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Development of the Segment Alignment Maintenance System (SAMS) for the Hobby-Eberly Telescope

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ABSTRACT

A sensing and control system for maintaining optical alignment of ninety-one 1-meter mirror segments forming the Hobby-Eberly Telescope (HET) primary mirror array is now under development. The Segment Alignment Maintenance System (SAMS) is designed to sense relative shear motion between each segment edge pair and calculate individual segment tip, tilt, and piston position errors. Error information is sent to the HET primary mirror control system, which corrects the physical position of each segment as often as once per minute. Development of SAMS is required to meet optical image quality specifications for the telescope. Segment misalignment over time is thought to be due to thermal inhomogeneity within the steel mirror support truss. Challenging problems of sensor resolution, dynamic range, mechanical mounting, calibration, stability, robust algorithm development, and system integration must be overcome to achieve a successful operational solution.

Keywords: mirror alignment, segmented mirror, edge sensor, inductive sensing

1. INTRODUCTION

The HET is a 9.2-m fixed elevation telescope with a segmented primary mirror. It is located at McDonald Observatory in far West Texas at an elevation of 2,008m. Descriptions of the telescope[1], its operation[2], scientific instrumentation[3,4,5,6], recent commissioning experience[7,8], and early science results[9] may be found at the indicated references. A cutaway view of the facility with its major components is shown in Figure 1. Telescope commissioning was completed in early October 1999, and the instrument is currently used for early science operations about half of the available nighttime hours. The remaining nighttime hours are devoted to engineering and test activities. This paper describes the current alignment maintenance problem with the primary mirror and details the early development and current status of a solution to it. Following completion of the SAMS project in mid-2001, it is the intention of the authors to report on the final development, implementation, and baseline performance of SAMS on the HET.

2. BACKGROUND

The HET was funded and built by a consortium of five universities, the University of Texas at Austin, the Pennsylvania State University, the Ludwig-Maxmilians Universität München, the Georg-August-Universität Göttingen, and Stanford University.

The HET employs a spherical segmented primary mirror supported by a steel truss as an essential part of the telescope's low-cost, Arecibo-style design concept (see Figures 1 and 2). The unique design of the HET allows the primary mirror to remain stationary during an observation; it can be rotated and repositioned in azimuth between observations to access different areas of the sky. The mirror has a constant zenith angle of 35 degrees, and thus always has the same orientation with respect to gravity. Images of astronomical objects are acquired and followed across the mirror

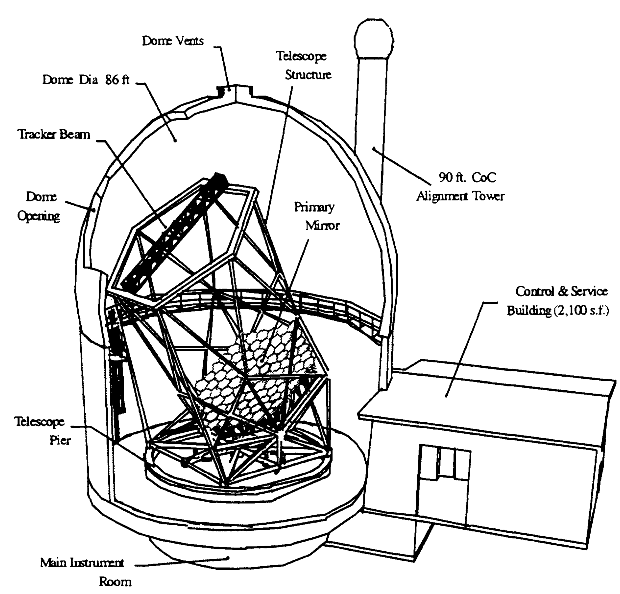

Figure 1 - HET Facility

In *Optical Design, Materials, Fabrication, and Maintenance*, Philippe Dierickx, Editor, Proceedings of SPIE Vol. 4003 (2000) • 0277-786X/00/$15.00

array at prime focus for up to 2.5 hours by means of a tracking device (Tracker Beam in Figure 1, above) mounted atop the telescope structure

This design simplifies the mirror support problem and significantly reduces the total cost of the telescope. The construction cost of the telescope was $13.5 M, about 15% of the cost of fully-steerable telescopes of comparable size. Design and construction time was approximately five years.

HET first light was achieved in December 1996 with seven mirror segments collecting and focusing light through a test optical corrector. During initial testing of the telescope after first light, composite star image formed by individual mirror segments were observed to "de-stack", or move with respect to each other, over a period of time after the segments had been "stacked", or aligned with each other. While minor segment motion over a period of an hour or more had been anticipated in the original design, misalignment of the segments on a time scale of tens of minutes under some conditions was unexpected. Partially as a result of this behavior, the HET image quality averages 2.5 arcseconds at present. The objective of the SAMS upgrade is to correct the effects of this phenomenon, maintaining primary mirror segment alignment to within the specifications and requirements contained in the original Spectroscopic Survey Telescope (SST, now HET) Science Requirements document[8].

3. PRIMARY MIRROR ARRAY DESCRIPTION

For the reader who wishes to understand the sources of the de-stacking behavior and our developing solution to it, an understanding of the physical components forming the primary mirror array is essential. The telescope primary mirror is comprised of a close-packed array of 91 1-m (flat-to-flat) regular hexagons. Figure 2 shows the segment array installed on the mirror truss and supported by the telescope structure at the use angle of 35 degrees from the zenith. For reader orientation, the large "X" braces visible in the Figure 1 diagram can be seen in the Figure 3 photograph enclosing the primary mirror.

Segments are made of Schott Zerodur low-expansion glass ceramic material. Each segment is 50 mm thick, weighs 114 kg, and is supported axially at nine points by three, 3-point whiffletrees. For radial support, each segment is constrained by a partial ring in the plane of the segment's center of mass. The ring is supported through a central blind hole bored into the segment from the back side. The radial and axial supports are attached to the mirror segment support frame shown in Figures 3 and 4. The mirror segments are not phased with each other in the array, but are designed to be pistoned to within 25 microns of a master sphere radius of 26,163.9 mm.

Figure 2 - HET Mirror Array and Truss

The array spans 11.1 meters point-to-point and 9.8 meters flat-to-flat, and is supported by the three-layer steel truss contacting the telescope structure on three kinematic points. Two of these points are visible in Figure 2, indicated by the white arrows. The third, upper point forms an equilateral triangle with the lower two points, 7 meters on a side. The truss is fabricated from steel tubing 50-100 mm in diameter, and spherical steel nodes 100-200 mm in diameter.

The upper side of the truss in turn provides three symmetrical support points for each mirror segment, for a total of 273 nodes in the truss top layer. Mirror supports are bolted directly to these nodes and provide axial and radial support to the mirror segments, as well as motion control in tip/tilt and piston.

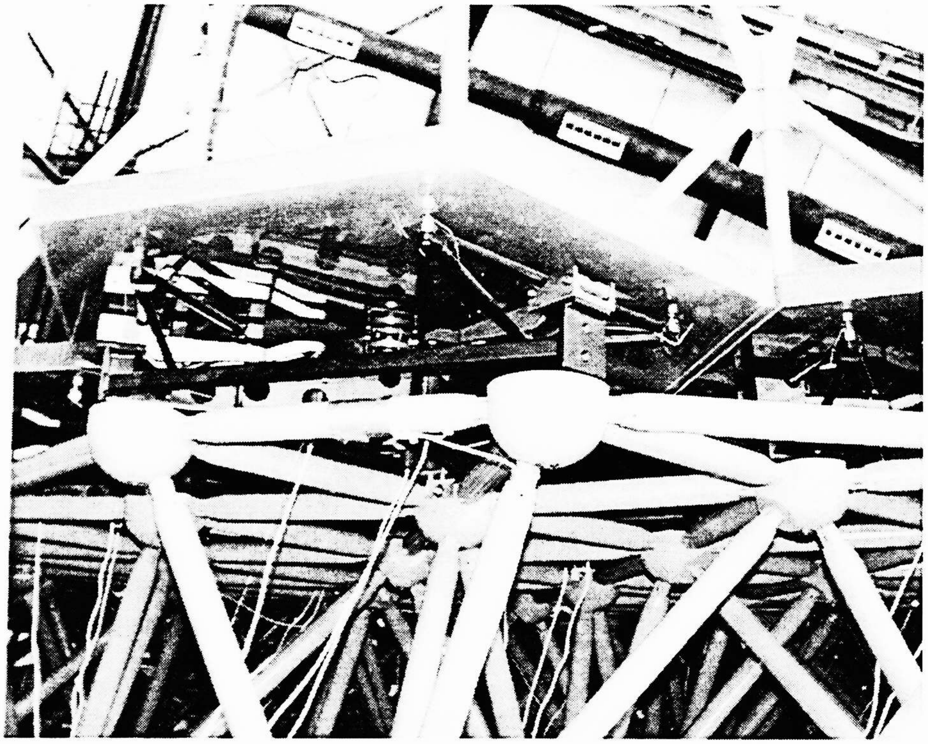

Figure 3 - Mirror Truss, Segment Support, and Segments

A side view of this arrangement may be seen in Figure 3. The mirror truss upper layer and upper diagonals are visible in the lower half of the photograph. The black mirror support is bolted to the truss below and supports the back of the segment, above. The bright plated actuator lever arm can be seen at left, along with its reflection on the underside of the segment.

A drawing of the support frame and lever assembly is shown in Figure 4. The mirror segment support consists of a steel triangular support frame that attaches to the mirror truss and supports three tetrahedral whiffletrees. The whiffletrees spread the mirror segment load from 9 axial contact points at the back segment surface through a compound lever to 3 motor micrometer actuators within the support frame. Bearing pivot points are steel pins in bronze bushings. The radial support hub shown inserts into the segment radial support pocket to support the segment laterally. The mounting points insert into threaded holes in the truss nodes, and provide rough initial adjustment.

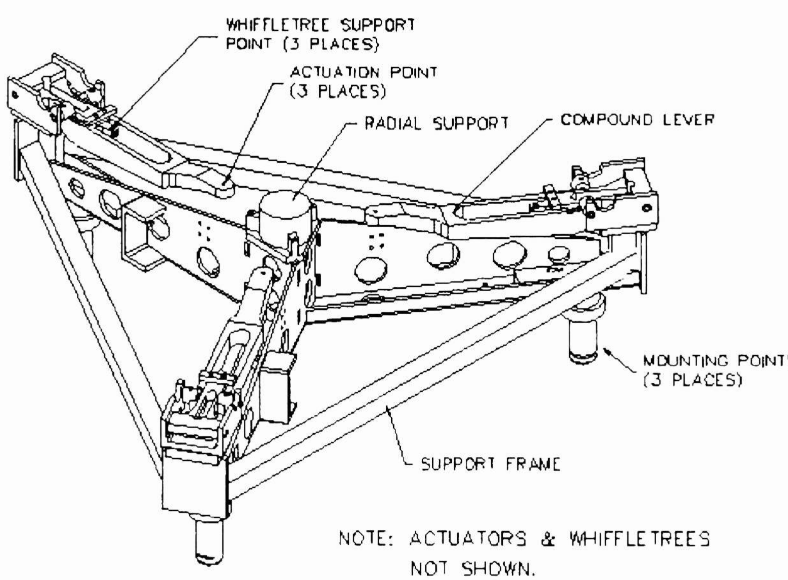

Figure 4 - Mirror Support Frame

4. PRIMARY MIRROR ALIGNMENT

4.1 Overview

In order for the primary mirror array to achieve alignment within the optical error budget requirements, each segment must be aligned in tip and tilt to within 0.06 arcseconds of nominal, and pistoned to within 0.3 mm of a master sphere of radius 26,263.9 mm. A more detailed discussion of this process may be found elsewhere in these proceedings.[12]

4.2 Tip/Tilt alignment

The primary mirror array is aligned into a precise spherical surface using the Center of Curvature Alignment System (CCAS) instrument located in the small dome on the alignment tower shown in Figure 1. Since the tracker obscures some mirror segments, it is first moved to one side of the array while the other side is aligned. Divergent helium-neon laser light is broadcast down to the array from a pinhole at the Center of Curvature (CoC), and return spots are formed on a CoC faceplate visible through video cameras in the telescope control room.

Figure 5a is a photograph of the return spot pattern from one half of the mirror array. The spots are arranged in the three-ring pattern shown to facilitate identification, and are then centroided and stacked into a single common spot. Then the tracker is moved to the other side of the array, and the second half of the array is arranged into a three-ring pattern as shown in Figure 5b. (The central bright spot is the ensemble image from the first array half.) Once these segments are identified and centroided, the second half is collapsed into the central spot shown in Figure 5c.

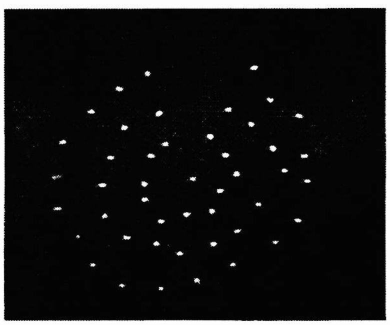

Figure 5a

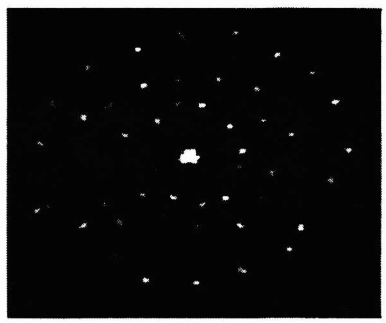

Figure 5b

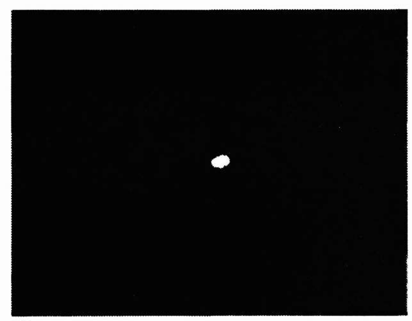

Figure 5c

Figure 5 a,b,c - CCAS Faceplate Alignment Patterns

4.3 Piston alignment

At present, the mirror array is aligned in piston approximately monthly using a hand-held spherometer from the basket of the person lift. Relative segment-to-segment height differences are thus measured manually. This relative measurement does not seem to change much from month to month, as long as the mirror segments are not disturbed in any way. It should be noted that this is not the same as measuring piston against a master sphere. The current average piston variation for the array is about 40 microns RMS.

4.4 Radius of Curvature alignment

Currently we focus the return spot of the center mirror segment on the CCAS faceplate by moving the faceplate axially. The remaining segments are then stacked on the faceplate using this location. We have no means at present of maintaining this global radius of curvature (GRoC) while observing with the telescope. GRoC is recovered each time stacking is performed.

4.5 Primary Mirror Array Alignment Degradation

Once the primary mirror array is aligned on the CCAS faceplate (typically to a 1-1.2 arcsec EE(50%) return spot size), the telescope can be moved in azimuth and acquire objects. However, particularly in correlation with temperature gradients exceeding 0.5 degrees C/hr, the spot size is observed to enlarge at an average of 0.6 arcseconds/hr. A typical plot of this measured behavior is shown below. Details of the genesis and refinement of this measurement, known as the "alignment maintenance baseline test" (AMB), are to be found at the indicated reference[12].

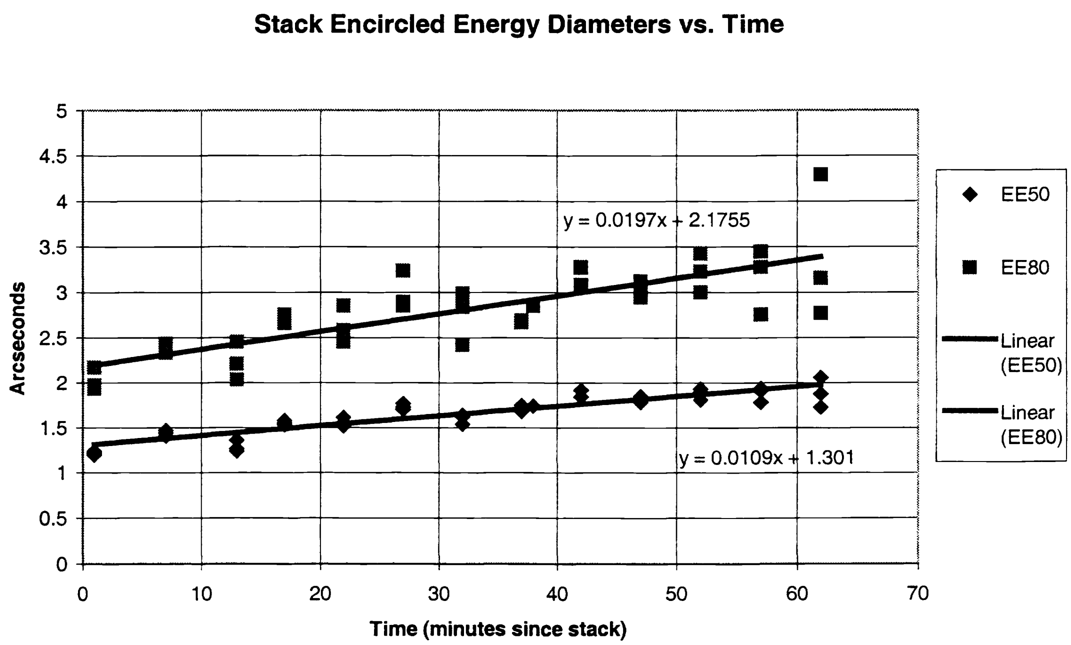

Figure 6 – Typical stack degradation with time

Once the stack degradation had been quantified with the AMB tests in September/October 1998, the source of the de-stacking phenomenon had to be determined. Three possible source areas were identified and explored: 1) A purely thermal source associated with temperature variations within the truss itself, 2) thermally-induced mechanical creep somewhere within the mirror segment support, and 3) purely mechanical settling (isothermal creep) following stacking.

Mechanical settling after stacking was eliminated as a possibility by measuring motion of several test segments relative to their mounts immediately after stacking was performed. A sensitive linear variable displacement transducer (LVDT) was attached to the mount, and the LVDT probe was placed against the back of the mirror segment. No significant segment motion was discovered after stacking during repeated testing of several segments.

The thermally induced mechanical creep error source was placed in doubt but not completely eliminated by using a similar measurement technique. The segments were instrumented as above, and the facility air conditioning system was used to vary the ambient temperature of the truss. An effort was made to compensate for the apparent mechanical drift of the LVDT caused by the changing temperatures, but the result was not fully satisfactory.

The conclusion of the solid mount test and other testing was that the truss thermo-elastic response to its local ambient environment was responsible for the majority of mirror segment drift after alignment.[12]

Note: Early results had confirmed a correlation between the rate of unstacking and the thermal rate of change with time. A thermal model was developed in early 1998 to predict required tip/tilts, but was never shown to have predictive capability. The model could best be described as a geometric temperature interpolator, not a mathematical finite element analysis (FEA) model of the physical truss in the classical sense. That is, the model did not employ thermal impedance, section properties of nodes and struts, and heat transfer information (convection, conduction, and radiation) into and out of the truss as an FEA model would do. It is thus unlikely that the interpolator will be able to predict accurately the physical truss performance in a changing thermal environment.

5. SEGMENT ALIGNMENT MAINTENANCE SYSTEM

At the HET Primary Mirror Optimization workshop II held on 13 October 1998, a management decision was taken to pursue development and procurement of some type of SAMS system. This was based on the preliminary results of various tests on the mirror array, most prominently the solid mount mirror testing described elsewhere in these proceedings[11,12]. Such a system would be similar in control architecture to the highly successful edge sensor system on the Keck telescopes[13], but would have to depart from the Keck paradigm in many respects for technical and cost reasons.

The HET system would clearly be a retrofit to the existing mirror array. The Keck capacitive sensing paddles weigh on the order of one kilogram, and Keck segments were figured to take into account this extra mass. Since similar paddles attached to HET segments would destroy the existing segment optical figure; another solution had to be developed. Also, a SAMS system was not originally envisioned to be necessary for HET, and its capital cost had not been budgeted for to this point. A relatively inexpensive solution (<$1M) was required.

5.1 SAMS Procurement Effort

Following the decision to procure SAMS, and intensive effort was initiated to develop the system requirements and write a statement of work and specification for SAMS. Simultaneously, an effort was begun to develop in-house expertise into capacitive and inductive sensors. Other technologies were investigated (interferometric and fiber optic sensors) and rejected on a cost or technical basis. Table 1, below, shows the subsequent actual timeline for the SAMS procurement to date. Of particular note is that it took over a year of continuous, high-level effort from the decision to procure SAMS to a signed agreement with a technically capable vendor.

Table 1 – SAMS Procurement Timeline

Activity	Date
First draft Statement of Work (SOW) released for internal review	15 February 1999
Second draft SOW released for review	26 March 1999
Formal SAMS Review meeting	13 April 1999
Final draft of SOW delivered to Purchasing	03 June 1999
RFQ/Invitation to Bid sent from Purchasing	07 June 1999
Pre-bid Conference at HET site	24 June 1999
SAMS bid opening	03 August 1999
SAMS proposal evaluation/selection meeting	12 August 1999
Recommendation of award	16 August 1999
Purchasing notified to award to MSFC	25 August 1999
Purchase Order issued	13 September 1999
Preliminary Meeting	30 September 1999
SAMS Agreement signed	01 November 1999
Concept Design Review	19 January 2000

The SAMS proposal evaluation team selected the NASA Marshall Space Flight Center/Blue Line proposal on basis of technical excellence, completeness, and overall value.

5.2 SAMS ARCHITECTURE

SAMS is a sensing and computing system that supplies mirror segment position data to the HET Primary Mirror Control (PMC) system required to maintain the alignment of the primary mirror array. SAMS senses mirror segment positions and computes the corrections necessary to bring the segments back into alignment. The SAMS baseline design concept consists of position sensors and sensor targets located along each edge pair of each segment in the primary mirror. Edge pairs are areas of the primary mirror array where two hexagonal segment edges face each other across an air gap. There are 240 edge pairs in the array. Additional sensors are necessary to determine large scale radius variations in the primary mirror truss due to temperature changes, as we have no way to directly and continuously measure absolute piston position at present.

SAMS provides complete correction updates to the PMC upon request by the PMC every 10 seconds, 24 hours per day, 365 days per year. The PMC evaluates these updates and determines whether action is necessary. Following initial optical alignment of the mirror array segments, SAMS can provide accurate information to maintain tip/tilt alignment and global radius of curvature to the mirror control system for a minimum of 14 days without additional external intervention. SAMS piston information is accurate for a minimum of 90 days between alignments. SAMS can also operate in a degraded mode, where it is not necessary to have all 91 mirror segments installed or working properly for the mirror array to be useful for science data gathering.

5.2.1 General Overview

The proposed SAMS alignment maintenance system is based largely on technology developed at Blue Line Engineering Co. in conjunction with Marshall Space Flight Center. The underlying control strategy is based on work pioneered by Nelson and Mast[13] in which they demonstrated that an array of position sensors could be used to sense and maintain the figure of a segmented primary mirror array. These position sensors are commonly referred to as edge sensors, and the accuracy of these measurements is critical to the ultimate performance of the system.

By performing suitable matrix operations on the full vector of all edge sensor readings, an error vector may be derived, comprised of all actuator corrections needed to restore the array of mirror segments to some pre-calibrated orientation, which defines the overall figure of the segmented primary mirror. It can be shown that given ideal edge sensors and actuators, this approach will correct all figure error terms except what we refer to as GRoC (global radius of curvature) errors. This error term in the primary mirror figure is not sensed by the array of edge sensors in their purest form.

Nelson and Mast employed a particular arrangement of the edge sensor that can weakly sense this GRoC error term and this is the approach that is used on the Keck telescopes. The Blue Line/NASA approach to figure maintenance is to sense GRoC errors more directly by implementing a subsystem of sensors specifically suited to this requirement. These sensor readings are then processed along with the edge sensor data in the same matrix operation to remove all error terms, including the GRoC error.

In the following subsections, we will describe the specific details and merits of our particular approach to each of these issues. We will begin by describing the overall system architecture and how all the various subsystems relate to each other. Then we will discuss the functional behavior of the system in terms of its operational modes. Next we will treat each of the critical subsystems in detail including edge sensing subsystem, SAMS operations console, and control system issues.

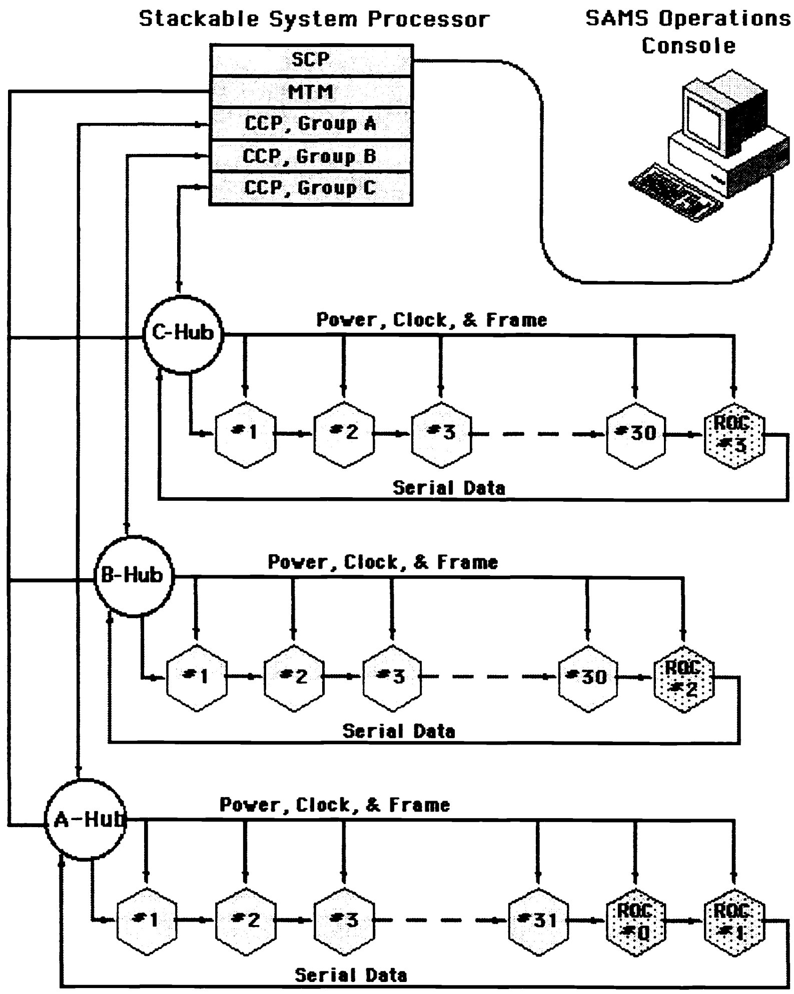

Figure 7 - System block diagram for SAMS. Power supply and SSP to be located in enclosure behind telescope truss. Console to be located in control room. All other system modules to be located on the truss.

5.2.2 Functional and Physical Layout

Functionally and physically, the entire system divides into two major components. The most visible and perhaps most accessible component is the SAMS console, which will reside in the control room for easy access by the telescope operators. All human and system level interfaces to SAMS during normal operations are via this console, and all control system operations are performed in the console's CPU. Physically, this portion of SAMS consists of a single desktop workstation running a variety of software modules specifically developed for SAMS.

The second main component of SAMS is the array of edge sensors, data acquisition and signal processing electronics, radius of curvature sensors, digital signal processors (DSPs), and the necessary cable harnesses and support elements that are all located just behind or very near the HET's segmented primary mirror. The main function of this component of SAMS is to acquire and pre-process high quality measurement data. Communications between the two components is via a single fiber optic, serial data link.

5.2.3 System Processing Architecture

For the HET SAMS application, a modified version of Blue Line's Segmented Mirror Control System has been adopted. This distributed, highly modular processing system was originally developed to meet the challenge of a closed-loop control of arrays of several thousand segments, and at frame rates of 5 kHz. The extensible architecture allows the system to be scaled up or down to meet a wide range of applications. As a result, the processing system for SAMS will have exceptional computational ability, allowing us a great deal of flexibility in distribution of processing tasks throughout the system. A block diagram is presented in Figure 7.

5.2.4 Console

At the top of the SAMS architecture sits the executive level processor, or console. It provides a graphical user interface (GUI) between the human operator and SAMS with features similar to those found in Figure 8. It also performs numerical computation on data it receives from the sensor subsystems and communicates the actuator correction commands to the primary mirror controller (PMC) when requested to do so by the PMC. Communications between the SAMS and the PMC shall be via an Ethernet local area network (LAN).

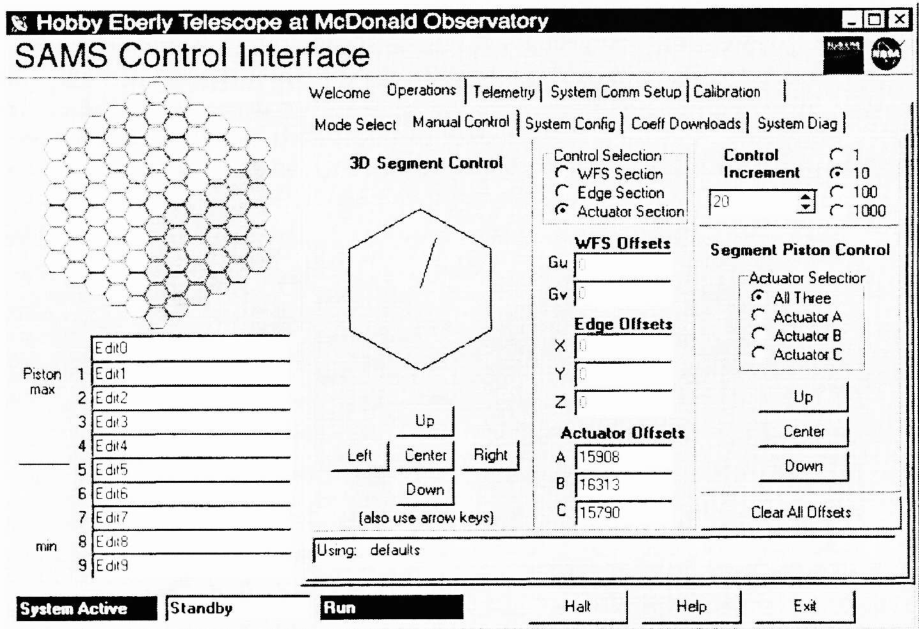

Figure 8 – Prototype SAMS Graphical User Interface

The console also provides a SAMS virtual instrument front end which allows operators to perform a rich variety of diagnostic and data analysis functions on user selected data streams. This virtual instrument (VI) front end to SAMS is also available to the operator at the PMC via X Windows.

The console communicates with the rest of the SAMS system via a single-serial data link to the stackable system processor, which will be described next. The format for all command and control communications will be ASCII. Preprocessed sensor data may be sent in either packed binary or ASCII format in response to requests for data issued by the console. The preferred physical medium for this serial data link is fiber optic lines. The preferred protocol is RS-422 since it provides more complete control of the data transfers, but this communications protocol is usually implemented in multiconductor copper cable. Final decisions regarding medium and communications protocol will be made prior to the preliminary design review (PDR) and subject to the approval of HET.

5.2.5 Stackable System Processor

The stackable system processor (SSP) is a powerful parallel processing system that is packaged in a small, modular format. The individual modules are stacked together to build up the system as needed for the application at hand. The low power processors do not require forced air cooling so the hardware is very well suited to a wide range of field conditions. The basic building blocks are each described below.

5.2.6 System Control Processor

Just below the console in the system hierarchy is the system control processor (SCP). The SCP provides the single point interface to the sensor and data acquisition component of SAMS. All sensor-side communications with the console are handled by the SCP. The main function of the SCP is to coordinate the operation of a bank of parallel DSP-based modules referred to as cluster control processors (CCP) and other auxiliary modules connected to a stackable parallel data bus. The SCP also handles a wide variety of mission-specific tasks as well as telemetry extraction, general health and status monitoring, downloading and initialization, and master timing control.

Several important features of the SCP need to be pointed out. First it is itself a single-board computer that significantly reduces the complexity of controlling and operating the system from the user or host perspective. It allows a very complex distributed sensing and data processing system to appear to the console user as a highly programmable intelligent instrument, much like some of the latest generations of IEE488 test instrumentation. Since all command and control directives are issued as ASCII text strings, it is possible to connect a simple keyboard and monitor directly to the system via the SCP. This will be beneficial for maintenance and diagnostic operations. In the current hardware, the SCP consists of a commercially available board which uses a Motorola 68332 processor and measures roughly 2.5" x 8".

5.2.7 Cluster Control Processor

As mentioned above, the SCP communicates with a bank of processing modules referred to as CCPs. Each CCP is essentially a high-speed dedicated processing unit that handles some reasonable grouping of sensors/actuators/subsystems, which we refer to as a cluster. For SAMS we will partition the 91 segment primary mirror into three clusters as illustrated in Figures 9-11.

The DSP selected for the CCP module is the Motorola 56301. This 24-bit processor is capable of 80M arithmetic operations per second. Note that in figure 7 each CCP was connected to two serial data buses (A and B busses). These busses allow full duplex interprocessor communication at 22 MHz. Processor-to-processor as well as broadcast modes are available. The 56301 has seven DMA channels, four of which may be used for interprocessor communication over the A and B busses. This allows extremely efficient interprocessor data exchanges that do not require any on-going processor time or intervention.

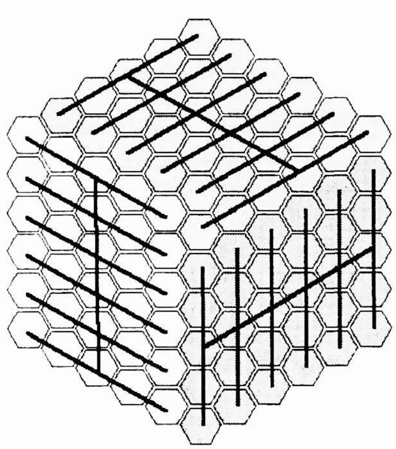

Figure 9 – Power & timing signal distribution

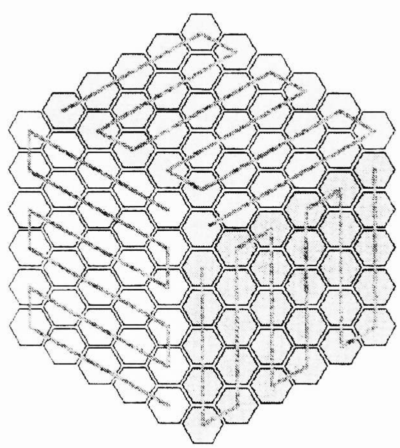

Figure 10 - Daisy chain routing of serial lines

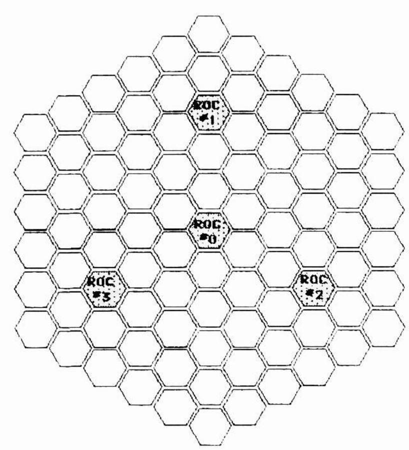

Figure 11 – Locations of GRoC sensors

5.2.8 Master Timing Module

The master timing module (MTM) was designed and developed by Blue Line to provide the timing signals needed for SAMS, including a 4 MHz master clock, and a frame sync. These signals are used to clock data through the system, and to indicate the start of a new "frame". This function is also important for two other reasons: The clock signal is used by the edge sensor system, and the frame sync sets the sample rate for SAMS.

Since SAMS is a conventional sampled data system, it is important that the frequency of the frame rate is set so that it meets system requirements in terms of latency (phase delay), while minimizing power consumption. The segment level DSPs go into a sleep mode as soon as their tasks are completed and only "wake up" at the start of the next frame. Therefore, the slower the frame rate, the better in terms of power consumption. Fortunately, the MTM provides considerable control over the frame rate by means of a block of jumpers that will be set at Blue Line during initial development work. We expect to set the frame rate to be 10 times faster than the sample rate called for in the SOW so that the data may be digitally filtered before being relayed to the console for control processing. The clock signals generated by the MTM are derived from a temperature compensated crystal oscillator and are made available to the rest of the processor modules through the stacking connector that connects the CCP board(s). Fiber optic links are also provided to allow these timing signals to be sent to the segmented mirror array and an optional wavefront sensor (WFS).

5.2.9 Hubs

The Hubs serve two important functions in SAMS. They serve as the main branching point in the distribution harness for power and timing signals. The Hubs also play an essential role in the reliable transmission and reception of data to and from the segments. This function is completely transparent to the user or operator. We have also included enough intelligence in this module to aid in system diagnostics and troubleshooting operations. This intelligence is provided by means of a field programmable gate array, which is a firmware programmable device of the sort used elsewhere in the system to very good effect.

The data handling function is performed by a small circuit board referred to as cluster data router/concentrator (CDRC). The CDRC receives the high-speed serial data stream coming from the CCP via fiber optic lines and synchronizes the transmission of data through a daisy chain of segment electronics that ultimately returns back to the CDRC and from there back to the CCP. The CDRC also receives the system clock and frame sync signals via fiber optic links.

5.2.10 Nodes

At the lowest level in the system architecture is what we generically refer to as "nodes." A node is actually composed of two functional elements. The first is a DSP board that performs local processing operations on sensor data. It also sends and receives data via the serial data link to its respective group control processor. The second functional portion of each node is the edge sensor electronics and analog to digital converters.

5.2.11 Edge Sensing Subsystem

The inductive edge sensors developed by Blue Line are excellent candidates for phase matching segments on large segmented mirror telescopes. They are insensitive to dust, condensation, relative humidity, and dielectric changes. And even with relatively simple signal conditioning electronics they are capable of sub-nanometer resolution with very high dynamic range.

The unique geometric arrangement allows differential sensing techniques to be employed. Differential sensor arrangements are well noted for their ability to significantly reduce or even eliminate error terms due to common mode effects. In the case of edge sensors this includes gap changes as well as temperature changes, among others. Another big advantage of this geometric arrangement is that it measures edge mismatch in the gap, generally closer to the mirror surface than other designs. This helps eliminate Abbe error terms since it is measuring right at the shear plane. Note that the inductors can be deposited in thin films of Kapton, which is then bonded to the edge of the mirror segment for a very low-mass installation.

5.2.12 General Description of Edge Sensor Operation

The inductive edge sensor requires that pairs of inductors be deposited on the opposite "passive" side, since they require no power and are not physically connected to the other pair of coils referred to as the "active" side. These two pairs of coils, or the active and passive sides of the sensor, are separated by the gap between adjacent segments. They are located on the opposing faces of adjoining segments, such that they are geometrically opposite each other when the two segments are properly aligned. It is the geometric relationship of these four coils which proves to be the key to the behavior of the transducer.

The two active sensing elements are a series connected to form an RLC network, which is driven by a frequency-stabilized source. These two coils are also inductively coupled to the two passive coils, which are connected to form two completely passive LC networks. The arrangement of the coils is such that any relative motion of the adjacent edges in the direction orthogonal to the mirror surfaces will cause a change in the complex impedance of the active coils. This impedance change is detected with a synchronous demodulator to produce a voltage signal, which is linearly related to the relative motion, or edge match error, between segment edges.

5.2.13 SAMS System Performance Modeling

It is understood that modeling and simulation play a vital role in proving the SAMS concept. System modeling is also important for assessing SAMS performance sensitivity to various internal and external parameters. In support of PAMELA and NGST work, MSFC has developed MATLAB based modeling tools that can readily generate image point spread functions from primary mirror segment tip, tilt, and piston wavefront errors. The modeling tools comprise MATLAB M-files that evaluate the Kirchoff integral, using tip, tilt and piston as arguments of the phase in the complex exponential. Modeling tools were adapted to the HET configuration in support of this project. Figure 12 on the following page shows sample output of the MSFC SAMS simulation.

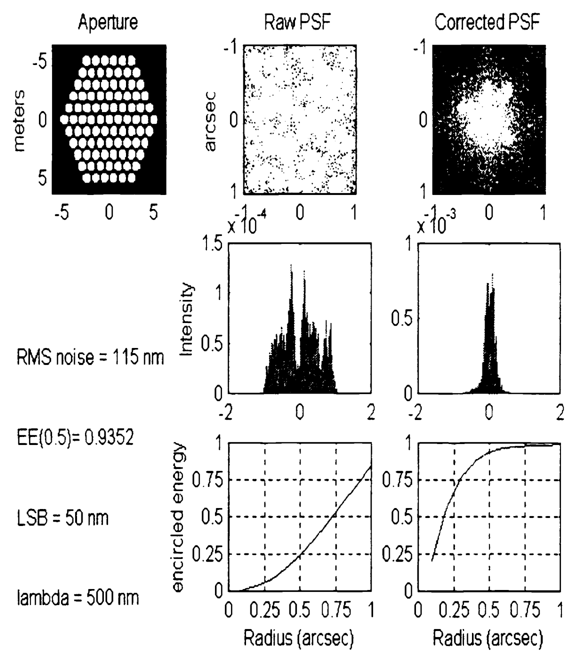

Figure 12 - MATLAB simulation of HET imaging performance with SAMS

The existing HET modeling software allows up to 480 active edge sensors and 91 segments with a total of 273 degrees of freedom (DOFs). The software also allows three differential tilt sensor outputs. Flexibility is built into the algorithms and software to arbitrarily choose which three DOFs to use to constrain the global tip, tilt, and piston DOFs. This flexibility facilitates trade studies for evaluating the best boundary conditions for overall SAMS performance. The software also accommodates arbitrary fixing of any DOF in the system to simulate actuator failures. The capability of removing any number of segments currently exists, thereby allowing performance sensitivity studies to segment removal. The algorithms have already been developed, streamlined, and implemented in MATLAB code. This development facilitates easier incorporation of the algorithms into the SAMS console software. The existing HET model allows modeling of sensor and actuator characteristics. Current software includes random noise models and sensor quantization (least significant bit) models. These models permit analyses of SAMS sensitivity to sensor accuracy and resolution. The software allows for linear models for the edge sensors, including gain scale factors and biases from calibration curves. The option also exists to apply a nonlinear model of the edge sensors, utilizing the calibration curves over the entire expected operating range. The actuator resolutions specified in the RFP Interface Control Document (ICD) are currently implemented in the code.

5.3 Recent Activity and Current Status

As of this writing, the SAMS project is on schedule and progressing well. The contractual agreement was signed 01 November 1999 between the University of Texas, which operates HET on behalf of the partner institutions, and MSFC/Blue Line. The concept design review was held at McDonald Observatory on 19 January 2000. There have been no major departures from the proposed concept outlined above. Activity is currently focussed on examining optimal sensor mounting schemes, finite element analysis of permissible sensor weight and moment, and planning for the proof-of-concept testing scheduled for April 2000. The proof-of-concept test will evaluate baseline performance of two sensors mounted to two mirror segments. A seven-segment sub-array test will be conducted on the telescope in July 2000.

6. SUMMARY

A closed-loop segment position sensor system must be implemented on the HET in order for it to achieve its original image quality performance specifications. A system, known as the Segment Alignment Maintenance System (SAMS), was specified in detail and put before to the precision position sensing community for bid last year. SAMS is currently under development by the successful contracting team of Marshall Space Flight Center and Blue Line Engineering Company. We are still early in the development phase of the project, and anticipate successful testing of prototype sensor systems in the coming months. Full-scale production implementation of SAMS on the telescope is scheduled for summer 2001.

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