SIM Lite is the only mission concept that is ready to go now that is capable of finding one-Earth-mass planets in the habitable zone of 60 to 100 nearby sun-like stars.

SPIE 7734-16

SIM Lite Astrometric Observatory Progress Report

Jim Marr, Project Manager
Mike Shao, Project Scientist
Renaud Goullioud, Instrument Manager

28 June 2010, 10:10 A.M.
17 Related papers at the conference

**Overview papers:**
- J. Marr, "SIM-Lite Astrometric Observatory: Progress Report" (7734-16) [This Paper]
- R. Goullioud, "SIM-Astrometric Observatory: engineering risk reduction activity" (7734-62)

**System Engineering & Modeling papers:**
- M. Moshir, "Systems engineering and application of system performance modeling in SIM-Lite Mission" (7734-52)
- M. Milman, "SIM-Lite narrow-angle modeling and processing" (7734-23)
- F. Dekens, "SIM-Lite: ground alignment of the instrument" (7734-55)
- C. Zhai, "SIM-Lite instrument calibration sensitivities and refinements" (7734-54)

**Science papers:**
- X. Pan, "SIM-Lite detection of habitable planets in P-type binary-planetary systems" (7734-126)

**Hardware papers:**
- X. An, "SIM brassboard astrometric beam combiner (ABC) integration and performance testing" (7734-169)
- I. Hahn, "Progress on SIM-Lite brassboard interferometer integration and test" (7734-168)
- R. Smythe, "Flight qualification and performance testing of SIM precision optical mechanisms" (7734-58)
- O. Alvarez-Salazar, "On-orbit dynamics and controls system architecture for SIM-Lite" (7734-53)

**Testbed papers:**
- B. Nemati, "SIM interferometer testbed (SCDU) status and recent results" (7734-57)
- B. Nemati, "Mitigation of angle tracking errors due to color dependent centroid shifts in SIM-Lite" (7734-166)
- X. Wang, "SCDU testbed narrow angle astrometric performance" (7734-167)
- T. Werne, "SCDU testbed automated in-situ alignment, data acquisition, and analysis" (7734-162)
- I. Hahn, "Results of the Guide-2 Telescope testbed for the SIM-Lite Astrometric Observatory" (7734-165)
SIM Lite Astrometric Observatory

**Salient Features**
- 6 meter science Michelson Stellar Interferometer (MSI) with 50 cm siderostats
- One 4m MSI and one 30cm T-scope Guides
- Visible wavelength
- KSC launch on medium-class ELV
- Earth-trailing solar orbit, 5 year mission
- SIM is a JPL, Caltech, NGAS, KSC, and SIM Science Team partnership

**Science (observing time: 50% unallocated)**
- Finding Earths (searches habitable-zones of 60-100 nearby sun-like stars)
- Dark Matter & Galaxy Assembly
- Precision Stellar Astrophysics
- Supermassive Black Hole Astrophysics

**Brief History**
- Investment over past 14 yrs, ~$600M, has evolved design to minimum configuration able to meet prior NRC Decadal and AAAC Exoplanet Task Force recommendations.

**Currently under review by the NRC Astro2010 Decadal Survey**

**Technical Status**
- Technology development completed in 2005.
- Developed/developing flight form-fit-function hardware for all critical instrument subassemblies.
  - Flight environmentally tested.

**For further details**
# SIM Performance Meets Prior NRC Goals

1990 and 2000 NRC Decadal Reviews

“...emphasized the dual capability of SIM, noting that this capability would enable
“...both... detecting planets and ... mapping the structure of the Milky Way and other nearby galaxies.”

## 2010 NRC Decadal Review ???

<table>
<thead>
<tr>
<th>Concept</th>
<th>Wide-Angle Astrometry</th>
<th>Narrow-Angle Astrometry</th>
<th>Magnitude Limit (V)</th>
<th>Nulling?</th>
<th>Synthesis Imaging?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Requirement (µas)</td>
<td>Goal (µas)</td>
<td>Requirement (µas)</td>
<td>Goal (µas)</td>
<td></td>
</tr>
<tr>
<td>1982 AASC (SOI)</td>
<td>Space Optical Interferometer (SOI) with resolutions of 1 to 10 µas by early part of next century.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991 AASC (AIM)</td>
<td>30</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>2001 AASC (SIM)</td>
<td>10</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2002 CAA Assessment*</td>
<td>10</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>SIM-Lite** Performance</td>
<td>4 µas</td>
<td>1 µas†</td>
<td>19-20</td>
<td>No</td>
<td>6 m baseline (plus rotation)</td>
</tr>
</tbody>
</table>

* J.H. McElroy (chair, SSB) & J.P. Huchra (chair BoPaA), CAA assessment of SIM redesign in letter to Dr. E. Weiler (AA for Space Science), 9/12/2002
** Current performance prediction, without margin, based upon SIM’s completed technology development program and mature flight design.
† Instrument noise floor less than 0.035 µas for long integrations (demonstrated during technology program).
Recent SIM-Lite Activities
Since the last SIM progress report given at SPIE 2008

• Science:
  – Nineteen SIM Science Studies completed. New ways to use SIM Lite’s astrometric capabilities.
  – Double-blind astrometric planet-finding capability study completed.
  – First study of effects of multiple planets on direct imaging mission performance with/without precursor astrometry mission.
  – Independent cost and technical assessment by the Aerospace Corp.
  – Submissions to Astro2010 Decadal survey.

• Hardware:
  – Completed Guide 2 Telescope Testbed demonstration.
  – Completed 100 B cycle PZT actuator life test w/o failures.
  – Brassboard control mirrors/actuators completed (MOM, POM, FSM)
  – Spectral Calibration Development Unit (SCDU) completed testing.
  – Brassboard Astrometric Beam Combiner (ABC) subassemblies completed.

• New SIM Lite web site released (http://sim.jpl.nasa.gov)
What Additional Science can SIM Lite Do?

- **SIM Science Studies (SSS)**
  - Competition for 1-year studies was held in 2008
  - Studies completed in 2009
- **Selected 19 proposals for study**
  - 12 studies expand existing Key Projects
  - 7 studies are *entirely new*
- **Topics include:**
  - Planets & Planetary Systems – 6 studies
  - Dark Matter & Galactic Dynamics – 3 studies
  - Precision Stellar Astrophysics – 7 studies
  - Other – 3 studies
- **Study summaries at:** [http://nexsci.caltech.edu](http://nexsci.caltech.edu)
- **Any of these topics could be candidates for General Observer (GO) proposals.**

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**New Science Topics**

- Gaia-SIM legacy project.
- Measuring the astrometric signature of transiting planets with SIM.
- The dynamical legacy of star formation.
- Sizes and shapes of Kuiper belt objects and Centaurs with SIM.
- Searching for Solar system giant analogs with SIM.
- 1% luminosity-independent distances to nearby galaxies with the rotational parallax method.
- Stellar astrophysics with SIM and optical long-baseline interferometry.
SIM Lite will find Earth-Analogs around nearby sun-like FGK stars!

Discovery space is above each curve.
Double-Blind Study

NASA conducted a double-blind test of astrometric detection capability in multiple-planet systems.

- **5 theory teams** to generate “fake” planetary systems
- **Data generation team** to generate 5 yrs of astrometric data, and 15 years of RV data.
- **5 Data analysis teams** to analyze a total of 108 planetary systems, with a total of 135 planets, 27 of which were “Earths in the HZ”.

The results of the data analysis teams were scored according to two statistics:

- **Completeness:** What % of planets that “could have been detected” (SNR > 5.8) were actually detected.
  \[ \frac{\text{planets-detected}}{\text{planets that could have been detected}} \]

- **Reliability:** When a detection was claimed to have been made, what fraction was real?
  \[ \frac{\text{valid-detections}}{\text{reported detections}} \]

- Paper for part-2 of the study is in preparation (Traub, et al).
## Double Blind Study Results

<table>
<thead>
<tr>
<th>Scoring Category</th>
<th>Phase 1†</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completeness: Terrestrial</td>
<td>18/20</td>
<td>37/43</td>
</tr>
<tr>
<td>Completeness: HZ</td>
<td>13/13</td>
<td>21/22</td>
</tr>
<tr>
<td>Completeness: Terrestrial HZ</td>
<td>9*/9</td>
<td>17**/18</td>
</tr>
<tr>
<td>Completeness: All planets</td>
<td>51/54</td>
<td>63/70</td>
</tr>
<tr>
<td>Reliability: Terrestrial</td>
<td>25/27</td>
<td>38/39</td>
</tr>
<tr>
<td>Reliability: HZ</td>
<td>16/16</td>
<td>20/20</td>
</tr>
<tr>
<td>Reliability: Terrestrial HZ</td>
<td>12/12</td>
<td>16/16</td>
</tr>
<tr>
<td>Reliability: All planets</td>
<td>64/67</td>
<td>66/68</td>
</tr>
</tbody>
</table>

- Analysts were asked to be aggressive in Phase-1 and conservative in Phase-2. This is reflected in the denominators of the Completeness and Reliability sections.
- All 9 T/HZ Phase-1 detected planets were in multiple-planet systems.
- **10 of the 17 T/HZ Phase-2 detected planets were in multiple-planet systems**
- † Results here are from Analysis Team C5 only; Best comparable to Phase-2.
Double Blind Study Results

Period, Mass and Inclination results:

- **Period:**
  - Fitted vs True
  - Period error < ~3%

- **Mass:**
  - Fitted vs True
  - Mass error < ~25%

- **Inclination:**
  - Fitted vs True
  - Inclination error < ~10%

High P/T or long period companion vs SNR

Fractional period error vs SNR

Fractional mass error vs SNR

Error in deg vs SNR
A-priori knowledge of exo-Earths existence (from Astrometry) substantially increases the exo-Earth yield of a JWST + Starshade mission.

- And provides planet masses.

**# planets**: the number of planets discovered that “could” be a terrestrial planet in the HZ

**# Earths**: the number of planets that actually are terrestrial planets in the habitable zone

**False Alarm**: Percent (%) of “claimed” earths in the HZ that aren’t.

**Prob_0**: is the probability that zero Earths are imaged.

### JWST+Starshade 70Visits/5yrs
Single-visit per star, no follow-ups

<table>
<thead>
<tr>
<th>Eta_Earth</th>
<th>#Planets</th>
<th>#Earths</th>
<th>False Alarm</th>
<th>Prob_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>4.5</td>
<td>1.9</td>
<td>58%</td>
<td>14%</td>
</tr>
<tr>
<td>20%</td>
<td>7.9</td>
<td>3.8</td>
<td>52%</td>
<td>2%</td>
</tr>
<tr>
<td>30%</td>
<td>11.0</td>
<td>5.6</td>
<td>49%</td>
<td>1%</td>
</tr>
</tbody>
</table>

### JWST+Starshade 70Visits/5yrs
With confirmation follow-up visits

<table>
<thead>
<tr>
<th>Eta_Earth</th>
<th># Earths</th>
<th>Prob_0</th>
<th># Earths</th>
<th>Prob_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.9</td>
<td>41%</td>
<td>4.7</td>
<td>0.7%</td>
</tr>
<tr>
<td>20%</td>
<td>1.9</td>
<td>16%</td>
<td>9.1</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>30%</td>
<td>2.7</td>
<td>7%</td>
<td>12.0</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

SIM Lite and Gaia are Complementary

- Gaia is a survey mission
  - Large number of stars
  - Limited accuracy
  - *Like the Palomar 48”*
- SIM Lite is a pointed observatory
  - Extreme precision
  - Targets selected for science
  - *Like the Palomar 200” or Keck*

<table>
<thead>
<tr>
<th></th>
<th>V &lt; 6 mag</th>
<th>6 - 13</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GAIA</strong></td>
<td>N/A</td>
<td>36 µas</td>
<td>60 µas</td>
<td>150 µas</td>
<td>420 µas</td>
<td>1200 µas</td>
</tr>
<tr>
<td>(fixed cadence; 83 Obs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SIM</strong></td>
<td>0.2 µas</td>
<td>0.2 µas</td>
<td>&lt;2 µas</td>
<td>&lt;2 µas</td>
<td>&lt;2 µas</td>
<td>&lt;2 µas</td>
</tr>
<tr>
<td>(flexible cadence; nominal=200 obs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Astrometry with an stellar interferometer

\[ \theta = \arccos\left(\frac{X}{B}\right) \]

Pathlength control to \(~10 \text{ nm (}\lambda/50)\) required for high fringe visibility.

- The peak of the interference pattern occurs at zero OPD to star
SIM Lite Configuration

- Spacraft Bus
- Instrument Electronics
- Short Faring
- Intermediate Class Launch Vehicle e.g., Atlas V 521
- Delay Lines
- 6 m Science Baseline
- External Metrology Truss
- Guide 1, 4.2 m baseline
- Guide 2
- Science FOR = 15°
• NGAS completed a preliminary workable layout of the S/C bus components and cabling, to address an Aerospace ICE packaging density concern.

• Brassboard PSS strut built to characterize properties.
SIM Lite Brassboard Status - Today

- **Brassboards – form, fit and function to flight**
- **Completed:**
  - Guide-2 Telescope.
  - Internal & External Metrology beam launchers.
  - Fine Steering Mirror.
  - Beam Compressor & Bench.
  - Modulation Optical Mechanism (not shown).
  - Pathlength Optical Mechanism (not shown).
  - Double Corner Cube.
  - 30 cm Siderostat mirror.
  - Precision Structure Strut.

- **In process now:**
  - Astrometric Beam Combiner (next 2 pages).
  - Metrology source pump diode assembly (not shown).

- **Planned but not yet started:**
  - Optical Delay Line
  - Siderostat gimbal mechanism.
SIM Lite Astrometric Beam Combiner

Astrometric Beam Combiner (ABC) Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMM1</td>
<td>Alignment Mirror Mechanism on arm 1</td>
</tr>
<tr>
<td>AMM2</td>
<td>Alignment Mirror Mechanism on arm 2</td>
</tr>
<tr>
<td>AT</td>
<td>Angle Tracker = ATA + ATC</td>
</tr>
<tr>
<td>ATA</td>
<td>Angle Tracker Assembly</td>
</tr>
<tr>
<td>ATC</td>
<td>Angle Tracker Camera head</td>
</tr>
<tr>
<td>CC1</td>
<td>Self-check corner cube 1</td>
</tr>
<tr>
<td>CC2</td>
<td>Self-check corner cube 2</td>
</tr>
<tr>
<td>CCA</td>
<td>Compensated combiner assembly</td>
</tr>
<tr>
<td>FM-AT1</td>
<td>Fold mirror on AT input (arm 1)</td>
</tr>
<tr>
<td>FM-AT2</td>
<td>Fold mirror on AT input (arm 2)</td>
</tr>
<tr>
<td>FM-IMET</td>
<td>Fold mirror on IMET path</td>
</tr>
<tr>
<td>FM-IP1</td>
<td>Fold mirror on input port 1 (arm 1)</td>
</tr>
<tr>
<td>FM-IP2</td>
<td>Fold mirror on input port 2 (arm 2)</td>
</tr>
<tr>
<td>FT</td>
<td>Fringe Tracker = FTA + FTC</td>
</tr>
<tr>
<td>FTA</td>
<td>Fringe Tracker Assembly</td>
</tr>
<tr>
<td>FTC</td>
<td>Fringe Tracker Camera head</td>
</tr>
<tr>
<td>IAM</td>
<td>IMET Alignment Mechanism</td>
</tr>
<tr>
<td>IMET</td>
<td>Internal Metrology beam launcher</td>
</tr>
<tr>
<td>SAM</td>
<td>Stimulus Alignment Mechanism</td>
</tr>
<tr>
<td>SCA</td>
<td>Stimulus collimator assembly</td>
</tr>
<tr>
<td>SIB</td>
<td>Stimulus Injection Beamsplitter</td>
</tr>
<tr>
<td>SM1</td>
<td>Shutter mechanism 1</td>
</tr>
<tr>
<td>SM2</td>
<td>Shutter mechanism 2</td>
</tr>
</tbody>
</table>

ABC Bench (purple) supports the ABC assemblies.
Astrometric Beam Combiner – Status

- Shutter Mechanisms:
- Alignment Corner-Cubes:
- IMET
- FTA
- FTC
- ATC
- ATA
- ABC Bench: 7734-169

(*) Motorized actuators:
Was: 4/20/10; Is: 7/15/10
Cause: Aeroflex delay due to MSL
Brassboard Interferometer I&T

- Single Interferometer Test
  - Astrometric, Dynamics & Control (D&C)
MOM/POM/FSM (Delivered)

MOM = Modulation Optical Mechanism
POM = Pathlength Optical Mechanism
FSM = Fine Steering Mirror
PZT AC Life Test Completed

- PZT AC life test stopped at 100B cycles (~5x one life) as planned.
  - 20 PZTs in life test.
    - 10 Active; 10 Inactive
  - ~2 to ~3% degradation in deflection at end of life; very acceptable.
  - No failures.
  - Re-polling of the PZTs at 100V restores full deflection.
Guide-2 Telescope (G2T) Testbed

- **Goal:** demonstrate ability to remove SIM Lite baseline rotation around Guide-1 line-of-sight to better than 50 µas.

- **Method:** build up a full scale G2T using previously built SIM brassboard hardware with minimum modifications.

- **Results:** Demonstrated 42 µas.

7734-168 & 7734-56
Spectral Calibration Development Unit (SCDU) Objectives:

- Breadboard for ABC design.
- Developed approach for Color Dependent Centroid Shift (CDCS) of fringe when chopping between stars of different temperatures.

Results:

- SCDU testing concluded in April 2010.
- Objectives achieved.

Papers: 7734-162 & 7734-167
Astro2010 Submittals

- Astronomy and Astrophysics Decadal Survey underway.
  - Astro2010 Decadal Survey.
  - Reportedly due out ~ September 2010.

- SIM Lite provided three inputs to Astro2010:
  - Eleven Science white papers.
  - Response to RFI Part 1 on 4/1/09.
  - Response to RFI Part 2 on 8/3/09.
  - Significantly more material then for RFI Part 1.

- Web sites:
  - Astro2010 Decadal Survey official web site: [http://sites.nationalacademies.org/bpa/BPA_049810](http://sites.nationalacademies.org/bpa/BPA_049810)
SIM Lite Book

- Contents:
  - Theme I: The Search for Habitable Worlds
  - Theme II: Dark Matter and the Assembly of Galaxies
  - Theme II: Precision Stellar Astrophysics
  - Theme IV: Supermassive Black Holes and Quasars
  - Theme V: Charting the Uncharted Waters
  - Theme VI: Project Technology Readiness

- Pick up copy at SIM booth; get it online; or order a copy at:
SIM Lite Astrometric Observatory

For Everyone
What is SIM Lite?
Quick Technical Facts
SIM Lite Science
How Does SIM Lite Work?
Related Missions & Sites
Multimedia

Search

For Astronomers
Science Motivations
Instrument
Science Discussions
Astro2010 Decadal Survey
Key Published Papers
SIM Lite in Context

SIM Lite Capabilities:
- Find Earths
- Dark Matter & Galaxy Assembly
- Precision Stellar Astrophysics
- Black Hole Astrophysics

Latest News - Synergy of Exoplanet Imaging and Astrometry
Project Manager’s Update - 2010/3/19 - FTA and FTC delivered & installed

7734-16 SIM Lite Progress Report

J. Marr, R. Goullioud, M. Shao, 6/27/08 - 26