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

SIM (Lite)

SIM Lite is ready to go now and is capable of finding one-Earth-mass planets in the habitable zone of nearby sun-like stars.

SIM: Progress Report & Current Status

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

3 October 2008

Quick Update

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.

Astrometric Mission Option Study Sequence

SIM (Lite)

SIM PlanetQuest
↓
Planets-only
↓
Planets-only Lite
↓
New Planets-only
↓
SIM-Lite 30cm
↓
SIM-Lite 50 cm

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

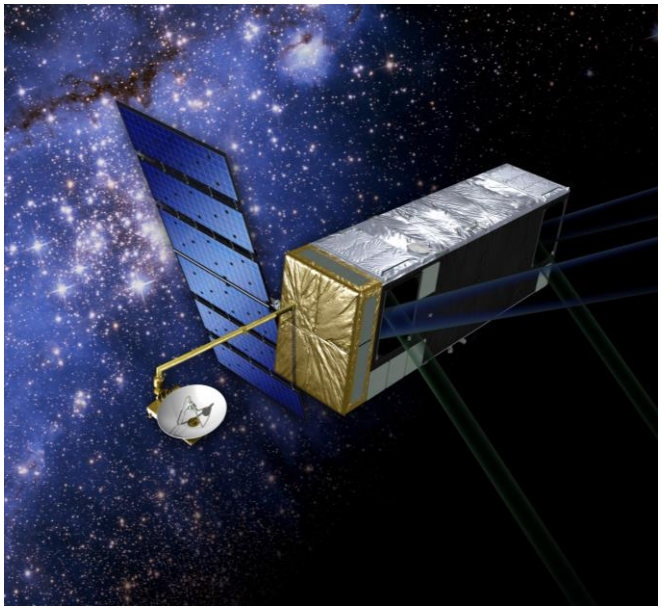
SIM-PlanetQuest vs. SIM-Lite

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***

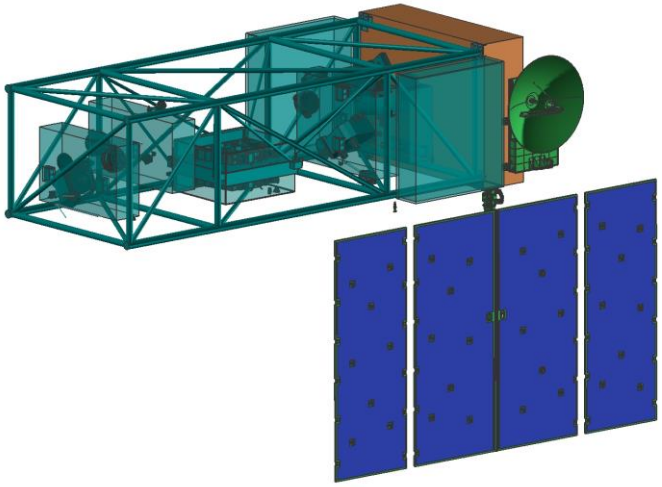
Was



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

Is



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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."*

Concept	Wide-Angle Astrometry		Narrow-Angle Astrometry				
	Requirement (µas)	**Goal (µas)**	Requirement (µas)	**Goal (µas)**	Magnitude Limit (V)	Nulling?	Synthesis Imaging?
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 (Lite)

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.

See Unwin talk, next up.

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

Exec Summary of P.F. Study Results

SIM (Lite)

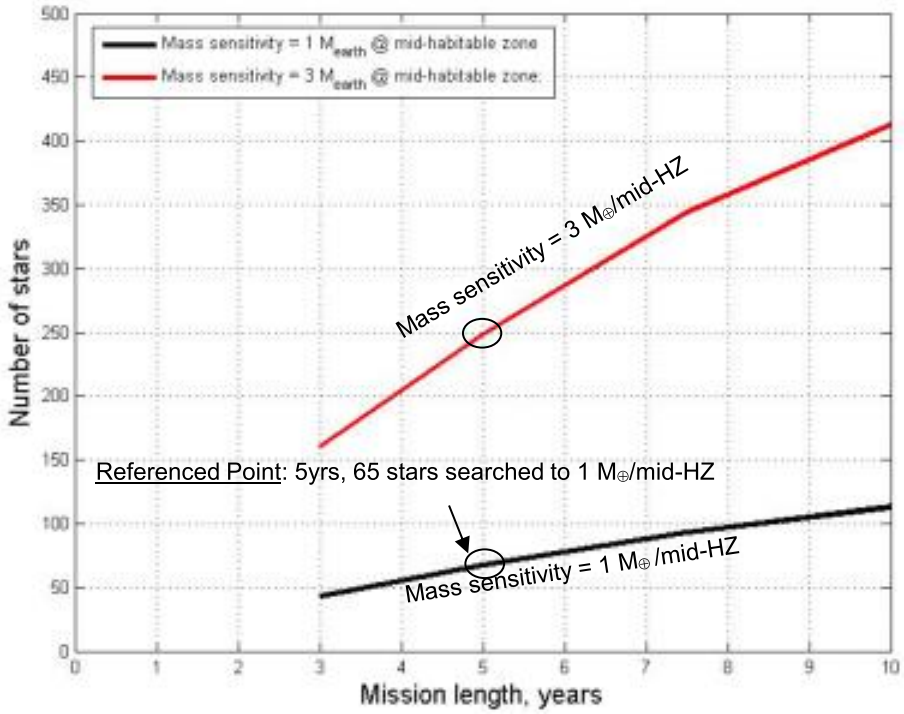
- 48 planetary systems (all 1 Sun @ 10 pc).
  - 32 random, 8 Solar-system-analogs, 4 single terrestrial in HZ, 4 no-planets.
  - Noise added to all systems (4 levels).
- Reliability in detections, (what fraction of reported detections were valid?), varied between teams from 40% to 100% (3 teams > 80%)*.
- 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!

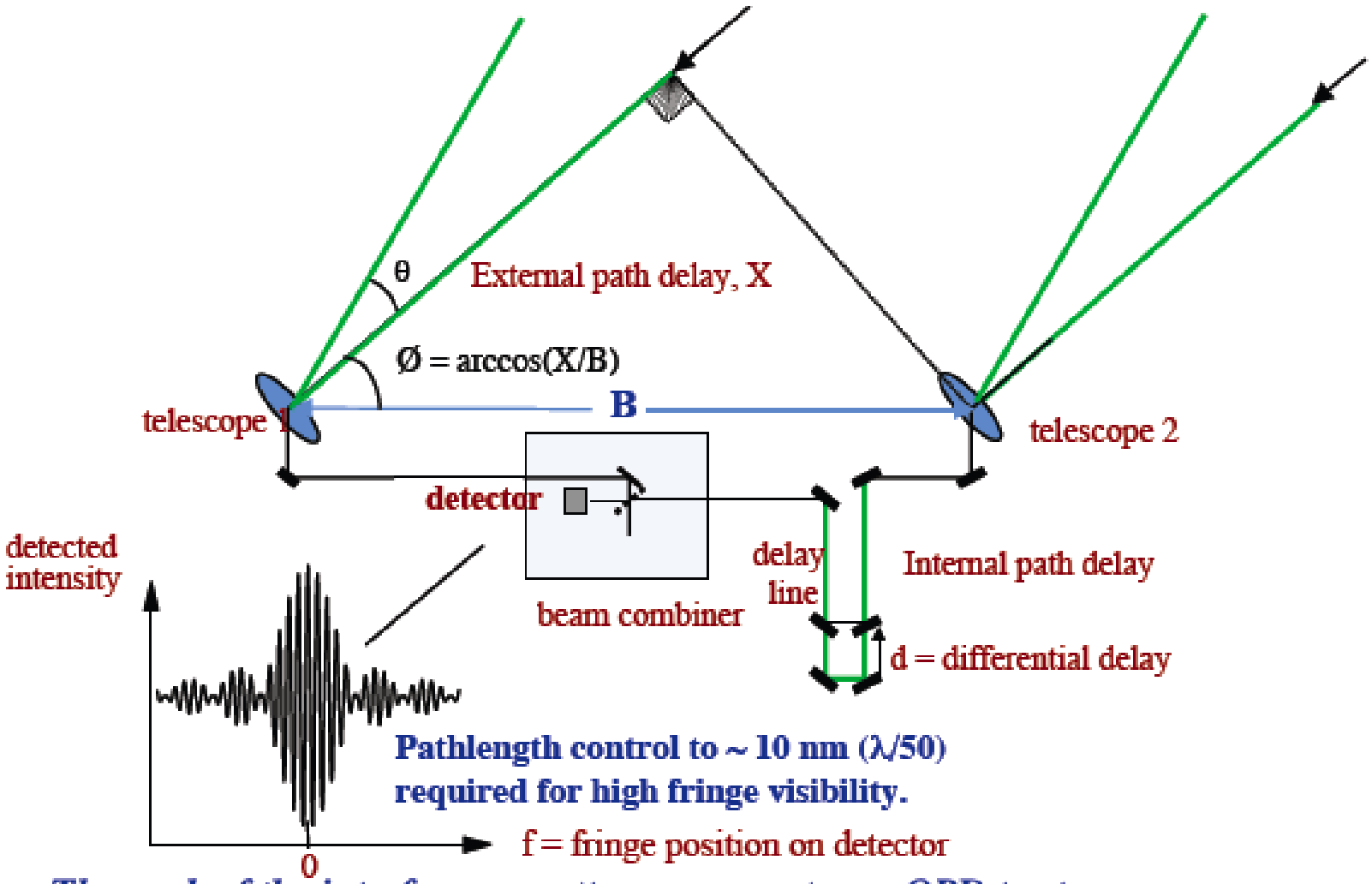
SIM (Lite)

- 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.



Astrometry with an stellar interferometer

SIM (Lite)

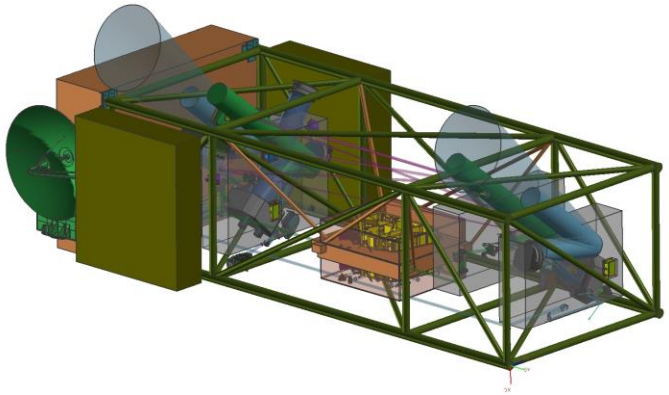


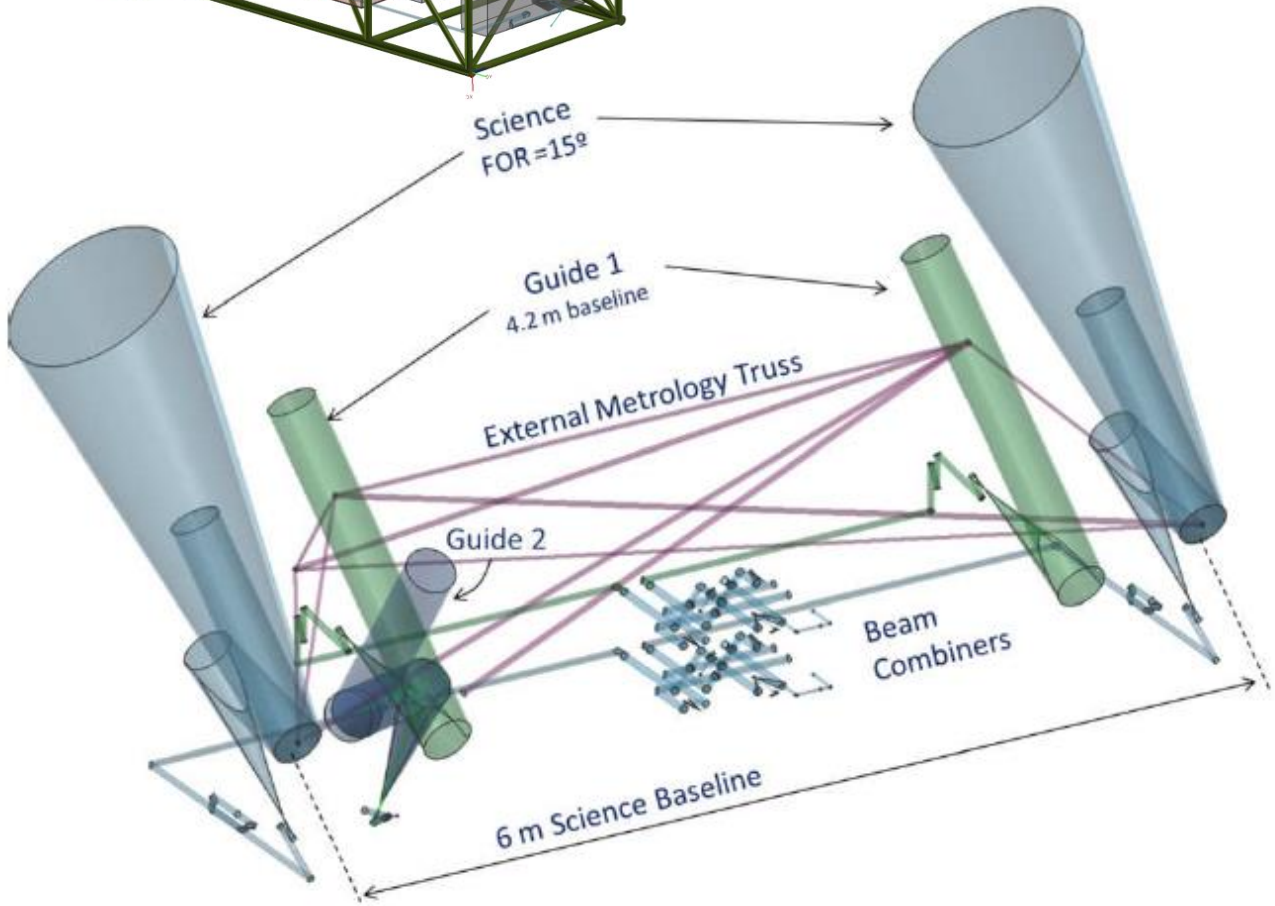
Pathlength control to ~ 10 nm (λ/50) required for high fringe visibility.

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

SIM-Lite Configuration

SIM (Lite)





Note: Centaur upper stage used inside fairing on 521.

Atlas V 521

Why is SIM-Lite More Affordable?

SIM (Lite)

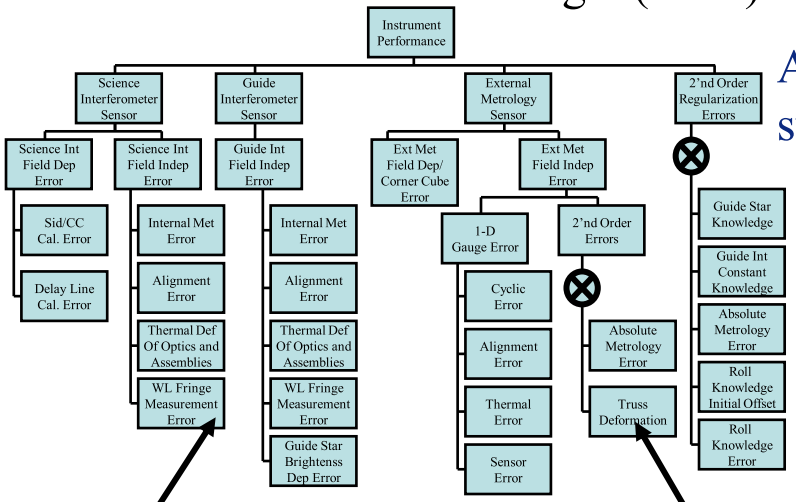
- Takes advantage of excess performance over NRC Goals, so…
- Less hardware.
  - Guide-2 Telescope replaces G2 Michelson Stellar Interferometer (MSI).
  - Fewer structure bays with fewer supports.
- Simpler hardware and software.
  - Guide-1 MSI co-bore-sighted with Science MSI FOR.
  - Eliminated second 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.

Performance Prediction & Validation

SIM (Lite)

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

Astrometric Error Budget (AEB)

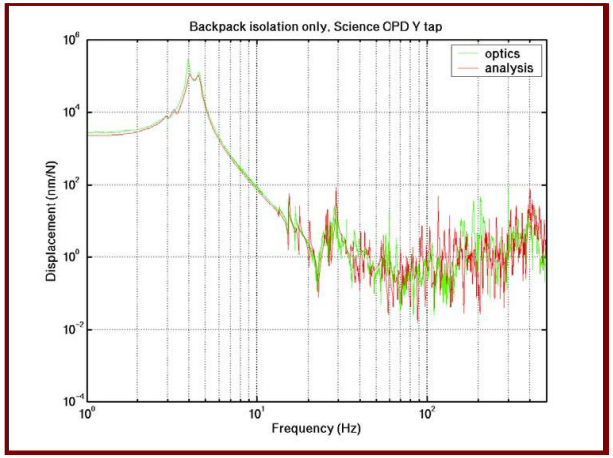


AEB top-level summary.

Verify Physics

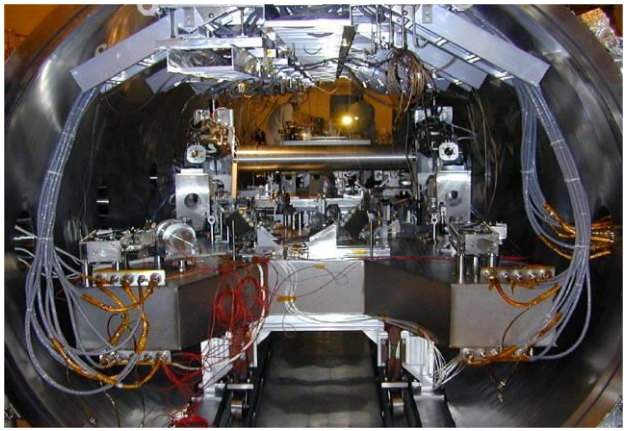
Independent Review & Assessment

-Allocation/Capability
-Verify no missing terms



Model Predictions

Confirm physics-based predict match actual?



Testbed Demonstrations

Technology Complete; Exceeded Goals

SIM (Lite)

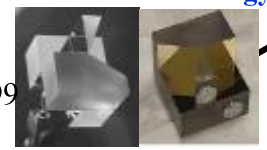
Component Technology | Subsystem-Level Testbeds | System-Level

1999

Metrology Source

2001

Absolute Metrology



1999

Multi-Facet Fiducials

Picometer
Knowledge
Technology

Aug2001

Beam Launchers

1998

High Speed CCD

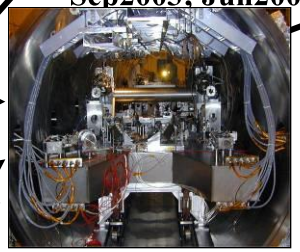
2000

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

Overall system Performance via Modeling/Testbed Integration

Completed In 2005

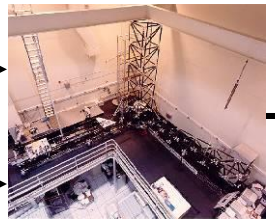
Nanometer
Control
Technology

Optical Delay Line

1998

Hexapod Reaction Wheel Isolator

1998



1999

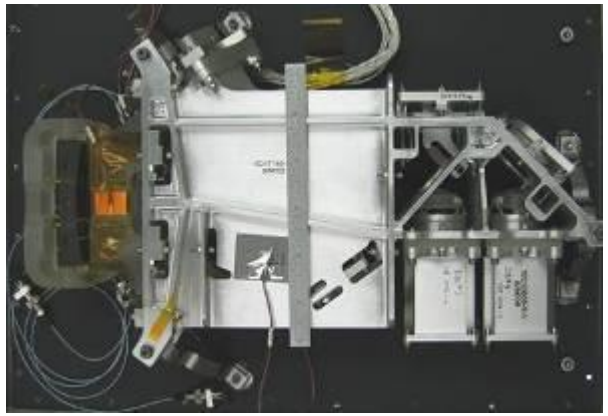
STB-1 (single baseline nanometer testbed)

Nov2001

STB-3 (three baseline nanometer testbed)

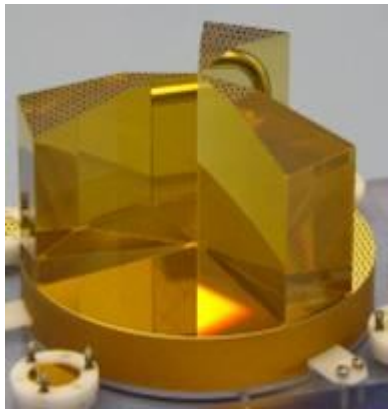
Each testbed's performance correlates to an analytical model to within a factor of 2.

Metrology Hardware Qual-Level Tested!

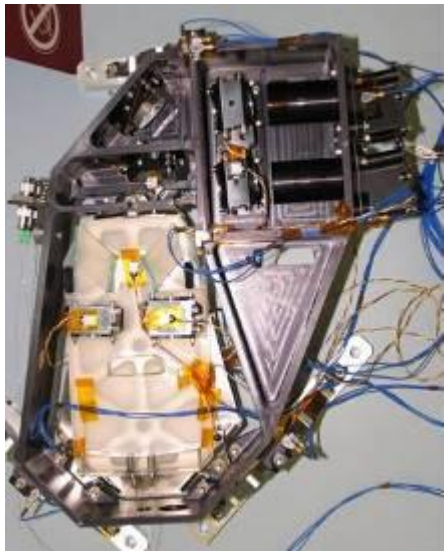


External Metrology Launcher

Metrology Source



Double Corner Cube



Internal Metrology Launcher

SIM Lite Near Term Events

SIM (Lite)

- Double-Blind ExoPlanet Finding Study continuing…
  - An array of additional tasks are being defined now.
  - Will look at specific SIM Lite target stars (vs. Suns at 10 pc as before).
- 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 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.

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 (≤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.*

Backup

SIM Basic Definitions and Parameter Values

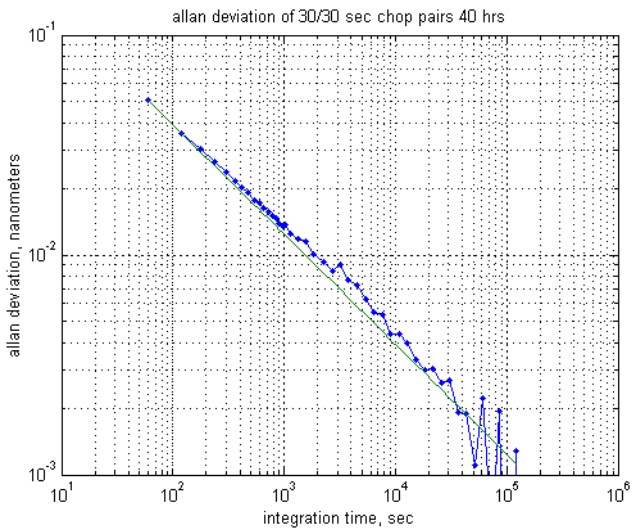
SIM (Lite)

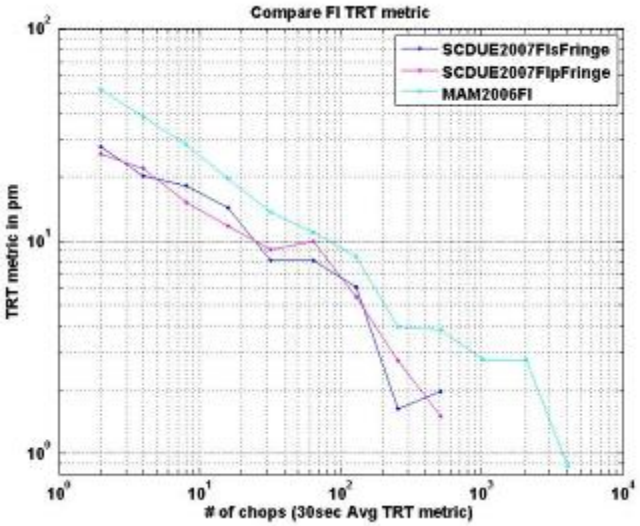
Term	Description	Value
Interferometer Baseline (BL)	The distance between two collecting mirrors.	6 m
Single Measurement Accuracy (SMA)	The uncertainty associated with measuring the angle between the baseline vector and target star.	1.0 µas, 1-sigma RMS
One-Dimensional (1D) Measurement Accuracy or Differential 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

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. See papers 88, 183 & 184.

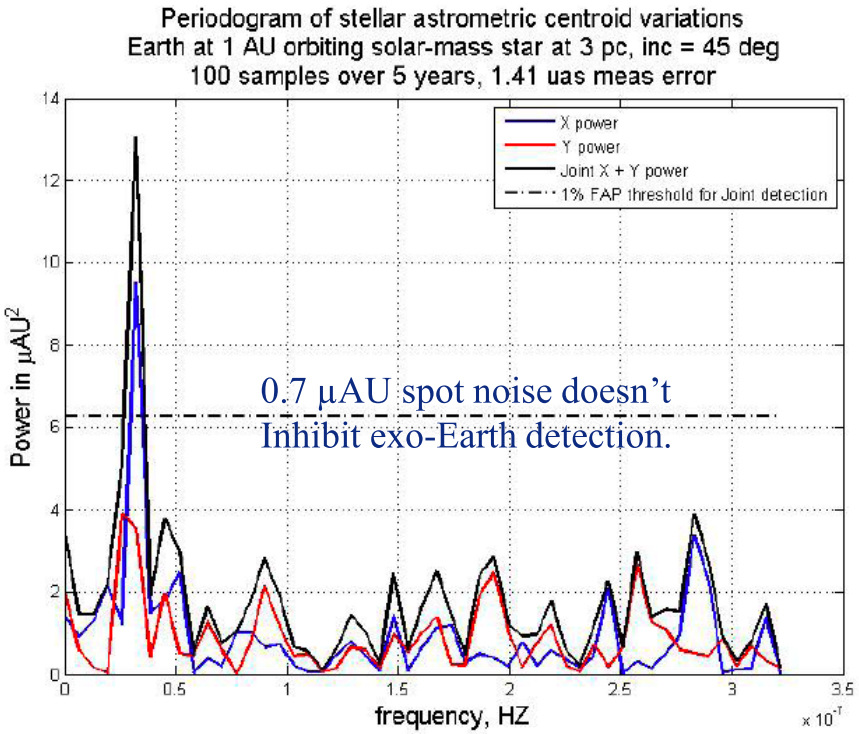




Astrophysical Errors

SIM (Lite)

- Reference star companions
  - Three cases:
    - (1) Large, pre-screened by RV;
    - (2) Too small;
    - (3) Solved for along with target star companions.
  - See paper #187.
- 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.
  - See paper #91.



Technology Gates & Results

SIM (Lite)

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

Engineering Milestones

SIM (Lite)

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

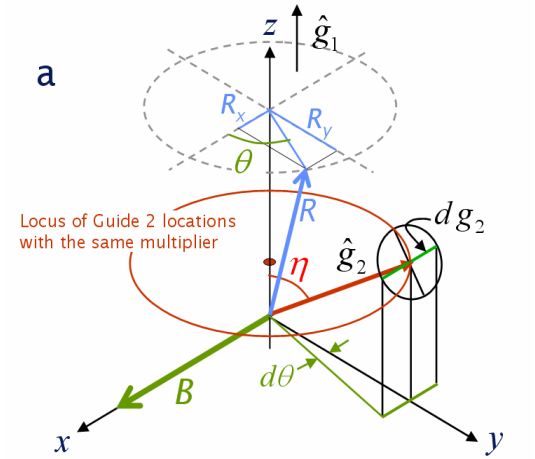
Formulation Phase				
EM-1	External Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	5/31/06	6/5/06	Exceeded Objective
EM-2	Internal Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	4/30/06	5/3/06**	Exceeded 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

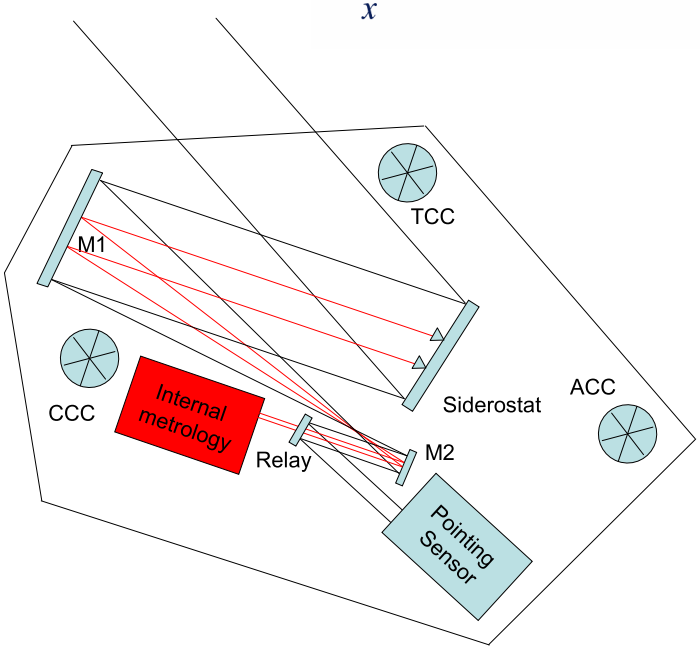
- Additional Brass-Board Units currently under development:
  - Astrometric Beam Combiners assembly.
  - Fringe Tracker and Star Tracker cameras.
  - Fine Steering and Phasing Mirror mechanisms.
  - Siderostat mechanisms

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

Guide 2 Telescope

50 micro-arcsec accuracy Star Tracker over 1 arcsec range.

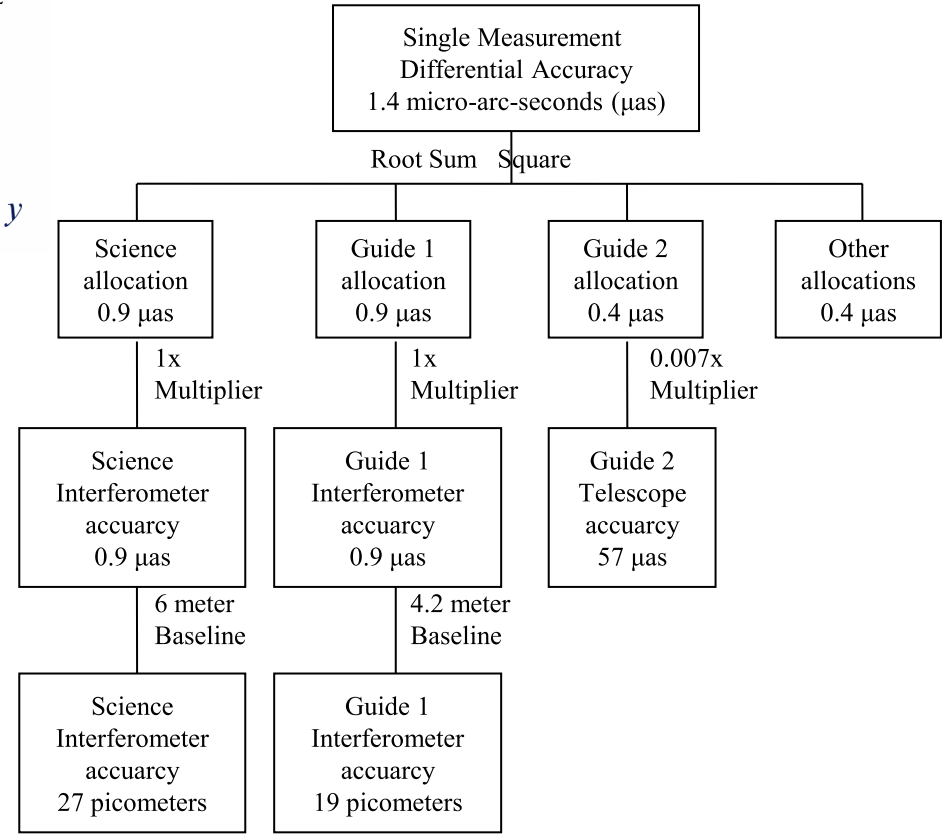




Guide 2 Multiplier

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

Astrometric Error Budget (Top level)



What About Kepler?

SIM (Lite)

- 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.

What About Gaia?

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 (≤ 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).