A SPACEBORNE OPTICAL INTERFEROMETER: THE JPL CSI MISSION FOCUS

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INTRODUCTION

The JPL Control Structure Interaction (CSI) program is part of the larger NASA-wide CSI Program and as such is a focused technology effort in intellectual partnership with the Langley Research Center and the Marshall Space Flight Center. NASA's CSI Program is managed from the Office of Aeronautics and Space Technology (OAST) by the Materials and Structures Division. OAST is specifically focusing CSI technology to enable or enhance classes of missions which are supported by NASA's Office of Space Science and Applications (OSSA). OAST and OSSA are coordinating to assure direct applicability of the CSI effort to future missions.

Within this larger context, the JPL CSI program will emphasize technology for systems that demand micron or sub-micron level control, so-called Micro-Precision Controlled Structures (u-PCS). The development of such technology will make it practical to fly missions with large optical or large precision antenna systems. In keeping with the focused nature of the desired technology, the JPL approach is to identify a focus mission, develop the focus mission CSI system design to a preliminary level, and then use this design to drive out requirements for CSI technology development in the design and analysis, ground test bed, and flight experiment areas.

- **JPL CSI PROGRAM**
  - **PART OF THE NASA-WIDE CSI PROGRAM**
  - **PARTNERSHIP WITH NASA LANGLEY RESEARCH CENTER AND NASA MARSHALL SPACE FLIGHT CENTER**
  - **EMPHASIS ON MICRO-PRECISION CONTROLLED STRUCTURES (μ-PCS)**
    - **ENABLING FOR CLASS OF LARGE OPTICAL SYSTEMS**
    - **ENHANCING FOR LARGE PRECISION ANTENNA SYSTEMS**

- **STRATEGY**
  - **IDENTIFY A JPL CSI FOCUS MISSION**
  - **USE THE FOCUS MISSION TO ESTABLISH TECHNOLOGY DEVELOPMENT REQUIREMENTS**
    - **REQUIREMENTS FOR GROUND TEST BED**
    - **REQUIREMENTS FOR DESIGN/ANALYSIS TOOLS**
    - **REQUIREMENTS FOR THE CSI DESIGN ENVIRONMENT**
    - **REQUIREMENTS FOR FLIGHT EXPERIMENTS**

CSI FOCUS MISSION IDENTIFICATION

In the intial phase of choosing a focus mission a number of potential future missions were under consideration. These included:

1. Precision Optical Interferometers such as
   COSMIC - Coherent Optical System of Modular Imaging Collectors
   OSI - Optical Space Interferometer
   POINTS - Precision Optical Interferometry in Space
2. Large Segmented Reflectors such as
   LDR - Large Deployable Reflector
   AST - Advanced Space Telescope
3. Multiple Payload Platforms such as evolutionary versions of
   EOS - Earth Observing System
   SSF - Space Station Freedom
4. Large Telescopes with Monolithic Primaries such as
   ATF - Astrometric Telescope Facility
   CIT - Circumstellar Imaging Telescope
5. Large Space Antennas such as MSS (Mobile Satellite System)
6. Flexible Space Manipulators for use on space platforms

Some of these and others are discussed in the References.

The criteria for selection of the focus mission are listed on the chart below. Particular care had to be exercised to ensure that the last two criteria could be satisfied simultaneously.

- **MISSIONS CONSIDERED**
  - **PRECISION OPTICAL INTERFEROMETERS (COSMIC, OSI, POINTS)**
  - **SEGMENTED REFLECTORS (LDR, ADVANCED SPACE TELESCOPE)**
  - **MULTIPAYLOAD PLATFORMS (EOS, SSF, EVOLUTIONARY EOS & SS)**
  - **LARGE TELESCOPES WITH MONOLITHIC PRIMARIES (ATF, CIT)**
  - **LARGE SPACE ANTENNAS (MSS)**
  - **FLEXIBLE SPACE MANIPULATORS**
- **CRITERIA FOR SELECTION**
  - **IMPORTANCE OF MISSION TO NASA**
  - **MISSION'S NEED FOR CSI TECHNOLOGY**
  - **ABILITY TO DRIVE DEVELOPMENT OF GENERAL PURPOSE CSI TECHNOLOGY**
  - **CONSISTENT WITH JPL EMPHASIS ON μ-PCS**
- **SELECTION**
  - **FOCUS MISSION INTERFEROMETER (FMI)**

MISSION CHARACTERISTICS MATRIX

The rationale for choosing a spaceborne optical interferometer as the focus mission can be gleaned from the table below. All of the missions listed were judged to be of significant importance to NASA's future plans for space science and exploration. Likewise all the missions were seen as benefiting from CSI technology development, although the benefits are least compelling for multiple payload platform payloads such as large telescopes with monolithic primaries.

The key to choosing the focus mission interferometer (FMI) lies in the column of the table labeled "Positional Accuracy". Optical interferometers, with positional control tolerances on the order of one nanometer over baselines of 10 to 30 meters and up, are most clearly consistent with JPL's emphasis on u-PCS. In addition the FMI configuration that has been evolved has numerous articulating and translating controlled elements. In this respect it is similar to a multiple payload platform (MPP) which was judged to be the second most fertile JPL CSI focus mission. Hence the FMI would seem to be a good means of promoting generic CSI technology development.

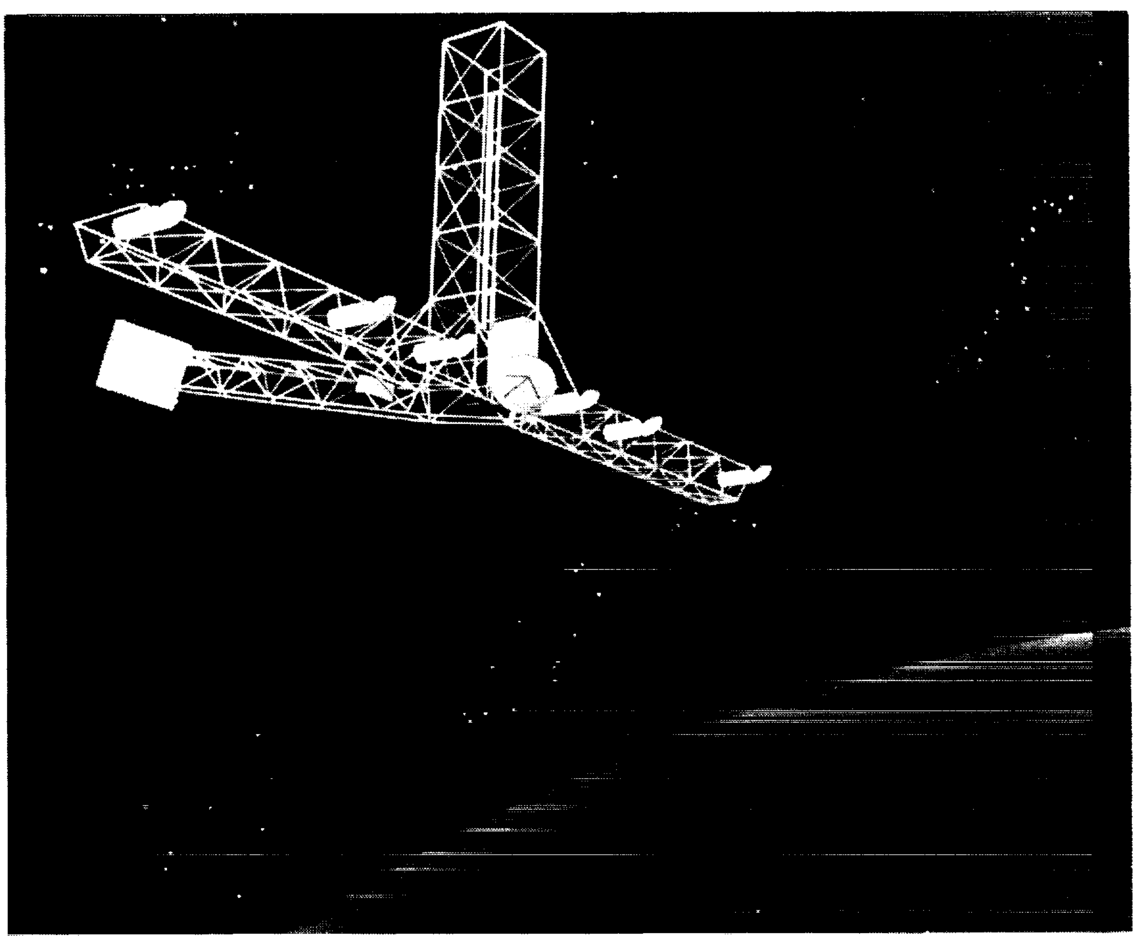
FLIGHT EXPERIMENT	SIZE	OPERATING WAVELENGTH	POSITIONAL ACCURACY	ANGULAR ACCURACY	DISTURBANCE ENVIRONMENT
INTERFERO-METERS	10 to 30 m baseline	0.1 to 1.5 microns (UV to IR)	10^{-9} meter	Optics: 10 milliarcsec Siderostats: 0.1 arcsec	LEO: Drag, Thermal Stresses, Gravity Gradient, Internal
SEGMENTED REFLECTORS	20 m across	30 microns (LDR) 0.5 micron (AST)	5×10^{-7} meter 10^{-8} meter	<.05 arcsec (LDR) <.001 arcsec (AST)	LEO
MULTI-PAYLOAD PLATFORMS	9 to 150 m	Not Applicable	$\sim 10^{-3}$ meter	3 to 5 arcsec	LEO
MPP PAYLOADS	8 to 21.3 m length 1.5 to 2.5 m dia	0.4 to 0.9 micron (Visible)	2×10^{-6} meter to 3×10^{-4} meter	.01 to .50 arcsec for several hours	LEO
LARGE ANTENNAS	5 to 200 m dia	8.3 to 200 mm (K,X,C, and S Bands)	$\sim 10^{-4}$ meter	14 to 430 arcsec	GEO
LARGE MANIPULATOR ARMS	10 to 50 m	Not Applicable	10^{-3} meter	Not Applicable	LEO

THE FOCUS MISSION INTERFEROMETER (FMI)

Shown below is an artist's conception of the FMI in its 750 km orbit around the earth. An optical interferometer is an instrument that utilizes a number of distinct telescopes, each of modest aperture, whose outputs are combined in such a way as to produce an effective aperture equivalent to the largest baseline distance between telescopes. In the case of the FMI, six telescopes are used in an extremely sparse linear array. The telescope outputs are combined in pair-like fashion such that the FMI operates as three distinct two telescope interferometers.

An optical interferometer can be used for high resolution imaging as well as extremely precise astrometry (astrometry is the mapping of stellar positions in the sky). When used for imaging, the FMI's effective baseline of 24 meters would give it roughly 10 times the resolving power of the Hubble Space Telescope. This translates into a resolution of 5 milliarcseconds.

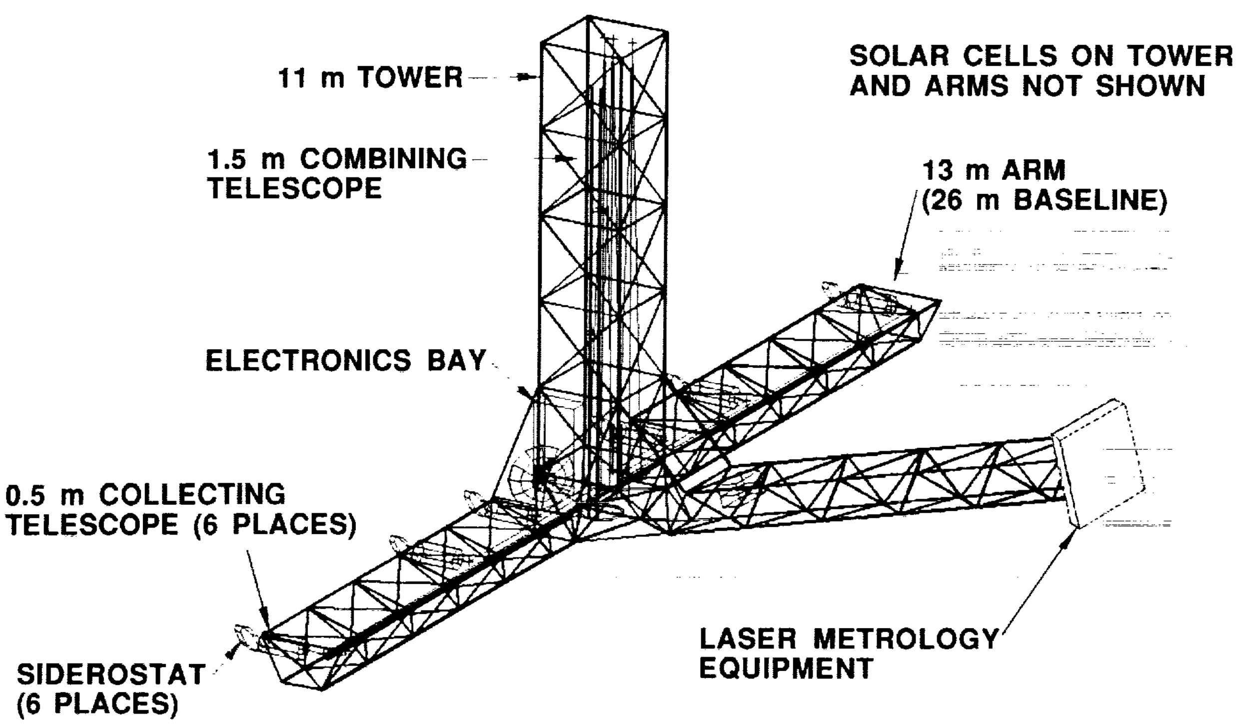
The basic layout of the FMI was inspired by the work of Mike Shao of the Harvard Smithsonian Astrophysical Observatory. Dr. Shao currently has in operation, on Mount Wilson in Southern California, a ground based version of the FMI.



FMI CONFIGURATION

The line rendering below shows the essential features of the FMI. The six 0.5 meter aperture collecting telescopes are arrayed along the FMI's two 13 meter "arms". In front of each telescope is an appropriately sized flat mirror called a siderostat whose function it is to steer stellar photons into the telescope. Each siderostat is articulated in two axes, ± 20 degrees about the axis of the telescope and ± 5 degrees about an axis parallel to the arms. Hence the siderostats can expose the FMI to a 40 by 20 degree field of view without any attitude motion of the overall system. When a pair of siderostats on one of the three interferometers rotates about the axes of its respective collecting telescopes and "looks off to the side", it is effectively reducing the baseline of that interferometer. In this way all baselines intermediate in length between those of the inner and outer interferometers can be synthesized. Combining this effect with rotation of the system around the target line-of-sight allows a filled aperture of diameter equal to the largest baseline to be synthesized. This is in fact the mode in which the FMI would be operated for stellar imaging.

Other FMI features of note are the 11 meter "tower" that houses the combining telescope and the similarly sized laser metrology boom. A very precise laser metrology system is necessary to measure the individual interferometer baselines as well as the internal optical pathlengths through the system.



OPERATIONAL SCENARIO - ASTROMETRY MODE

The mode in which the FMI would be operated for stellar imaging was very briefly described on the preceding page. The operational mode for stellar astrometry is at once more straightforward than for imaging and at the same time places tighter CSI requirements on the FMI. Hence it is described in greater detail here.

The general procedure discussed below is one of acquiring guide stars with the two inner interferometers and then mapping target stars relative to the guide stars within the 20 by 40 degree target field using the outer, highest resolution, interferometer. By proceeding from target field to target field, with the appropriate angular overlap, the entire sky can be mapped. In fact the entire procedure must be accomplished twice: once as described and then again with the baselines rotated by 90 degrees around the tower axis. This is due to the fact that, as is explained in the ensuing pages, the FMI, with its linear interferometric array, is fundamentally a one axis machine capable of measuring angles about only a single axis when in a given orientation.

One of the things, besides the extreme precision, that makes the astrometry mode so challenging for CSI is the timeline on which it is to be accomplished. Target star acquisitions are expected to occur at roughly 40 second intervals and over siderostat slew angles of up to 40 degrees, thus driving structural settling time requirements.

1. **SLEW SYSTEM TO 10° x 40° TARGET FIELD**
2. **ACQUIRE FIRST GUIDE STAR WITH INTERFEROMETERS A, B, & C**
3. **TRUE UP METROLOGY SYSTEM**
4. **ACQUIRE SECOND GUIDE STAR WITH INTERFEROMETER B**
5. **ACQUIRE FIRST TARGET STAR WITH INTERFEROMETER A**
6. **ACQUIRE SECOND TARGET STAR WITH INTERFEROMETER A**
7. **REPEAT FOR N TARGETS WITHIN 20° x 40° TARGET FIELD**
8. **SLEW SYSTEM TO NEXT TARGET FIELD**
9. **REPEAT FOR M TARGET FIELDS**

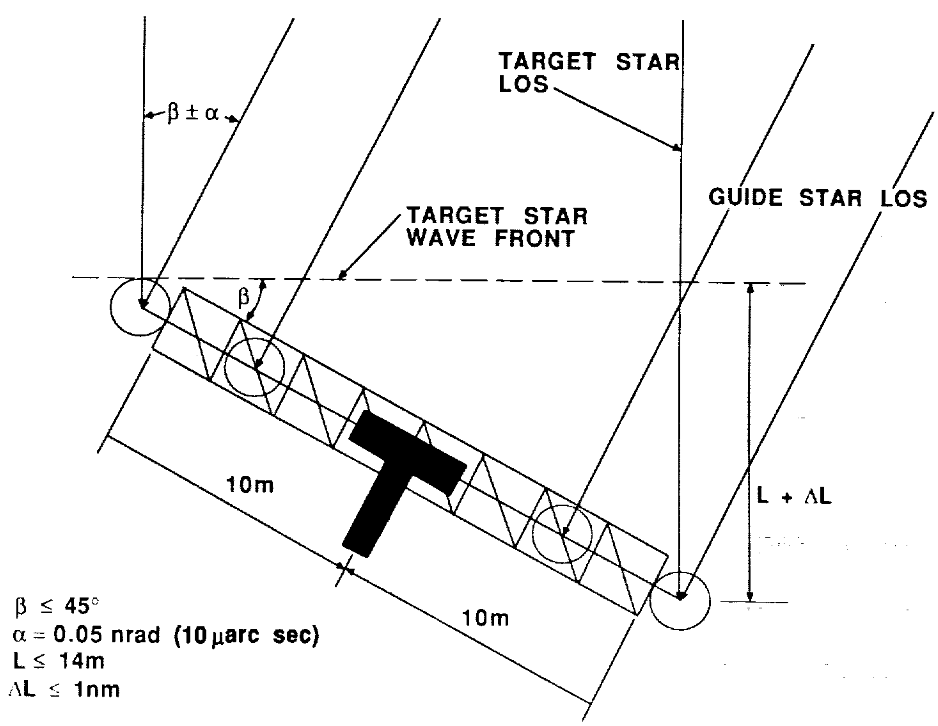
FMI - FUNDAMENTAL ACCURACY REQUIREMENT FOR ASTROMETRY

The figure below, along with the one on the next page, illustrates the way in which an optical interferometer can measure angles between stars for astrometry. For the sake of simplicity, only two interferometers are shown. Each of them is first commanded to lock on to a guide star. For an interferometer, "locking on" means more than angular acquisition of a star by both siderostats. In addition the two wavefronts, one from each collecting telescope, must be combined on the interferometric focal plane where fringes are produced. The object is to track the "zero fringe" which results when the optical pathlengths from the star to the focal plane coming through each side of the interferometer are equal.

Once guide star acquisition has been accomplished, the siderostats of the "science" interferometer (in this case the outer interferometer) are slewed to acquire a target star. If the target star is an angle beta from the guide star, and if the baselines are precisely perpendicular to the guide star line-of-sight, then a differential path length of

L = Baseline * sin(beta)

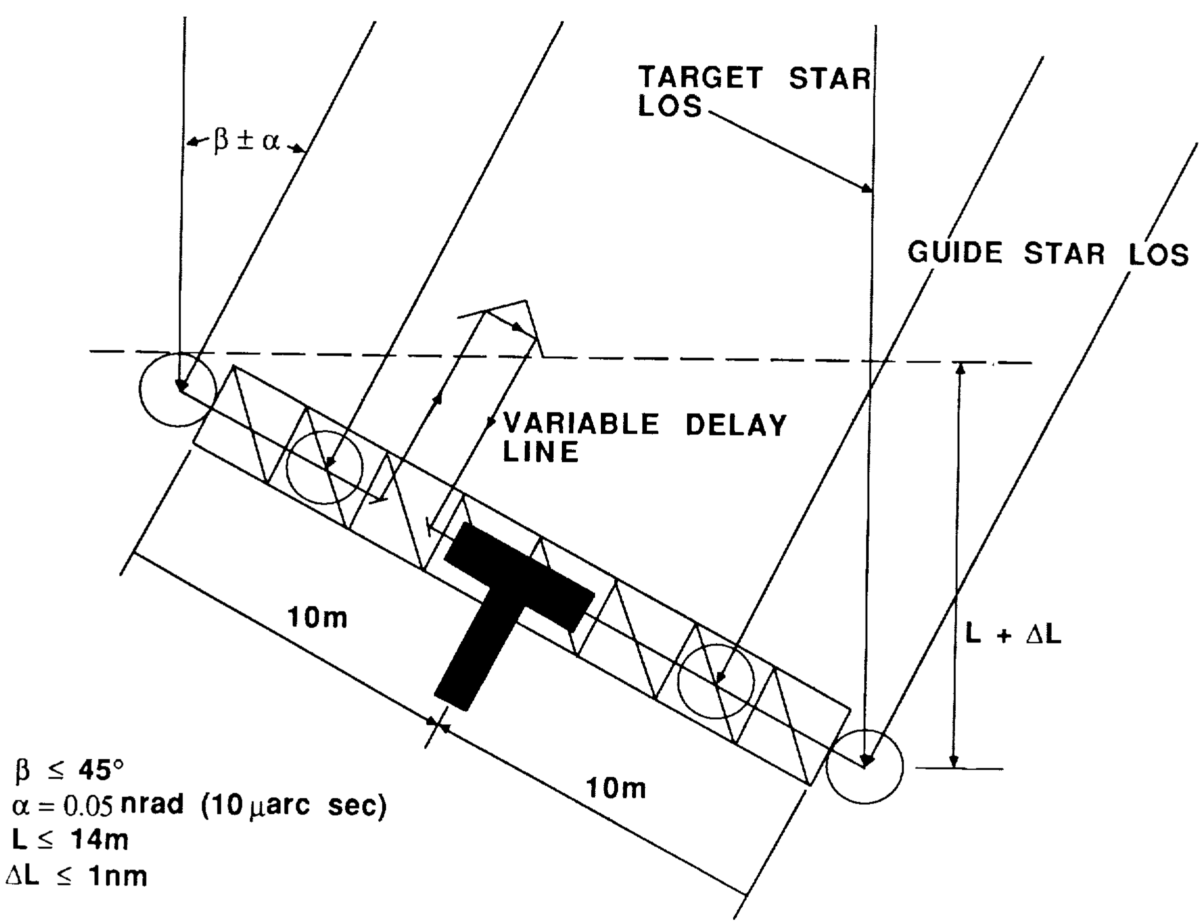
will exist across the science interferometer. The instrument is able to measure the length, L, and in this way the angle, beta, can be derived. The manner in which L is measured is described on the next page. Note that if L is measured to an accuracy of, dL = 1 nm, then the angle beta can be solved to an accuracy of, alpha = dL/Baseline = 10 microarcsecs.



INTERFEROMETRIC PATHLENGTH COMPENSATION

What remains is to describe the manner in which the differential pathlength, L, is measured. This is fairly straightforward. Internal to each interferometer is an optical element, variously known as a "trolley" or a "trombone" or a "delay line", which translates along a track and is capable of changing the optical pathlength along one leg of the interferometer. The position of this delay line is monitored, to nanometer accuracy, by the internal metrology system. Thus when the science interferometer is slewed to the target star and locked onto the target star's zero fringe, the internal metrology system is all the while measuring the distance that the trolley had to move in order to effect zero fringe acquisition. This distance is precisely the differential pathlength, L.

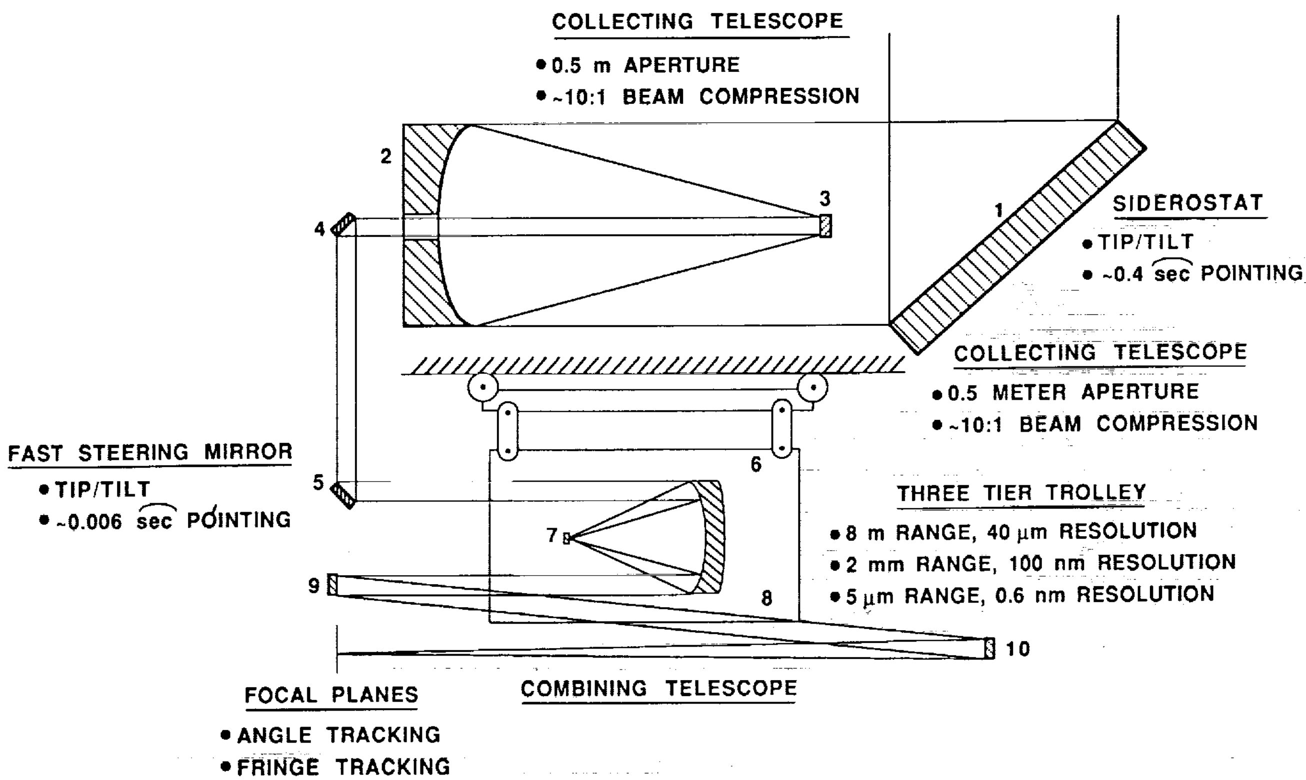
Note that in order to solve the equation (previous page) for beta, it is necessary to know not only L but also the baseline. This is what necessitates the external metrology system mounted on the metrology boom.



SIMPLIFIED FMI OPTICAL SCHEMATIC

A schematic representation of one leg of one of the FMI's interferometers is pictured below. Photons will encounter at least ten optical surfaces before reaching the focal planes, which will put a premium on optical coating technology, particularly if ultraviolet science is a requirement.

Preliminary control requirements on the positioning and articulation of the optical elements are listed. The 6 milliarcsec fast steering mirror spec looks relatively innocuous next to the sub-nanometer requirement on trolley position. Note that the trolley consists of three levels of control: a "boxcar" on a track driven by a timing belt for gross positioning, a voice coil actuated flexure stage for intermediate accuracy, and a piezoelectrically driven vernier mirror for fine control. Although one nanometer positional measurement capability would be necessary to support 10 uarcsec astrometry, it is likely that tolerances on positioning control could be relaxed to the sub 10 nm level.



ON-ORBIT DISTURBANCE SOURCES

Although the FMI will be exposed to the LEO orbital environment, it is expected that the most stressing disturbances to the control system will be generated on board the vehicle itself. In fact nonlinearities and parasitic forces/torques in control system prime movers will likely dominate. Thus far preliminary investigation has shown that reaction wheel imbalance forces, from Hubble Space Telescope class wheels, result in 1 to 2 micron open loop pathlength error response. This response is rather broadband, out to the 50 - 100 Hz region, and hence the higher harmonics can be expected to be beyond the trolley control loops ability to compensate. Some means of structural disturbance suppression would seem to be indicated.

The environmental disturbances all occur at low frequency and so the expectation would normally be that they are easily compensated by the optical positioning/articulation control loops. However, very little is known about the sub-micron regime with which we are dealing. It is quite possible that phenomena such as thermal "snapping" in a joint dominated structure such as the FMI could present the CSI system with a low, but significant, level of background structural vibrations.

- **ORBITAL ENVIRONMENT**
  - **GRAVITY GRADIENT**
  - **THERMAL GRADIENTS**
  - **AERO - DRAG**
- **ON-BOARD ENVIRONMENT**
  - **REACTION WHEELS/CMG's**
  - **SIDEROSTATS**
    - **MOTOR COGGING, RIPPLE, AND IMBALANCE**
    - **BEARING NOISE**
    - **SLEW REACTION TORQUES**
  - **TROMBONES**
    - **NONLINEARITIES**
    - **SLEW REACTION FORCES**
    - **MOTOR AND BEARING NOISE**
  - **TAPE RECORDERS**
    - **START/STOP TRANSIENTS**
    - **MECHANISM NOISE**

CSI STRUCTURAL CONTROL HARDWARE SYSTEM BUILDING BLOCKS

To achieve the levels of optical surface control required by the FMI will require great resourcefulness in the CSI system. We expect to reach deep into the CSI bag of tricks for design solutions. Some of the hardware "tricks" that we are considering are delineated below.

At this point we have yet to make the system and component trades necessary to arrive at a strawman CSI system design. We are confident, however, that the design that emerges will be comprised of a combination of high bandwidth controlled optical elements and active/passive structural control and isolation. Such a design exhibits the essential features of the CSI problem. Hence, at this early stage at least, we are satisfied that we have a focus mission capable of driving generic CSI technology development.

PASSIVE DAMPING OPTIONS

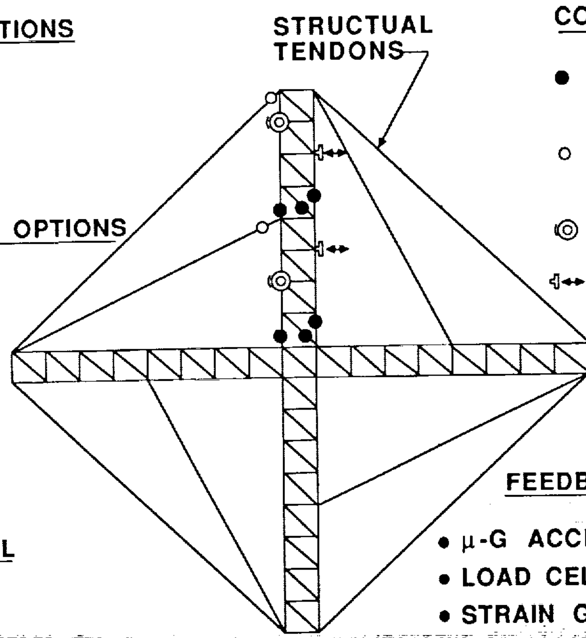
- VISCOELASTIC
- VISCOUS

VIBRATION ISOLATION OPTIONS

- MAGNETIC
- PIEZOELECTRIC
- ELECTRODYNAMIC
- VISCOUS
- ELASTOMERIC

STRUCTURAL CONTROL REQUIREMENTS

300 μm, DC
3μm, 1 Hz
30 nm, 10 Hz
0.3 nm, 100 Hz AND ABOVE
(REPRESENTS ~12 μ-G LEVEL)



CONTROL ACTUATOR OPTIONS

- ● PIEZO/INCH WORM ACTUATORS
- ○ VOICE COIL/SCREW JACK ACTUATORS
- ◎ TORQUE WHEEL ACTUATORS
- PROOF MASS ACTUATORS

FEEDBACK SENSOR OPTIONS

- μ-G ACCELEROMETERS
- LOAD CELL FORCE SENSORS
- STRAIN GAUGE FORCE/DISPL SENSORS
- LIN DISPL VOLT TRANSDCRS
- CAPACITIVE DISPL SENSORS
- LASER METROLOGY DISPL SENSORS
- EDDY CURRENT RATE SENSORS
- ANGLE RATE/ACCELERATION SENSORS

FMI - MAJOR ISSUES

There are several major issues that face the development of the FMI design in the months ahead. The high level CSI system trades first need to be accomplished. These trades will involve determination of the proper mix of vibration compensation, vibration suppression, and vibration isolation for the problem at hand. Sirlin discusses the considerations involved in making these high level trades for multiple payload platform systems in another paper presented at this conference (see Reference).

The metrology system certainly represents a critical area with bearing on the feasibility of the FMI. Since there is virtually no hope of implementing an absolute metrology system with sub-nanometer capability, the realizability of a relative system will be addressed. Such a system will demand an initial calibration of the interferometer baselines, based on stellar observations, before operation can commence. It is important to point out that our interest in metrology lies mainly in establishing the feasibility of using this technology on the FMI. Once this has been established we will focus our attention on CSI related issues like the use of a metrology system in a closed loop setting.

Component level trades and the issue of actuator/sensor placement will be addressed following completion of the system level trades. Plans call for the FMI to be at a preliminary design stage in the May/June 1989 timeframe.

- **SYSTEM TRADES**
  - **VIBRATION COMPENSATION**
    - **HIGH BANDWIDTH OPTICAL ELEMENT CONTROL**
    - **ACTUATOR/SENSOR NONCOLLOCATION**
  - **VIBRATION SUPPRESSION & DISTORTION CORRECTION**
    - **ACTIVE STRUCTURAL CONTROL**
    - **PASSIVE DAMPING**
  - **VIBRATION ISOLATION**
    - **ACTIVE ISOLATORS**
    - **PASSIVE ISOLATORS**
- **METROLOGY SYSTEM**
    - **SUBNANOMETER RELATIVE POSITION MEASUREMENT**
    - **SYSTEM ARCHITECTURE IN A CLOSED-LOOP SETTING**
- **COMPONENT LEVEL TRADES**
    - **ACTUATOR & SENSOR TYPES**
    - **DAMPER TYPES**
    - **ISOLATOR TYPES**
- **ACTUATOR/SENSOR PLACEMENT**

SUMMARY AND CONCLUSIONS

The JPL CSI team is concentrating its efforts on designing the control/structure system for a large spaceborne interferometer. The Focus Mission Interferometer will be carried to a preliminary design level in order to drive CSI technology development requirements in the principal analysis, software, and hardware disciplines and to shape the process of developing the new CSI design methodology within which the disciplines fit.

In addition it is intended that the FMI will serve an on-going purpose as a benchmark u-PCS problem so that the benefits accruing from the new CSI methods and tools can be demonstrated and quantified.

- **JPL's CSI TEAM IS DESIGNING THE CONTROL/STRUCTURE SYSTEM FOR A LARGE OPTICAL INTERFEROMETER (THE FMI)**
- **INITIAL FMI REQUIREMENTS CHALLENGE CSI TECHNOLOGY TO PROVIDE 3 TO 4 ORDERS OF MAGNITUDE RESPONSE REDUCTION**
- **THE FMI DESIGN WILL BE CARRIED TO A PRELIMINARY DESIGN LEVEL IN ORDER TO**
  - **DRIVE REQUIREMENTS ON THE GROUND TEST BED**
  - **DRIVE REQUIREMENTS ON DESIGN/ANALYSIS TOOLS**
  - **DRIVE REQUIREMENTS ON FLIGHT EXPERIMENTS**
  - **SHAPE THE PROCESS OF DEVELOPING THE NEW CSI DESIGN METHODOLOGY**
- **THE FMI DESIGN WILL SERVE AS A BENCHMARK μ-PCS PROBLEM TO DEMONSTRATE CSI METHODS AND TOOLS**

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