A Combined Fast Steering and Alignment Mirror for Space-Based Interferometers

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Abstract

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Key words: optical interferometry, space telescopes, fast steering mirrors, pointing mechanisms

1.0 introduction

Paragraph 1: introduce technology of pointing mech (Larry)
“describe technology

- application references
- reference require what types of performance in disturbance envt
- range and bandwidth
- cost and reliability will govern applicability of these mechanism
- favorable cost and reliability may enable new types of missions

One application that will rely extensively on pointing mechanism technology are space-based optical interferometers, a new class of science instruments under development at NASA. Optical interferometers provide extremely high angular resolution for imaging and astrometry of astrophysical targets through the use of discrete, widely separated collecting apertures. Operation of an interferometer requires light from two collecting apertures to be steered towards a central beam combiner where the beams are interfered and science data is extracted from the resulting interference pattern. Interference patterns can be measured if the optical path which each light beam travels can be made sufficiently stable (to 1 nm in starlight differential pathlength and to 1 arcsec in wavefront tilt) in the presence of spacecraft disturbances and misalignments. To reject these disturbances, interferometers employ both high bandwidth and quasistatic active optics for pointing and pathlength compensation.

Ground-based optical interferometers demonstrated hat active optics, incorporating fast steering mirrors and optical delay lines for high bandwidth control of beam tilt and pathlength, could be used to compensate for atmospheric turbulence and permit astrometry at baselines of tens of meters (Shao et al, 1988). Space-based optical

2.0 Requirements

Requirements for fast steering and alignment mechanism are driven by the system requirements of individual interferometer missions. A description of the Space Interferometry Mission (SIM) is chosen to illustrate the functional requirements of these mechanisms. Fast steering and alignment mirrors are also necessary for the New Millennium Interferometer (NMI) (Colavita et al, 1 996) and, although the mission is not described here, the functional requirements for the NMI mechanisms 'are presented along with the SIM requirements in Section 2.2.

2.1 System Requirements for SIM

Fig 1 Spacecraft configuration for the Space Interferometry Mission (SIM)

Fig 2 SIM optical train

SIM is a long-baseline optical interferometer with capabilities for ultra-high accuracy (1 -4 uas) astrometry and high-resolution (1 0 mas) synthetic imaging -- 4 times that of the Hubble Space Telescope. SIM uses three interferometer baselines on a deployed 10 meter structure linked by laser metrology to provide a precision structure. The SIM architecture makes extensive use of deployment and active optics technologies to lower cost and increase mission performance. Table 1 summarizes important mission and instrument parameters. Figure 1 illustrates key elements of the SIM instrument and spacecraft: seven siderostat bays for collecting stellar light distributed along a deployed 10 meter boom, an optics boom for beam combining anti fringe detection, and a deployed boom which contains the beam launchers for the laser metrology used to establish the precision structure. Recent mission conceptual designs feature an eight-siderostat architecture.

Table 1 SIM mission summary

Instrument	
Baseline	10 meters
Wavelength Range	0.4 to 1.0 micron
No. of Siderostats	7 (or 8)
Aperture Diameter	33 cm
Astrometric FOV	10 x 10 degrees
Imaging FOV	0.4 x 2.4 arcsec
Detector	Si-CCD & Avalanche Photo Diode
Mission/Flight System	
Orbit	900 km Sun-synchronous
Orbit Period	103 min
Launch Vehicle	Delta-II 7920
Mass	1791 kg
Power	1029 W
Lifetime	5 years
Science Performance	
Astrometry (Global)	4 uas on 20th mag in 10 hrs
Astrometry (Narrow-angle)	1 uas on 15th mag in 3 hrs
Imaging (Point Source)	25th mag in 1 hr
Imaging (Extended Source)	20th mag/pixel in 1 hour

A representative subset of the SIM optical train is illustrated in Figure 2. Stellar light is reflected off of a 40-cm flat, gimbaled siderostat mirror and enters a 11:1 beam compressor and emerges as a 3 cm diameter compressed beam. The compressed beam encounters a fast steering mirror (used for high bandwidth wavefront tilt correction) and then two alignment mirrors, of which only Alignment Mirror B is actively controlled. The alignment mirror steers the light to the central optics boom of the truss where two switchyard mirrors (3 degree range) steer the beam into one of eight optical delay lines and then into a beam combiner where it is combined with light from another siderostat located at the opposite end of the 10 meter siderostat boom. Interference fringes will be produced by the beam combination if the pathlength followed by the starlight in each arm of the interferometer is stable to 1 nm RMS; the active delay lines provide this stability over a total optical delay range of 2 meters. Eight delay lines -- of which four are active -- permit pairing of different siderostats in order to achieve different baselines for synthetic imaging.

Inside the beam combiner the starlight encounters a series of optics that focus the combined light on a Silicon CCD which provides three independent measurements at high bandwidth: fringe detection, wavefront tilt, and beam shear. The latter two are error signals used to drive the pointing mechanisms at the siderostat bay. The alignment mirror performs quasi static compensation of beam shear due to thermal deformations on orbit and corrects for misalignments due to launch. The fast steering mirror, on the other hand, servoes the wavefront tilt error signal at closed loop bandwidths of 100 Hz or more; the lower bandwidth siderostat desaturates the fast steering mirror to provide greater dynamic range for pointing control. System level performance requirements for fringe detection require that the pointing system provide wavefront tilt control of the compressed beam in each arm of the interferometer to better than 1 arcsecond over integration times on the order of 1 to] O seconds. This stability must be maintained in the presence of high frequency structural vibrations due to disturbance forces originating at four Hubble-class reaction wheels used for spacecraft attitude control.

2.2 Component Requirements

Fig 3 SIM collecting apertures and pointing mechanisms

Requirements for fast steering, alignment and switchyard mechanisms are listed in '1'able 2 for two missions, NMI and SIM. Mirror requirements arc listed in Table 3. In general the requirements for each actuator and each mechanism are similar except for range and bandwidth. The range requirements for alignment mechanisms are set by the expected misalignments due to launch and by the expected quasitatic thermal distortions to the optical train. The +/- 6.2 arcmin range for the NM] fast steering mechanism is needed to compensate for the attitude control deadband of the separated spacecraft in which the instrument is mounted. The 3 degree range of the SIM switchyard mirror is required to steer the starlight beam to different delay line pairs. During actuation each fast steering mirror must be rotated about the front surface to within 5 nm to avoid introducing additional pathlength delay into the optical paths at high frequencies, close to the control bandwidth of the optical delay line.

The stability limit of 2 arcsec over 24 hours is required for case of maintaining alignment of the optical train. Resolution, jitter and relative pointing accuracy are set to approximately 1/20th of the subaperture diffraction limit of the 4 cm mirrors. Momentum compensation for the fast steering mechanisms is desirable in order to dynamically decouple the pointing loop from the delay line loop; however, recent simulations and tests at JPL indicate that this coupling may be negligible for the SIM spacecraft. For the New Millennium Interferometer, the coupling may matter at the nanometer level due to the small size of the host spacecraft.

Table 2 Performance requirements for fast steering mirrors. FSM = fast steering mirror, AM = alignment mirror, SM = switchyard mirror.

Articulation Requirements (1)	NMI		SIM		
	FSM	AM	FSM	AM	SM
Momentum Cancellation (2)	desirable	No	**desirable**	No	**No**
Caging for Launch	undesirable	undesirable	undesirable	**undesirable**	**undesirable**
Angular Range, (Mechanical Motion)	±6.2 arcmin ±1.8 mrad	±3.4 arcmin ±1. mrad	±2 arcmin ±0.58 **mrad**	±6 arcmin ±1.8 **mrad**	±3. **deg** **+52, mrad**
Angular Position Knowledge	derived reqmt	**derived** reqmt	derived reqmt	'**derived** reqmt	derived reqmt
Resolution (Minimum Commendable Motion)	**0,05** arcsec **0.24** µrad	**0.05** arcsec **0.24** µrad	0.05 arcsec **0.?4 prad**	**005 arcsec** **0.24** µrad	**0.05** arcsec **0,24** µrad
Linearity (Time Invariant Position Response) Max over Full Travel	±2.arcsec ±9.7 µrad	±2.arcsec ±9.7 µrad	±2.arcsec ±9.7 **prad**	±2.arcsec ±9.7 µrad	±2.arcsec ±9.7 µrad
Jitter, 1sigma over 1 sec	0.1**arcsec** **0,5** µrad	0.1 arcsec **0,5** µrad	'**0.1** arcsec 0.5 µrad	**0.1** arcsec 0.5 µrad	0.1 arcsec 0.5 µrad
Stability/Drift, Max over 24hrs over op temp range	±2.arcsec ±9.7 µrad	±2. arcsec ±9.7 µrad	±2.arcsec ± **9,7 prad**	±2.arcsec ±9.7 **prad**	±2.arcsec ± **9.7** µrad
Relative Pointing Accuracy, Max over specified angular range over 1 rein, quasistatic temp	±0.1arcsec ±0.5mr **over full range**	N/A	±0.1arcsec ±0.5mr **over full range**	N/A	**N/A**
Closed-loop bandwidth using on-mechanism angle sensing, at maximum angular acceleration	**250** Hz	**1 Hz**	600 **Hz**	**1 Hz**	0.1 **Hz**
Angular Velocity	**17** deg/s **0,3** rad/s	.34deg/s **,006** rad/s	17deg/sec **0,3** rad/s	.34deg/s **.006** rad/s	0.57deg/s **O,Oi** rad/s

Angular Acceleration	200. rad/s^2	2.3deg/s^2 0.040 rad/s^2	200. rad/s^2	2.3deg/s^2 0.040 rad/s^2	5.7deg/s^2 0.10 rad/s^2
Piston over any 50 µrad of travel	<5 nm	N/A	<5 nm	N/A	N/A
Absolute Pointing Accuracy is a Derived Requirement = |Linearity| + |Stability/Drift|					
Absolute Pointing Accuracy, over full angular range, Max over 24hr over operating temp range	±4. arcsec ±19. µrad	±4. arcsec ±19. µrad	±4. arcsec ±19. µrad	±4. arcsec ±19. µrad	±4. arcsec ±19. µrad

Table 3: Mirror requirements for fast steering and alignment mirrors

Parameter	Requirement
Nominal Beam Diameter, mm	30
Nominal Angle of Incidence, deg	45
Minimum required clear aperture, mm (circular mirror is optional)	35
Front Surface Figure over Beam Diameter (Projected)	$\lambda/100$ rms at 0.633 μm
Cosmetic Surface Quality	40/20 scratch/dig
Mirror Material	unspecified
Mirror Front Surface Coating (reflects starlight at λ=500--900 nm)	protected silver*

*Denton FSS-99 or equivalent

Perhaps the most challenging requirements are those imposed by the anticipated operational environment of the mechanisms. Tables 3 and 4 list the vibration and thermal environments in which the fast steering and alignment mirrors must function. Although both SIM and NMI mission designs are in only the conceptual design phase, a set of mildly conservative environmental parameters has been established that is representative of the launch vehicles and spacecraft orbits. The mechanisms must be tested to these levels in order to establish design qualification.

Table 3 Environmental requirements: vibration and shock

Vibration Environmental Requirements (Qual Levels)	
Random Vibe Spectrum (duration 3 min/axis)	
20-50 Hz	+6 dB/octave
50-800 Hz	0.4 g**2/Hz
800-2000 Hz	-6 dB/octave
Shock Spectrum	
100-1000 Hz	+12 dB/octave
1000-10,000 Hz	3000 g
Sine Survey Test Spectrum	
5-2,000 Hz	0.25 g 0-to-peak
Sine Test (only if some resonances are below 100Hz)	Upsweep only at 2 octaves/minute
5-16 Hz	1.9 cm (0.75 in) D.A.
16-60 Hz	10 g's 0 - peak
60-100 Hz	*5 g's 0* - peak

*Power is off during launch

Table 4 Environmental requirements: thermal

Thermal Environmental Requirements	**Optomechanical Assembly (Deg C)**
Survival	-50 to +65
Demonstrate Turn-on	-50
operational	+10 to +30
Thermal Rate of Change	
Operational	1 deg/hr
Survival	10 deg/hr

3.0 Component Design and Performance Prediction

4.0 Fabrication and Tests

5.0 Impact on System Design

Fig 3 SIM collecting aperture, beam compressor and pointing mechanisms

The development of a mechanism that meets the requirements for angular range. and bandwidth for both alignment and fast steering mirrors is an advantage for interferometer system design. Figure 3 illustrates the opto-mechanical architecture at one of the siderostat bays. The dual-function mechanism would be located at Alignment Mirror B, and the fast steering mechanism would be replaced by a passive flat mirror. Since the current SIM architecture calls for eight siderostat bays, a total of eight mechanisms (and associated cabling and electronics) would no longer be required for the flight instrument, an anticipated benefit for both the mass and cost budgets of the mission.

6.0 Conclusions and Recommendations for Future Work

- must perform functional and environmental tests (vib, thermal)
- must evaluate in end-to-end interferometer testbeds to verify functional performance
- re-engineer based on test results
- more complete design qualification design and test
- Larry, you can add a lot here.

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References

1. M. Shao, M.M. Colavita, B.E. Hines, et al., "The Mark III stellar interferometer, " Astron. Astrophys. 193, 357-371 (1988).

2. M. Shao, D. M. Wolff, "orbiting Stellar Interferometer," Proc. SPIE 2477, 228-239 (1995).

3. M.M. Colavita et al, "Separated Spacecraft Interferometer Concept for the New Millennium Program," Proc. SPIE ????, 1996.

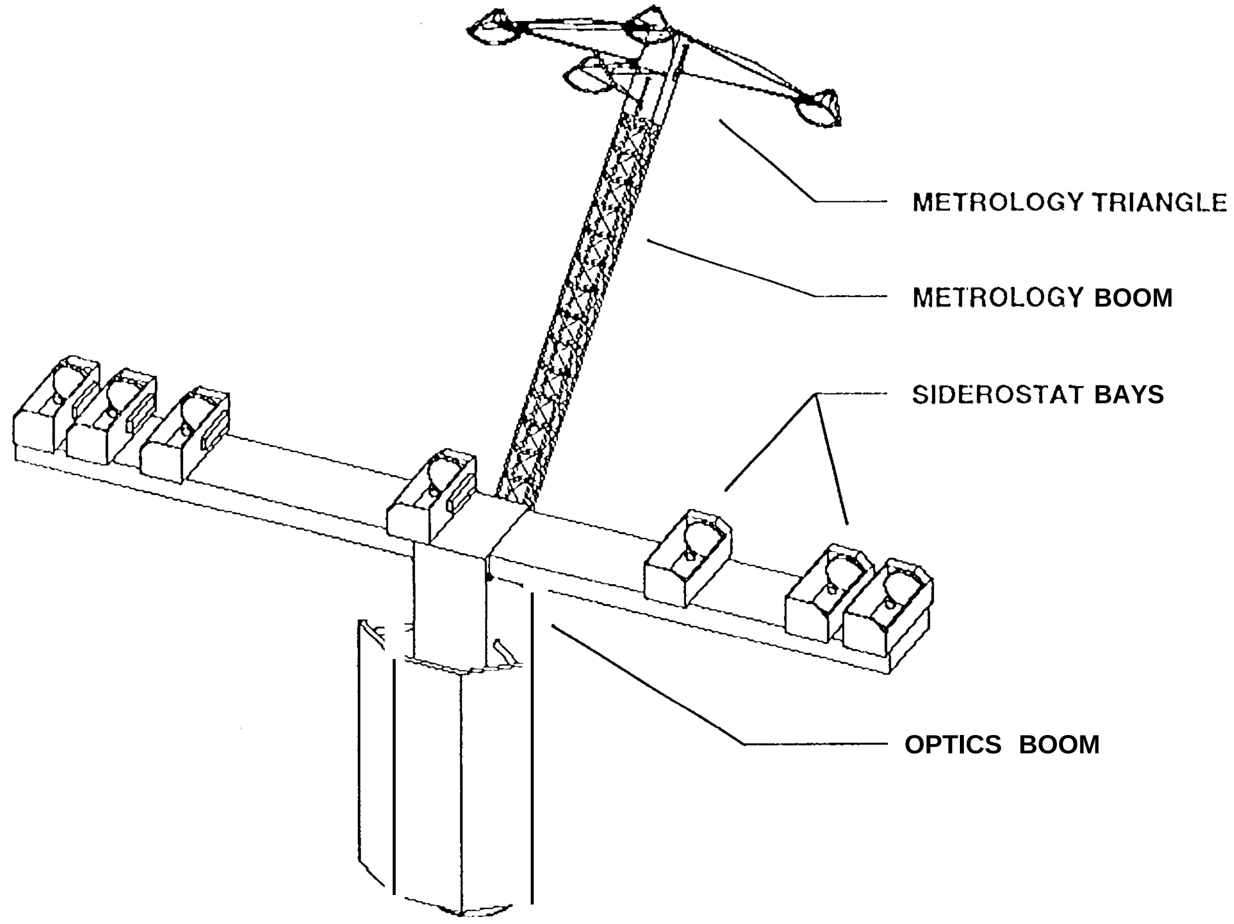
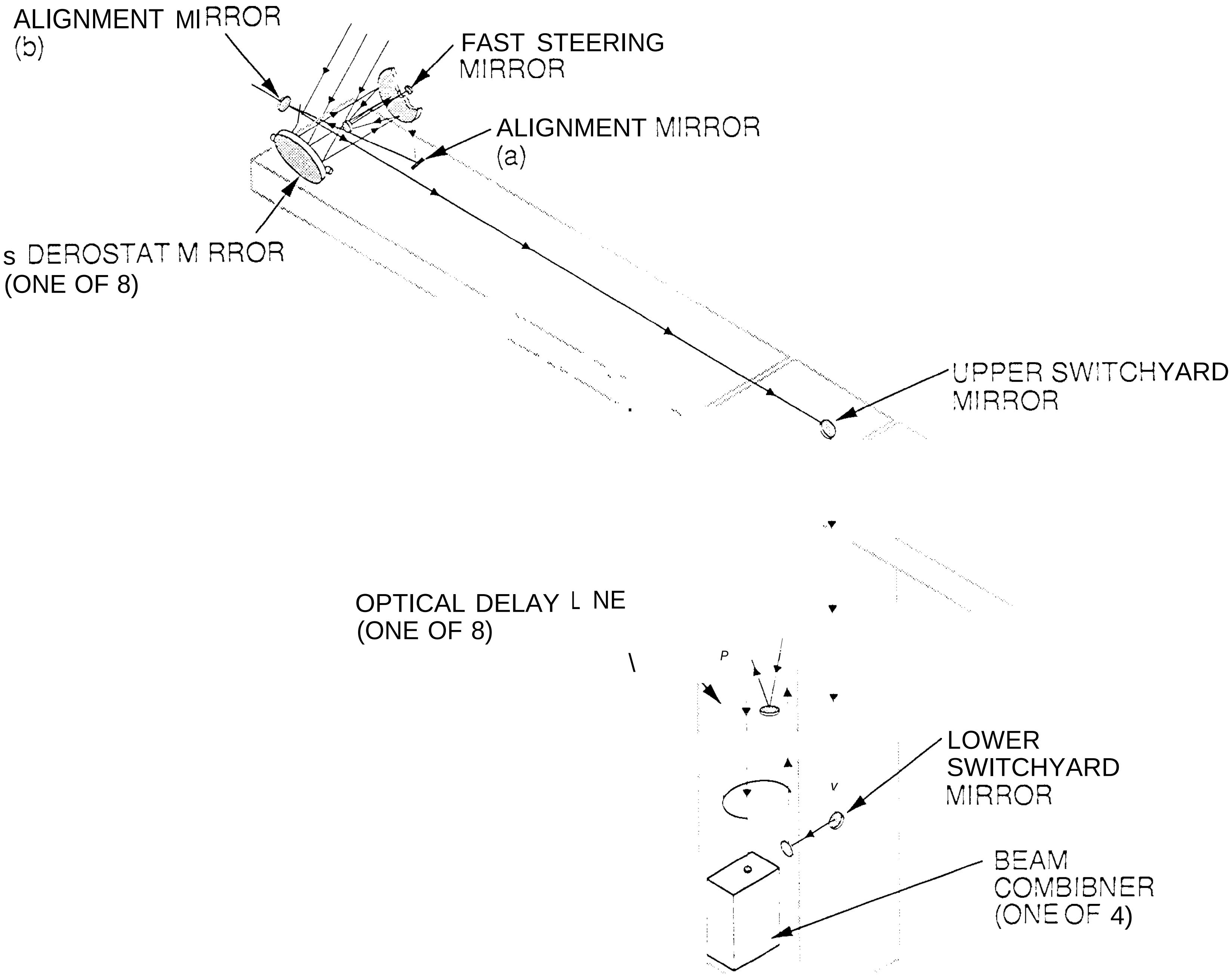
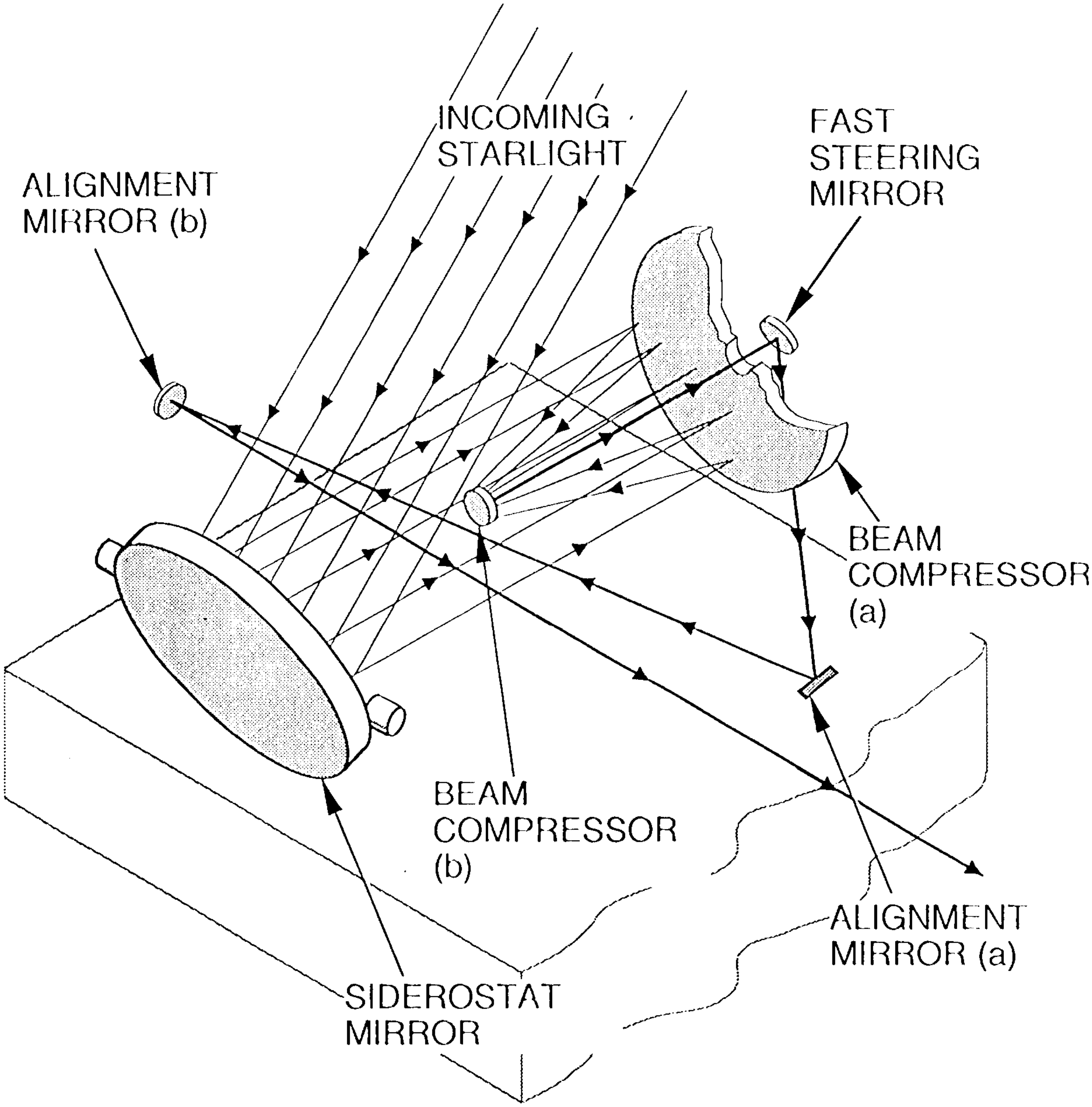


Figure 1. Space Interferometry Mission


ALIGNMENT MIRROR
(b)
FAST STEERING
MIRROR
ALIGNMENT MIRROR
(a)
SIDEROSTAT MIRROR
(ONE OF 8)
UPPER SWITCHYARD
MIRROR
OPTICAL DELAY LINE
(ONE OF 8)
LOWER
SWITCHYARD
MIRROR
BEAM
COMBIBNER
(ONE OF 4)

2


INCOMING
STARLIGHT
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MIRROR (b)
FAST
STEERING
MIRROR
BEAM
COMPRESSOR
(a)
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ALIGNMENT
MIRROR (a)
SIDEROSTAT
MIRROR