A SIM gauge:

- Must:
  1. Measure distance between two fiducials.
  2. Relative accuracy ~ 10 pm.
  3. Minimal sensitivity to metrology head mis-orientation.
  4. Minimal sensitivity to electronic drift. (Favor use of heterodyne technique.
  5. Be consistent with ~20 other gauges. (Requires use of single laser wavelength standard.)

- Basic components include:
  1. Laser, stabilized, $\lambda=1.3$ micron (to not contaminate starlight in the visible)
  2. Frequency shifters to enable heterodyne detection
  3. Fiber optics for laser light distribution to ~20 metrology heads
  4. Metrology heads (includes photodiodes which produce heterodyne interference signals)
  5. Fiducial retro-reflectors (corner cubes).
  6. Electronics to measure phase of metrology heads' heterodyne outputs.

A generic gauge

- Photodetectors detect heterodyne interference signal, $f_2-f_1$ (~100 kHz)
- Relative phase of Reference vs. Measurement photodiode signals tells us the Optical Path Difference (OPD) of the M beam vs. the R beam: basis for gauge readout. $L=\text{OPD}/2$.
- For $\lambda=1.3$ microns, we need to measure phase difference to $1.5\times10^{-5}$ cycles.
- Incomplete split of M and R beams causes cyclic error.
How precision engineering will help find planets like earth

Space Inter-Country Mission Metrology

Expedite

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How precision engineering will help find planets like Earth.

A presentation to the students of Nagaoka University

July 17, 2002

Peter Halverson

Planet finding missions: NASA timeline

http://origins.jpl.nasa.gov/

- Hubble Space Telescope
- Far Ultraviolet Spectroscopic Explorer
- Stratospheric Observatory for Infrared Astronomy
- Space Infrared Telescope Facility
- Starlight
- Space Interferometry Mission
- Next Generation Space Telescope
- Terrestrial Planet Finder
- Life Finder, Planet Imager
SIM measures Relative Angular Positions of Stars

Do stars move? Yes, of course

- Parallax
- Intrinsic proper motion (each star has its unique orbit about the center of the Galaxy)
- Gravitational pull of unseen partners orbiting (planets, brown dwarfs)
- Gravitational lensing
- Stellar aberration (relativistic effects)
Intrinsic Proper Motion

Distant Object (Quasar)

A and C don't seem to move, but B does

Gravitational Pull of Dark Partners

Center-of-mass

Planet (invisible)

Star

Pull

C.M.
Planet detection with astrometry: reflex motion of stars due to gravitational pull of planets.

Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

Parallax

\[ \Delta \theta = \theta_p \cdot e_f \]

Use to calculate distance: \( D = \frac{\Delta \theta}{\text{Earth-Sun distance}} \)
Gravitational lensing: simulated data

**MICROLENSING IN THE LMC**
Numerical simulation of the astrometric signature of a microlensing event in the Large Magellanic Cloud.
To find PLANETS...

Angle: About 5 picoradians
for Earth-like planets

This star has a planet!

Basic Idea - use pair of telescopes
to measure wavefront delay, the compute angle

Get results: \[ \theta = \cos^{-1}\left(\frac{D}{s}\right) \]

Mixer - White light interferometry
only see fringes when
\[ s = s_D \]
Maximise signal, get central
white light fringe, then \( s = s_D \)
SIM has three interferometry.
A & C tell us SIM's angular position.
B tells us the science star's angular position.

To get 5 picometer accuracy with baseline $D = 10$ meters, we need metrology to know $D$.

Define
\[ \Delta\theta = \frac{\Delta D}{D} \]
\[ \Delta D = D \Delta \theta = (10 \, \text{m}) \times (5 \times 10^{-12}) \]
\[ = 50 \, \text{picometers} \]
SIM project description

- Launch in 2008:
- Pico-radian accuracy space "theodolite".
- Compares rapidly changing **angular positions** of local stars to unchanging distant "reference" objects (such as active galactic nuclei).
- Parallax angles as SIM orbits the sun provides accurate distance measurements to stars and nearest galaxies.
- Detects planets orbiting stars, providing planet mass and orbital parameters.
- Detects mysterious Massive Compact Halo Objects (MACHOs) which are a possible explanation for intergalactic dark matter, providing distance & mass from gravitational lensing measurements.
- Measures transverse velocities of stars locally and in nearest galaxies.
- Complements line-of-sight (Doppler) velocity measurements.

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Artist conception

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SIM specs

- Four stellar interferometers (two are for bright local “guide” stars, two for dimmer “science” objects.)
- ~10 meter baselines
- Angular accuracy: 5 pico-radians
- Interferometers measure starlight wavefronts to 50 picometer accuracy (because 5 pico-radians = 50 pm / 10 m).
- This implies that relative locations of interferometer optics must be known to better 50 picometers.

- Metrology in SIM is expected to measure distance between optics to ~10 pm relative accuracy.
- Metrology expected to measure same distance to ~10 micron absolute accuracy.

Michelson Interferometer

![Diagram of Michelson Interferometer]

External Path Delay
\[ d = |B| \cos(\theta) \]

Incoming Stellar Wavefront

Telescope 1

Telescope 2

Hearn Combiner

Detected Intensity

External Delay - Internal Delay

Delay Line
Michelson relative astrometry

If baseline length and orientation are known, the astrometric observable \( s_1 - s_2 \) can be deduced directly from the relative delay difference between the stars.

Global Astrometry

**GLOBAL ASTROMETRY**

SIM's astrometric "tiles." Grid stars tie the tile data into the global astrometric frame.
SIM ORBIT

TRAJECTORY

SIM will be launched into an Earth-trailing solar orbit.

Optical delay line
The role of metrology in SIM: internal metrology

Simplified sketch of SIM's internal metrology light path (red line) and starlight (blue). Internal metrology measures the difference in starlight path (adjusted by the delay lines) required to keep the central starlight fringe locked at the fringe detector. The baseline vector $D$ is the vector from the center of siderostat 1 to siderostat 2.
The role of metrology in SIM:
External metrology

Each line represents one metrology beam or "strut".

4m x 4m metrology "kite" with 6 "struts".

Vertex formed by triple corner-cube. (4 places)

Corner cube on each siderostat mirror. (8 places)

External metrology used to monitor the geometry of SIM to ~100 pm. Geometry means the precise lengths, relative directions and positions of $D_x$, $D_y$, $D_z$, the baseline vectors of the three interferometers (science and two reference).

Metrology structure ties the interferometers together

3-dimensional web of metrology struts monitors relative positions of interferometer baselines.

Science interferometer baseline 1 (10 m)

Science interf. baseline 2 (8 m)

Two guide interferometer baselines (6 m)

Internal metrology (not shown) measures starlight propagation distance to beam combiners.
## SIM metrology requirements

<table>
<thead>
<tr>
<th>Internal metrology requirement</th>
<th>External metrology requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of gauges</td>
<td>8</td>
</tr>
<tr>
<td>Number of gauges for mission success (assuming dispersed failures)</td>
<td>6 (two siderostats are spares)</td>
</tr>
<tr>
<td>Number of gauges for mission success (assuming dispersed failures)</td>
<td>42 (kite: 6, roll estimation: 4, siderostats: 32)</td>
</tr>
<tr>
<td>Distance between fiducials</td>
<td>20 meters</td>
</tr>
<tr>
<td>Distance between fiducials</td>
<td>Varies: shortest are 4 meters, longest are 12 meters.</td>
</tr>
<tr>
<td>Motion; ranges of distances</td>
<td>2.6 meters while changing stars; 10 microns while observing</td>
</tr>
<tr>
<td>Motion; ranges of distances</td>
<td>10 microns</td>
</tr>
<tr>
<td>Velocity</td>
<td>2 cm/s while changing stars, 1 micron/sec while observing</td>
</tr>
<tr>
<td>Velocity</td>
<td>&lt;10 microns/sec ?</td>
</tr>
<tr>
<td>Accuracy (absolute)</td>
<td>Solved for with astrometric data</td>
</tr>
<tr>
<td>Accuracy (absolute)</td>
<td>3 microns rms</td>
</tr>
<tr>
<td>Accuracy (relative)</td>
<td>15 pm rms (1 hour time scale); 8 pm rms (5 minute s)</td>
</tr>
<tr>
<td>Accuracy (relative)</td>
<td>~5 microns</td>
</tr>
<tr>
<td>Accuracy (relative)</td>
<td>~30 picometers</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>2 pm/mK (soak); 50 pm/mK (sensitivity to gradients)</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>~8 nm/K</td>
</tr>
</tbody>
</table>

SIM metrology requirements, subject to change as SIM's design evolves.

## Current metrology performance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1.3 microns</td>
</tr>
<tr>
<td>Distance between fiducials</td>
<td>2.5 meters</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td>Accuracy (absolute)</td>
<td>~5 microns</td>
</tr>
<tr>
<td>Accuracy (relative)</td>
<td>~30 picometers</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>~8 nm/K</td>
</tr>
</tbody>
</table>
Proof-of-concept metrology fiducial mounted on siderostat

Metrology Fiducials

SIM Triple Corner Cube  Prototype TCC
Metrology system block diagram

Digital phasemeter

- VME based
- 6 gauges per board
- (This setup can handle 18 gauges)
Specifications for the JPL phasemeter. Specifications in picometers assume a 100 kHz heterodyne frequency and 1.3 micron wavelength.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels (gauges)</td>
<td>6</td>
</tr>
<tr>
<td>Maximum clock frequency</td>
<td>128 MHz</td>
</tr>
<tr>
<td>Stability</td>
<td>$10^{-5}$ cycles (6.5 pm) for ambient temperature held to 0.1 C</td>
</tr>
<tr>
<td>Range</td>
<td>$2^{32} \approx 4.3 \times 10^9$ cycles (2795 meters)</td>
</tr>
<tr>
<td>Heterodyne frequency range</td>
<td>1954 Hz to 1.33 MHz</td>
</tr>
<tr>
<td>Phase resolution (no averaging)</td>
<td>$1.6 \times 10^{-5}$ cycles at 2 kHz to 0.01 cycles (650 pm) at 1.3 MHz heterodyne frequency. (Improves with averaging)</td>
</tr>
<tr>
<td>Velocity range at maximum heterodyne frequency</td>
<td>+/- 0.88 x 10^6 cycles per second (0.58 meters/second)</td>
</tr>
<tr>
<td>Temperature sensitivity</td>
<td>&lt;500 picoseconds/C (32 pm/C)</td>
</tr>
</tbody>
</table>

The JPL/MAM phasemeter - block diagram.

**NOTES:**
1. The diagram is highly simplified for teaching purposes only.
2. The phasemeter block diagram is depicted as shown in the diagram.
3. The instrumentation block diagram is labeled as "JPL/MAM phasemeter schematic".
4. The instrumentation block diagram may be divided in three parts (a) upon which individual phase shift input edge (b) upon which Unknown phase input edge. Methods (a) and (c) have been used for clarity.
5. The phasemeter block diagram may be divided in three parts (a) upon which JPL/MAM phase shift input edge. Methods (a) and (c) have been used for clarity.
Upgrade for absolute metrology

Laser source upgrade for absolute metrology. Light from lasers A and B are held 15 GHz apart by the laser offset locking electronics. A clock signal (in practice, the phasemeter readout clock) toggles intensity modulators A and B. The resulting 500 Hz rate, 15 GHz amplitude FM is fed to the metrology gauge for absolute calibration, as described in the text.

- Synthetic wavelength is 20 cm.
- Know absolute distance modulo 10 cm
- Current accuracy: ~5 microns

Absolute Metrology

- SIM external metrology requires knowledge of absolute distances to 3 μm
- For Kite, the requirement is 10 μm
Absolute Metrology Gauge Implementation

- Based on Switched Heterodyne Architecture

1. bring two fiducials into repeatable, measurable separation via contact
2. measure the change in the distance as they are separated
3. insert Abs Met gauge: \( \text{LGauge constant} = \text{Abs Met - Calibration} \)
4. repeat for a range of fiducial separations

MISSiON

Presentation 15

 Absolute Metrology Gauge Offset Calibration

- Basic approach:
  1. bring two fiducials into repeatable, measurable separation via contact
  2. measure the change in the distance as they are separated
  3. insert Abs Met gauge: \( \text{"Gauge constant" = Abs Met - Calibration} \)
  4. repeat for a range of fiducial separations

 calibration interferometer

 Vertical spread measures absolute metrology system performance
Two separate runs used to get performance estimate:

\[ \Delta = 3.9 \, \mu m \]

\[ \sigma = 3.3 \, \mu m \]

\[ \epsilon_{Abs \, Met} < 6 \, \mu m \]
Source beam is physically split at double sided mirror into a small narrow reference beam which passes directly to the detector and the larger measurement beam that is circulated around the racetrack.

- The reference and measurement beams are rejoined but remain physically separated on the other side of the double sided mirror. They each mix with the LO at the beam splitter.
- The measurement and reference beams are then redirected to their own detector by the scraper mirror each with their own share of the LO beam.
Metrology gauge setup for thermal test

2-Gauge Test Configuration
Block diagram of laser heterodyne interferometer which measures changes in $L$, the distance between retroreflectors CC1 and CC2. An optional second gauge (shown in gray) can measure the same distance, allowing useful gauge comparisons. The letters A..E indicate regions where cyclic error originates. For cyclic error detection, the piezoelectric (PZT) actuator moves CC1 with a voltage ramp that has been precompensated for piezo hysteresis, to achieve near-constant velocity.

Cyclic error: a periodic non-linearity

- Imperfect split of Measurement beam away from reference beam causes constant leakage of M light into wrong path.
- At recombination: M beam + leakage M causes periodic phase advance/retardation ----> Cyclic Error
- To keep cyclic error below 10 pm, must have
  - Optical leakage < 80 dB (low optical cross-talk)
  - Electronic cross-talk < 80 dB
  - Or, if we’re lucky, use some “tricks”.

Phasor Diagram

Round trip phase

Constant leakage

(2\pi of phase for every $\lambda$ of OPD change)
The Role of Kite

- The role of Kite is to verify SIM external metrology performance
- SIM external metrology tracks baseline changes as the fiducials move
- Testing up to now has been 1D (2-gauge)
- The Kite 2D truss will show it can track similar changes to the level required by the SIM performance model (Currently PM36a).

Ideally, Kite performance should be limited by the gauge performance, where the gauge performance is derived from the SIM error budget.

Kite Approach and Architecture

- Build a redundant metrology truss:
  - 4 fiducials (2 corner cubes + 2 triple corner cubes)
  - 6 metrology gauges connecting the 4 vertices
  - All in a plane (to required level)

- Compare the readings from one gauge with prediction using the other 5 as a CC is articulated by various amounts of tip and tilt or translation

- Account for CC imperfections using CC calibration and model

- Take the difference of the residual before vs after

Show the rms error is below requirement for the various cases of:
- 0.5 deg articulation (NA) at 50 pm rms
- 7.5 deg articulation (WA) at 300 pm rms
- simulated PSS thermal deformation (1um, 10 um)
Kite Testbed Configuration

- Kite table is situated in the MAM vacuum chamber
  dictated by triple corner cube constraints

Kite Installed in Vacuum Chamber

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SIM evolves...

- New configuration uses fewer metrology measurements
- Is more compact: fits into Space Shuttle or Expendable Launch Vehicle
Fit into shuttle bay or EELV

In Shuttle Bay

Deployable 2-piece sunshade/contamination cover

In EELV Delta IV Heavy Fairing

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