

NASA-CR-194419

Final Report

1N-74-CR

186128

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Dynamic System Technologies, Inc.
P.O. Box 18213, Huntsville, Alabama 35804-8213

**Small Scale Adaptive Optics Experiment
Systems Engineering**

Prepared by
William H. Boykin, Ph.D.
Technical Report No. HSV-93-0003

for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

under

NASA Contract NAS8-39216

N94-14548

Unclas

G3/74 0186128

(NASA-CR-194419) SMALL SCALE
ADAPTIVE OPTICS EXPERIMENT SYSTEMS
ENGINEERING Final Report (Dynamic
System Technologies) 41 p

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1.0 BACKGROUND AND PURPOSE

Adaptive optics are used in telescopes for both viewing objects with minimum distortion and for transmitting laser beams with minimum beam divergence and "dance". Small scale experiments are conducted to prove, at lowest cost, that advanced concepts of physics and engineering design are valid. After confidence is gained by way of small scale experiments, the developer proceeds with development of the higher cost, full scale system.

Adaptive optics have been applied to relatively small telescopes before. Small telescopes have apertures of the order of 1 meter in diameter. In order to provide high power reliably to spacecraft and to the moon by laser energy beamed to them, a much larger telescope is needed. A much larger telescope would have a diameter of the order of 10 meters. Since the larger telescopes have aperture areas that are 100 times greater than those of small telescopes, most aspects of the adaptive control of the larger telescopes would be expected to be two orders of magnitude more complex than similar control of the smaller telescopes.

Our work has supported Marshall Space Flight Center in the development of a small scale adaptive optics prototype and experiment. Adaptive optics work is on-going at Marshall Space Flight Center. The primary emphasis of our work was on reducing the complexity of the adaptive optics control system, and included the following specific tasks.

The first task was to assess the current technology relating to the laser power beaming system, which in full scale is called the Beam Transmission Optical System (BTOS). Over the last several years a number of researchers from industry, universities and government have been investigating technologies for components and subsystems. They have arrived at a preliminary design, identified risks and constructed small scale prototypes of elements and subsystems. Our initial assessment concluded that for a full scale BTOS of about 12 meters in diameter, the current technology and preliminary design using that technology is far too complex for reliable performance. Our final assessment developed herein produced the same conclusion. The question then arises, how can this complexity be reduced? We have laid a framework herein to answer that question.

The BTOS has been envisioned to consist of: (1) a beam expander to maintain beam collimation and to reduce the laser power density (watts/m²) levels well below damage thresholds, (2) a "pointing" subsystem to point the beam expander (and thereby the laser) at the target, (3) an adaptive beam expander optics subsystem to compensate for atmospheric diffraction (and any other observable defraction) of the beam, (4) fast steering optics to adjust for global beam tilts, (5) digital controls of the pointing, fast steering and adaptive subsystems, and (6) a health maintenance system that includes power and thermal conditioning subsystems.

The second task was to evaluate the system integration efforts being conducted by the various government agencies and industry. We were to recommend actions to correct any system integration shortfalls. In addition, we were to attend design review meetings.

The third and final task was to develop concepts for prototypes of adaptive optics for a BTOS. These prototypes were to be constructed at Marshall Space Flight Center. The prototype to be used in small scale experimentations was to be composed of 7 to 36 individually controlled optical elements, actuators for control actuation, drive electronics, a gimbal pointing subsystem, and various sensors for feedback control.

Our assessment of the current technology and the development of BTOS prototype concepts had to be innovative since current concepts are quite complex and carry with them the risks associated with high complexity. Herein, we have taken what we believe is a "fresh" look at BTOS design and have defined an approach with fewer risks. In order to reduce the BTOS's complexity and number of high risk elements, it was found that end-to-end sensing of optical phase errors and a stiff control system design is needed. An end-to-end sensing and control system would measure across a chain of sensing and control elements and eliminate their errors. The current chain of elements and their error contributors are discussed below in **Section 2**. As discussed in **Section 3** only the residual error of the end-to-end sensing system and some uncompensated servo errors would remain. An adequate end-to-end sensing subsystem apparently needs to be "invented". An end-to-end sensing subsystem has high development risk associated with it, since it does not yet exist. Although the chain of elements is reduced so that risk to reliable performance is reduced by the end-to-end approach, the risk of any invention is, by definition, high. Since this effort falls under advanced systems, some elements of high risk should be acceptable as long as there are parallel developmental efforts to develop high risk items for risk reduction.

2.0 BTOS BEAM DIVERGENCE ASSESSMENT

The **current** technology relating to the Beam Transmission Optical System (BTOS) is assessed in this section. Here we only investigate beam divergence and its control. Equally important are laser beam pointing errors caused by automatic target tracking errors and servo stabilization errors. The tools of this beam divergence assessment are error trees down to the lowest, significant errors sources; and, sensitivity analyses of beam divergence to the critical error source parameters. We begin with the construction of the beam divergence error sources.

2.1 Beam Divergence Error Sources

To date a number of error trees have been constructed for various purposes. These error trees appear to either represent the view of the optiker or the control engineer. That is, one error tree contains basic natural physical effects while another depict only residual errors of the controlled system. The author believes that a single diagram with both uncorrected (natural) errors and control system residual (corrected) errors may be

helpful. Such an error tree may be helpful because it clearly shows how our man-made inventions may correct for natural errors. With an error tree that covers all error contributors from source to sink it is easy for the designer to see how an end-to-end and nested control system might be designed in order to minimize complexity. First we develop diagrams of system elements with their sources of errors or imperfections.

Figure 2.1-1 provides a top level view of system elements within (1) the BTOS and (2) the reference beacon measurement system when no control compensation is applied. Potential controls are indicated by C. This top level view shows error sources from a control system prospective. That is, it overlays errors (caused by imperfections from our ideal design concept) with subsystems, subsystem measurements, and their control inputs (where available). This figure does not provide the control system needed to compensate for imperfections. It does indicate potential measurement device locations. Such measurement devices, if available, might be used within the control system to compensate for errors caused by the imperfections.

When an error source is compensated (to reduce the error effect of that source), the compensation uses measurements of the error source to "cancel" the error. However, this compensation does not do a perfect job and leaves a residual error. In an error tree this residual error replaces the error of the source being compensated. In **Figure 2.1-1** the left side represents the basic system elements without adaptive optical details. This basic system can be considered as a system without adaptive optics compensation. The right side of this figure illustrates potential information (measurements) that might be used in the control compensation of system (including atmosphere) errors. A laser beacon located above the atmosphere and near the line between the BTOS and the target center must be pointed back at the BTOS as shown. The beacon's rays must be diffracted by the same atmospheric turbulence effects as the power beam to the target. Such a reference beacon is part of any of the measurement subsystems shown. When such measurement subsystems are used in a control system to reduce certain BTOS beam imperfections, the corresponding error tree should show the basic system errors replaced by the residual errors of the compensating control subsystem.

The free electron power laser is expected to have "ideal" phase and amplitude characteristics, but they will not be flat and must be accounted for. However, the end-to-end approach could also compensate for power laser imperfections were they to occur. This compensation would be external to the power laser.

A fast steering mirror could be needed to globally correct for beam tilt that is not practicable to correct with either the massive BTOS's beam expander's structure's gimbal control or any adaptive optics on this structure. This fast steering mirror introduces both optical and steering errors. Mirror flatness and reflectivity are the optical error sources. Steering errors are due to imperfections in sensing and control actuation, and basic "shaping" limitations (frequency response). A fast steering mirror adds errors and complexity to the system. We should not use a fast steering mirror unless it has a net payoff in reducing errors and complexity someplace else in the

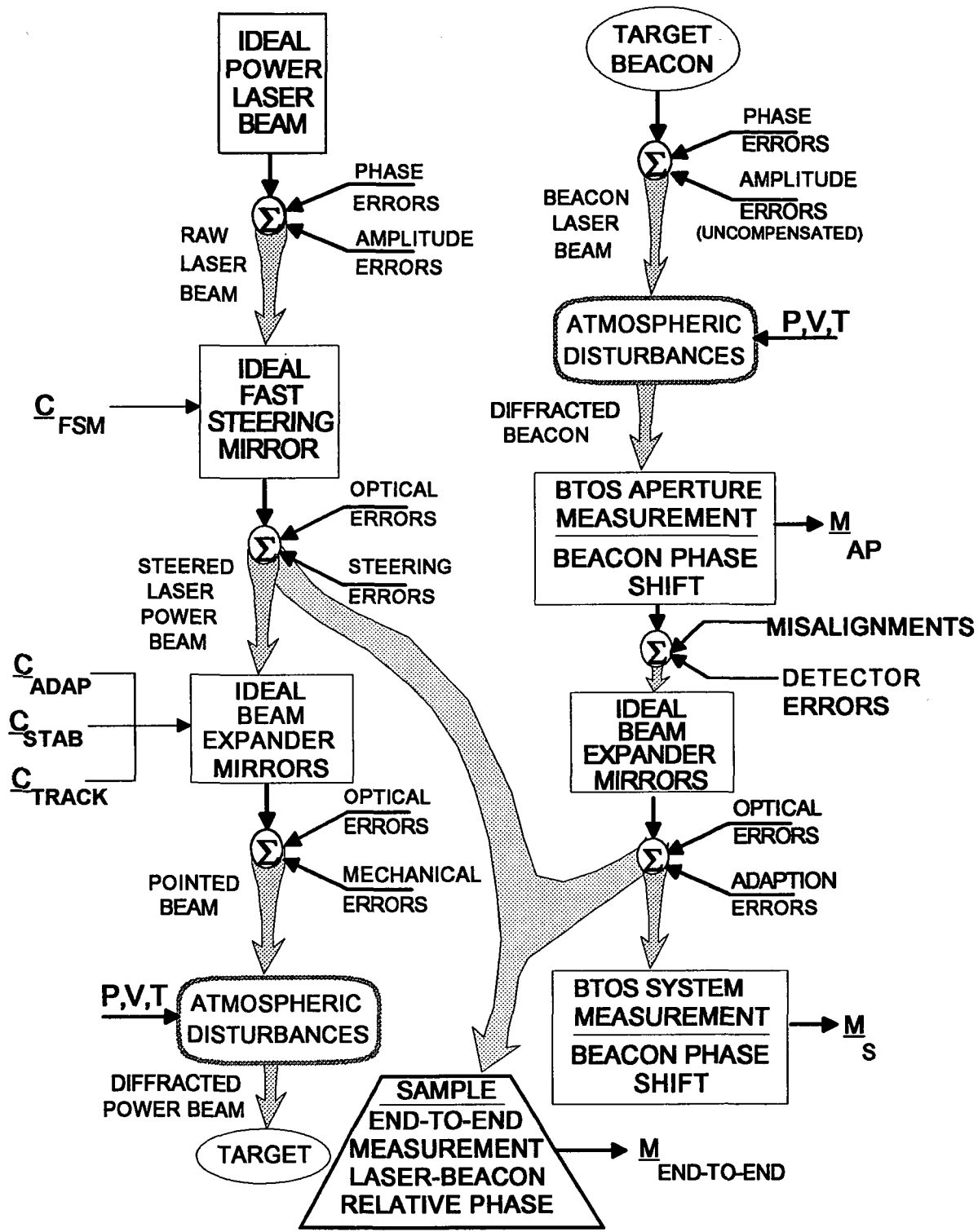


FIGURE 2.1-1. Top Level BTOS System Error Tree.

system. In the current approach the fast steering mirror significantly reduces the "throw" requirements on the segments' actuators and the accuracy to which the large telescope must be pointed.

The beam expander mirrors are mounted on a gimbaled structure for pointing the beam expander and hence the beam. For optical adaptation purposes the beam expander mirrors may be envisioned to be segmented. There are four possible designs. Either segment (1) both the large (12 meter diameter) primary and the small (1 meter) secondary, or (2) only the primary, or (3) only the secondary, or (4) segment none of these. The last of the possible designs has not been seriously considered. No segmentation of any beam expander mirror would mean no compensation for atmospheric errors unless an optic that transfers the laser beam to the beam expander (transfer optics) is segmented. Atmospheric errors are far too great without compensation. To date only the large primary mirror has been considered for segmentation in the Space Laser ENERGY (SELENE) program. The small secondary mirror is expected to have laser power densities 100 time greater than the large mirror so that water cooling is being considered. In addition, segmentation of smaller mirrors would require very small segments whose servo systems would be very small and more difficult to develop. Never the less, it could likely prove optimal to move the secondary mirror as a whole for focus and comma corrections.

With no optical adaptation (or error compensation) the beam pointing and expanding subsystem is called the **basic** BTOS. Without atmospheric disturbances, this optical structure's design is expected to be nearly adequate for power beaming to the moon. Initial optical figure errors and dynamic figure errors due to thermal and mechanical loads (including gravity) may also need to be reduced by compensation in order that the BTOS be fully adequate in the absence of atmospheric errors. **Figure 2.1-2** illustrates the **basic** BTOS.

Error compensation is to be provided by adaptive optics. The most complex and highest risk part of this design is the measurement and control system of the adaptive optics that are used to reduce the optical errors. The adaptive optics are currently envisioned to consist of a system of about 160,000 controllable, hexagonal primary mirror segments mounted on about 90 controllable, hexagonal clusters. **Figure 2.1-3** illustrates the relationships between the **basic** primary mirror structure onto which controlled **clusters**, with their controlled **segments**, are mounted and these clusters and segments. Currently each segment and each cluster is to have three actuators and three pickoffs to provide control in tip, tilt and piston.

Currently, the clusters and segments are hexagonal in shape. However, from the view point of avoiding adverse interactions between the control and the structure, triangles may be better. On the other hand, hexagonals with the same triangular actuator spacings provide greater area coverage than triangles, and for a given area an hexagonal element has the smaller circumference and thereby the smaller potential adverse edge effect. Since there are multiple sensing and control elements per segment, the 160,000 or so segments result in a very large number of pickoffs,

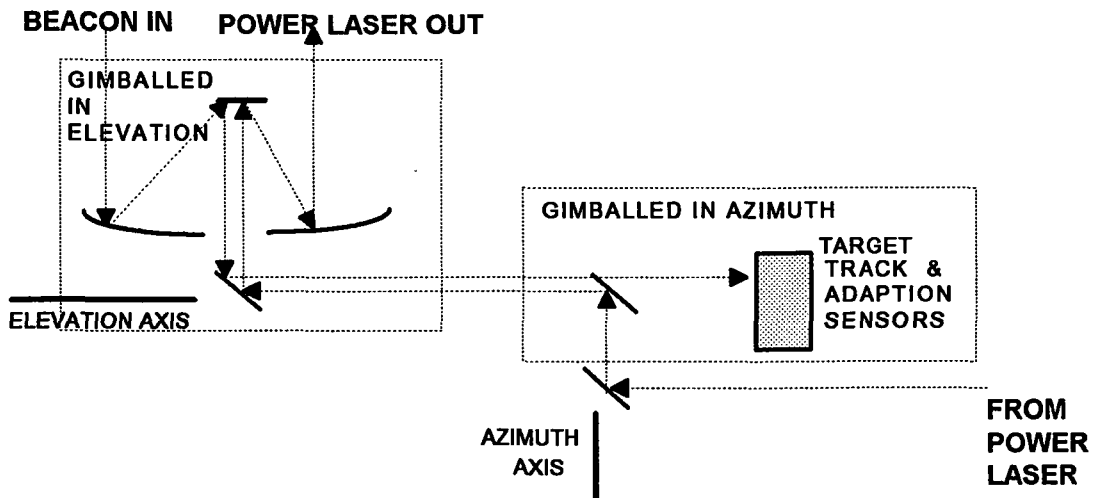
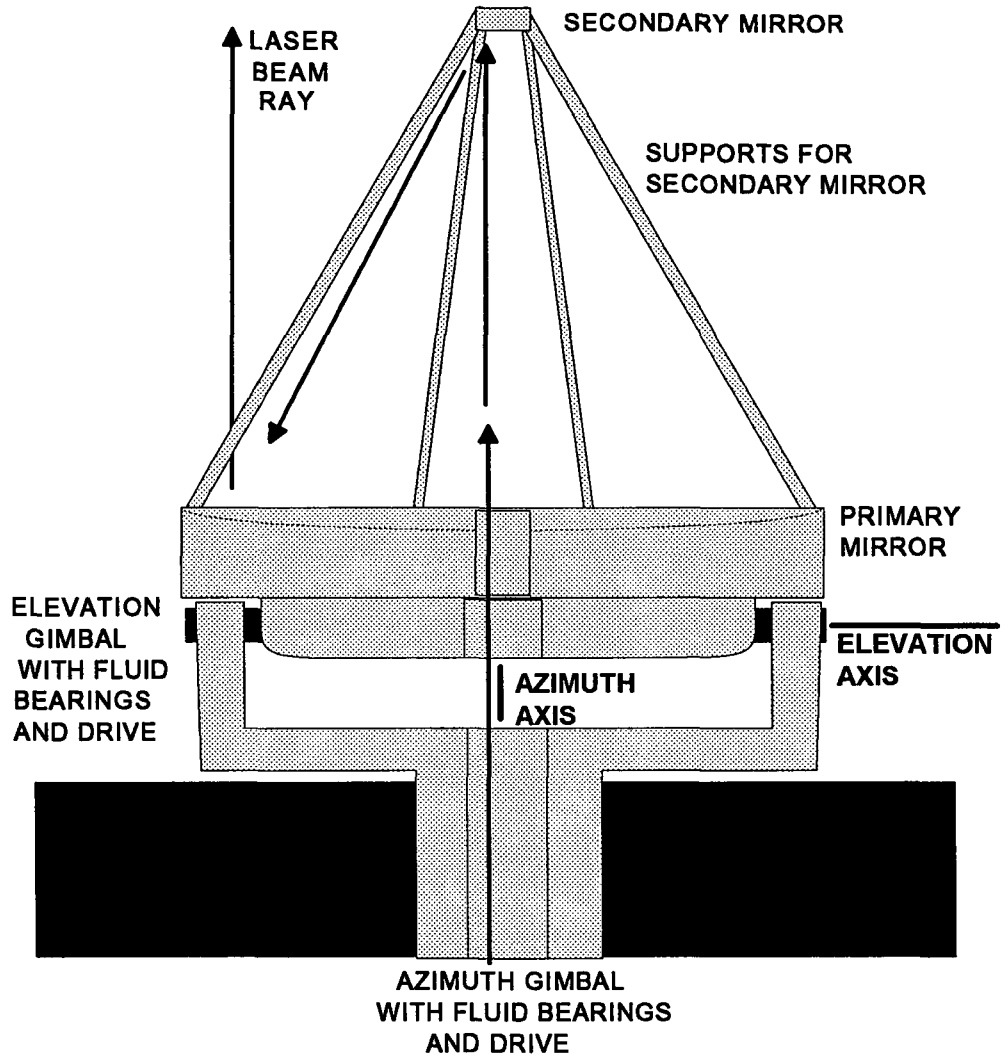


FIGURE 2.1-2. Schematics of Basic BTOS Design.

actuators, signal and power conductors, control electronics and computer, etc. elements.

We treat the atmosphere as an uncontrollable subsystem that receives its inputs *diis ex machina*. However, we attempt to compensate for atmospheric disturbances to the power beam by adaptive optical control.

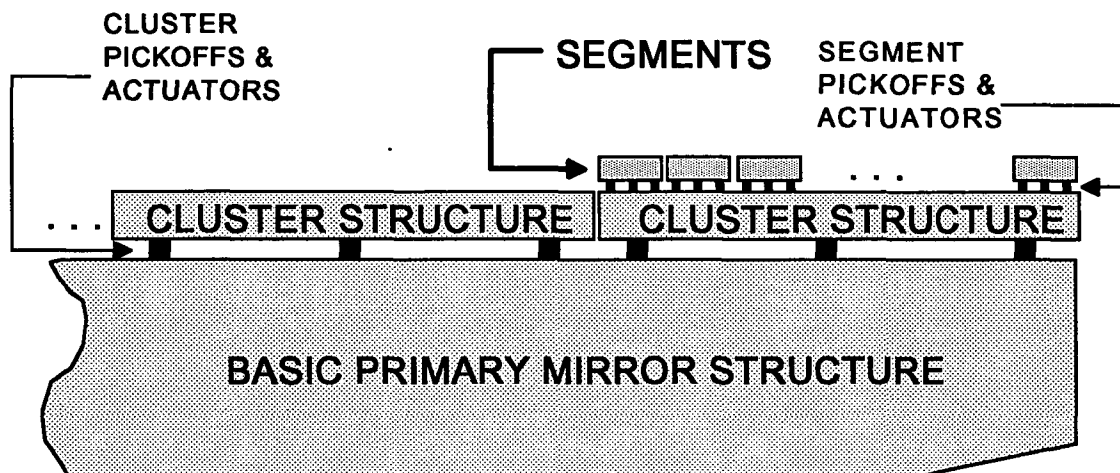


FIGURE 2.1-3. Illustration of Connections Between Segments, Clusters, and the Basic Primary Mirror Structure.

The beacon exists solely for the purpose of control compensation of optical errors. It, in conjunction with a "phase" sensor, may be viewed as the measurement part of a corrective subsystem that, together with the associated servo, compensates for a variety of errors. Optical errors encompassed by measurements that use the "reference" beacon can be replaced by the residual errors of the compensating control system. The beacon is one of two key elements of a measurement system to be used with servo elements to form this compensating control system. The compensating control system may encompass some error sources in the basic system and may compensate for their errors. Then basic error sources will no longer contribute to the total beam error. Only the residual errors of this measurement and control system will contribute.

The beacon's beam is treated as uncontrollable once it is placed into operation. Its imperfections are internally compensated and not a part of this compensating control system design problem. It is important to note that any imperfections in the beacon's reference beam will be sensed by the measurement system and passed through the

control system into the adaptive optics. These errors will then show up in the laser power beam.

Specifics of the BTOS measurements are discussed below, after we have laid out the error trees and the control theoretic structure for adaptive optics.

2.2 Beam Divergence Error Trees

Currently, there is a design concept for the BTOS. In order to keep design options open, we develop a **basic** system error tree for the uncompensated system, and two **compensated** system error trees. **Figures 2.2-1 a,b,c and d** provide these error trees. **Figure 2.2-1 a** shows elements of all three error trees without branches so that the reader can easily see "cost-benefit" relationships between them. Then the details of each of the three error trees are given in **Figures 2.2-1 b, c and d**. **Figure 2.2-1 b** provides an error tree for the uncompensated system. The first compensated system error tree (**Figure 2.2-1c**) is for the current adaptive optics design, and the other compensated system error tree (**Figure 2.2-1d**) is for our hypothetical end-to-end adaptive optics design.

Note that the current design induces segment edge mismatch errors in its attempt to compensate for beam wavefront errors caused by the atmosphere. That is, the atmosphere adaptive optics compensation scheme induces another kind of beam imperfection. The induced edge mismatch errors are then partially compensated for by (invented) edge mismatch sensors that complexly drive piston motions of segments and clusters. It is not possible to "match" the six edges of a hexagonal segment as well as provide finite element phase correction in tip, tilt and piston with only a 3-degree-of-freedom segment motion.

The "trunk" of a detailed error tree (**Figures 2.2-1 b, c and d**) flows from the branches that represent the many internal error contributors. Beam divergence is at the "root" of this analysis. The detailed "branches" flow into the trunk elements that represent subsystems with multiple imperfections. These multiple imperfections are represented by the error branches.

Typically analysts treat the error sources as random with "normally" distributed errors. This is appropriate for optical errors arising from random phase disturbances with spatial scales small compared to the size of the beam, and which lead to such wide-angle scatter that the associated power is effectively lost. However, ones with large spatial scales, i.e. those which lead to wavefront tilt which causes the beam to steer from the intended path and/or to aberrations which actually spread the central lobe of the beam, must be treated in a discrete manner. Statistics when invoked should be applied with the error source in mind. In particular, random oscillatory error contributions such as those due to structural resonances are better described by the SINE distribution. The SINE distribution is almost the inverse of the normal distribution. When the mean is zero, the SINE distribution has the majority of its occurrences at larger values of the random variable, while the majority of occurrences of zero mean

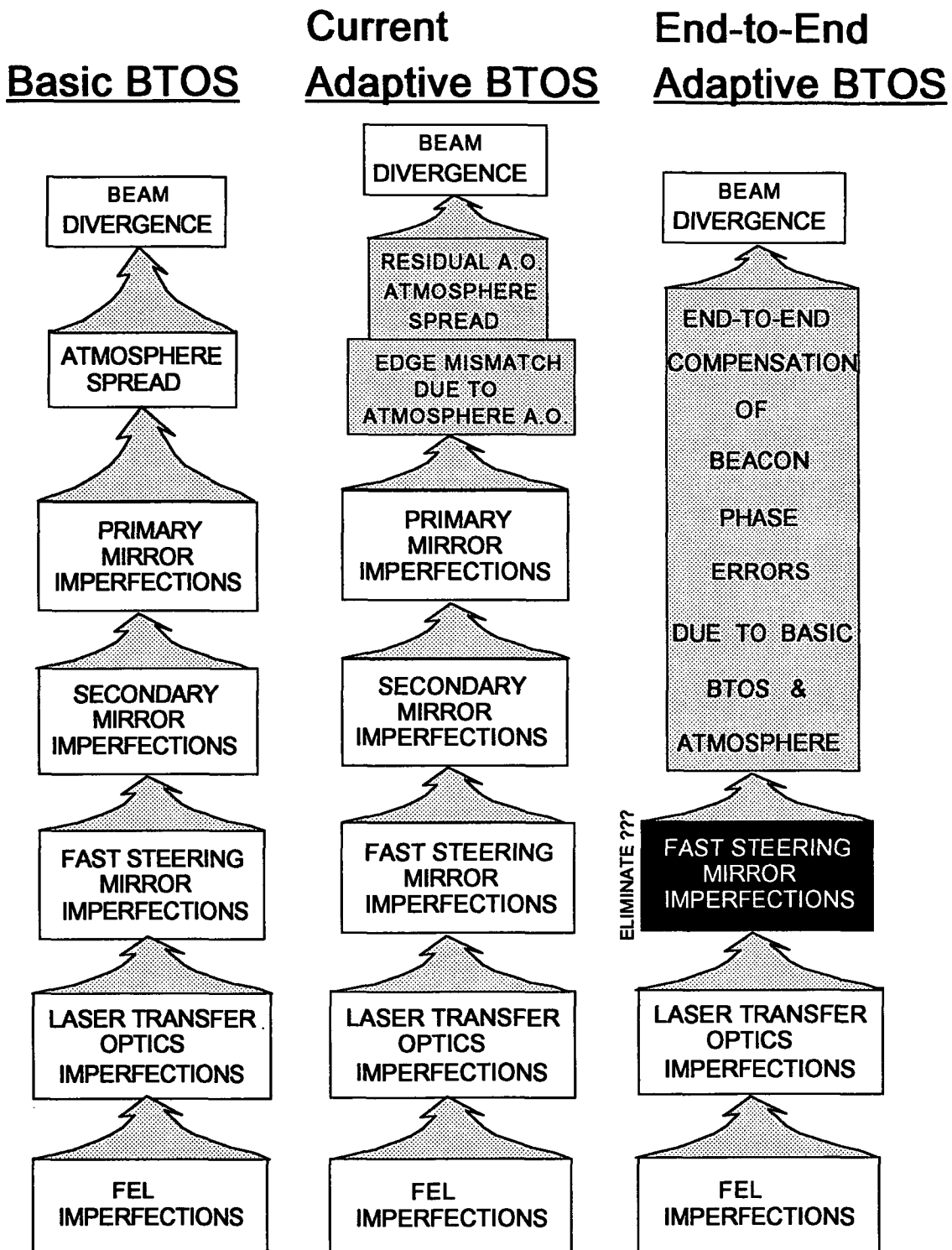


FIGURE 2.2-1a. Beam Divergence Error Trees for Basic BTOS, Current Adaptive BTOS and an "End-to-End" Adaptive BTOS.

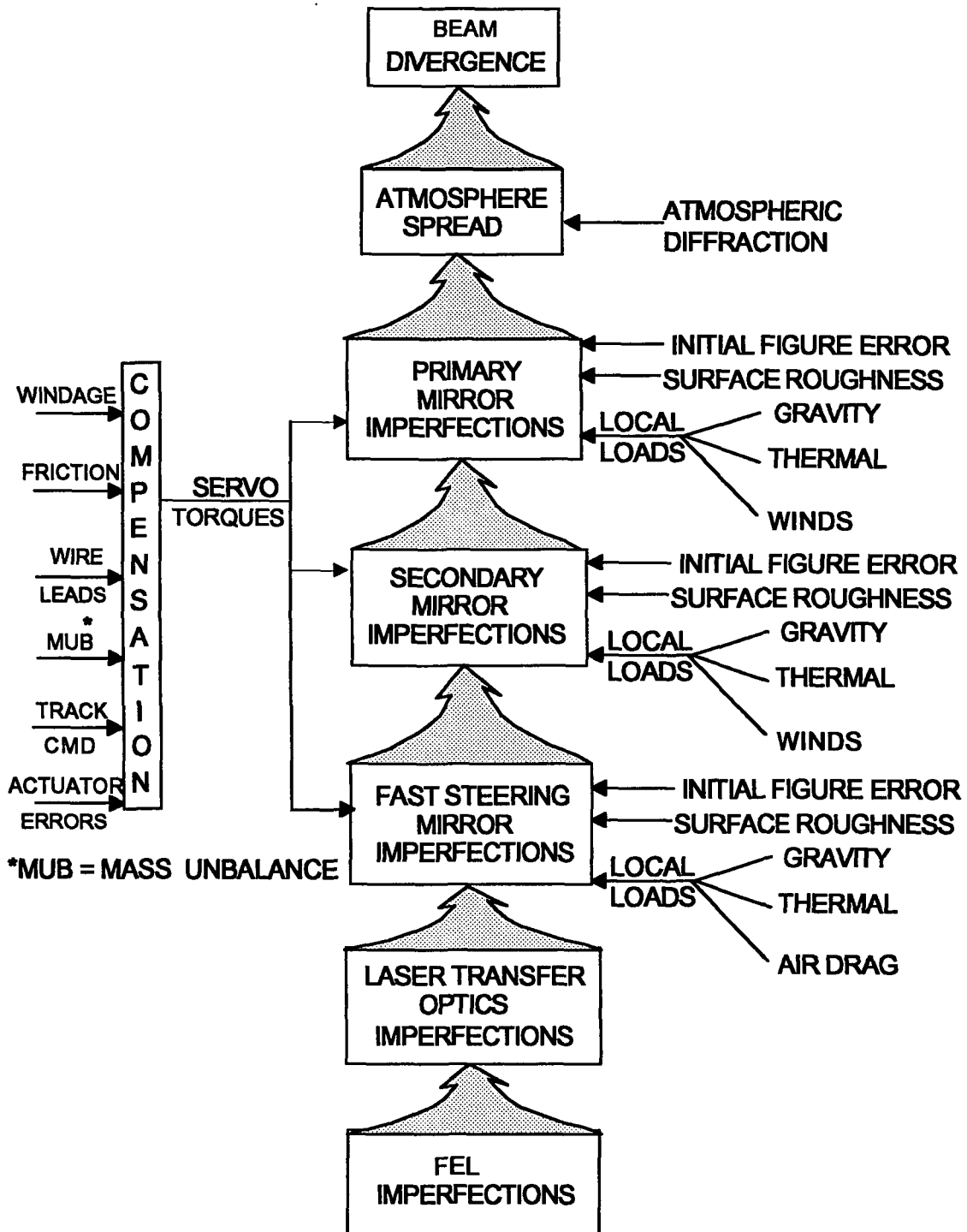


FIGURE 2.2-1b. Beam Divergence Error Tree for Basic BTOS (without Adaptive Optics).

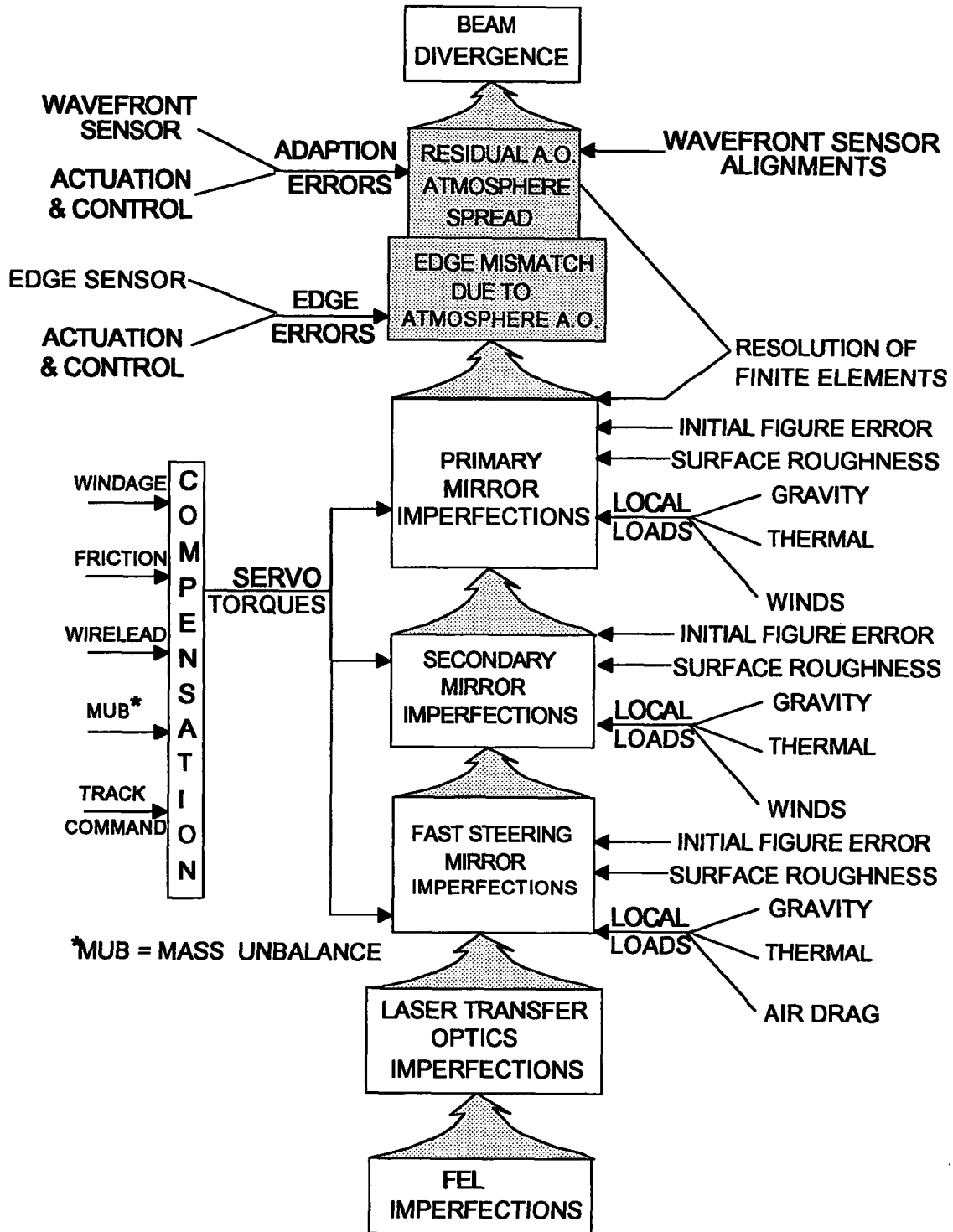


FIGURE 2.2-1c. Beam Divergence Error Tree for Current Adaptive Optics BTOS.

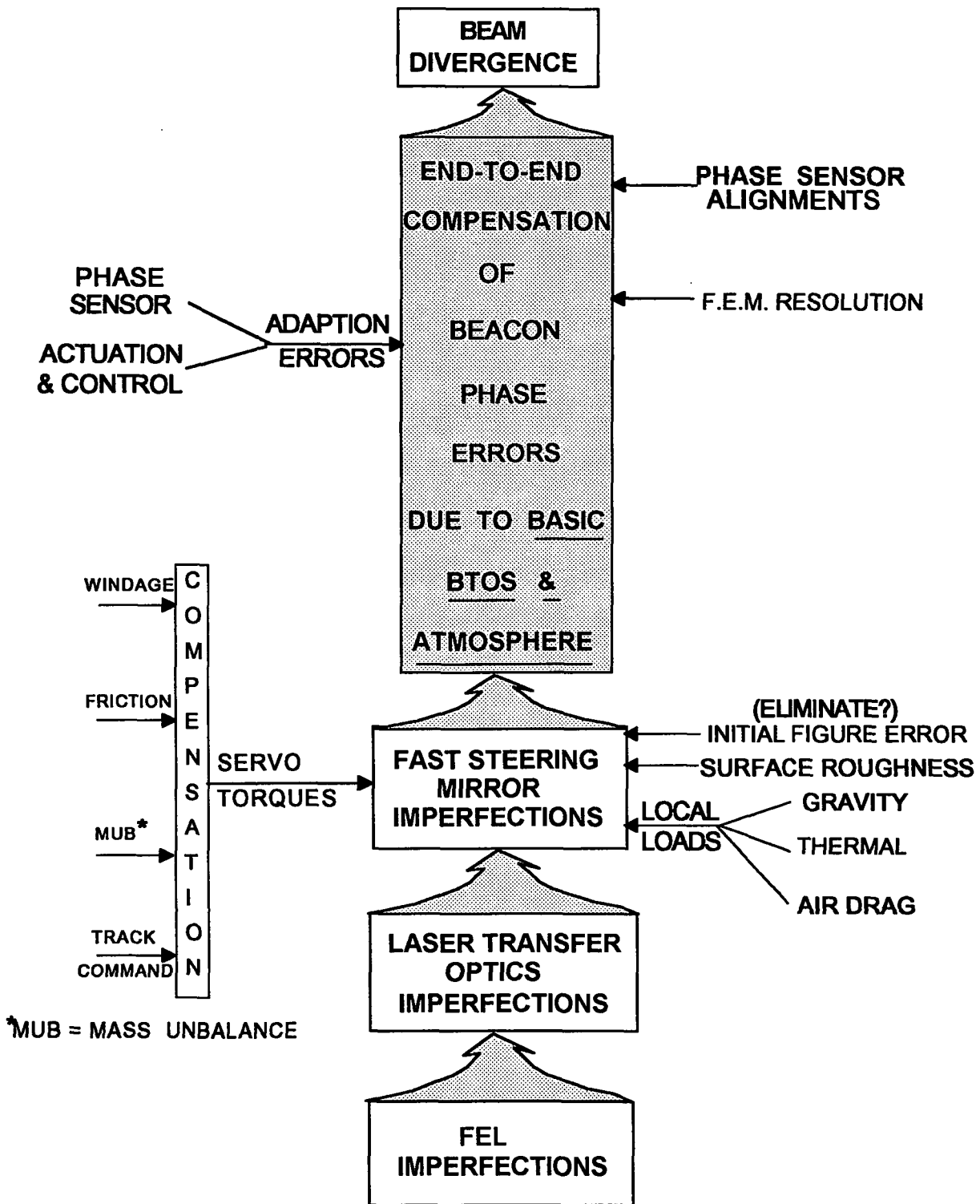


FIGURE 2.2-1d. Beam Divergence Error Tree for "End-to-End" Compensated BTOS.

normally distributed random variables are around zero. Analysts sometime justify their assumption that the random errors are normally distributed by invoking the Central Limit Theorem. However, the Central Limit Theorem requires a large number (hundreds) of identically distributed, independent random variables acting together. In the case analyzed here the number of significant variables are in the tens not hundreds. Monte Carlo studies of random errors that are not identically distributed have confirmed that the assumption of normally distributed random variables, when they are not normally distributed, results in optimistic performance predictions. Thus, we must use the correct distributions, not just normal distributions, for the various random error variables or our predicted performance will be optimistic.

2.3 Control Structure For Beam Divergence Compensation

Beam divergence results from (1) the divergence of the basic free-electron-laser (FEL) power beam as it exits the "laser transfer optics" that brings the beam to the BTOS, (2) phase distortions caused by imperfections in the BTOS optics, and (3) wavefront distortions caused by atmospheric refraction and scatter. Control compensation of all beam divergence contributors is possible. Compensation is both temporal and spacial because errors vary with both.

Ideally, the optical control compensation should be a continuum over the selected optic and precise in time. Control of a continuum theoretically requires an uncountably, infinite number of actuators and pickoff transducers. Practically, we can only build a finite number and this number should be minimized to the extent that the beam divergence stays within its error budget. Its error budget may be backed out from the target size, target range, and the stabilization and tracking error statistics of the beam's centroid.

Figure 2.3-1 illustrates this error budget. For the type of system considered for SELENE, the energy on the target can be envisioned as distributed into a central lobe with divergence slightly larger than ideal and with fixed and random pointing errors, as well as into a "background" of widely-spread incoherent blur. To date NASA has budgeted the Strehl ratio (the peak intensity relative to the ideal value) to about 0.5, but this number continues to undergo revision. The combination of short wavelength and a large aperture results in an ideal spread of tens of nanoradians, and the beam must be pointed to this accuracy if the benefits of the optical design are to be realized. We are concerned here with the control of the beam in a manner such that it meets both its Strehl and pointing error budget specifications.

If the beam's lightwaves' phases are controlled across the beam to counter phase distortions, beam divergence at a point in time may be reduced to a residual value that is determined by the "finite element" approximation of the controlled optics, and imperfections in phase sensing, actuators, and control response shaping.

A top level beam divergence control block diagram is depicted in **Figure 2.3-2**. Two wavefront integration systems are being considered by NASA, one with a sensor in the

back of each segment, and a more conventional one in which a sensor array is located between the FEL and the BTOS. Although it appears to offer certain advantages, the former does not sense and compensate for BTOS optical errors, so the line in **Figure 2.3-2** between the BTOS optics and the Beam Phase Measurement system is shown as

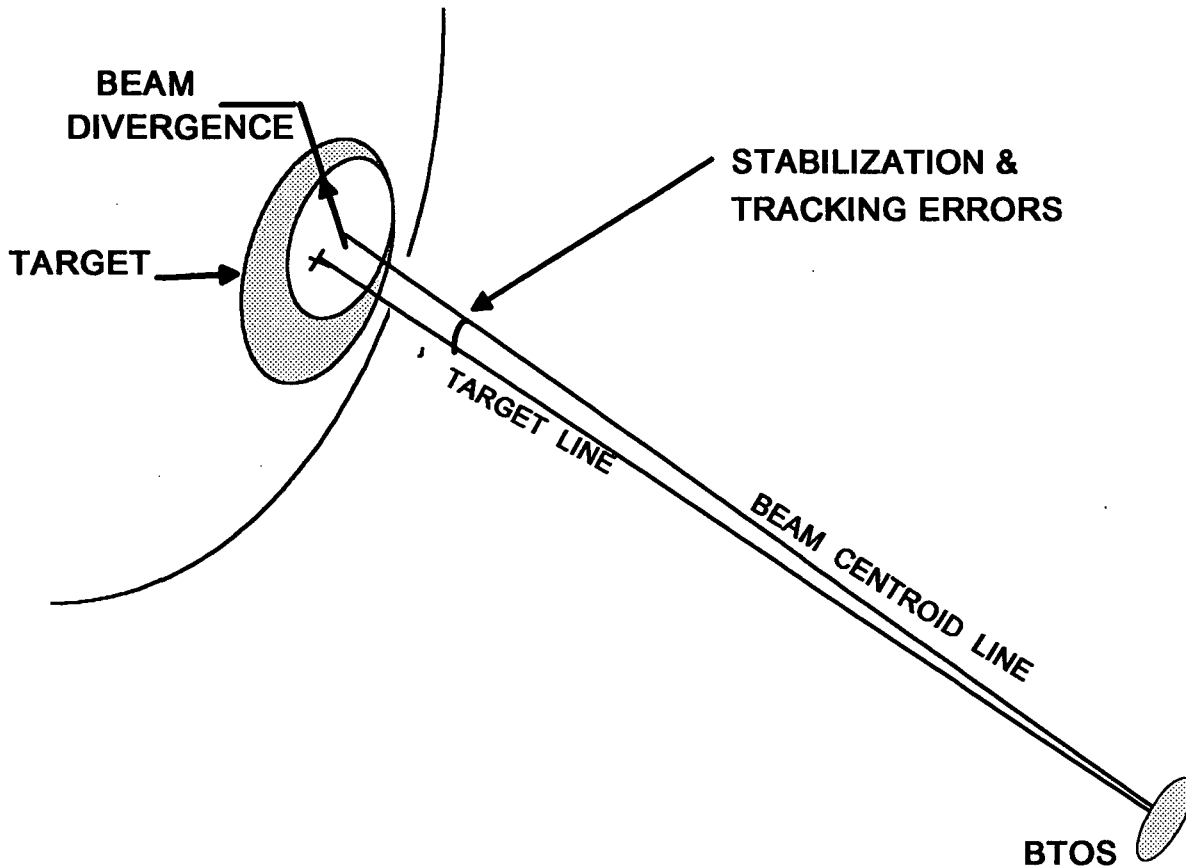


FIGURE 2.3-1. Beam Divergence Is an Error Budget Contributor Along with Stabilization and Tracking Contributors.

dashed. Such errors may prove significant though, especially since either design in its attempt to compensate for atmospheric beam divergence by wavefront tilt correction of mirror segments introduces additional optical imperfections. Discontinuities between mirror segments at their edges cause beam scattering, and power may be lost in the gaps between the segments. Edge sensors have been invented for control of the average out-of-plane mismatch between adjoining segments, but the entire line of discontinuity cannot be removed with rigid segments with piston-tip-tilt control, nor can the gaps be realistically caused to vanish (even approximately) with regular segments on a curved surface.

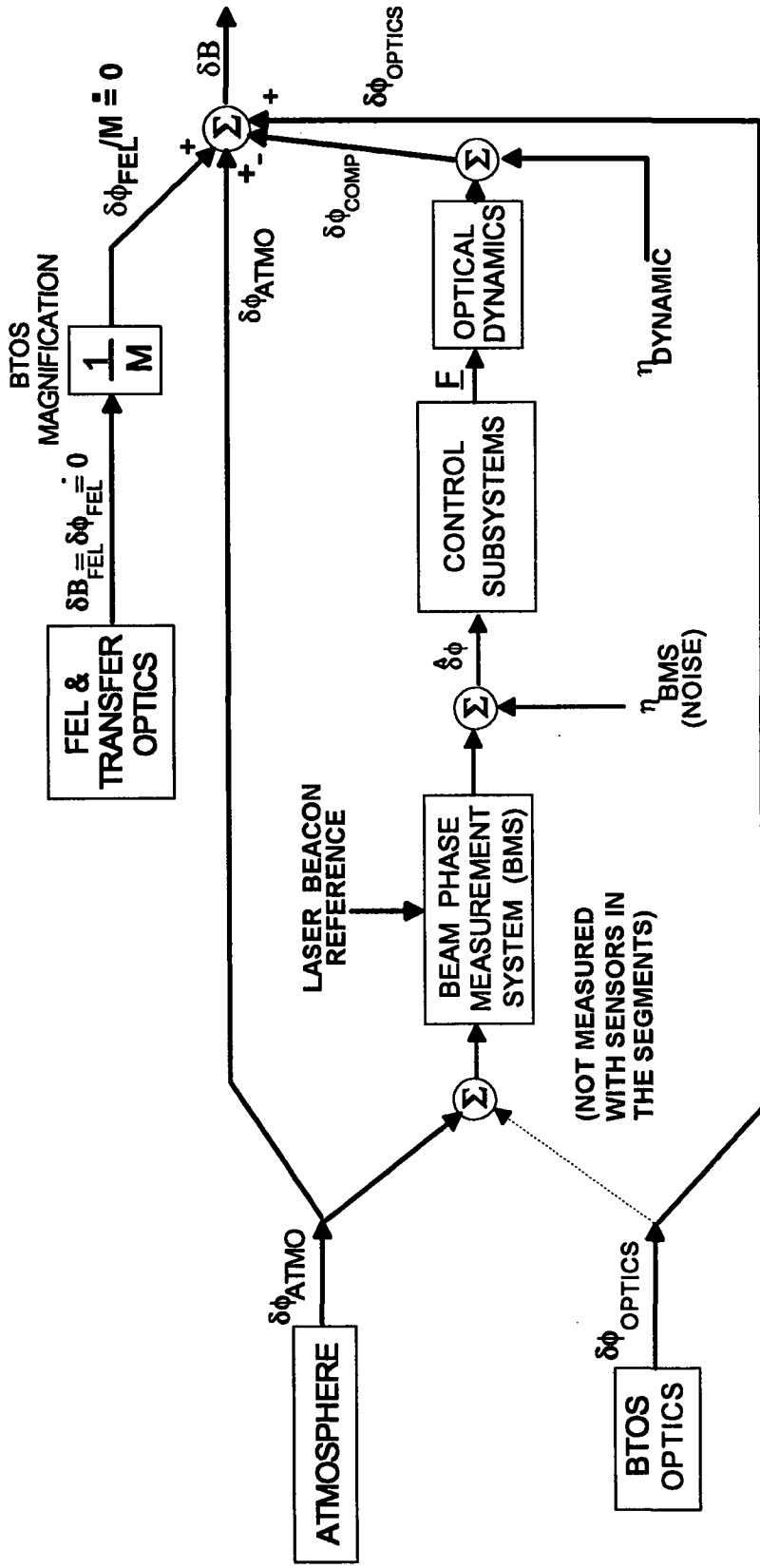
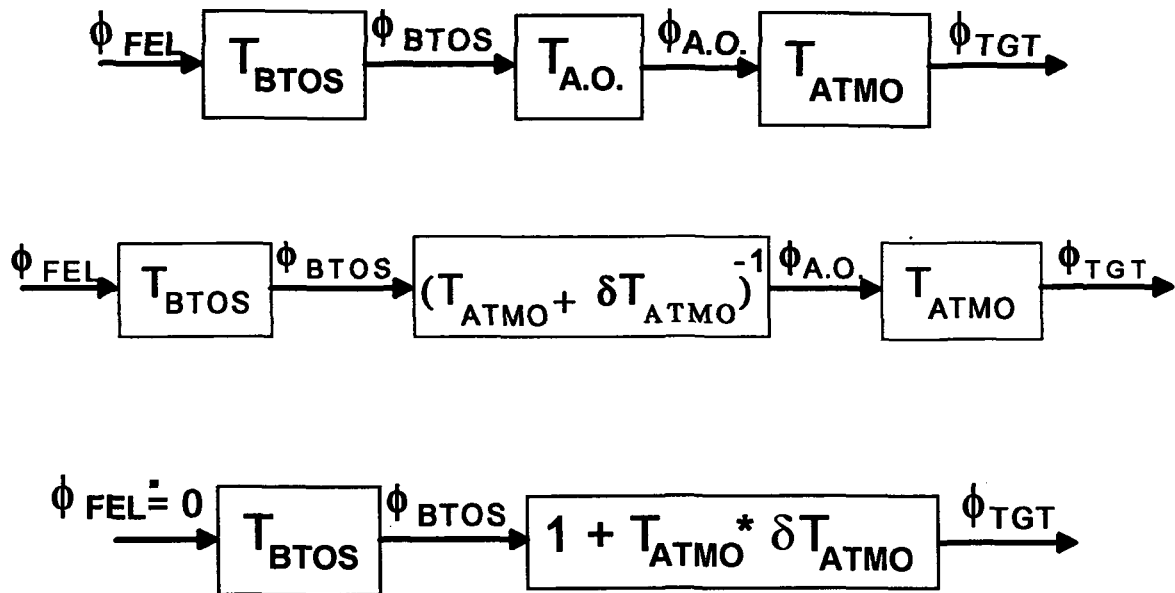


FIGURE 2.3-2. Top Level Control Block Diagram for Beam Divergence (δB) Compensation.



NOTE: Phase shifts through transfer functions are additive.

FIGURE 2.3-3. Equivalent Time Domain Transfer Function Block Diagram of an Adaptive Optics System for Each Spatial Element.

From a control theoretic viewpoint this control system may be thought of as a disturbance accommodating (compensation) controller. **Figure 2.3-3** is a time "coordinate" (as opposed to spatial) transfer function representation of the top level system block diagram of **Figure 2.3-2**. Each spatial segment of the adaptive optics system may be controlled in this way. Since it is not practicable to control amplitude or intensity at the target except indirectly through phase control, the inputs and outputs of the blocks are phase components. The adaptive optics transfer function represents the complex wave measurement and control process

$$T_{A.O.}$$

which attempts to "cancel" the atmospheric affects. This cancellation process is imperfect so that

$$T_{A.O.} = (T_{ATMO} + \delta T_{ATMO})^{-1}$$

The adaptive optics control may be diagrammed as shown in **Figure 2.3-4**. This diagram shows standard transfer function blocks within dashed boxes along with the ideal dynamic phase shift effects of the current adaptive optics design. If the block for

"Measurement of Phase" does include the BTOS within the beacon's measurement path, then the final output at the target

$$\phi_{TGT}$$

will include most of the dynamic phase errors introduced by the BTOS. This again illustrates the importance of end-to-end measurements in this imperfection or disturbance compensation control system.

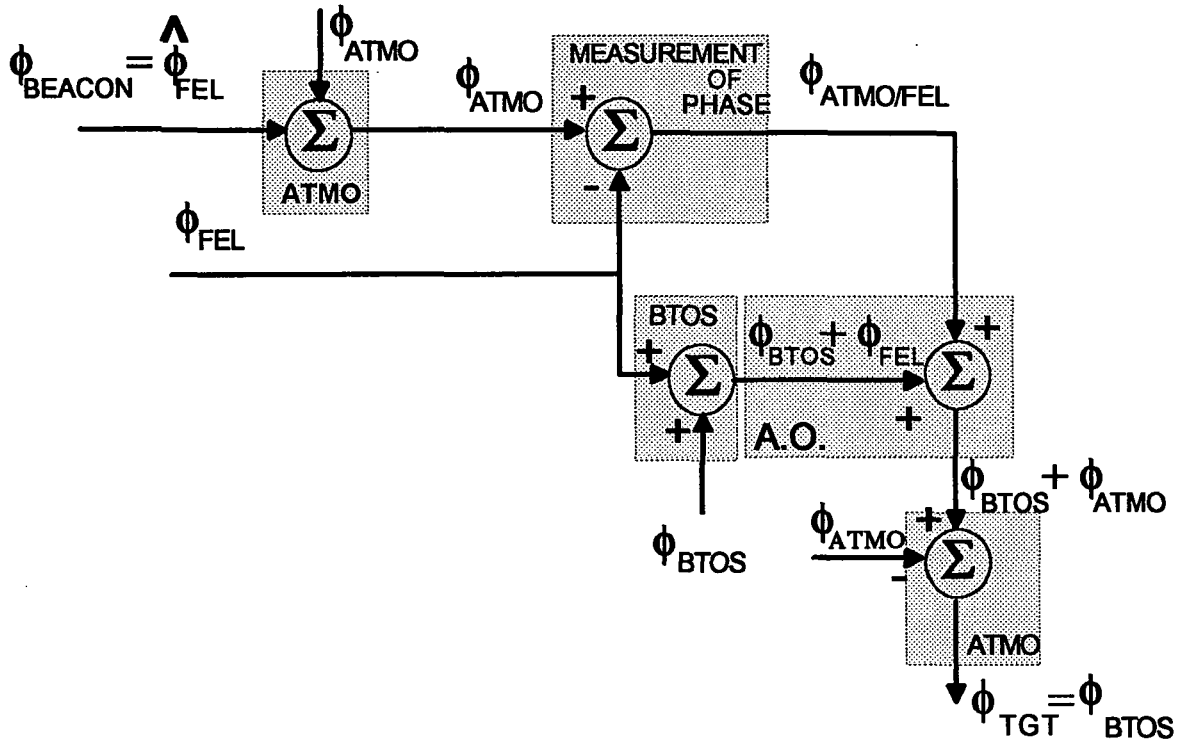


FIGURE 2.3-4. Adaptive Optics Control Block Diagram That Shows Only Signal Phase Effects.

In this report our concentration is on the fundamental control elements. In a forthcoming report on the design and testing of the adaptive optics of the PAMELA (Phased Array Mirror Extendible Large Aperture) telescope we consider in more detail the control of a large number of adaptive optical elements (clusters and segments). A fundamental source of residual error in the control of many small adaptive optical elements is "control-structures interactions" (CSIs). Next we examine fundamentals of these and other interactions and set the stage for a conceptual design (Section 4) that minimizes CSIs and other imperfections that may occur while end-to-end adaptation is being performed.

Our approach is to examine simple models that we believe capture the essence of the various phase measurement, motion measurement, actuation, and control response shaping imperfections and their effects.

Figure 2.3-5 depicts the simple dynamical structural model used. The dynamical differential equations for this simplified model can be Laplace transformed and used in the block diagram provided in Figure 2.3-6, which was taken from our MatrixX control system design and analysis tool. This figure does not include phase sensing imperfections, actuator imperfections, pickoff imperfections, and any control compensation. It strictly shows mechanical interactions.

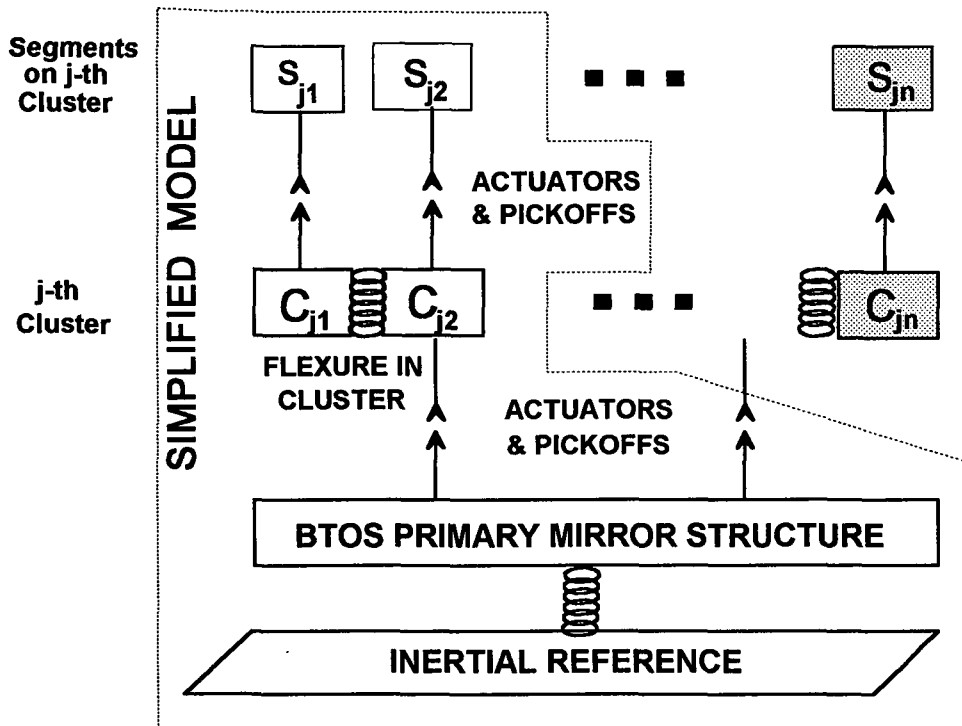


FIGURE 2.3-5. Simplified Dynamic Model of Segments, Clusters, and the BTOS Primary Mirror Structure.

Examination of Figure 2.3-6 without consideration of measurements, actuation and control shaping imperfections leads to the following observations:

- (1) Any relative motion between the various clusters or within a cluster along the segment actuation direction will result (because the pickoffs measure only relative position) in that amount of segment position error (and laser beam phase error) unless (a) the control compensation filters out the cluster motions or (b) the clusters' lowest deformation and control frequencies are well above segment control bandwidth.

(2) If an inertial segment sensing device is used on every segment, then cluster deformations and other relative cluster motions only increase segment actuation power requirements.

(3) Segment actuations generally excite all structural modes, if atmospheric optical phase errors are indeed random across the structural resonances. The lower frequency cluster actuation may excite the lower frequency base structure modes that couple into the segment position errors.

For the controller to filter out the cluster motions and not filter out the segment motion in the same relative position pickoff signal, the segment motion cannot occupy the same part of the signal's spectrum as the cluster's structural motion. Basically, this says that the clusters' lowest deformation frequencies must be well above segment control bandwidth, since segment motions cover the lower frequency band of atmospheric motions (about zero to 300 Hertz). There are no notches in this segment motion spectrum that can accommodate cluster natural frequencies. Thus, cluster natural frequencies must be either below the segment spectrum or above it. They cannot be below it.

These observations lead us to the following conclusions about motion pickoffs and structural deformations. When relative motion transducers are used in the current design (1) there can be essentially no relative motions between the mounts (clusters or elements of the primary mirror's base structure) for the large number of segments; and, (2) it is necessary for each segment supporting structure (cluster or base) to be very stiff. All this boils down to: (1) the need for very stiff and probably smaller clusters; and, (2) precision measurements of relative motion between clusters or precision inertial stabilization of all clusters. Inertial stabilization should result in no relative motions between clusters or precision measurements of all cluster motion relative to a common frame.

The following **Figure 2.3-7** of a simplified inner control loop is used to further illustrate the effects of the imperfections in phase sensing, actuation, and control response shaping .

The PHASE SENSOR COMMAND in the current design represents both the wavefront sensor and the edge sensor. Note that the PHASE SENSOR COMMAND may command the segment's position relative to any reference frame, moving or inertial, provided all segments have the same reference. The problem with the segment movement PICKOFF shown is that it measures segment motion relative to one part of one cluster that is probably not moving precisely with other parts of the same cluster or precisely with other clusters.

All segments must follow with high fidelity the wavefront and edge matching commands or the phase sensor's path length error correction command. From **Figure 2.3-7** the following transfer functions may be constructed to see the effects of the inner-loop on segment phase following caused by pickoff noise, segment disturbances such as windage, and phase sensor noise.

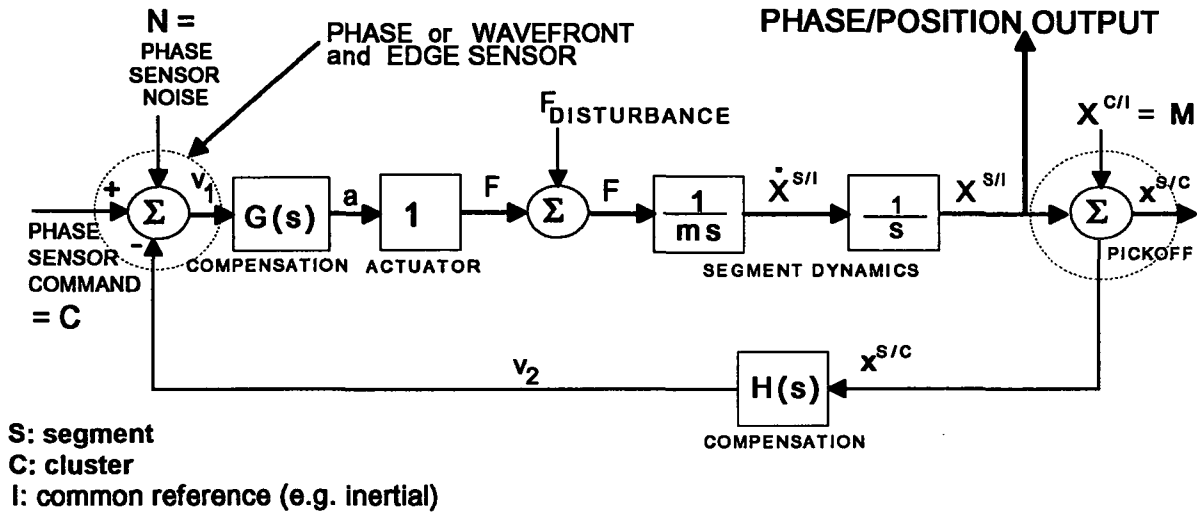


FIGURE 2.3-7. Simple Block Diagram for Segment Inner-Loop Control.

From Equation (2.3-1) it is clear that $1 / [ms^2 + G H]$ must provide disturbance rejection over the bandwidth of the disturbance. With small segment masses(m) the natural rejection will generally not be sufficient so that rejection through control will be necessary. Such rejection is proportional to bandwidth so that a wide bandwidth is needed for disturbance rejection as well as command following at atmospheric turbulence frequencies. However, without a low noise, wide bandwidth segment rate measurement device it is difficult to achieve wide bandwidth with flat response. Without such a rate device the damping needed for a flat response can only be achieved in the compensation G or H. Equation 2.3-2 differs from Equation 2.3-1 only in the factor G.

$$X^{S/I} / F_{\text{DISTURBANCE}} = 1 / [ms^2 + G H] \quad (2.3-1)$$

$$X^{S/I} / C = G / [ms^2 + G H] \quad (2.3-2)$$

$$X^{S/I} / M = H * G / [ms^2 + G H] \quad (2.3-3)$$

Equation 2.3-2 should have a unity transfer function over the system bandwidth needed for command following for atmospheric turbulence corrections. One technique for obtaining such damping is pseudo-differentiation $s / [\tau s + 1]$. This differentiator amplifies pickoff noise in the band $(1, 1/\tau)$ where $1/\tau$ should match the closed loop bandwidth of the inner-loop system.

Equation 2.3-3, when compared to the other two transfer functions, indicates that H must be flat within the band $(1, 1/\tau)$ while rejecting noise from the pickoff. Since this noise is primarily due to the effects of cluster deformations on pickoff errors, we may be able to design the clusters with lowest deformation mode well above the upper end

$1/\tau$ of the atmospheric turbulence band and closed loop bandwidth. Then H may be designed as a low pass filter to reject this noise without affecting command following for atmospheric turbulence corrections. However, if the clusters are this stiff, there is probably no need for H to serve as such a noise filter. The bottom line, again, seems to be that the clusters must be stiff or the pickoffs must measure segment motion from a common reference such as an inertial reference.

Some advantage may be gained from the addition of compensation of the PHASE SENSOR in an outer-loop control system. Figure 2.3-8 illustrates an outer-loop closed around the inner-loop of Figure 2.3-7. The output of the PHASE SENSOR is compensated by the transfer function $L(s)$. The outer-loop feedback path is not accessible for additional compensation, since this feedback path exists only within the phase sensor. The inner-loop provides the basic stability that allows for a design of adequate bandwidth. The outer-loop enables the system to be of a type 2 to properly follow the servo command provided the closed-loop bandwidth is adequate. Precision system transient response not only requires fast stability, that provides great disturbance rejection, but also requires a type 2 or better design. The compensation $L(s)$ may allow us to finalize these goals.

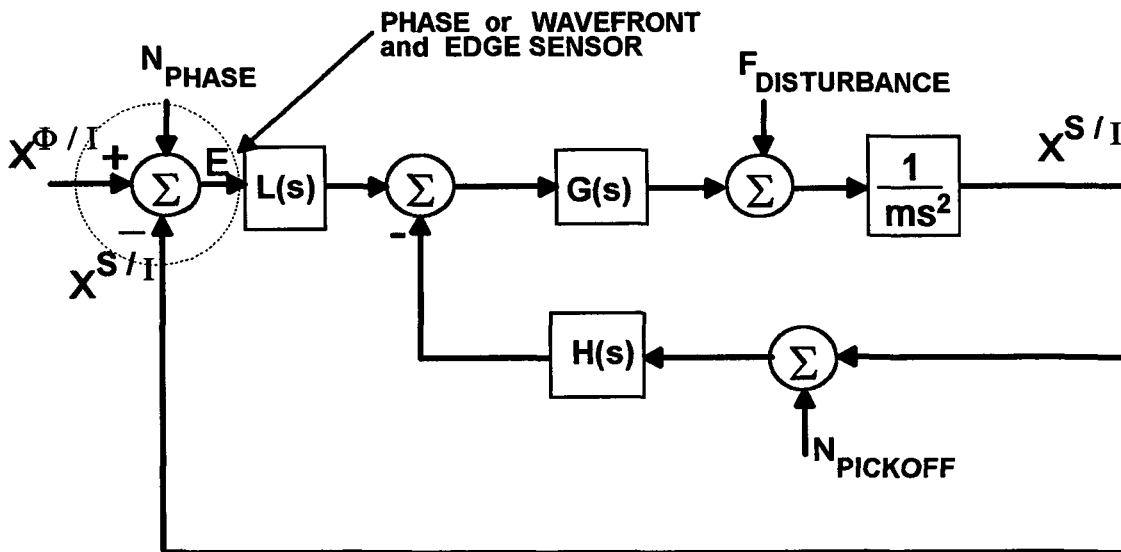


FIGURE 2.3-8. Simple Block Diagram for Segment Outer-Loop Control.

2.4 Sensitivity Of Beam Divergence To System Errors

The current BTOS adaptive optics design was described above along with an introduction to a modified design concept. Figure 2.2-1c diagrams the current design's top level error sources before any compensation. Figure 2.3-8 describes potential

compensations of some of the groups of error sources. The following **Figure 2.4-1** overlays the potential compensation error groups with the top level error sources. The beam divergence will only be affected by the uncompensated errors and the residuals of the compensated errors.

The errors of the wavefront sensors (indicated by the group N_{PHASE}) pass through the system unaffected unless, in the unlikely case, this noise is outside the control bandwidth needed for correction of the primary disturbance of the atmosphere. Thus, the sensitivity (or influence) coefficient of beam divergence to wavefront sensor noise is essentially unity.

Effects of segment disturbances (indicated by the group $F_{\text{DISTURBANCES}}$) may be reduced to the order of $\lambda/20$ by shielding the segments from some disturbances and by proper design of the disturbance accommodation part of the inner-loop control subsystem. Thus, the tolerance or n-sigma limit on beam divergence due to segment disturbances is about

$$(\lambda/20)/r_o = (0.84 \times 10^{-6}/20)/0.03 = 1.4 \text{ microradians}$$

This error distribution needs to have an n of about seven for segment disturbances to contribute essentially no beam divergence. The sensitivity of beam divergence to segment disturbances is inversely proportional to segment size r_o for disturbances within the bandwidth of the inner-loop control system. Outside this frequency band beam divergence is influenced by disturbances inversely proportional to segment mass which is proportional to the square of segment size.

Uncompensated optical figure errors directly affect beam divergence so that the sensitivity coefficient is essentially unity for this group.

3.0 BTOS SYSTEM INTEGRATION EFFORT

This section describes our efforts in attending system integration meetings and evaluating system integration efforts. We also provide recommendations for future system integration activities.

3.1 System Integration Meetings

System integration meetings were held with the BTOS structure builders and with system development managers, both in person and by teleconferencing. The BTOS structures meetings were held for the purpose of defining the design, the construction material, the construction process and the development responsibilities.

Meetings were held to plan the total SELENE system (Space Laser Electric Energy), including BTOS, program through the end of the century. Since many organizations, including a Russian high energy laser group, are involved in the SELENE program, the scheduling of the various subsystem developments is a challenge. A result of a

meeting held on 23 April, 1993 was the determination that critical path items in this development are the free-electron-laser (FEL) and an end-to-end phase sensor. The end-to-end phase sensor was felt to be needed in order to have design margin and to reduce complexity. Complexity would be reduced by the elimination of edge sensors and perhaps by moving the adaptive optics to a collimated light location so that single axis control would be feasible. The complexity of the control software would also be reduced by almost an order of magnitude by such hardware changes.

Teleconferences were held to determine progress by the various organizations and their development plans for the next time period. The teleconference of 9 May, 1993 primarily involved discussions of the BTOS structure and interactions with the adaptive optics control system. Structural deformations due to thermal effects were also discussed. This teleconference lead to the selection of a composite material BTOS structure because of its stiffness and low coefficient of thermal expansion.

A goal set in a Washington, D.C. meeting of 27 May, 1993 with NASA management was to test the PAMELA adaptive optics telescope by viewing stars through the turbulent atmosphere. Another long term goal envisioned for SELENE was to provide power for electrically powered unmanned air vehicles (UAVs). Such vehicles could be used to detect illegal intrusions and smuggling.

On 28 June, 1993 a meeting was held in which the shapes of segments and clusters were discussed. Triangles have been suggested to possibly offer structural advantages, but hexagons provide the minimum perimeter-to-area ratio of any repeated polygonal shape, and this is significant from the stand point of the edge losses discussed previously.

3.2 Evaluation Of System Integration Progress

A significant system integration effort was intended for fiscal year 1993 as anticipated by our contract. Because funding for the SELENE project was considerably less than anticipated, little system integration effort was performed. Almost all of the effort was spent on the research and development activities since they could be performed on a much smaller budget.

The system consists of the high energy free electron laser, the transfer optics for transferring the laser's output to the pointing and tracking telescope, the BTOS pointing and tracking telescope, the gimbals and drives for pointing the telescope, and the adaptive optics used to compensate for atmospheric beam spread. A joint effort between Duke University and Russian scientists to develop key technologies for the free-electron-laser was on-going. Design and construction planning of the BTOS structure was completed with the plan to construct a composite material structure in fiscal year 1994. Some preliminary design work was accomplished on the BTOS gimballed pointing and tracking subsystem. The PAMELA adaptive optics telescope, developed under the Strategic Defense Initiative, was brought to Marshall Space Flight Center and set up for testing its adaptive control system which may be copied for use in SELENE. Some of the precision test equipment needed to test the PAMELA was

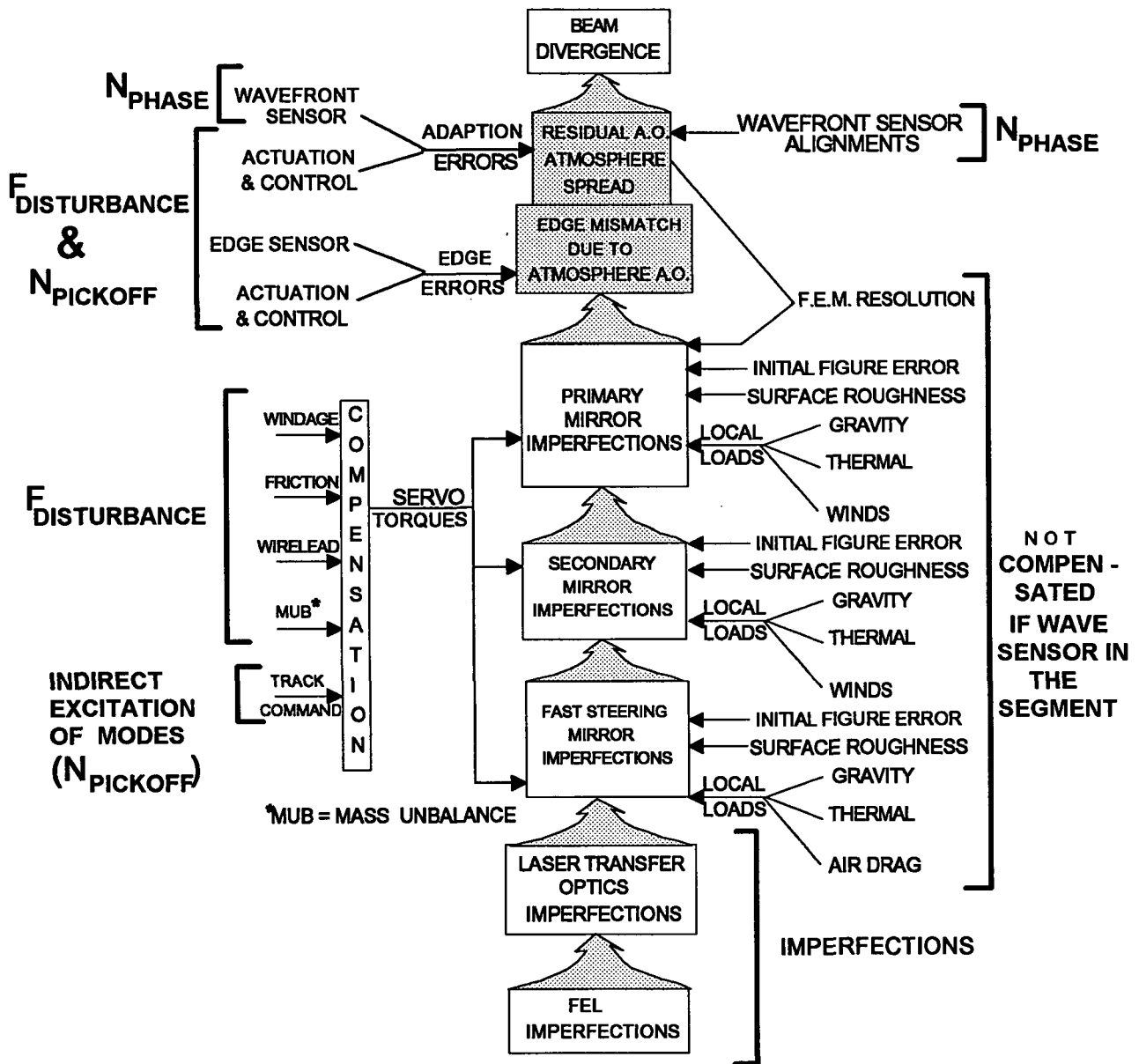


FIGURE 2.4-1. Beam Divergence Error Groups for Current Adaptive Optics BTOS Control Compensation.

purchased. No other system integration work of any significance could be performed because of an extremely tight budget.

In our opinion progress on SELENE and the BTOS was exceptionally good because of the innovations used to get the job done. This innovative effort reminded us of the stories from World War II wherein technical miracles were produced by empowered and innovative people.

3.3 System Integration Recommendations

Because of the very number of parts in the BTOS with the adaptive optics it is recommended that system integration follow thorough design studies to reduce complexity and to simplify production by way of maximum utilization of common elements.

It is clear that system integration should not proceed, even at large subsystem levels, until more than minimal funding is made available. The system cannot be integrated in a piecemeal fashion. The telescope structure could be constructed according to a design that could accommodate either the current adaptive optical subsystem or feasible alternatives. Certain parts of the free electron laser could be assembled. However, site construction and full system integration must await a final design of all but the adaptive optical subsystem, which can be added into the system later.

4.0 ADAPTIVE OPTICAL SUBSYSTEM CONCEPTS

The current concept is to place the adaptive optical subsystem on the face of the primary mirror of the BTOS telescope. The adaptive optical system may be placed anywhere in the path of the laser beam and provide some level of compensation for optical imperfections and atmospheric disturbances. Where it is placed will (1) determine the optical imperfections corrected, and (2) set attendant system level problems. System level problems include: heating of subsystems by errant laser energy without a design for adequate cooling; a requirement for miniaturization of optical, transducer, and actuator devices that is beyond the current state-of-the-art; design complexity caused by second and third tier requirements placed on an adaptively controlled optical element; and, isolation from or compensation for environmental effects. **Figure 4.0-1** illustrates the alternatives, without regard for the technology or system problems they may cause, for placement of adaptive optical subsystem.

The current location of the adaptive optical elements (segments and clusters) is indicated by the number 1 in a circle. The current approach places the adaptive optical elements on the large parabolic, primary part of the beam expander telescope. An advantage of this location is that the adaptive optical elements may be relatively large (about 3 centimeters across) so that miniaturization is not quite so severe.

Another advantage is that laser power density is lower so that beam losses and system heating due to these losses might be minimized. However, the percent loss of power

is probably the same for either low power density locations of adaptive optical elements or high power locations. Basically, the power loss as a percent of total power is related to the loss area as follows.

$$\begin{aligned}
 \%loss &= \\
 100 \times loss/total_power &= loss_area \times density/total_power \\
 &= loss_area \times total_power/area/total_power \\
 &= (loss_area/area) \times 100 = \%area
 \end{aligned}$$

The loss area depends largely on segment edge effects. Segment edge effects depend on the excess circumference for the area enclosed by a polygon segment, the gap between segments to accommodate segment control (piston and/or tip/tilt), the segment control method, and edge finishing method. The excess circumference is the difference between the circumference of the polygonal segment and the circumference of a circle that contains the same area. As the number of sides of a polygon increase the excess circumference decreases. However, a hexagon is the greatest sided polygon that can be fitted together into a cluster from purely identical parts.

A disadvantage of the current approach is that the size of the structures (base, clusters and segments) may result in errors due to controls-structure interactions (CSIs). Miniature structures can be stiffer with their lowest structural modes at frequencies well above atmospheric frequencies so that CSI is less significant. Location of the adaptive optical control system within the laser beam path influences the size of the structure.

Four other possible locations for the adaptive optical elements are shown as indicated by numbers 2 through 5.

4.1 An End-To-End Adaptive Optics Concept

As illustrated by **Figure 2.2-1a,b,c,d** more of the natural imperfections of the system can be compensated by end-to-end adaptive optical control compensation. At the same time fewer control and sensor imperfections would be introduced by this end-to-end approach. Thus, a double advantage may be gained in that the design may be simpler and the residual errors may be smaller. End-to-end means to place the phase sensors as far into the SELENE system (toward the FEL) and away from the target beacon as possible. The location in **Figure 4.0-1**, indicated by the number 5, would measure all imperfections except those within the laser. This would be the best location in terms of end-to-end compensation of the BTOS and transfer optics. Theoretically phase measurements at this location could also be used to correct for phase errors in the FEL beam that comes from the opposite direction. Phase corrections by controlled optical segments are best done between the target beacon and the phase measurements at location 5.

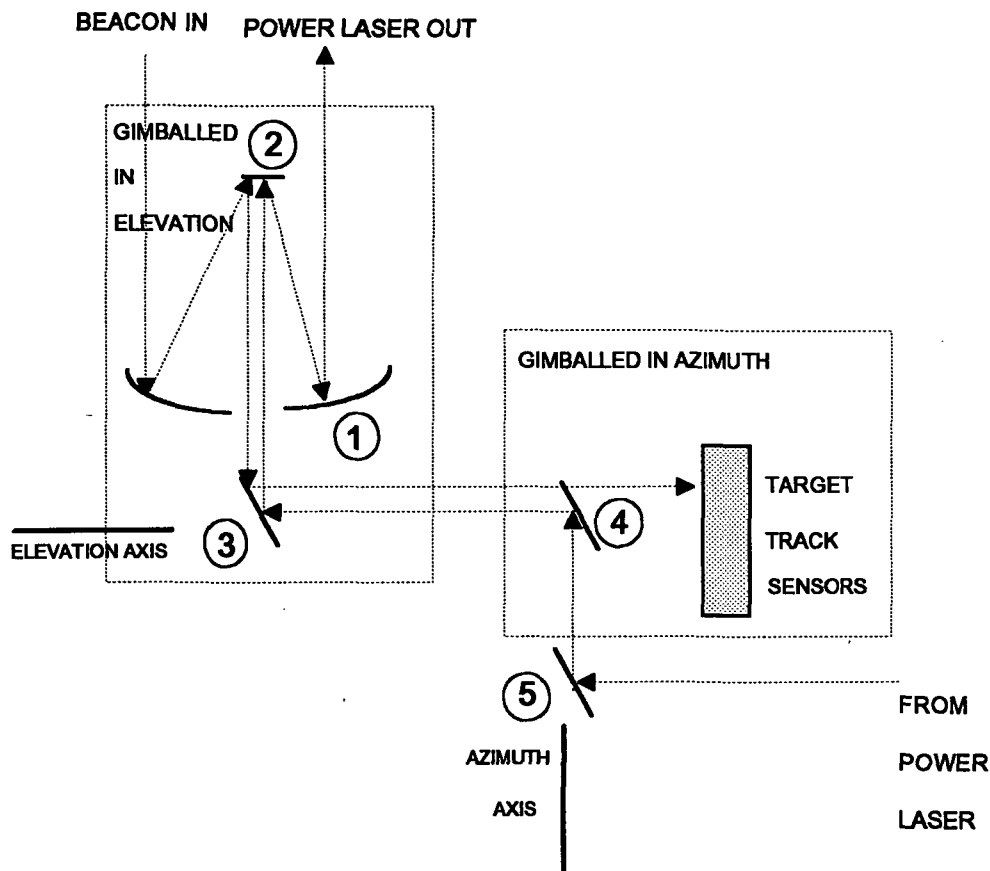


FIGURE 4.0-1. Adaptive Optical Control Alternative Without Regard for System Level Impacts or the State of Technology.

Currently, either the wave front sensor is planned to be located with the target track sensor shown in **Figure 4.0-1** or on the back of each segment. For end-to-end measurements it is proposed that an array of phase sensors be located at 5. The array may be thought of as pixels of an imaging device with focus at infinity to accommodate the parallel light from two (2) adjacent segments of the adaptively controlled optics. **Figure 4.1-1** uses circles to illustrate the pixels that overlap projections of the two adjacent square controlled segments that are located at 3. Projections of controlled segments are shown as square. Location 5 could not be used because adaptive optical elements at 5 would preclude the beam splitter mirror needed for the target tracker and the FEL.

With the beacon phase measurement question settled by selection of position 5 we must decide the location of the motion control of the adaptive optical elements. The motion control of the adaptive optical elements uses the measurements of the phase sensors to drive the adaptive optical elements such that phase errors are driven toward null. We have ruled out locations 1 and 2 in **Figure 4.0-1** for motion control,

because segments and clusters at these locations add considerable weight. The underlying (gimbal based) structures must have a high stiffness-to-weight ratio for precision gimbal control and for less susceptibility to optical distortions due to gravity or other accelerations. (The basic gimbal stability and control-structure interactions will be discussed in **Section 4.3**. The placement of gimbal control, feedback motion, transducers is discussed there since it affects stability.) Of course, with end-to-end measurements, the low frequency optical distortions might be easily corrected. However, as pointed out in **Section 2.3** relative position transducers used in the precision control of optical segments and clusters coupled with structural distortions cause phase correction errors. That is, the distortions of clusters introduce errors in segment positions and distortions of the base structure coupled with relative position measurements cause cluster position errors.

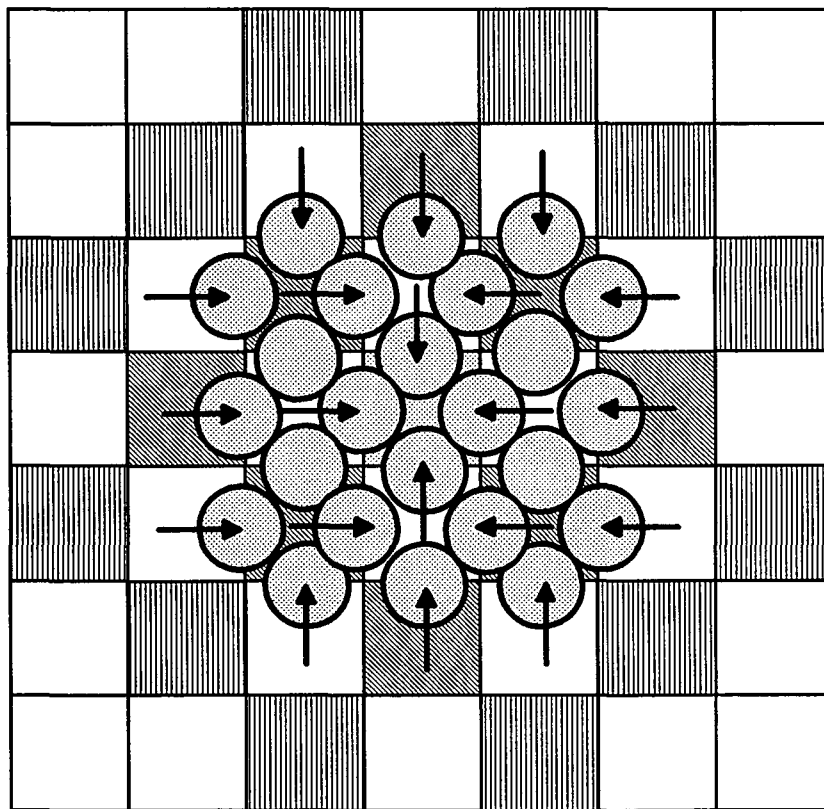


FIGURE 4.1-1. "Pixels" Overlaying Projections of Square Segment Pairs.

In the concept developed herein the segment control law is considerably simpler than control laws used in the current approach. No least squares estimation, etc. is required. Instead a "follower" approach with frequency separation is used. For example, four segments surrounding a fixed reference segment move in piston to equalize phase path length with the reference while moving toward their center positions. Brightness is maximized by each of the four moved in phase with the

reference. The eight segments surrounding the four follow the four to also maximize pairwise brightness. (The idea is based on "Bellman's Principle of Optimality": For the system to be optimal every subarc must be optimal.) This process continues in concentric rings until maximum brightness across a cluster of segments is achieved. All segment motions must be complete before the highest frequency significant atmospheric disturbance passes through a cycle.

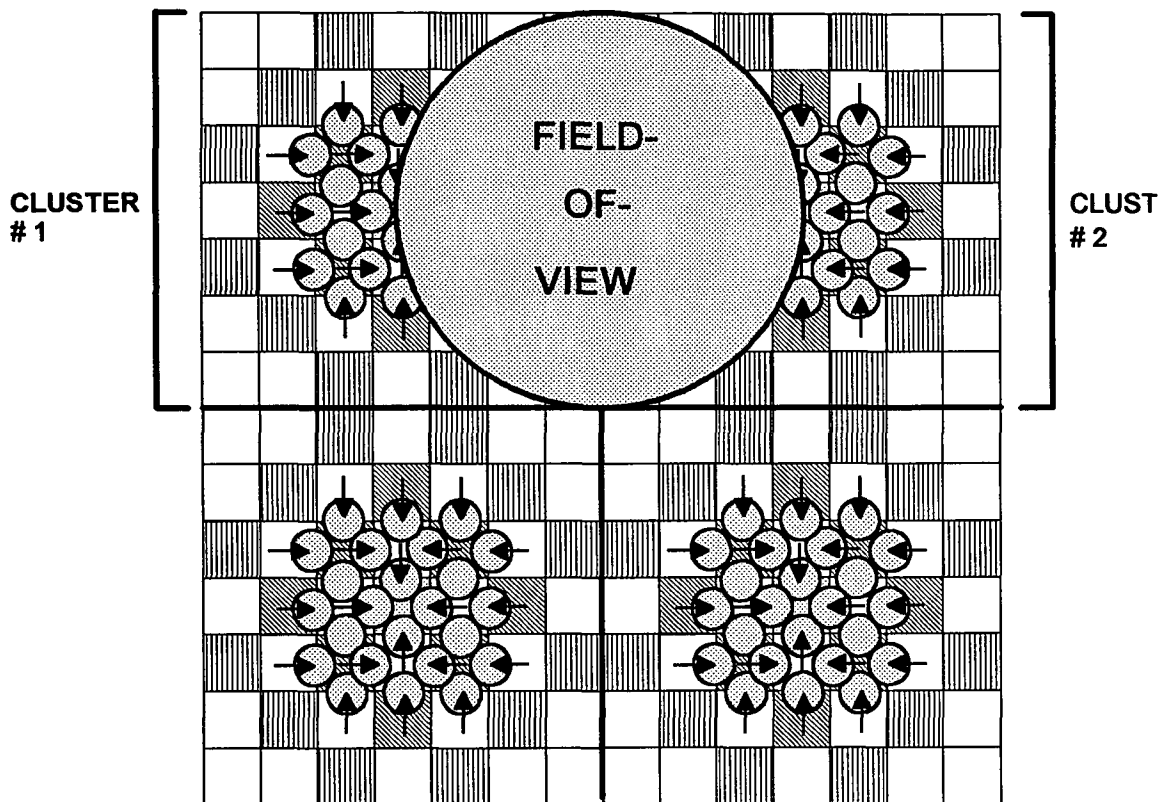


FIGURE 4.1-2. Imaging Device Field-of-View Overlaying Projection of Two Square Clusters.

Mirror segments for this control concept are about 1/4 centimeter across or about the size of the piston actuator. An advantage of this approach is the small segment mass being driven by the piston actuator and the attendant reduced piston force on the supporting cluster. A "rubber" membrane may be needed to serve as the mirrored surface of the segments so that (1) losses are minimized, (2) the finite optical element approximation is better, and (3) damping is inherent in the design. Since this mirror would be within the error sensing loop, local imperfections would be sensed.

Clusters would be controlled in a similar fashion but at lower frequencies. The imaging device's field-of-view would span about half of the cluster's dimension as shown in **Figure 4.1-2**. Clusters in this concept would be relatively small and stiff. Clusters

would be mounted on a very stiff support or their motions would be measured relative to a common, precision reference.

The mirror at location 3 is not currently controlled but rigidly fixed. If the adaptive optical elements are placed at 3, their supporting base structure may be very stiff. Sensing of both power laser beam imperfections, and optical and atmospheric errors induced in the beacon laser are also possible at position 3. Any phase errors introduced at position 3 will be sensed at position 5. Thus, the control compensation loop may be closed around the actuation and finite optical element errors. With the loop closed around such errors it is possible to reduce them.

The mirrored surface of the adaptive optical elements will probably need to be made continuous under piston motion of the elements with a thin film membrane or "rubber" mirror. Since this mirror would be within the error sensing loop, local imperfections would be sensed.

4.2 Overview Of Expected Concept Performance

The design approach taken herein has been one of (1) minimizing error sources and (2) end-to-end measurement and control correction of any errors. Philosophically, as long as the resulting design does not require elements that are beyond the state-of-the-art, this approach should provide a best design in terms of performance reliability and robustness.

5.0 SUMMARY CONCLUSIONS

The most complex and highest risk part of this design is the measurement and control system of the adaptive optics that are used to reduce the optical errors. The adaptive optics are currently envisioned to consist of a system of about 160,000 controllable, hexagonal primary mirror segments mounted on about 90 controllable, hexagonal clusters. The number of clusters could increase in order to improve control stiffness.

In order to reduce the BTOS's complexity and number of high risk elements, it is concluded that end-to-end sensing of optical phase errors and a stiff control system design is needed. An end-to-end sensing and control system would measure across a chain of sensing and control elements and eliminate their errors. As discussed in **Section 3** only the residual error of the end-to-end sensing system and some uncompensated servo errors would remain. An adequate end-to-end sensing subsystem apparently needs to be "invented".

When an error source is compensated (to reduce the error effect of that source), the compensation uses measurements of the error source to "cancel" the error. However, this compensation does not do a perfect job and leaves a residual error that becomes part of the error budget

A fast steering mirror could be needed to globally correct for beam tilt that is not practicable to correct with either the massive BTOS's beam expander's structure's gimbal control or any adaptive optics on this structure.

The beacon at the target exists solely for the purpose of control compensation of optical errors. Optical errors encompassed by measurements that use the "reference" beacon can be replaced by the residual errors of the compensating control system. The beacon is an element of a measurement system to be used with servo elements to form this compensating control system.

The beacon's beam is treated as uncontrollable once it is placed into operation. Its imperfections are internally compensated and not a part of this compensating control system design problem. It is important to note that any imperfections in the beacon's reference beam will be sensed by the measurement system and passed through the control system into the adaptive optics. These errors will then show up in the laser power beam at the target.

The current design induces segment edge mismatch errors in its attempt to compensate for beam wavefront errors caused by the atmosphere. That is, the atmosphere adaptive optics compensation scheme induces another kind of beam imperfection, namely edge mismatch. The induced edge mismatch errors are then partially compensated for by (invented) edge mismatch sensors that complexly drive piston motions of segments and clusters. It is not possible to "match" the six edges of a hexagonal segment as well as provide finite element phase correction in tip, tilt and piston with only a 3-degree-of-freedom segment motion. Only the mismatches between edge centers can be minimized by the current approach.

The assumption of "normal" distributions for all random error variables facilitates analysis, but may result in a predicted beam divergence error that is approximately fifty (50) percent too small. In fact, random oscillatory error contributors, such as those due to structural resonance are better described by the SINE distribution which produces more extreme error occurrences than a "normal" distribution would.

Optical control compensation should be precisely a continuum spatially over the selected major optical element and over the time. Control of a continuum theoretically requires an uncountably, infinite number of actuators and pickoff transducers. Practically, we can only build a finite number and this number should be minimized to the extent that the beam divergence stays within its error budget. Its error budget may be backed out from the target size, target range, and the stabilization and tracking error statistics of the beam's centroid. The number of elements is minimized to reduce complexity and thereby improve performance reliability.

If the beam's lightwaves' phases are controlled across the beam to counter phase distortions, beam divergence at a point in time may be reduced to a residual value that is determined by the "finite element" approximation of the controlled optics, and imperfections in phase sensing, actuators, and control response shaping.

Without consideration of measurements, actuation and control shaping imperfections we conclude the following:

- (1) Any relative motion between the various clusters or within a cluster along the segment actuation direction will result (because the pickoffs measure only relative position) in that amount of segment position error (and laser beam phase error) unless (a) the control compensation filters out the cluster motions or (b) the clusters' lowest deformation and control frequencies are well above segment control bandwidth.
- (2) If an common reference segment sensing device is used on every segment, then cluster deformations and other relative cluster motions only increase segment actuation power requirements.
- (3) Segment actuations generally excite all structural modes, if atmospheric optical phase errors are indeed random across the structural resonances. The lower frequency cluster actuation may excite the lower frequency base structure modes that couple into the segment position errors

When relative motion transducers are used in the current design (1) there can be essentially no relative motions between the mounts (clusters or elements of the primary mirror's base structure) for the large number of segments; and, (2) it is necessary for each segment supporting structure (cluster or base) to be very stiff. All this boils down to: (1) the need for very stiff and probably smaller clusters; and, (2) precision measurements of relative motion between clusters or precision inertial stabilization of all clusters. Inertial stabilization should result in no relative motions between clusters or precision measurements of all cluster motion relative to a common frame.

The bottom line is that the clusters must be stiff or the pickoffs must measure segment motion from a common reference such as an inertial reference.

The errors of the wavefront sensors pass through the system unaffected unless, in the unlikely case, this noise is outside the control bandwidth needed for correction of the primary disturbance of the atmosphere. Thus, the sensitivity (or influence) coefficient of beam divergence to wavefront sensor noise is essentially unity.

The current approach places the adaptive optical elements on the large parabolic, primary part of the beam expander telescope. An advantage of this location is that the adaptive optical elements may be relatively large (about 3 centimeters across) so that miniaturization is not quite so severe. Another advantage is that laser power density is lower so that beam losses and system heating due to these losses might be minimized. However, the percent loss of power is probably the same for either low power density locations of adaptive optical elements or high power locations. Basically, the power loss as a percent of total power is related to the loss area.

A disadvantage of the current approach is that the size of the structures (base, clusters and segments) may result in errors due to controls-structure interactions (CSIs). Miniature structures can be stiffer with their lowest structural modes at frequencies well

above atmospheric frequencies so that CSI is less significant. Location of the adaptive optical control system within the laser beam path influences the size of the structure.

More of the natural imperfections of the system can be compensated by end-to-end adaptive optical control compensation. At the same time fewer control and sensor imperfections would be introduced by this end-to-end approach. Thus, a double advantage may be gained in that the design may be simpler and the residual errors may be smaller.

The underlying (gimbal based) structures must have an adequate stiffness-to-weight ratio for precision gimbal control and for less susceptibility to optical distortions due to gravity or other accelerations. With end-to-end measurements, the low frequency optical distortions might be easily corrected. Relative position transducers used in the precision control of optical segments and clusters coupled with structural distortions cause path length or phase correction errors. That is, the distortions of clusters introduce errors in segment positions and distortions of the base structure coupled with relative position measurements cause cluster position errors. This chain of errors is combined into a total error.

In the concept developed herein the segment control law is considerably simpler than control laws used in the current approach. No least squares estimation, etc. is required. Instead a "follower" approach with frequency separation is used. For example, four segments surrounding a fixed reference segment move in piston to equalize phase path length with the reference while moving toward their center positions. Brightness is maximized by each of the four moved in phase with the reference. The eight segments surrounding the four follow the four to also maximize pairwise brightness. (The idea is based on "Bellman's Principle of Optimality": For the system to be optimal every subarc must be optimal.) This process continues in concentric rings until maximum brightness across a cluster of segments is achieved. All segment motions must be complete before the highest frequency significant atmospheric disturbance passes through a cycle.

Mirror segments for this control concept are about 1/4 centimeter across or about the size of the piston actuator. An advantage of this approach is the small segment mass being driven by the piston actuator and the attendant reduced piston force on the supporting cluster. A "rubber" membrane may be needed to serve as the mirrored surface of the segments so that (1) losses are minimized, (2) the finite optical element approximation is better, and (3) damping is inherent in the design. Since this mirror would be within the error sensing loop, local imperfections would be sensed.

If the adaptive optical elements are placed at the current location of a rigidly fixed transfer optical element, their supporting base structure may be very stiff. Sensing of both power laser beam imperfections, and optical and atmospheric errors induced in the beacon laser are also possible at a transfer optical element position. Any phase errors introduced at the controlled segments' location will be sensed at the phase sensors' location. The control and sensing locations are separate but located within

DSTI

the transfer optics. Thus, the control compensation loop may be closed around the actuation and finite optical element errors.

The design approach taken herein has been one of (1) minimizing error sources and (2) end-to-end measurement and control correction of any errors. Philosophically, as long as the resulting design does not require elements that are beyond the state-of-the-art, this approach should provide a best design in terms of performance reliability and robustness.

It is clear that system integration should not proceed, even at large subsystem levels, until more than minimal funding is made available. The system cannot be integrated in a piecemeal fashion. The telescope structure could be constructed according to a design that could accommodate either the current adaptive optical subsystem or feasible alternatives. Certain parts of the free electron laser could be assembled. However, site construction and full system integration must await a final design of all but the adaptive optical subsystem, which can be added into the system later.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 30 Sept. 1993		3. REPORT TYPE AND DATES COVERED Final Report for 30 Dec. 92 - 30 Sept. 93	
4. TITLE AND SUBTITLE SMALL SCALE ADAPTIVE OPTICS EXPERIMENT SYSTEMS ENGINEERING				5. FUNDING NUMBERS NAS8-39216 1-2-PP-02229	
6. AUTHOR(S) Dr. William H. Boykin, Jr.					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dynamic System Technologies, Inc. 114 C. Lincoln Street NE Huntsville, AL 35801				8. PERFORMING ORGANIZATION REPORT NUMBER HSV-93-0003	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812				10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/ AVAILABILITY STATEMENT Unlimited				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Assessment of the current technology relating to the laser power beaming system, which in full scale is called the Beam Transmission Optical System (BTOS). Evaluation of system integration efforts being conducted by the various government agencies and industry. Development of concepts for prototypes of adaptive optics for a BTOS.					
14. SUBJECT TERMS space power, power beaming, lasers, adaptive optics					15. NUMBER OF PAGES 39
					16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT None		