SECTION IV
WORKSHOP PANEL REPORT:

1. WAVEFRONT SENSING, CONTROL, AND POINTING

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INTRODUCTION

A majority of future NASA astrophysics missions from orbiting interferometers to 16-m telescopes on the Moon have, as a common requirement, the need to bring light from a large entrance aperture to the focal plane in a way that preserves the spatial coherence properties of the starlight. Only by preserving the phase of the incoming wavefront, can many scientific observations be made, observations that range from measuring the red shift of quasi-stellar objects (QSOs) to detecting the IR emission of a planet in orbit around another star. New technologies for wavefront sensing, control, and pointing hold the key to advancing our observatories of the future from those already launched or currently under development.

As the size of the optical system increases, either to increase the sensitivity or angular resolution of the instrument, traditional technologies for maintaining optical wavefront accuracy become prohibitively expensive or completely impractical. For space-based instruments, the low mass requirement and the large temperature excursions further challenge existing technologies. The Hubble Space Telescope (HST) is probably the last large space telescope to rely on passive means to keep its primary optics stable and the optical system aligned. One needs only look to the significant developments in wavefront sensing, control, and pointing that have occurred over the past several years to appreciate the potential of this technology for transforming the capability of future space observatories.

Future developments in space-borne telescopes will be based in part on developments in ground-based systems. Telescopes with rigid primary mirrors much larger than 5 m in diameter are impractical because of gravity loading. New technologies are now being introduced, such as **active optics**, that address the scale problem and that allow very large telescopes to be built. One approach is a segmented design such as that being pioneered by the W.M. Keck telescope now under construction at the Mauna Kea Observatory. It consists of 36 hexagonal mirror segments, supported on a framework structure, which are positioned by actuators located between the structure and the mirrors. The figure of the telescope is initialized by making observations of a bright star using a Shack Hartmann sensor integrated with a white light interferometer. Then, using sensed data from the mirror edges to control these actuators, the figure of the mosaic of 36 segments is maintained as if it were a rigid primary mirror. Another active optics approach is the use of a thin meniscus mirror with actuators. This technique has been demonstrated on the European Southern Observatory's New Technology Telescope (NTT) and is planned for use in the Very Large Telescope (consists of four 8-m apertures), which is now entering the design phase. Figure 3 illustrates the interrelation of key technologies necessary to wavefront sensing, control, and pointing.

The control bandwidth for active optics systems is measured in periods of seconds to minutes. To correct for atmospheric distortion of the wavefront in ground-based applications, the U.S. Department of Defense (DoD) has developed **adaptive optics** systems whose technology has recently been declassified. Because of the much higher control bandwidth, wavefront control is performed at a pupil plane using a small active mirror. Systems with as many as 2000 actuators have been built and demonstrated for use on the ground. The STARLAB Wavefront Control Experiment (WCE) is a 69 degree of freedom system designed for use in space that incorporates a shearing interferometer as a wavefront sensor.

Both adaptive and active optics systems are concerned with maintaining or restoring wavefront fidelity over a single contiguous aperture. Interferometers, which sample the wavefront at discontinuous points, have also been developed for ground-based astronomy. Narrow band systems using heterodyne techniques are applicable for the wavelength range from microwave to submillimeter wave (as previously discussed in the mission set review by Swanson in Section II). However, for observation of wide spectral bands at visible or near infrared wavelengths, the control and knowledge of

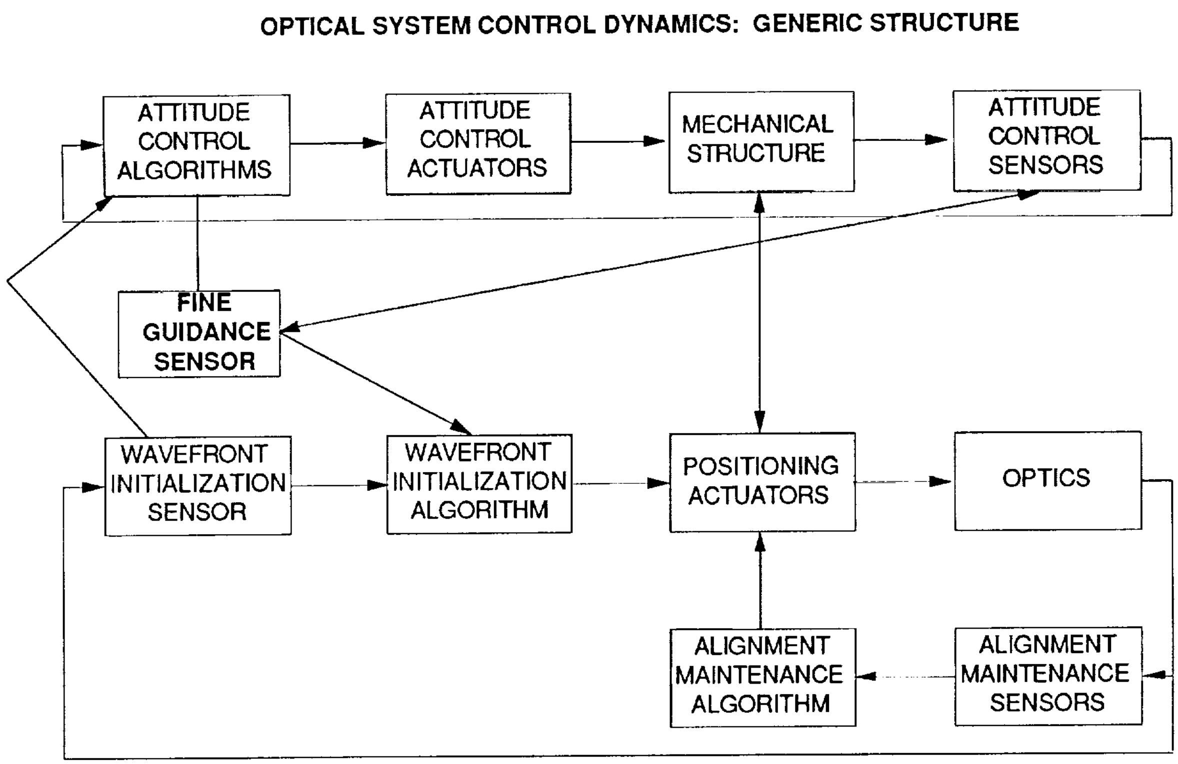


Figure 3. Interrelation of Key Technologies in Wavefront Sensing, Control, and Pointing

the wavefront is extremely demanding. The first Michelson interferometer to implement active white light fringe tracking through control of laser monitored delay lines (Mark III interferometer) is currently operating at Mt. Wilson Observatory, California and is designed primarily for astrometry. Other much more powerful systems are now being planned for visible and near infrared interferometric imaging, including the W.M. Keck Interferometer at Mauna Kea, Hawaii, and the Very Large Telescope (VLT) Interferometer planned by ESA.

The space missions in the Astrotech 21 mission set include filled-aperture telescopes, partially filled-aperture telescopes, heterodyne interferometers, starlight Michelson interferometers with astrometric and imaging capabilities, and the laser gravitational wave detection mission which uses laser interferometry between spacecraft to detect the space time perturbations introduced by the passage of gravitational waves. The characteristic aperture and baseline, rms wavefront error, pointing accuracy, and pointing stability for these missions are summarized previously in Table 4 of Section II. Although atmospheric perturbations are clearly not a source of wavefront errors and gravity loading will only be important for lunar observatories, there are several sources causing time variable wavefront and pointing perturbations. These include thermal or dynamic changes in telescope support structures, in the optical elements, or in the alignment and spacing of discrete elements.

Previous Astrotech 21 workshops, one on technologies for space-based interferometry identified developmental needs in wavefront sensing, control, and pointing. Characteristics of the interferometer concepts are extreme path length control (3 nm visible, 0.3 nm UV). This requires metrology systems; ultra-quiet structures; measurement of spacecraft disturbance sources to nanometer levels; actuator responses to millinewton level; and development of quasi-static, lightweight, space-qualified set-and-forget actuators with step sizes of 10 nm at 1 nm accuracy and a dynamic range of 100 mm. Large filled-aperture concepts require pointing control systems with >10 Hz bandwidth and slew rates >20°/min; active optics actuators with sub-micron accuracy at 100 K; segment sensing of 10 nm rms at 10 Hz bandwidth and 100 K; and validation of sensing techniques. Additionally, the LAGOS workshop identified a laser pointing requirement of 3 x 10^{-9} (f/1 Hz)$^{-1/2}$ rad Hz$^{-1/2}$ for 10^{-3} to 1 Hz.

In many cases, a given problem has many solutions, and the challenge is not just to find an answer but to find the optimal choice. Technologies involved in the solution can be broken down into six categories: (1) Active Optics, (2) Active Interferometry, (3) Pointing and Attitude Sensing and Control, (4) Laser Metrology, (5) Structures Control, and (6) System-Control Architecture. Table 5 summarizes the technology needs for future astrophysics missions, and Table 6 summarizes the recommended technologies, identified by the panel, in light of the mission needs.

Table 5. Wavefront Sensing, Control, and Pointing Mission Technology Needs for Astrophysics Missions

	ACTIVE OPTICS	ACTIVE INTERFER-OMETRY	POINTING AND ATTITUDE SENSING AND CONTROL	STRUCTURES CONTROL	LASER METROLOGY	SYSTEM CONTROL ARCHITECTURE
Filled-Aperture Telescopes						
FUSE						
SIRTF	●[1]		●			
SMIM	○		○	○	○	○
LTT						
NGST	●		●	●	●	●
LDR	●		●	●	●	●
Fizeau Interferometer						
II/FFT	●		●	●	●	○
Michelson Interferometers						
AIM/OSI		●	○	●	●	●
AIM//POINTS		●	○	○	●	●
II/VISTA		●	○	○	●	●
II/LOI		●	○	○	●	●
Heterodyne Interferometers						
SVLBI	○		○	○	○	○
SMMI	○		○	○	○	○
Grazing Incidence Telescopes						
AXAF						
VHTF						
WFXT						
II/LOI		●	○	○	●	●
Laser Gravitational Wave Detection						
LAGOS	●		●	●	●	●

● = Enabling Technology

○ = Supporting Technology

= (Blank) Not Required or Unknown

[1] SIRTF pointing mirror is considered here as active optics

Table 6. Wavefront Sensing, Control, and Pointing Technologies for Astrophysics Missions : 1992–2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Active Optics	To Achieve and Maintain Diffraction Limited Performance in Large Optical and Submm Systems Employing Active Optical Techniques	Figure Sensing	NGST	'02
		Phase Sensors	II/FFT	'04
		Deformable Mirrors	SMMI	'05
		Precision Actuators	LDR	'01
		Line of Sight Stabilization	SVLBI	'00
			LTT	'95
			SMIM	'96
			SIRTF	'96
Active Interferometry	To Develop Systems and Elements for the Active Sensing of Wavefronts, Pathlength Control, and Beam Combination for Physically Separated Collection Elements	Wavefront Sensing	AIM/OSI	'97
		Optical Pathlength Control	AIM//POINTS	'97
		Beam Combination	II/LOI	'04
		Stray Light Cancellation	II/VISTA	'04
Pointing, Attitude Sensing and Control	Precision Pointing (Optical Axis) and Attitude (Interferometer Baseline), Knowledge, and Control for Large Optics and Structures	Star Trackers	SMIM	'92 - '08
		Fine Guidance Sensors	NGST	
		Attitude Transfer Devices	LDR	
		Inertial Attitude Sensors	II/FFT	
		Attitude Actuators	II/VISTA	
		Fine Pointing Mirrors	II/LOI	
			NGOVLBI\SMMI	
			AIM/OSI	
			AIM/POINTS	
			LAGOS	
Structures Control	Control Vibration and Changes in Lightweight Flexible Structures to a Level Consistent With the Performance Envelope of Optical Control and Pointing Control Subsystems	Isolation	NGST	'02
		Damping	II/AII	'04
		Control Structure Interaction	LDR	'01
		Modal Control	SVLBI	'00
		Smart Structures	SMIM	'96
		Control Design Optimization	LAGOS	'08
			SMMI	'05
Laser Metrology	Precision 3-D Measurement and Control Over Large Distances for Long Baselines and Optical Trusses	Laser Sources	NGST	'02
		Fiducial References	AIM/AII	'97
		Components	II/AII	'04
		Innovative Architectures	LDR	'01
			SMMI	'05
			LAGOS	'08
System-Control Architecture	Integration of Component Technologies (Optics and Structures) for Optical System Control	Vibration Isolation Systems	SMIM	'92 - '08
		Damping Augmentation	NGST	
		Control Structure Interaction	LDR	
		Modal Control	II/AII	
		Smart Structures	SVLBI	
		Integrated Structure Control Design Optimization	SMMI	
			AIM/AII	
			LAGOS	

ACTIVE OPTICS

A. Technology Assessment

The only foreseeable approach to the construction of very large filled-aperture telescopes and long baseline interferometers in space includes the concept of active control of the optical surface figure and the alignment of the supporting structure. Active, segmented optical systems that are space deployable or erectable offer the possibility of essentially unlimited aperture size which would otherwise be limited by manufacturing and launch constraints to 4 m diameters or less. Active systems also allow the use of low areal density materials and structures. Densities of 10–20 kg/m^2, a factor of 10 reduction over the Hubble Space Telescope optics, are achievable in very large sizes.

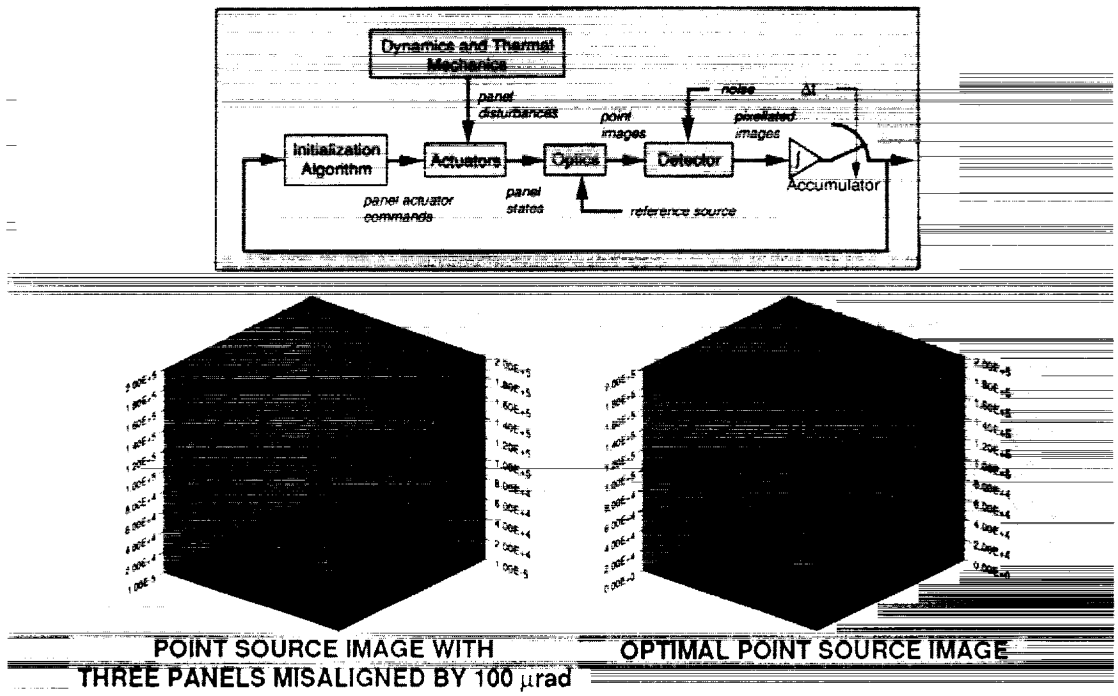
Active optics can be realized using one of two distinct wavefront control system architectures. The most accessible of the two, from the standpoint of required new technology, is a two phase approach in which initialization and maintenance are accomplished by separate but nested control loops. Initialization is accomplished by periodically slewing the system to a sufficiently bright illumination source and actively optimizing the configuration of the optics (e.g., by image sharpening or image inversion). Between initialization times, the configuration is maintained by a faster control loop using information from a dedicated maintenance sensor (e.g., an optical truss of laser metrology sensors). Further into the future is a single phase approach in which initialization and maintenance are accomplished by the same control loop using one sensor. This can be accomplished, for example, by introducing an illumination source on board that can be used continuously for wavefront control without interrupting science observations. Although the required level of technology development is greater than that of the two stage approach, the benefits are obvious. Figures 4 and 5 illustrate techniques for figure initialization and maintenance.

Considerable progress has been made in the area of active optics for laser beam control and military surveillance. This technology has direct applications to astrophysics, however many of the Astrotech 21 mission needs will drive the technology well beyond the state of the art defined by DoD requirements.

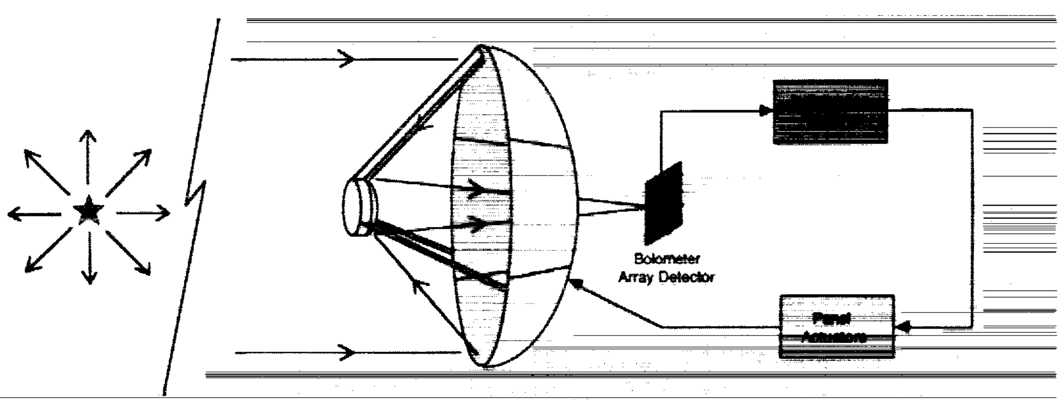
Wavefront Sensing – DoD resources have been invested in pupil plane wavefront sensors including the Shack Hartmann device and shearing interferometers, such as the device developed for the WCE adaptive optics system. Recently, wavefront sensing based on near image plane curvature and image inversion data has been developed. The comparative advantages of these various techniques have not been fully investigated and their ultimate reliance on new detector and optics technology remains speculative. The basic issues to be investigated include the number of subapertures that must be independently controlled, the control bandwidth and the required brightness of the control signal (natural or artificial).

Wavefront Control – Wavefront control includes two subsystems: a reconstructor that converts the wavefront sensor output into actuator drive signals, and the actuator arrays that adjust the optical path between each subaperture and the controlled image. Most reconstructors integrate wavefront tilt (slope) information to produce phase errors and associated control signals. They require supplemental information about the relative positions of the individual control actuators in order to form the final control signals.

The actuator arrays drive the individual mirror segments or sections of continuous surface deformable mirrors in response to the control signals. The key requirements are areal number density of actuators, response bandwidth, displacement range, and operating temperature and cost. High yield fabrication techniques have not been developed and therefore costs are high. Space applications will require actuator materials that produce large displacements while operating at low temperatures to cryogenic temperatures.



(a)



USE 10 BY 10 SCIENCE DETECTOR BOLOMETER ARRAYS WHICH COVERS 100 TO 300 μm BAND

SUITABLE TARGET SOURCES ARE NML CYG, IRC 10216, BETELGEUSE, ARCTURUS AND MARS

CANDIDATE ALGORITHMS ARE PAIRWISE CO-ALIGNMENT AND CO-PHASING, HILL CLIMBING, AND SIMULATED ANNEALING

FOCAL PLANE IMAGE SHARPENING

(b)

Figure 4. Figure Initialization

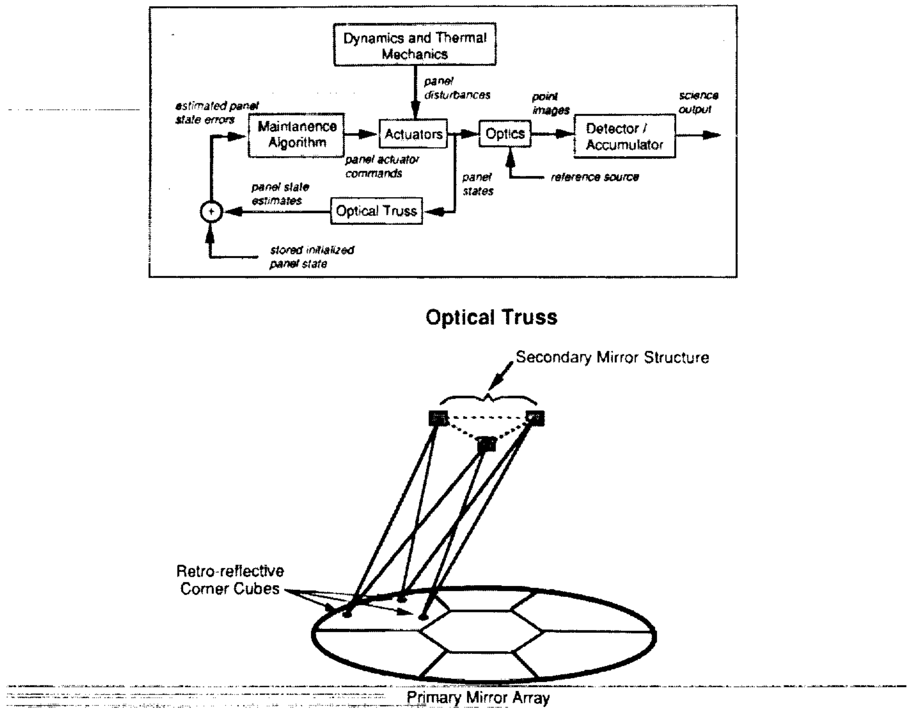


Figure 5. Figure Maintenance

B. Development Plan Needs

Future astrophysical missions will require active optics to initialize and maintain their optical elements in the optimal positions, orientations, and shapes to enable diffraction-limited performance and performance robustness. This will be especially critical for missions with large apertures or baselines. Table 7 is a summary of the active optics technology areas requiring significant advances to meet the Astrotech 21 requirements for 1998 and beyond.

Wavefront Sensing – Figure and wavefront sensors will be needed to measure the quality of the wavefront at a representative location in the optical train in order to provide appropriate error signals to a wavefront control system. Current technology is characterized by low-resolution (i.e., a few hundred samples over the aperture) pupil plane techniques (i.e., shearing interferometers and Shack-Hartman sensors). The use of pupil plane sensors (which measure wavefront slope) on segmented telescopes necessitates the use of edge matching sensors as well, which adds to the cost and complexity of the system. Future large optical systems will require spatial resolution in excess of 10,000 over the aperture consistent with the correlation length of anticipated wavefront errors. The sensors must be capable of operating from natural (perhaps even extended) broadband sources to maximize their utility. The use of focal plane techniques will minimize the amount of special purpose hardware required, thus minimizing mass, cost and complexity, and maximizing reliability. Moreover, it will support segmented optics without the need for special provisions. Fast reconstruction algorithms (e.g., neural nets) will be required to solve for the controlled variables (e.g., segment coordinates and deformation states) in real time. Finally, the use of onboard sources and associated optics will eliminate the need to have specific targets within the field of view, thus maximizing operability of the system.

Table 7. Active Optics Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Figure Sensing	Low Resolution Pupil Plane Techniques, Shearing Interferometers, Hartman Sensors	Real Scene White Light Sensors Fast Reconstruction Algorithms (e.g., Neural Nets) Focal Plane Sensors Onboard Sources	'95 - '06 '95 - '06 '96, '04 '10	'93 - '04
Phase Sensing	Breadboards Electronic Sensors : 10 nm	Optical and Electronic Sensors : < 1 nm Space Qualifiable Prototype Phasing Mirror	'95 - '05 '06	'93 - '06
Deformable Mirrors	Operations at IR Wavelengths Low Resolution, mm Range	High Resolution, Long Stroke Deformable Mirror Operation at VIS Wavelengths	'04 '95 - '05	'93 - '04
Actuators	0 -100 mm Stroke 0.01 mm Precision < 1 Hz Bandwidth Non Cryogenic	0 - 10 mm Stroke 1 nm Precision > 10 Hz Bandwidth Cryogenic	'95 - '05 '96, '04, '10	'93 - '10

Wavefront Control – Deformable mirrors (or their segmented equivalents) will be needed to correct the wavefront errors introduced by motions and deformations of the optics and support structure. The displacement and spatial resolution will have to be smaller than 1 nm and 10,000 actuators per aperture (10-m structure with 10 cycles over aperture), respectively. The stroke will have to be on the order of 100 mm, and the bandwidth will have to exceed 1 kHz. The state of the art deformable mirror contains of a few hundred actuators and is capable of stokes of a few microns. Major advances are needed to reach the required level of development. One promising approach is to apply micro-machining principles to this class of problem.

For positioning and aligning optical elements on orbit, space flyable precision positioning actuators are needed. These will require strokes up to 10 mm, precision better than 1 nm, and bandwidths in excess of 10 Hz. Furthermore, they must be capable of operating at temperatures down to 1 K in a vacuum. Currently available positioners are roughly an order of magnitude away in performance, and cryogenic device development is in its infancy.

ACTIVE INTERFEROMETRY

A. Technology Assessment

Active interferometry, as used here, refers to the same process of wavefront sensing and control between the elements of a Michelson interferometer as is provided by active optics for a filled or partially filled aperture telescope. In one sense, active interferometry is a limiting case of active optics, with a very sparse aperture sampling the incident wavefront at a small number of points. Like active optics, the phase of this sampled wavefront must be sensed, and its phase adjusted, in order that the light from the individual apertures combine coherently. However, compared with active optics, active interferometry incorporates some key differences in both wavefront sensing and wavefront control. It also imposes some special requirements on the recombination of the wavefronts that are unique to interferometry. For reference, Figure 6 provides a schematic of a simple two-element Michelson stellar interferometer.

Wavefront Sensing – Wavefront sensing for active interferometry is similar to wavefront sensing for a segmented (non-monolithic aperture), in that wavefront continuity cannot be used to reconstruct the wavefront from slope measurements — the phase of the white-light fringe must be measured directly. Thus, there will be an initial

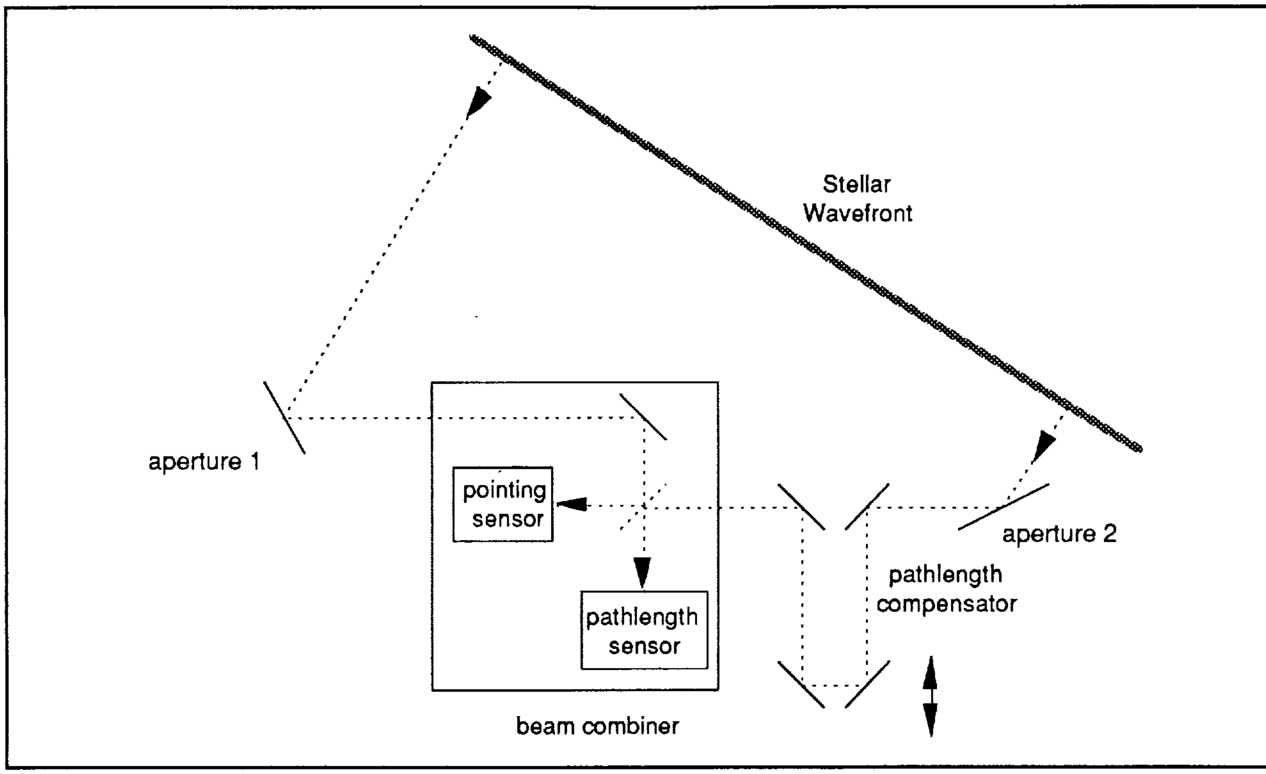


Figure 6. Essential Components of a Two-Element Stellar Interferometer. (Courtesy of Mark Colavita.)

uncertainty in the wavefront phase, which could be ~10–1000 μm, depending on the calibration of the geometry of the instrument. As quasi-monochromatic sensing leads to 2 pi ambiguities in the measured phase once the fringe is found, for active interferometry it is necessary to use broadband (white) light ($\lambda/\Delta\lambda < 5$), and to incorporate acquisition techniques to find the white-light envelope and determine the central white-light fringe. Photon-efficient techniques are essential because signal fluxes are always low.

For a two-element interferometer, the wavefront is usually sensed with pathlength-modulation or dispersed-fringe techniques. With pathlength modulation (Figure 7(a)), as is used on the Mark III interferometer (and would be used in AIM/OSI), a systematic modulation of the optical path is introduced into one arm of the interferometer. This modulation sweeps the interference fringe across a detector, producing a temporally modulated intensity, from which the phase of the interference fringe can be determined. The fringe phase can also be detected using dispersed-fringe techniques, which use a spectrometer to disperse the interfered light across an array detector, producing fringes in wavenumber space (Figure 7(b)) as in AIM/POINTS.

For an interferometer with more than two beams, the sensing problem becomes more complicated, and is different depending on the beam combination method. For example, with Michelson combination (e.g., II/LOI), the phase of each baseline pair is measurable, and pathlength modulation or dispersed-fringe methods are applicable. However, their application becomes far more complicated: with pathlength modulation, multi-frequency or multi-cycle modulation is required to separate the various baselines, while for dispersed-fringe techniques, fiber-fed array detectors are required to accommodate the various baselines. At the other extreme, with Fizeau combination (e.g., II/FFT), phasing information may not be directly available in the image plane if the array geometry is partially redundant, and a auxiliary Michelson combiner may be needed for phasing.

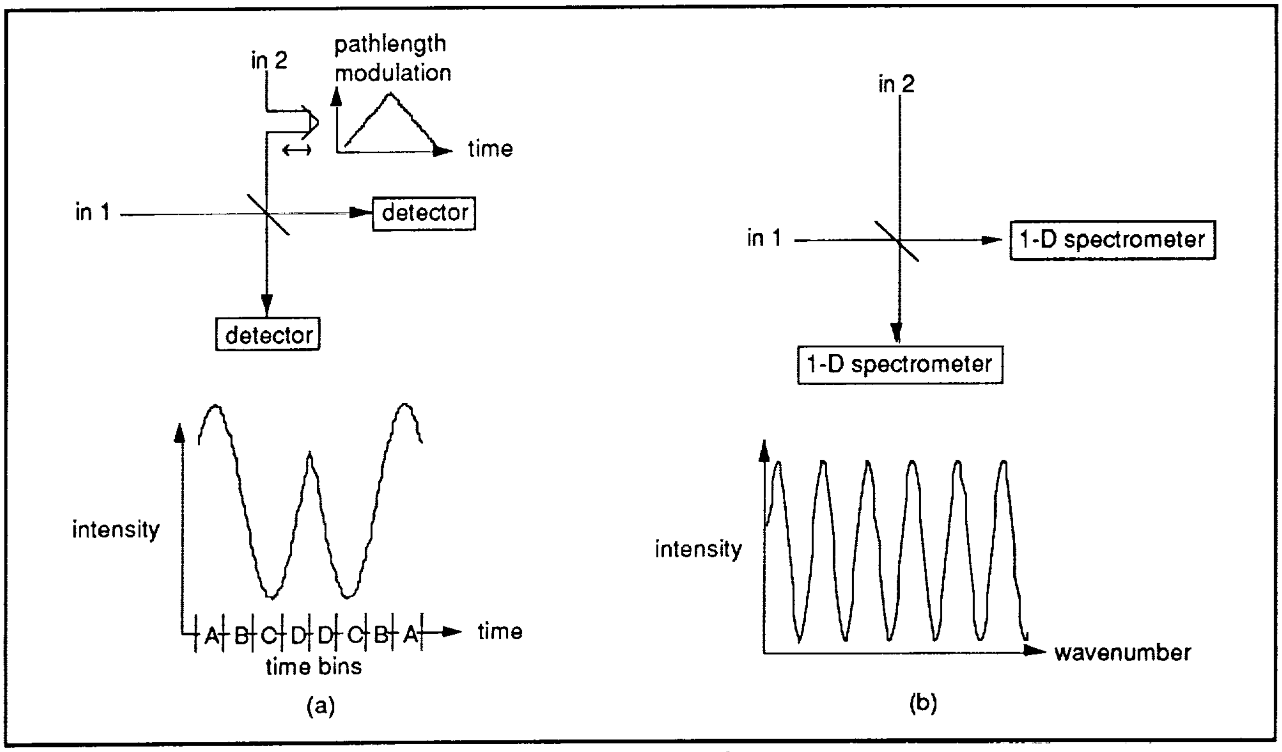


Figure 7. Wavefront Sensing, using: (a) pathlength modulation – the bin counts A-C and B-D are proportional to the sine and cosine quadratures of the interference fringe; the fring ephase is just the arctangent of these quantities, and (b) a dispersed fringe – the optical pathlength error is proportional to the frequency of the interference in wavenumber space. (Courtesy of Mark Colavita.)

Optical Pathlength Control – While the individual elements of an interferometer could employ active optics, wavefront control of the interferometer does not require deformable mirrors. Rather, piston control of the phase at each subaperture is normally all that is required. Unlike active optics systems where phase errors can be compensated with motions of a small number of wavelengths, for some interferometer architectures, where the subaperture telescopes must be pointed relative to the baseline (e.g., AIM/OSI, II/LOI), the phasing mirrors must be mounted on delay lines. The total travel of these delay lines may be a substantial fraction of the total baseline, and phase must be maintained in the vibration environment generated by motion of the delay line. Even for designs where the interferometer is pointed as a solid body (e.g., AIM/POINTS, II/FFT), short-travel delay lines could be used to compensate for pointing errors, although this may not be required. For very long delay line travels, it frequently makes sense to partition the delay function into two parts, a coarse correction with a large dynamic range, and a fine correction over a smaller range. Figure 8 gives the schematic of a delay line developed for a ground-based stellar interferometer.

Control bandwidths for pathlength control vary depending on the application. For free-flying space applications, high control bandwidths can be used to compensate for structural deformations and vibrations. Essentially, the measured fringe phase from observation of some target is a function of both the orientation of the baseline vector and the delay-line position. If laser metrology is used to monitor the baseline motions, the baseline error can be converted to an equivalent optical path error and fed forward to the delay line in order to synthesize a stable structure. Similarly, for a system with coarse and fine delay lines, errors in the coarse delay can be compensated by the fine system. However, as an optical delay line is essentially a one-element deformable mirror with a stroke measured in meters,

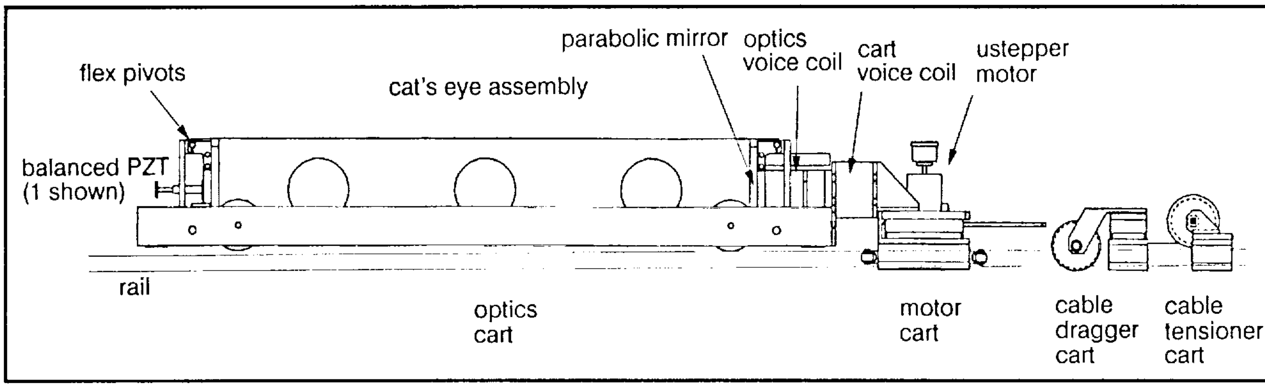


Figure 8. Schematic of a Delay-Line System Developed for a Ground-Based Interferometer. (Courtesy of Mark Colavita.)

high bandwidths, which are normally applied to only one element of the delay-line system, can be achieved.

Beam Combination – In an active optics system with a monolithic primary, the combination of light at a focus presents no special optical problems; the measure of success is the ability to concentrate light from a point source into a spot with a high Strehl ratio. For a two-element interferometer, the beam combination is also relatively straightforward, and has been demonstrated on ground-based interferometers, although the current combiner designs are very bulky relative to the constraints of space missions.

However, in a multiple-element (e.g., II/LOI, II/FFT) interferometer, the combination of beams at either an image plane or a pupil plane presents substantial optical challenges. There are two broad types of beam combiners for interferometry: 'Fizeau' and 'Michelson'. Examples of these combiners are shown in Figure 9. Fizeau combiners (e.g., II/FFT) preserve the geometry of the projected interferometer pupil and produce a direct image. In the case of II/FFT, the image is created at the focal distance of the equivalent full-aperture system. Alternatively, a scaled image of the interferometer pupil as seen by an incident wavefront can be reimaged onto the pupil of a combining telescope that produces the image. In exchange for a large field of view, Fizeau techniques have tight tolerances on not only the piston, but also the translation and magnification of the individual (or reimaged) subapertures. If the telescopes are individually pointed, the reimaging needs to be dynamic.

Multiway Michelson combiners (e.g., II/LOI), on the other hand, do not aim to produce a 1:1 mapping of object spatial frequencies to image spatial frequencies, and are more similar to radio techniques (aperture synthesis imaging). The field of view for imaging with a Michelson combiner is set by the spectral resolution. One variant of the Michelson technique reimages the input pupils onto a combining telescope in such a fashion that the resulting Fourier components of the image correspond to unique baseline pairs. Alternatively, a pupil-plane technique can be used which employs beamsplitters to interfere the beams pairwise. With both Fizeau and Michelson techniques, the incorporation of spectral resolution, guiding, infrared observation, and passive cooling, complicates the design.

B. Development Plan

A list of enabling technologies in active interferometry is given in Table 8.

Wavefront Sensing – Photon-noise limited wavefront sensing has been demonstrated on the ground for two-element systems. However, while the systematic phase accuracy necessary on the ground is only ~0.1 rad, space astrometric interferometers require systematic errors of 0.001 (AIM/POINTS) – 0.009 rad (AIM/OSI). Thus the development goals for two-element, visible-wavelength sensing includes the control of

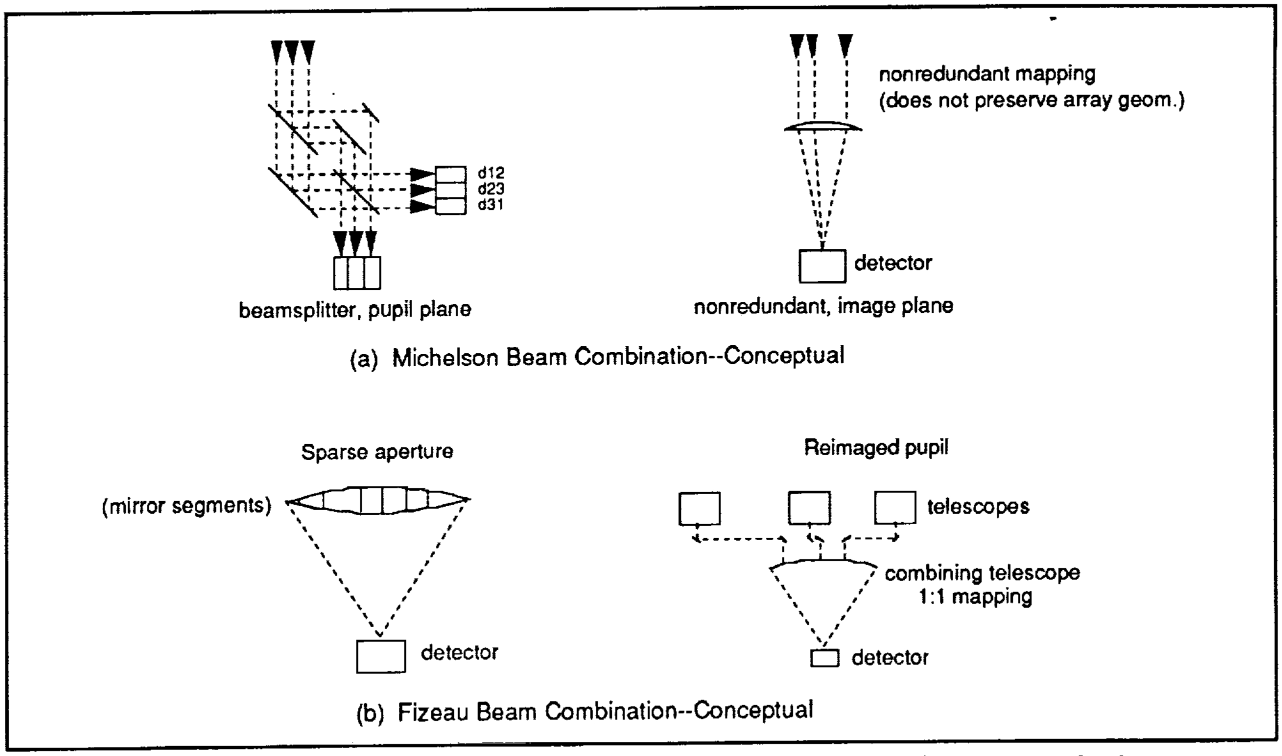


Figure 9. Geometries for: (a) Michelson (pairwise) beam combination, using beamsplitters or nonredundant pupil remapping, and (b) Fizeau beam combination, using a spares-aperture and reimaged pupils. Lenses are illustrated for combination instead of telescopes for simplicity. (Courtesy of Mark Colavita.)

systematic phase errors, robustness, and space qualification. Detectors are also a key area, especially high-rate, solid-state photon-counting devices for pathlength-modulation methods, and fast-readout, low-read-noise CCD detectors for dispersed-fringe methods. For multi-element combiners, goals include the development of sensing architectures that are photon efficient and are consistent with science constraints on observation wavelength, cooling, and sensing bandwidth, and that are robust enough for space application. These architectures may include the development of hybrid pupil-plane/image-plane techniques that partition the wavefront sensing and science observation components for application to II/FFT (dependent upon whether II/FFT implements edge sensors or whether the individual parts are sensed as individual sparse aperture interferometers).

Optical Pathlength Control – Optical pathlength control is key to all interferometers. While active delay lines have been developed for ground-based applications with acceptable optical performance, these designs tend to be massive, exploiting their large inertia, in part, to provide isolation from external vibrations. In addition, as they assume a massive mounting structure that serves as a reaction mass, the actuators are usually not momentum balanced, nor are they designed to minimize random vibrations induced into the supporting structure. For space applications (e.g., AIM/OSI, II/LOI), these shortcomings need to be addressed, and a robust, space-qualifiable, low vibration system is among the development goals. In addition, for high sensitivity observations in the thermal infrared, interferometers, like any observational system, require cooling of all optics in the beam train, including the delay lines. Thus, delay lines for such missions as II/LOI require a design compatible with the proposed passive cooling systems. Also, for long-baseline systems such as II/LOI, it makes sense to partition the path-delay

Table 8. Active Interferometry Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Wavefront Sensing	Fringe-scanning or dispersed-fringe techniques for 2-element systems	Phase-measurement accuracies of 0.03 (AIM/POINTS) – 0.5 (AIM/OSI) deg	'97	'93 - '05
		High dynamic range (1 – 10 MHz) photon-counting systems for high bandwidth astrometry: AIM/OSI, II/LOI, II/VISTA	'96	
		Fast readout, low-read-noise CCD detectors: all		
		Stray light efficient wavefront sensing for multi-element systems: II/FFT, II/LOI	04	
Optical Pathlength Control	3–4 stage active delay lines for ground-based applications	Lightweight, momentum-compensated, low induced vibration delay lines: AIM/OSI, II/VISTA, II/LOI	'97, '04	'93 - '05
		Cryogenically cooled (or coolable) delay lines: II/VISTA, II/LOI	'04	
		Switched delay lines with absolute pathlength measurements: II/VISTA, II/LOI	'04	
Beam Combination	Two-way pupil-plane beam combiners for ground-based applications at visible wavelengths	Lightweight, compensated or self-aligning 2-way combiners: all	'97, '01, '02, '04	'93 - '06
		2-way combiners incorporating laser metrology for astrometry: AIM/POINTS, AIM/OSI, II/LOI	'97, '04	
		Multiway combiners with spectroscopic capability: II/LOI, II/FFT	'04	
		Low emissivity beam combiners for IR observations: II/VISTA, II/LOI	'04	
		Stray light cancellation (rotational shearing interferometers): II/VISTA, II/LOI	'04	

function into a coarse, switched system with a large range, plus a fine system of the type described above. For the former, an absolute metrology system enables continuous monitoring of the optical path when switching among segments. Even for smaller baseline systems like AIM/OSI, absolute metrology can be employed to monitor beam reconfigurations, enhancing imaging performance.

Beam Combination – Most of the proposed space interferometers require a two-beam combiner as one of their back-end instruments. The development goals and technology challenges for a visible-wavelength combiner are mostly in the area of space qualification and robustness, and in particular, the development of designs that are alignment compensated or else present only minimal requirements on active alignment. For infrared observations, the requirement for optics cooling makes the development of the beam combiner more challenging. However, the greatest challenges arise when multiway combiners are considered, and the choices for combination are greatly increased, as discussed above. Thus, the development goals for beam combination also include the development of detailed optical configurations for beam combination that are consistent with the measurement goals, the wavefront sensing architecture, and space environment. A final goal is the development of beam combiners that uses interferometric cancellation of starlight to enable direct imaging of such high dynamic range objects as star-planet systems.

POINTING AND ATTITUDE SENSING AND CONTROL

A. Technology Assessment

The pointing and attitude sensing and control requirements for future astrophysics missions range widely and a variety of technologies must be brought to bear to address them.

The need for accurate and stable pointing of telescopes is basic. Large diameter visible and UV filled-aperture and partially filled-aperture telescopes (NGST and II/FFT) present the most exacting sensing and control requirements (see Table 4 in Section II). Infrared and submillimeter telescopes need not usually be pointed as accurately but, as we shall see, this does not necessarily make the task easier.

In the case of an interferometer, it is important to distinguish between the pointing requirements for the individual telescopes and the requirements on attitude knowledge and control for the baselines connecting elements of the interferometer array. Typically, the pointing requirements are comparable to the requirements for a telescope of that aperture used singly. The orientation of the baseline, on the other hand, typically must be known to much greater accuracy for performing high dynamic range imaging and astronomy.

If the telescopes comprising the interferometer are mounted on a single space structure, knowledge of the orientation of the baseline must derive from metrology of the structure and measurements of its attitude in space. If the telescopes orbit separately, then baseline knowledge must include measurements between the spacecraft and perhaps reference stations on the earth also.

Measurement of gravitational waves using laser metrology between free flyers spacecraft places extreme demands on both the pointing of the telescopes uses as laser beam directors and collectors and the metrology techniques for determining changes in their spacing.

We now consider the status of techniques and technologies for sensing of pointing and attitude.

Pointing and Attitude Sensing – The fundamental reference is always a star field although inertial measurements of angular drift are becoming increasingly important as these techniques can be made more accurate. The guidance system used on the Hubble Space Telescope (HST) represents the state of the art, circa 1980, and will be used as a reference for this discussion. The HST guidance system consists of orthogonal star trackers for initial orientation. The Fine Guidance Sensor (FGS), which shares the main telescope focal plane with the science instruments, is able to locate reference stars close to the targeted science object that are bright enough for accurate angular positional measurements. The HST FGS is shown in Figure 10.

Fine Guidance Sensors – The use of fine guidance sensors like the HST/FGS, which share the main telescope optics with the science payload, presents special challenges for infrared and submillimeter telescopes. The use of a reference frame of infrared stars is not currently practical because there are no infrared star catalogs comparable to the visible catalog used for HST. There may not be a sufficient number of suitable stars in some regions of the sky. The alternative is to use tracking in the visible range. This introduces two kinds of problems. In some missions, such as Submillimeter Intermediate Mission (SMIM) and the Large Deployable Reflector (LDR), the telescope is not figured to operate in the visible and so the approach is clearly not practical. In other missions, such as Space Infrared Telescope Facility (SIRTF), the telescope is figured adequately to operate in the visible, but the telescope and instruments are also cooled with superfluid helium, and visible star sensors designed with current technology will not function at the temperature of the helium bath. Accordingly, the SIRTF project has embarked on a technology program to develop a cryogenic fine guidance sensor that can be located internal to the telescope.

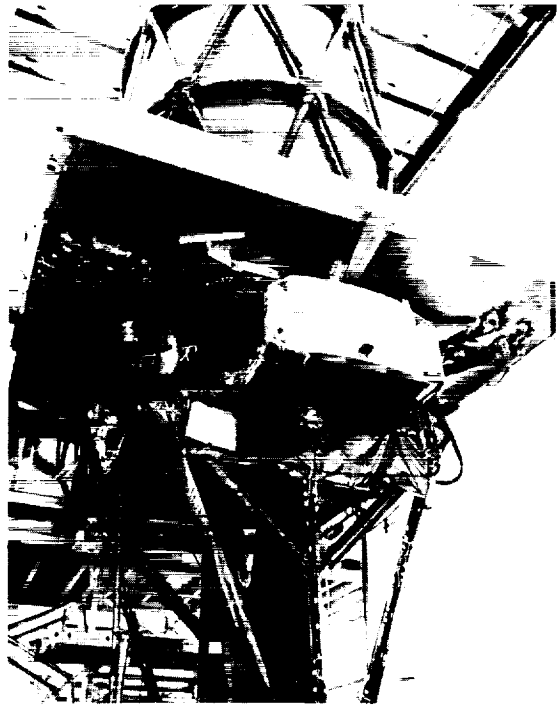


Figure 10. HST Fine Guidance Sensor

Star Trackers – The alternative to guidance systems that share the primary optics is the use of a coaligned external tracker. In this case it is necessary to cross calibrate the sensors and minimize the drift in this calibration as a function of changing thermal conditions for example.

Inertial Attitude Sensors – Sensors are needed for targets where there are no nearby reference stars. The key parameters are the accuracy with which pointing information can be transferred from the nearest reference star field which will depend among other things on the time required to slew and the exposure time on the science object. Current gyros have drift rates of 0.003 degrees per hour which is unacceptable for high precision pointing. Development of inertial attitude sensors is necessary to enable initialization, slewing and nodding of future astrophysics systems.

Pointing and Attitude Control – The requirements on telescopes pointing range from rapid slewing between science targets to accurate low-jitter stabilization on the science target for the duration of the integration. In addition, infrared and submillimeter telescopes require a nodding motion to facilitate background subtraction. This involves a sequence of small slews punctuated by rapid settling of pointing for the integration on the science object and the background scene. In all cases, there is a requirement for low noise and vibration so that wavefront (figure) control and in some cases inertial pointing knowledge are not disturbed by the operations.

Slewing Actuators – To maximize observational efficiency, astrophysical instruments have to be slewed rapidly between science targets. The infrared and submillimeter instruments also have to be nodded for background suppression. Since future instruments will be large, attitude actuators capable of high torque and large momentum capacities will be required. Interferometer slewing poses the problem of moving large structures quickly, quietly, and efficiently. Actuators that give high rates, low jitter, and low mass do not exist.

Quiet Attitude Actuators – What makes this a difficult challenge is that the actuators must, at the same time, be extremely quiet. The state of the art in quiet attitude actuators is characterized by a peak torque of 0.82 N-m, a momentum capability of 264 N-m-sec, a torque ripple of about 0.02%, and emitted force and torque vibration levels as large as 0.5 N and 0.1 N-m, respectively. Evolutionary improvements in noise properties by advances in bearing technology, balance, and new isolation techniques are a possibility.

Control of telescope pointing can involve pointing the telescope as a rigid structure as is done on the HST or using an active secondary as is being considered for the SIRTF. For X-ray telescopes, where photon flux rates are low and photon detectors are standard, pointing control can be relaxed considerably. Thus with the AXAF, the telescope is allowed to drift with a 0.5 arcsec stability (half-cone angle) over 10 sec. Frequent pointing knowledge updates are acquired to allow accurate positional reconstruction of the time-tagged photon events.

B. Development Plan

Table 9 is a summary of the pointing and attitude sensing and control technology needs to meet the Astrotech 21 requirements for 1998 and beyond. Details of the recommended development program are given below.

Pointing and Attitude Sensing – The pointing and attitude sensing technology program focuses on star trackers, fine guidance sensors, attitude transfer devices, and inertial attitude sensors. Developments in these areas are key to the success of future astrophysics missions.

Star Trackers - Star trackers are needed to establish absolute attitude in space. Today's star trackers have accuracies of about 1 arcsec. In the future, more accurate star trackers will be needed not only to support pointing of telescopes but also to support orientation of the interferometer array. Today's star trackers rely on complex ground interaction for acquisition. In the future, the need to lower operations costs will make autonomous operations costs a necessity. The panel recommends development of autonomous star trackers with accuracy of better than 0.1 arcsec.

Fine Guidance Sensors – Sensors are needed to maintain accurate and stable pointing with long integration times for all locations on the sky for large UV, visible, and IR/submillimeter telescopes. The most advanced visible fine guidance sensor today has an accuracy of 0.003 arcsec, uses a visible star catalog, operates at relatively warm temperatures, and has a very narrow capture range (i.e., about 0.02 arcsec). Development efforts are recommended to advance the state of the art by more than an order of magnitude in accuracy (to 0.0001 arcsec) and to increase the capture range to 60 arcsec. Continued development of cryogenic visible fine guidance sensors for missions like the SIRTF is urged along with the development of an accurate star catalog in the UV/VIS/IR.

Attitude Transfer Devices – Devices are needed to relay attitude information between components, such as the main telescope and an auxiliary star tracker, bypassing the dimensional instabilities of mechanical structure. The technology of such devices is currently at an immature stage of development. Prototypes that have been built are accurate to approximately 1 μrad and have poor control of thermal radiation leakage across the interface. Both the Air Force Weapons Laboratory (now Phillips Laboratories) and the Charles Stark Draper Laboratories have (or had) state-of-the-art development programs at the breadboard stage. The development of attitude transfer devices with nanoradian accuracy and very low thermal and radiation leakage is recommended.

Inertial Attitude Sensors – Sensors are needed to relay attitude information in time to allow pointing in areas where there are no suitable reference stars. Future missions demand very stable inertial attitude sensors. The panel recommends the development of gyros capable of better than 0.0001 arcsec bias stabilities and lifetimes of greater than 15 years.

Table 9. Pointing and Attitude Sensing and Control Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Star Trackers	Resolution : 1 as Ground Commanded	Resolution : < 0.1 as Autonomous Star Trackers	'94, '96	'93- -'96
Fine Guidance Sensors	Resolution : 0.003 as Visible Guide Stars Warm Focal Plane Very Narrow Capture Range (i.e., ≈ 0.02 as)	Resolution : ≤ 0.0001 as Cryogenic, Visible Fine Guidance Sensor Accurate UV-VIS-IR Correlated Star Catalog Wide Capture Range : > 60 as	'94, '96, '10	'93 - '10
Attitude Transfer Devices	Accuracy : 1 mrad Poor Thermal and Radiation Leakage Control	Accuracy : 10 nrad Negligible Thermal and Radiation Leakage	'94, '96	'93- -'96
Inertial Attitude Sensors	Drift : 0.003°/hr Lifetime : 10 years	Drift : < 0.0001°/hr Lifetime : > 15 years	'97, '10	'93 - '10
Attitude Actuators	Peak Torque; 0.82 N-m Momentum Cap: 264 N-m-s Torque Ripple: 0.02% Emitted Force Vib: 0.5 N Emitted Torque Vib: 0.1 N-m	Peak Torque; 82 N-m Momentum Cap: 26400 N-m-s Torque Ripple: 0.002% Emitted Force Vib: 0.05 N Emitted Torque Vib: 0.01 N-m	'97, '10	'93 - '10
Fine Pointing Mirrors	Moderately Compensated Steering Mirrors Non-Cryogenic	Large Diameter, Projected Center of Rotation, Highly Compensated Steering Mirror, Space Qualifiable Cryogenic	'95 - '05 '96, '04, '06 '96	'93 - '07

Pointing and Attitude Control – Two areas are encompassed by the pointing and attitude control technology program. These are the development areas of actuators and fine pointing mirrors.

Actuators – An improvement of two orders of magnitude in torque capability and momentum capacity, with a simultaneous improvement of at least one order of magnitude in quietness is recommended. This may be achievable by modifying existing large actuators to make them quieter (e.g., by improving bearings and balance properties, and by incorporating appropriate isolation mechanisms). Another feature that will need improvement is repeatability. High repeatability will make nodding possible without driving attitude control bandwidths, which are generally limited to about 1 Hz by control-structure interaction (CSI) and saturation avoidance concerns, to unsupportable levels. This may indeed be mission enabling. Repeatabilities of about 1 part in 1,000,000 are called for. An effort is recommended to study this issue and, if necessary, to develop ways improving attitude actuator repeatabilities to these levels.

Fine Pointing Mirrors – Line of sight or pointing error is equivalent to a tilt error in the wavefront at the telescope output. As such, the task of controlling or regulating a telescope line of sight requires a wavefront tilt sensor and a tip-tilt wavefront corrector (e.g., a tip-tilt mirror). To date, steering mirror assemblies for large mirrors have been relatively slow, massive devices, which generate rather large mechanical disturbances. High bandwidth operation and momentum compensation has only been achieved in small mirror assemblies (i.e., on the order of 2 inches across). In either case, the center of rotation in current technology devices is near the center of mass of the mirror, a point that is generally sub-optimal from an optical performance point of view. This panel therefore recommends that efforts be applied toward the development of highly compensated (i.e., better than 99% in all degrees of freedom) steering mirrors assemblies with projected centers of rotation. The effort should include technology for large mirrors (i.e., on the order of 1 m) as well as small mirrors. It should also produce technology for cryogenically cooled mirrors needed for missions in the infrared.

LASER METROLOGY

A. Technology Assessment

Laser metrology is the most widely applicable of the technologies considered by the panel. It plays a role in implementing capabilities in active optics, active interferometry, pointing and attitude sensing, and structures control. It is also important for ultra-accurate ranging within a constellation of instrumented spacecraft.

In active optics, laser metrology may play a role in the two stage approach for wavefront maintenance. However, for advanced single stage techniques, laser metrology is essential. This requires absolute measurements over distances of the order of tens of meters with an accuracy of better than 50 nm. In addition, it requires innovations in transferring the metrology measurements and knowledge about the wavefront originating from the science object. Some work on single stage techniques using lasers has been performed in the NASA's Precision Segmented Reflector program but no demonstration has been performed.

In active interferometers, laser metrology is critical to monitoring the interferometer baseline and internal optical paths, which is important for precise astrometric measurements in particular. Tolerances on the order of 10^{-3} µm over distances of 10 to 100 m are required for imaging interferometers and absolute ranging is also required. The tolerances will be tighter for an active astrometric interferometer (e.g., AIM/OSI). However, laser interferometry is also useful in interferometers that do not use active components for calibrating the interferometers internal geometry (e.g., AIM/POINTS). Here the requirement is 20 pm accuracy and accurate transfer of the metrology measurements to the science wavefront. Innovative homodyne techniques have been developed and laboratory measurements have now shown <20 pm consistency between two lasers over the same path. However, these demonstrations are far from the demonstration of a complete system.

In pointing and attitude sensing, laser technology may be exploited in new technologies for inertial pointing using the Sagnac effect and in attitude transfer devices.

In structures control technology, laser metrology is important in sensing and verification. Laser metrology is planned for verification of ground demonstrations in the NASA's Control Structure Interaction program. Deployment on complex three dimensional structures is generally a required part of implementing laser metrology in support of the other three technologies.

A final application is ranging between spacecraft in a constellation. This is important in the Imaging Interferometer implemented with the VISTA approach and for gravitational wave detection with the Laser Gravity-Wave Observatory in Space (LAGOS) mission.

B. Development Plan

Technology needs have been classified into four areas: laser sources, fiducial references, active components, and innovative metrology architectures.

Laser Sources – the requirement on laser sources for the variety of applications considered here are quite diverse. For most applications, the power requirements are modest; as in most other respects, the LAGOS application is an exception. Frequency stability is a critical property in almost all applications. For the near term astrometry missions, the frequency stability requirements are best defined with AIM/OSI and AIM/POINTS having similar requirements of $\sim 10^{-10}$.

Recent work on the development of lasers for AIM/OSI and AIM/POINTS has confirmed the feasibility of being able to use lasers for ultraprecise distance measurements using a variety of approaches (see Figure 11). However, while certain laboratory lasers, such as a HeNe laser with an iodine absorption cell, can meet the required stability, such

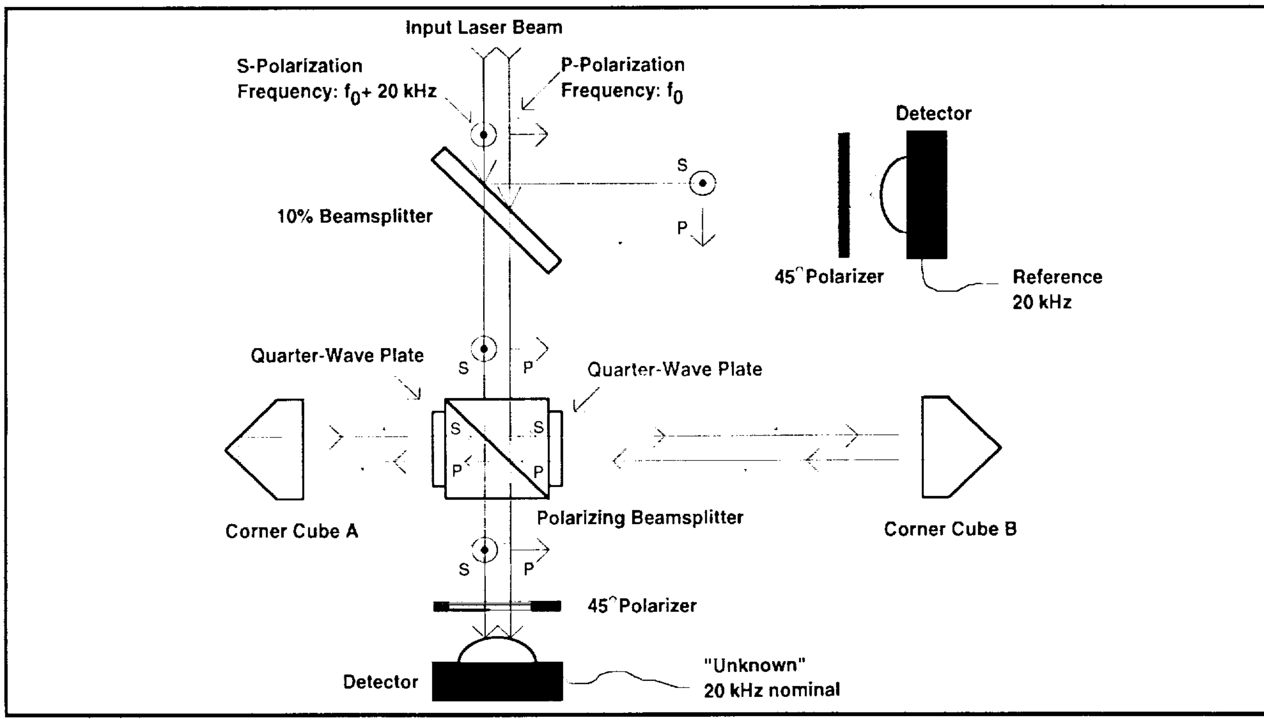


Figure 11. Point-to-Point Laser Metrology Using a Dual-Frequency Heterodyne Technique. (Courtesy of Mark Colavita.)

systems cannot be readily space qualified, are limited in optical output, and consume significant power. High efficiency diode-pumped solid-state lasers are far more promising for space applications. The immediate need is for the development of a suitable stabilization scheme for the solid-state laser, and the packaging into a low-mass, low-power package for space qualification.

For absolute distance measurements, tunable lasers are required. However, the tuning must be precise, either instantaneously, or else between well known frequency markers. In addition, the larger the tuning range, the higher the absolute range accuracy. Current techniques using tuned dye lasers have both insufficient accuracy and are not feasible for space applications. Thus a goal for the program is the development of tunable solid state lasers, with similar stability (or frequency knowledge) specifications as above; such a laser, with the tuning disabled, could also serve as the primary frequency source. The tuning range should be at least 1 part in 10^{-5}, which should allow 10–100 mm absolute accuracies over ranges of ~10 m. With a greater tuning range, absolute metrology to ~1 mm may be possible, which would resolve all ambiguities in a relative metrology system.

For both relative and absolute distance measurement, packaging of the metrology interferometers (fed from the stabilized laser) will be important. Many metrology system designs require clusters of beam launchers with accurate and stable pointing. Manifolds of beam launchers are currently just a glimmer in the eyes of large optical system designer, and existing hardware is little more than massive assemblies of individual beam launchers. Much work is needed to demonstrate small low mass manifolds. Beam launchers that provide beams tailored to the configuration of the fiducial references will also be needed, but the exact specifications of these devices await specifics on the system design.

Fiducial References – In order to use lasers to perform accurate metrology, fiducial references that define the geometry to be monitored are required. Retroreflectors represent one class of fiducial reference. Although they only generate point to point range information, they can be used in optical truss structures to determine three dimensional position information within the optical system. Key requirements on metrology retroreflectors include that the measured pathlength be invariant under rotations of the fiducials and beam translation across the fiducial. To minimize restrictions on the overall system configuration, the retroreflectors must also have a wide acceptance angles (i.e., angles over which they operate efficiently and accurately as retroreflectors). Devices that are available today (Figure 12 shows cat's eye type and corner cube type) are characterized by relatively narrow acceptance angles (i.e., less than 90 deg) and low precision (i.e., about 0.1 µm). The panel recommends a program of concept development and manufacturing process technology to improve these properties to over 120 deg and 1 nm respectively for applications in optical truss structures. Retroreflectors in innovative configurations have been conceived for specialized applications such as AIM/POINTS, which uses a complex corner cube structure (Figure 13).

Fiducial references for mirrors are also needed. For active optics systems using single stage wavefront sensing, retroreflectors within the primary mirror will be needed. Holographic approaches may have applications in this case. A holographic filled-aperture metrology (FAM) concept has also been investigated for transfer of the science and laser metrology reference frames for the POINTS interferometer.

Components – Certain active components will be needed in laser metrology systems. These include Bragg cells or Pockels cells to introduce modulation necessary for frequency stabilization, as well as to provide the frequency modulation needed for heterodyne metrology schemes. Single-mode fiberoptics and fiber couplers also will be needed to distribute the metrology laser signal among the various metrology launchers.

Innovative Metrology Architectures – New approaches and new design tools are needed for putting together the elements of metrology systems. Optical truss configuration design, for example, is currently done by trial and error. The design objectives include maximum observability of degrees of freedom, minimum sensitivity to parameter uncertainties, minimum number of individual beams, avoidance of obscurations, and satisfaction of component placement restriction (e.g., due to stray light and thermal consideration) thus the design

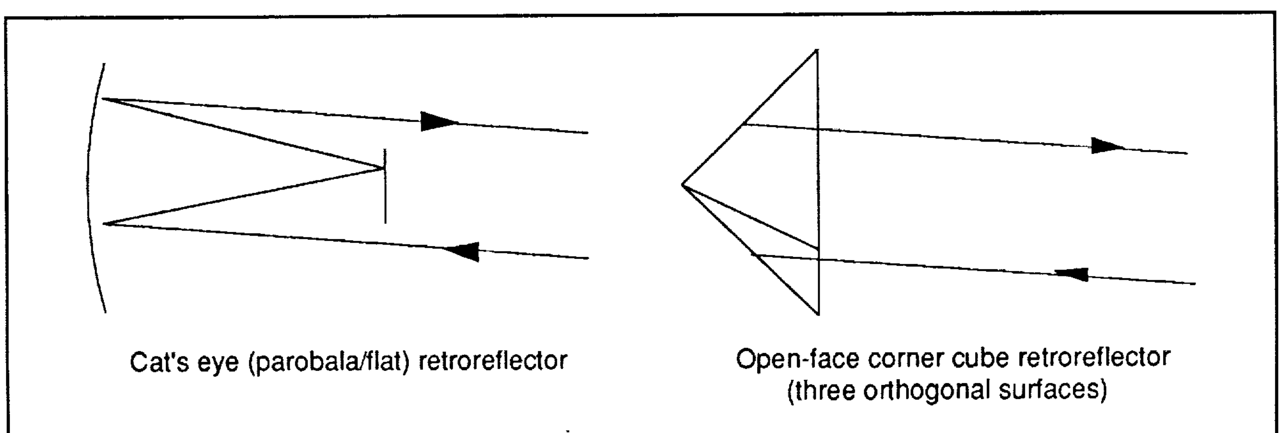


Figure 12. Cat's Eye and Corner Cube Retroreflectors. (Courtesy of Mark Colavita.)

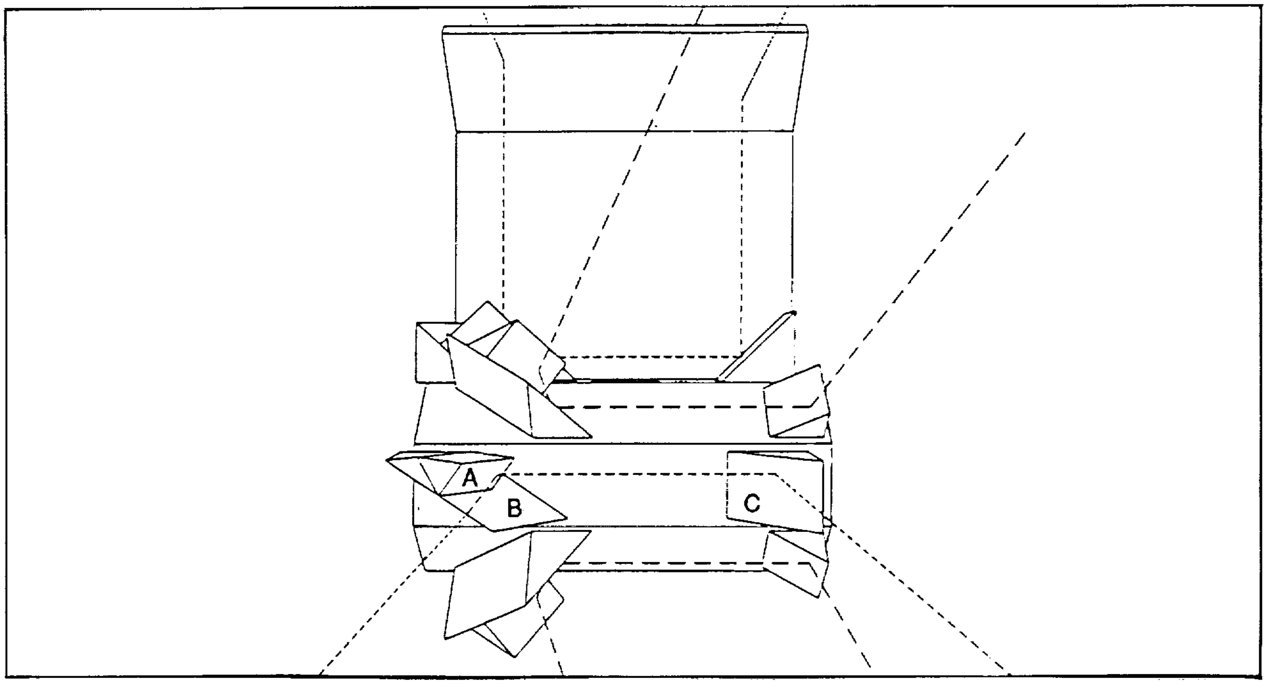


Figure 13. AIM/POINTS Retroflector Assembly (Courtesy of Mark Colavita.)

problem is a multiobjective constrained optimization. Computer-aided design tools are needed to streamline the design process and, more importantly, to allow true optimal designs to be produced.

Table 10 summarizes the laser meterology technology area.

STRUCTURES - CONTROL TECHNOLOGY

A. Technology Assessment

As the optical system size increases to 4 m and beyond, and the precision of these systems increases by 10 to 100 times that of the Hubble Space Telescope, precision lightweight structures of a kind never employed before will be required. These structures will be needed for filled aperture telescopes, partially filled-aperture telescopes, and interferometers. The materials will need to be very lightweight with very low coefficients of thermal expansion. The stiffness, damping, and dimensional stability of these structures will have to be actively controlled to achieve the nanoradian pointing stability and nanometer positioning accuracy needed after a system slew, and to compensate for the thermal effects of the space environment. These structures will also be very susceptible to vibration from onboard disturbances. This is an area where, due to complex non-linear control systems and control system interaction, a testbed is essential to prove the technology feasibility down to optical tolerances and validate models for system design. Table 11 summarizes previous flight system capabilities and the future direction of structures control.

Table 10. Laser Metrology Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Laser Sources	Tunable Lasers: Prototype Units Frequency Stabilization: Lab Demos Large and Massive Beam Launcher Manifolds	Tuning Range: 1 part in 10^5 Frequency Stability: 10^{-10} Low Mass Manifold Designs	'97, '08	'93 - '10
Fiducial References	Narrow Acceptance Angle : < 90° Precision: 0.1 mm	Wide Acceptance Angle : 120° Precision : 1 nm Rotation Invariance Beam Translation Invariance	'97, '08	'93 - '10
Active Components	Temporally Unstable Bragg Cells Temporally Unstable Optical Fibers	Stable Space Qualified Bragg Cells Stable Space Qualified Optical Fibers	'97, '08	'93 - '10
Innovative Metrology Architectures	Ad Hoc	Metrology System Optimization Tool Optical Truss Design Tool	'97, '08	'93 - '10

Table 11. Previous, Current, and Planned Structures Control Capabilities

TECHNOLOGY AREA	PREVIOUS FLIGHT SYSTEMS	HUBBLE SPACE TELESCOPE	CURRENT TECHNOLOGY	LOW LEVEL DEVELOPMENT PROGRAM 5 years	LOW LEVEL DEVELOPMENT PROGRAM 10 Years	AGGRESSIVE DEVELOPMENT PROGRAM 5 years	AGGRESSIVE DEVELOPMENT PROGRAM 10 Years
ACTIVE STRUCTURE CONTROL	NONE	NONE	Ground Testbeds Local Feedback Low Authority (10 dB Vibration Suppression)	Ground Testbeds Global Feedback Mod. Authority (20 dB Vibration Suppression)	Ground Testbeds Global Feedback Limtd. Bandwidth (30 dB Vibration Suppression)	Flight Ready Global Feedback Mod. Bandwidth (40 dB Vibration Suppression)	Flight Proven Global Feedback Wide Bandwidth (60 dB Vibration Suppression)
PASSIVE STRUCTURAL DAMPING	Galileo - Single Viscous Damper for Mag Boom	NONE	Viscoelastics- Temp. Sensitive, Nonlinear (10 dB Vibration Suppression)	Ground Testbeds Distributed Viscous Dampers	Ground Testbeds Improved Viscoelastics (20 dB Vibration Suppression)	Viscous struts flight ready (30 dB Vibration Suppression)	Viscoelastics flight ready (30 dB Vibration Suppression)
ACTIVE MEMBERS	NONE	NONE	Ground Testbeds 50 mm Stroke Signif. Hysteresis	Ground Testbeds 50 mm Stroke Mod. Hysteresis	Ground Testbeds 100 mm Stroke Slight Hysteresis	Flight Ready 100 mm Stroke High Linearity	Flight Proven 1 - 10 mm Stroke High Linearity
VIBRATION ISOLATION	Hubble passive RW isolator	Passive/ Viscous (10 dB Isolation)	Passive (10 dB Isolation)	Passive/Active (15 dB Isolation)	Active/Passive (20 dB Isolation)	Tuned Active (40 dB Isolation)	Tuned Active (60 dB Isolation)
OPTICAL ELEMENT ARTICULATION CONTROL	Secondary Mirror Angular Articulation on STS-borne Telescope (200 Hz Bandwidth)	NONE	Flight Proven Mod. Bandwidth (200 Hz) Angular Articulation Ground Testbeds Translational Control (300 Hz)	Ground Testbeds Improved Bandwidth Translational Control (1 kHz)	Ground Testbeds High Bandwidth (2 kHz) 90% Reactionless Actuation	Flight Ready High Bandwidth (5 kHz) 99% Reactionless Actuation	Flight Proven Very High Bandwidth (10 kHz) Adv. Dig./Analog Implementation
SIMULTANEOUS STRUCTURE CONTROL OPTIMIZATION	NONE	NONE	No Capability	No Capability	Ground Testbeds 10% Weight Savings At Nominal Perf.	Flight Ready 20% Weight Savings At Nominal Perf.	Flight Proven 40% Weight Savings At Nominal Perf.
DISTRIBUTED ACTUATOR PLACEMENT	NONE	NONE	Ground Testbeds Heuristic Energy Methods	Ground Testbeds Heuristic Energy Methods	Ground Testbeds Systematic Energy Methods (10 dB Perf. Improvement)	Flight Ready Systematic Input/Output Methods (20 dB Performance Improvement)	Flight Proven Systematic Input/Output Methods (30 dB Performance Improvement)

B. Development Plan

A comprehensive structures-control technology program is recommended, with development efforts in isolation systems, damping augmentation methods, control-structure interaction suppression, modal control, smart structures, and integrated structure-control design optimization. An overview of the proposed program is shown in Table 12.

The structure of an optical system supports the optics, and thus has a central role in determining the quality of the output wavefront. It also supports the internal mechanical disturbance sources such as reaction wheels and chopping mechanisms. Structure-related wavefront errors arise because of temperature variations and gradients, mechanical vibrations and aging. As the threats are manifold, a corresponding multi-tier technology approach is recommended.

Vibration Isolation Systems – Isolation systems are needed to isolate the structure from disturbance sources and the optics from the structure. These devices must be stiff at low frequencies to preserve alignment, yet soft at high frequencies to be effective isolators. The transition must be sharp and predictable. Moreover, the properties of the device must be preserved over a wide temperature range, including temperatures below 100 K. In general, the devices must function as isolators in some degrees of freedom but must be transmissive in others. The state of the art in this technology is represented by the HST reaction wheel isolators and the Space Active Vibration Isolation (SAVI) prototypes. Advances are needed in performance and low temperature operation. Furthermore, the active techniques required for very high performance must be made practical in terms of mass, power, complexity, and reliability.

Damping Augmentation – New techniques are needed to lower vibration levels due to persistent disturbances (e.g., momentum wheel bearing rumble) and to hasten settling after transient excitations (e.g., slews). In addition, damping augmentation is required to lower structural resonance peaks, thus enabling higher control

Table 12. Structures Control Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Vibration Isolation Systems	Special Purpose Prototypes and Passive Techniques Isolation : 80 dB 1 – 1000 Hz	10 X Improvement, Low Temperature Operations Isolation : 100 dB, 0.1 – 10^4 Hz Active Techniques, Magnetic Suspension	'97, '04	'93 - '10
Damping Augmentation	Room Temperature Operations Only, None Space Qualified, Passive Techniques	10 X Improvement Low Temperature Passive and Active Damper Active Techniques	'97, '04	'93 - '10
Control Structure Interaction	Analytical Studies	Testbed Demonstrations	'97, '04	'93 - '05
Modal Control	Analytical Studies, Demonstration Under Idealized Conditions	Robustness Against Modelling Errors Modal Control System Testbed Demonstration	'97, '04	'93 - '97
Smart Structures	Breadboards Exist	Structural Shape Control Full Scale System Demonstration	'97, '04	'93 - '97
Integrated Control Structure Design Optimization	Analytical Studies	Control Structure Optimal Design Tool System Demonstration	'97, '04	'93 - '10

system (e.g., pointing system) bandwidths and hence better control system performance. Both passive and active damping treatments are currently limited to operation near room temperature, and are capable of delivering only a few percent damping. The technology is generally not space qualified. Thus, improvements are needed in performance and temperature range. Moreover, developments are needed to enable operation in the radiation environment of space for long periods. Active techniques, which promise to overcome the limitations of passive methods, must be refined in terms of reliability, low temperature operation, and operation off of low voltage power supplies, which are less susceptible to arcing than the high voltage supplies that are currently required.

Control Structure Interaction – Closed loop electromechanical control systems generally interact dynamically with the structure that supports them. This interaction may effect control system performance and may even give rise to unbounded structural resonances. A great deal of analytical work has been done on methods of preempting undesirable control structure interaction (CSI), however, no generally successful design architecture or procedure exists. Therefore, current practice relies on wide separation of control and structure bandwidths, which is obviously very limiting in terms of performance. It is recommended that support be given to the development of robust yet practicable methods of design and to the identification of appropriate control architectures for the class of problems of interest to the optical community. Furthermore, it is recommended that this work include the development of relevant system testbeds to serve as proving grounds for the technology. To provide realistic test environments for space missions, these testbeds should include high vacuum and gravity off-loading capabilities.

CSI technology is being cooperatively developed at three NASA centers: Langley Research Center (LaRC), Jet Propulsion Laboratory (JPL), and Marshall Space Flight Center (MSFC). The technology is being developed to quiet large space optics, reduce stringent design/operation constraints, and increase the probability of mission success. Quieting is achieved to the nanometer level by inserting progressive layers of passive and active structure/optical control. Each CSI layer (disturbance isolation, structural quieting, optical motion compensation) reduces critical motions by one to two orders of magnitude, enabling overall quieting factors of up to 10,000. Work on quieting micro-precision structures of large space optical systems is being carried out at JPL. A precision structural actuator design has been built and a Honeywell heavy-viscous damper (D-Strut) has been adapted for precision structure control. Both have shown excellent and repeatable behavior at the tens-of-nanometer level. A microprecision component tester has been built for component and material characterization and a measurement facility has been made available to the effort. Additionally, new integrated structure/control design methods have been in development, and results from these methods have been used to design control systems for the JPL Precision Truss Testbed. Future plans include an advanced "Phase 1 Testbed" if funding can be solidified.

Modal Control – One very promising method of active structural quieting is modal control. This method attempts to regulate the natural vibration modes of a structure by extracting energy from it at fixed or adaptively tuned frequencies. As it is not restricted to applying force feedback from collocated rate sensors, it offers the potential of great effectiveness. Indeed, the method has been shown to be highly effective in analytical studies and laboratory demonstrations where the structural dynamics are well understood. What is needed in the future is improved robustness against modelling errors and demonstration in dynamically rich realistic test environments. Research is recommended on controlled structure system identification, self-tuning (i.e., multi-variable adaptive or phase locked loop) structural control, and systematic robust controller design (i.e., H_∞ or μ synthesis).

Smart Structures – By actively accommodating thermal deformations, so called smart structures can maintain their overall shape while individual structural elements undergo dimensional changes. Thus, smart structures, in conjunction with good thermal control and thermally stable materials, are required to achieve the very high levels of dimensional stability needed by future missions. To date, only breadboard components exist, and complete systems exist only as concepts. It is recommended that reliable, flight qualifiable components be developed, and that the system concept be demonstrated within a realistic testbed.

Integrated Structure Control Design Optimization - The standard practice in structure and control system design consists of individual design efforts which respond to independent requirements. Iteration between the disciplines is generally limited to mutual expressions of preferences. The stringent requirements of future space-based optical systems will require that designs eke out all the performance possible from a given system. This will make it necessary to optimize the structure, control system, and even the optics simultaneously. Such an integrated optimal design discipline is currently in the formative stage. A practical design tool is needed. Moreover, experience on representative systems is essential, and robustness on real systems must be demonstrated.

SYSTEM-CONTROL ARCHITECTURE

A. Technology Assessment

Active optics, interferometric phase control, and active structures in space represent control problems of unprecedented dimensional complexity. Most of the current work in this area is limited to theory with very little hardware verification. As the control systems become a more integral part of the payload and spacecraft, new methods must be found to detect and compensate for component failures. The control architectures must be robust enough to deal with a wide range of conditions and changes This is another critical area where a system-level testbed capable of control experiments at optical tolerances is essential. Testing control systems at these levels requires special isolated test facilities and diagnostic tools capable of interferometric accuracies.

B. Development Plan

Table 13 is a summary of the system-control architecture technology areas requiring significant advances to satisfy the Astrotech 21 mission set requirements. Each is discussed in the following paragraphs.

The large astrophysical missions in the Astrotech 21 mission set will generally require active control of optics, structures, and pointing. The level of required performance and complexity is without parallel within control system engineering practice. Existing control theory and algorithm design methods are poorly equipped to deal with this challenge. Furthermore, they do not address the unique interdependencies among optics, structures, and pointing control. New control theory and algorithm types will be needed to cope with these challenges. These developments are closely tied to, and essential for, the end-to-end simulation capability of the integrated modeling technology development effort. In particular, it is recommended that NASA's Optical System Technology program include fundamental but highly focused research on systematic design and analysis methods, adaptive control, system identification, robust control, multiobjective optimal control, and control of high-dimensional systems.

Among the specific issues that need to be addressed is the interaction between the many control loops that will be operating simultaneously. As is the case in control structure interaction, this control-control interaction can degrade performance and bring about instability. Tools for coping with this problem are nonexistent. Therefore, the committee recommends that an effort be initiated to develop methods of suppressing optics control system interactions.

Table 13. System-Control Architecture Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Theory and Algorithms	Disconnected	Systematic Design and Analysis Theory for Multi-Loop Optics Control Systems	'96, '10	'93 - '10
Control System Interaction	Non-Existent	Optics Control System Loop Decoupling Techniques	'96	'93 - '96
Computation and Processing	Multiple, Independent Serial Processors	Massively Parallel Architectures and Algorithms Neural Network Prototype Controllers	'97, '10	'93 - '10
Modeling and Simulation	Special Purpose Prototypes, Idealized	Simulation, Design and Analysis Tool for Control Elements	'96, '04	'93 - '04
Optimal Design	Non-Existent	Multi-Loop Optics Control System Design Optimization Technique	'97, '10	'93 - '10

The very high dimensionality of typical optical system control problems (i.e., hundreds to many thousands of degrees of freedom) will overwhelm the capabilities of current computational resources. The design, analysis, and real-time implementation of such system will require massively parallel architectures, algorithms, and hardware. It is recommended that the Optical System Technology program aggressively pursue these areas, including the development of neural net based controllers.

To evaluate candidate designs, end-to-end system modelling, and simulation will be essential. Although the subject of integrated system modelling is covered extensively in the Optical Systems Integrated Modeling panel report, the Wavefront Sensing, Control, and Pointing panel feels it is appropriate to point out that specific developments are necessary to model and simulate the complex control elements within large optical systems. The current sate of the art consists of special purpose idealized models and codes. This panel recommends the development of general tools (e.g., like $Matrix_x$ or the Matlab Control System toolbox) for design, analysis, and simulation of optical system control elements.

Another area in which standard control system engineering practice falls short of meeting the needs of controlled optical systems is optimal design. The modern optimal control theory is well suited to traditional spacecraft guidance and navigation problems, but contains essentially no results of direct relevance to optical systems. Research in optimal design, leading to multi-loop optics control system design optimization techniques, is recommended. Specific problems in need of attention include simultaneous optics and control design optimization (e.g., optimal trade-off between optical sensitivities and control accuracies), minimum time figure and alignment initialization, and wavefront error minimizing figure and alignment maintenance.

SUMMARY

Many of the sensing and control technologies examined by the panel are just now emerging and maturing to the point where they are serious candidates for space missions in the next 5 to 10 years. A committed effort that leverages to the greatest extent possible the government work sponsored to date can allow the technology to be available in a timely way.

The complexity of the Astrotech 21 missions and the new sensing and control technologies needed will require a growing cadre of scientists and optical engineers versed in the new interdisciplinary technologies discussed here. Educational institutions should be encouraged to add sensing and controls courses, as related to optics, to their engineering curricula.

Finally, much of the sensing technology considered by this panel will be similar to the optical manufacturing and test metrology of the future. Additionally, the control system sensors developed under this technology program may (in some form) be substituted for the metrology sensors required during the fabrication process. Coupled with the computer controlled nature of the fabrication process, these sensors will support in-process testing of optics and will enable a reduction in the manufacturing and test time required.