	-.0008	-.0016	.0016	.0026	.0004
47	-.0010	-.0008	.0008	.0008	+0.010	+0.008	-.0010	-.0020	-.0008	-.0016	.0020	.0030	.0006
50	-.0010	-.0008	.0008	.0008	+0.010	+0.008	-.0010	-.0020	-.0008	-.0016	.0020	.0030	.0006
55	-.0010	-.0010	.0010	.0010	+0.010	+0.010	-.0010	-.0020	-.0010	-.0020	.0020	.0030	.0006
60	-.0010	-.0010	.0010	.0010	+0.010	+0.010	-.0010	-.0020	-.0010	-.0020	.0020	.0030	.0006
65	-.0010	-.0010	.0010	.0010	+0.010	+0.010	-.0010	-.0020	-.0010	-.0020	.0020	.0030	.0006
70	-.0010	-.0012	.0010	.0010	+0.010	+0.012	-.0010	-.0020	-.0012	-.0024	.0020	.0030	.0006
75	-.0012	-.0012	.0012	.0012	+0.012	+0.012	-.0012	-.0024	-.0012	-.0024	.0024	.0034	.0007
80	-.0012	-.0012	.0012	.0012	+0.012	+0.012	-.0012	-.0024	-.0012	-.0024	.0024	.0034	.0007
90	-.0012	-.0012	.0012	.0012	+0.012	+0.012	-.0012	-.0024	-.0012	-.0024	.0024	.0034	.0007
100	-.0014	-.0014	.0014	.0014	+0.014	+0.014	-.0014	-.0028	-.0014	-.0028	.0028	.0038	.0008
110	-.0014	-.0014	.0014	.0014	+0.014	+0.014	-.0014	-.0028	-.0014	-.0028	.0028	.0038	.0008
120	-.0014	-.0014	.0014	.0014	+0.014	+0.014	-.0014	-.0028	-.0014	-.0028	.0028	.0038	.0008
140	-.0014	-.0014	.0014	.0014	+0.014	+0.014	-.0014	-.0028	-.0014	-.0028	.0028	.0038	.0008
160	-.0016	-.0016	.0016	.0016	+0.016	+0.016	-.0016	-.0032	-.0016	-.0032	.0032	.0042	.0010
180	-.0016	-.0016	.0016	.0016	+0.016	+0.016	-.0016	-.0032	-.0016	-.0032	.0032	.0042	.0010
200	-.0018	-.0018	.0018	.0018	+0.018	+0.018	-.0018	-.0036	-.0018	-.0036	.0036	.0046	.0011
250	-.0018	-.0018	.0018	.0018	+0.018	+0.018	-.0018	-.0036	-.0018	-.0036	.0036	.0046	.0011
300	-.0018	-.0018	.0018	.0018	+0.018	+0.018	-.0018	-.0036	-.0018	-.0036	.0036	.0046	.0011
350	-.0020	-.0020	.0020	.0020	+0.020	+0.020	-.0020	-.0040	-.0020	-.0040	.0040	.0050	.0012
400	-.0020	-.0020	.0020	.0020	+0.020	+0.020	-.0020	-.0040	-.0020	-.0040	.0040	.0050	.0012

Total Width Tolerance - Duplexed Type A Bearings:

Up thru 2" Bearing Bore	+0.000	-.020
Over 2" thru 5" Bore	+0.000	-.030
Over 5" thru 14" Bore	+0.000	-.040
Over 14" Bore	+0.000	-.050

Race Width Tolerance - Single Type X, A Bearings

Up thru 12" Bearing Bore	+0.000	-.005
Over 12" Bearing Bore	+0.000	-.010

*Diametral clearance after installation theoretically can range rather widely if all contributing bearing, housing, and shaft tolerances are at either of their extremes. Clearances shown are the amounts expected according to the laws of probability. Diametral clearances shown do not apply to type A (angular contact) bearings.

All dimensions in inches.

KEENE
CORPORATION

KAYDON BEARING DIVISION

Kaydon Real-Slim Ball Bearings

TYPE C
TYPE X
TYPE A

KAYDON Precision Tolerances and Recommended Fits For Real-Slim Ball Bearings in Normal Applications

PRECISION CLASS 3												
Bearing Size (All Series)	Bearing Diameters		Radial & Axial Runout		Rotating Shaft		Stationary Shaft		Bearing Diameter Clearance*			
	Bearing Bore	Bearing O.D.	Inner Race	Outer Race	Shaft Diameter	Housing Bore	Shaft Diameter	Housing Bore	Before Installation		Expected Minimum After Instal.	
	Nominal +.0000	Nominal +.0000			Nominal +.0000	Nominal +.0000	Nominal	Nominal				
10	-.0002	-.0003	.0003	.0004	-.0002	+.0003	-.0002	-.0004	-.0003	-.0006	.0007	.0011
15	-.0003	-.0003	.0004	.0004	+.0003	+.0003	-.0003	-.0006	-.0003	-.0006	.0008	.0012
20	-.0004	-.0004	.0004	.0005	+.0004	+.0004	-.0004	-.0008	-.0004	-.0008	.0008	.0018
25	-.0004	-.0004	.0004	.0005	+.0004	+.0004	-.0004	-.0009	-.0004	-.0008	.0008	.0018
30	-.0004	-.0004	.0004	.0006	+.0004	+.0004	-.0004	-.0008	-.0004	-.0008	.0008	.0018
35	-.0005	-.0004	.0005	.0006	+.0005	+.0004	-.0005	-.0010	-.0004	-.0008	.0010	.0020
40	-.0005	-.0004	.0005	.0006	+.0005	+.0004	-.0005	-.0010	-.0004	-.0008	.0010	.0020
42	-.0005	-.0005	.0005	.0008	+.0005	+.0005	-.0005	-.0010	-.0005	-.0010	.0010	.0020
46	-.0005	-.0005	.0005	.0008	+.0005	+.0005	-.0005	-.0010	-.0005	-.0010	.0010	.0020
47	-.0006	-.0005	.0006	.0008	+.0006	+.0005	-.0006	-.0012	-.0005	-.0010	.0012	.0022
50	-.0006	-.0005	.0006	.0008	+.0006	+.0005	-.0006	-.0012	-.0005	-.0010	.0012	.0022
55	-.0006	-.0006	.0006	.0009	+.0006	+.0006	-.0006	-.0012	-.0006	-.0012	.0012	.0022
60	-.0006	-.0006	.0006	.0009	+.0006	+.0006	-.0006	-.0012	-.0006	-.0012	.0012	.0022
65	-.0006	-.0006	.0006	.0009	+.0006	+.0006	-.0006	-.0012	-.0006	-.0012	.0012	.0022
70	-.0006	-.0007	.0006	.0010	+.0006	+.0007	-.0006	-.0012	-.0007	-.0014	.0014	.0024
75	-.0007	-.0007	.0008	.0010	+.0007	+.0007	-.0007	-.0014	-.0007	-.0014	.0014	.0024
80	-.0007	-.0007	.0008	.0010	+.0007	+.0007	-.0007	-.0014	-.0007	-.0014	.0014	.0024
90	-.0007	-.0007	.0008	.0010	+.0007	+.0007	-.0007	-.0014	-.0007	-.0014	.0014	.0024
100	-.0008	-.0008	.0010	.0012	+.0008	+.0008	-.0008	-.0016	-.0008	-.0016	.0016	.0026
110	-.0008	-.0008	.0010	.0012	+.0008	+.0008	-.0008	-.0016	-.0008	-.0016	.0016	.0026
120	-.0008	-.0009	.0010	.0014	+.0008	+.0009	-.0008	-.0016	-.0009	-.0018	.0018	.0028
140	-.0008	-.0009	.0012	.0014	+.0008	+.0009	-.0008	-.0016	-.0009	-.0018	.0018	.0028
160	-.0009	-.0010	.0014	.0016	+.0009	+.0010	-.0009	-.0018	-.0010	-.0020	.0020	.0030
180	-.0009	-.0010	.0014	.0016	+.0009	+.0010	-.0009	-.0018	-.0010	-.0020	.0020	.0030
200	-.0010	-.0012	.0016	.0018	+.0010	+.0012	-.0010	-.0020	-.0012	-.0024	.0024	.0034

*Diametral clearance after installation theoretically can range rather widely if all contributing bearing, housing, and shaft tolerances are at either of their extremes. Clearances shown are the amounts expected according to the laws of probability. Diametral clearances shown do not apply to Type A, angular contact, bearings.

All dimensions in inches.

Total Width Tolerance - Duplexed Type A Bearings:
Up thru 2" Bearing Bore +.000 - .020
Over 2" thru 5" Bore +.000 - .030
Over 5" thru 14" Bore +.000 - .040
Over 14" Bore +.000 - .050

Race Width Tolerance - Single Type C, X, A Bearings:
Up thru 12" Bearing Bore +.000 - .005
Over 12" Bearing Bore +.000 - .010

Kaydon Real-Slim Ball Bearings

KAYDON Precision Tolerances and Recommended Fits For Real-Slim Ball Bearings in Normal Applications

T Y P E C
T Y P E X
T Y P E A

PRECISION CLASS 5

Bearing Size (AR Series)	Bearing Dimensions		Radial & Axial Runout		Rotating Shaft		Stationary Shaft		Bearing Diametral Clearance*	
	Bearing Bore	Bearing O.D.			Shaft Diameter	Housing Bore	Shaft Diameter	Housing Bore	Before Installation	Expected Min. After Instal.
	Nominal + .0000	Nominal + .0000	Inner Race	Outer Race	Nominal + .0000	Nominal + .0000	Nominal	Nominal		
10	-.0002	-.0002	R.0002, A.0003	R.0002, A.0003	+ .0002	+ .0002	-.0002, -.0004	-.0002, -.0004	.0005, .0009	.0001
15	-.0002	-.0002	R.0002, A.0003	R.0002, A.0003	+ .0002	+ .0002	-.0002, -.0004	-.0002, -.0004	.0005, .0009	.0001
20	-.0003	-.0003	R.0002, A.0003	R.0003, A.0004	+ .0003	+ .0003	-.0003, -.0005	-.0003, -.0005	.0006, .0012	.0002
25	-.0003	-.0003	R.0002, A.0003	R.0003, A.0004	+ .0003	+ .0003	-.0003, -.0005	-.0003, -.0005	.0006, .0012	.0002
30	-.0003	-.0003	R.0002, A.0003	R.0004, A.0005	+ .0003	+ .0003	-.0003, -.0005	-.0003, -.0005	.0006, .0012	.0002
35	-.0003	-.0003	R.0003, A.0004	R.0004, A.0005	+ .0003	+ .0003	-.0003, -.0005	-.0003, -.0005	.0006, .0012	.0002
40	-.0003	-.0003	R.0003, A.0004	R.0004, A.0005	+ .0003	+ .0003	-.0003, -.0005	-.0003, -.0005	.0006, .0012	.0002
42	-.0003	-.0004	R.0003, A.0004	R.0004, A.0005	+ .0003	+ .0004	-.0003, -.0005	-.0003, -.0005	.0008, .0014	.0002
45	-.0003	-.0004	R.0003, A.0004	R.0004, A.0005	+ .0003	+ .0004	-.0003, -.0005	-.0003, -.0005	.0008, .0014	.0002
47	-.0004	-.0004	R.0003, A.0004	R.0004, A.0005	+ .0004	+ .0004	-.0004, -.0006	-.0004, -.0006	.0008, .0014	.0002
50	-.0004	-.0004	R.0003, A.0004	R.0004, A.0005	+ .0004	+ .0004	-.0004, -.0006	-.0004, -.0006	.0008, .0014	.0002
55	-.0004	-.0005	R.0003, A.0004	R.0005, A.0006	+ .0004	+ .0005	-.0004, -.0006	-.0005, -.0010	.0010, .0016	.0003
60	-.0004	-.0005	R.0003, A.0004	R.0005, A.0006	+ .0004	+ .0005	-.0004, -.0006	-.0005, -.0010	.0010, .0016	.0003
65	-.0004	-.0005	R.0003, A.0004	R.0005, A.0006	+ .0004	+ .0005	-.0004, -.0006	-.0005, -.0010	.0010, .0016	.0003
70	-.0004	-.0005	R.0004, A.0004	R.0005, A.0006	+ .0004	+ .0005	-.0004, -.0006	-.0005, -.0010	.0010, .0016	.0003
75	-.0005	-.0005	R.0004, A.0005	R.0005, A.0006	+ .0005	+ .0005	-.0005, -.0010	-.0005, -.0010	.0010, .0016	.0003
80	-.0005	-.0005	R.0004, A.0005	R.0005, A.0006	+ .0005	+ .0005	-.0005, -.0010	-.0005, -.0010	.0010, .0016	.0003
90	-.0005	-.0005	R.0004, A.0005	R.0005, A.0006	+ .0005	+ .0005	-.0005, -.0010	-.0005, -.0010	.0010, .0016	.0003
100	-.0005	-.0005	R.0005, A.0006	R.0006, A.0007	+ .0005	+ .0005	-.0005, -.0010	-.0005, -.0010	.0010, .0016	.0003
110	-.0005	-.0005	R.0005, A.0006	R.0006, A.0007	+ .0005	+ .0005	-.0005, -.0010	-.0005, -.0010	.0010, .0016	.0003
120	-.0005	-.0006	R.0005, A.0006	R.0007, A.0008	+ .0005	+ .0006	-.0005, -.0010	-.0006, -.0012	.0012, .0018	.0003
140	-.0006	-.0006	R.0005, A.0007	R.0007, A.0008	+ .0006	+ .0006	-.0006, -.0012	-.0006, -.0012	.0012, .0018	.0003
160	-.0006	-.0007	R.0007, A.0008	R.0008, A.0009	+ .0006	+ .0007	-.0006, -.0012	-.0007, -.0014	.0014, .0020	.0004
180	-.0006	-.0007	R.0007, A.0008	R.0008, A.0009	+ .0006	+ .0007	-.0006, -.0012	-.0007, -.0014	.0014, .0020	.0004
200	-.0007	-.0008	R.0008, A.0009	R.0009, A.0010	+ .0007	+ .0008	-.0006, -.0014	-.0007, -.0016	.0014, .0022	.0004

Total Width Tolerance - Duplexed Type A Bearings:

Up thru 2" Bearing Bore	+ .000 - .020
Over 2" thru 5" Bore	+ .000 - .030
Over 5" thru 14" Bore	+ .000 - .040
Over 14" Bore	+ .000 - .050

Race Width Tolerance - Single Type C, X, A Bearings:

Up thru 12" Bearing Bore	+ .000 - .005
Over 12" Bearing Bore	+ .000 - .010

*Diametral clearance after installation theoretically can range rather widely if all contributing bearing, housing, and shaft tolerances are at either of their extremes. Clearances shown are the amount expected according to the laws of probability. Diametral clearance shown do not apply to type A (angular contact) bearings.

All dimensions in inches.

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KAYDON BEARING DIVISION

Kaydon Real-Slim Ball Bearings

TYPE C**TYPE X****TYPE A****KAYDON Precision Tolerances and Recommended Fits
For Real-Slim Ball Bearings in Normal Applications****PRECISION CLASS 7**

Bearing Size (All Series)	Bearing Dimensions		Radial & Axial Runout		Rotating Shaft		Stationary Shaft		Bearing Diametral Clearance*				
	Bearing Bore	Bearing O.D.	Inner Race	Outer Race	Shaft Diameter	Housing Bore	Shaft Diameter	Housing Bore	Before Installation	Expected Minimum After Instal.			
	Nominal +0.0000	Nominal +0.0000			Nominal +0.0000	Nominal +0.0000	Nominal	Nominal					
10	-.00015	-.00020	.00015	.0002	+0.00015	+0.00020	-.00015	-.00030	-.00020	-.00040	.0004	.0008	.0001
15	-.00020	-.00020	.00015	.0002	+0.00020	+0.00020	-.00020	-.00040	-.00020	-.00040	.0005	.0009	.0001
20	-.0002	-.0002	.00015	.0002	+0.0002	+0.0002	-.0002	-.0004	-.0002	-.0004	.0004	.0010	.0001
25	-.0002	-.0002	.00015	.0002	+0.0002	+0.0002	-.0002	-.0004	-.0002	-.0004	.0004	.0010	.0001
30	-.0002	-.0003	.00015	.0002	+0.0002	+0.0003	-.0002	-.0004	-.0003	-.0006	.0006	.0012	.0002
35	-.00025	-.00030	.0002	.0002	+0.00025	+0.00030	-.00025	-.00050	-.00030	-.00060	.0006	.0012	.0002
40	-.00025	-.00030	.0002	.0002	+0.00025	+0.00030	-.00025	-.00050	-.00030	-.00060	.0006	.0012	.0002
42	-.00025	-.00040	.0002	.0003	+0.00025	+0.00040	-.00025	-.00050	-.00040	-.00080	.0008	.0014	.0002
45	-.00025	-.00040	.0002	.0003	+0.00025	+0.00040	-.00025	-.00050	-.00040	-.00080	.0008	.0014	.0002
47	-.0003	-.0004	.0003	.0003	+0.0003	+0.0004	-.0003	-.0006	-.0004	-.0008	.0008	.0014	.0002
50	-.0003	-.0004	.0003	.0003	+0.0003	+0.0004	-.0003	-.0006	-.0004	-.0008	.0008	.0014	.0002
55	-.0003	-.0004	.0003	.0003	+0.0003	+0.0004	-.0003	-.0006	-.0004	-.0008	.0008	.0014	.0002
60	-.0003	-.0004	.0003	.0003	+0.0003	+0.0004	-.0003	-.0006	-.0004	-.0008	.0008	.0014	.0002
65	-.0003	-.0004	.0003	.0003	+0.0003	+0.0004	-.0003	-.0006	-.0004	-.0008	.0008	.0014	.0002
70	-.0003	-.0004	.0003	.0004	+0.0003	+0.0004	-.0003	-.0006	-.0004	-.0008	.0008	.0014	.0002
75	-.0004	-.0004	.0003	.0004	+0.0004	+0.0004	-.0004	-.0008	-.0004	-.0008	.0008	.0014	.0002
80	-.0004	-.0004	.0003	.0004	+0.0004	+0.0004	-.0004	-.0008	-.0004	-.0008	.0008	.0014	.0002
90	-.0004	-.0004	.0003	.0004	+0.0004	+0.0004	-.0004	-.0008	-.0004	-.0008	.0008	.0014	.0002
100	-.0005	-.0005	.0004	.0004	+0.0005	+0.0005	-.0005	-.0010	-.0005	-.0010	.0010	.0016	.0003
110	-.0005	-.0005	.0004	.0004	+0.0005	+0.0005	-.0005	-.0010	-.0005	-.0010	.0010	.0016	.0003
120	-.0005	-.0005	.0004	.0005	+0.0005	+0.0005	-.0005	-.0010	-.0005	-.0010	.0010	.0016	.0003
140	-.0005	-.0006	.0004	.0005	+0.0005	+0.0006	-.0005	-.0010	-.0006	-.0012	.0012	.0018	.0003

*Diametral clearance after installation theoretically can range rather widely if all contributing bearing, housing, and shaft tolerances are at either of their extremes. Clearances shown are the amounts expected according to the laws of probability. Diametral clearance shown do not apply to type A (angular contact) bearings.

All dimensions in inches.

Total Width Tolerance - Duplexed Type A Bearings:

Up thru 2" Bearing Bore +.000 -.020
 Over 2" thru 5" Bore +.000 -.030
 Over 5" thru 14" Bore +.000 -.040
 Over 14" Bore +.000 -.050

Race Width Tolerance - Single Type C, X, A Bearings:

Up thru 12" Bearing Bore +.000 -.025
 Over 12" Bearing Bore +.000 -.010

slo-syn®

1.8° STEP ANGLE DC STEPPING MOTORS

These motors include the new M Series SLO-SYN Stepping Motors which represent the most advanced permanent magnet stepping motor design available. They offer the most complete range, both in torque ratings and in size and configuration. M Series motors provide the highest torque per pound and torque to inertia ratios and can be driven at rates to 20,000 steps per second.

Larger frame size SS and X types with bifilar windings complete the line of 1.8° steppers. Bifilar windings provide greater torque at higher stepping rates than do standard three-lead motors and are ideal for use with electronic drive circuits.

CONSTRUCTION

SLO-SYN Stepping Motors have permanent magnet rotors and eight-pole stators. They have no brushes, ratchets or detents and use shielded ball bearings to insure maximum reliability and long life.

TEMPERATURE

SLO-SYN motors have Class B winding insulation and may be operated at ambient temperatures from -40°C to $+65^{\circ}\text{C}$. The continuous duty temperature rise is 65°C .

HIGH SPEED CAPABILITY

The speed vs torque characteristics shown in the curve were obtained using a special drive circuit to step an M061-FC08 motor. Drives for operation at the high stepping rates shown can be supplied on special order.

STEP ANGLE

Using the full-step drive mode, the motor step angle is 1.8° with a choice of $\pm 5\%$ or precision $\pm 3\%$ accuracies available as standard. The half-step drive mode gives a step angle of 0.9° .

HOLDING TORQUE

Standard types are offered in holding torque ratings from 53 to 4000 ounce-inches.

SS and HS SERIES REPLACEMENTS

The M Series motor line includes stepping motors which are exact mechanical and electrical replacements for earlier SS and HS Series motors. The cross reference list shows these M Series Motors and indicates the specific motors which they replace.

STEPPING MOTORS

.072 KP-cm = 103-in

1.8° STEP ANGLE DC STEPPING MOTORS (Cont'd.)

OPERATION

SLO-SYN Stepping Motors operate on phase-switched d-c power. The motor shaft advances 200 steps per revolution (1.8° per step) when a four-step input sequence (full-step mode) is used and 400 steps per revolution (0.9° per step) when an eight-step input sequence (half-step mode) is used. Power transistors connected to flip-flops or other logic devices are normally used for switching as shown in the wiring

diagram. The four-step and eight-step input sequences are also given in the charts. Since current is maintained on the motor windings when the motor is not being stepped, a high holding torque results. Six-lead motors can be used as five-lead motors by connecting the black and white motor leads together. Use a dropping resistor that is one-half the resistance and twice the wattage of that required for six-lead connection.

STEP	SW1	SW2	SW3	SW4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
5	ON	OFF	ON	OFF

STEP	SW1	SW2	SW3	SW4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
9	ON	OFF	ON	OFF

STATIC LOAD

When a load torque is applied to the rotor shaft, the shaft will move from the no-load position. The curve shows shaft deflection vs. percent of rated holding torque for all 1.8° SLO-SYN motors.

TRANSIENT VOLTAGE SUPPRESSION

Transient voltages are generated as current is switched through the windings during stepping. These voltages can cause faulty operation and damage to the motor or drive components unless a means of limiting or removing them is provided. The most common method for suppressing transient voltages uses shunting diodes as shown in the wiring diagram.

(Continued on page 16)

TRANSIENT VOLTAGE SUPPRESSION (Cont'd)

Typical diodes for this purpose are 1N4002, 1N4003 and similar types. Resistance may be varied between 0 and 50 ohms, as needed, to reduce transient voltages to the desired level. Capacitors can also be used in place of the diodes. Capacitor values can be varied between 0.1 and 1.0 mfd. to suit the characteristics of the switches used.

HOLDING AND RESIDUAL TORQUE

Because of the permanent magnet design, a SLO-SYN stepping motor has a small residual torque which holds the motor shaft in position when the motor is not energized. Much greater holding torque can be obtained by keeping one or both motor windings energized with d c voltage when the motor is not stepping. The Ratings and Specifications charts (pages 29 and 30) list values for each motor for residual torque and for holding torque with both windings energized at rated voltage and current. Holding torque with only one winding energized will be within 60% to 75% of the rating given for both windings energized.

OTHER STEP ANGLES

Bifilar-wound versions of the TS and LS series of motors are available as standard to provide a greater choice of step angles. The TS series motors provide step angles of 5° in the full-step mode and 2.5° in the half-step mode. Step angles with LS series motors are 0.72° in the full-step mode and 0.36° in the half-step mode. Complete ratings and specifications for these motors are given in the DC Stepping Motor charts.

A 15° step angle motor is also available. The M051-DW01 motor is a variable reluctance motor which is constructed using Class F insulation and provides 24 steps per revolution of the motor shaft. Step accuracy is $\pm 3\%$ noncumulative. The performance curve shows speed vs. torque characteristics for the M051-DW01 motor when driven by a 3-phase, 28 VDC drive.

A permanent magnet motor which provides a 15° step angle is also available. This motor is physically similar to the M061 and is 2 1/4" in diameter and is wound for 2- or

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4-phase operation. Step angles of 2° and 2.5° are also available. Others can usually be supplied. Submit requirements to the factory.

TORQUE VS. SPEED CHARACTERISTICS

The torque vs. speed characteristics of a SLO-SYN stepping motor are greatly dependent on the drive circuit used to step the motor. A set of curves is given for each family of SLO-SYN Motor Controls showing the torque vs. speed characteristics for various SLO-SYN motors when driven by these controls. Each set of curves includes the motors having windings which are the best impedance match for the specific motor control. All SLO-SYN motor controls except the STM1800D and STM1800DV translator modules employ the full-step drive mode. The STM1800D and STM1800DV can be operated in either the full- or the half-step mode. Complete details on each control are given in the SLO-SYN Motor Control section of this catalog.

TORQUE VS. SPEED CHARACTERISTICS

STM1800, STM1800V TRANSLATOR MODULES

ST1800B, ST1800BV TRANSLATORS

SP1800B-5 PRESET INDEXERS

These motor controls are 15VDC, unipolar, L/R type drives. The torque vs. speed curves show both running and start without error characteristics for each motor. With a given load, a motor must be started at the speed shown in the lower curve. Once the motor has started, speed can be increased to that shown in the upper curve. However, when operated from an SP1800B-5 Preset Indexer, the motor can be started at the rate shown in the upper curve since the control automatically provides acceleration to this rate. The curves shown were obtained with various torque loads and with negligible external inertia.

STEPPING MOTORS

RATINGS AND SPECIFICATIONS MECHANICAL SPECIFICATIONS, 1.8° SLO-SYN® STEPPING MOTORS

BASIC MOTOR SERIES	NOMINAL RATED TORQUE (OZ-IN)	HOLDING TORQUE* (OZ-IN)	RESIDUAL TORQUES (OZ-IN)	ROTOR INERTIA (LB-IN ²)	TORQUE TO INERTIA RATIO †	NUMBER OF LEADS OR TERMINALS	SHAFT DIAMETER (INCHES)	MAXIMUM OVERLOAD LOAD (LB)	MAXIMUM THRUST LOAD (LB)	APPROX. WEIGHT (LB)	
										NET	SHIPPING
M051	35	53	5	0.03	42 × 10 ³	6	.250	15	25	1½	1½
M062	65	100	8	0.08	30 × 10 ³	6	.250	15	25	2	2½
M083	100	150	10	0.11	33 × 10 ³	6	.250	15	25	2½	3½
M091	110	150	5	0.22	16.3 × 10 ³	6	.375	25	50	3½	4
M092	200	300	10	0.42	17.2 × 10 ³	6	.375	25	50	5½	6½
M093	300	450	15	0.64	16.8 × 10 ³	6	.375	25	50	7½	9
M111	425	625	15	1.34	11.2 × 10 ³	6	.375	25	50	5	9½
M112-FD	840	1125	30	2.75	9.8 × 10 ³	6	.500	25	50	14½	18½
M112-FI	840	1125	30	2.75	9.8 × 10 ³	6	.625	25	50	14½	16½
M113	1360	1900	55	4.1	11.1 × 10 ³	6	.625	25	50	22	25
M112	1900	2700	150	21	31 × 10 ³	6	.625	50	100	60	56
X1000	1000	1600	40	10.4	3.7 × 10 ³	5	.625	50	100	31	33
X1500	1500	2500	100	13.0	4.6 × 10 ³	5	.625	50	100	38	42
SS1600	1800	3000	75	15.8	4.6 × 10 ³	5	.625	50	100	45	50

*Both windings energized at rated current. †Approximate value with neither winding energized. ‡Calculated from holding torque in oz.-in., and rotor inertia in oz.-in.-sec.² (lb.-in.²/24).

ELECTRICAL RATINGS, 1.8° SLO-SYN® STEPPING MOTORS

MOTOR TYPE		TIME FOR SINGLE STEP† (in sec) ¹	DC VOLTS	2X AMPERES PER WINDING	RESISTANCE WINDING (25°C)	INDUCTANCE (MILLI-AMPERES PER WINDING)
3% ACCURACY	5% ACCURACY					
M051-FC02	M051-FC02	2.5	5.1	1.0	5.1	10.0
M051-FC08	M051-FC08	2.0	7.3	3.9	0.33	0.03
—	M051-FC031	7.5	11.8	0.44	5.9	11.0
—	M051-FC032	4.2	5.8	0.88	5.6	3.5
—	M051-FC011	12	23.6	0.22	85	142
M062-FC03	M062-FC03	3.5	5.3	1.6	3.4	8.6
M062-FC04	M062-FC04	2.8	4.3	1.8	2.6	5.7
M062-FC08	M062-FC08	2.2	1.7	4.7	0.77	0.8
M083-FC06	M083-FC06	2.6	3.4	2.9	1.16	2.9
M083-FC08	M083-FC08	2.4	2.2	4.8	0.48	1.2
M091-FC03	M091-FC03	8.5	5.5	1.3	3.5	16.2
M091-FC05	M091-FC05	3.9	2.9	3.1	0.95	3.8
M091-FC08	M091-FC08	3.1	1.8	4.7	0.39	1.5
—	M091-FC038	11	8.0	0.65	7.3	27.5
M092-FC08	M092-FC08	3.9	2.5	4.6	0.55	2.5
M093-FC07	M093-FC07	6.3	4.5	3.5	1.1	5.5
M093-FC11	M093-FC11	4.1	2.8	5.5	0.52	2.0
M093-FC14	M093-FC14	3.4	2.2	7.0	0.31	1.85
—	M111-FC12	4.4	2.3	6.1	0.37	2.4

MOTOR TYPE		TIME FOR SINGLE STEP† (in sec) ¹	DC VOLTS	AMPERES PER WINDING	RESISTANCE WINDING (25°C)	INDUCTANCE (MILLI-AMPERES PER WINDING)
3% ACCURACY	5% ACCURACY					
—	M111-FC18	4.0	1.7	8.0	0.21	1.1
—	M111-FC032	27	9.0	7.95	4.6	30
—	M111-FC010	32	10	1.25	7.0	45
—	M111-FC027	23	4.6	3.1	1.1	3.3
—	M112-FC06	7.5	7.2	3.1	2.3	22
—	M112-FC08	7.0	5.7	3.8	1.5	14
—	M112-FC08	8.5	4.7	4.7	1.0	9.0
—	M112-FC12	5.5	3.6	6.1	0.50	5.3
—	M112-FC25	6.0	1.8	12.7	0.14	1.0
—	M113-FC40	6.5	1.3	20	0.062	0.5
—	M113-FC031	24	6.8	20	0.040	0.45
—	X1000-1002	33	10.0	3.8	2.9	45
—	X1500-1001	35	12.0	3.8	3.2	31
—	X1500-1002	35	8.0	5.3	1.5	13
—	SYNCS-1031	70	14.4	3.1	4.0	66
—	S81800-1007	50	11.5	3.9	2.3	48

†With 24 volt d-c drive. See step function curve, page 30.

slo-syn®

BASIC MOTOR TYPES

M051

DC STEPPING MOTOR DIMENSIONS

**M061
M062
M063**

BASIC MOTOR TYPE	DIMENSION A	MAX. STEPPING ANGLE VARIATION 5% OF ONE STEP NONCUMULATIVE	MAX. STEPPING ANGLE VARIATION 5% OF ONE STEP NONCUMULATIVE
M061	1.500 (38.1 mm)	± 0.001 (0.025 mm) MAX.	± 0.001 (0.025 mm) MAX.
M062	1.500 (38.1 mm)	± 0.001 (0.025 mm) MAX.	± 0.001 (0.025 mm) MAX.
M063	1.500 (38.1 mm)	± 0.001 (0.025 mm) MAX.	± 0.001 (0.025 mm) MAX.

**M091
M092
M093**

BASIC MOTOR TYPE	DIMENSION A	MAX. STEPPING ANGLE VARIATION 5% OF ONE STEP NONCUMULATIVE	MAX. STEPPING ANGLE VARIATION 5% OF ONE STEP NONCUMULATIVE
M091	1.500 (38.1 mm)	± 0.001 (0.025 mm) MAX.	± 0.001 (0.025 mm) MAX.
M092	1.500 (38.1 mm)	± 0.001 (0.025 mm) MAX.	± 0.001 (0.025 mm) MAX.
M093	1.500 (38.1 mm)	± 0.001 (0.025 mm) MAX.	± 0.001 (0.025 mm) MAX.

HDM-150 MOTORS

FOUR PHASE: **EIGHT PHASE:**
HDM-150-1000-4 **HDM-150-2000-8**
HDM-150-800-4 **HDM-150-1600-8**

	4 PHASE		8 PHASE	
	800 Steps/Rev	1000 Steps/Rev	1600 Steps/Rev	2000 Steps/Rev
Step Size (Degree)	0.45	0.36	0.225	0.18
Steps Per Revolution	800	1000	1600	2000
Rated Torque (in. lbs.)	10	10	10	10
Holding Torque (in. lbs.)	18	18	18	18
Max. Step Rate Per Sec.	1500	1500	3000	3000
Rotation	Bi-directional	Bi-directional	Bi-directional	Bi-directional
Recommended Driver	LD-4-5	LD-4-5	LD-8-5/D-4-5	LD-8-5/D-4-5
Winding	4 Phase 5 Wire	4 Phase 5 Wire	8 Phase 9 Wire	8 Phase 9 Wire
Resistance Per Phase (ohms) At 20°C	5	5	10	10
At Operating Temperature	6.6 (Approx.)	6.6 (Approx.)	13 (Approx.)	13 (Approx.)
Rated Current (amps) Per Phase	1.5	1.5	0.75	0.75
Total	3	3	3	3
Switching Sequence	AB,BA,AB,AB etc.	AB,BA,AB,AB etc.	AC BD,CB DA, BD AC,DA CB,etc.	AC BD,CB DA, BD AC,DA CB,etc.
Torsional Stiffness (in. lb./rad.)	1640	1640	1640	1640
Equivalent Rotor Inertia Lb. in. ²	0.07	0.07	0.07	0.07
Lb. in. Sec. ²	0.00017	0.00017	0.00017	0.00017
Weight (lbs.)	3.3	3.3	3.3	3.3

HDM-15-480-4 MOTOR

SPECIFICATIONS

Step Size (Degree)	0.75
Steps Per Revolution	480
Rated Torque (in. oz.)	22
Holding Torque (in. oz.)	24
Max. Step Rate Per Sec.	2400
Rotation	Bi-Directional
Recommended Driver	LD-4-5
Winding	4 Phase 5 Wire
Resistance Per Phase (ohms) At 20° C	5
At Operating Temperature	6.6 (Approx.)

Rated Current (amps)	
Per Phase	1.2
Total	2.4
Switching Sequence	AB, BĀ, ĀB, AB etc.
Torsional Stiffness (in. lb./rad.)	236
Equivalent Rotor Inertia	
Lb. In. ²	.0012
Lb. In. Sec. ²	1.3×10^{-6}
Weight (ozs.)	18

LOAD INERTIA VS. SPEED FOR
ERROR FREE START-STOP

OUTPUT TORQUE VS. SPEED

APPENDIX B

CAPABILITIES AND EXPERIENCE

1.0 RELEVANT BACKGROUND

AESC qualifications for design and fabrication of the SHIVA control system stem from extensive background and facilities for design, fabrication, and test of electro-optical systems and from recent participation in the preliminary design phase of the Laser Fusion System Study.

Aerojet experience in the control system area has developed over a period of 20 years of extensive design studies, equipment design, hardware fabrication, and laboratory testing of electro-optical-mechanical control systems. This experience comes from the design of servos, signal processing systems and gimbals required to stabilize, point and track infrared missile seekers, imaging systems, surveillance systems and cameras. Accuracy levels achieved are comparable to those required by this program. The years of experience of the engineers who developed these advanced control systems are available to SHIVA at AESC.

Table B-1 is a partial listing of directly related programs by contract number, title, and contract value. These programs illustrate the breadth of 20 years' experience in electro-optical systems wherein electronics, optics, sensors, and controls have been developed.

Table B-2 is a matrix which lists the most directly relatable programs and their specific areas of applicable engineering experience and expertise. The equipment listed in Table B-2 is basically divided into four categories, each of which will be briefly described in the following paragraphs.

Equipment with the letter T preceding the model number is optical tracking gimbal systems. That is, they comprise a gimbal, a servo, and an

TABLE B-1 RELATED CONTRACTUAL EXPERIENCE

Contract No.	Customer	Title	Contract Value (\$)
N00019-75-C-0120	Naval Air Systems Command, Washington, D.C.	Scan Converter/Image Stabilized Scanner	99,610
N00156-73-C-0326	Naval Air Engineering Center, Philadelphia, Pa.	Dual Seeker Concept Validation Program	43,470
N00019-69-C-0676	Naval Air Systems Command, Washington, D.C.	Captive flight, free- flight model and FLIR	1,237,045
N00019-68-C-0509	Naval Air Systems Command, Washington, D.C.	Air-to-surface seeker	559,000
F33615-70-C-1779	Air Force Avionics Lab., WPAFB, Ohio	Night Owl Seeker Study	95,000
F33615-70-C-1568	Air Force Avionics Lab., WPAFB, Ohio	OASIS Study	93,000
PL-78372-S	AVCO-Everett Research Lab., Everett, Mass	TRAP-1 Servo-Gimballed Pedestals	1,000,000
DAAH01-67-C-2194	U.S. Army Missile Command	Passive optical seeker (POS) for forward area air defense	63,000
DAAA25-67-C-0471	Frankford Arsenal, Philadelphia, Pa.	Forward-looking infrared (FLIR) fire-control system	8,680,000
F04695-67-C-0034	Air Force Space and Missiles Systems Organization, Los Angeles (SAMSO)	W71 Sensor Program	140,000,000
F33657-67-C-0727	Aeronautical Systems Division, WPAFB, Ohio	AMSA Task IV Infrared	1,500,000

TABLE B-1 RELATED CONTRACTUAL EXPERIENCE (cont.)

Contract No.	Customer	Title	Contract Value (\$)
AF 04(695)-371	Air Force Space and Missiles Systems Organization, Los Angeles, Calif.	W66 Sensor Program	64,000,000
AF 04(694)-720	Air Force, SAMSO Los Angeles, Calif.	Measurements and Data Reduction, TRAP 7	3,975,000
F33615-70-C-1799	Aeronautical Systems Division, WPAFB, Ohio	AAA Detection System	497,317
DAHC-60-69-C-0033	U.S. Army Advanced Ballistic Missile Defense Agency (ABMDA), Huntsville, Ala.	Special defense program	99.553
F33615-69-C-1314	Aeronautical Systems Division WPAFB, Ohio	Optical feature extraction	92,800
N00019-69-C-0428	Naval Air Systems Command, Washington, D.C.	LWIR mosaic, captive-flight test system	166,859
DAHC-60-70-C-0006	U.S. Army SAFEGUARD System Command, Huntsville, Ala.	Missile sensor study	237,748
DAHC-60-70-C-0018	U.S. Army SAFEGUARD System Command, Huntsville, Ala.	Detector-preamplifier	116,428
F33625-69-C-1679	Air Force Avionics Lab., WPAFB, Ohio	High density multispectral	96,500
DAAH01-67-C-1964	U.S. Army Missile Command	IRDA for forward-area air defense	71,000

TABLE R-2 AESC SYSTEM TECHNOLOGY

	Sensor Model														
Technology Area	T8	T9	T29	T38	T77	TRAP 1	TRAP 7	FLIR	W28	W66	W71	J186	T200	HERVA	L ³
Electro-optical LOS error signal processing	x	x	x	x	x	x	x	x		x	x				x
<u>Basic Accuracy</u>															
< 50 sec	x				x			x		x				N/A	
< 5 sec or 25 μ rad						x	x		x		x				x
< 1 sec or 5 μ rad		x		x								x	x		x
< 1/10 sec w 1 μ rad			x												x
Piezo-electric crystal drives			x	x											x
Ultra precision bearing & gimbals		x	x		x	x	x		x			x	x		
Multiple control channels						x	x			x	x	x	x		
<u>Aperture</u>															
> 12 in.			x							x	x	x	x		x
< 6 in.					x			x						N/A	x
Digital processing system					x			x		x	x	x	x		x
Integration of vehicle & facilities	x	x			x		x	x	x	x	x			x	x
Use of torque motors, gyros, & resolvers		x	x	x	x	x	x	x	x			x	x		
Video tracking					x		x	x			x				

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electro-optical error sensor which develops the necessary error signals for the servo to null the line of sight error. To illustrate the range of experience in optical trackers, two examples of hardware are shown in Figures B-2 and B-3. Figure B-1 is a 1-meter aperture telescope (T-29) which is capable of target tracking to accuracies of better than 1/10 second of arc. Figure B-2 is a small seeker/tracker which develops pointing error signals by video processing of the target image. This type of tracker points at the target centroid for increased precision.

Equipment prefaced with the letter W is surveillance equipment, which searches specific areas with multiple channels of detectors. Its purpose is to generate target positional data by processing the coincidence of target and detector. By noting the detector location, the time of coincidence, and some reference data, one is able to track known targets. Figure B-3 illustrates the W-71 sensor, a system having a very large number of highly accurate data channels.

FLIR systems require a high degree of gimbal stability to achieve high resolution imagery. Figure B-4 is a photograph of an Aerojet FLIR sensor mounted on a UH-1C helicopter. This system uses a four-axis stabilized gimbal, and adaptive gate video processing to provide closed loop tracking.

The J series equipment was in-house test equipment developments that were required to permit performance testing of space surveillance equipments to the required accuracy. Figure B-5 illustrates this equipment. The pointing and readout accuracy performance of these units is comparable to L^3 requirements. Stabilization and structure techniques have shown methods for solution of L^3 problems.

The NERVA control work was in support of the NERVA nuclear rocket engine program and involved both engine related controls and test facility controls. The engine controls program maintained the nuclear rocket engine thrust chamber pressure and temperature levels during start up, run, and

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FIGURE B-1 PRECISION 1-METER TRACKING TELESCOPE

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971-084

FIGURE B-2 PROTOTYPE SEEKER GIMBAL

FIGURE B-3 0.6 METER IR TELESCOPE

CN 270-093

FIGURE B-4 FLIR FIRE CONTROL SYSTEM (AN/AAQ-5)

FIGURE B-5 J-225 OPTICAL TEST SYSTEM

shut down in conjunction with other engine control systems, such as tank pressure and cool down, as well as facilities controls for cryogenic pumping and purging of propellants.

The TRAP systems were designed to point optical instruments at designated targets while in flight aboard a KC-135 aircraft. Figures B-6 and B-7 are photographs of the three and four axis TRAP gimbals, while Figure B-8 shows the gimbals on board the aircraft. Each aircraft system pointed the master tracking sensor at the expected target area and was provided with automatic acquisition. The master tracker followed the target and provided gimbal commands for the five slave systems to follow.

A number of technology capabilities were required to accomplish these programs, including signal processing design, controls design, and gimbal design. For example, the signal processing systems designed for these programs have included AM, FM, pulse width, pulse location, pulse amplitude, and gated video techniques. The signal levels were quite low and are generally limited by thermal or background noise voltages. These signals require filtering, precise shaping, and automatic gain processing to generate a voltage proportional to the angular line of sight error for each axis of the servo system.

The accuracy is generally determined by a combination of servo and signal processing. The accuracy region of these tracking systems is generally comparable to that required by the L^3 program, particularly when normalized to comparable configurations. Laboratory testing of these systems verified their performance. AESC has the equipment and personnel to perform the precision measurements.

Aerojet is also experienced in multiple axis servo systems. The TRAP systems have approximately 25 servo axes per system and represent a complexity which is comparable to the laser system.

CN 969-004

FIGURE B-6 TRAP-1 SERVO-GIMBALED PEDESTALS

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166-374

FIGURE B-7 TRAP-7 FOUR-AXIS GIMBAL

CN 566-084

FIGURE B-8 TRAP-7 GIMBAL SYSTEM INSTALLATION KC-135

The NERVA control system, built by AESC, controlled a number of interdependent variables, each requiring precise start up, run, shut down, and cool down time phasing with the highest reliability in operation. The immense quantity of energy being generated could easily be improperly released in the advent of a control failure.

2.0 AEROJET ELECTROSYSTEMS COMPANY FACILITIES, EQUIPMENT, AND ORGANIZATION

AESC is an autonomous company. A major operating element of Aerojet-General Corporation of El Monte, California, it evolved from AGC's former Electronics Division. Thus, it is part of the billion-dollar General Tire and Rubber family of companies and enjoys the fiscal stability of a large company while retaining the flexibility and vigor of a moderate-sized business.

AESC is actively engaged in the development and production of electro-optical systems, and associated data systems hardware and software. Work in optical discrimination has covered fields from basic system analysis, through algorithm development and implementation, to sensor fabrication and sensor data processing. Aerojet has more than 20 years of solid experience in optical sensor technology.

The AESC facilities are located on 75 acres with 945,000 sq ft divided into the following general functional areas:

	<u>Area, sq ft</u>
Office space	407,000
Laboratory and testing	100,000
Manufacturing	205,000
Storage	149,000

Available AESC facilities and equipment, in conjunction with specialized commercial model shops, are adequate to perform the SHIVA design, development, and test program. The specific facilities and equipment that

would be used in support of the program are described in the following paragraphs. No new facilities or equipment are required.

AESC provides a Study Center for work on contracts which are basically study or design oriented. Its use offers several benefits to AESC customers. Since manufacturing and major test facilities are not involved, the Study Center carries a significantly lower overhead burden, and hence more direct labor hours can be provided for given dollar amount. In addition, the Study Center provides exclusive use of the services of key personnel during their period of assignment to the program.

Within the 100,00 sq ft allocated to laboratories, development shops, and testing operations, individual shop facilities of varying sizes provide the capability for research, product development, and testing within the broad product lines of electro-mechanical, electro-optical, and electronic systems, and associated subsystems, and components. Typical laboratories of particular interest to the proposed program are as follows:

2.1 MANUFACTURING MODEL SHOP

AESC maintains a precision model shop which is primarily geared to one-of-a-kind fabrication and is located for convenient liaison with the design engineer or program staff members. This shop fabricates prototype hardware, and is used in conjunction with outside speciality shops as required to accomplish mechanical system manufacturing.

2.2 ELECTRONIC LABORATORY

The assembly of electronic circuitry will be accomplished in the electronic laboratory. This laboratory contains the skilled personnel and equipment necessary to assemble the electronic components in printed circuit cards or on cards suited for computer program wiring.

2.3 VIBRATION AND SHOCK LABORATORY

A shock and vibration laboratory is designed to test and provide data on displacements, deflections, reactions, vibrations, resonances and

their intercorrelation over a significant range of frequencies. It is fully instrumented and capable of accurate control and data results to aid development and manufacture of components and systems according to military specifications.

2.4 SUPPORT FACILITIES

A primary calibration standards laboratory is maintained at the Aerojet facilities in Azusa. All equipment is periodically cycled through the calibration facility to ensure the accuracy of laboratory test equipment. Calibrations are performed by competent, experienced technicians to written procedures issued by the Naval Ordnance Systems Command, the Air Force, or the appropriate manufacturer. The laboratory is constructed in accordance with National Bureau of Standards Bulletin 578, and is operated consistent with MIL-Q-45662, NASA NPC 200-2, and MIL-Q-21549 requirements.

3.0 COMPANY AND PROGRAM ORGANIZATION

3.1 COMPANY ORGANIZATION

AESC is functionally organized to provide its customers with the professional staff required to efficiently manage and execute programs. As shown in Figure B-9, the company is under the direction of Mr. Sheldon Jones, President, with company directors for functional areas, such as Engineering, Marketing, Industrial Relations, Manufacturing, Materiel, and Quality Assurance. Technical development programs are the responsibility of Engineering and specifically the project engineer assigned to the program.

3.2 ENGINEERING ORGANIZATION

The AESC Engineering organization is based on providing specialized project engineering for each program and on supporting the project engineers with basic functional engineering disciplines from design service organizations. This type of organization provides highly competent technical direction to each program, while performing detail design by technical specialists.

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FIGURE E-9 AESC ORGANIZATION

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The project engineers coordinate and monitor the design as it progresses through the functional design group, follow the fabrication, and perform the checkout and integration of the systems.

The design organization is composed of 90 technical personnel, one-third of which are electrical or electronic design engineers, and the remaining are optical or thermal or mechanically oriented. Figure B-10 is an organization chart for the design engineering section.

3.3 SHIVA DETAILED DESIGN PROGRAM ORGANIZATION

The Laser Fusion Control System will be performed at AESC, Azusa, California. To provide for optimum efficiency, the principal individuals will be the same as those who performed the SHIVA design study.

All of the individuals performing technical tasks on the program are under the direction of AESC's Director of Engineering, as shown in Figure B-11. Thus, integrated administration, as well as project direction of the program, is readily accomplished.

The individual task leaders have participated in the preliminary design phase and will provide the design coordination and liaison to the design or analysis groups. Brief resumes have been included in the following pages.

FIGURE B-10 AESC DESIGN ENGINEERING

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FIGURE B-11 PROGRAM ORGANIZATION

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EUGENE H. DRYDEN - Project Engineer

Education

BS, MS (EE) - California Institute of Technology

Experience

During his 16 years at AESC, Mr. Dryden has been responsible for the design and development of a large number of infrared and electro-optical guidance, homing and tracking sensors. He has also been responsible for the development of precision gimbal stable platforms, precision tracking infrared theodolites, specialized controls, and electronic systems. He has participated in and directed design and study efforts concerning application of systems to ballistic missile defense. In this capacity, he has been concerned with combinations of system analysis, system design, and mechanical, thermal, and electronic design. Mr. Dryden previously directed all electrical and electronic design and development work at AESC on search, tracking, surveillance, guidance, instrumentation and communications equipment. His responsibilities also included the analysis and synthesis of specialized signal-processing systems for high-performance infrared satellite sensors. Mr. Dryden is a member of Tau Beta Pi and the American Ordnance Association. He has on file, or applied for, several patents for infrared signal processing techniques. He is an author or co-author of several classified technical papers relating to state-of-the-art infrared tracking devices.

BRUCE W. LITTLE - Electrical Engineer

Education

BSEE - University of California at Los Angeles; graduate studies, automatic controls and electronics, UCLA

Experience

Mr. Little has 18 years of project management and design engineering experience with several major electronic and electro-optical engineering companies in Southern California. His most recent responsibility has included the design and development of a real-time thermal imaging system designated the AN/AAQ-5 FLIR. All systems have been delivered and are presently undergoing tactical field evaluation. Prior assignments at AESC included management of an Electronic Design Department in which he participated in the detail design and development of the electronics for signal processing systems for IR search track equipments, as well as the servo design for stable platforms and trackers. Prior to joining AESC in 1968, he was employed at Electronic Engineering Company and Hughes Aircraft Company where he was involved in design engineering for the development of digital computers and servo controls. Mr. Little is a registered professional electrical engineer in the state of California.

JAMES R. GRIME - Mechanical Engineer

Education

BSME - University of Southern California;

BSME - University of Southern California

Experience

Mr. Grime has over 19 years of experience in the design and development of infrared instruments including cryogenically cooled seekers and radiometers, thermal imaging air-to-surface seekers, and the FLIR system. He was Program Manager on the AEMDA Missile Sensor Study and Cold Optics Study Program. He was responsible for testing the Aerojet cold optics M48 Radiometer at AEDC, Tullahoma. Previously, Mr. Grime participated in the mechanical, thermal, and optical design efforts on the Aerojet AN/AAQ-5 FLIR, IR Target and Groundspeed Simulator, and AMSA programs. He has been responsible for the design and development of diverse optical and optical-related equipment, including wide-angle IR trackers and search sets, IR cameras, radiometers and spectrometers, specialized test equipment, solid cryogen coolers, thermally compensated telescopes for space application, and precision gimbals for highly accurate infrared tracking and surveillance sensors.

ROY Y. KAKUDA - System Analysis

Education

KSEE - California State Polytechnic College

Experience

Mr. Kakuda has extensive experience in the design, analysis, and testing of star sensors for attitude determination of space satellites. He has spent the majority of his career in work on the design of feedback systems, both digital and analog servo systems. Recently, Mr. Kakuda has been performing electro-optical system design and analysis on infrared imaging and detection systems. The tasks performed include the requirements definition of optical systems, focal planes, thermal control systems, and signal processing systems.

Mr. Kakuda has two patents on solid-state synchro-to-digital converters and has presented a paper to the Bureau of Naval Weapons Symposium on Rotating and Static Components.

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