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# ORBITING STELLAR INTERFEROMETER: AN OVERVIEW

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## Abstract

The Orbiting Stellar interferometer (0S1) is a concept for a first-generation space interferometer with astrometric and imaging capabilities and is responsive to the recommendations of the Astronomy and Astrophysics Survey Committee for an astrometric interferometry mission, 0S1 is a triple Michelson interferometer with articulating siderostats and optical delay lines. The design uses a 7m maximum baseline and aperture diameters of 33 cm; the targeted astrometric performance is a wide-field accuracy of 5μas for 20-mag objects. The instrument would also be capable of synthesis imaging with a resolution of 10mas. Laser metrology is used to relax structual requirements thereby reducing cost, The currently envisaged flight system fits into an Atlas 11 shroud, for insertion into a 900 km sun-synchronous orbit.

## Introduction

The quest for higher angular resolution, higher sensitivity, and higher accuracy has driven observational astrophysics in all of its wavelength bands since the time of Galileo. At optical wavelengths, this quest has been limited by the Earth's atmosphere. In particular, atmospheric turbulence limits the angular resolution and astrometric accuracy achievable with ground-based instruments. While the application of Compensated-imagiag schemes such as adaptive optics and adaptive optics with laser guide stars, offers great promise for ground-based imaging, the compensation will be limited to narrow fields at wavelengths transmitted by tbc atmosphere. Similarly, there is great promise for high accuracy narrow-angle astrometry from the ground, but fundamental atmospheric limitations remain for wide fields. Thus, besides the fundamental advantage of transparency at all wavelength bands, space provides the ability to conduct wide-field astrometry limited only by photon statistics and instrumental limitations, as well as to image with diffraction-limited resolution over wide fields.

In wide-field astrometry, the state of the art from the ground is 6-10 milliarcsec (mas), limited by the atmosphere. The 111 PPARCOS astrometry satellite accuracy is 2 mas for stars brighter than -10 msg. The possibility of a several order-of-magnitude increase in the accuracy of wide-field astrometry with long-baseline interferometry, and the wide range of science made possible by such a significant increase in capability, led the National Research Council's Astronomy and Astrophysics Survey Committee, chaired by John Bahcall, to recommend an astrometric interferometer mission capable of performing 3 to 30 microarcsecond (p-as) astrometry on objects as faint as magnitude 20 [1]. This mission's goals include improved determination of the cosmic distance scale by making direct parallax measurements of Cepheid variables; measurements of the dynamics of stars within globular clusters and the clusters themselves through parallax and proper motion measurements; and studies of the mass, mass distribution, and dynamics of our galaxy and nearby galaxies.

Orbiting Stellar Interferometer (0S1) is an interferometer concept developed at JPL [2]. It has astrometric as well as imaging goals, and is responsive to the recommendatio ns of the Bachall report. The targeted astrometric performance is a wide-field accuracy of 5μas for 20-mag objects; the targeted imaging performance is a resolution of 1 Omas.

Interferometers have fundamental advantages over telescopes for astrometry. One advantage is in the control of systematic errors. The primary observable for interferometric astrometry is the fringe position or optical delay $d$. This is given as $d = \mathbf{B} \bullet s + c$, where $\mathbf{B}$ is the baseline vector, s is the unit vector to the star, and c is the delay offset. With an interferometer, the key instrument parameters $\mathbf{B}$ and c can be monitored directly, allowing high accuracy over wide fields. Long-baseline interferometers also have a significant advantage in photon-noise-limited accuracy, For imaging, the advantages of interferometry arc primarily economic. For a telescope, angular resolution is proportional to the di ffraction-spot diameter X/D, where $D$ is the telescope diameter; for an interferometer, resolution is proportional to the fringe spacing $\lambda/B$. Thus, an interferometer decouples sensitivity and resolution; for a given amount of collecting area, the interferometer can offer significantly higher angular resolution.

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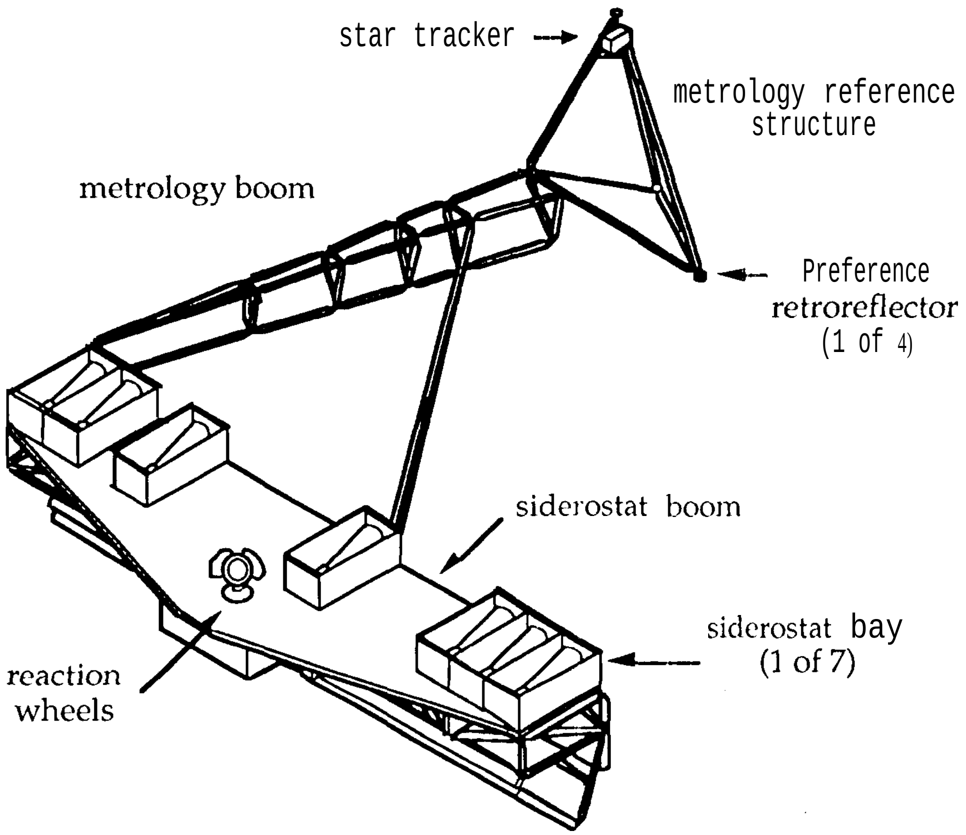

Figure 1 0S1 Flight System

## Science Objectives

0S1 will make important contributions to the studies of the evolution of interacting binary systems, stellar luminosities, trigonometric parallaxes and the cluster-Universe age problem, dynamics of small stellar systems, stellar dynamics of the Galaxy, and astrometry of AGNs.

imaging from space has many advantages including 1) ability to look in the UV where the atmosphere is opaque, 2) lower background for IR observations by eliminating airglow and thermal emission from the atmosphere, 3) a large field of view with a constant point-spread function, and 4) the ability to perform high-dynamic range observations.

0S1 was designed to be capable of very accurate wide angle astrometry. The design features that add redundancy and reduce risk for astrometry provide most of the additions required for imaging. The architecture limits the imaging field to approximately the subaperture diffraction pattern. At 0.5 pm, the resolution of the interferometer for synthesis imaging (0.71/*B*) is 10 mas: in the UV at 0.3 µm the resolution is 6 mas.

## Instrument Description

0S1 is a triple Michelson interferometer with three collinear interferometer baselines arranged on a single structure. Two of these interferometers (guide interferometers) are used to track bright guide stars to provide attitude information, while the third interferometer (the science interferometer) observes the science object. The 0S1 instrument is divided into three major sections: the siderostat boom, the metrology tetrahedron, and the metrology boom. (Figure 1)

The siderostat boom, measuring 7.55 x 1.2x 1.0 meters, houses the seven siderostat bays, starlight optics, delay lines, beam combiners and the internal metrology subsystem. The siderostat bays are spaced to provide the maximum u-v coverage for an imaging operation. All baseline lengths from 0.5 to 7.0 m in increments of 0.5m can be achieved. For astrometric measurements, the longest baseline is used to fringe track on the target star. Two other baselines are used to fringe track on the guide stars.

Starlight is collected by the siderostat mirrors and is compressed from a beam diameter of 0.33 m to 2.5 cm with a two-element Cassegrain. The compressed

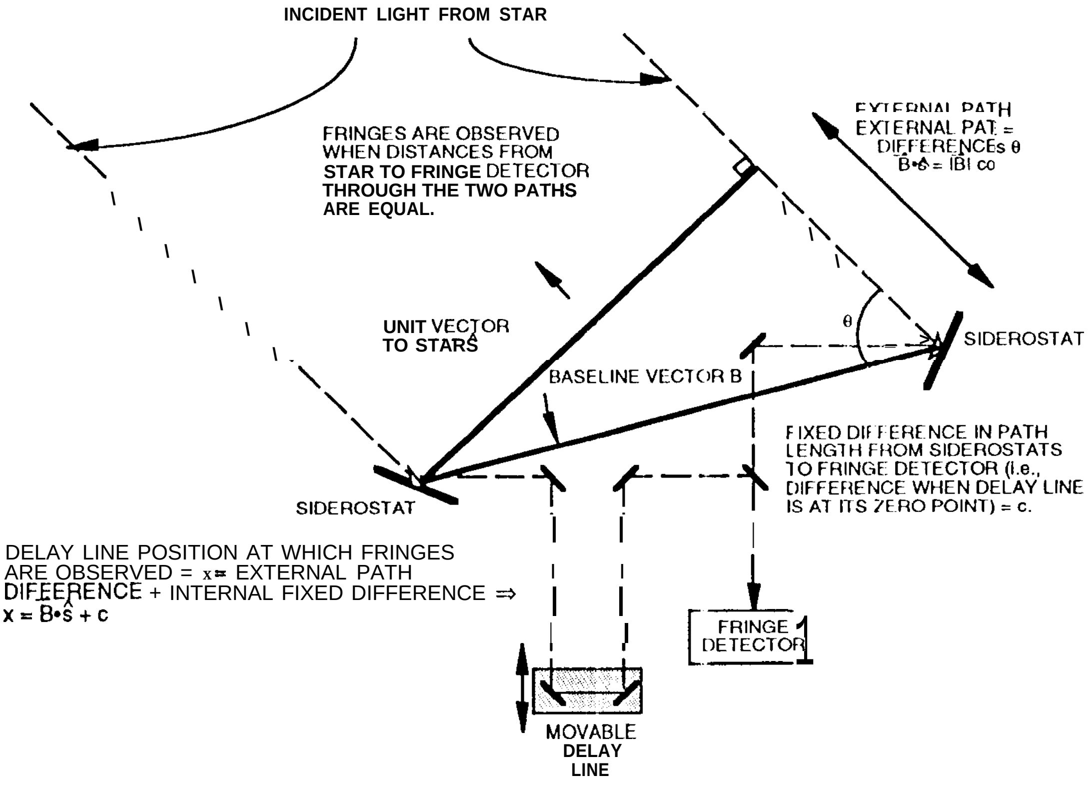

Figure 2 Astrometric Measurements using Interferometry

starlight beam then reflects off the fast steering mirror. This mirror is used to align the angle of the starlight so that beams from the two interferometer arms are parallel at the beam combiner. The starlight then goes to a switching mirror and is reflected to the delay line mirrors. These two sets of mirrors are adjustable so that light from any of the seven siderostats can be routed to any of the delay lines. Two mirrors are needed to guarantee that the light beam is parallel to the direction of delay line travel. There are 8 delay lines: 4 fixed and 4 movable. These are arranged in two columns alternating between fixed and movable types. The light exits the delay line and is reflected into the beam combiners. In order to increase reliability, there are a number of spare components: 1 siderostat bay, 1 beam combiner and 2 delay lines (1 of each type).

The metrology tetrahedron contains the external metrology beam launchers as well as some of the attitude control system hardware (2 star trackers and a gyro unit.) It forms a reference frame which is used to determine the position and motions of the baseline end points. The metrology tetrahedron's base is an equilateral triangle of sides 2.0 m and has a height of 1.75 m. The metrology tetrahedron is located 5.4 meters from the siderostat boom. The metrology boom structure offsets the metrology tetrahedron from the siderostat boom.

For astrometry, the spacecraft will orient itself with the axis containing the siderostats (and thus defining the interferometer baseline vector, B) normal to the line of sight to the region of the sky containing the stars to be measured. With two of the three interferometers locked on reference stars (the pointing being accomplished with the articulated siderostats), the third interferometer will switch among the targets to be observed. For each star, the delay line position at which the fringes are observed will be measured. To measure the two orthogonal coordinates of the stellar positions, the observations will be repeated with the spacecraft rotated 90° about the line of sight. Figure 2 shows how astrometric measurements are made with a single OSI interferometer.

In interferometric synthesis imaging, each baseline length and orientation at which a measurement of a fringe position is made corresponds to a point in the Fourier-transform plane of the spatial brightness distribution of the source. Creating an image requires making measurements throughout enough of the u-v plane to reproduce the interesting features of the source. To do so, OSI will rotate about the line of sight while

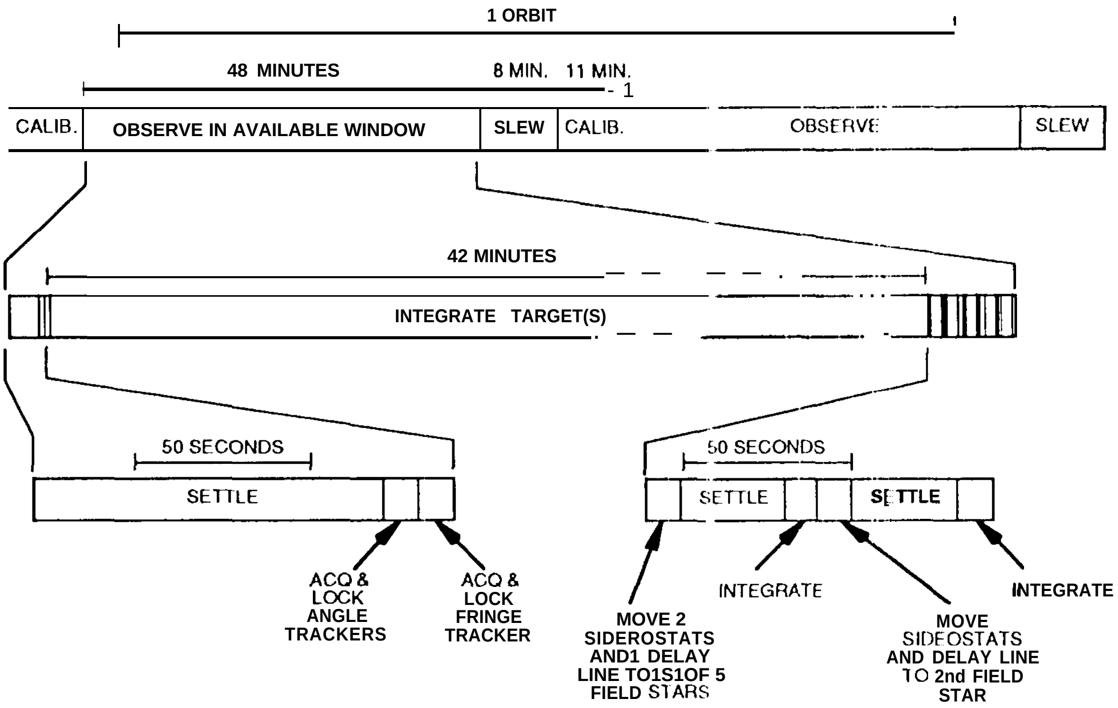

Figure 3 0S1 Observation Timeline

taking fringe measurements. At all times, two interferometers will be locked on guide stars, while the third will be directed at the target. With six siderostats forming the three interferometers, pairings can be made in any combination. The seventh siderostat, included for redundancy for the higher-priority astrometric measurements, allows greater coverage of the u-v plane. After each fringe measurement is made, a new pair of siderostats will view the target, Measurements are made throughout 180° of rotation. (Of course, the rotation may be interrupted by the need to reorient as Earth moves into unfavorable positions, but there is no need to collect the data in one observing session). The rotation and switching among different interferometer baselines will allow coverage throughout the u-v plane. For complex objects, in which more thorough coverage is required, the baseline will be rotated in the plane defined by the line of sight to the target and the baseline vector, and observations will be conducted during one or more 180° rotations with foreshortened baselines.

## Mission Description

The baseline orbit selected for 0S1 is circular and Sun-synchronous. The altitude is 900 km, the inclination is 99.034°, and the period is 102.6 minutes. By synchronizing the orbit to pass over the terminator (a "dawn-dusk" orbit), the spacecraft receives relatively uniform solar illumination both throughout individual orbits as well as throughout the year. Even under worst-case launch vehicle injection errors and orbit decay over five years, the spacecraft will enter Earth's shadow on only 71 days/year, for a maximum of less than 16 minutes per orbit.

The launch vehicle chosen for 0S1 is an Atlas II/Centaur. After withholding reserves, this Atlas has a payload capability to the desired orbit of 3825 kg. This allows a large margin above the estimated spacecraft mass of 2800 kg (which includes contingency).

Tracking will be provided by the 26m stations of the Deep Space Network. At a rate of 5Mbits per second, it will take less than 35 minutes per day to transmit the (worst-case) expected data volume to the ground. The DSN stations will be in view from the selected orbit at least 149 minutes per day, with at least 10 passes of 10 minutes or more uninterrupted contact time.

For a preliminary conceptual design of the observation scenario, the key constraints are on the direction in which the nominal viewing axis may point. The siderostats articulate ± 15° in both azimuth and elevation about this axis. To satisfy thermal constraints on the siderostat mirrors, shades protect the siderostats from direct heating by the Sun and Earth. Given the geometry of the shades, it is required that the Sun not be within 90° of the nominal axis and that the limb of the Earth not be within 30°. It takes about 150 days for all targets in the sky to be visible.

The instrument can maintain a fixed altitude for at least 48 minutes before having to move due to Earth viewing constraints, Part of this observation period will be used for calibration and settling of the spacecraft after a slew; 42 minutes will actually be used for observation of the science target. The time required to slew to the next observation window is 8 minutes. In total, the observation sequence will take 67 minutes and 0S1 will be able to make science measurements 63% of the time. Figure 3 shows the 0S1 observation timeline.

## Spacecraft Description

The 0S1 flight system accommodates a single instrument described previously. The instrument is incorporated into 3 primary structural components (siderostat boom, metrology boom, and metrology structure). The metrology structure and boom arc required to deploy once. They are folded towards the siderostat boom in the slowed launch configuration and deployed with a hinge and mechanism, respectively, once the spacecraft is separated from the launch vehicle.

Due to the stringent requirements on stability of optical path length, every effort was made to make the spacecraft as quiet as possible. For example, the orbit selection allowed for launch-vehicle injection errors and natural orbit decay over a five-year mission thereby eliminating the need for a propulsion system. By eliminating a propulsion system, mechanical disturbances driven by motion of propellant in tanks are eliminated; furthermore, the cost and complexity are reduced, and a potential source of contamination for the optics is removed.

The flight system is 3-axis stabilized. Four reaction wheels, one for redundancy, are located on the siderostat boom near the center of mass and provide the attitude control required of the spacecraft. Passive isolation for the reaction wheels reduces the coupling of their vibrations into the spacecraft, Magnetic torque rods are used to unload the wheels. A fine star tracker and inertial reference unit are mounted on the metrology structure. They are tied to the external metrology system to aid in defining the baseline vector, 11, in inertial space. The star tracker provides 5 arcsec knowledge about the axis of the siderostat boom (roll axis). Knowledge requirements about the other two axes are looser (about 15 arcsec), as the guide interferometers provide that attitude information. This system is capable of providing 10 control about each axis, sufficient to let the internal instrument optics keep any target from moving out of the field of view without moving the large siderostats, and pointing stability less than 6 arcsec/sec. A Sun sensor provides coarse attitude knowledge and is used in safing the spacecraft.

The command and data handling subsystem provides the functions of command and data processing, telemetry data processing, mass data storage, computational support and executive control. It is all solid state, thus eliminating mechanical disturbances caused by tape recorders. The 10 Gbits of storage available is more than enough for all the science and engineering data from 24 hours of astrometry or imaging sequences. Storage of data on board until confirmation of receipt on the ground allows the system to be immune to temporary communications failures. The use of three-dimensional packaging of memory chips reduces the mass, volume, and cost of the data storage.

The telecommunications subsystem will transmit 5 Mbits per second at S-band to the 26-m stations of NASA's Deep Space. Network (DSN). Because of the short range, only 2.5 W of RF transmitted through a low gain antenna is needed to provide adequate link margin. With two antennas, there is no need to change the spacecraft attitude or use an articulating antenna (mechanical disturbances from which could interfere with observations). It will take less than 35 minutes per day to transmit the (worst-case) expected data volume to the ground, and the DSN stations will be in view substantially longer than that. The telecommunications system also includes three GPS receivers for the spacecraft velocity measurements needed to correct for stellar aberration. Velocity uncertainty of 4 mm/sec is budgeted, well within what is capable with the GPS receivers.

The GaAs solar array consists of three panels which form one half of a hexagon and fit into the lower portion of the Atlas 11 shroud. Each panel is 1.8m x 3.6m for a collecting area of 6.48m$^2$. At O degrees sun angle, a panel of this size will produce 1296W (end of life). Each panel at 60 degress sun angle adds 712W (end of life). NiCd batteries are sized to provide the power for the observation times when the arrays are far off-Sun and are used during passes through Earth's shadow.

The structure consists of the two primary booms and the metrology reference structure. The booms are trusses of aluminum struts. With the 0S1 architecture, aluminum was found to be good enough and was selected over graphite epoxy 10 save cost. The bays in which the siderostats and telescopes are housed are graphite epoxy. The siderostat bays and subsystem components mount on an aluminum-honeycomb plate. The metrology boom deploys by pivoting at the end of the siderostat boom, and the metrology structure pivots up to allow it to see the siderostats.

A preliminary thermal analysis indicates that a passive thermal control subsystem consisting of multilayer insulation, thermal control surfaces (paints, films, etc.), thermal conduction control, and passive thermal louvers will meet the mission and system requirements for temperature level and temperature stability.

A mass summary for the flight system is given in Table 1.

Table 1. Flight system mass summary

| COMPONENT | MASS (kg) |
|---|---|
| Interferometer optics | 500 |
| Delay lines | 145 |
| Beam combiner | 80 |
| Laser metrology | 60 |
| Electronics | 75 |
| Instrument subtotal | 860 |
| Instrument Structure | 235 |
| Attitude control | 290 |
| Power/pyro | 160 |
| Command and data | 10 |
| Telecommunications | 10 |
| Onboard GPS | 30 |
| Thermal | 125 |
| Spacecraft Structure | 90 |
| Mechanisms | 50 |
| Cabling | 80 |
| Subsystem subtotal | 1080 |
| Instrument contingency (60%) | 515 |
| Subsystem contingency (30%) | 325 |
| night system total | 2780 |

## Technology Requirements

Optical interferometers have been in use on Earth for a number of years, so the principles and supporting technologies are well understood, Indeed, the Mark 111 interferometer, currently operational on Mt. Wilson [31, has demonstrated the operation of delay lines, laser metrology, and fringe tracking. Nevertheless, improvements are required in the performance of some of the technologies to meet the requirements of 0S1. Development of 0S1 involves a fusion of results of technology work supported by NASA and other agencies in metrology, interferometry, and controls-structures interactions. Other 0S1 subsystems take advantage of hardware that is flight-proven or will be flown in the next few years.

0S1 component technology development needs, in order of priority, are as follows [4,5]:

metrology and starlight detection systems
high fidelity integrated modeling
active delay lines and siderostats
fine pointing and isolation
quiet structures and subsystems
precision deployment
thermally stable optical elements

## Conclusion

The study of 0S1 has identified no insurmountable problems in development of a spacebased optical interferometry capability that will significantly extend the horizons of astrophysics. The design presented here is based on strong heritage and experience gained from the Mark III interferometer, a variety of technologies that are available today or will be proven within the next few years, plus some new technologies which have been assigned a high priority in NASA's technology development planning. 0S1 will be capable of performing a great deal of exciting and important astrophysics and will demonstrate the value of interferometry for follow-on space-based facilities.

## Acknowledgments

Many people have been members of the 0S1 design team over the years and much of the current design described here has been based on their work. In addition to myself, the current team consists of Michael Shao (study scientist), Robert Laskin (study technologist), Mark Colavita, Yekta Gursel, Ram Manvi, James Melody, and Jeffery Yu.

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## References

[1] National Research Council, *The Decade of Discovery in Astronomy and Astrophysics* (National Academy Press, Washington DC, 1991).

[2] M. D. Rayman, ct. al., *Orbiting Stellar Interferometer (0S1): FY92 Study Team Progress Report,* JPL D- 10374,1 December, 1992

[3] Laskin, R. A., "'1'ethnology Requirements Plan for Space Interferometry Missions," *AstroTech 21 Volume I- Missions*

*[4]* R.A. Laskin and J.L. Fanson, "Technology for Space Optical Interferometry," AIAA 95-0825, January 1995

[51 M. Shao, et. al., "The Mark III stellar interferometer," *Astron. Astrophys.*, 193, pp. 357-371, 1988