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EXEP Optical Astrometry

ExoPlanet Masses& Orbits via Precision Astrometry

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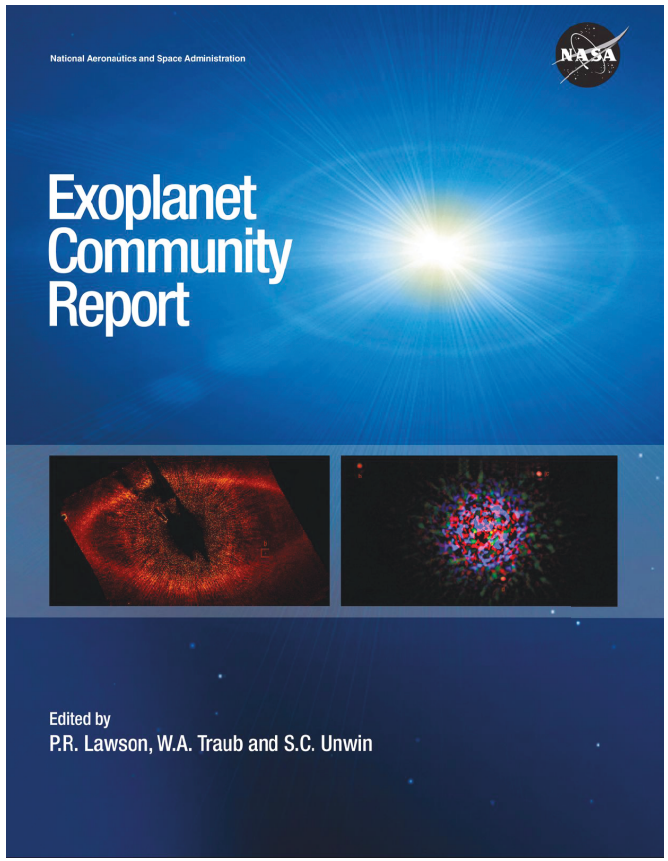
ExoPlanet Discovery Methods

EXEP Optical Astrometry

- Radial velocity (RV) – optical - Doppler
- Transits – CoRoT & Kepler
- **Astrometry – *This talk*.**
- Optical imaging
- Infrared imaging
- Exozodiacal disks
- Microlensing
- Magnetospheric emission



http://exep.jpl.nasa.gov/documents/ExoplanetCommunityReport.pdf

AAAC Exoplanet Task Force Called Out a Space-Based Astrometry Mission

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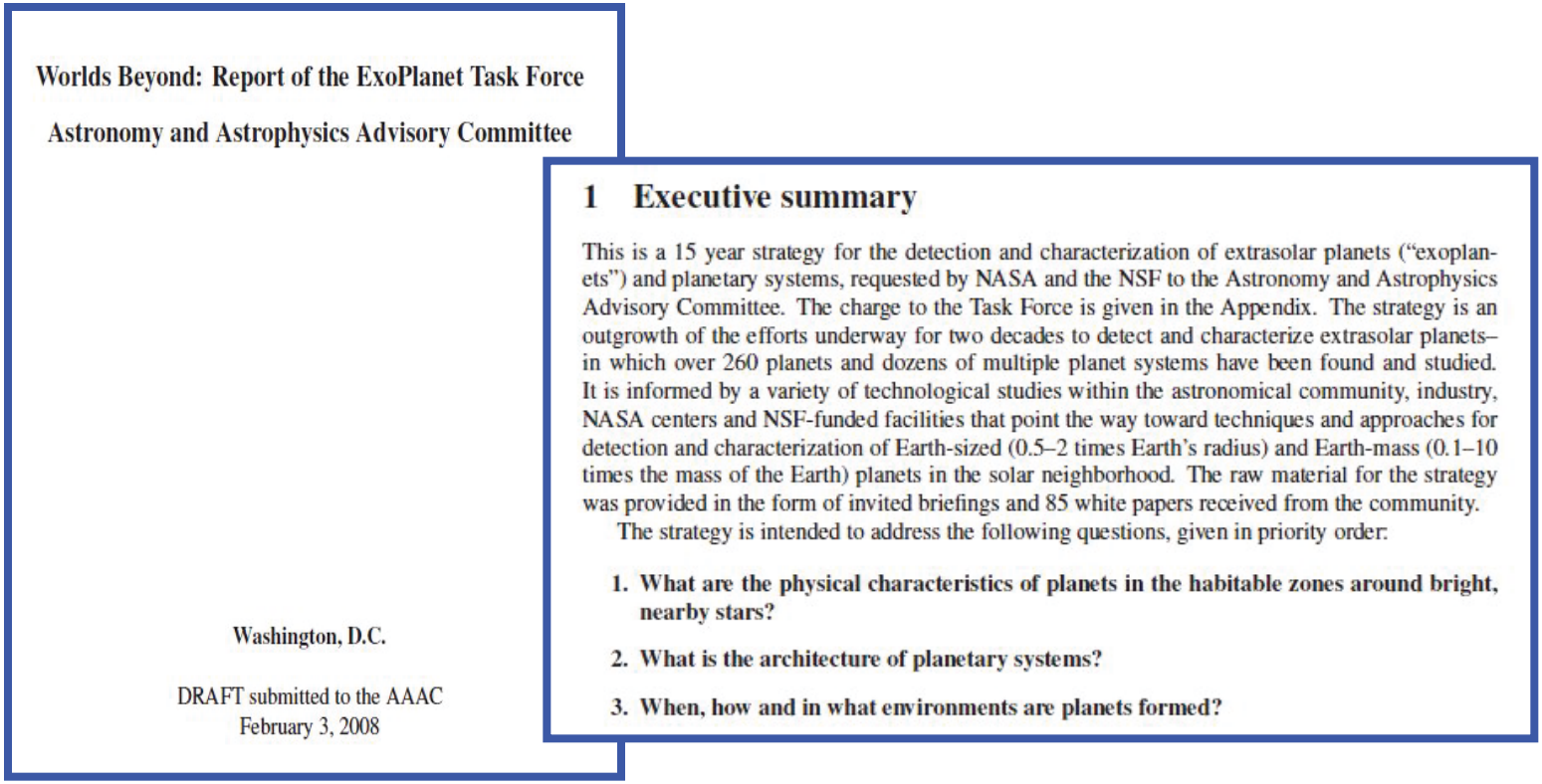

Worlds Beyond: Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee

Washington, D.C.

DRAFT submitted to the AAAC
February 3, 2008

1 Executive summary

This is a 15 year strategy for the detection and characterization of extrasolar planets ("exoplanets") and planetary systems, requested by NASA and the NSF to the Astronomy and Astrophysics Advisory Committee. The charge to the Task Force is given in the Appendix. The strategy is an outgrowth of the efforts underway for two decades to detect and characterize extrasolar planets– in which over 260 planets and dozens of multiple planet systems have been found and studied. It is informed by a variety of technological studies within the astronomical community, industry, NASA centers and NSF-funded facilities that point the way toward techniques and approaches for detection and characterization of Earth-sized (0.5–2 times Earth's radius) and Earth-mass (0.1–10 times the mass of the Earth) planets in the solar neighborhood. The raw material for the strategy was provided in the form of invited briefings and 85 white papers received from the community.

The strategy is intended to address the following questions, given in priority order:

1. **What are the physical characteristics of planets in the habitable zones around bright, nearby stars?**
2. **What is the architecture of planetary systems?**
3. **When, how and in what environments are planets formed?**

"The ***only*** technique appropriate to survey the nearest hundred or so bright sun-like stars in the mid-term is *space-based astrometry*, and this is one cornerstone of the Task Force recommendations."

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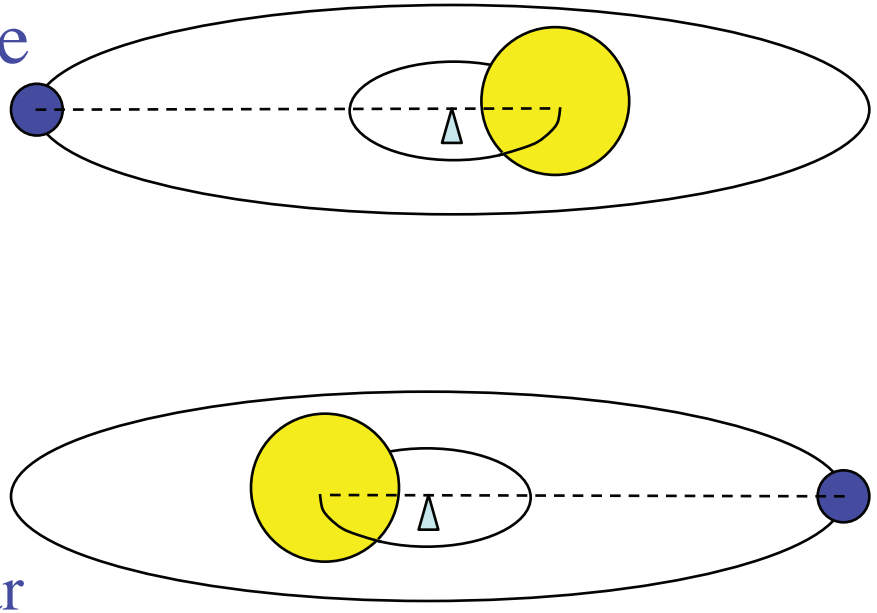
Optical Astrometry?

- Measurement of the positions of stars (relative to other stars) over time.
- Astrometry discovers & measures exoplanets indirectly.
  - Measures star's transverse motion (wobble) as the star & planet(s) move around their common center of mass (barycenter).
  - Determines planet(s) mass & orbit.



Stellar transverse motion (wobble) about system barycenter.

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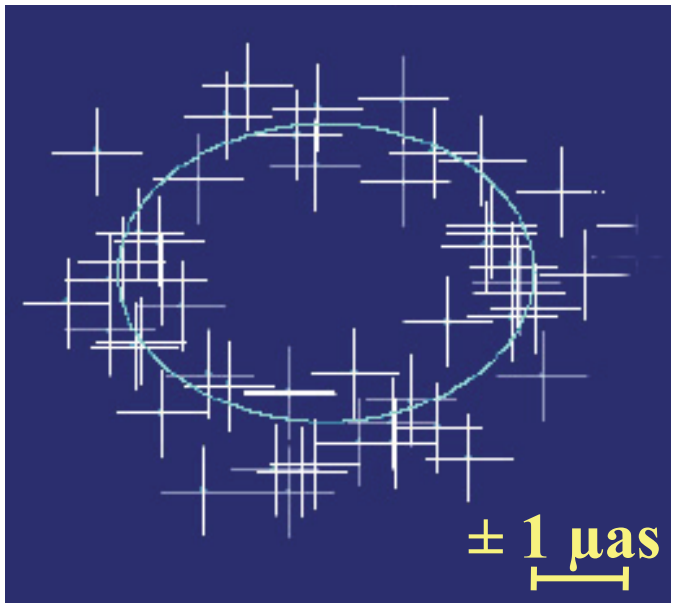
Astrometric Planet Detection

EXEP Optical Astrometry

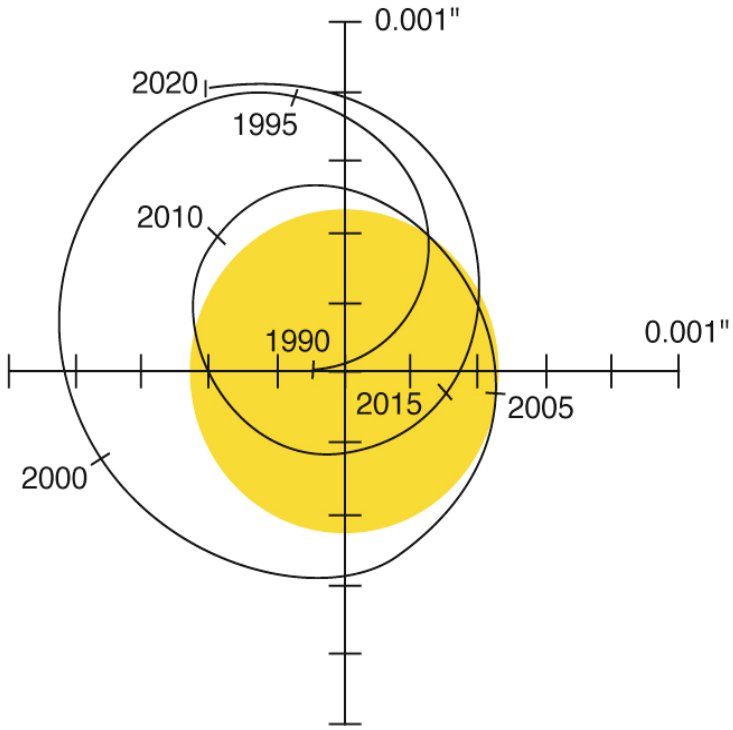
What is a microarcsecond (μas) ?

1 μas = 4.8 x 10^{-12} radians
= 30 pm over a 6-m baseline
= thickness of a nickel
at the distance of the Moon !



Simulation:

Detecting a planetary orbit with a series of 2-D measurements



"The wobble effect":

Our Solar System as seen at 10 pc distance

- 1 tickmark = 200 μas
- SIM accuracy = **1 μas** (single meas.)
- Sun-Jupiter wobble = 500 μas
- Sun-Earth wobble = 0.3 μas

Optical Astrometry - Long History

- Since 1980's:
  - Many operational ground-based systems.
  - Space-based systems, outside of the Earth's atmosphere, needed to realize full potential.
- Space-based missions under development:
  - 2012: ESA's GAIA astrometric *survey* mission (~10 μas)
  - TBD: SIM Lite pointed observatory with ~10x precision beyond GAIA (~1 μas).

-1980's:
Ground: MkI & MkIII interferometers on Mt. Wilson.
Space: Hipparcos (survey).
- 1990's:
Ground: Palomar Test Interferometer.
Space: HST FGS.
- Now:
Ground: Keck Interferometer, VLTI, CHARA array, NPOI
- Future:
Space: Gaia (survey), SIM Lite (observatory)

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Earth-Analogs around *nearby sun-like* FGK stars!

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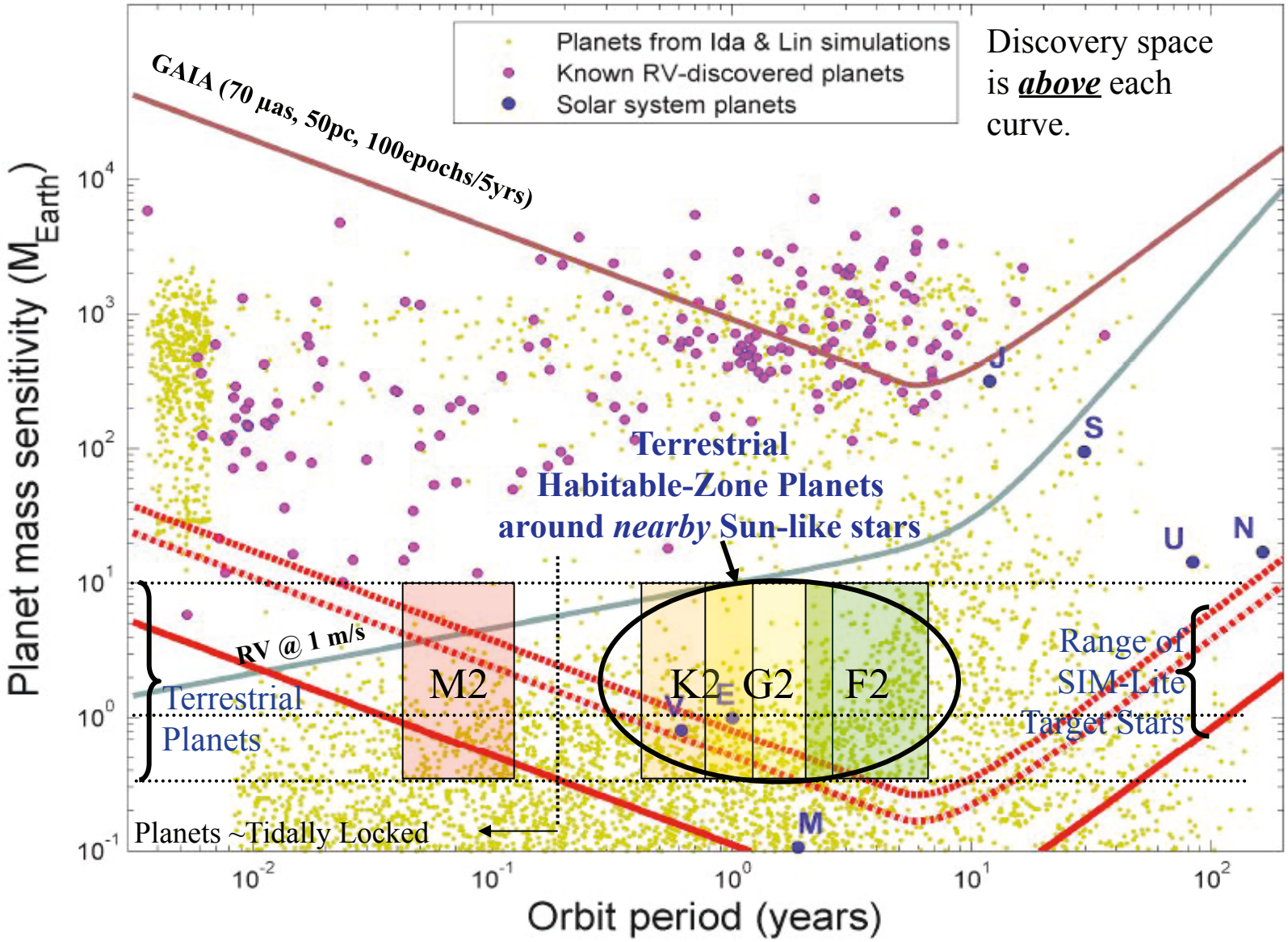


Planet Finding Capability Study

- NASA HQ study requested EXEP conduct a study to determine astrometric planet finding capability.
- Two part study conducted between Jan'08 & Apr'09:
  - 48 planetary systems, all 1-Sun @ 10 pc
  - 60 planetary systems around candidate nearby FGK target stars (real potential target stars).
  - Mission capabilities similar to NASA's SIM Lite concept.
- Description of teams & roles:
  - 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).
  - NASA HQ External Independent Review Board (EIRB) subset for review.

Planet Finding Capability Study Results

- Reliability in detections (fraction of reported detections valid):
  - 131 valid planets of all types out of 137 reported to be found.
  - 28 valid terrestrial habitable-zone planets out of 28 reported found.
- Completeness (fraction of detectable planets detected?)
  - 114 planets of all types found, out of 124 planets expected to be detectable at SNR ≥5.8.
  - 26 terrestrial habitable-zone planets found, out of 27 planets expected to be detectable at SNR ≥ 5.8.

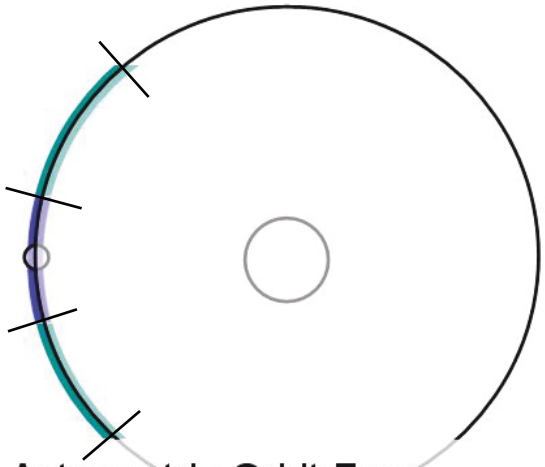
Study Conclusions:

- Presence of multiple planets has essentially no impact on the ability to detect terrestrial planets in the habitable-zone (Major Conclusion).
- Double Blind study validated methods used to predict astrometric mission performance.

EXEP Optical Astrometry

Astrometry-Imaging Synergy-1: Astrometric Orbit Error

- At SNR~6 an astrometric orbit gives
  - Period +/- ~ 3%
- Orbit phase = sqrt(2)/SNR = ~0.25 rad
- Error looks like an arc ➔
- The phase error ~0.25 rad is at mid epoch of SIM mission. To extrapolate to a later date:
  - P_err(T) ~ RSS(0.25, T*3%*2π)
  - ~1 radian @ T=5 yrs
- When to look
  - T=0 +/- 14 days
  - T=5yrs +/- 58 days



Astrometric Orbit Error
Blue – mid-epoch (σ_r~0.03 AU),
(σ_θ ~0.25 radians)
Green – 5 yrs after mid-epoch

- An astrometric orbit + 1 image of the planet 5 years later, greatly decreases the orbital phase uncertainty (by almost 10X).

- The gain comes mostly from the 5 year time span (imaging astrometry ~10mas).

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Astrometry-Imaging Synergy-2

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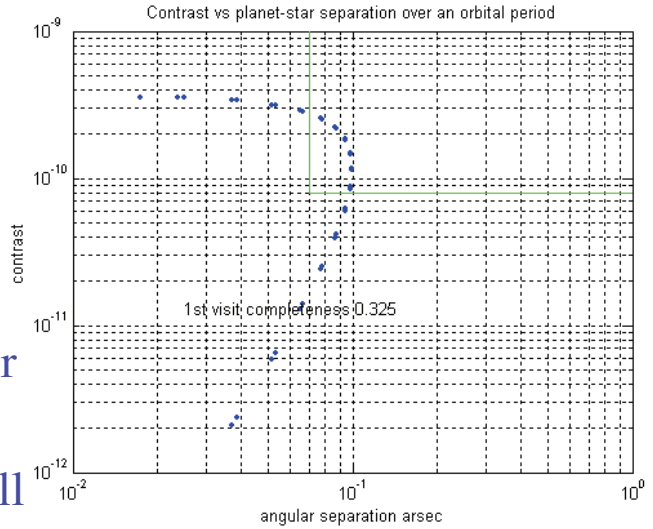
- There will be many planets, only a few will be Terrestrial in the HZ.
- Precise planet orbit can be obtained by:
  - 4 images of the planet (3 to get orbit, 4th confirm all 4 image are of same planet) 4 images of the planet will take ~12 images for IWA~0.7Rmax
  - Or Astrometry + 2 images of the planet. Will take 4~5 images for IWA~0.7 Rmax
- If eta_Earth ~10%, will need to observe many stars many times to verify the planets are NOT T/HZ planets.
  - Reduce the number of images by **~30X** if eta_earth~10%. ~10X if eta_Earth ~30%.
- Astrometry informs us where we do and don't need to look for T/HZ planets.



When IWA ~ 0.7* R_{max} Earth is observable 32% of the orbit

Brightness of planet with constant albedo varies by 3X over orbit. 3X albedo variation ~10X brightness change (and still be T/HZ)

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SIM Lite Mission Overview

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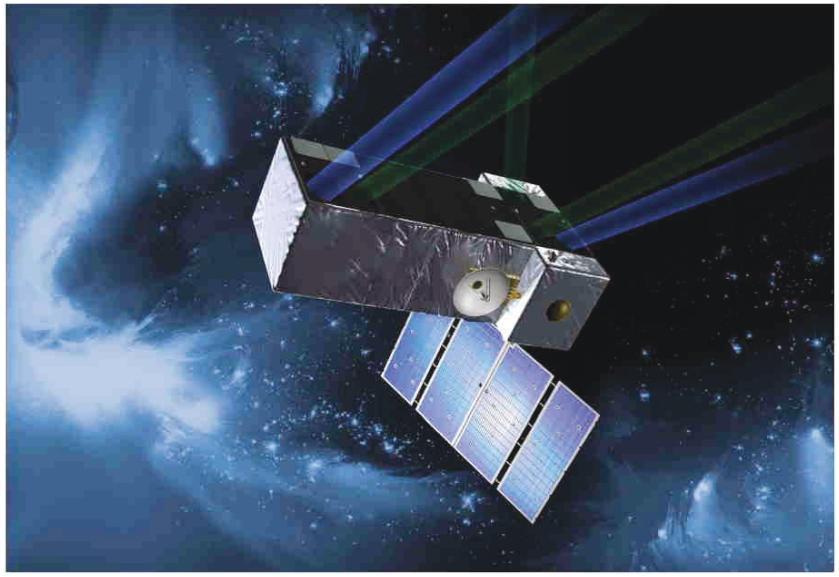
Salient Features

- **6 meter science Michelson Stellar Interferometer (MSI) with 50 cm science siderostat apertures**
- **One 4m MSI and one 30cm T-scope Guides**
- **Visible wavelength (450-950nm)**
- **Earth-trailing solar orbit, 5 year mission**
- **SIM is a JPL, Caltech, NGAS, KSC, and SIM Science Team partnership**



Science

- **Finding Earths – Reveal the population, masses, and orbits of terrestrial and giant planets around nearby stars, and the formation, evolution, and architecture of planetary systems.**
- **Dark Matter & Galaxy Assembly – Determine the age of and probe the hierarchical formation history of the Milky Way. Map the distribution of local dark matter, and place limits on the mass of the dark matter particle. Include rotational parallaxes.**
- **Precision Stellar Astrophysics – Precision measurements of the masses and luminosities of the highest and lowest mass stars allow testing of models of stellar evolution, from brown dwarfs to black holes.**
- **Supermassive Black Hole Astrophysics – Understand how black holes accelerate jets, from stellar masses to galaxy central engines.**

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Astrometry with an interferometer

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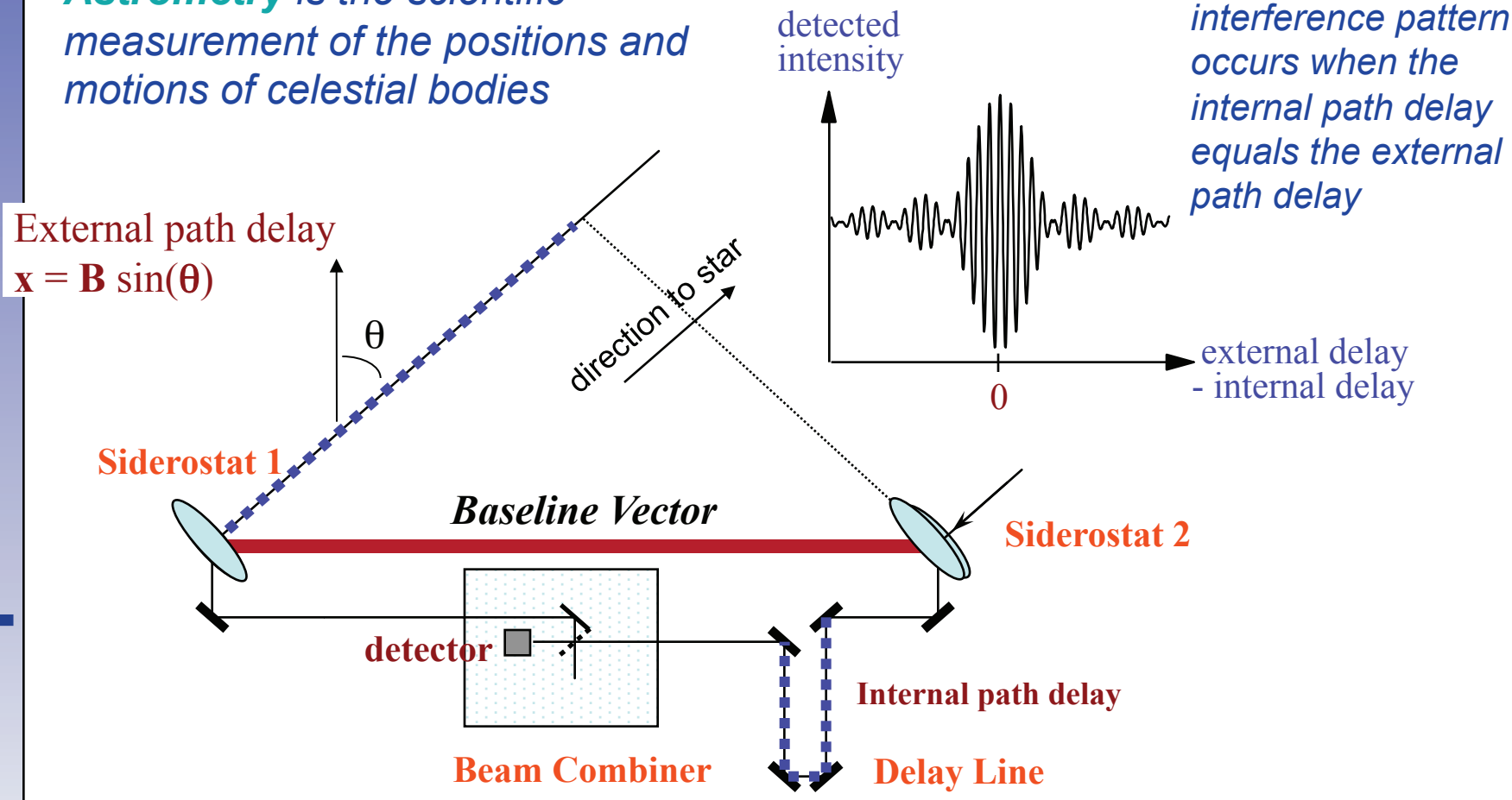
Astrometry *is the scientific measurement of the positions and motions of celestial bodies*



The peak of the interference pattern occurs when the internal path delay equals the external path delay

Science interferometer *is used to measure position of target star with respect to interferometer baseline vector*
Guide interferometers *determine the baseline vector*

SIM Lite Configuration

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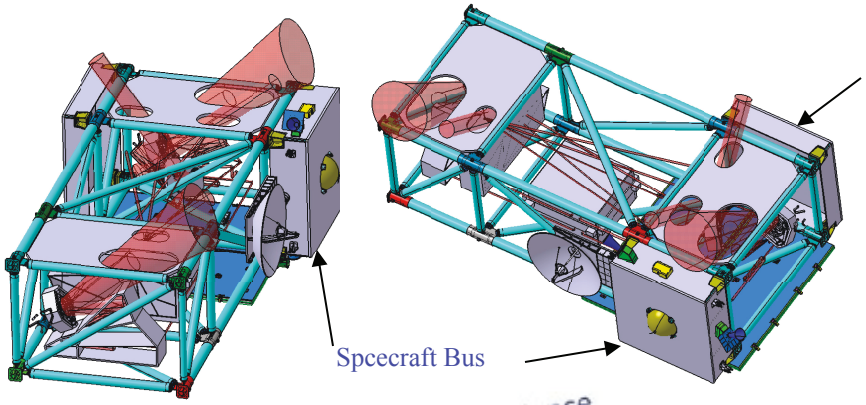

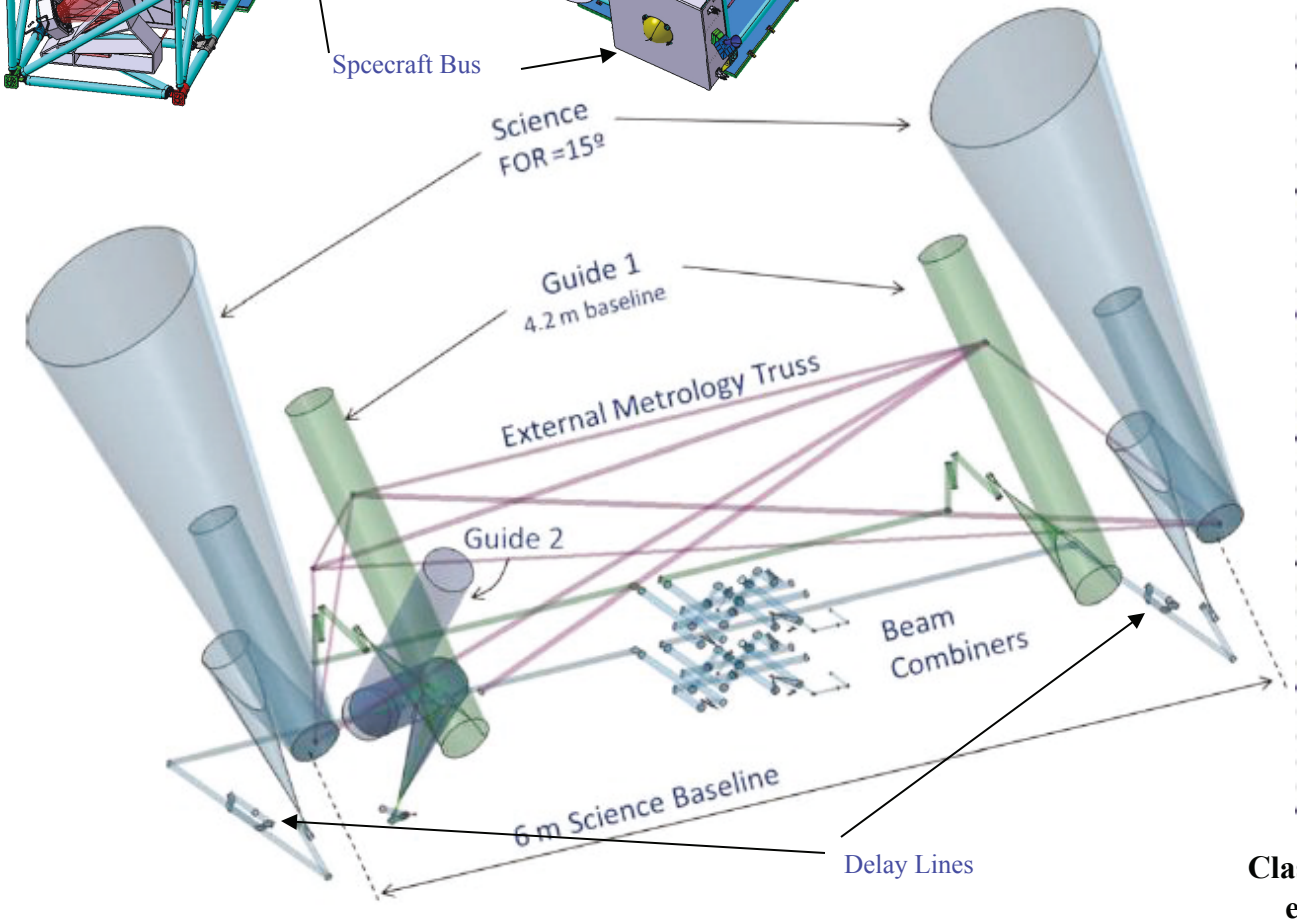

Intermediate Class Launch Vehicle e.g., Altas V 521

SIM Lite Instrument Exploded Diagram

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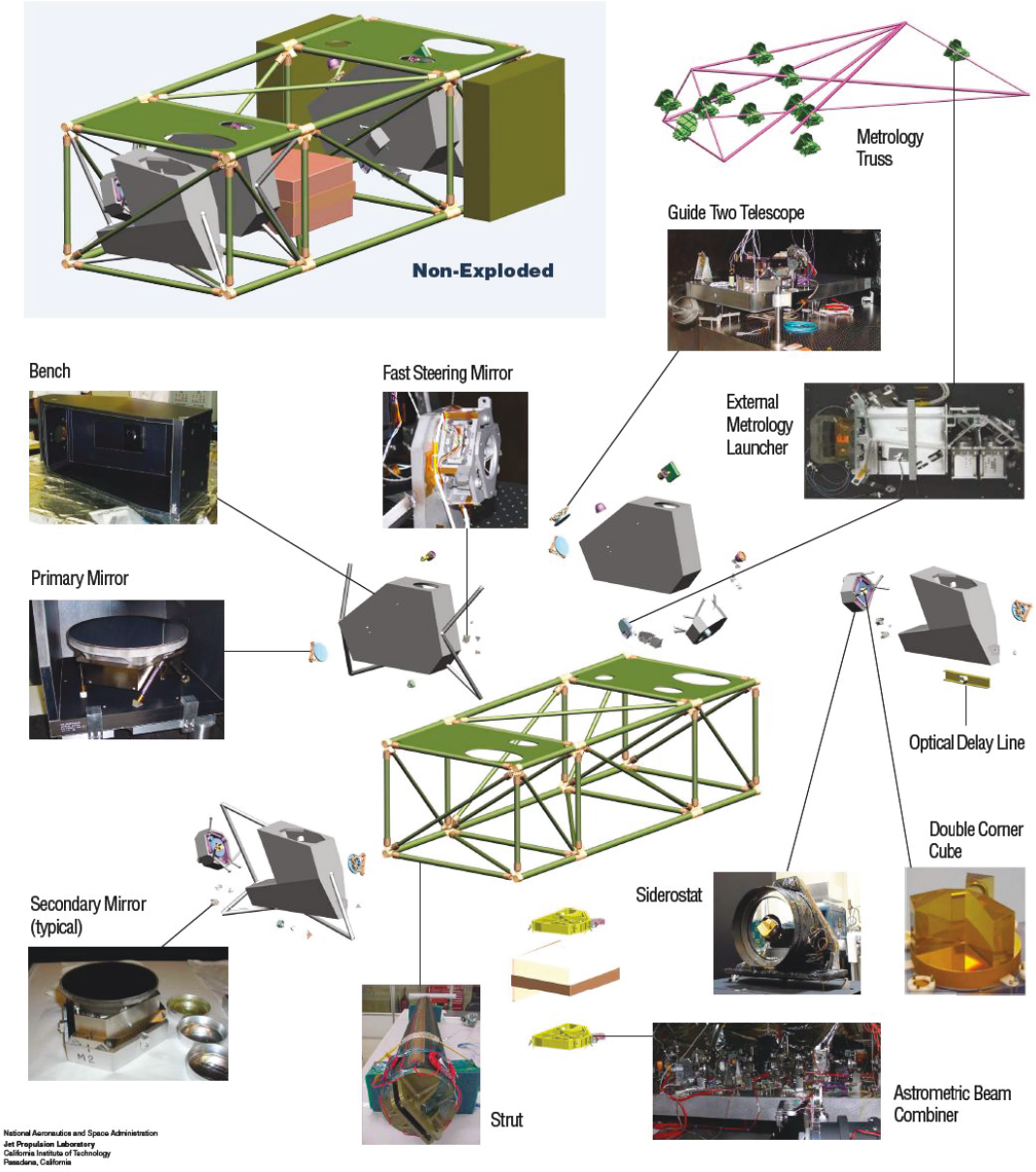
- Most instrument assemblies have been or are being built as brassboards (form, fit, function to flight) and subjected to full qualification-level environmental testing.
- Flight units would be identical.



Performance Prediction & Validation

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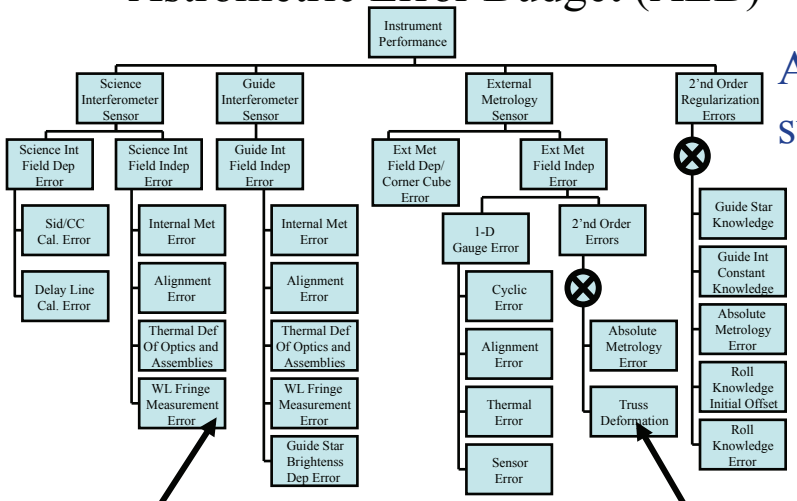
AEB, testbeds, model predictions & integrating analytical models used to verify overall system performance (for both Technology Development and Flight)

Astrometric Error Budget (AEB)

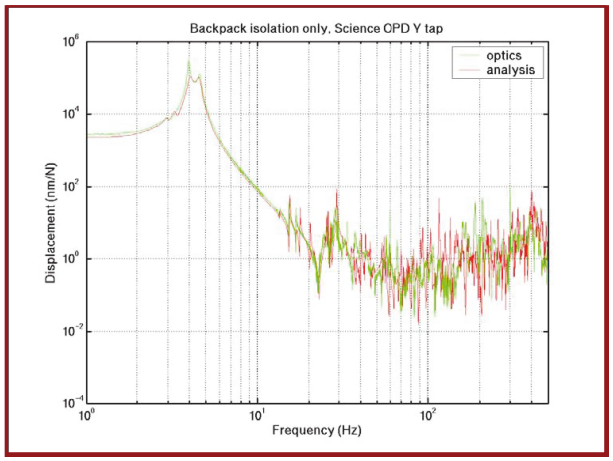


AEB top-level summary.

Verify Physics

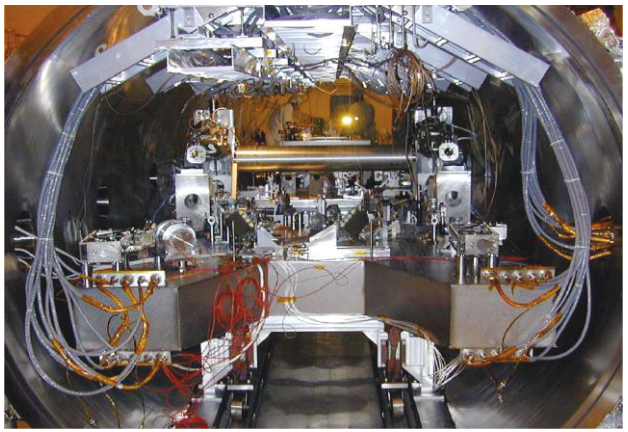
-Allocation/Capability
-Verify no missing terms

Independent Review & Assessment



Model Predictions

Confirm physics-based predict match actual?



Testbed Demonstrations

Technology Complete; Exceeded Goals

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Component Technology

Subsystem-Level Testbeds

System-Level

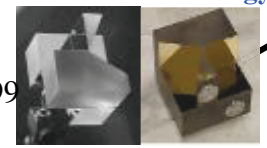
1999

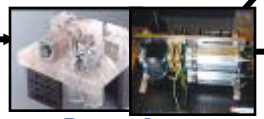
Metrology Source

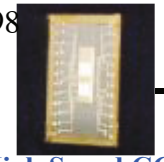
2001

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

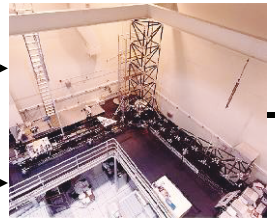

Overall system Performance via Modeling/Testbed Integration

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.

Optical Astrometry Summary

- Technology development for a pointed astrometric observatory successfully completed.
  - More successful than originally expected (better performance).
  - Demonstrated TRL-6 technology readiness for possible implementation on a space mission.
- Optical Astrometry would be capable of indirectly detecting Earth-class planets orbiting in the habitable zone of *nearby* Sun-like stars.
  - Those that can be followed up with direct imaging missions.
- The SIM Lite Astrometric Observatory is a mature mission implementation option.

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Parting Thoughts…

"One excellent measurement is better than many mediocre measurements." (Confucius)

"You understand something truly only when you can measure it precisely." (Lord Kelvin)

http://planetquest.jpl.nasa.gov