THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Division on Engineering and Physical Sciences
Board on Physics and Astronomy – Space Studies Board

500 Fifth Street, NW
Washington, DC 20001
Phone: 202 334 3520
Fax: 202 334 3701
E-mail: caa@nas.edu
www.nas.edu/ssb/caa1.html

September 12, 2002

Dr. Edward Weiler
Associate Administrator for Space Science
NASA Headquarters
300 E Street, SW
Washington, DC 20546

Dear Dr. Weiler:

This letter responds to your request (attachment 1) that the Committee on Astronomy and Astrophysics (CAA; see attachment 2 for membership roster), a joint committee of the Space Studies Board and the Board on Physics and Astronomy, review the redesigned Space Interferometry Mission (SIM) to assess how its current scientific capabilities compare with what was originally envisioned by the 1991 Astronomy and Astrophysics Survey Committee (AASC) report[1] and later reaffirmed by the 2001 AASC report.[2] The CAA met in Washington, D.C., on May 1-2, 2002, was briefed by the Jet Propulsion Laboratory (JPL) project team on the redesigned SIM (see attachment 3), and undertook a review of the redesigned mission's scientific capabilities.[3]

SIM (originally AIM, the Astrometric Interferometry Mission) was prioritized in the 1991 AASC report as the fourth-ranked space program of moderate class. The science goals specified in the 1991 report were ". . . definitive searches for planets around stars as far away as 500 light-years through the wobbles of the parent star, trigonometric determination of distances throughout the galaxy, and the study of the mass distributions of nearby galaxies from stellar orbits" (p. 85). The report defined the wide-angle astrometric precision necessary for AIM to achieve the specified scientific goals: "The mission requirement would be to measure positions of widely separated objects to a visual magnitude of 20 with a precision of 30 millionths of an arcsecond; a more challenging goal would be to measure positions with a precision of 3 millionths of an arcsecond" (p. 85). The report also noted AIM's technology demonstration potential for future space interferometry missions.

In the intervening decade, the discovery of extrasolar planets opened up an entirely new and exciting scientific field, providing the impetus for a more ambitious narrow-angle astrometry capability on SIM that would allow the detection of planets with masses as low as a few times that of Earth. As presented to the 2001 AASC by the JPL project team during the AASC's deliberations in 1999, SIM would have had a capability for wide-angle astrometry (10 microarcseconds requirement;

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[1] Astronomy and Astrophysics Survey Committee, National Research Council. 1991. *The Decade of Discovery in Astronomy and Astrophysics* (Washington, D.C.: National Academy Press).
[2] Astronomy and Astrophysics Survey Committee, National Research Council. 2001. *Astronomy and Astrophysics in the New Millennium* (Washington, D.C.: National Academy Press).
[3] The CAA was not asked for, nor did it attempt to conduct, a technical assessment of the redesigned mission concept; however, two outside experts in interferometry (David Mozurkewich, Naval Research Laboratory, and Roger Angel, University of Arizona) were invited to the meeting to provide independent technical expertise during public discussions of the redesigned mission. The CAA was also briefed on the conclusions of a 2001 NASA external review board report (available at http://sim.jpl.nasa.gov/library/SIM_ERB.pdf) by Harold McAlister, Georgia State University.

4 microarcseconds goal) and for narrow-angle astrometry (3 microarcseconds requirement; 1 microarcsecond goal), an astrometry magnitude limit of 20, full synthesis imaging plane coverage from 1 to 10 meters, and nulling capability (the last two being precursor technology demonstrations for TPF, the Terrestrial Planet Finder, which was one of the recommended new major missions in the 2001 report). As the scientific capabilities were enhanced, and as the technical understanding of the mission matured, the estimated mission cost increased so that the mission graduated from the astronomy surveys' moderate mission category (with an estimated mission cost of ~$250 million in FY1990 dollars) to the major mission category (with an estimated mission cost of ~$1,000 million in FY2000 dollars).

The 2001 AASC report reaffirmed the recommendation of the 1991 AASC by endorsing the completion of SIM, although the 2001 report did not explicitly mention the increased estimated cost of SIM, which had the effect of moving it from the decadal surveys' moderate-mission category to the major-mission category. The scientific capabilities explicitly called for by the 2001 AASC were ". . . [enabling] the discovery of planets much more similar to Earth in mass and orbit than those detectable now, and . . . [permitting] astronomers to survey the Milky Way Galaxy 1,000 times more accurately than is possible now" (p. 20). The report emphasized the "particular attraction" of the dual capability of the new SIM, noting that this capability would enable ". . . both narrow-angle astrometry for detecting planets and wide-angle astrometry for mapping the structure of the Milky Way and other nearby galaxies" (p. 111). The report of the 2001 AASC's Panel on Ultraviolet, Optical, and Infrared Astronomy from Space (UVOIR Panel),[4] which contains more detailed and explicit statements about SIM and its scientific goals than those included in the main AASC report, stressed that "the primary scientific objective of the SIM mission is ultrahigh-accuracy astrometry" (p. 337). SIM's capabilities for making distance measurements of "1 percent accuracy to distances of several kiloparsecs and of 10 percent accuracy throughout the Galaxy" would address the astrophysical goals of "providing a firm foundation for the understanding of stellar astrophysics . . . [making] luminosity determinations for key classes of stars . . . [to] reduce the calibration uncertainties in the cosmological distance scale . . . [and refining] our understanding of galactic structure, and in particular the structure of the Galactic halo, thus tracing the distribution of dark matter" (p. 338). The UVOIR Panel stated that "[s]earching for planets near stars in the solar neighborhood is the most ambitious of SIM's goals . . . [because the search] should generate a preliminary survey of the local planetary population and a more extensive survey of the Jovian-mass planets . . . and . . . [thereby] not leave any ambiguity about the masses of extrasolar planets" (p. 338).

To contain rising costs, NASA's Office of Space Science directed in October 2000 that SIM be redesigned. The simpler (shared-baseline) design selected in May 2001—precisely one year after the recommendations of the AASC were made public—omits the nulling and synthesis imaging intended as technology demonstrations for the future Terrestrial Planet Finder mission, thus lowering SIM's estimated cost and significantly reducing the technical risk. Loss of synthesis imaging translates to a loss of SIM's capability to study certain high-surface-brightness structures, a capability that would have permitted, for example, measurement of the rotation of the inner parts of galaxies and the diameters of supernova remnants. Loss of nulling translates to loss of SIM's so-called "nulling-imaging" capability that would have enabled the study of objects with a large dynamic range in brightness such as astrophysical processes occurring near a star, for example, winds of Wolf-Rayet stars, circumstellar dust disks of main sequence stars, and disks of young stellar objects. These imaging and nulling studies are interesting in their own right, but they are not integral to the core astronomical goals described in the 1991 and 2001 AASC reports, such as, for example, mapping of galactic structure, calibration of the cosmological distance scale, and detection of extrasolar planets.

At the May 1, 2002, CAA meeting, the SIM project team from JPL reported that current component performance suggests the project's ability to meet the 2001 UVOIR Panel report's stated wide-angle requirement of 10 microarcseconds and to exceed the goal (3.2 microarcseconds, compared to

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[4] Panel on Ultraviolet, Optical, and Infrared Astronomy from Space, Astronomy and Astrophysics Survey Committee, National Research Council. 2001. *Astronomy and Astrophysics in the New Millennium: Panel Reports*, pp. 327-374 (Washington, D.C.: National Academy Press).

the goal of 4 microarcseconds), making it possible for SIM to address the fundamental wide-angle astrometric science goals emphasized by the UVOIR Panel and the 1991 and 2001 AASC reports. SIM's predicted narrow-angle accuracy performance will meet the UVOIR Panel report's recommended requirement of 3 microarcseconds and is within a factor of two of the performance goal (1.7 microarcseconds, compared to the goal of 1 microarcsecond). Table 1 summarizes the key AASC and corresponding JPL expected mission parameters. SIM's predicted narrow-angle capability will allow the detection of planets with masses five times that of Earth out to a distance of 10 parsecs. Progress toward the narrow-angle performance goal is continuing, and additional improvement in narrow-angle precision will lead to greater capability in an area where the SIM contribution will be unique: the measurement of masses and orbits for extrasolar planets with masses a few times that of Earth. However, the CAA notes that the size of the sample of such planets that SIM will detect and accurately characterize is very uncertain.

Table 1 Key SIM Parameters Defined by AASC Reports and JPL's SIM Project Team

Concept	Wide-angle Astrometry		Narrow-angle Astrometry				
	Requirement (μs)	Goal (μs)	Requirement (μs)	Goal (μs)	Magnitude Limit (V)	Nulling?	Synthesis Imaging?
1991 AASC (AIM)	30	3	–	–	20	No	No
2001 AASC (SIM)	10	4	3	1	20	Yes	Full UV plane from 1 to 10 m
2002 JPL redesign plan	30	4	3	1	20	No	10-m baseline only (plus rotation)
Reported current performance	3.2		1.7				

The CAA was pleased to hear the JPL team's report that excellent progress has been made in meeting SIM's technical goals. The committee concludes that the core astronomical capabilities motivating the original recommendation for SIM in the 1991 AASC report, and the enhanced astronomical and planet-finding capabilities endorsed by the 2001 AASC report, have been preserved in the current rescope. The CAA reaffirms the scientific excitement of the 2001 AASC for the important new planet-finding narrow-angle science capability of SIM. Nevertheless, the CAA is concerned by the JPL redesign plan's stated wide-angle accuracy requirement of 30 microarcseconds—which was the level recommended by the 1991 AASC but not by the 2001 AASC. The 2001 recommendation is the benchmark to which a redesigned SIM should be compared. Accordingly, the CAA reaffirms the following statement made in the 2001 UVOIR Panel report: "The majority of exciting astrophysical goals already pose a challenge under the floor requirements currently proposed: 3 microarcseconds for narrow-angle astrometry and 10 microarcseconds for wide-angle astrometry. Relaxing these floor requirements might eliminate large fractions of the important science. If SIM is unable to meet these requirements within its presently planned budget and schedule, it should be reevaluated by the scientific community to determine if it should remain a high priority as a major mission" (p. 338). Specifically, the CAA notes that not meeting the wide-angle astrometry requirement recommended by the 2001 AASC report would preclude the ability to accurately measure the distances to, and ages of, globular clusters, and to pursue almost all of the fundamental galactic structure science, such as the accurate measurement of the distance from Earth to the center of the galaxy, the shape of the galaxy's outer rotation curve, and other basic properties of the Milky Way.

In conclusion, the CAA finds that the scientific capabilities (based on the current component analysis) of the redesigned SIM meet the core capabilities originally envisioned by the 1991 AASC report and reaffirmed by the 2001 AASC report. In making this assessment, the CAA compared the reported astrometric performance of the redesigned SIM with the performance requirements and goals stated in the report of the 2001 AASC's UVOIR Panel, and not with the less exacting wide-angle requirement level stated in the decade-old 1991 AASC report as was apparently expected by the JPL project team based on its May 2002 presentation to the CAA. This distinction should not matter in practice since (1) the JPL team reported that the wide- and narrow-angle capabilities are coupled in such a way that the wide-angle requirement/goal will be met on the road to meeting the more demanding narrow-angle requirement/goal, and (2) the JPL team reported an expected performance better even than the performance goal accuracy recommended by the 2001 AASC. Nevertheless, if the developing SIM project fails at some future time to meet the 2001 AASC performance requirements, it should be reevaluated by the scientific community to determine if it should remain a high-priority astronomy and astrophysics mission.

The CAA notes that it did not conduct a thorough assessment of the impact of current and future ground- and space-based astrometry missions on the science enabled by SIM, so no discussion of these other capabilities is included in this letter. In addition, while the current assessment has focused on an evaluation of the extent to which the mission can still meet the scientific objectives considered by the 1991 AASC and assumed by the 2001 AASC, the CAA did not address the question of whether the redesigned SIM would be given high ranked-priority in the context of the major missions recommended by the 2001 AASC report. As a result, neither a previous decadal survey committee nor the CAA has ever explicitly priority-ranked SIM against other major (as opposed to moderate-cost) astronomy and astrophysics missions. Finally, since the CAA conducted a scientific, not a technical, assessment of the mission, the committee expects that the SIM project will continue to be peer reviewed by non-advocate panels—as is standard NASA practice.

Sincerely,

/s/

John H. McElroy, *Chair*
Space Studies Board

/s/

John P. Huchra, *Chair*
Board on Physics and Astronomy

Attachments:

1–Letter of request from E. Weiler to J. McElroy
2–Membership roster of the CAA as of May 2002
3–Presentation to CAA by SIM Project Office at JPL

cc: Wendy L. Freedman, Co-chair, CAA
Richard M. McCray, Co-chair, CAA
Joel R. Parriott, Study Director, CAA
Joseph K. Alexander, Director, Space Studies Board
Donald C. Shapero, Director, Board on Physics and Astronomy

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

Reply to Attn of: SZ

March 18, 2002

Dr. John H. McElroy, Chair
Space Studies Board
National Research Council
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Dr. McElroy:

I am requesting that the Committee on Astronomy and Astrophysics (CAA) provide an updated assessment of the Space Interferometry Mission (SIM).

Since the last time SIM was presented to the CAA in May of 2000, and since the decadal report of 1990, SIM has simplified its architecture and has reduced the scope of the technical demonstration goals of the mission. This was done to meet a cost cap established by the Office of Space Science (OSS) and to reduce programmatic risks. OSS believes the important science, which was the original motivation for SIM, has been preserved.

SIM hopes to be ready to enter the second half of formulation, during which the design and capabilities will become definitive, later this year. At that time, OSS needs to decide if SIM is ready to enter its definition phase.

We would like the CAA to conduct a review of the redesigned SIM mission and make an assessment as to its current scientific goals as compared to what was originally envisioned by the 1990 Decadal Review and as reaffirmed by the 2000 Decadal Review. It would be convenient to have the results of this review by August 2002, as input to the OSS strategic plan and the OSS decision whether SIM is ready to enter the definition phase.

If you have any programmatic questions regarding SIM, you may contact Lia LaPiana at 202-358-0346, the SIM Program Executive.

Cordially,

Edward J. Weiler
Associate Administrator for
Space Science

BOARD ON PHYSICS AND ASTRONOMY • SPACE STUDIES BOARD
COMMITTEE ON ASTRONOMY AND ASTROPHYSICS
MEMBERSHIP LIST
July 31, 2001

BPA CO-CHAIR

WENDY L. FREEDMAN 6/04
Observatories of the Carnegie Institute
813 Santa Barbara Street
Pasadena, CA 91101-1292
626/304-0204
Fax: 626/795-8136
Wendy@ociw.edu

SSB CO-CHAIR

RICHARD A. McCRAY 6/03
JILA
University of Colorado
Boulder, CO 80309-0440
303/492-7835
Fax: 303/492-5235
dick@jila.colorado.edu

STUDY DIRECTOR

JOEL PARRIOTT
National Research Council
2101 Constitution Avenue, NW
Washington, DC 20418
202/334-3520
Fax: 202/334-3701
jparriot@nas.edu
Fedex Address
2001 Wisconsin Avenue, NW
Washington, DC 20007

* * * * * * * * * * * * * * *

Lars Bildsten 6/04
University of California, Santa Barbara
Institute for Theoretical Physics
Kohn Hall
Santa Barbara, CA 93106
805/893-3979
Fax: 805/893-2431
bildsten@itp.ucsb.edu

John E. Carlstrom 6/04
University of Chicago
Department of Astronomy & Astrophysics
5640 S. Ellis Avenue
Chicago, IL 60637
773/834-0269
Fax: 773/702-6645
jc@hyde.uchicago.edu

Roger A. Chevalier 6/02
Department of Astronomy
P.O. Box 3818
University of Virginia
Charlottesville, VA 22903
434/924-7494
Fax: 434/924-3104
rac5x@virginia.edu
Fedex Address
530 McCormick Road

Richard S. Ellis 6/04
California Institute of Technology
Astronomy Department –MS 102-24
Pasadena, CA 91125
626/395-2598
Fax: 626/568-9352
rse@astro.caltech.edu

Andrea Ghez 6/03
Division of Astronomy and Astrophysics
8935 Mathematical Sciences Building
University of California at Los Angeles
Los Angeles, CA 90095-1562
310/206-0420
Fax: 310/206-2096
ghez@astro.ucla.edu

Alyssa Goodman 6/03
Harvard-Smithsonian Center for Astrophysics
MS 42
60 Garden Street
Cambridge, MA 02138
617/495-9278
Fax: 617/495 7345
agoodman@cfa.harvard.edu

Richard F. Mushotzky 6/02
Astrophysicist
Laboratory for High Energy Astrophysics
Code 662
NASA Goddard Space Flight Center
Greenbelt, MD 20771
301/286-7579
Fax: 301/286-1684
mushotzky@lheavx.gsfc.nasa.gov
or richard@xray-s-gsfc.nasa.gov

Philip Nicholson 6/03
Department of Astronomy
418 Space Science Building
Cornell University
Ithaca, NY 14853-6801
607/255-8543
Fax: 607/255-5907
nicholso@astrosun.tn.cornell.edu

Frazer N. Owen 6/04
National Radio Astronomy Observatory
Array Operations Center
P.O. Box O
Socorro, NM 87801
505/835-7304
Fax: 505/835-7027
fowen@pilabo.aoc.nrao.edu

Judith L. Pipher 6/03
Department of Physics and Astronomy
Bausch & Lomb Hall
University of Rochester
P.O. Box 270171
600 Wilson Boulevard
Rochester, NY 14627-0171
716/275-4402
Fax: 716/275-8527
jlpipher@boris.pas.rochester.edu

Paul Steinhardt 6/03
Department of Physics
Jadwin Hall
Princeton University
Princeton, NJ 08544-0708
609/258-1509
Fax: 609/258-6853
steinh@princeton.edu

Space Interferometry Mission

SIM

A NASA Origins Mission

Science History, Overview of SIM
Space Interferometry Mission

M. Shao

Project Scientist

PROJECT OVERVIEW

- **Salient Features**
  - 3 collinear Michelson Stellar Interferometers
  - 10 meter baseline
  - Visible wavelength
  - Launch Vehicle: Space Shuttle or EELV
  - Earth-trailing solar orbit
  - 5 year mission life with 10 year goal
  - SIM is a JPL, Caltech, Lockheed Martin, TRW, and SIM Science Team partnership

- **Science**
  - Perform a search for other planetary systems by surveying 2000 nearby and young stars for astrometric signatures of planetary companions
  - Survey a sample of 200 nearby stars for orbiting planets down to terrestrial-type masses
  - Improve best current catalog of star positions by >100x and extend to fainter stars to allow extension of stellar knowledge to include our entire galaxy and QSO's.
  - Study dynamics and evolution of stars and star clusters in our galaxy to understand how our galaxy was formed and how it will evolve.
  - Calibrate luminosities of important stars and cosmological distance indicators to improve our understanding of stellar processes and to measure precise distances in the distant universe

Historical Summary

Space Interferometry Mission

SIM

- SIM was recommended in the 1990 decadal survey report as AIM, an astrometric interferometry mission
- From the early 1990's to ~ 1997 technology development at a low level.
- In FY 1998, NASA started Phase A funding for SIM.
- In 2000 to reduce the apparent cost growth of the mission NASA requested JPL to rescope the SIM mission.
- NAS request (letter from Weiler to McElroy)
  - SIM science capability as perceived in 1990
  - SIM science capability as planned in 1999
  - SIM science capability as currently planned 2002

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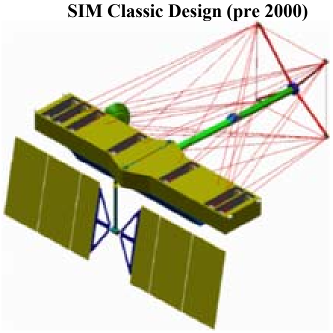
Redesigned SIM, SIMPLER and MORE ROBUST

Space Interferometry Mission

SIM

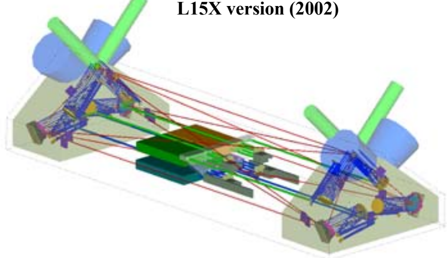
SIM Classic Design (pre 2000)



- 36 external metrology beams

- 9m deployed boom (for external metrology)
- 7 siderostats/telescopes 1m to 10m baseline
- Beam switchyard to combine any 2 telescopes
- 4 astrometric beam combiners, 1 nulling combiner

SIM Shared Baseline Design L15X version (2002)



- 15 external metrology beams (simpler because they're not deployed)
- No deployed boom
- 4 siderostats (8 telescopes)
  - 10m baseline only, for science
- No Beam switchyard
- No nulling beam combiner

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SIM Science 1990, 1999, 2002

Space Interferometry Mission

SIM

A NASA Origins Mission

- 1990 Bahcall Report
  - *"The mission requirement would be to measure positions of widely separated objects to a visual magnitude of 20 with a precision of 30 millions of an arcsecond;, a more challenging goal would be to measure positions with a precision of 3 millions of an arcsecond."*
  - Science listed in the report, planets, parallax throughout the galaxy, mass distributions of nearby galaxies from stellar orbits
  - *"AIM (SIM) would demonstrate the technology required for future space interferometry missions".*
- 1999 SIM (Before rescoping activities)
  - Wide angle astrometry 30 µas requirement 4 µas goal
  - Narrow angle astrometry 3 µas requirement 1 µas goal
  - Astrometry mag limit 20 mag
  - Imaging full uv plane coverage from 1m to 10m
  - Nulling < 10^{-4} visible null, same path and tip/tilt control as for 10^{-6} null at 10um

SIM 2002 Science Capability

Space Interferometry Mission

SIM

A NASA Origins Mission

- 2002 SIM (After Rescoping)
  - Wide angle astrometry 30 µas requirement 4 µas goal
  - Narrow angle astrometry 3 µas requirement 1 µas goal
  - Astrometry mag limit 20 mag
  - Imaging uv plane coverage only a 10m baseline, (plus rotation)
    - Sufficient for crowded field astrometry of a few point sources, not sufficient for targets with significant complexity.
  - Nulling removed from SIM.
    - Adequate testing possible with laboratory testbeds, prior to its removal, nulling system was demonstrated to < 0.0001 in white light, (transient null in laser light to 10^{-6})

SIM Science Team Selected in 2000

Space Interferometry Mission

SIM

A NASA Origins Mission

Key Science Projects

Names	Institutions	Topic
Dr, Geoffrey Marcy	University of California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL (science team chair)	Extrasolar Planets
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Clusters Ages
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	Raytheon ITSS Corporation	Dynamic Observations of Galaxies
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects
Dr. Ann Wehrle	NASA/JPL	Active Galactic Nuclei

Mission Scientists

Dr. Guy Worthey	Washington State	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	University of California, San Diego	Data Scientist
Dr. Stuart Shaklan	JPL	Instrument Scientist
Dr. Shrinivas Kulkarni	California Institute of Technology	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Institute	Imaging and Nulling Scientist (crowded fields)

Astrometric Planet Detection
What's Measured?

Space Interferometry Mission

SIM

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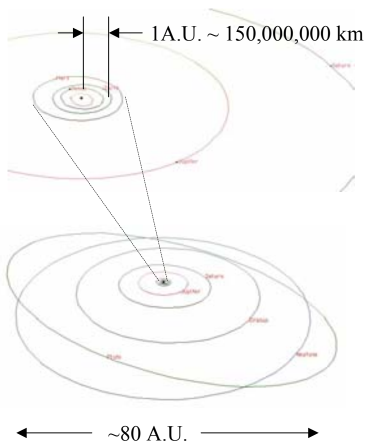


Astrometry can measure all of the orbital parameters of all planets.

Orbit parameter	Planet Property
Mass	atmosphere?
Semimajor axis	temperature
Eccentricity	variation of temp
Orbit Inclination	Coplanar planets?
Period	

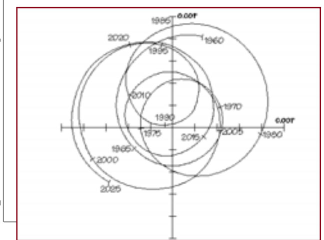
Basic mission is 5 years, with an additional 5 year extended mission, which will help characterize planets with longer periods.

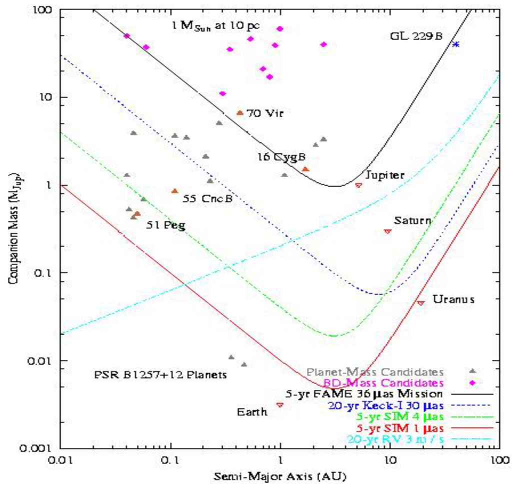
Sun's reflex motion (Jupiter) ~500 μas
Sun's motion from the Earth ~0.3 μas

Astrometric Planet Detection

Space Interferometry Mission

SIM





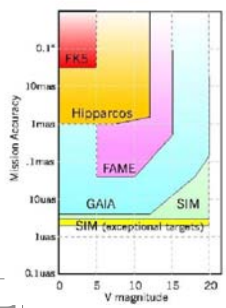
A NASA Origins Mission

Detection Limits
SIM: 1 µas over 5 years (mission lifetime)
Keck Interferometer: 20 µas over 10 years

Planet Detection Comparison

Space Interferometry Mission

SIM



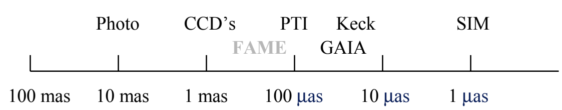
Global Astrometry comparison does not illustrative the true difference between SIM and other Space Astrometry Missions

(Other astrometry mission(s) are scanning spacecraft.)

SIM is a pointed spacecraft and in the area of planet detection SIM is orders of magnitude more sensitive than other planned future astrometry missions

SIM Planet detection program ~ 50 measurements (x,y) over a 5 yr period (10 yrs if extended mission is approved) single measurement accuracy ~ 1 µas, equivalent mission accuracy is ~0.15 µas.

GAIA mission accuracy is 4 µas, data can be split into 50 measurements, each accurate to **~28 µas**, (vs **1 µas** for SIM)



A NASA Origins Mission

SIM Science Summary
SIM Planet Science

- The SIM planet science program has 3 components.
- Achieves the goal of searching ~250 nearby stars for terrestrial planets, in its **Deep Search** at (1 µas).
  - **SIM will characterize targets for Terrestrial Planet Finder**
- Achieves the goal of searching ~ 2000 stars in a **Broad Survey** at lower but still extremely high accuracy (4 µas) to study planetary systems throughout this part of the galaxy.
  - **If planets are found via other means (direct imaging in visible or IR using TPF), SIM can determine masses a factor of ~3 smaller than survey mode limit since orbital parameters are known**
- Achieves the goal of studying the birth of planetary systems around **Young Stars** so we can understand how planetary systems evolve.
  - Do multiple Jupiters form and only a few or none survive during the birth of a star/planetary system?
  - Is orbital migration caused primarily by Planet-Planet interaction or by Disk-planet interaction?
  - **Suitable information for young stars cannot be obtained from radial velocity studies due to effects of rotation and stellar active** (starspots limit survey to Jupiter masses)

Space Interferometry Mission SIM

SIM Preserves General Astrophysics Goals of AIM

- Two NAS decadal reviews have endorsed the fundamental astrophysics enabled by wide-angle astrometry
- 7 of 10 SIM Key projects are not aimed at finding exo-planets.
- This represents ~ 50% of the time allocated so far
- While not making up for the loss of FAME's survey of 10^7 stars, SIM can capture many of the key science goals of FAME
  - Distance scale (Cepheid and RR Lyrae stars)
  - Stellar properties and evolution through precise mass measurements
  - Dynamics of Milky Way
- SIM goes beyond FAME by enabling astrometric measurements of nearby galaxies at V=16-20 mag and of AGN

The Distance Scale and Stellar Evolution

SIM Space Interferometry Mission

- Distances to galactic cepheids to a Kpc can be measured to <1% accuracy, a key element in the cosmic distance scale
- The utility of RR Lyrae stars as a distance indicator depends on knowing their properties as a function of metallicity
  - SIM will observe RR Lyrae stars in globular clusters spanning -2.0 < [Fe/H] < -0.7
- SIM will permit 1% mass measurements over the whole range of stellar types, including
  - Black holes, OB stars to brown dwarfs, and white dwarfs
  - In addition, by obtaining precision masses for stars in clusters covering a range of ages (1 Myr -- 5 Gyr) and a variety of metallicities, SIM will directly probe stellar evolution as a function of age as well as mass.

A NASA Origins Mission

Dynamics of Galaxies

SIM Space Interferometry Mission

- SIM will investigate the dynamics of the Milky Way
  - Determine 3-D gravitational potential of Milky Way via precise distances to stars, globular clusters and satellite galaxies to ~100 kpc
- SIM will investigate galaxy dynamics based on true orbit determinations
  - SIM will measure proper motions of 30 Local Group and other nearby galaxies (50 µas/yr) from observations of individual V=16 ~ 20 mag stars
  - Results will include dark matter distribution, merger history, mutual influence of groups

A NASA Origins Mission

Active Galaxies and Fundamental Physics

Space Interferometry Mission SIM

- SIM astrometry at different colors will distinguish between various jet and disk models of AGN
  - SIM can detect the orbital motions of two merging AGN (OJ287?)
- SIM will use astrometry and photometry of micro-lensing events to determine physical properties of lensing stars
- Comparison of inertial frames
  - By comparing SIM (ecliptic inertial frame) and radio (QSO rest frame) positions of the white-dwarf/pulsar binary, PSR J1012+5307, SIM will test the linkage between these different reference frames
- SIM in a 1AU solar orbit, is subject the solar gravitational deflection of starlight everywhere it looks. The sum total data set can be used to solve for the PPN parameter gamma to ~ 1e-5.

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Science Team Preparatory Activities

Space Interferometry Mission SIM

- Two areas of preparatory science
  - Project directed preparatory science (Grid star selection, and RV observations)
    - Global least squares grid solutions (invert very large matrices)
  - Science team activities (10 Key projects and 5 mission scientists have been selected)
- Preparatory science activities have started
  - Target selection
  - Ref star selection (needed for planet programs)
  - Supporting ground based observations
    - RV survey of candidate grid stars, have led to the discovery of the first planet around a K giant star. (previous RV surveys were of FGK (M) dwarfs only)
    - RV surveys play a significant role in preparing for SIM, (finding binaries for stellar mass studies, avoiding binaries for planetary/grid/ref star selection)
  - Science extraction from SIM data
    - Model multiple planetary orbits
    - Model mass distribution in the galaxy
    - Model mass distribution between galaxies
  - Instrument calibration/data analysis (and observation planning)

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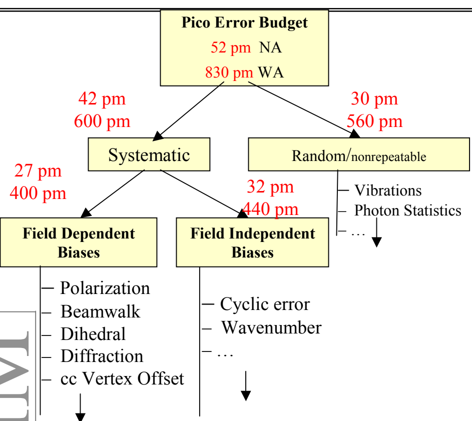
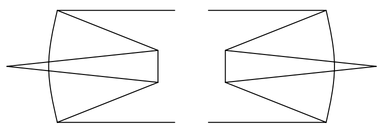
Calibration, Analysis, and Observation Planning,

- 1 µas (5 picoradian) means the total error for narrow angle measurement is 50 picometers, λ/10,000 for a 10m baseline. No mechanical structure is this accurate or even this stable. (1/2 angstrom over 10m). No optical surface is this accurate.
- SIM achieves 1 µas accuracy through a combination of
  - Metrology (measures changes in the optical bench)
  - Calibration (to remove biases due to imperfect optics)
  - Chopping (to reduce stability requirements to 30~60 sec)
- This is an activity that is currently pursued by instrument developers on the project but will eventually include several members of the science team.
- Calibration is the key element of converting repeatable and precise measurements into accurate measurements.
  - We have a preliminary plan for how we will calibrate SIM. (Flight article)
  - We have a test plan to verify the calibration of SIM.

Calibration, Testing, and Science Analysis





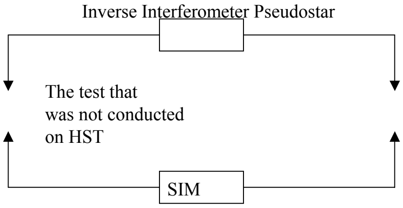
Pseudo Star

If the same null lens (incorrect spherical aberration) is used to test both the test article **and** pseudo star, an end to end test will measure twice the spherical aberration in the null lens.

Test Article

An end to end TEST does **NOT** need a perfect pseudo star to identify a serious flaw in the fabrication and testing of the test article

Inverse Interferometer Pseudostar



Ground based verification of SIM follows this same basic idea.

Summary

- The basic science, microarcsec astrometry, for SIM has remain unchanged from 1990 to 2002. While the loss of imaging and nulling is regrettable, the core science for SIM is intact and is as compelling today as it was in 1990.
- The demise of FAME and slips in the schedule for GAIA make SIM the only astrometry mission currently underway to build on the revolution pioneered by Hipparcos
- SIM is closely aligned with NASA's long term goals of finding and characterizing terrestrial planets, culminating with the flight of the Terrestrial Planet Finder (TPF)
- The science team has started the long lead time observations needed prior to launch.

Space Interferometry Mission
SIM
A NASA Origins Mission

Backup Science Viewgraphs

Knowledge and Ignorance of Extrasolar Planets

Space Interferometry Mission
SIM

- **What we know**
  - Giant-Planet occurrence is high: ~7%
  - Mass distribution extends below Saturn mass
  - Eccentric orbits are common: scattering?
  - Several multiple systems of giant planets are known

- **What we *don't* know**
  - Existence of terrestrial planets
  - Planetary system architecture
    - Coplanarity of orbits, eccentricities
  - Mass distribution
    - Only astrometry measures the *mass* of a planet unambiguously
  - Low-mass planets in 'habitable zone' ?

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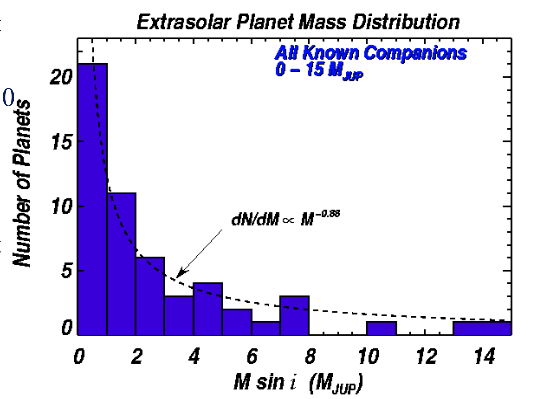
Deep Search for Terrestrial Planets

Space Interferometry Mission
SIM

- Sample of ~ 250 of the nearest stars
- Focus on F, G, K stars within 10 pc
- Concentrate on the habitable zone
- Sensitivity limit is ~3 M_e at 10pc
- Requires 1 µas single-measurement accuracy



Marcy, Butler, Fischer, Vogt

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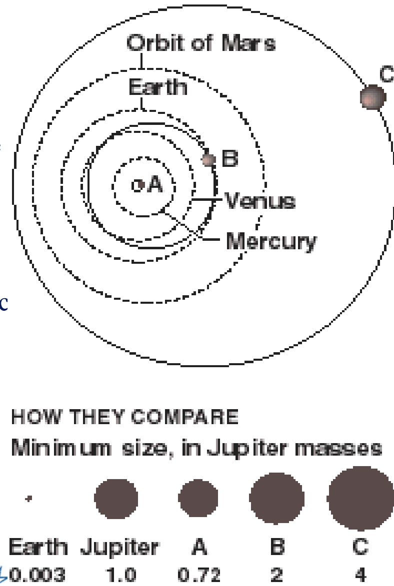
Broad Survey of planetary *systems*

- What is the range of planetary system architectures ?
- Is our solar system normal, or unusual ?
- Are planets more common around solar-type stars ?

- Sample of ~2000 stars, mostly within ~ 25 pc
- Requires 4 μas accuracy



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SIM
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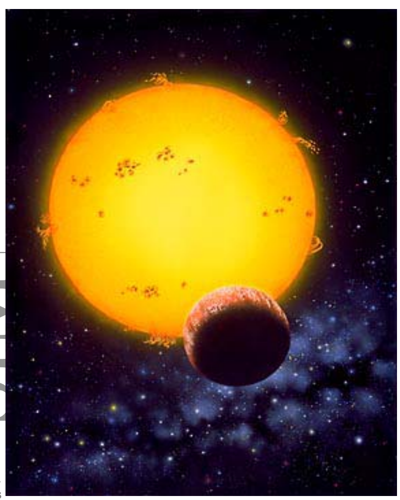
Planets around Young Stars



- How do planetary systems form?
- How do they evolve?
- Do multiple Jupiters form and only a few (or none) survive during the early evolution of a stellar system?
- Is orbital migration caused primarily by planet-planet interaction or by disk-planet interaction?

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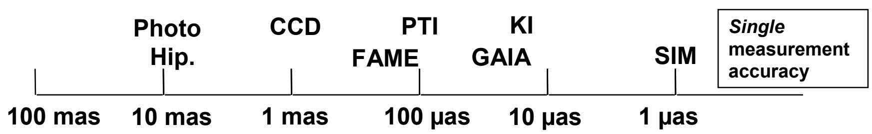
Unique Contributions from SIM

- First terrestrial planets (within 10 pc)
- Masses: Earths & giant planets
- Understand planetary systems
- Planetary ‘demographics’
- Unambiguous masses of known planets
- Reconnaissance for TPF
  - *Specific* targets for TPF around *nearby* stars
  - Target masses known (needed to calculate planet density)

Planet Detection Comparison



- FAME and GAIA are scanners - no control over observations
- SIM is a pointed spacecraft - optimize for planet detection
- SIM is much more sensitive than other planned future astrometry missions
- Accuracy comparison:
  - Hipparcos mission accuracy: 1 mas
  - FAME mission accuracy: 36 µas
  - GAIA mission accuracy: 4 µas
  - SIM equivalent mission accuracy: 0.2 µas
    - In a local reference frame, after 50 measurements

A Broad Range of Astrophysics Highlighted by Two Decadal Survey Reports

Space Interferometry Mission

SIM

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"Rewrite the text books in a wide range of astrophysical topics"

- What is the mass of the largest star ?
- What is the true dependence of the mass-luminosity relation on age ?
- How often are planets found in binary systems ?
- What are the masses of stellar black hole candidates ?
- Where is the emission in 'exotic' binaries ?
- How well can RR Lyraes calibrate the distance scale ?
- What are the distances to LMC, SMC, Andromeda ?
- Are massive stars still forming in the Milky Way halo ?
- What is the 'fossil' history of the Milky Way halo ?
- What is the age limit of the Universe from globular clusters ?

SIM: Exploring the corners of parameter space

Space Interferometry Mission

SIM

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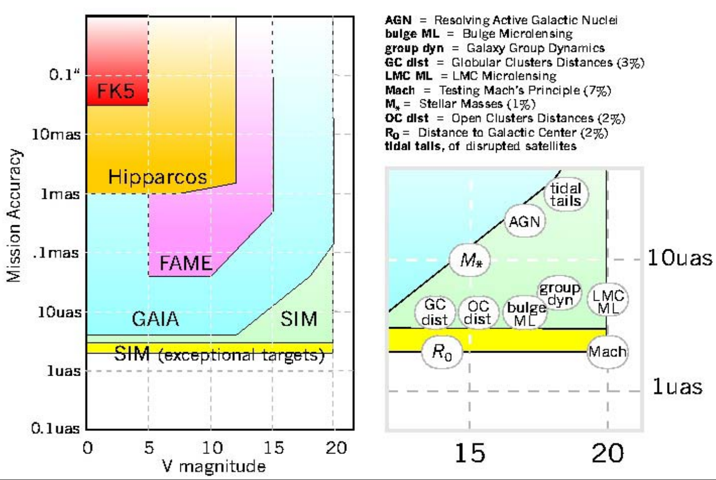
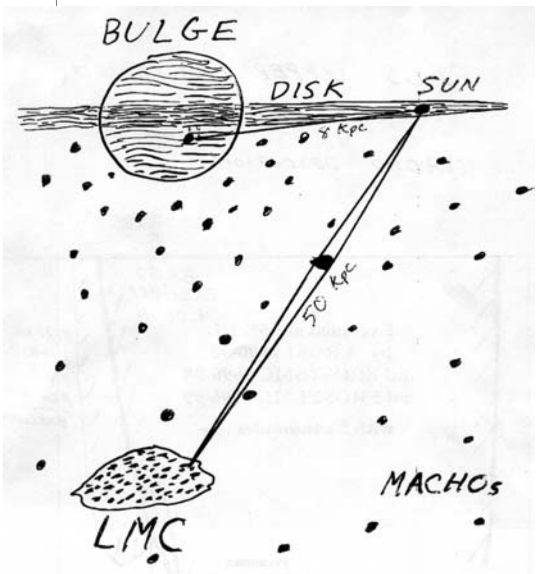
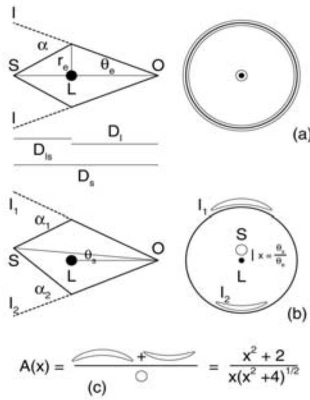
- SIM observe faint objects that FAME cannot observe at all (V >15 mag)
- SIM will operate before launch of GAIA



Galactic Structure from Microlensing



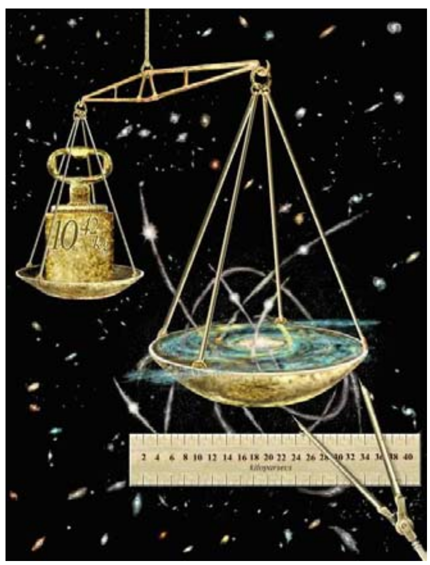


Taking the Measure of the Milky Way

Space Interferometry Mission

SIM

- *Unique, legacy, measurements* of fundamental parameters of the Milky Way:
  - Mass scale → Total mass
  - Distance scale → Size
  - Dynamical scale → Rotation curve



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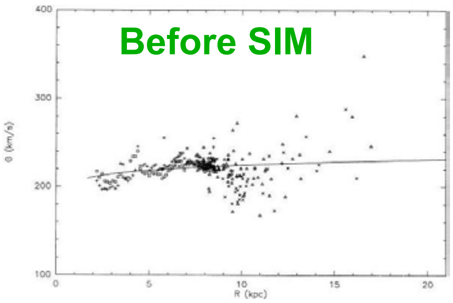
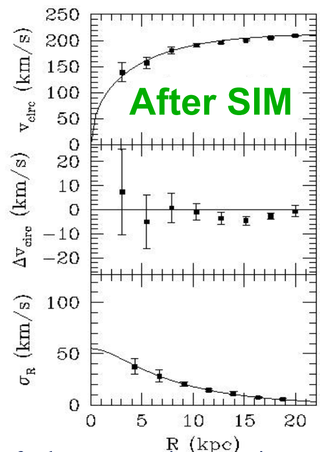
Probe of Inner Galactic Potential

Space Interferometry Mission

SIM





- SIM will measure:
  - Galactic rotation curve across entire disk
  - $V_{circ}(R) \rightarrow$ disk potential to 2-3% $\leq 2R_o$
  - Local mass volume density and column density
  - Amplitude, pattern speed, shape, wavelengths, phase for large non-axisymmetries:
    - bars, warps, spiral arms

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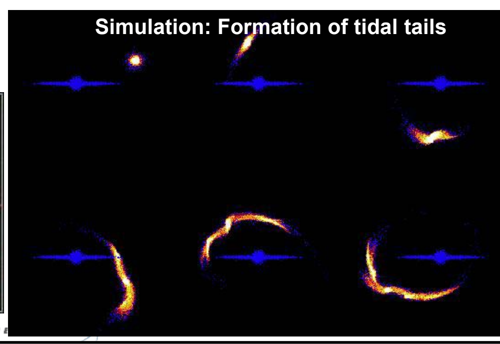
Mass of the Galaxy (Dark Halo)

Space Interferometry Mission

- SIM is the only means for obtaining precision velocities in outer Galaxy
- SIM can determine mass vs. radius to $R > 200$ kpc via complementary methods:
  - **Jeans Equation**: ~1000 random field giants, Galactic globulars and satellite galaxies
  - Stars in **tidal streams** (e.g., Sagittarius): Milky Way potential from true 3-D orbits



Dynamics of the Local Universe

Space Interferometry Mission

SIM

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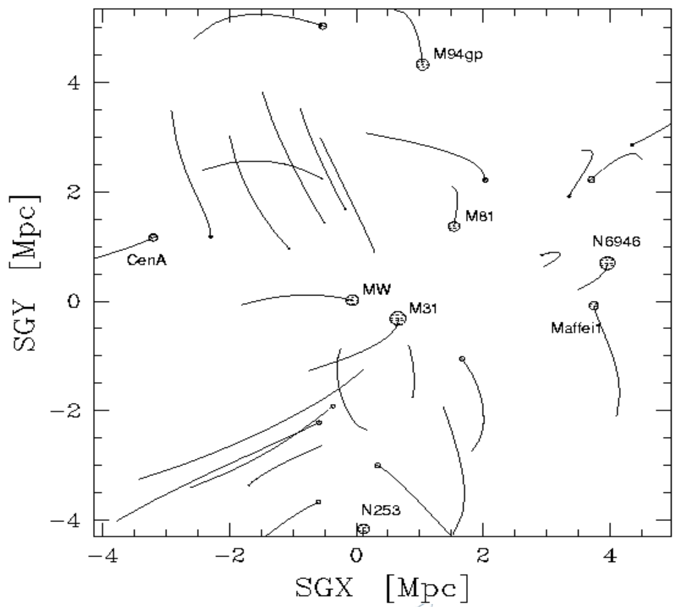

Physics of Active Galactic Nuclei

Space Interferometry Mission

SIM

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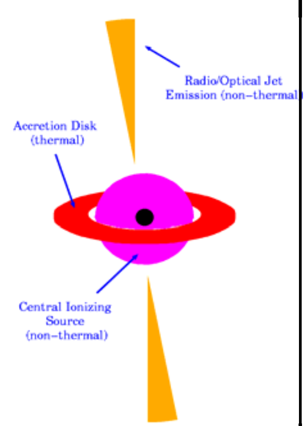
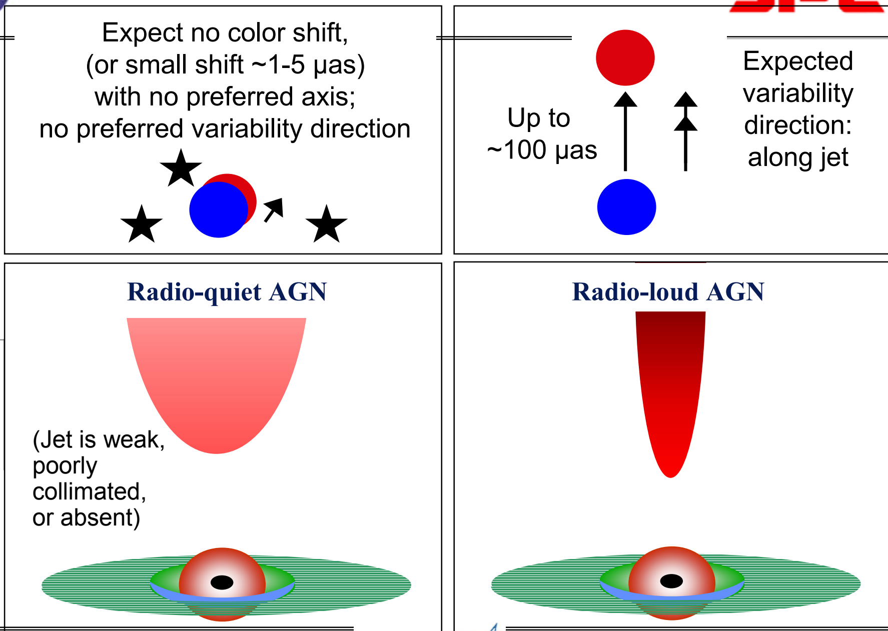
- Does the most compact non-thermal optical emission from an AGN come from an *accretion disk* or from a *relativistic jet* ?
- Do the cores of galaxies harbor *binary supermassive black holes* remaining from galaxy mergers ?
- Can AGNs be used to 'anchor' the SIM astrometric reference frame (the grid) ?



Location of the non-thermal emission



Stellar Astrophysics Goals

- Precise Masses and Luminosities
  - Open clusters
  - Selected classes of objects
- Population II Distance Scale
  - Ages of globular clusters
  - RR Lyraes as standard candles
  - MS turnoff stars and subgiants in the halo
- Dynamics
  - Black hole and RS CVn binary emission
  - Paths of neutron stars and OB stars

Space Interferometry Mission

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Stellar Masses: questions

- Measuring *accurate* stellar masses is hard
- We don't have good answers to the following questions:
  - What is the mass of the largest star?
  - What are the masses of black hole candidates?
  - What are the masses of very young stars?
  - What is the true dependence of the MLR on age?

Space Interferometry Mission

SIM

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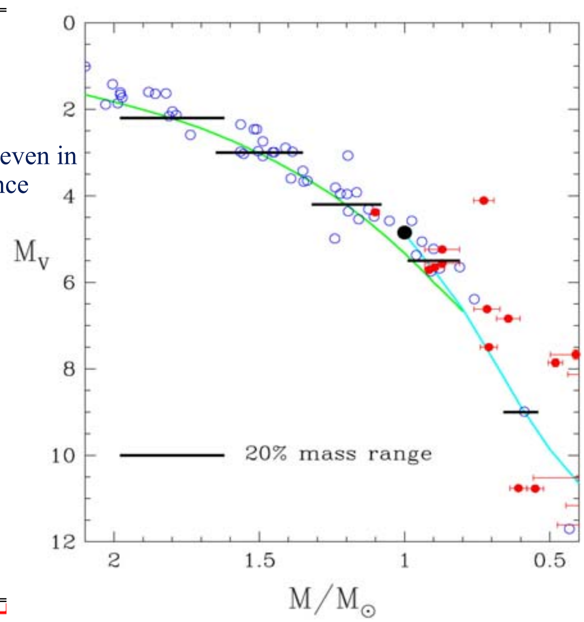
Measuring Stellar Masses

- Masses are poorly known - even in the middle of the main sequence



Why Measure Precise (1%) Masses?

- **Individual stars:**
  - challenge stellar astrophysics models
    - location of true 'zero-age' main sequence
    - evolution within the main sequence
    - abundance effects
  - beginning and end of main sequence
    - what is the largest star?
    - boundary between stars and brown dwarfs
  - primary stars for planet detection

- **Populations of stars:**
  - mass-luminosity-age-metallicity relation
  - mass function of stars $dN / dM = f(M)$

Space Interferometry Mission
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JPL LOCKHEED MARTIN TRW

State-of-the-art Masses for Binary System GL748AB

Masses — four parameters with HST:

P	2.4664 ± 0.0081	(0.3%)
a	0.1480 ± 0.0009	(0.6%)
π	0.0981 ± 0.0004	(0.4%)
f	0.3358 ± 0.0021	(0.6%)
M_A	0.3750 ± 0.0088	(2.4%)
M_B	0.1896 ± 0.0046	(2.4%)

The Need for SIM:

- this is a relatively easy system
- if P, a errors = 0 mass error still 1.3%
- if P, a errors = 0.1% and SIM determines π to 4 μas, f to 0.000014 (both 0.004%)

masses are known to 0.4%

Space Interferometry Mission
SIM
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Space Interferometry Mission

SIM

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Space Interferometry Mission (SIM)

Presentation to Committee on Astronomy and Astrophysics

James C Marr

SIM Project Manager

May 1, 2002

SIM Key Objectives

Space Interferometry Mission

- **Salient Features**
  - 3 collinear Michelson Stellar Interferometers
  - 10 meter baseline
  - Visible wavelength
  - Launch Vehicle: Space Shuttle or EELV
  - Earth-trailing solar orbit
  - 5 year mission life with 10 year goal
  - SIM is a JPL, Caltech, Lockheed Martin, TRW, and SIM Science Team partnership

- **Science**
  - Perform a search for other planetary systems by surveying 2000 nearby stars for astrometric signatures of planetary companions
  - Survey a sample of 200 nearby stars for orbiting planets down to terrestrial-type masses
  - Improve best current catalog of star positions by >100x and extend to fainter stars to allow extension of stellar knowledge to include our entire galaxy
  - Study dynamics and evolution of stars and star clusters in our galaxy to understand how our galaxy was formed and how it will evolve.
  - Calibrate luminosities of important stars and cosmological distance indicators to improve our understanding of stellar processes and to measure precise distance in the distant universe

The SIM Partnership: Many Partners

Space Interferometry Mission

SIM

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One Team

Metrology Subsystem
Starlight Subsystem
Interferometer I&T
Interferometer Operations

Spacecraft
Precision Support Structure
Assembly, Test, & Launch Operations
S/C Operations

Interferometry Science Center

Science Data Analysis and Archiving
Science Operations
Science Planning
Science Community Interface
Outreach

SIM Science Team
UC Berkeley
JPL
Ohio State University
Raytheon ITSS
USNO
Dartmouth College
Georgia State University
University of Virginia
Caltech
Washington State
UC San Diego
STScI

Project Management
System Engineering
Integrated Modeling
Real Time Control Subsystem
Mission Systems
Mission Assurance
Risk Management

Brief History

Space Interferometry Mission
SIM
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- SIM's last presentation to this committee was by Tom Fraschetti (then SIM Project Manager) & Mike Shao in Dec 2000
  - Project had just completed an Independent Assessment (IA) by the NASA Independent Program Assessment Office (IPAO)
  - IPAO cost estimates were ~50% greater than the SIM team's cost estimate
  - NASA OSS issued Oct 27, 2000 letter directing SIM to conduct a mission re-design to identify options that would achieve a Phase B/C/D cost of $930M or less. Further direction included:
    - Reach agreement with NASA IPAO on cost of options presented to within 20%
    - Science capability of options to be reviewed by a NASA appointed science External Review Board
    - The SIM Project, IPAO and the science ERB to report on mission options to OSS by May 2001
  - SIM team was in midst of conducting the directed mission studies
- Mission studies completed and reports made by SIM, IPAO and ERB in May 2001 as directed
  - The most capable ("Shared Baseline") of the three designs presented was selected
    - Preserves all SIM science capability (only gave up part of technology demonstrations)

Progress Since May 2001

Space Interferometry Mission
SIM
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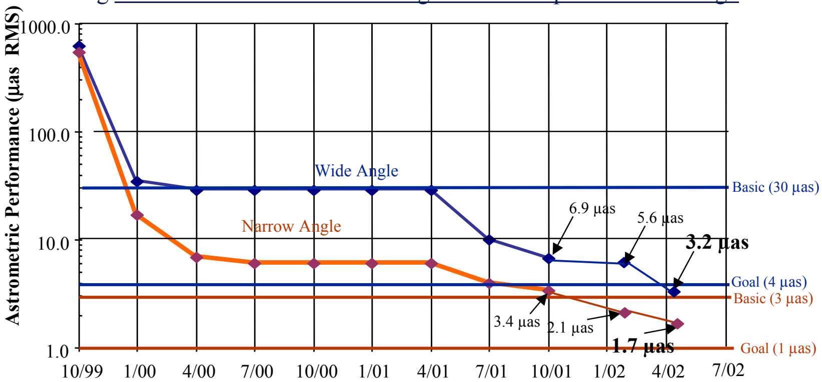
- Technology progress has been exceptional:
  - Out of the four (4) top level technology milestones required for Phase B entry:
    - **Two are complete** (beam launcher performance & science star fringe tracking performance)
    - Remaining **two are on schedule** for July 2002 completion
  - Out of 24 intermediate level technology milestones published in May 2001:
    - **20 are complete**
    - 1 no longer needed
    - 3 delayed with no expected impact on July top level milestone completion
- Flight Shared Baseline design simplified, risk reduced, and performance improved
  - Eliminated deployable Metrology stub
  - Eliminated challenging embedded double corner cubes
  - External metrology geometry improved
- Flight Shared Baseline design has been reviewed by the SIM Technical Advisory Committee (TAC) and the Navigator Program Independent Review Team (IRT)
  - Both have endorsed the continuing design evolution

SIM Astrometric Performance
--Based on "today's" component Technology

- Calculated Wide Angle and Narrow Angle performance
  - Based on current component performance (as of 2/02)
  - Using the latest Shared Baseline configuration & improved Grid design



- Predicted Wide Angle (Global Astrometric) performance better than Goal performance; Narrow Angle Astrometric performance within factor of 2 of Goal!

SIM Space Interferometry Mission

A NASA Origins Mission

SIM Flight System Design Update

SIM Space Interferometry Mission

A NASA Origins Mission

SIM Flight System as of Dec 2000 (Obsolete)

Space Interferometry Mission

SIM

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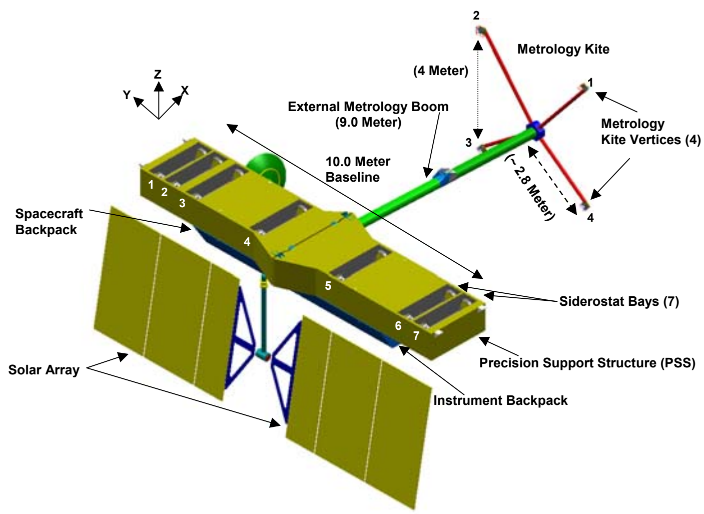

Current Shared Baseline Configuration

Space Interferometry Mission

SIM

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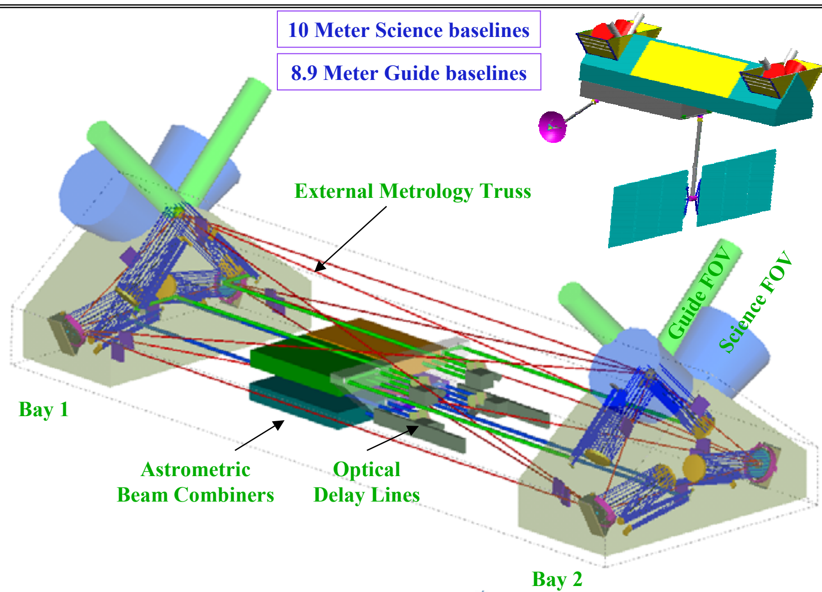
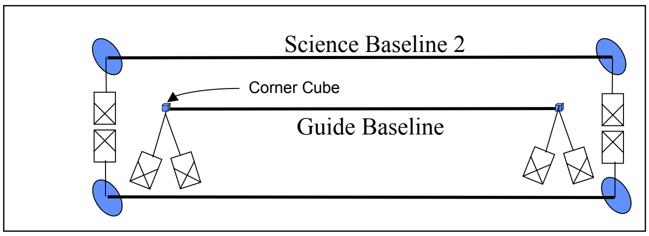


Current Version (L15X) Shared Baseline

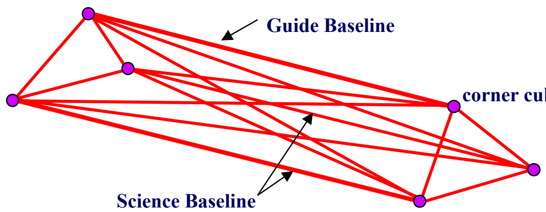
Space Interferometry Mission

SIM



The science interferometers do NOT share a baseline. The guide interferometers DO share a baseline. The guide baseline is defined only by the corner cubes that attach it to the external metrology truss (i.e. no siderostats for the guides).

External metrology truss measures relative motion of guide and science baselines



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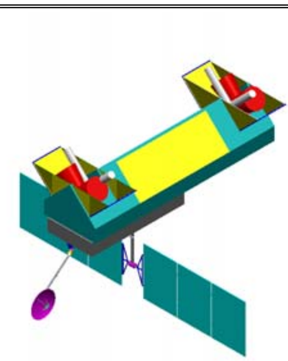
Shared Baseline-L15x Version

Space Interferometry Mission

SIM

- Characteristics & Distinguishing Features

Number of Siderostats	4
Siderostat Field of Regard	15 degrees
Number of Corner Cubes	6
Types of Corner Cubes	4 on-siderostat embedded double corner cubes; 2 Guide Triples
Number of Telescopes	8 off-axis TMAs
Number of Operating Baselines	2
Number of Total Baselines	3
Number of simultaneously operating interferometers	3
Number of External Metrology Beam Launchers	15
Number of Internal Metrology Beam Launchers	4 SAVV
Number of Delay Lines	8
Number of Lasers	3
Number of Astrometric Beam Combiners	4



- Improvement Opportunities

Mass reduction and layout optimizations
EELV compatibility

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LV Trades (Ongoing)

Space Interferometry Mission

SIM

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LV Option	What is it?	Cost [M FY01$ w/ 10% Reserve]	STS "marginal" Cost [M FY01$]†††	Total Cost [M FY01$]
STS #1	ATK Star 92 SRM based upper stage	$104	$97	$201
STS #2†	**TRW Integral Propulsion Module**	**$107**	**$97**	**$204**
EELV #1*	Atlas V 541 with Medium Faring	$114	N/A	$114
EELV #2††	Delta IV Heavy with 19m Faring	$176	N/A	$176

† Current SIM Reference Design

††† $120M RY$

* Requires a separate hinged SIM design to allow a fit into the medium faring

†† New option now under study. Cost has come down considerably; still many questions

- STS Option #2 chosen as reference design because
  - Need to support early STS design and safety reviews to preserve STS option
  - TRW Chandra-derived Integral Propulsion Module (IPM) lower risk than any other STS upper stage option available to date
- Delta IV Heavy (EELV #2) offers a new attractive EELV option that doesn't require folding of the SIM bench (allows use of STS SIM configuration)

L15x CAD Views

Space Interferometry Mission

SIM

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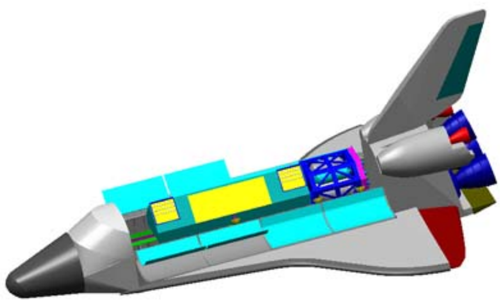
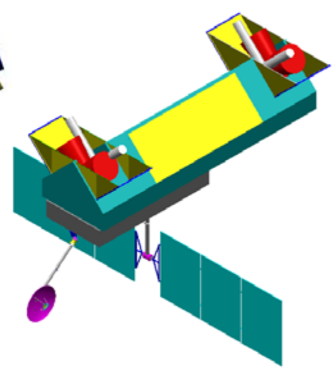


In Shuttle Bay



Deployable 2-piece sunshade/contamination cover

Space Interferometry Mission

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Schedule

Space Interferometry Mission

SIM

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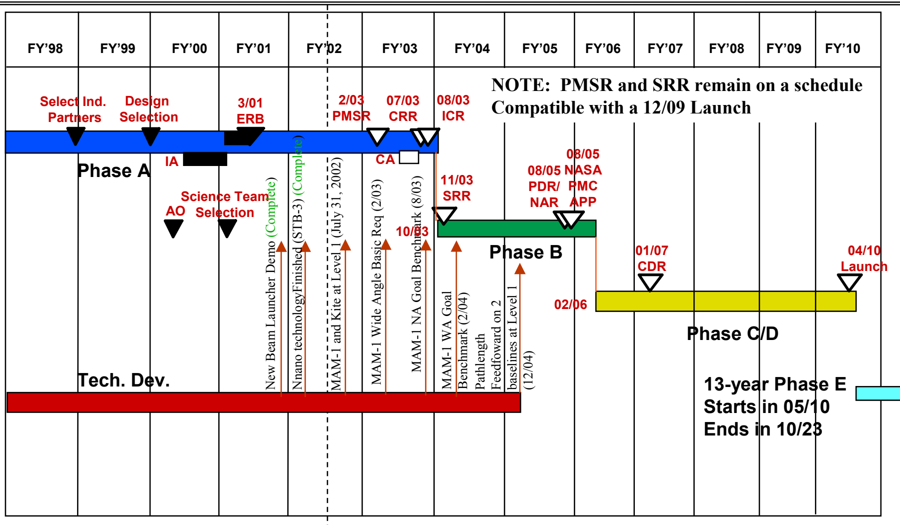
Program Operating Plan (POP) 2002 Options Submitted

- Options Provided (options differ by and are driven by NASA OSS ability to support required funding profile):
  - President's Budget Request (LRD 05/10)
  - In-Guide Submittal (LRD 04/10)
  - Option 1 (LRD 12/09)
  - Option 2 (LRD 08/09)
- All options:
  - Assume identical 6.5 yr, $930M FY01$ Phase B/C/D duration
    - Moved as a block to fit launch date
  - Assume identical 13 yr Phase E
    - 5 year basic flight operations; 10 yr goal flight operations
    - 3 yr post flight data reduction and archival
  - Duration of Phase A is adjusted to support proposed launch date
    - Current project plans consistent with Option 1 (LRD 12/09)
    - In-Guide and President's budget delay launch only to fit NASA funding availability
    - Shorter Phase A in Option 2 considered challenging but doable if the SIM team continues to make the expected technology progress

In-Guide Project Schedule
LRD 4/10



ATLO = Assy, Test & Launch Ops
CA = Confirmation Assessment
CDR = Critical Design Review
CR = Confirmation Review (NASA PMC)
ERB = External Review Board
IA = Independent Assessment
I&T = Integration & Test
PMSR = Preliminary Mission & Systems Review
NAR = Non Advocate Review
PDR = Preliminary Design Review
NASA PMC = Programmatic Management Council (APP = Approved)
SRR = System Requirements Review
CRR = Confirmation Readiness Review (JPL PMC)
ICR = Initial Confirmation Review (Code S)

Take Away

- SIM has completed the mission re-design directed by NASA OSS in Oct 2000
  - Resulted in a lower cost, lower risk mission that preserves all science capability of the earlier design
- SIM team continues to make outstanding technology progress
  - SIM Predicted performance at Goal for Wide Angle measurements and within a factor of two for Narrow Angle measurements
  - Completion of system level technology demonstrations required for entry into Phase B will be completed by this summer
- SIM will be ready to enter Phase B by CY 2003
  - When SIM enters Phase B will be determined by NASA OSS funding availability

SIM Space Interferometry Mission

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Space Interferometry Mission

SIM

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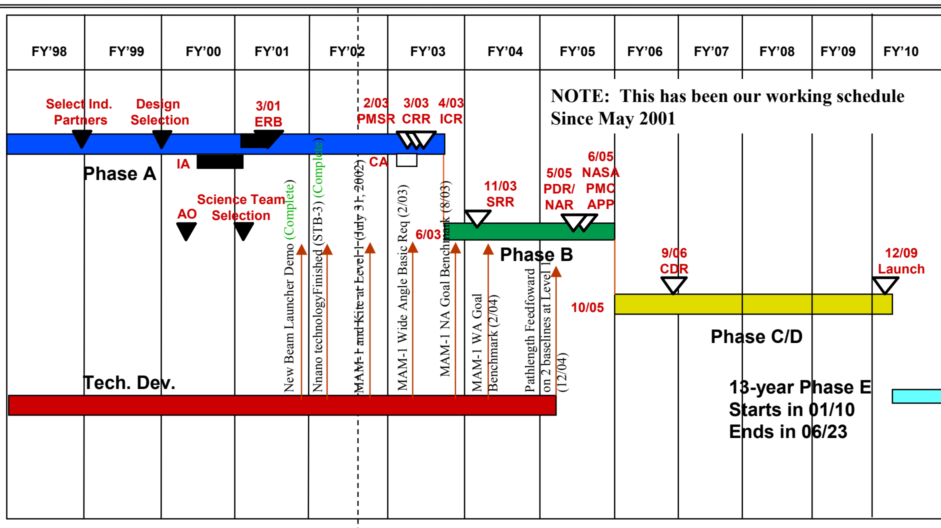
Backup

Option 1 Project Schedule LRD 12/09

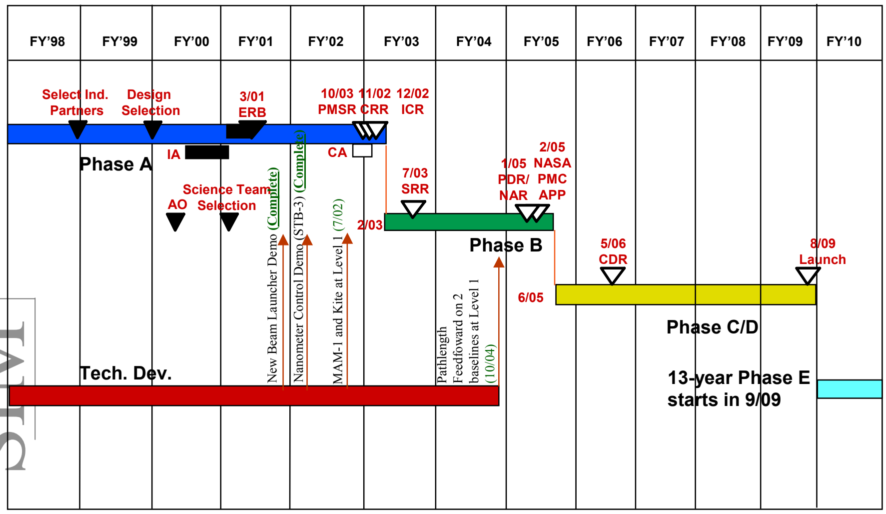


ATLO = Assy, Test & Launch Ops
CA = Confirmation Assessment
CDR = Critical Design Review
CR = Confirmation Review (NASA PMC)
ERB = External Review Board
IA = Independent Assessment
I&T = Integration & Test
PMSR = Preliminary Mission & Systems Review
NAR = Non Advocate Review
PDR = Preliminary Design Review
NASA PMC = Programmatic Management Council (APP = Approved)
SRR = System Requirements Review
CRR = Confirmation Readiness Review (JPL PMC)
ICR = Initial Confirmation Review (Code S)

Option 2 Project Schedule
LRD 8/09

Space Interferometry Mission

SIM



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Why SIM Can Launch Earlier

Space Interferometry Mission

SIM

- It is technically feasible to accelerate the SIM launch date by shortening Phase A
- Present SIM Technology milestones support an earlier launch date
  - Key technology milestones will be completed and peer reviewed, by NAR, on a schedule that supports the earlier launch date
  - Component technology for SIM is complete
  - Nanometer control technology for SIM is complete
  - Picometer knowledge at the system level is on track for completion July 2002
    - Recent achievement of 30pm on White Light MAM Experiment provides confidence
  - The Picometer Knowledge Transfer testbed schedule supports the earlier launch
- Key personnel at JPL and our industry partners are available and ready to take SIM into Phases B/C/D, and support the earlier launch date
- Facilities and equipment are available at JPL and our industry partners to support the earlier launch date

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