Space Interferometry Mission: Measuring the Universe

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Abstract

The Space Interferometry Mission (SIM) will be the NASA Origins Program's first space based long baseline interferometric observatory. SIM will use a 10 m Michelson stellar interferometer to provide 4 µas precision absolute position measurements of stars down to 20th magnitude over its 5 yr. mission lifetime. SIM will also provide technology demonstrations of synthesis imaging and interferometric nulling. This paper describes the what, why and how of the SIM mission, including an overall mission & system description, science objectives, general description of how SIM makes its measurements, description of the design concepts now under consideration, operations concept, and supporting technology program.

1. Introduction

The Space Interferometry Mission (SIM) is in response to the Bahcall Report's [1] recommendation for a space based optical interferometer. SIM will continue the revolution in precision astrometry begun by the ESA Hipparcos mission by improving on the Hipparcos results by more than two orders of magnitude, providing a wealth of new astronomical data and serving as a technology pathfinder for future astrophysics missions.

SIM uses a 10-m Michelson stellar interferometer in Earth-trailing solar orbit to provide 4 microarcsecond (µas) precision absolute position measurements of stars down to 20th magnitude. This precision will allow parallax measurements to 10% accuracy at 25 kiloparsec (kpc) and proper motion measurement accuracy of about 2 µas/yr. over its 5 year mission (equivalent to 10 m/s at 1 kpc). In addition, SIM will produce images with a resolution of about 10 milliarcsecond (mas), equivalent to a 10-m diffraction-limited optical aperture. It will also demonstrate interferometric achromatic nulling with suppression of the on-axis starlight to a level of 10^{-4}.

2. SIM Mission/System Overview

The SIM flight segment will be launched in 2005 on a Delta-III class vehicle into a heliocentric Earth-trailing orbit for a 5 yr. mission.

SIM is a cost-capped, as opposed to capability-driven, mission, currently in its Formulation Phase with full scale development slated to begin in the Summer of 2001.
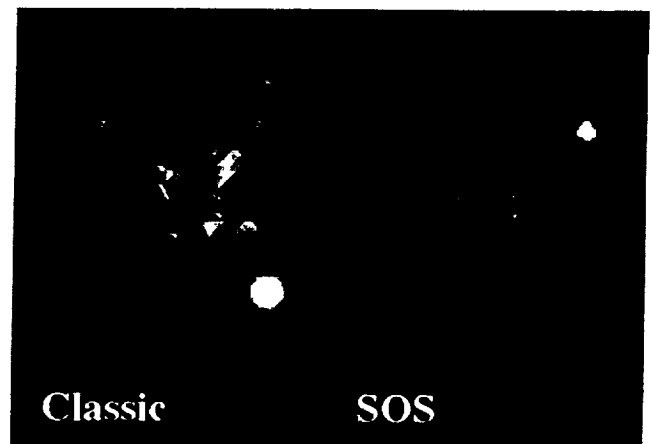

Figure 1 SIM Candidate Designs

The flight segment consists of the spacecraft system and the interferometer instrument system. Two flight segment design concepts (Figure 1) are currently under study, Classic and Son of SIM (SOS). Selection of the final design is expected by November 1999.

The spacecraft system consists of structure, propulsion and avionics subsystems (antenna, telecom, power/pyro, 3 axis attitude control, command and data) provided by SIM's spacecraft industrial partner, TRW in Redondo Beach, CA.

The SIM instrument system, which is being developed as a joint effort between JPL and Lockheed Martin Missiles and Space (LMMS), Sunnyvale, CA, USA, consists of four optical (0.4-1.0 µm) interferometers. One of these is used for making science measurements, two are used to acquire bright guide stars essentially performing as a precision star tracker, and the fourth is a spare.

The ground segment will consist of standard NASA DSN based X-band uplink/downlink and navigation services, separate spacecraft and instrument control centers, and an Interferometry Science Center (ISC) which will be shared with NASA's Keck and DS3 interferometer projects to process interferometer science data.

3. Science Introduction

SIM has four science measurement modes of operation: global astrometry, narrow-angle astrometry, imaging, and nulling.

Global astrometry is the process of measuring the positions of objects of interest by building on a full sky grid of roughly 4000 stars which will form the reference Grid. SIM's requirements are to provide 10 µas single-observation accuracy on objects as dim as 20th magnitude, which will be improved to 4 µas accuracy by the end of mission as knowledge of the astrometric Grid improves. Note that 4 µas yields distances accurate to 10% anywhere in our Galaxy. Figure 2 shows how SIM's astrometric accuracy compares with that of the Hubble Space Telescope (HST) and the Hipparcos mission (left side figure text) and gives some examples of SIM science targets (right side figure text).
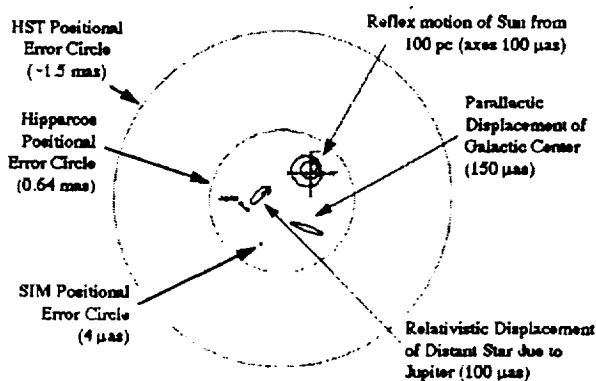

Figure 2 Global Astrometry

The astrometric grid is constructed (Figure 3) by dividing the 4π sky into discrete "tiles" of 15°. Objects within these tiles are measured serially and tied together by the common baseline orientation as determined by the Guide interferometers. Tiles overlap so that stars within the overlap region tie adjacent tiles together. Quasi orthogonal

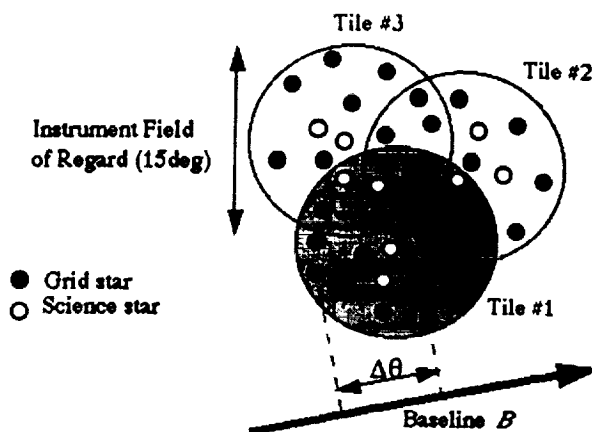baseline orientations are used for each tile to achieve isotropic position errors.

Figure 3 Astrometric Grid

SIM will detect planets around nearby stars by measuring the position displacement of the star due to motion of the star around the star-planet barycenter. The science interferometer chops rapidly between the target star and nearby reference stars within a 1° field. Narrow-angle measurements will achieve 1 µas relative accuracy on objects to 20th magnitude and will achieve 1 µas/yr. proper motion accuracy, which is equivalent to 85 mph at the center of our Galaxy and will make motion due to parallax at 10 parsec (pc) detectable in a few minutes. Figure 4 shows the expected performance of SIM in detecting planetary systems relative to the Keck interferometer.
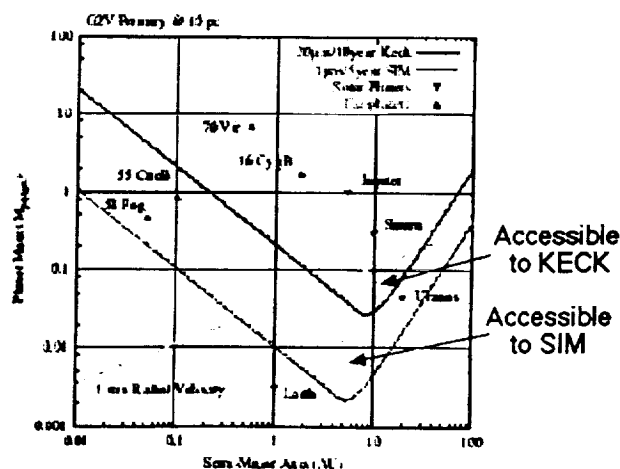

Figure 4 Astrometric Planet Detection

SIM provides rotational synthesis imaging over small fields of view of about 0.3 arsecond (as) to 10 mas accuracy on objects as dim as 20th magnitude. This capability provides high resolution narrow field of view images yielding details which currently elude large

2

telescopes. Figure 5 shows a simulation of SIM's expected imaging capability compared with that of the HST.
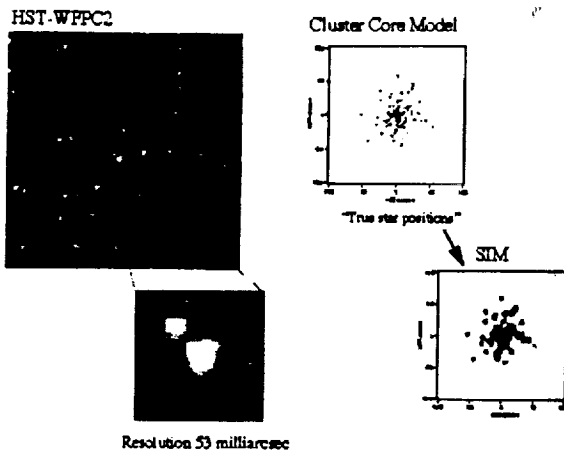

Figure 5 High Resolution Imaging

SIM forms images by aperture synthesis: rotating the baseline around the line of sight to the target and varying the baseline length to 'fill in' the Fourier (u,v) plane with phase and amplitude measurements taken at each orientation. Fourier transforming these amplitudes and phases yields an image. Figure 6 shows the steps needed to build a synthesis image using SIM.
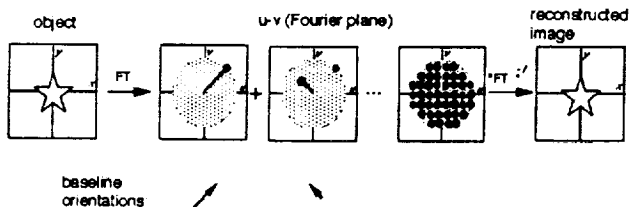

Figure 6 SIM Imaging

As a technology demonstration for future interferometric missions, SIM will demonstrate the achievement of a 10^{-4} depth achromatic interferometric null over about 20% of the visible spectrum. This null will yield a nulling radius of about 0.05 as, with an instantaneous field of view of 0.3 as. Figure 7 shows how SIM's nulling capability will compare with HST's for a star at about 18 pc.

Using the capabilities described above, SIM will be able to contribute exceptionally to a large number of scientific issues. A sample of some of the areas where SIM can contribute includes:

- Frequencies of occurrence of binary stars, brown dwarfs and planetary systems,
- Investigations into stellar structure, composition, and evolution,
- Dynamical evolution of our stellar neighborhood,

- Density of the local interstellar medium,
- Refining the extragalactic distance scale,
- Studying the dynamics of our own and other galaxies,
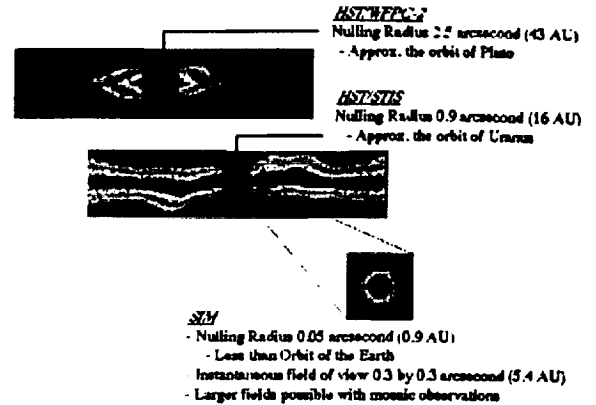- Structure of circumstellar discs

Figure 7 SIM Nulling

4. SIM Design Concepts

Figure 8 illustrates how SIM makes astrometric measurements. Shown are two telescopes separated by a baseline, B, looking at an incoming stellar wavefront arriving at an angle, θ, relative to the baseline. If the angle, θ, is not 90°, light from the stellar wavefront will arrive at telescope-2 before telescope-1, due to the extra external pathlength delay, x. Assuming that the length and orientation of the baseline, B, are known, if the external pathlength delay, x, can be determined, then the angle, θ, can be found by simple trigonometry.
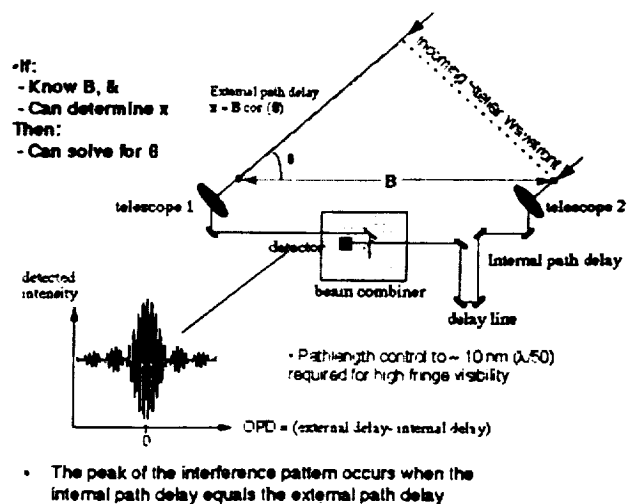

Figure 8 Astrometric Measurement

The external pathlength delay, x, can be determined by inserting an active delay line into the interferometer's

3

internal optical path from telescope 2. Adjusting the length of this active delay line to match the external pathlength delay, x, allows interferometric white light fringes to form on the interferometer detector in the beam combiner. Since the correlation length of visible light from a star is on the order of a few to 10's of microns, depending upon wavelength, fringes will not be seen on the detector at all until the pathlengths are matched to within that optical path difference. Once fringes are found, the active delay line can be adjusted to track the peak in the interference fringe which occurs when the internal path delay from the active delay line equals the external path delay. Internal metrology beams then measure the optical path difference between these two arms of the interferometer providing a direct measurement of the active delay line length, which is in turn a direct measurement of the external pathlength delay.

The two guide interferometers track Grid stars and are used as a precision star tracker to determine the orientation of the instrument baseline and external metrology (see the metrology discussion below) determine the baseline length, completing the information needed for astrometric measurements.

4.1 Son-of-SIM Design

Figure 9 shows a cartoon of the Son-of-SIM (SOS). In this design, there are eight individual telescopes (referred to as beam compressors) with four each mounted in starlight Collector Pods located at both ends of the baseline. The four telescopes in a Collector Pod are oriented so that the center of their line of sight passes through the corner cube fiducial which makes up the end of the common baseline for that Collector Pod, resulting in each telescope looking in a different direction. Each telescope is individually articulatable over a 15° solid angle. Taking, pairwise, corresponding telescopes in each Collector Pod yields four interferometers, all sharing the same baseline, B. The remainder of the optical path for each interferometer is as described for Figure 8.
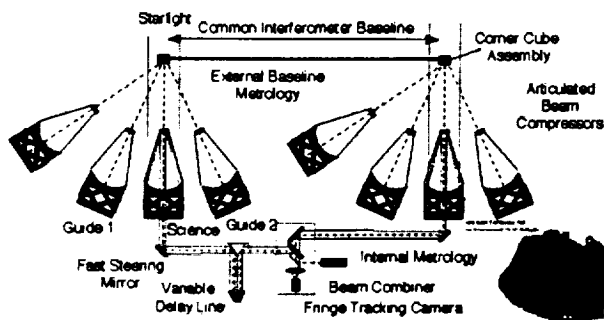

Figure 9 SOS

Baselines of various lengths can be constructed by either physically moving the Collector Pods closer or farther apart or by switching between interferometers with telescopes mounted at different angles, effectively giving a selection of foreshortened baselines. The latter option by itself provides only annular coverage of the (u,v) plane, which would impact imaging science for some targets.

4.2 SIM Classic Design

The SIM Classic design concept (Figure 10) uses seven separate telescopes mounted along the two arms of the instrument. Individual interferometers are formed by taking telescopes pairwise, with the two outermost telescopes normally forming the astrometric science pair and the two other longest remaining possible pairs forming the guide interferometers. For imaging, any pair of telescopes can be taken, allowing 21 different baselines ranging from 0.5m to 10m.
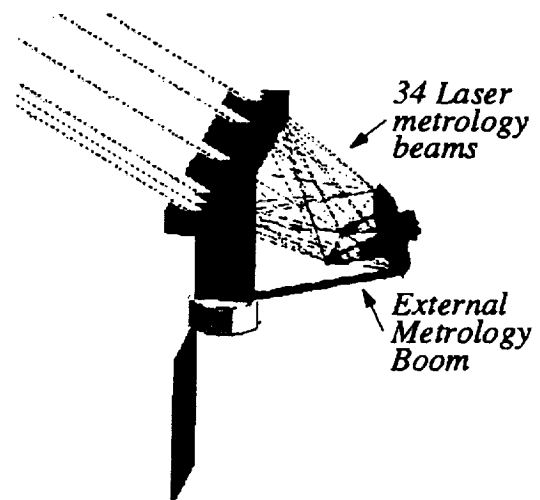

34 Laser metrology beams

External Metrology Boom

Figure 10 SIM Classic

The three interferometers formed from any three pairs of telescopes do not all share a common baseline so baselines must be determined individually and tied together using an external metrology system consisting of 28 laser beams making measurements from an external metrology truss to optical fiducials attached to the face of each telescope's siderostat (which is an articulated flat mirror used to steer light into the telescope). Six additional laser metrology beams are required to tie together four reference fiducials located in the metrology tetrahedron located at the end of the external metrology boom. Internal metrology for Classic is the same as for SOS (except see the Metrology discussion below).

4.3 Starlight Optical Components

The optical paths from both arms of the interferometer must have high optical throughput, maintain wavefront quality and match polarization between interferometer arms in order to provide interferometer fringe visibility on the order of 0.7.

Acquisition of dim objects by the science interferometer must be done open loop. This requires local pointing control for siderostats or beam compressor telescopes. Several schemes are under consideration including an array of lasers to provide alignment locking for the Classic design and local pointing control cameras for each SOS telescope.

Nanometer level pathlength control is provided by three stage active optical delay lines. The three stages are: (1) translation along precision guide rails, (2) voice coil, and (3) piezo crystal stack. Several versions of flight qualifiable active delay lines have been constructed as part of the SIM technology program and have been shown to provide nanometer level pathlength control.

The astrometric beam combiner accepts starlight from each leg of an interferometer and provides fringe tracking and optical alignment information. It also allows launching of the internal metrology beams into each leg of the interferometer in sub-aperture metrology (SAM) options (see the metrology section below). Low noise CCD detectors are being developed for the dispersed fringe tracking cameras within the beam combiner.

Two competing designs of achromatic nulling beam combiners are currently under study. One (under development by JPL and Lockheed Martin) uses rooftop prisms to accomplish the phase reversal between the two arms of the interferometer. Using this approach, the JPL team has demonstrated an interferometric null of 10^{-4} in the lab using laser light. The second design, under development at the University of Arizona, uses phase inversion at a beamsplitter.

4.4 Metrology

Picometer class metrology is required to determine interferometer baseline lengths (external metrology) and optical path differences within the instrument (internal metrology). External metrology for both designs use heterodyne laser gauges to measure the distance between optical corner cubes (fiducials). Two approaches are currently under development for internal metrology: sub-aperture metrology (SAM) and full-aperture metrology (FAM).

SAM uses pencil laser beams launched from the beam combiner and going out to corner cube fiducials located either at the apex of the SOS Collector Pods or on the face

of the Classic siderostat mirrors and returning to the heterodyne gauge. The infrared laser beam passes down only the center 5 mm of the optical train and is thus subject to errors in sensing the starlight optical path resulting from distortions of the optics which are not sensed by the metrology beams. Internal SAM is applicable to both SIM design approaches.

FAM uses a dispersed laser source at the apex of each SOS Collector Pod to fully illuminate all collector telescopes. Each collector telescope will have a grating on the mirror surface to collimate the FAM laser beam so that it follows the same optical path as the starlight. Analysis to date indicates that FAM may provide much better performance, but is applicable only to SOS and may be more difficult to implement.

4.5 Precision Structure

SIM requires a dynamically quiet, thermally stable, accurately deployable structure. Deployment accuracy and thermal stability, while not simple to achieve, appear to be within current state of the art. Most open issues involving the precision structure revolve around dynamics, specifically reaction wheel disturbance attenuation and thermally induced microdynamics.

The SIM structure will use Graphite Fiber Reinforced Polymer (GFRP) with surface treatment to achieve a sufficiently low temperature coefficient (10^{-7}/°C).

4.6 Modeling

Ground testing of the SIM instrument at full performance levels may not be possible (solutions have eluded the design team so far). This results in modeling being of central importance in the design and verification of SIM. Models must predict instrument on-orbit performance based upon calibrations from partial ground system tests.

SIM uses three classes of models: (1) dynamics performance models, (2) thermo-optical models, and (3) opto-metrology performance models, all of which are being developed using a JPL-developed toolbox called Integrated Modeling of Optical Systems (IMOS) which integrates structural, thermal, optics and controls into an integrated environment. SIM's models will be validated on technology testbeds currently under development as part of the SIM project.

4.7 Spacecraft Engineering Systems

The spacecraft (S/C) engineering bus, to be developed by TRW, is essentially identical for the two SIM design

concepts. It provides standard engineering services to the SIM instrument, including:
- Power: Gimbaled 2 kW solar array,
- Telecom: X-band with high and low gain antennas,
- Command and data handling:
  • Onboard data storage: 48 GB solid state recorder,
  • Uplink command/sequence decoding and distribution,
  • Downlink of science and engineering data,
- Coarse attitude determination and control:
  • 2-axis coarse digital sun sensors,
  • High precision star tracker,
  • 4 reaction wheels,
  • Monoprop for reaction wheel unloading.

Spacecraft subsystems are expected to use available off the shelf elements whenever possible to reduce non-recurring costs.

4.8 Launch and Mission Operations

Launch vehicle and launch operations will be handled by the Kennedy Space Center under supervision of TRW.

Uplink, downlink, and Navigation services will be provided by NASA's Deep Space Network and JPL's Multimission Ground Data System, Multimission Command System, and Multimission Navigation Facility. Spacecraft engineering system operations will be conducted from an existing TRW facility. Instrument operations and science data reduction will be done at the Interferometry Science Center (ISC) at the California Institute of Technology, Pasadena, CA, USA.

Launch will be from the Eastern Test Range at the Cape Canaveral Air Station in 2005 into an Earth Trailing Solar Orbit with a drift away rate of approximately 0.1 AU/yr., reaching a maximum communication distance of 95 million kilometers after 5 years. S/C velocity will be determined from ground based ranging and doppler data to an accuracy of 4 mm/sec or better to allow correction for stellar abberation. Science observations will be made at any angle greater than 50° from the Sun to avoid thermal impact from Sun illumination of instrument optics. Data will be returned at a data rate of 0.4 Mbits/sec during the roughly 20 hrs/wk required to gather ranging and doppler data.

5. Technology Program

SIM has technology challenges in three areas: (1) nanometer level control and stabilization of optical elements on a lightweight flexible structure, (2) subnanometer level sensing of optical element relative positions over 10 meters of separation, and (3) overall instrument complexity and the implication for

interferometer integration & test and autonomous on-orbit operation.

Figure 11 shows how mission objectives map into measurement requirements, engineering implications, and key technologies.

SIM has a well funded technology program broadly addressing all of the key technologies.
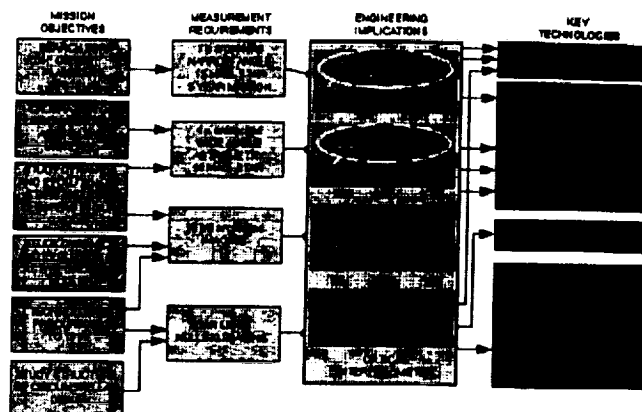

Figure 11 Technology Drivers

6. Summary

This paper has briefly described the what, why and how of the SIM project, a key element of the National Aeronautics and Space Administration's (NASA) Origins program. A wealth of additional information is available on all aspects of the SIM project via the SIM web site [2].

7. Acknowledgments

8. References

[1] Decade of Discovery in Astronomy and Astrophysics, Astronomy and Astrophysics Survey Committee Board on Physics and Astronomy, John Bachall, Chariman, National Academy Press, 1991, ISBN 0-309-04381-6

[2] Further information regarding all topics discussed in this paper can be obtained at the SIM web site at URL: http://sim.jpl.nasa.gov