SIM (Lite)

> *SIM Lite is ready to go now*
> *and is capable of finding one-Earth-mass planets*
> *in the habitable zone of <u>nearby</u> sun-like stars*
> *as well as addressing the NRCs astrophysics objectives.*
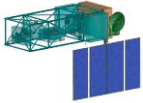
SIM Lite Overview

Jim Marr, Project Manager

Mike Shao, Project Scientist

Renaud Goullioud, Instrument Manager

24 September 2008

National Aeronautics and Space Administration
Jet Propulsion Laboratory
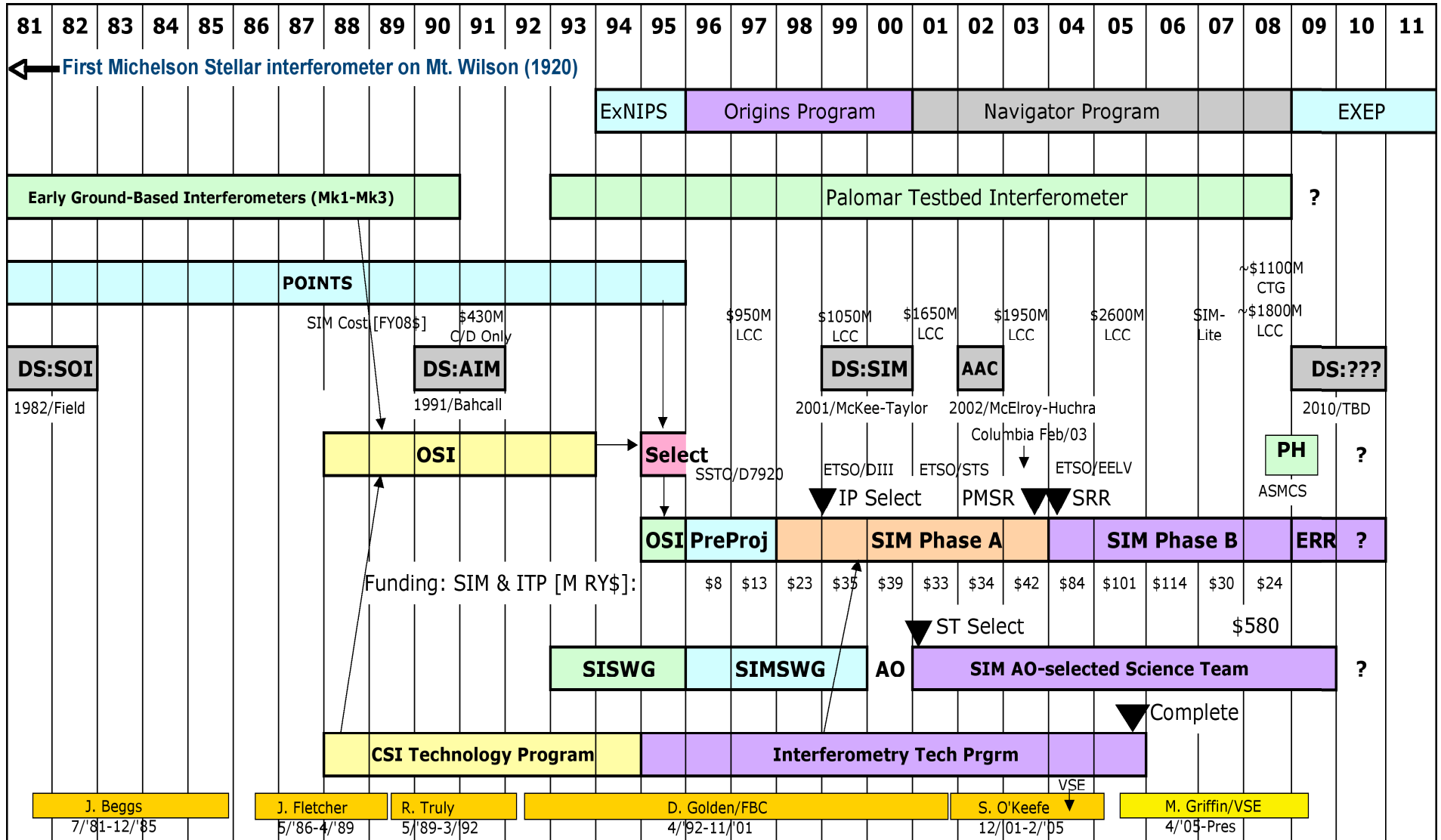**California Institute of Technology**

SIM (Lite)

- Technology development completed in 2005.
  - Unexpectedly good performance produced 40% margin to Goal-level performance.
- NASA indefinitely delayed the project for budgetary reasons.
- Project team has developed more affordable options using the completed technology but taking advantage of excess performance.
  - Performance is reduced to Goal-level.
  - Full breadth science program.
  - Independent cost estimating now underway.
- Project just completed a double-blind planet finding capability study to determine capability to find habitable zone terrestrials in complex systems like our solar system at 10 pc.
  - Demonstrated SIM Lite's ability to find HZ terrestrials in the presence of large planets.
- SIM Lite future depends upon upcoming Decadal survey.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

SIM History & Context

| 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 |

← **First Michelson Stellar interferometer on Mt. Wilson (1920)**

ExNIPS | Origins Program | Navigator Program | EXEP

Early Ground-Based Interferometers (Mk1-Mk3) | Palomar Testbed Interferometer | ?

POINTS

~$1100M CTG
~$1800M LCC

SIM Cost [FY08$] $430M C/D Only

$950M LCC $1050M LCC $1650M LCC $1950M LCC $2600M LCC SIM-Lite

DS:SOI **DS:AIM** **DS:SIM** **AAC** **DS:???**

1982/Field 1991/Bahcall 2001/McKee-Taylor 2002/McElroy-Huchra 2010/TBD

Columbia Feb/03

OSI → **Select** **PH** ?

SSTO/D7920

ETSO/DIII ETSO/STS ETSO/EELV

ASMCS

▼ IP Select PMSR ▼▼ SRR

OSI | PreProj | SIM Phase A | SIM Phase B | ERR | ?

Funding: SIM & ITP [M RY$]:

| $8 | $13 | $23 | $35 | $39 | $33 | $34 | $42 | $84 | $101 | $114 | $30 | $24 |

▼ ST Select $580

SISWG | SIMSWG | AO | **SIM AO-selected Science Team** | ?

▼ Complete

CSI Technology Program | **Interferometry Tech Prgrm**

VSE

J. Beggs | J. Fletcher | R. Truly | D. Golden/FBC | S. O'Keefe | M. Griffin/VSE

7/'81-12/'85 5/'86-4/'89 5/'89-3/'92 4/'92-11/'01 12/'01-2/'05 4/'05-Pres

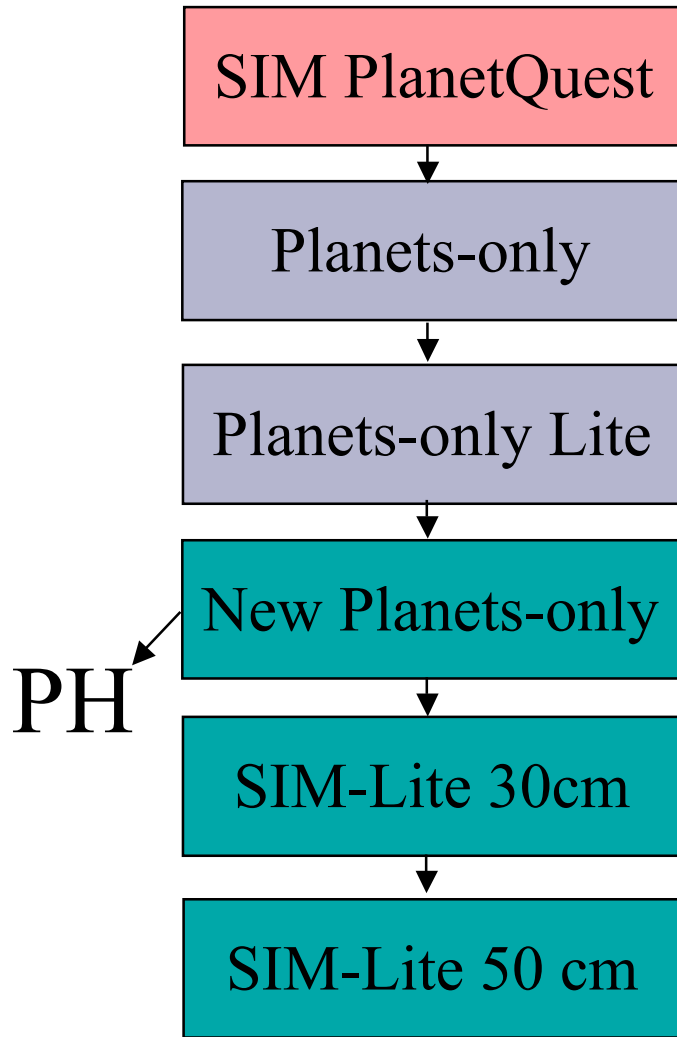SOI - Space Optical Interferometry

MO Loss MCO MPL Loss Spear FBC Report

Astrometric Mission Option Study Sequence

SIM (Lite)

	Interfero-meter Baseline	Science Interf. Aperture	Guide #2 Config.	Science Observation Types
SIM PlanetQuest	9 m	30 cm	Interfero-meter	NA and WA
Planets-only	6 m	30 cm	Telescope	NA only
Planets-only Lite	4 m	18 cm	Telescope	NA only
New Planets-only	6 m	30 cm	Telescope	NA only
SIM-Lite 30cm	6 m	30 cm	Telescope	NA and WA
SIM-Lite 50 cm	6 m	50 cm	Telescope	NA and WA

PH

SIM-PlanetQuest vs. SIM-Lite

SIM (Lite)

SIM-PlanetQuest Salient Features

- *9 meter science Michelson Stellar Interferometer (MSI) with 30 cm siderostats.*
- *Two 6.7m MSI Guides*
- Visible wavelength
- Earth-trailing solar orbit
- 5 year mission, *with a 10 year mission goal*
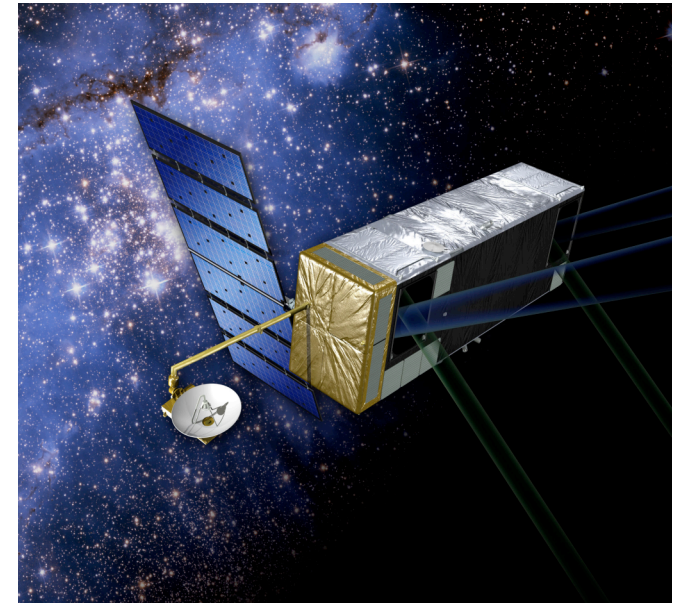
SIM-Lite Salient Features

- *6 meter science Michelson Stellar Interferometer (MSI) with 50 cm siderostats.*
- *One 4.2m MSI and one 30cm Telescope Guides*
- *Simplified mechanism, lower cost hardware*
- *Simplified controls, analysis & operation*
- Visible wavelength
- Earth-trailing solar orbit
- 5 year mission
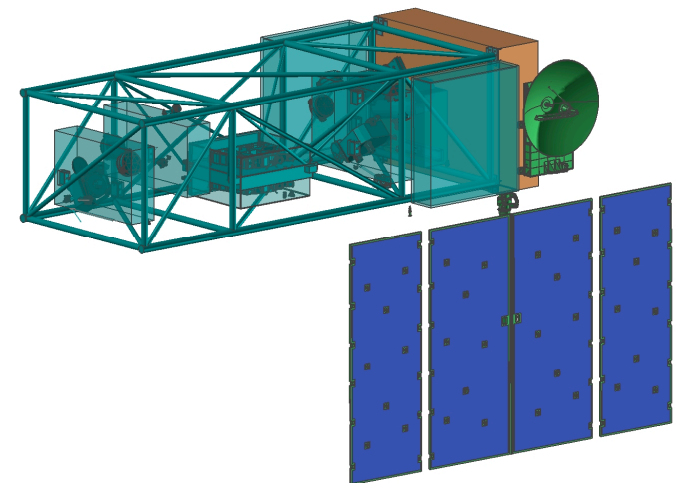
SIM Performance Meets NRC Goals

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."
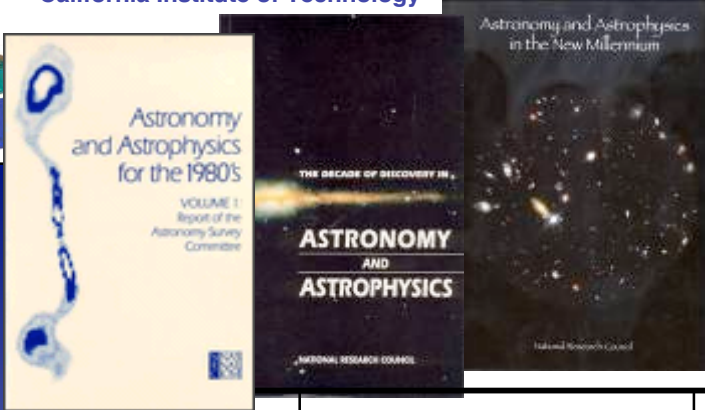
SIM (Lite)

Concept	Wide-Angle Astrometry		Narrow-Angle Astrometry		Magnitude Limit (V)	Nulling?	Synthesis Imaging?
	Requirement (µas)	**Goal (µas)**	Requirement (µas)	**Goal (µas)**			
1982 AASC (SOI)	Space Optical Interferometer (SOI) with resolutions of 1 to 10 µas by early part of next century.						
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 CAA Assessment*	10	4	3	1	20	No	10 m baseline (plus rotation)
SIM-PQ** Performance	2.4 µas		0.7 µas[†]		20	No	9 m baseline (plus rotation)
SIM-Lite** Performance	4 µas		1 µas[†]		19-20	No	6 m baseline (plus rotation)
Planet Hunter** Performance	N/A		1 µas[†]		10	No	6 m baseline (plus rotation)

* 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).

SIM Basic Definitions and Parameter Values

SIM (Lite)

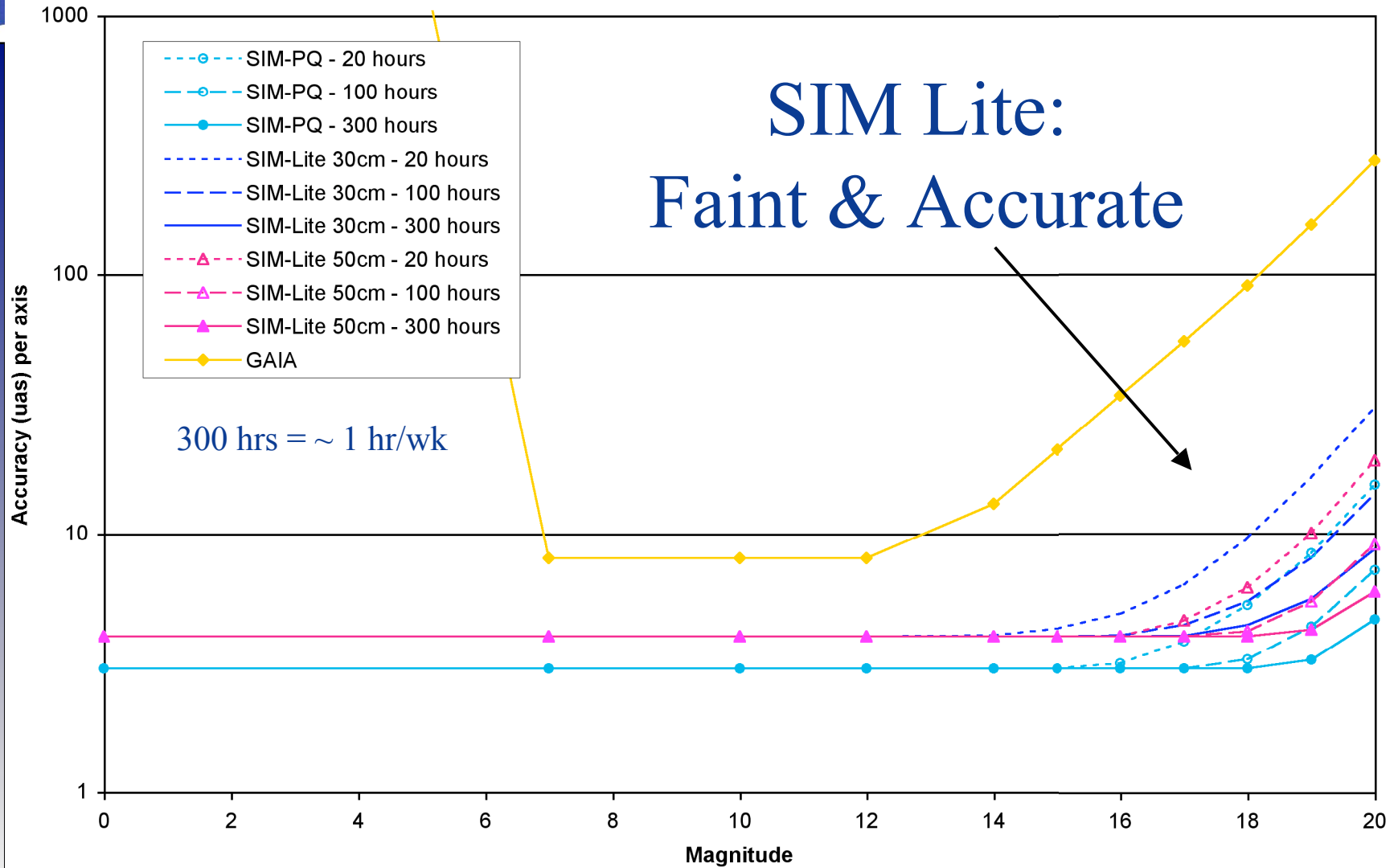| Term	Description	Value
Interferometer Baseline (BL)	The distance between two collecting mirrors.	6 m
Single Measurement Accuracy (SMA)	The uncertainty associated with measuring the angle between the baseline vector and target star.	1.0 µas, 1-sigma RMS
One-Dimensional (1D) Measurement Accuracy or Differential Measurement Accuracy (DMA)	During a typical ~1100 s measurement, the angle between the target star and baseline vector is measured to the SMA. Similarly, the angle between the baseline vector and a reference star (or the average of a group of reference stars) is determined to the SMA. Both angles are measured from one interferometer baseline orientation in inertial space. The angle between the target star and the reference is the difference between these two angles with a resulting accuracy given by the root-sum-square (RSS) of these two measurement accuracies.	1.4 µas, 1-sigma RMS
Two-Dimensional (2D) Measurement Accuracy	Two one-dimensional (1D) measurements made with roughly orthogonal interferometer baseline orientations and made relatively close together in time.	2-axis, 1.4 µas on each axis, 1-sigma RMS.
External Delay Uncertainty Noise Floor (EDUNF)	Uncertainty in measuring the difference in external delays resulting from all instrument errors (see the Astrometric Error Budget (AEB)) as validated by testbed measurements.	1 picometer, 1-sigma RMS
Instrument Noise Floor (INF)	Noise floor for measuring the angular distance between two stars, determined from the fringe position uncertainty noise floor and the interferometer baseline (EDUNF/BL*asec/radian).	0.035 µas
N_Obs_Max, or N_lim (2D)	The number of 2D differential measurments that can be made on a single target star that results in net noise reaching the Instrument Noise Floor. Equals (DMA/INF)^2.	1,600
Minimum Detectable Astrometric Signature (MDAS)	Instrument Noise Floor times desired SNR. For 1% false alarm probability (FAP), want SNR=~6. INF*SNR=0.035µas*6= 0.21µas.	0.21 µas
Minimum Detectable Earth-like Planet Mass	This is dependent upon the MDAS, star distance, stellar mass, and the planet's orbit. For a one Solar mass star at 10 pc, the minimum detectable habitable-zone planet mass depends upon where the planet is in the habitable-zone as shown below.	See below
	At the outer edge of habitable zone (1.6 AU)	0.44 Mearth
	Mid habitable zone (1.0 AU)	0.70 Mearth
	At the inner edge of the habitable zone (0.82 AU)	0.85 Mearth

Mission Wide Angle Performance
(For a 5 yr mission)

SIM (Lite)

Accuracy (uas) per axis

- - - o - - - SIM-PQ - 20 hours
- - - o - - SIM-PQ - 100 hours
———•——— SIM-PQ - 300 hours
- - - - - - SIM-Lite 30cm - 20 hours
- - - - - SIM-Lite 30cm - 100 hours
——— SIM-Lite 30cm - 300 hours
- -△- - SIM-Lite 50cm - 20 hours
- -△- SIM-Lite 50cm - 100 hours
——▲—— SIM-Lite 50cm - 300 hours
——◆—— GAIA

300 hrs = ~ 1 hr/wk

SIM Lite:
Faint & Accurate

Magnitude

SIM Unique Science - Still Relevant

SIM (Lite)

Planet Surveys

Deep Survey:

- Search 60-100 stars within 30 pc for habitable zone (HZ) terrestrials.
- *Search depth determines how many HZ terrestrials will be found.*

Broad Survey:

- 1000 stars for masses a few $M_{\oplus}$ and greater.
- Variety of spectral types, ages, and metallicities.
- *Explore the diversity of planetary systems.*

Young Planet Survey:

- ~50 stars of 1-100 Myr ages.
- Not accessible by other methods.
- *Test theories of planetary system formation and evolution.*

General Astrophysics

- Precision M-L relation for extreme stellar types.
- Late stages of stellar evolution.
- Stellar evolution, extragalactic distances & galaxy formation.
- Cepheids in the Milky Way.
- Accurate ages and distances for population II objects.
- Galactic stellar populations and dark matter on galactic scales.
- Astrometric microlensing.
- Dynamics of galaxy motions.
- Quasar jets and accretion disks.
- Cosmology: H_0 & EOS; rotational parallaxes.
- Imaging.
- Measuring the PPN parameter γ.

Planet Finding Capability Study

SIM (Lite)

- NASA asked:
  - Can an astrometric mission detect Earths in the habitable zone (HZ) of a solar system analog at 10pc?
- Four sets of teams:
  - A-system modelers (5 teams, 100 systems each),
  - B-generate simulated data sets (1 team),
  - C- data analysis (5 teams),
  - D-data synthesis (1 team).
  - HQ External Independent Review Board (EIRB) subset for review.
- Timeline:
  - Start Jan'08;
  - Team C's on contract Apr'08;
  - Team C-analysis completed Aug'08.

Planet Finding Team Membership

SIM (Lite)

Team A groups (system modeling)

- Team A-1: Eric Ford, Univ. of Florida, eford@astro.ufl.edu
- Team A-2: Greg Laughlin, UC Santa Cruz, laugh@ucolick.org
- Team A-3: Hal Levison, Southwest Research Institute, hal@boulder.swri.edu
- Team A-4: Doug Lin, UC Santa Cruz, lin@ucolick.org
- Team A-5: Sean Raymond, Univ. of Colorado, Raymond@lasp.colorado.edu

Team B (data simulation)

- Andy Boden, Michelson Science Center, bode@ipac.caltech.edu
- Valeri Makarov, Michelson Science Center, vmakarov@ipac.caltech.edu

Team C groups (data analysis)

- Team C-1: Stefano Casertano, STScI, Stefano@stsci.edu
- Team C-2: Debra Fischer, San Francisco State Univ., fischer@stars.sfsu.edu
- Team C-3: Jeremy Kasdin, Princeton Univ., jkasdin@princeton.edu
- Team C-4: Matt Muterspaugh, UC Berkeley, mathew1@ssl.berkeley.edu
- Team C-5: Mike Shao, JPL, Michael.Shao@jpl.nasa.gov

Team D (results synthesis)

- Chair: Wes Traub, JPL, wtraub@jpl.nasa.gov
- Vice-Chair: Alan Boss, Carnegie Institution, boss@dtm.ciw.edu
- Andy Gould, Ohio State University, gould@astronomy.ohio-state.edu
- Angelle Tanner, MSC, angelle.tanner@jpl.nasa.gov
- Chas Beichman, MSC, Charles.A.Beichman@jpl.nasa.gov
- Team C leaders.
- May include one member from Teams A and one member from Team B.

External Independent Readiness Board (EIRB)

- Chair: Vern Weyers, GSFC retired, vjweyers@comcast.net
- Alan Boss, Carnegie Institution, boss@dtm.ciw.edu
- Ed Groth, Princeton Univ, groth@pupgg.princeton.edu
- Joseph Wampler, consultant, jwampler@mail.cruzio.com

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Jet Propulsion Laboratory
California Institute of Technology

SIM (Lite)

- 48 planetary systems (all 1 Sun @ 10 pc).
  - 32 random, 8 Solar-system-analogs, 4 single terrestrial in HZ, 4 no-planets.
  - Noise added to all systems (4 levels).
- Reliability in detections, (what fraction of reported detections were valid?), varied between teams from 40% to 100% (3 teams > 80%)*.
- Completeness (what fraction of detectable planets were detected?)
  - 48 of 95 planets were reasonably detectable.
  - All were found by at least one team (most by 3 or 4 teams).
- 16 detectable HZ planets - all were found by at least 2 teams.
- 12 detectable terrestrial HZ planets - all were found by at least 2 teams.
- **Presence of multiple planets has essentially no impact on the ability to detect terrestrial planets in the HZ (Major Conclusion).**
  - **SIM Lite can find Earths in complex systems such as our solar system.**
- **Double Blind study validated methods used to predict performance.**

* Teams were starting from different levels; JPL team had head start and did best. Expect that, given more time, all teams would approach performance of the best.
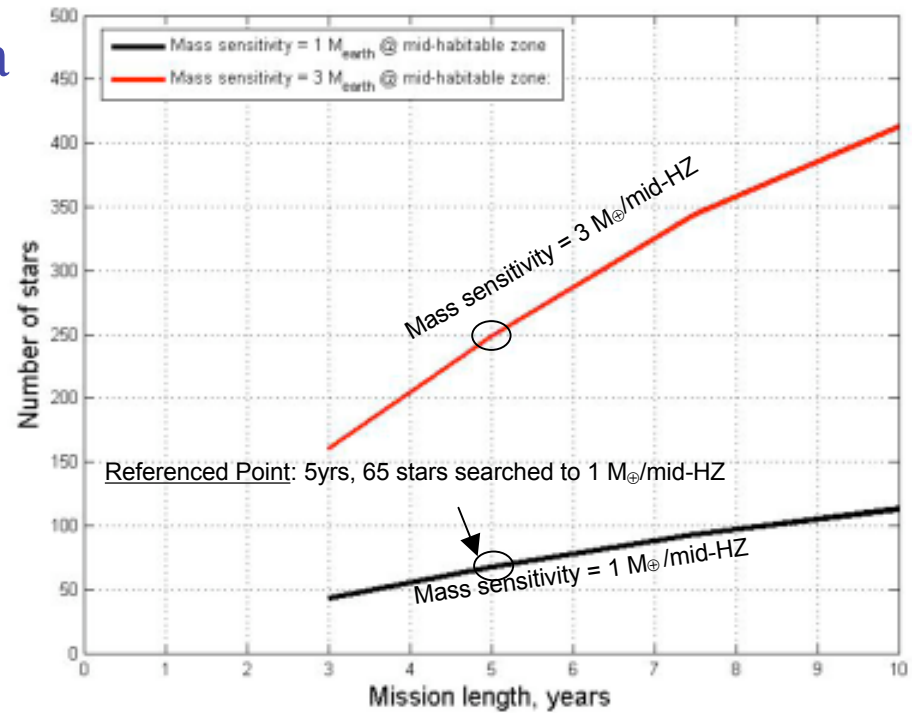
1 μas Astrometry will find Earth-Analogs around solar-type stars!

SIM (Lite)

- AAAC Exoplanet Task Force recommended:
  - 0.22 μas astrometry after hundreds of visits.
  - 60-100 nearby FGK stars searched for 1 M_{Earth} at inner edge of the Habitable Zone.
- SIM-Lite can search ~60 stars for search down to 1 M_{Earth}
  - using 40% of the mission time.
- Relaxing search depth even a little enables broader search or search in less time.
  - Can adjust search depth after Kepler results are in.
- SIM can accurately determine stellar distances for Kepler and CoRot to allow better planet diameter estimates from transit photometric data.
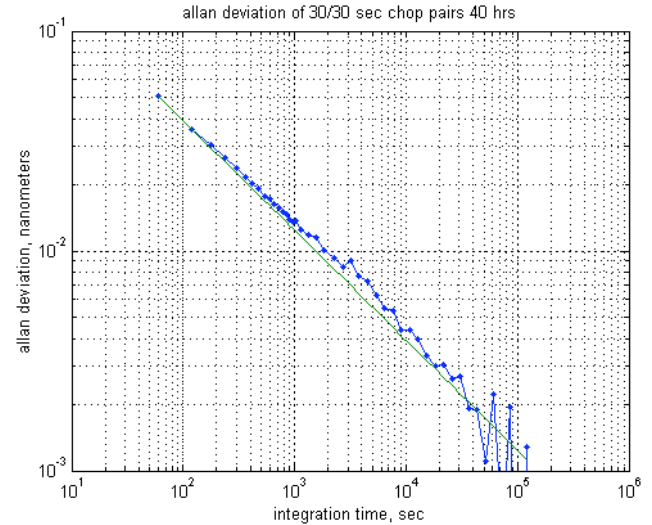

Mass sensitivity = 1 M_{earth} @ mid-habitable zone
Mass sensitivity = 3 M_{earth} @ mid-habitable zone:

Mass sensitivity = 3 $M_{\oplus}$/mid-HZ

Referenced Point: 5yrs, 65 stars searched to 1 $M_{\oplus}$/mid-HZ

Mass sensitivity = 1 $M_{\oplus}$/mid-HZ

Number of stars — Mission length, years

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Jet Propulsion Laboratory
California Institute of Technology

Instrument Errors

SIM (Lite)

- Thermal drift
  - Modeling predicts performance better than that of ground testbeds.
  - Ground testbed data (MAM & SCDU) show thermal noise to be white after chopping and averages to less than 1 pm with no floor based upon longest data sets taken to date.

- Field dependent (e.g., beamwalk)
  - SIM-Lite NA measurements all made within 1° of center of field.

- Color dependent
  - Spectral Calibration Development Unit (SCDU) showed how to correct for stellar color dependent errors when chopping.

allan deviation of 30/30 sec chop pairs 40 hrs

Compare FI TRT metric

- SCDUE2007FIsFringe
- SCDUE2007FIpFringe
- MAM2006FI

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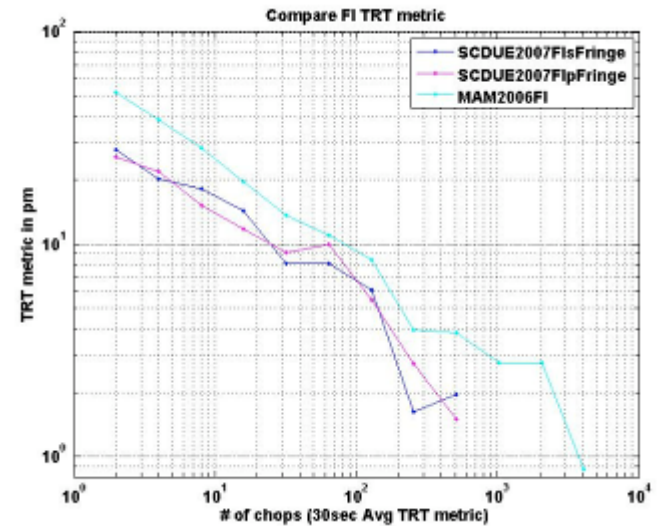
SIM (Lite)

- Reference star companions
  - Three cases:

    (1) Large, pre-screened by RV;

    (2) Too small;

    (3) Solved for along with target star companions.

- Star Spots impact on detection of habitable exo-Earths:
  - Astrometry: Spot noise significantly below exo-Earth signature and instrument noise.
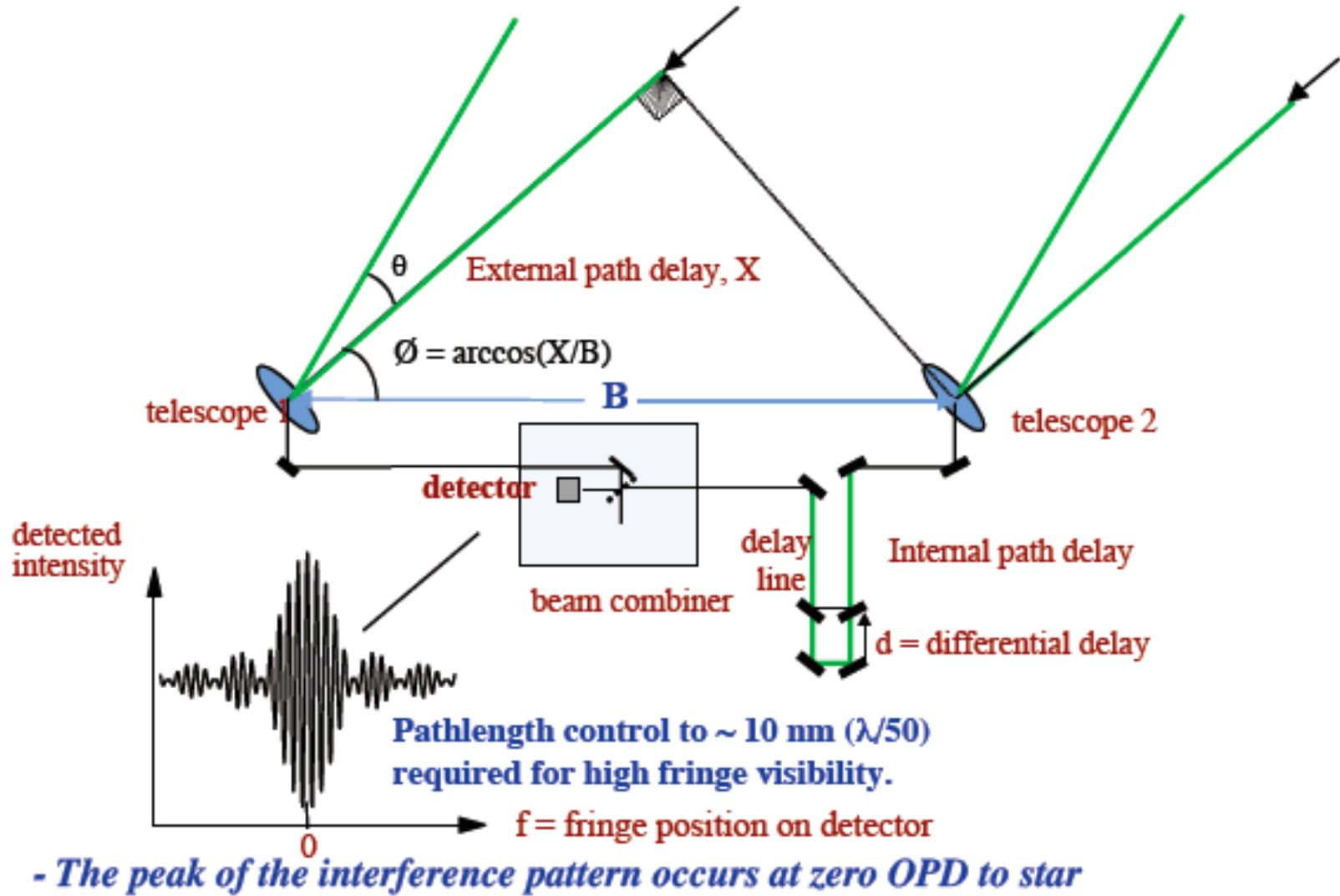 - RV: Spot noise larger than exo-Earth signature.

Periodogram of stellar astrometric centroid variations
Earth at 1 AU orbiting solar-mass star at 3 pc, inc = 45 deg
100 samples over 5 years, 1.41 uas meas error

- X power
- Y power
- Joint X + Y power
- 1% FAP threshold for Joint detection

0.7 µAU spot noise doesn't Inhibit exo-Earth detection.

Power in µAU^2

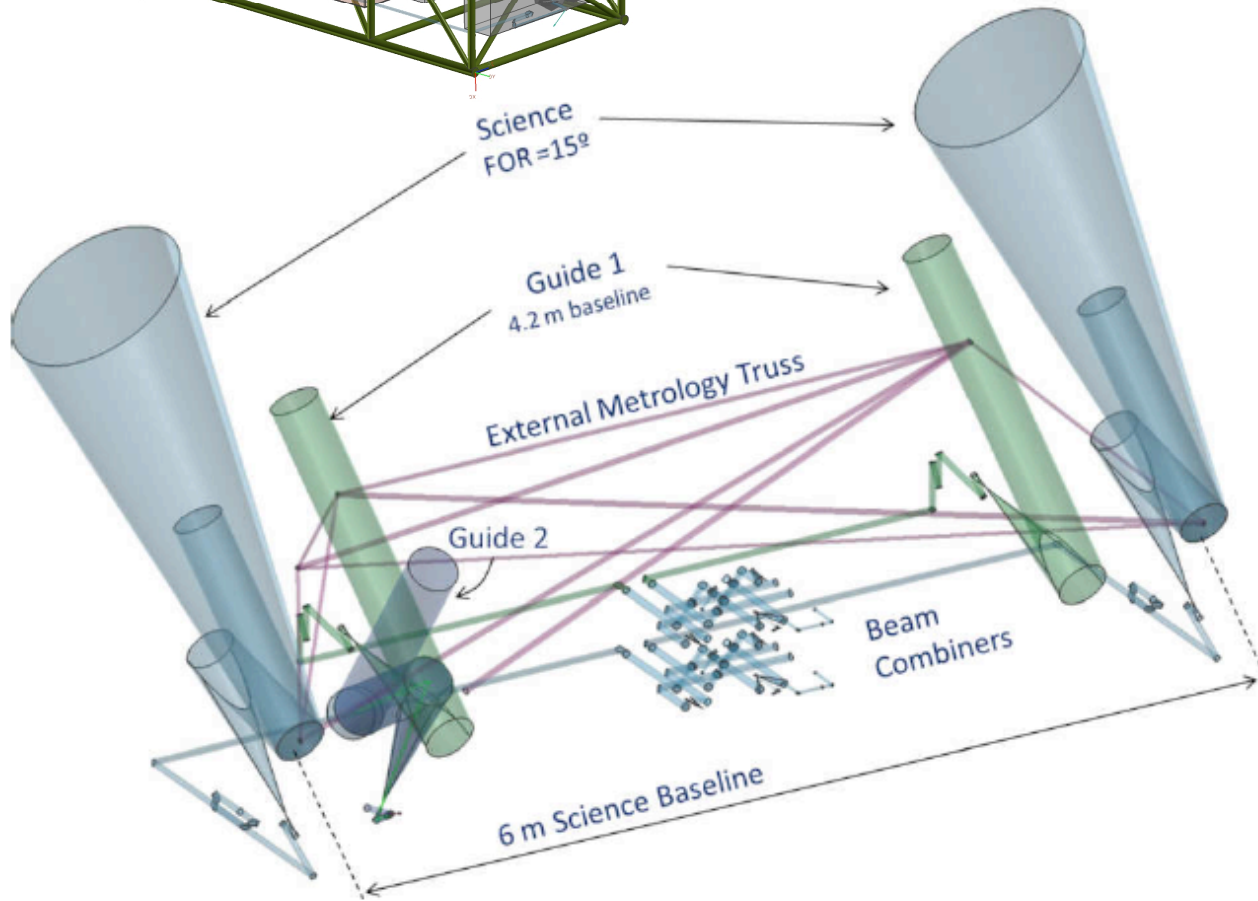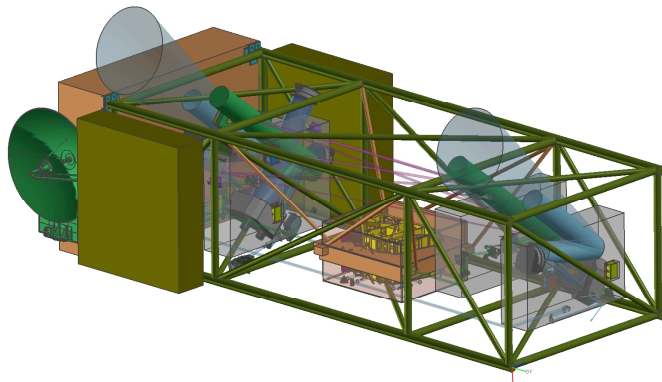frequency, HZ   x 10^{-7}
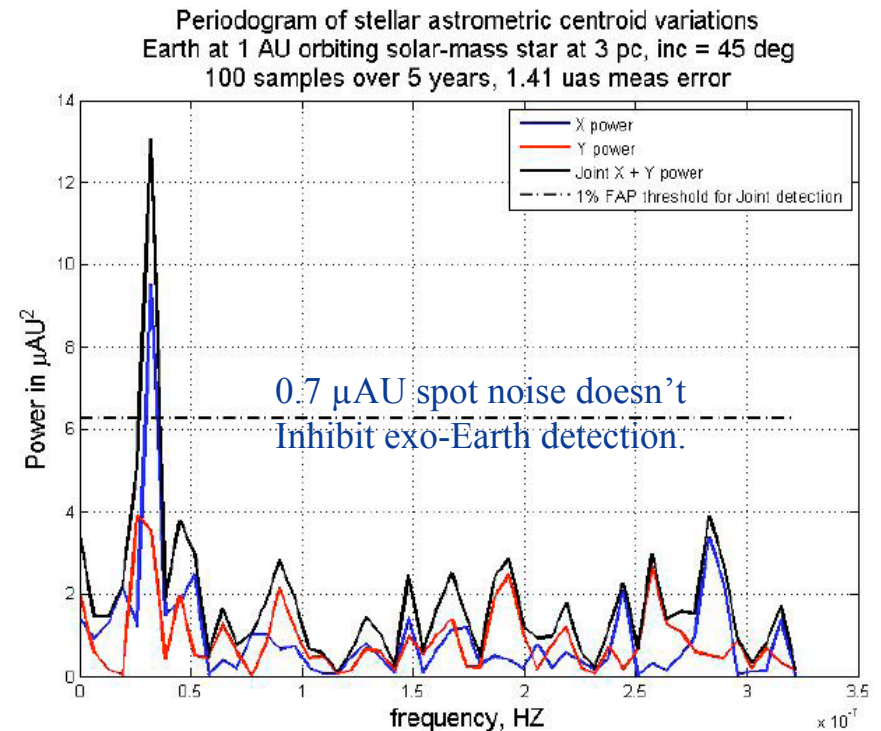
Astrometry with an stellar interferometer

SIM (Lite)

External path delay, X

θ

$\emptyset = \arccos(X/B)$

B

telescope 1

telescope 2

detector

beam combiner

delay line

Internal path delay

d = differential delay

detected intensity

Pathlength control to ~ 10 nm (λ/50) required for high fringe visibility.

f = fringe position on detector

0

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

SIM-Lite Configuration

Science FOR =15º

Guide 1
4.2 m baseline

External Metrology Truss

Guide 2

Beam Combiners

6 m Science Baseline

Atlas V 521

Note: Centaur upper stage used inside fairing on 521.
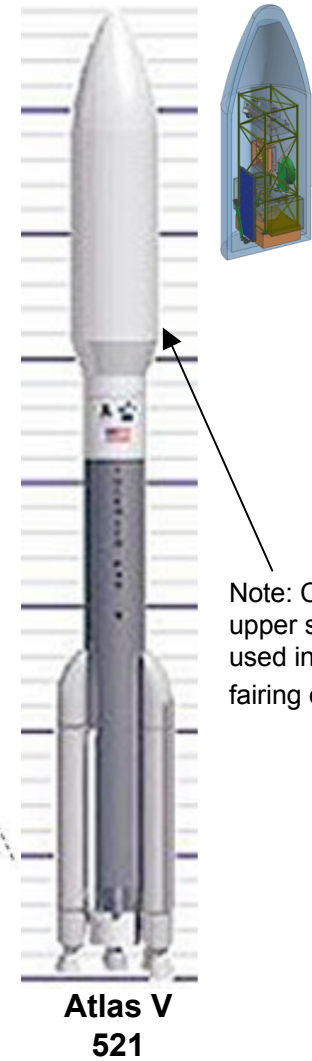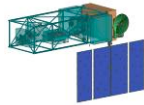
SIM (Lite)

Why is SIM-Lite More Affordable?

- Takes advantage of excess performance over NRC Goals, so…
- Less hardware.
  - Guide-2 Telescope replaces G2 Michelson Stellar Interferometer (MSI).
  - Fewer structure bays with fewer supports.
- Simpler hardware and software.
  - Guide-1 MSI co-bore-sighted with Science MSI FOR.
  - Eliminated second stages of many actuators.
  - Delay lines moved to collector benches (no separate structure)
  - Standardized instrument actuators, electronics & S/W.
- Less expensive hardware.
  - Lower cost off-the-shelf spacecraft components with fixed HGA.
- Smaller baseline, lower mass.
  - Shorter, simpler system integration and test.
    - Field independent testing only.
  - Smaller launch vehicle.
- Simpler (less flexible) science operations approach.
  - As much as possible, operations laid out pre-launch.
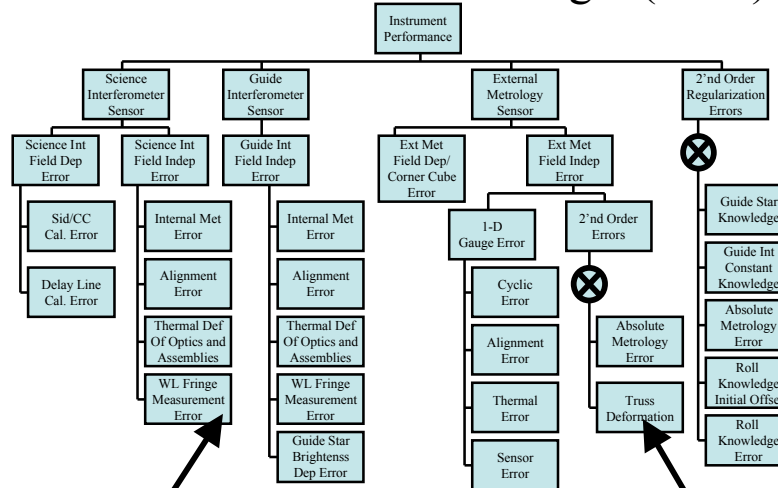
SIM (Lite)

Performance Prediction & Validation

AEB, testbeds, model predictions & integrating analytical models used to verify overall system performance (for both Technology Development and Flight)

Astrometric Error Budget (AEB)

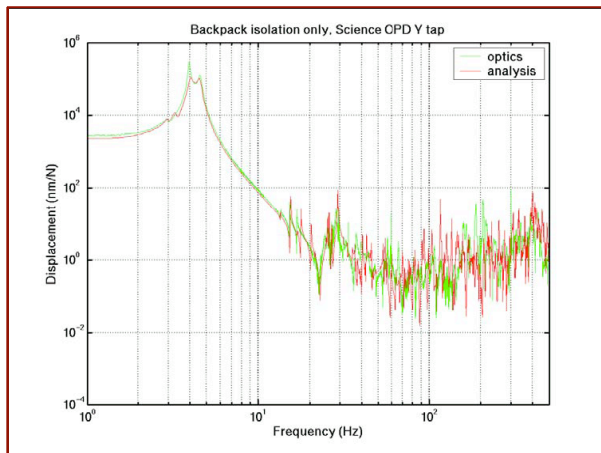AEB top-level summary.

Verify Physics

Independent Review & Assessment

-Allocation/Capability
-Verify no missing terms

Model Predictions

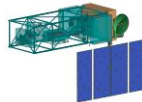Confirm physics-based predict match actual?

Testbed Demonstrations
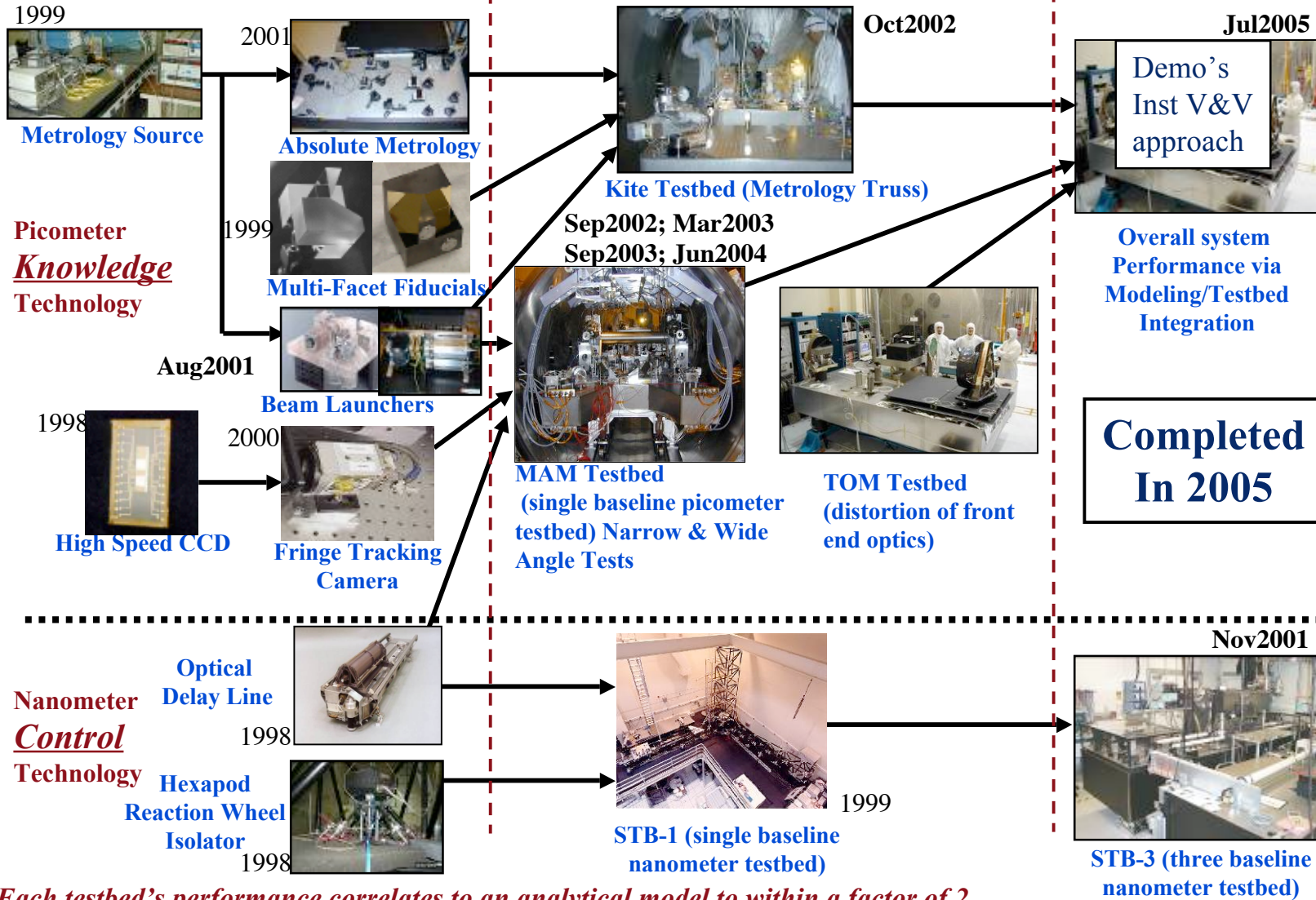
SIM (Lite)

Technology Complete; Exceeded Goals

Component Technology	**Subsystem-Level Testbeds**	**System-Level**

SIM (Lite)

1999
Metrology Source

2001
Absolute Metrology

Picometer *Knowledge* **Technology**

1999
Multi-Facet Fiducials

Aug2001
Beam Launchers

1998
High Speed CCD

2000
Fringe Tracking Camera

Oct2002
Kite Testbed (Metrology Truss)

Sep2002; Mar2003
Sep2003; Jun2004
MAM Testbed (single baseline picometer testbed) Narrow & Wide Angle Tests

TOM Testbed (distortion of front end optics)

Jul2005
Demo's Inst V&V approach

Overall system Performance via Modeling/Testbed Integration

Completed In 2005

Nanometer *Control* **Technology**

Optical Delay Line
1998

Hexapod Reaction Wheel Isolator
1998

STB-1 (single baseline nanometer testbed)
1999

Nov2001
STB-3 (three baseline nanometer testbed)

Each testbed's performance correlates to an analytical model to within a factor of 2.

Metrology Hardware Qual-Level Tested!

SIM (Lite)
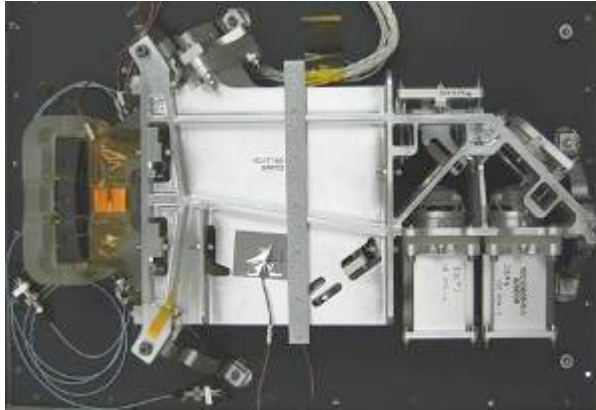
External
Metrology
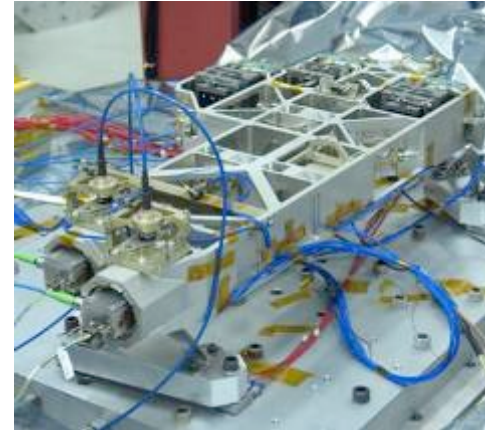Launcher

Metrology
Source
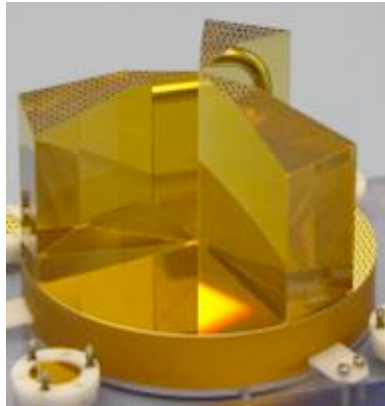
Double Corner
Cube

Internal Metrology
Launcher

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
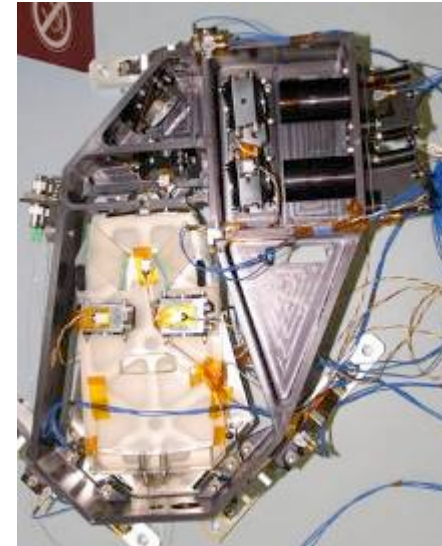
- Double-Blind ExoPlanet Finding Study continuing…
  - Part 2 of the study now defined.
  - Will look at specific SIM Lite target stars (vs. Suns at 10 pc as before).
  - A number of additional tasks.
- Complete and qualification test additional instrument brassboard hardware.
  - Astrometric Beam Combiners assembly.
  - Fringe Tracker and Star Tracker cameras.
  - Fine Steering and Phasing Mirror mechanisms.
- Complete last two major testbed activities: SCDU & G2T
- Complete life testing of PZT actuators and ball screw actuators.
- SIM Lite Independent Cost Estimate by NASA SMD APD beginning in Oct 2008.
- Exploring additional partnerships - especially international.

SIM (Lite)

Summary

SIM (Lite)

- SIM-Lite's technology development program is complete.
  - Perhaps the most heavily externally reviewed technology program ever.
  - Demonstrated better than NRC Goal-level performance capability.
- Subsequent engineering risk reduction has demonstrated flyable hardware for critical elements (e.g., picometer metrology).
- SIM-Lite science remains as compelling today as it was in 1990.
  - SIM-Lite's combination of dim-star ($\leq$V20) with ultra astrometric precision (1 μas) reaches where no other mission can.
- The project has developed more affordable options.
- SIM-Lite is *technically* ready to launch as early as mid-decade.
- *SIM-Lite is ready to go now and is capable of finding one-Earth-mass planets in the habitable zone of **nearby** Sun-like (FGK) stars as well as addressing the NRCs astrophysics objectives.*

SIM (Lite)

Backup

Technology Gates & Results

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

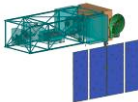| Technology Gate	Description	Due Date	Complete Date	Performance
1	Next generation metrology beam launcher performance at 100pm uncompensated cyclic error, 20pm/mK thermal sensitivity	8/01	8/01	Exceeded objective
2	Achieve 50dB fringe motion attenuation on STB-3 testbed (demonstrates science star tracking)	12/01	11/01	Exceeded objective
3	Demonstrate MAM Testbed performance of 150pm over its narrow angle field of regard	7/02	9/02	Exceeded objective
4	Demonstrate Kite Testbed performance at 50pm narrow angle, 300pm wide angle	7/02	10/02	Exceeded objectives
5	Demonstrate MAM Testbed performance at 4000pm wide angle	2/03	3/03	Exceeded objective
6	Benchmark MAM Testbed performance against narrow angle goal of 24pm	8/03	9/03	Exceeded objective
7	Benchmark MAM Testbed performance against wide angle goal of 280pm	2/04, 5/04*	6/04	Met objective
8	Demonstrate SIM instrument performance via testbed anchored predicts against science requirements	4/05	7/05	Met objective

Legend: pm = picometer
mK = milliKelvin
dB = decibel (50dB = factor of 300)

* HQS directed a scope increase (by adding a numerical goal to what had been a benchmark Gate) and provided a 3 month extension when performance fell short

SIM (Lite)

Engineering Milestones
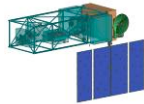
- ## Five EM's to be completed during Phase B.
  - ### All five now complete.
 - ### Exceptional performance confirms Goal-level performance.

Formulation Phase				
EM-1	External Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	5/31/06	6/5/06	Exceeded Objective
EM-2	Internal Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	4/30/06	5/3/06**	Exceeded Objective
EM-3	Metrology Source Assembly Validation (meet Qual environmental and allocated performance)	6/30/06	6/28/06	Exceeded Objective
EM-4	Spectral Calibration Development Unit (SCDU) (demo flight-traceable fringe error calibration methodology and validate model of wavelength-dependent measurement errors)	8/30/07	12/10/07	Met Objectives
EM-5	Instrument Communication H/W & S/W Architecture Demo (validate SIM's multi-processor communications system using two brassboard instrument flight computers, ring bus, and flight software version 2.0 with specific S/W functions as listed)	4/1/07	3/5/07	Met Objectives

- ## Additional Brass-Board Units currently under development:
  - ### Astrometric Beam Combiners assembly.
  - ### Fringe Tracker and Star Tracker cameras.
  - ### Fine Steering and Phasing Mirror mechanisms.
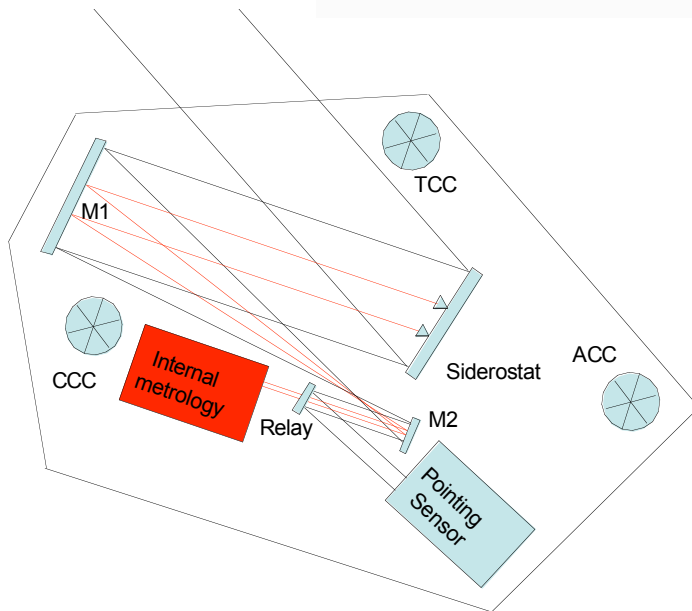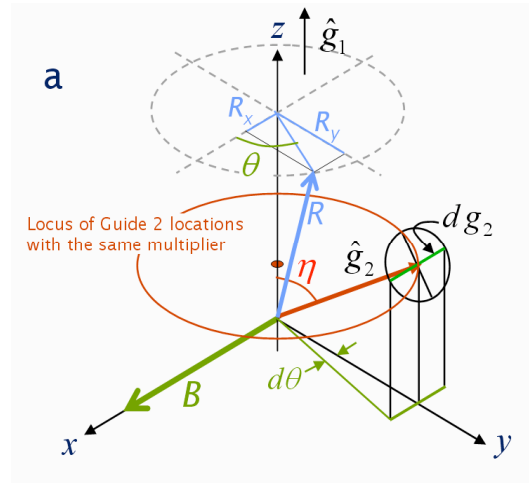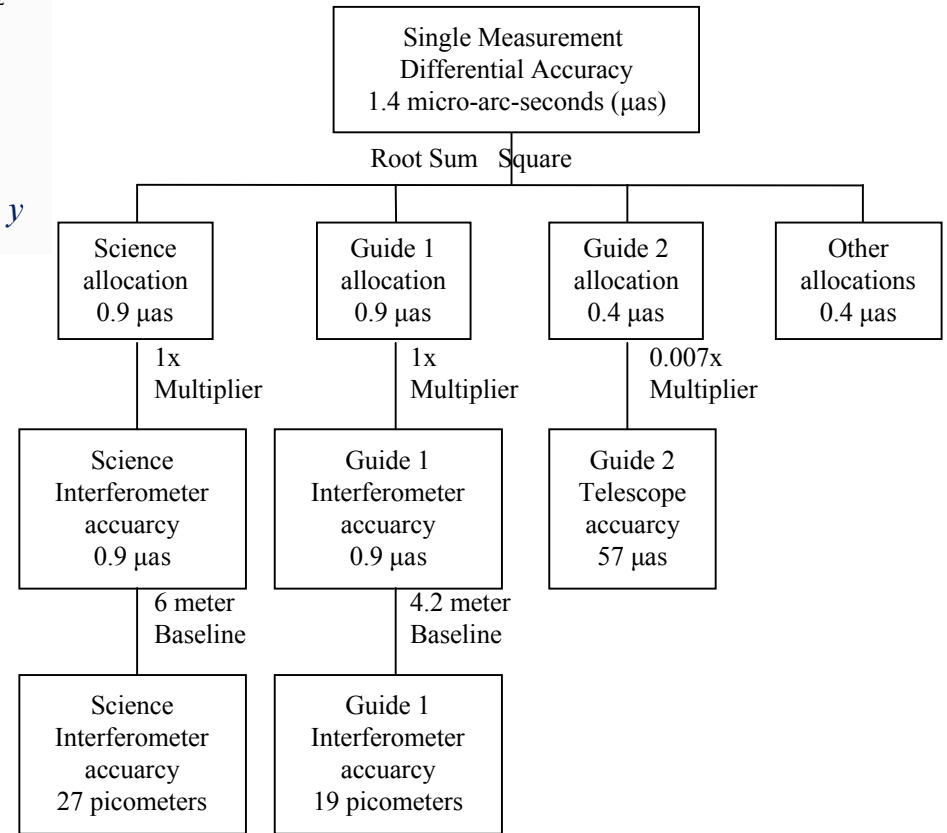 - ### Siderostat mechanisms

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Guide 2 Telescope
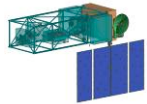
50 micro-arcsec accuracy Star Tracker over 1 arcsec range.

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a

Locus of Guide 2 locations with the same multiplier

SIM Lite Overview

Guide 2 Multiplier

$$M_{G2} = \frac{1}{2 \cdot \sin \eta} \alpha_{Science}$$

Astrometric Error Budget (Top level)

Single Measurement
Differential Accuracy
1.4 micro-arc-seconds (µas)

Root Sum   Square

| Science allocation 0.9 µas | Guide 1 allocation 0.9 µas | Guide 2 allocation 0.4 µas | Other allocations 0.4 µas |

1x Multiplier — 1x Multiplier — 0.007x Multiplier

Science Interferometer accuarcy 0.9 µas

Guide 1 Interferometer accuarcy 0.9 µas

Guide 2 Telescope accuarcy 57 µas

6 meter Baseline — 4.2 meter Baseline

Science Interferometer accuarcy 27 picometers

Guide 1 Interferometer accuarcy 19 picometers

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- Kepler is a transit mission that looks at ~10^5 stars in a 12° solid angle of sky in the direction of the Orion arm.
  - Stars at average distance of ~3 kpc.
    - Too far for follow up by direct detection.
  - Transit requires alignment of the planetary plane with line of sight.
    - 0.5% to 1% will be so aligned.
  - Transit methods can give size, if stellar distance is accurately known, but not mass.

- Kepler provides some indication of the frequency of habitable terrestrials.
  - That will be useful in selecting the PH depth of search.

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SIM (Lite)

- Gaia is a scanning astrometry mission like Hipparcos.
  - Will achieve a mission accuracy of ~6 μas for stars between ~V7 and ~V12.

- All PH target stars are too bright for Gaia ($\leq$ V7).

- Gaia's precision of 6 μas is not sufficient to detect HZ terrestrial planets.

What About Ground RV?

SIM (Lite)

- Radial velocity measures the Doppler shift in stellar spectrum resulting from the star's motion about the star-planet barycenter.

  – Currently limited to ~1 m/s precision. Possibly improving to high fractions of a m/s in coming decade.

  – Can find HZ terrestrials only around coolest M-dwarfs.

    - Can't reach FGK dwarfs in reasonable observation time (would take many 10's of yrs to accomplish PH mission).