Spherical Primary Optical Telescope (SPOT): A Cost-effective Space Telescope Architecture

Lee D. Feinberg
Code 443
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771
301-286-5923
Lee.D.Feinberg@NASA.Gov
John Hagopian, Jason Budinoff, Bruce Dean, Joe Howard
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract—This paper summarizes efforts underway at the Goddard Space Flight Center to demonstrate a new type of space telescope architecture that builds on the rigid, segmented telescope heritage of the James Webb Space Telescope but that solves several key challenges for future space telescopes. The architecture is based on a cost-effective segmented spherical primary mirror combined with a unique wavefront sensing and control system that allows for continuous phasing of the primary mirror. The segmented spherical primary allows for cost-effective 3-meter class (e.g., Midex and Discovery) missions as well as enables 30-meter telescope solutions that can be manufactured in a reasonable amount of time and for a reasonable amount of money. The continuous wavefront sensing and control architecture enables missions in low-earth-orbit and missions that do not require expensive stable structures and thermal control systems. For the 30-meter class applications, the paper discusses considerations for assembling and testing the telescopes in space. The paper also summarizes the scientific and technological roadmap for the architecture and also gives an overview of technology development, design studies, and testbed activities underway to demonstrate its feasibility.12

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1. INTRODUCTION

NASA’s first large space telescope, the Hubble Space Telescope, used a monolithic aspheric primary mirror in low earth orbit with an enclosed light baffle. This approach was not easily scaleable because of launch shroud mass and volume limitations. Thus the current generation space telescope, the James Webb Space Telescope1, makes use of a segmented aspheric primary that is passively stable. Key challenges of the current generation space telescope are the cost and schedule associated with fabricating the primary mirror and the cost and complexity of a passively stable architecture. These limitations make it difficult to implement the architecture both in thermally varying environments and when larger and thus costlier systems are needed. The aspheric segments are also complex to test and align which drives both cost and schedule. Thus, our team is working on a next evolutionary step called the Spherical Primary Optical Telescope (SPOT), aimed at addressing these challenges. The architecture is based on an active center-of-curvature wavefront sensing and control system that eases backplane stability requirements. It is also based on replicated mirror technology that will enable both more cost-effective Hubble class primary mirror sizes and will also enable a feasible path to much larger apertures that will be needed in the future. For early implementations of the architecture, proven lightweight glass mirror technology that have elements of replication, such as that developed as part of the Advanced Mirror System Demonstrator (AMSD) program, could be used. The center-of-curvature wavefront sensor and adequate mirror degrees of freedom provide an approach to both test and actively align the system in space. This can enable lower testing costs on the ground and aperture sizes larger then can be tested on the ground. The basic architecture will result in both lower cost Hubble-size apertures and eventually extremely large primary mirror architectures.

1 U.S. Government work not protected by U.S. copyright.
2 IEEEAC paper #1006, Version 2, Updated October 27, 2004
2. **SCIENCE AND TECHNICAL DRIVERS**

Our team envisions the first applications of the SPOT technology to be aimed at the least ambitious applications: laser based receivers for LIDAR and communications. Current LIDARs, such as GLAS and CALIPSO, use single primary mirror receivers that are only 1-meter and are strongly receiver signal limited. A factor of 5x increase in primary mirror area as proposed in first generation SPOT architecture (and 10x-100x in future generations) will translate into a directly proportional reduction in laser power. The reduction in power also is advantageous to potential receiving systems for Mars communication systems. Our team is currently studying an implementation of this as a potential interface between TDRSS and the Mars based laser system. Both LIDARs and communication receivers have fairly loose wavefront error requirements and limited field-of-view requirements that make these logical initial applications of this technology, though stray light issues need to be considered. Our team has also demonstrated well-corrected designs for larger field-of-view systems that could replace HST planet imaging capabilities and that could serve as a follow-on capability for significantly less cost than an aspheric telescope.

The low-cost nature of the primary mirror could also enable extremely large systems that cannot be cost-effectively built with aspheric mirrors. Replicated spheres are easier and faster to fabricate than aspheres which require unique castings for each prescription as well as complex testing with computer generated holograms. Studies of ground based systems and proposals (Hobby Eberly, OWL, ELT) lead us to believe that large (e.g., 25-meter) Spherical Primary solutions exist with imaging and spectroscopic applications. A major challenge of these systems is overcoming the spherical aberration induced by the spherical primary mirror. There are several potential solutions to this including multiple mirror corrector systems and refractive designs. Our team has recently evaluated a 25-meter telescope design proposed by Moretto et al \(^2\) that represents one potential design configuration. This design is shown below in Figure 1.

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**Figure 1: Optical Layout of a 25 meter design**

Our conclusion is that this design provides good optical performance over an arc-minute field and even better performance can be gained through follow-on correctors. Performance from this design is shown below in Figures 2 and 3.

An additional advantage of the CoC sensor is that a space assembled primary mirror can be tested during build up. This allows testing of a partially assembled mirror. Using the spherical surface on the back of the secondary or aft optics, in-situ alignment to the aft optics is also possible. Moreover, the system can be designed with sufficient degrees of freedom to assure final alignment.
3. SPOT ARCHITECTURE AND TESTBED

The initial concept for the SPOT architecture, shown in Figure 4, was compatible with in-space robotic or EVA assembly. The concept includes hexagonal shaped spherical primary mirror segments with radius of curvature and tip, tilt, and piston control. The segments are actively controlled using a center-of-curvature wavefront and control sensor. The follow-on optics can be optimized for particular applications and range from two to four mirror systems. While in-space assembly still seems a logical possibility for extremely large systems, our early work is focused on smaller systems that do not require in-space assembly. Specifically, we are targeting a testbed and early implementations that require minimal assembly or deployments.

In order to investigate the basic architecture, our team is pursuing a testbed funded by internal research and development funds. We are currently working on the first phase of the testbed, a segmented spherical primary mirror actively phased at center-of-curvature. An early conceptual view of the basic concept is shown in Figure 4 and a figure of the initial phase of the testbed is shown in Figure 5. An additional novel element of the architecture not shown in the figure is the incorporation of a spherical surface on the center-of-curvature facing side of the secondary or follow-on aft-optics that allows the secondary and aft-optics to be aligned to the primary mirror using the same CoC source and sensor as used for the primary. This allows for both initial alignment and for removal of drifts of the CoC sensor with respect to the primary mirror and follow-on optics. The return from the primary and this surface can be separated at the CoC by various means including focus or decenter.

The active control system is targeted to initially work at a bandwidth of 1 hertz, which should be fast enough to correct thermal drifts in the most active thermal environments. However, early implementations in flight hardware could use standard computers and operate at even slower rates (for example 1 minute) and still do adequate thermal compensation. The ultimate goal will be to get extremely high speed digital signal processors flight qualified, enabling speeds fast enough to correct structural vibrations as might be encountered in floppy structures. The limited degrees of freedom (only tip, tilt, focus are controlled at high speed) means that fast algorithms can be employed and gives a number of options for fast actuation, such as piezo and stepper motor type actuators.

The testbed, shown below in Figure 5, will also incorporate a multi-wavelength phase shifting interferometer that will allow us to check our algorithms. This approach is also a viable technique for the wavefront sensor although would have to be implemented as flight hardware (currently it is available as COTS ground equipment).
4. PROGRESS TO DATE

Our team made considerable progress in the design of the testbed, the wavefront sensing and control architecture, and optical design studies. Our team developed a capability for design and integrated modeling (structural, optical, thermal) of semi-rigid mirror segments that include radius of curvature matching and actuation, gravity sag analysis, thermal stability analysis, and overall performance analysis. We have applied this capability to the design of the casted/replicated mirror segment assembly design. An early conceptual figure of the primary design is shown in Figure 6 (later versions further optimize wavefront performance and casting techniques). The design makes use of GSFC-developed actuators. Our team also developed a novel concept for in-situ testing and polishing of the SPOT mirror. The mirror will be tested in-place with a novel RoC metrology setup. The configuration of the mirror in test is shown in Figure 7. Initial polishing of a smaller borosilicate piece along with tooling to support this are in process.

Various approaches have been considered for telescope designs for SPOT. Analytic solutions of one and two mirror correctors for the spherical primary have been used, as well as traditional ray-trace based optimization for one, two, and three mirror correctors. Additionally, existing designs in the literature (e.g. HET, OWL) have been considered as starting points for SPOT designs. All three approaches show similar trends: that fewer surfaces for correction require greater aspheric departures on the corrector optics themselves, which seems obvious since the correctors need to compensate for approximately 350 waves (at 1 micron light) of spherical aberration from the primary mirror.
Naturally, the alignment sensitivities are more severe with the one and two corrector aspheres, while a four-mirror corrector has been demonstrated for the Hobby Eberly Telescope. This design work was presented at the Novel Optical Design and Optimization Conference at the SPIE Annual Meeting in Denver, CO, in August of 2004.

Our team is currently developing techniques, laps, dies, and prototype borosilicate mirrors that serve as the basis for our casted mirror technology. Our team is not trying to aggressively lightweight the casted mirrors but methods for making extremely lightweight casted and/or slumped mirrors are conceptually feasible and would be a natural next step in the development.

Our team has developed a supercomputing architecture for image-based wavefront sensing and control. This architecture has been implemented on a desktop network of 32 DSP’s (digital signal processors) for a combined performance increase of 3-orders of magnitude (computation time reduced by a factor of 1000). The HDA (Hybrid Diversity Algorithm) has been implemented on the DSP architecture and the current implementation enables quasi-real time wavefront sensing and a demonstration of high-speed control using the novel DSP architecture. A wavefront sensing software protocol has also been developed which allows an ordinary laptop computer to call the DSP’s by way of an Ethernet port function call – thus creating a truly compact and portable wavefront sensing and control device. Thirty-two additional DSP’s (see Figure 8) are currently being added to the existing 32 (for a total of 64) to establish the additional wavefront sensing bandwidth needed to compensate jitter and other dynamical disturbances at Hz time scales. The technology enables future space telescopes to compensate for thermal stability and greatly reduces the extremely tight mirror-to-mirror stability specifications currently facing JWST. As a result, LEO and other mission applications with constantly changing thermal environments can be realized.

Wavefront sensing and control efforts for to date have centered on developing both the DSP hardware and software architectures. Key accomplishments have been the procurement and integration of 4-DSP boards, each with 8 DSP’s, which passed floating-point checkout and memory testing. Optimized Fourier transform performance has been obtained in addition to DMA (direct memory access) to enable computational performance at the theoretical maximum of the DSP. Also developed were multi-processor transpose algorithms to enable DSP processing of multiple image data sets. Additional software developments include function calls supporting 100Mbit Ethernet data transfers from a laptop computer to the DSP, and then wavefront sensing results back to the laptop for subsequent display, control, and processing. The function calls have been developed and tested for data sets consisting of 4 – 512 by 512 pixel diversity defocus data sets. Subsequent work in '05 will update the DSP function calls to handle image sizes as large 2048 x2048 pixels.

Figure 8 - DSP Block Architecture

5. CONCLUSION

A proposed architecture for future space telescopes has been described. The architecture addresses the key challenges of current generation systems including an actively controlled primary mirror for easing stability requirements and a cost-effective primary mirror that makes use of replicated mirrors. The architecture is being demonstrated on a testbed being developed at the Goddard Space Flight Center. The testbed has been designed and the team is focusing on fabrication of the hardware.
REFERENCES


BIOGRAPHY

Lee Feinberg is the NASA Optical Telescope Element Manager for the JWST telescope. In his previous position at NASA, Lee was the Assistant Chief for Technology in the Instrument Technology Center at GSFC. Prior to that, Lee served as acting Instrument Development Office head for the Hubble Space Telescope Project. While on HST, Lee also served as the STIS Instrument Manager and played a key role in the verification of optics and testing of COSTAR and WFPC-2. Lee also led the Conceptual Study Team for the HST Wide Field Camera-3. Before coming to NASA, Lee worked at the University of Rochester’s Laboratory for Laser Energetics, at Booz, Allen and Hamilton, and at Ford Aerospace. Lee has a BS in Optics from the University of Rochester and a MS in Applied Physics from The Johns Hopkins University.