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# EXPERIMENTAL INSTRUMENTATION SYSTEM FOR THE PHASED ARRAY MIRROR EXTENDIBLE LARGE APERTURE (PAMELA) TEST PROGRAM

prepared by:

William H. Boykin, Ph.D.

Dynamic System Technologies Incorporated

Technical Report No. HSV-93-0002

30 September, 1993

prepared for:

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

under

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## **1.0 BACKGROUND AND PURPOSES**

Adaptive optics are used in telescopes for both viewing objects with minimum distortion and for transmitting laser beams with minimum beam divergence and "dance". A program for development of a telescope for transmitting laser beams is called Space Laser Electric Energy (SELENE).

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 time greater than the 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.

In order to test alternate concepts on a smaller scale NASA MSFC is in the process of setting up an adaptive optics test facility with precision (fractions of wavelengths) measurement equipment. The initial system under test is the adaptive optical telescope called PAMELA which is an acronym for "Phased Array Mirror Extendible Large Aperture". The PAMELA, constructed by Kaman Sciences Company, is a adaptive optics demonstration telescope that consists of thirty-six (36) individual optical elements (segments) along with actuators, edge sensors, wavefront sensors, control and driver electronics, and a gimballed structure. The PAMELA telescope incorporates innovations in the measurement and control of the adaptive optical segments.

The first task under this contract was to provide an assessment of current technologies for PAMELA testing. This assessment included the analysis of test hardware specifications for PAMELA application and the determination of the sensitivities of instruments for measuring PAMELA (and other adaptive optical telescopes') imperfections. Tests have been partitioned into (1) end-to-end tests, and (2) error contributor tests. The error contributors for PAMELA include wavefront sensor errors that drive the adaptive optical segments out of loop, edge sensor errors that attempt to maintain a common reference for segment actuation while minimizing light losses, inner loop actuation errors due to actuator, pickoff and electronics' imperfections, and control algorithm errors.

The second task was to evaluate the PAMELA system integration effort and test progress and to recommend actions to enhance these activities. The initial system integration was performed at Kaman Sciences, but, since May '93 when the hardware was moved to Marshall, integration and test have been the responsibility of MSFC with support from KAMAN Sciences.

The third task was to develop concepts and prototypes of experimental apparatuses for PAMELA. Concepts for experimental apparatuses followed the test partitions (end-to-end and error contributor tests). The conceptual apparatuses include devices for measuring wavefront sensor errors that drive the adaptive optical segments outer loop, edge sensor errors that attempt to maintain a common reference for segment actuation while minimizing light losses, inner loop actuation errors due to actuator, pickoff and electronics' imperfections, and control algorithm errors. Prototype development included support in the selection, purchase and set-up of equipment.

Consultation to MSFC engineers and participation in design review meetings were required by the fourth and final task. DSTI participated in meetings and provided consultation as needed.

## **2.0 ASSESSMENT OF CURRENT TECHNOLOGIES FOR PAMELA TESTING**

An assessment of current technologies for PAMELA testing is developed in this section. This assessment includes the analysis of test hardware specifications for PAMELA application and the determination of the sensitivities of instruments for measuring PAMELA (and other adaptive optical telescopes') imperfections. Test instrumentation is partitioned into (1) end-to-end test devices, and (2) error contributor test devices. The error contributors for PAMELA include wavefront sensor (WFS) errors that drive the adaptive optical segments outer loop, edge sensor errors that attempt to maintain a common reference for segment actuation while minimizing light losses, inner loop actuation errors due to actuator, pickoff and electronics' imperfections, and control algorithm errors.

**Figure 2.0-1** illustrates the PAMELA design. The PAMELA consists of five major parts: (1) the adaptive optics telescope, (2) the coarse WFS, (3) the fine WFS, (4) the relay optics, and (5) the digital control computer. The major parts are shown within "dashed" boxes around them. The WFSs and the adaptively controlled optics of the telescope contain the key elements to be tested.

In full scale operation a light from a suitably-located point source (a distant star or an artificial beacon at about 90,000 meters altitude) would pass through the disturbing atmosphere and enter the telescope. This light would be reflected from the 36-element segmented primary mirror and then pass through the optics to the 36-element WFS. The dynamic range of the fine WFS is such that no need is currently envisioned for the coarse one. Each of the elements of the PAMELA WFS measure wavefront tilts of the light wave from the corresponding telescope segment. Each WFS element spatially averages the wavefront's tilt over most of the segment and provides an almost instantaneous (slightly averaged) temporal measure of tilt. Signals from the WFS are sent to the analog-to-digital converter and then to the digital control computer which commands each segment's actuators (3) in order to tip and tilt the wavefront opposite to the measured values of tip and tilt, and a Poisson-solving wavefront compensation algorithm (nearest-neighbor Jacobi at present) is applied to command the segments in piston.

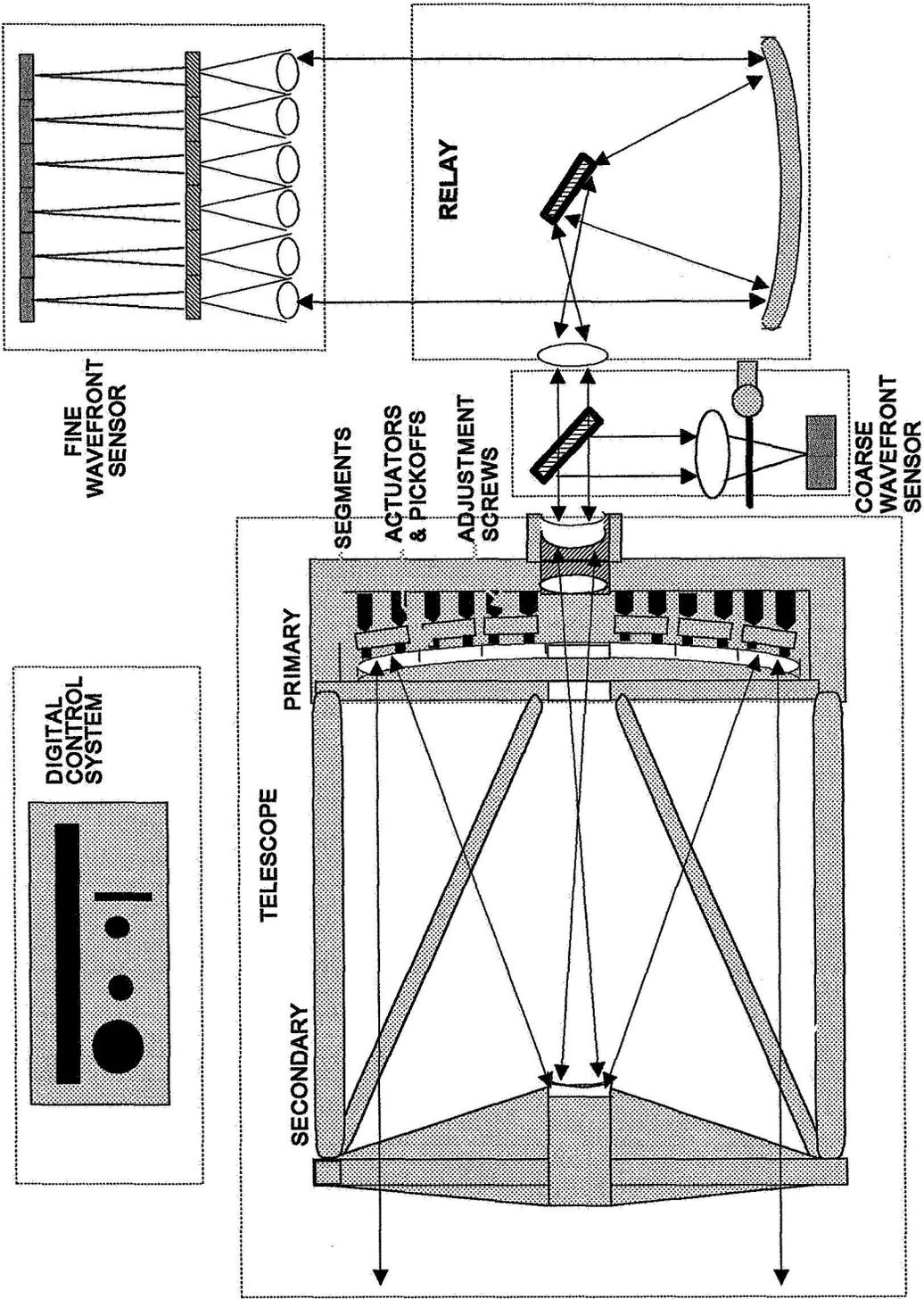


FIGURE 2.0-1. Schematic Diagram of the PAMELA Adaptive Optics Telescope.

Atmospheric wavefront and internal optical distortions are hence compensated over scales of the segment size or larger. Smaller scale distortions cannot be compensated for. Other residual errors will depend in large part on the calibration and alignment of the PAMELA and upon its control response. Control response errors are due to the control system's frequency response and to "concept" errors such as edge correction residuals. Edge correction residual errors are "concept" errors since the design concept did not intend to correct the six edges of a hexagon with only three degree-of-freedom motion.

The current PAMELA Test Plan, developed by KAMAN Sciences about a year ago, combines performance testing with system functional checks and calibration. The approach developed herein clearly separates calibration from performance or diagnostic measurements. It is assumed here that KAMAN has provided a functioning PAMELA system and that its has been calibrated to provide the required performance. The following developments are, thus, limited to system and component level tests.

As will be seen below interferometric test equipment that uses special dither and signal processing is state-of-the-art when it comes to characterizing adaptive optical system, such as PAMELA.

## **2.1 End-To-End Pamela Testing**

As in the component testing described below the system level or end-to-end testing may be partitioned into static and dynamic tests. By definition system level tests are conducted to test performance within the full envelop of system disturbances such as thermal and mechanical loads. Performance is measured by the level of adaptive control compensation of laser beam disturbances produced by the simulated atmosphere and actual system optical imperfections. The Strehl Ratio is one measure of this performance. The Strehl Ratio is defined as

$$SR = I_{TGT}(\text{peak})/I_{IDEAL}(\text{peak})$$

which may be related to the mean deviation in phase,  $\delta\Phi$ , of the ideal beam by

$$SR = \exp(-\delta\Phi^2)$$

**Figure 2.1-1** illustrates the test setup. The WYKO 6000PC laser interferometer can monitor the "static" figure of the telescope to an accuracy of about  $\lambda/100$ . A second laser provides the reference signal for the WFS and is the source of the end-to-end diagnostic beam. Both paths use a large precision optical flat at the telescope entrance to return the wavefronts to the system.

The current test instrumentation is "state-of-the-art". The procurement of other instruments that would improve static and dynamic measurements is not likely in the near term.

The end-to-end test, to completely understand the system's limitations, would operate the system in a "shake and bake" environment that would simulate the full envelop of thermal and mechanical loads found in the Space Laser Electric Energy (SELENE) system environment. SELENE mechanical loads will exist due to gravity, pointing motion and unwanted motions caused by motion disturbance such as wind. Thus, the end-to-end test would be conducted as if the PAMELA were operating in a SELENE environment that would include local heating of PAMELA elements, elevated and low temperatures, dynamic heating, and a realistic spectrum of motions. Of course, the environmental variables will be recorded by thermocouples, inertial rate sensors and strategically placed accelerometers. Currently the Test Plan calls for "bump" tests which could induce high frequency motions. In the SELENE environment the motions are expected to be of low frequency.

The WYKO 6000 laser interferometer with its calibrated "ideal" laser will illuminate the PAMELA telescope's adaptive optics. The PAMELA, due to system imperfections, will distort the beam's waves and use the wavefront sensors, edge sensors, actuators and control system to "correct" the "perfect" beam. Any errors or reductions in the Strehl Ratio will be due to static errors and system noise. Static errors may include "concept" errors such as the segments' finite element approximation of the correct figure of the primary mirror.

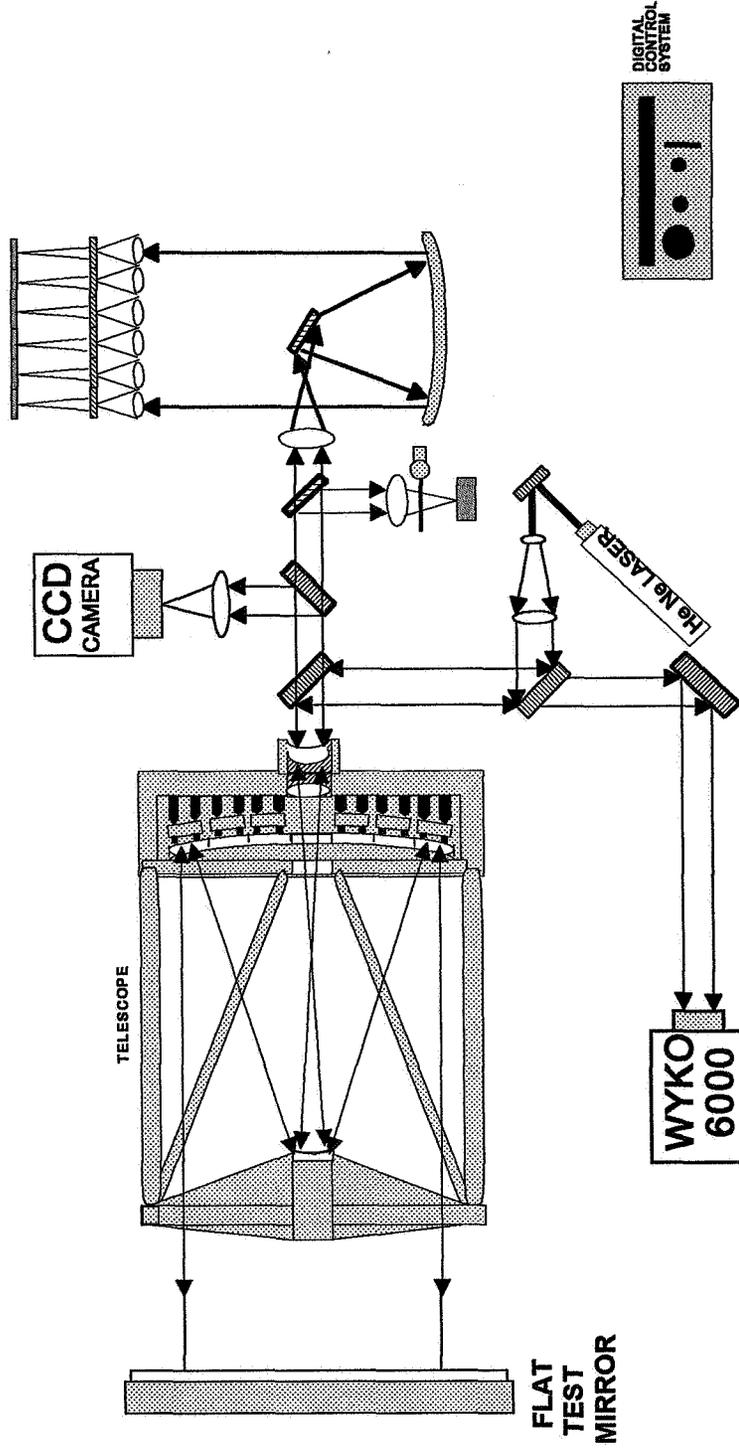
Performance is measured by the level of adaptive control compensation of laser beam disturbances produced by the simulated atmosphere and by actual system optical imperfections. The Strehl Ratio

$$SR = I_{TGT}(\text{peak})/I_{IDEAL}(\text{peak})$$

is the primary measure of this performance, and will be determined by an Image Sensor (IS) in which a diagnostic laser beam through the system will be focused on a CCD camera. The CCD camera's image is at frame rates of 30 or 60 Hertz and cannot sample the laser image over the temporal bandwidth of the overall PAMELA system (up to about 300 Hertz). That beam first passes through an aberration simulator, then through the telescope (twice), and is finally split into the IS and the WFS. A second optical path encompassing the telescope and the WYKO interferometer is used primarily for setting and checking the segments "static" reference position for the end-to-end tests.

The double transit of the beams through the telescope is significant because segment motion angular and piston motion is reflected 4X in the wavefront displacement, not twice as with a normal single transit, and this must be considered in data interpretation as well as in the segment control processing.

To calibrate and test the PAMELA system in the laboratory environment, a precision large flat reflecting mirror will be used. This mirror is shown in **Figure 2.1-1** mounted perpendicular to the telescope's optical axis.



**FIGURE 2.1-1. PAMELA Test Setup with Excitation Laser and Measurement Devices  
Including WYKO Interferometer and CCD Camera.**

The "ideal" end-to-end laser beam will be disturbed by a simulator of representative phase shifts of proper spatial and temporal frequencies corresponding to atmospheric turbulence. The KAMAN test plan calls for the use of a rotating aberrator plate to simulate these effects. The speed of rotation of the plate defines the temporal disturbance frequencies. These frequencies will be considerably higher than those associated with vibrational disturbances to the test setup from, say, passing vehicles outside the lab. The spatial frequency and strength of the disturbances produced by the aberrator plate must be chosen carefully, because the PAMELA system cannot, nor was it ever intended to, correct for disturbances with sub-segment spatial frequencies.

Once the end-to-end system characterization has been accomplished, the individual segments can be exercised in this test setup to further characterize each wavefront sensor, a segment's edge sensors, and a segment's inner-loop (position) control. These tests are discussed below.

## **2.2 Test For Pamela Error Contributors**

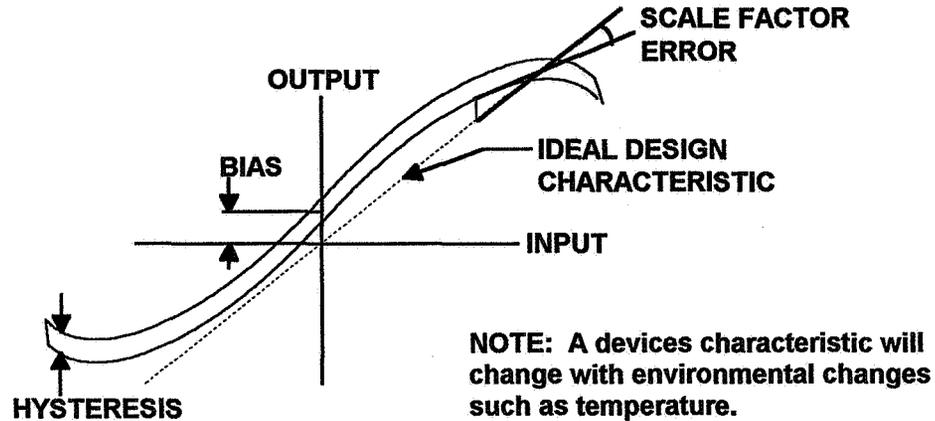
In the previous section the testing for total end-to-end imperfections in the PAMELA system as measured by the Strehl Ratio was discussed. Here the component error contributors to reductions in Strehl Ratio are measured. One might look upon the end-to-end test as a system level test, while component tests are more like diagnostic tests.

KAMAN Sciences in their test report plan to perform "alignments" of the components. These alignments are mostly calibrations, and in some cases would qualify for static measurements of some of the error contributors provided all of the inputs and outputs are recorded. With corrections applied this process reduces the basic assembly errors. Prior to use of the current PAMELA a number of time consuming, manual alignments are performed. Some of these, e.g. focusing and rough centering of the rays from the segments onto the corresponding elements of the wavefront sensor may be unavoidable after replacement of components internal to the WFS itself. However, once that is done, the actual fine adjustment and calibration process could be automated. Controlled rotation of a single transfer optic to provide "global" tilt could provide simultaneous calibration of all segments' WFS element. Controlled tip and tilt of individual telescope segments could "locally" calibrate each WFS and control channel.

"Global" excitation is more direct, but "local" inputs have considerable advantages from the system aspect (see the discussion below of axis orthogonality.) Motion of the tilting element(s) could be precisely measured with the WYKO interferometer or could be characterized in terms of command signal levels. Such measurements are static or "DC" since no movements take place during the measurements themselves.

The components of the system and their proper responses, as defined by the design analyses leading to the final design, are known. Deviations from proper responses contribute to reduced system performance such as defined by the Strehl Ratio. In this section tests for measuring all component errors are devised and summarized in Section 4. This process is one of characterization. Characterization is a process of

precisely measuring a devices response to simple, but precise, inputs. Deviations of the measured output for a given input characterize errors of the devices imperfections. **Figure 2.2-1** illustrates a typical characterization. The goal of the work presented here is to basically measure every deviation from an ideal design.



**FIGURE 2.2-1. Snapshot of a Typical Device's Characteristic with Error Names.**

The component error contributors are listed in **Figure 2.2-2** with test devices. In the case of response times of electronics, it is assumed that design analyses will suffice. Response times of diodes and detection devices are very short compared to the highest system frequency. Digital control elements may also be very fast, but processing throughput may limit the "AC" response.

ERROR CONTRIBUTING ELEMENT	TEMPORAL FREQUENCY	TEST DEVICE(S)
WAVEFRONT SENSORS	DC OVER FULL SCALE	SEGMENTS WYKO WFS
WAVEFRONT SENSOR	AC OVER 3XBANDWIDTH	ANALYSIS
EDGE SENSORS	DC OVER FULL SCALE	METROLOGY TESTS ( $\lambda/20$ )
EDGE SENSORS	AC OVER 3XBANDWIDTH	ANALYSIS
"PISTON" TRANSDUCERS	DC OVER FULL SCALE	WYKO SEGMENTS
EDGE SENSORS IN SITU	DC OVER FULL SCALE	EDGE&PISTON OUTPUTS
FULL CONTROL SYSTEM	DC & AC	CALIBRATED WFS, CALIBRATED EDGE, & CALIBRATED PISTON TRANSDUCED

**FIGURE 2.2-2. Tests for System Error Contributors.**

The Shack-Hartmann wavefront sensors (WFSs) measure locally averaged tilts of wavefronts. Local averaging is a spacial one. Disturbances to wavefronts such as caused by the earth's atmosphere are much slower than the wavefront sensors' rise time so that temporal averaging is essentially nil. The 36 mirror segments are required to be aligned to the 36 WFSs so that (1) the light transferred by the segments will fall onto and only onto its corresponding WFS, (2) it will be centered sufficiently to fully accommodate anticipated steering, and (3) the two measurement axes of the WFS are optically coincident with the controlled axes of the segments. If the WFS is calibrated separately from the telescope segments, the relative orientation of the segment and detector axes must be accurately known.

Internal to the WFS element, the 2-axis lateral effects diode, the axes must be orthogonal. The outputs of these lateral effect diodes are proportional to both the beam power and to the lateral displacement of the focused spot from a somewhat arbitrary reference point on the device. The spot size of the light on the WFS's diode will also have some effect.

Thus, each WFS element must have orthogonal axes and be properly: centered ( $x,y$ ), focused ( $z$ ), rotated for control axis alignment ( $\phi$ ), and tipped and tilted for accurate tip and tilt measurements ( $\theta, \varphi$ ). The outputs of the diodes are proportional, except for scale factor errors, to the lateral displacement of the focused spot from a somewhat arbitrary reference point on the device. The reference point could be at a non-zero voltage output which is stored in the control computer. The bias error could be as small as the quantization level of the digital word that represents the voltage output.

The reference point could be at a non-zero voltage output which is stored in the control computer. The bias error could be as small as the quantization level of the digital word that represents the voltage output. The present system compensates for beam power effects in the digital computer, but it might be preferable to do so with normalization (division) via a chip.

In the current PAMELA setup and calibration processes, which are done manually, such alignments are difficult and time consuming. This would suggest an automated process. All thirty-six of the wavefront sensors would be calibrated by changing the tip and tilt of each segment over their full ranges, measuring these tips and tilts with the WYKO interferometer, and comparing the WYKO measurements with the WFS outputs. These measurements are static or "DC" since no movements take place during the measurements.

The "AC" responses of the WFS elements are expected to be in the sub-microsecond range and not limit performance. However, the WFS signals must be "sampled" by an analog-to-digital converter unless the lateral effects diodes are constructed as digital devices. In any case the WFS signals will have a specific sample rate which must be at least twice the control bandwidth. Otherwise, "foldover" of a high frequency part of the WFS signal into the will fold into the lower control frequencies and cause (1) corrections at the low frequencies where none should be applied, and (2) an absence of corrections at the high frequencies where the correction is needed. Standard signal

analysis hardware may be used to test the frequency response of the digital electronics.

There is no precise way to determine edge sensor errors in situ without first a precise calibration of some other system measurement device. Thus, since the edge sensors' performances are critical to system performance, independent precision tests in a metrology lab would probably be prudent. Edge sensors are designed to measure the segment-to-segment misalignments in the piston direction at the centers of segments' edges. The gap between two segments and hence edge sensor gaps may affect the scale factor of the edge sensors. Because a segment may also have some level of tilt and tilt may couple into the edge sensor's measurement (perhaps to second order), the edge sensors probably need to be tested in the lab with tilt and segment gap variations.

The voice coil actuators used to drive the PAMELA segments show adequate linearity and repeatability for coarse adjustment, but they cannot be calibrated to the required  $\lambda/20$  accuracy. The inductive edge sensors are required for precise adjustments of segments. Since the edge sensors' performances are critical to successful system operation, independent precision tests in a metrology lab would probably be prudent. Edge sensors are designed to measure the segment-to-segment misalignments in the piston direction at the centers of segments' edges. The gap between two segments and hence edge sensor gaps may affect the scale factor of the edge sensors. Also, the tip and tilt may couple into the edge sensor's measurement as well (perhaps to second order). Because of these effects, an edge sensor set probably need to be tested in the lab with tilt and segment gap variations to determine the extent of the effects. There is no realistic way to compensate for the effects of tilt on edge sensors' errors, but one should be aware of them should they be found. On the other hand, it would not be surprising to find gap variations to be important, but their effects would be automatically included in the in situ calibrations which should be made of every edge sensor set using the WYKO interferometer.

### **3.0 EVALUATION OF THE SYSTEM INTEGRATION AND TEST PROGRESS**

The evaluation of the PAMELA system integration effort and test progress is provided in this section. This evaluation is accompanied by recommended actions to enhance these activities.

#### **3.1 Evaluation Of The Pamela System Integration Effort**

The system integration effort was primarily performed by MSFC with support from Kaman Sciences. This effort was delayed by delays in receiving optical test components. Otherwise the assembly of parts is on schedule. The integration effort also includes the alignment of the parts and calibration of the many parts of the PAMELA system. Until the PAMELA with the test apparatus has been aligned and calibrated, the PAMELA system cannot be tested and characterized.

### **3.2 Evaluation Of The Pamela Test Progress**

MSFC leads the PAMELA test effort with support from KAMAN. Tests as opposed to alignments and calibrations have not yet been performed. However, examination of the PAMELA Test Plan reveals several opportunities for improvement.

First, the test plan should include independent system level and component testing to ensure that the system meets its design goals or to provide MSFC with intimate knowledge of the PAMELA system's elements' characteristics. Currently there are no tests beyond calibration and alignment tests at the component level. At the system level there is the rotating aberration plate test described above.

A part of the Test Plan defines how a "remove and replace" test will be performed on a segment. The apparent concerns are alignments relative to the segment's WFS element, edge fit conflict and actuator travel limit. These are inherent problems with segmented mirrors as opposed to certain "rubber" mirror designs. Actuator travel limit concerns about the current design may be reduced by the steering-mirror-cluster-segment ("woofer", "mid-range", and "tweeter") approach proposed by MSFC. This would then allow some automatic adjustments of actuator center positions and preclude actuator travel limit problems. Currently height gages and edge guides are used to assemble a segment with its support.

The Test Plan also calls for "bumping" sensitivity tests along a segment's actuation axis and along lines perpendicular to this axis. This test is both a transient control system test and a steady-state hang-off test. The WYKO would monitor tip and tilt and piston errors as the control system corrects for wavefront errors caused by the "bump". However, in addition to "bumps" it would be useful to determine system performance under expected SELENE disturbances.

As pointed out above, it is prudent to characterize the component devices of PAMELA by independent tests. In addition, if system level tests result in a shortfall in performance, diagnostic tests will be needed. Herein characterization and diagnostic tests have been devised for the following elements: wavefront sensors (WFSs), edge sensors, piston motion pickoffs, actuator and control responses, and opto-mechanical alignments.

The Test Plan calls for the edge sensors to be calibrated by the controlled movement of a single segment in piston while measuring the movement with both a Laser Doppler Displacement Meter (LDDM) and the six edge sensors. For static characterizations it is not clear why another device (LDDM) needs to be used when the WYKO interferometer is specified at plenty of resolution. The LDDM apparently can measure positions accurately while segments move at higher frequencies than the WYKO can. Also this test of a segment in situ determines the gain of an edge sensor group not the gain of a particular edge sensor. Test of all segments in this way could however provide a 3-dimensional matrix of measurements (edge pairs and displacements) from which the individual edge sensor's gain may be determined. This process could and should be automated since multiple runs across all 36 segments with multiple piston positions and measurement samples of each segment's position at each position are needed to have

confidence in the results. While this edge sensor gain characterization is in progress the piston control transducers should also be characterized by monitoring their outputs.

The Test Plan calls for alignment of the Pupil Relay optics. These optics exist strictly for the purpose of getting the light waves from a reference beacon and reflected off of each segment to the correct wavefront sensor (WFS) element with the proper "orientation". As mentioned above, the 36 mirror segments are required to be aligned to the 36 WFSs so that (1) the light transferred by the segments will fall on and only on its corresponding WFS, and (2) the two measurement axes of the WFS are optically coincident with the controlled axes of the segments. Internal to the WFS element, the 2-axis lateral effects diode, the axes must be orthogonal. The spot size of the light on the WFS's diode will also have some effect. Thus, each WFS element must have orthogonal axes and be properly centered (x,y), focused (z), rotated for control axis alignment ( $\phi$ ), and tipped and tilted for accurate tip and tilt measurements ( $\theta, \varphi$ ). The outputs of the diodes are proportional, except for scale factor errors, to the lateral displacement of the focused spot from a somewhat arbitrary reference point on the device. The reference point could be at a non-zero voltage output which is stored in the control computer. The bias error could be as small as the quantization level of the digital word that represents the voltage output. The Pupil Relay is planned to be tested in isolation and aligned as an optical element that maintains collimation of light. The WYKO interferometer is planned to be used in this alignment by a pass of the laser light from and to the WYKO by way of two transients of the Pupil Relay. The flat test mirror (ZYGO) is planned to be used to return the light to the WYKO after it leaves the WYKO and transients the Pupil Relay twice.

An automated Pupil Relay alignment approach is possible, if the Pupil Relay is mounted on a translating table. (Minor rotations might also be desirable to test higher order imperfections.) With automatic control of the Pupil Relay each segment could be "wiggled" by the PAMELA control system and the wiggles sensed by the WFS elements. A map of the segment wiggles to WFS responses could be used to compute corrections for the Pupil Relay's position. These corrections would be sent to the Pupil Relay's control system for correction. Before the Pupil Relay's position can be automatically controlled, its axes of motion should be mapped into changes in the segments' maps onto the WFS elements. By making large movement (roughly more than one WFS element wide) the axes of Pupil Relay motion may be determined.

Orientations of the WFS elements' axes to the segments' axes can also be accomplished by a technique similar to the automatic Pupil Relay alignment. The Test Plan calls some of the corrections of these misalignments the "elimination of cross-coupling". The Plan proposes to tilt the entire Pupil Relay's parabolic mirror. Any movement of the Pupil Relay's components could affect the alignment described in the previous paragraph. Thus it appears better to use the actual control axes of a segment to produce a wave tilt that is measured by the corresponding WFS element, and use the segment's measured tip and tilt (previously characterized) with the WFS's measurement of the wavefront's tip and tilt to compute the rotation that causes "cross-coupling". This rotation value may be stored in the control computer and numerically corrected. There is no reason to physically adjust the WFS elements

provided their manufacturing errors do not produce measurements or control corrections that are significant fractions of full scale limits of the device.

The Test Plan also calls for global "offset" calibration, which is defined as the average "global" tilt across all actuators. This global tilt can be computed and corrected numerically by a correction command to each segment's control system. Again, there is no need to manually adjust the system to reduce global tilt, unless control and sensor limits are being approached. Local "offset" corrections are also called for. These are caused by various effects including "detector/electronics 'dark' offset differences." Regardless of the causes, the individual segment tilts and edge misalignments must be nulled. This setting of the segments into the proper primary mirror figure was discussed above. The WYKO interferometer would be used to compute the corrections and make these control adjustments. Similarly "gain matching and calibration" was discussed above.

#### **4.0 CONCEPTS AND PROTOTYPES OF EXPERIMENTAL APPARATUSES**

Concepts and prototypes of experimental apparatuses for PAMELA are described in this section. Concepts for experimental apparatuses follow the instrumentation partitions (end-to-end and error contributor test devices). The conceptual apparatuses include devices for measuring wavefront sensor errors that drive the adaptive optical segments outer loop, edge sensor errors that attempt to maintain a common reference for segment actuation while minimizing light losses, inner loop actuation errors due to actuator, pickoff and electronics' imperfections, and control algorithm errors. Here these concepts are summarized. Details of these concepts are provided in the assessments of current tests of PAMELA in Section 2.

Initial alignments to put the system into the state it was designed for involves many of the same steps used herein for performance testing of components and system. It appears that the alignment process could be more automated. Examples of experimental apparatuses and their uses in initial alignments are given below.

##### **4.1 Concepts Of Experimental Apparatuses For Pamela**

In the above assessments of current technologies for testing the PAMELA system various alternative concepts for test measurements were described.

It is suggested that a thermal chamber with an isolated low frequency motion table be used to characterize components and systems so that the test environment will be well known and recorded for any diagnostics investigations that might be needed.

The static and dynamic alignments could use a substantial increase in automation that could also be used in an operational SELENE system. This will be especially true once MSFC begins testing adaptive optical systems that have orders of magnitude more segments than the thirty-six segments of PAMELA.

Characterization and diagnostic tests have been devised above for the following elements: wavefront sensors (WFSs), edge sensors, piston motion pickoffs, actuator and control responses, and opto-mechanical alignments. The Section 2 is primarily an

assessment of the current state of PAMELA testing. However, while assessing the PAMELA tests, suggested additional test were described at the same time, rather than here in Section 4, so that the reader could compare "current" and "suggested" tests in the same section.

#### **4.2 Prototypes Of Experimental Apparatuses For Pamela**

Because most of the optical alignment and calibration equipment used before with PAMELA belonged to KAMAN, MSFC had to purchase replacement equipment in order to calibrate and test the system. DSTI ordered these experimental apparatuses according to the experimental concepts above and delivered them to MSFC.

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