SIM *PlanetQuest*

Astrometric Measurement of Planet Signatures

9-m Baseline Michelson Stellar Interferometer

Earth Trailing Solar Orbit

Launch Date: 2011

Mission Duration: 5–10 years

Early Search and Direct Measurement of Mass for Earth-like Planets

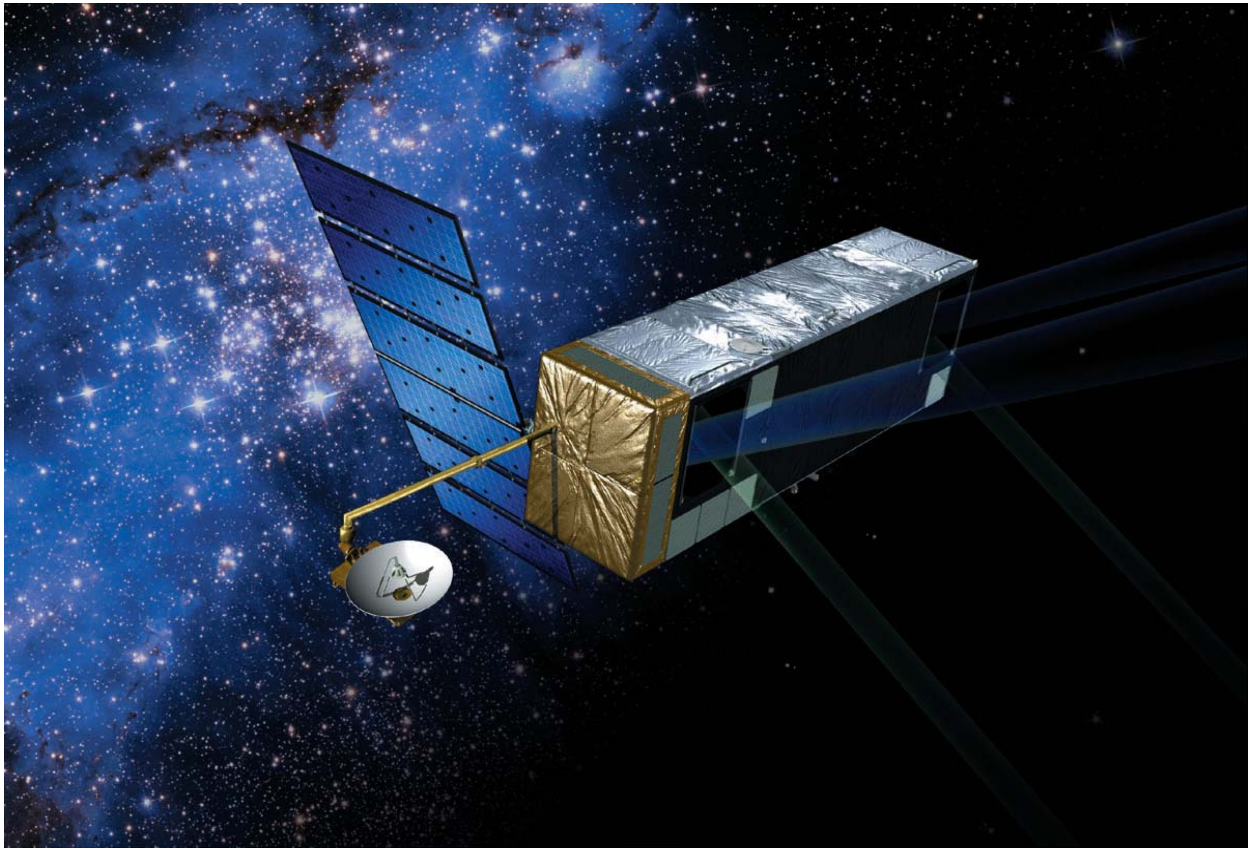
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

SIM PlanetQuest Overview

Salient Features

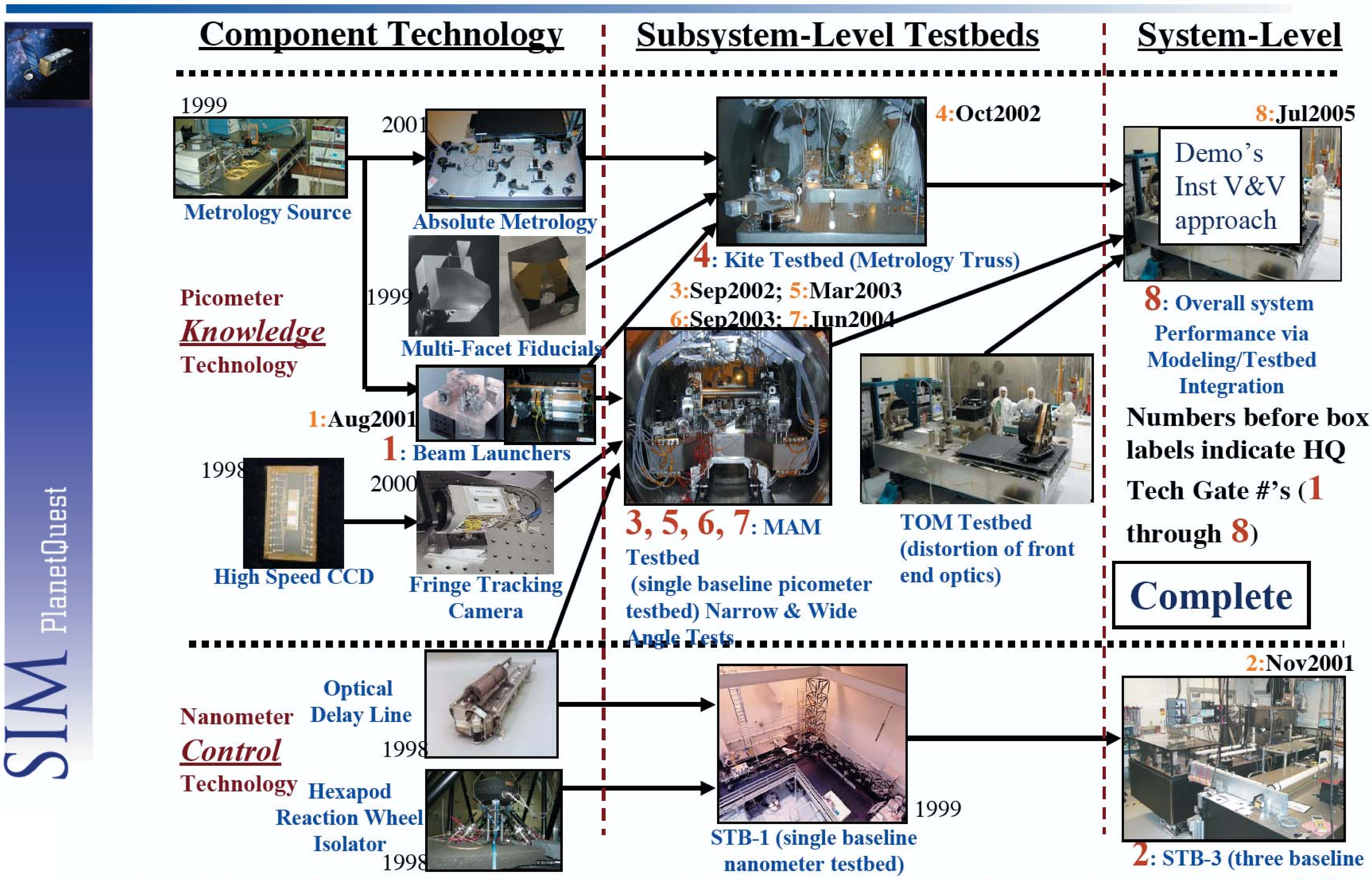
- 3 parallel Michelson Stellar Interferometers
- 9 meter baseline
- Visible wavelength
- Launch Vehicle: Atlas V or Delta IV ELV
- Earth-trailing solar orbit
- 5 year mission life with 10 year goal
- SIM: a JPL, Caltech, NGST, KSC, and SIM Science Team partnership



Science Goals

- Find and characterize nearby planetary systems (mass/orbits of all planets found)
- Address key issues in astrophysics
- Develop a precision stellar optical reference grid

SIM Technology Flow



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

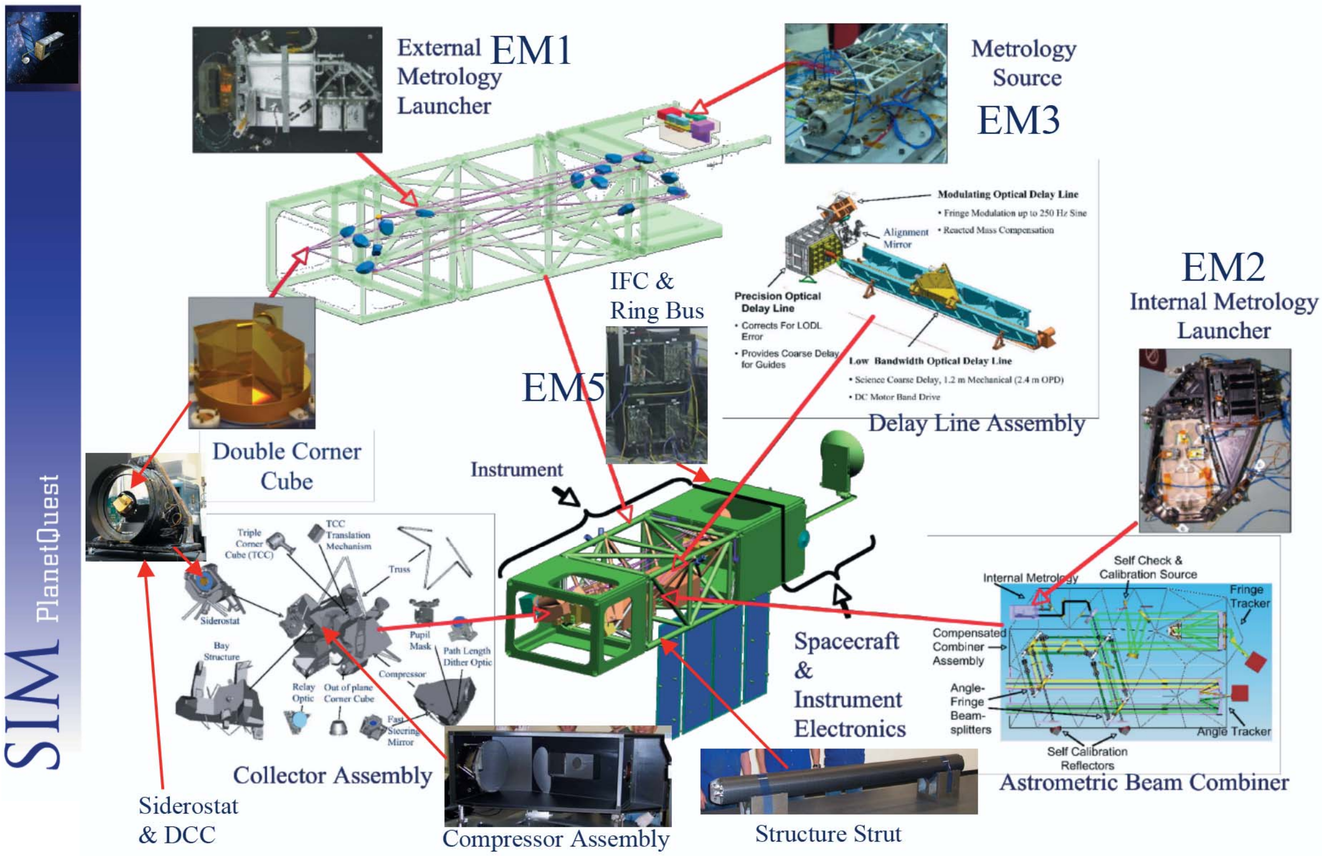
Technology Gates & Results

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

System Hardware



Engineering Milestones

Engineering Milestone	Description	Due Date	Complete Date	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	In test	
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
Implementation Phase				
EM-6	Engineering Models for Metrology Fiducials (double and triple corner cubes fully meeting SIM flight requirements)	9/30/2007*		
EM-7	Metrology Source Engineering Models (optical bench; fiber splitters; fiber switches; fiber distribution assembly; laser pump module: all fully meeting SIM flight performance requirements per table).	9/30/2008*		
EM-8	Instrument/Mission Performance Prediction (update Tech Gate #8 using latest hardware results).	9/30/2008*		
EM-9	Integration of S/C FSW build-1 with phase-1 of the S/C engineering model testbed (demonstrates specific S/W functions)	10/1/2008*		

* Completion dates deferred indefinitely due to FY07 NASA decision to delay SIM indefinitely.

** Actual signoff by NASA HQ delayed until 12/12/06 due to requests for additional thermal testing by the TAC and EIRB boards.

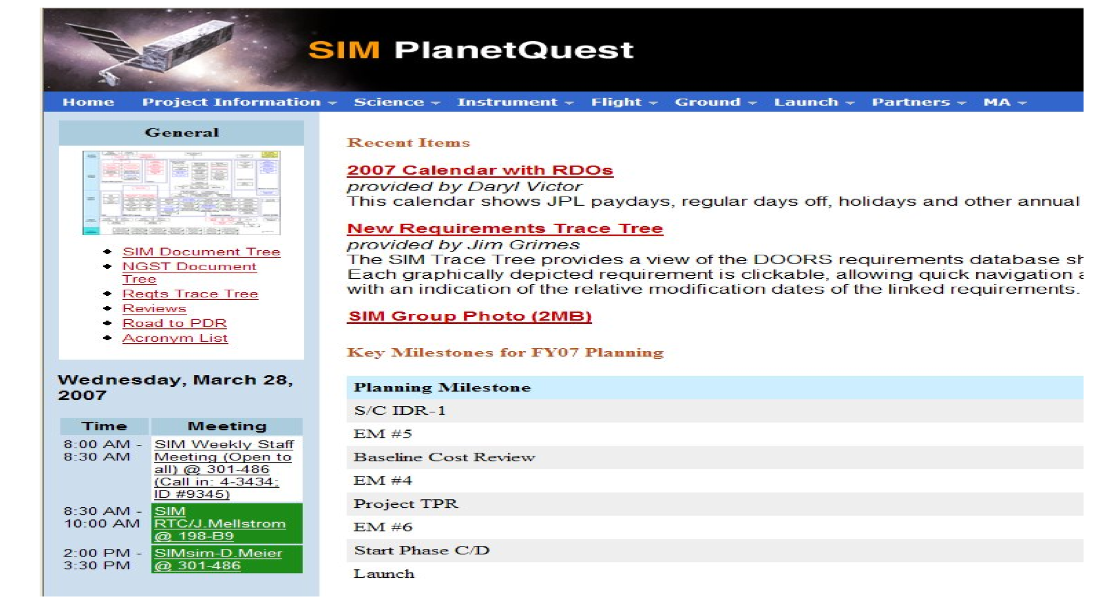
SIM Information Technology Resources

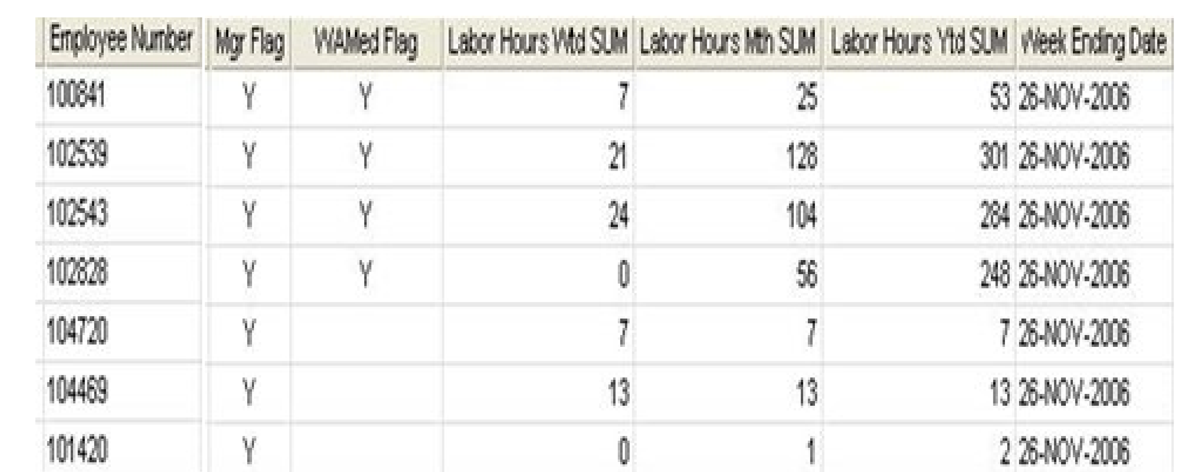
SIM Instrument Web Resources

Examples:

SIM Website

*Wiki Users Maintain Content





Employee Number	Mgr Flag	WAMed Flag	Labor Hours Wtd SUM	Labor Hours Mth SUM	Labor Hours Ytd SUM	Week Ending Date
100841	Y	Y	7	25	53	26-NOV-2006
102539	Y	Y	21	128	301	26-NOV-2006
102543	Y	Y	24	104	284	26-NOV-2006
102828	Y	Y	0	56	248	26-NOV-2006
104720	Y		7	7	7	26-NOV-2006
104469	Y		13	13	13	26-NOV-2006
101420	Y		0	1	2	26-NOV-2006

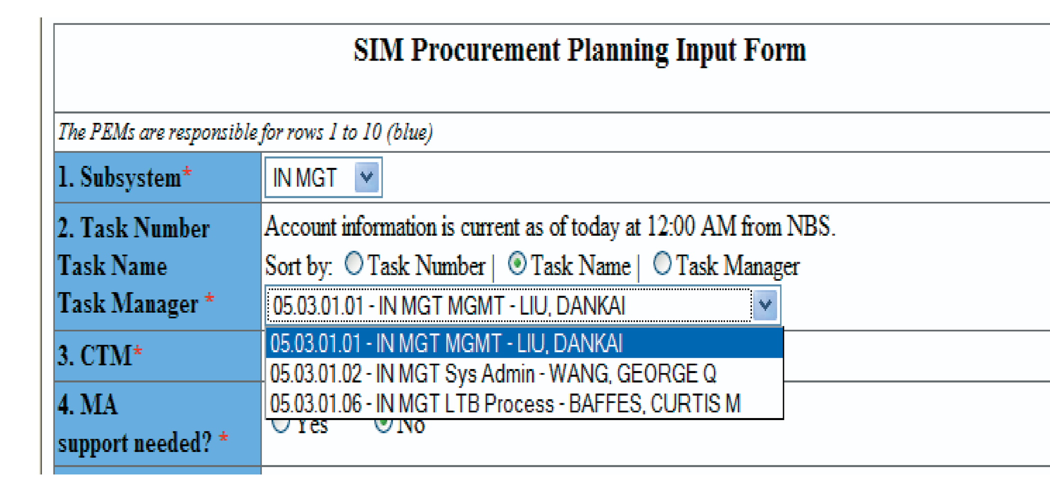
Financial Reporting Tool

*24/7 Web Browser Access to live Oracle data

*WAM list and supervisor

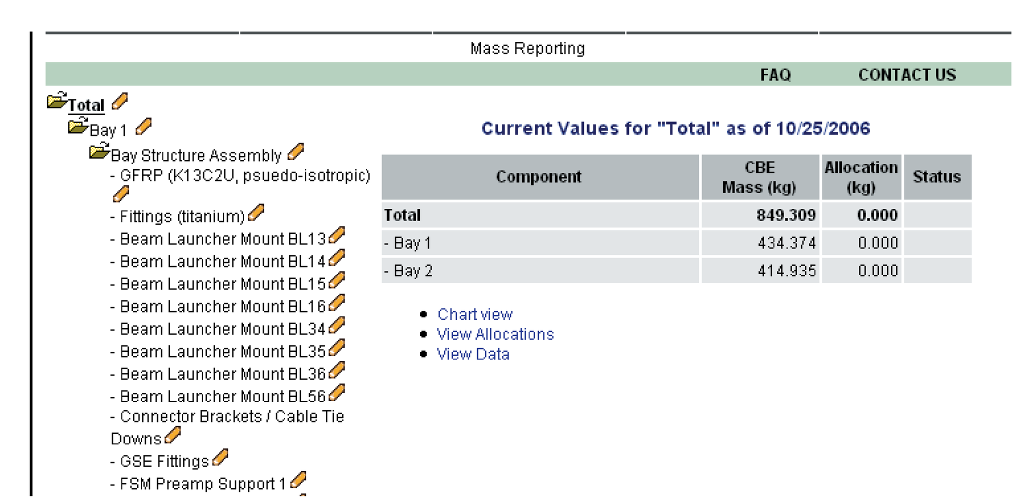
Procurement Planning Tool

*WBS Data from Oracle automatically updated daily



SIM IT Tools from Section 172

SIM Project Website and Wiki	Brian Smith
Action Item Tracking System	Sherry Bennett
Financial Reporting Tool	Melody Chang
Document Management Tool – PDMS and Docushare	Michael Stefanini
Mass Online Reporting Tool	Sandy Gutheinz, Eric Ramirez, Melody Chang
Risk Management System	Keevin Fisher
Significant Event System	Sherry Bennett
Procurement Planning Tool	Melody Chang, Boris Oks



Mass Online Tool

*Track Mass Changes for Measure Equipment List (MEL)

SIM believes in process automation using information technology.

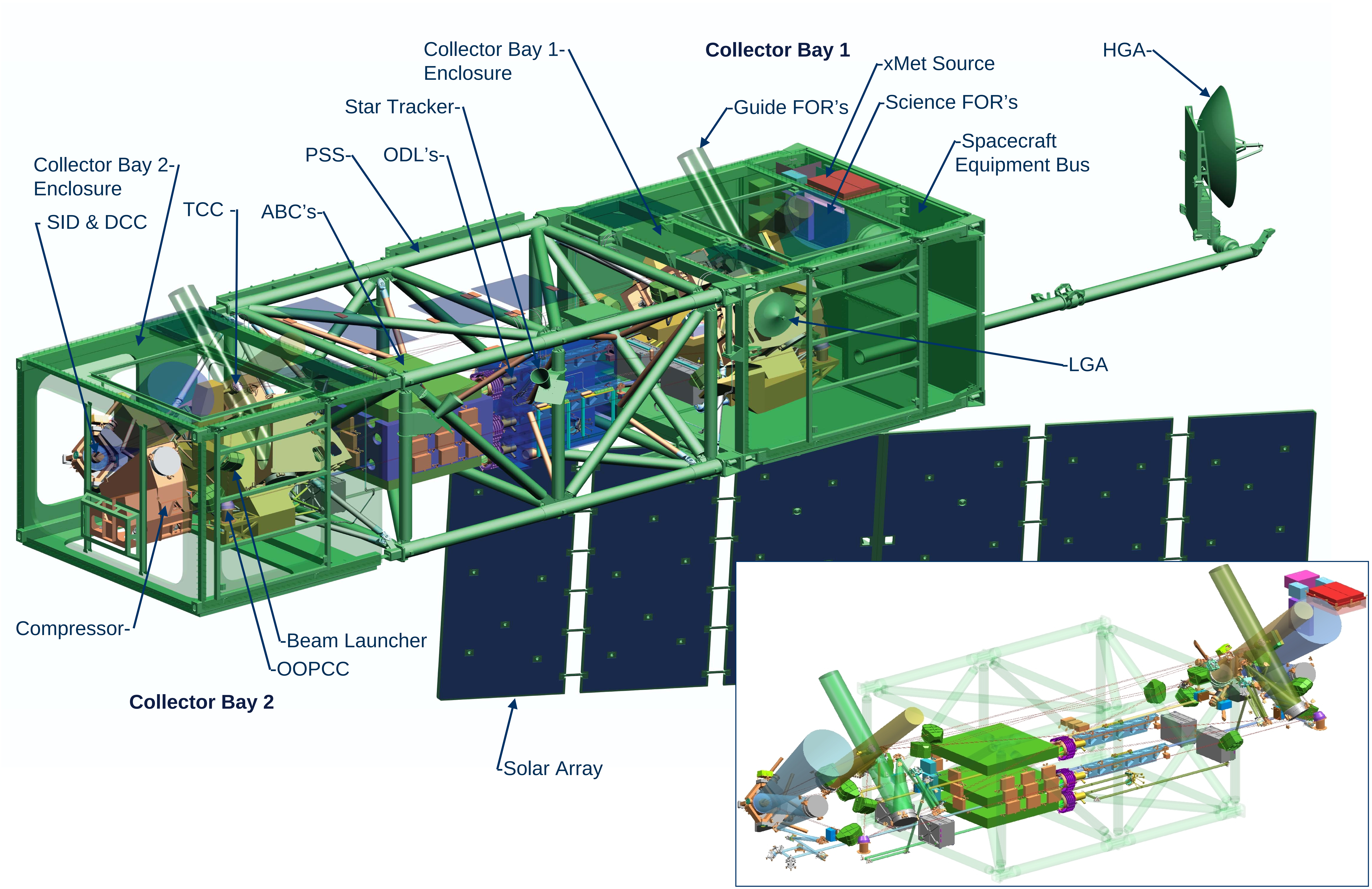
It is our job to make it happen.

SIM IT Contact: Melody Chang, Brian Smith

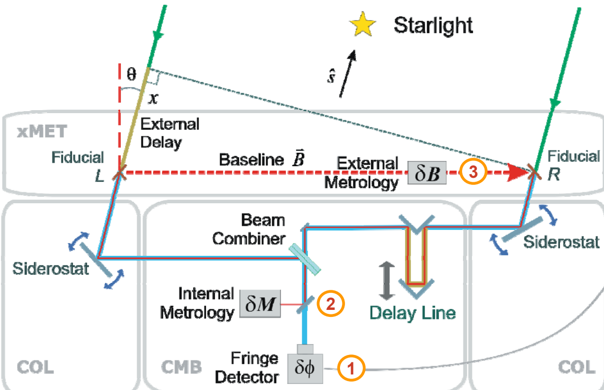
SIM Document Contact: Bob Vincent

OCIO

SIM Configuration

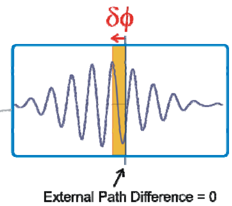


HOW SIM WORKS



Astrometry

The goal of astrometry is to measure angles between stars. Astrometry provides the underpinning for much of astrophysics. Boasting many orders of magnitude of improvement in astrometry dim targets, SIM is poised to revolutionize our understanding of the Universe.



OPD is broken into three distinctions: total (T), external (E), and internal (I)

$$\delta\phi = T_L - T_R = (E_L + I_L) - (E_R + I_R) = \underbrace{(E_L - E_R)}_{x} + \underbrace{(I_L - I_R)}_{\delta M}$$

The Stellar Astrometric Interferometer

An interferometer measure stellar angles by measuring

- The optical pathlength difference (OPD or delay) of light from the star to each end of its baseline.
- The length of its Baseline

The ratio of these two quantities gives the angle to the star

Three principal sensors are needed:

- Stellar Fringe Detector (1) gives the total OPD
- Internal Metrology (2) gives the internal OPD
- External Metrology (3) gives the baseline

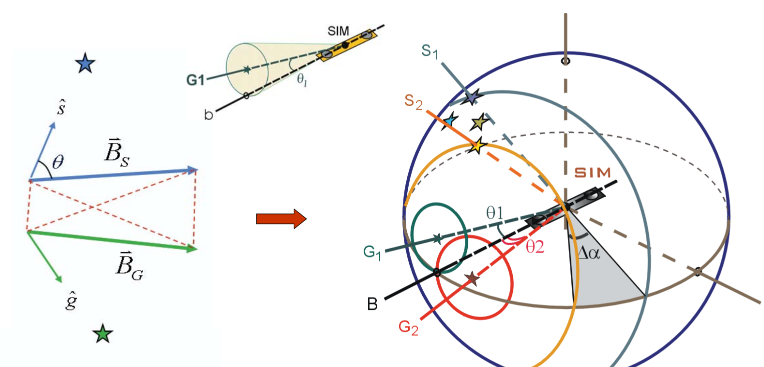
Three interferometers

One interferometer makes science measurements while two others, in conjunction with an external metrology system, track the changes in the baseline.

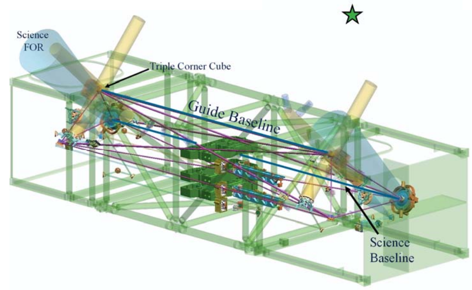
In a 2D world, a single ("guide") interferometer would measure its baseline motion relative to a fixed "guide" star while the "science" interferometer makes its science measurements.

The Science baseline vector changes are measured by the external metrology truss which links the Science baseline to the Guide baseline.

In a 3D world, two guide interferometers are needed. The SIM approach has these interferometers sharing their baseline.



Guide star locations shown near the baseline for clarity

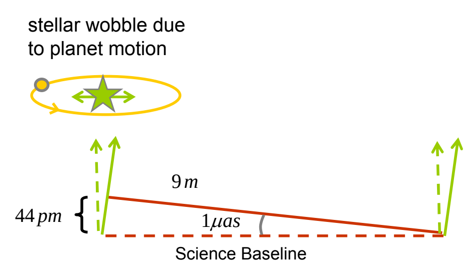


Micro Arcsecond Astrometry

To measure the wobble of an earth like planet at 10 parsecs away, SIM needs to achieve astrometric error of less than 1 micro-arcsecond per measurement.

Since the science baseline length is 9 meters, this translates to a total delay error of 44 picometers.

The delay error, expressed in picometers, is the basis of the SIM instrument Astrometric Error Budget (AEB).



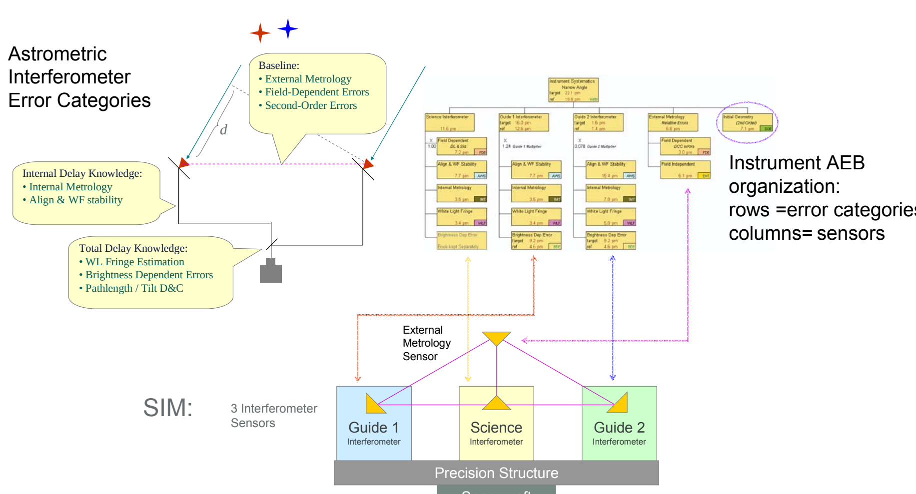
Main Error Categories in the AEB

The main error categories in the SIM instrument are shown in the figure to the right.

Each of these error categories constitutes a "branch" of the SIM error budget.

The SIM technology program and the brassboard development program have been aimed at retiring technical risk in meeting the requirements set forth in the AEB.

See the other presentations in this pavilion to learn more.

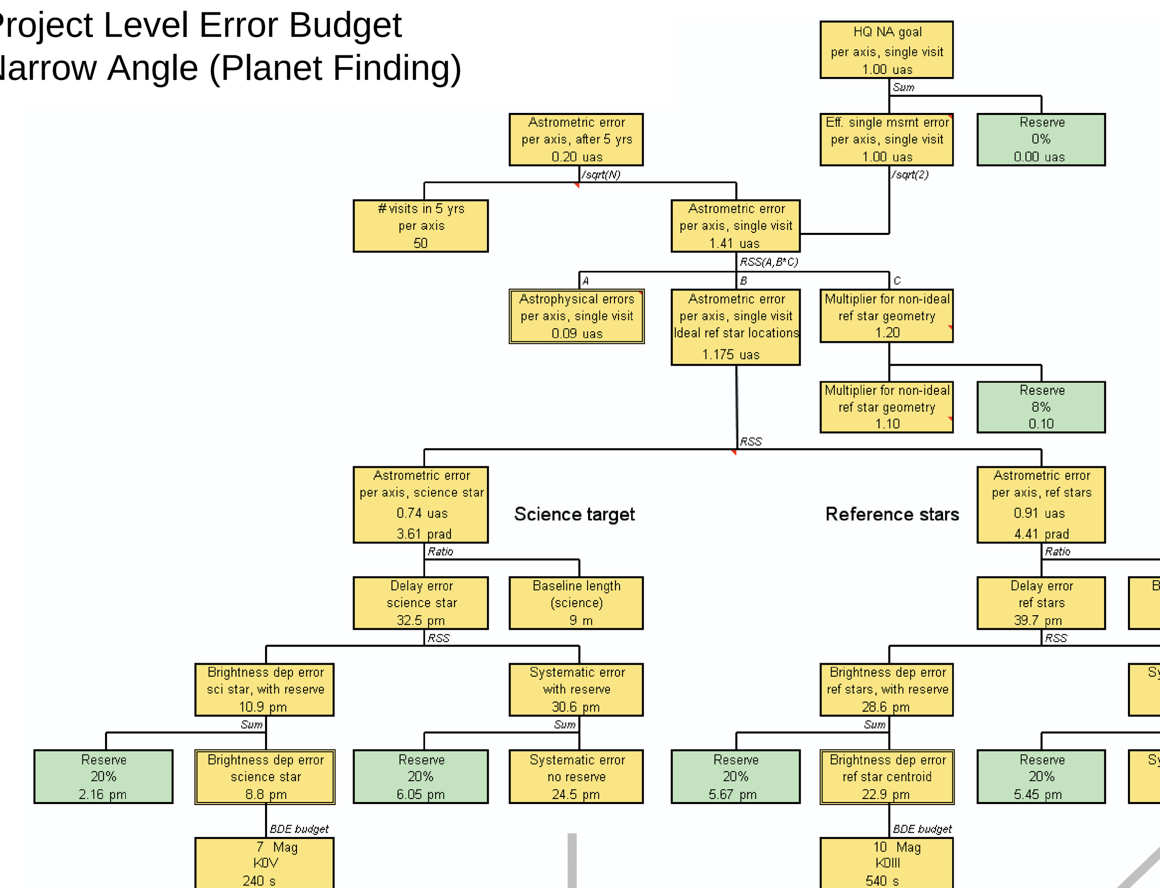


SIM Performance Requirements Flow Down

AEB Flowdown

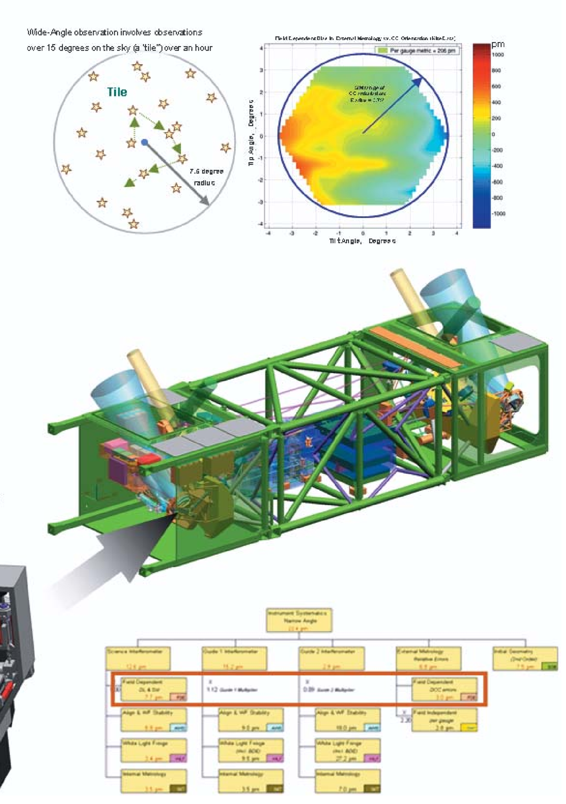
The AEB flows down micro arcseconds to picometers of delay error. These are in turn first broken down to the various error categories (Field Dependent, Alignment and wavefront stability, etc.). From there, using a variety of models the allocations in picometers are flowed down to engineering units.

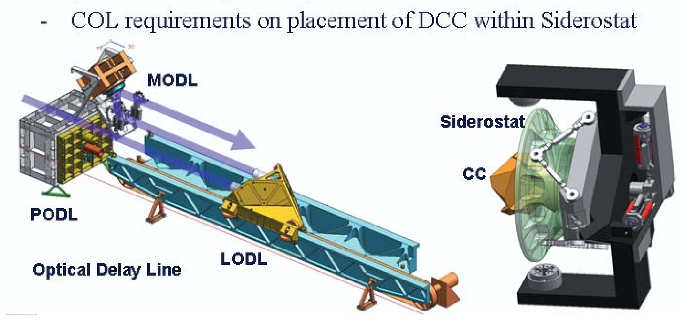
Project Level Error Budget
Narrow Angle (Planet Finding)



Field Dependent Errors

- Contributing Mechanisms
  - External Metrology Field Dependent Errors
    - Gauge errors resulting from the metrology beam walking on an articulating DCC
  - Science interferometer Field Dependent Errors
    - Coupling of ODL motion and diffraction of internal metrology and starlight beams
    - Coupling of the articulating Sid+DCC combination and knowledge error in the DCC-vertex to Siderostat surface distance
- Requirements Driving Design
  - Requirements on Double and Triple Corner Cubes (Size, NCVE, Coating, WFE)
  - Grid Processing is affected (Zernike fits to grid data)
  - COL requirements on placement of DCC within Siderostat

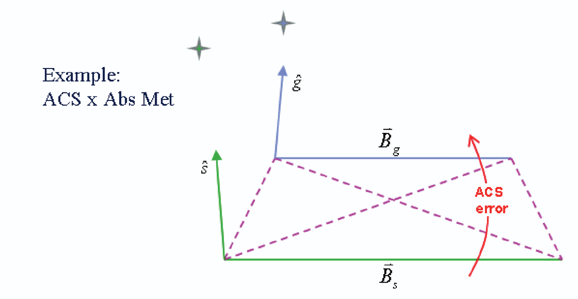


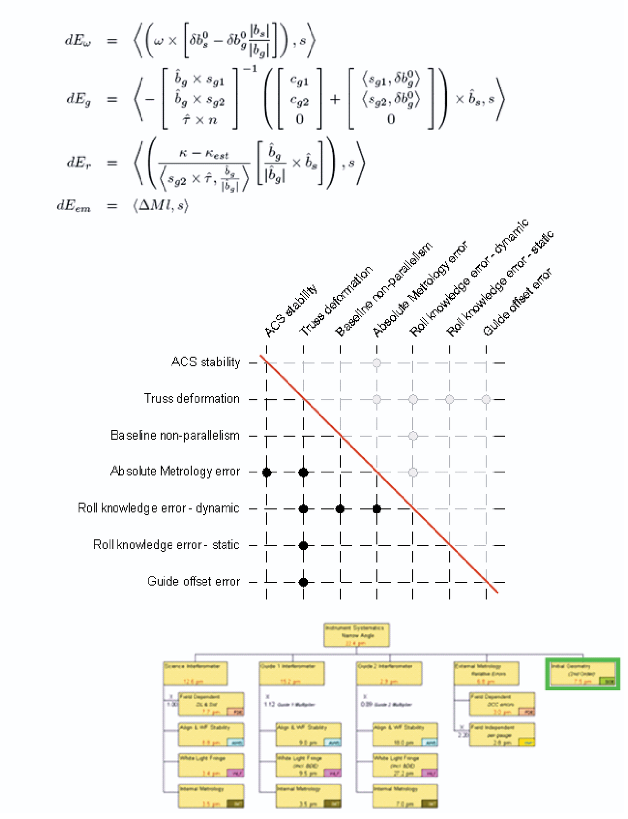


Second Order Errors

What are these?
- These mostly fall into the category of [motion] * [knowledge/meas. error]
  - These are errors we 'eat' – in that we cannot sense and correct for these.
- Contributing Mechanisms
  - The grid plot of SOE's shows the effects captured:
- Requirements Driving Design
  - ISE Alignment: Baseline parallelism
  - D&C: ACS Stability
  - External Met: Absolute Metrology
  - Roll LOS stability on Alignment & WF stability

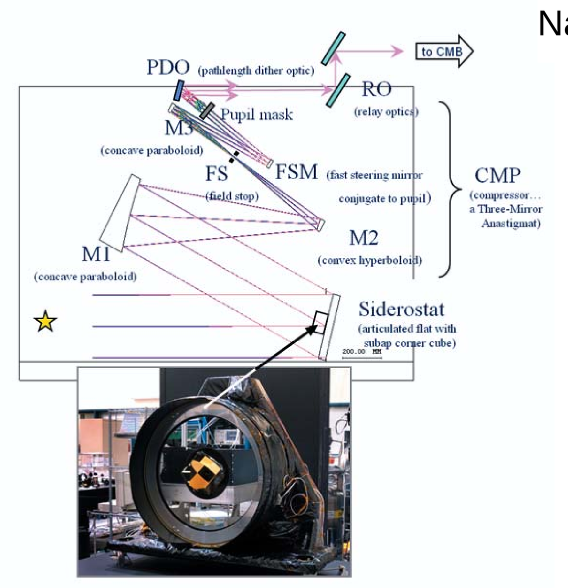
Example:
ACS x Abs Met

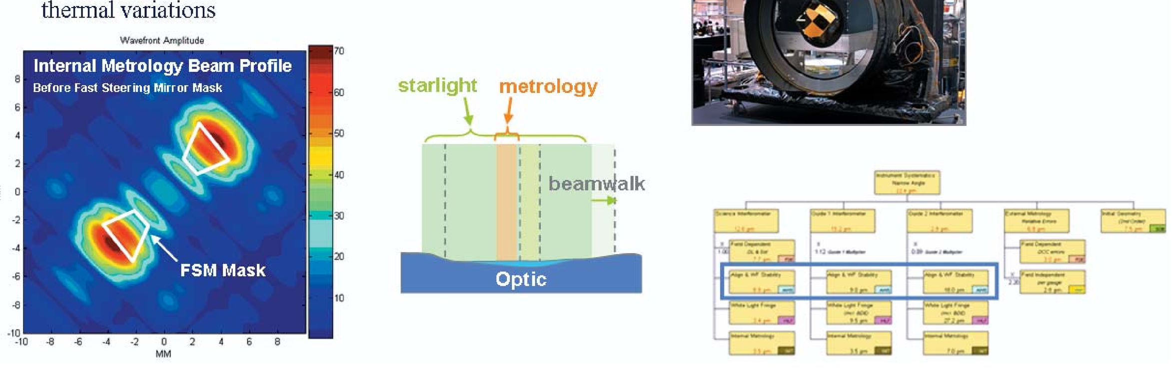




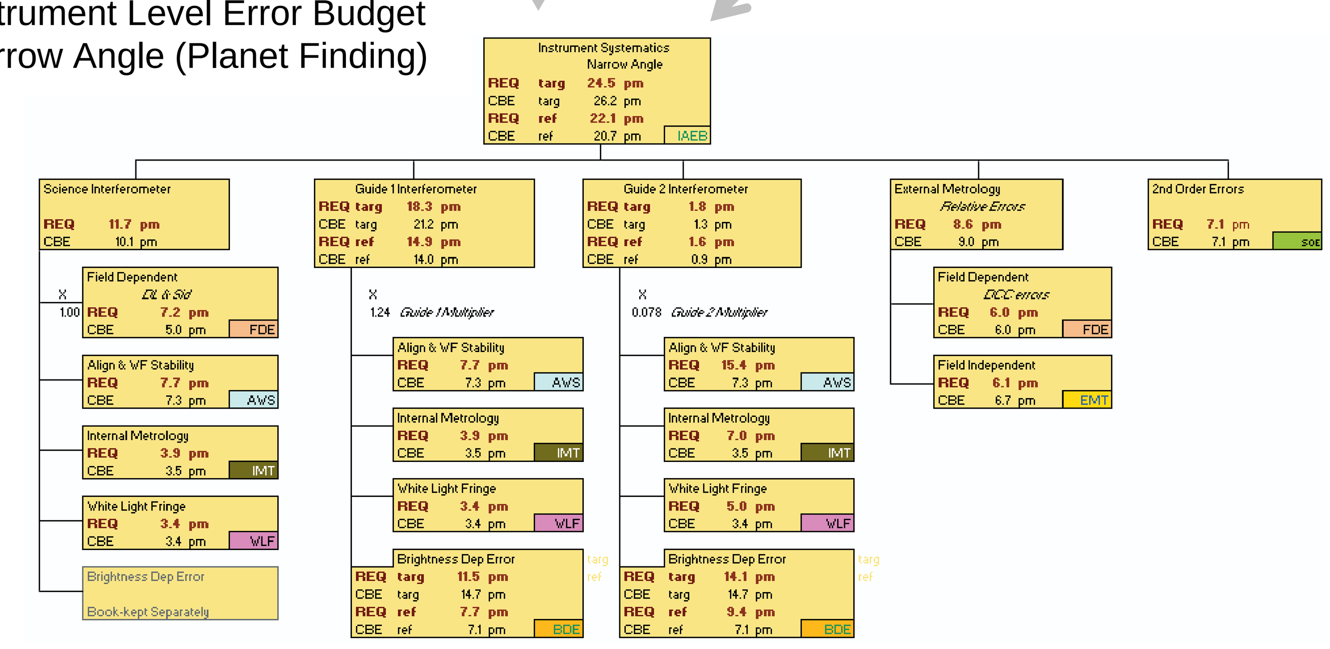
Alignment & Wavefront Stability

- Contributing Mechanisms
  - Beamwalk along the interferometer optical train
  - Couplings between beam shear and beam wavefront tilt
  - Couplings between beam shear and beam diffraction
  - Instabilities in the beam wavefronts due to thermal deformations
- Requirements Driving Design
  - PSS and COL truss allowed structural deformations from thermal variations
  - Internal metrology beam walk and shear on optics & Masks
  - LO beam tilt in the Internal Met Beam Launcher
  - Focus change in the collector due to milli-Kelvin level thermal variations



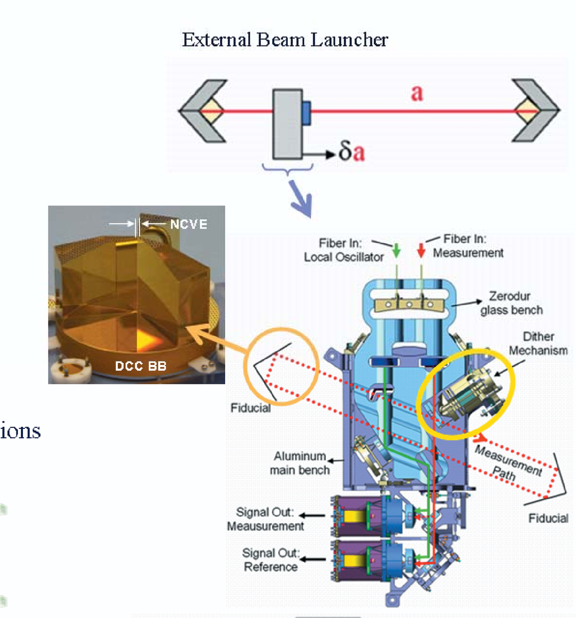


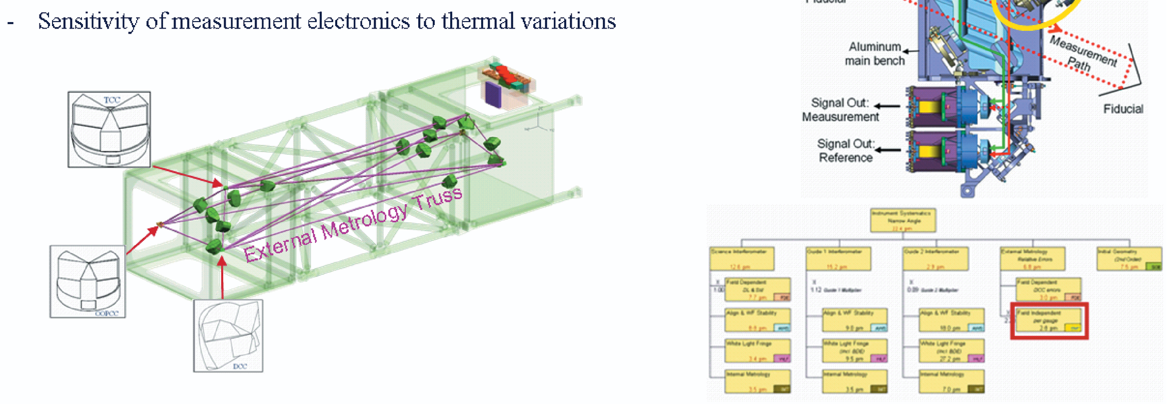
Instrument Level Error Budget
Narrow Angle (Planet Finding)



External Metrology Field-Independent Errors

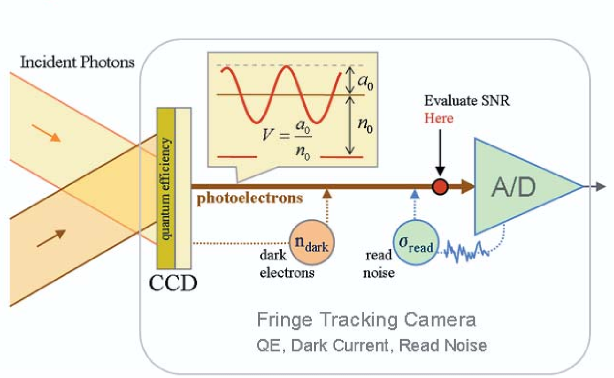
- Contributing Mechanisms
  - External metrology beam launcher errors
  - Metrology Source Errors
  - Metrology Electronics Errors
- Requirements Driving Design
  - Truss geometry/instrument configuration
  - Beam launcher pointing
  - Beam launcher cyclic (optical cross-talk)
  - Absolute metrology & NCVE
  - Stability of the Laser source and FDA delivered power
  - Sensitivity of measurement electronics to thermal variations



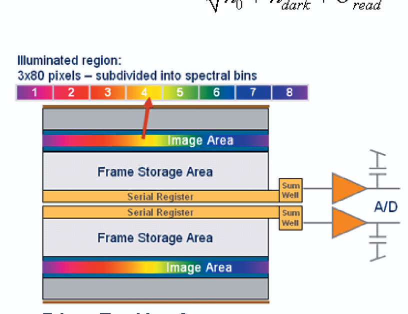


Brightness-Dependent Errors

- **Contributing Mechanisms**
  - These are essentially SNR related errors
  - Affecting the SNR are:
    - Visibility
    - Collecting area
    - Throughput
    - Fringe Tracking Camera
- **Requirements Driving Design**
  - Collecting area is directly driven by BDE budget
  - Dynamic Visibility is the driver for D&C pathlength & angle stabilization
  - Throughput drives silver coatings
  - BDE also drives Camera spectral response, read noise and dark current

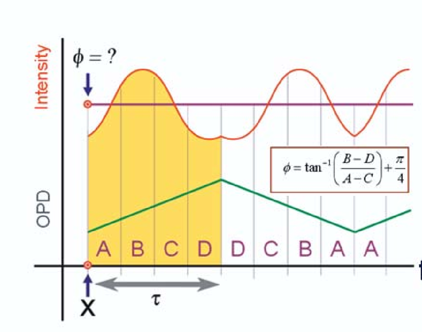


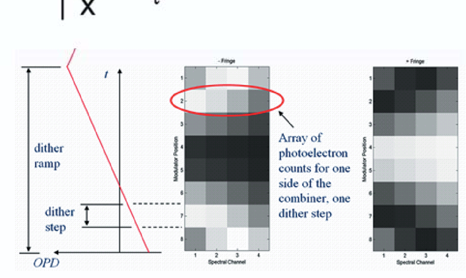
$$SNR = \frac{V\, n_0}{\sqrt{n_0 + n_{dark} + \sigma^2_{read}}}$$

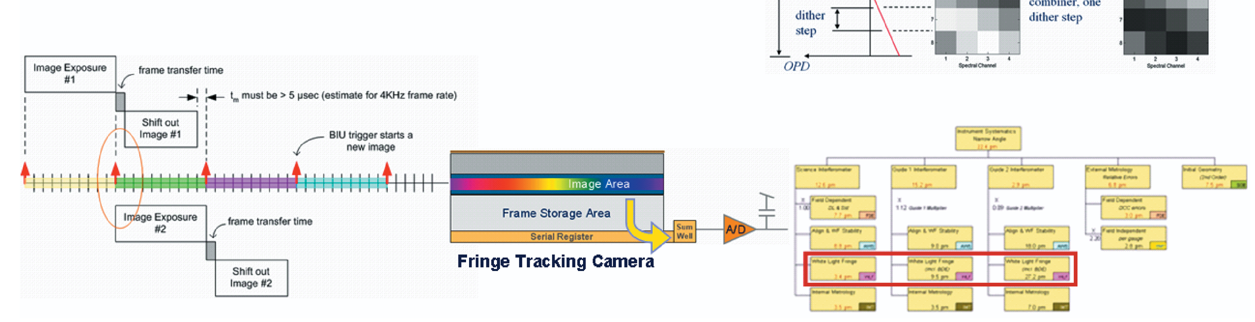


White Light Fringe Estimation Errors

- Contributing Mechanisms
  - Pathlength Modulation Errors (Spectral stroke curve vs. the assumed curve)
  - Timing Errors (Pathlength modulation vs. fringe camera timing)
  - Calibration Errors (Spectral and phase dispersion curves, stellar flux curves)
  - Drifts – Time degradation of calibration curves
- Requirements Driving Design
  - Starlight-polarization sensitivity drives combiner optical design, throughput
  - Tight requirements on camera frame acquisition timing
  - Dither distortion requirements drive D&C performance

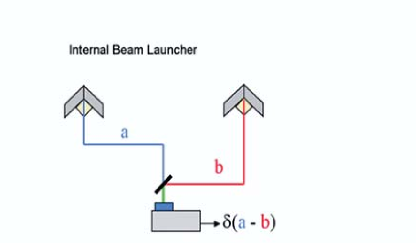


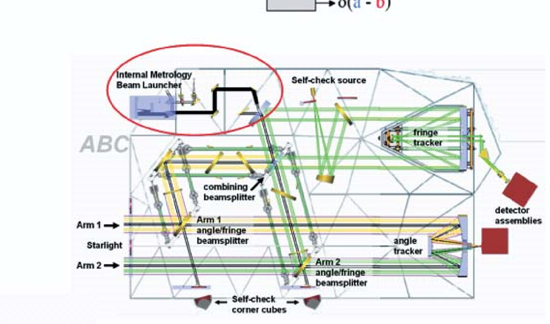


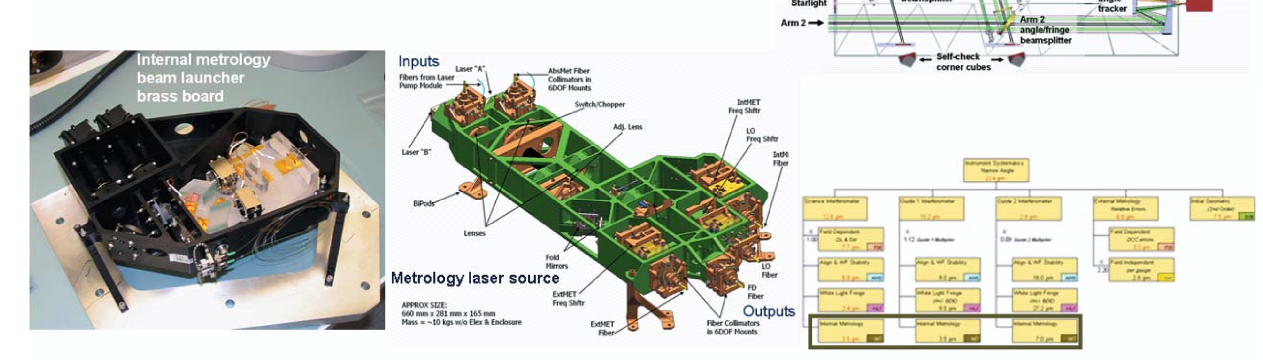


Internal Metrology Errors

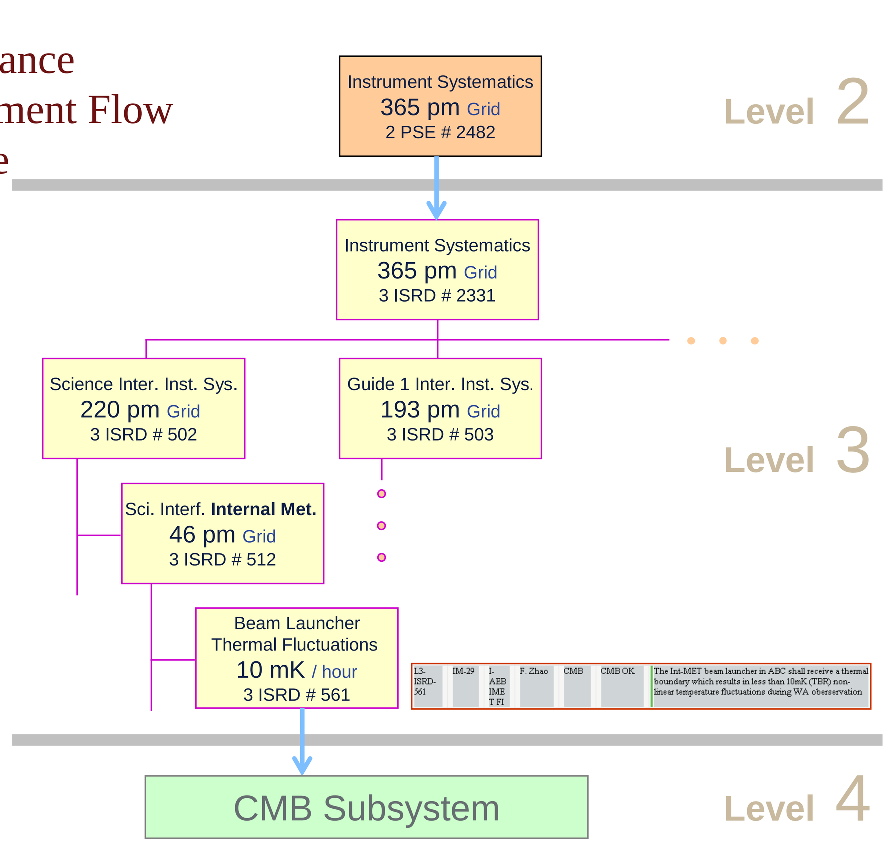
- Contributing Mechanisms
  - Errors in the estimation of the internal starlight path coming from internal metrology
  - These are primarily
    - Metrology gauge random noise errors
    - Metrology gauge cyclic errors
    - Metrology gauge thermal errors
- Requirements Driving Design
  - Shot-noise drives metrology laser source power
  - Optical/Electronic Cross-Talk (to suppress cyclic errors)
  - mK level thermal stability requirements in the ABC.

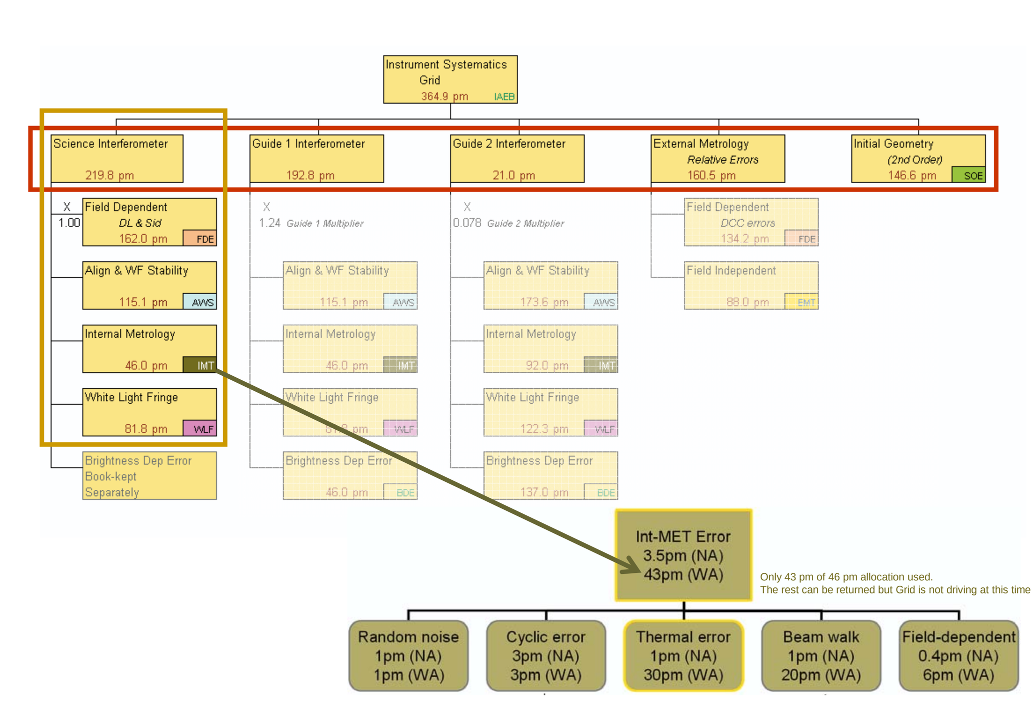






Performance Requirement Flow Example

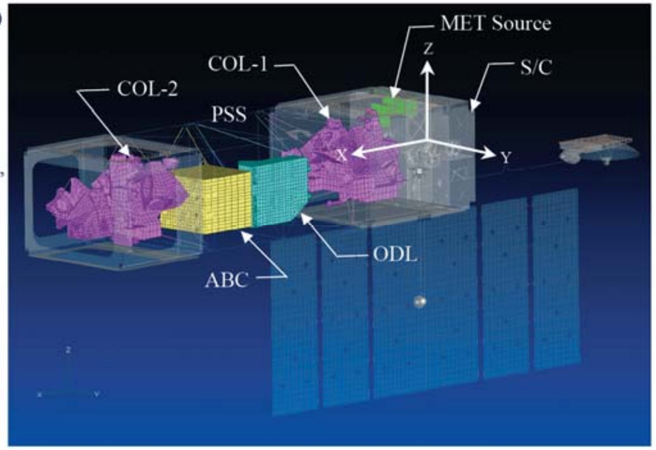


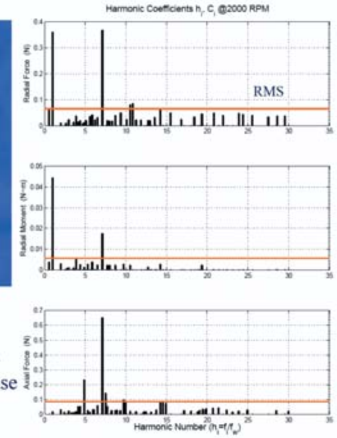


SIM Integrated Nano Model (FEM)

Contacts: John Spanos (JPL) Reem Hejal (NGST)

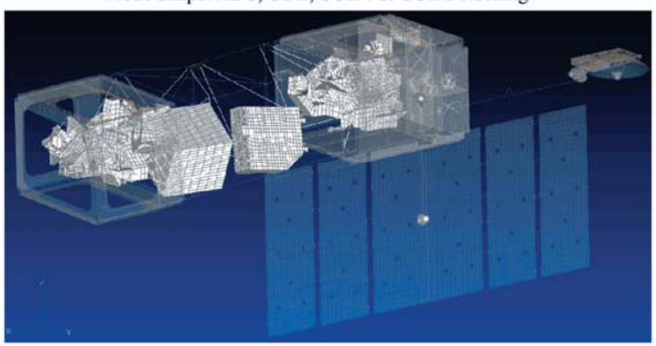
- Model Specifics (1.B)
  - Mass: 5,970 kg
  - Nodes: ~ 130,000
  - Elems: ~ 142,000
  - DOFs: ~ 702,000
- Model reduced to ~6,400 normal modes, all below 1000 Hz
  - First solar array mode at ~0.3 Hz
  - First S/C isolator mode at ~2 Hz
  - First RW isolator mode at ~7 Hz
  - First instrument mode at ~15 Hz
- Reduced model augmented with 146 "static correction" modes





- SIM uses 6 Teldix RDR-68 reaction wheels for ACS
- Modeled with 75 harmonics per wheel --estimated from fixed base measurements [Ref. R. Hejal]

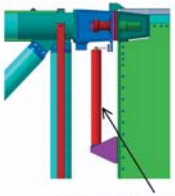
Mode Shape: ABC, ODL, COL 1 & COL 2 Rocking



Reaction Wheel Isolator (one per wheel)

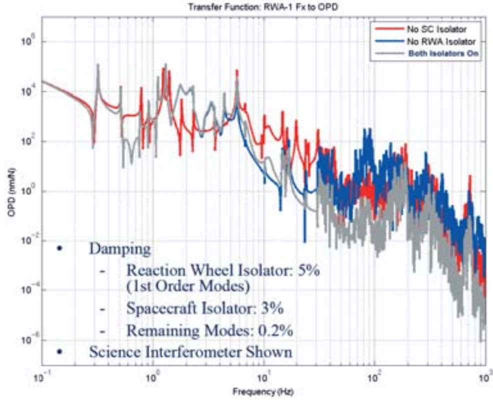
Hexapod config. w/ six "soft" struts

Spacecraft Isolator



Dynamic Isolator ("soft" strut, 4 places)

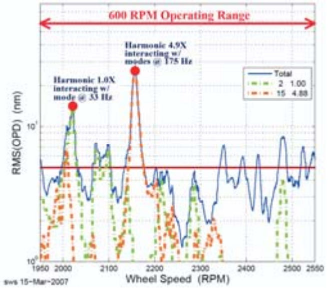
Effectiveness of Dual Stage Vibration Isolator



- Damping
  - Reaction Wheel Isolator: 5% (1st Order Modes)
  - Spacecraft Isolator: 3%
  - Remaining Modes: 0.2%
- Science Interferometer Shown

- Spacecraft isolator shows significant performance from 10 Hz and up
- Wheel isolator shows significant performance above 30 Hz
- Both isolator stages are critical for SIM

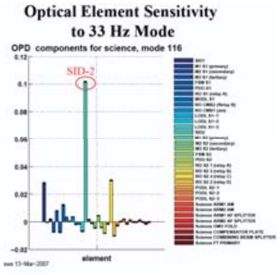
OPD Jitter in Science Interferometer



Significant Structural Modes to OPD Jitter

- SID piston motion is the primary contributor to OPD jitter for the 33 Hz mode
- The primary contributors to OPD jitter for the ~175 Hz modes are
  - Combined piston, tip & tilt motions of the Science-1 and Guide-5 FSMs as well as LODL Corner Cubes
  - Lateral bending of the RWA isolator struts
- Design modifications affecting the dynamics of these elements will significantly reduce OPD jitter

Optical Element Sensitivity to 33 Hz Mode



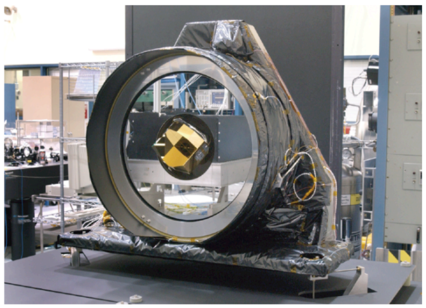
Field Dependent Performance Modeling

Contact: Mike Heflin x4-2823

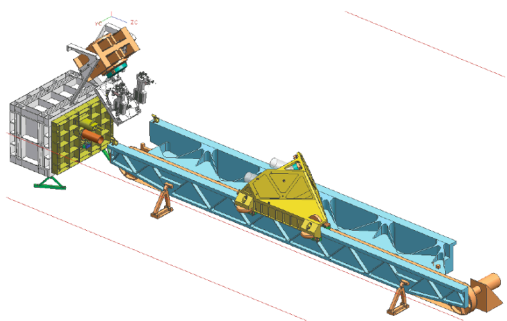
Field Dependent Errors

Observed when SID/DCCs articulate and delay lines move
Affect the science interferometer and external metrology
Diffraction is the main source for internal metrology and starlight
Corner cube imperfections are the main source for external metrology

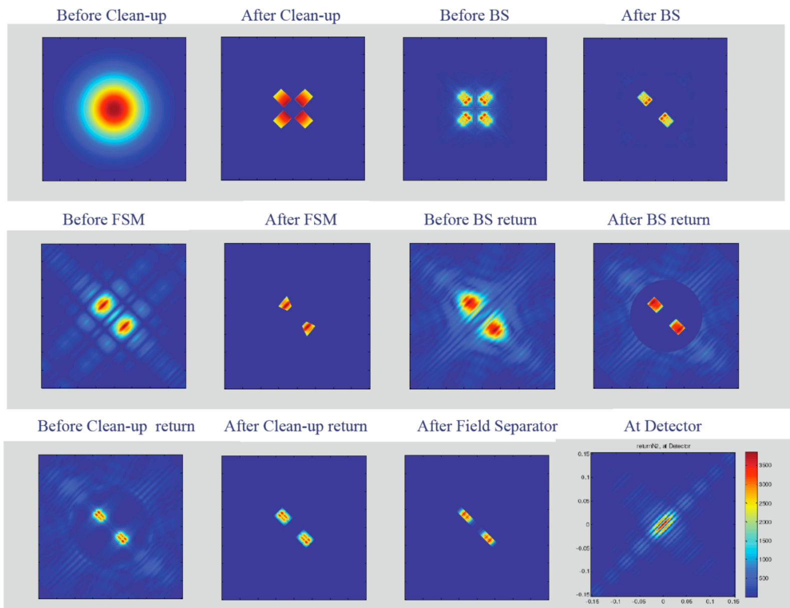
SID/DCC



Delay Line



Diffraction Model Example



Four parent allocations in pm from the AEB

1. WA Science FD - ISRD 507
2. NA Science FD - ISRD 488
3. WA Ext Met FD - ISRD 519
4. NA Ext Met FD - ISRD 500

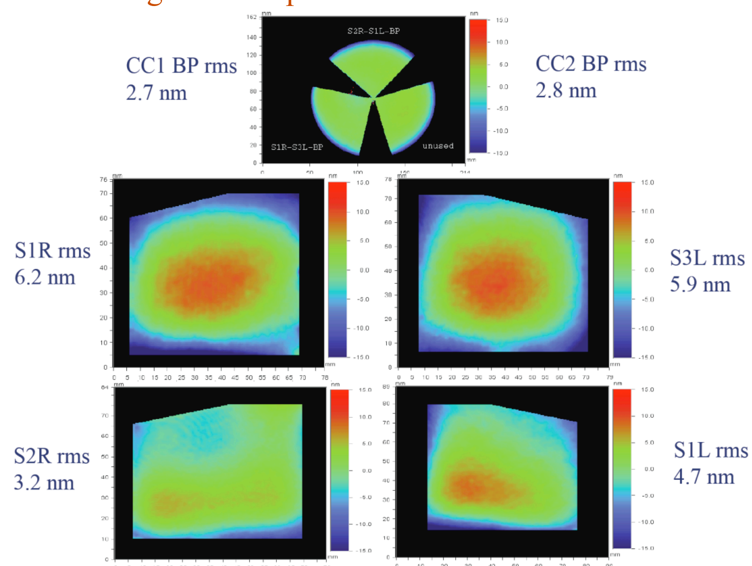
Five models necessary to connect requirements to performance

1. Internal Metrology Corner Cube Model - Xu Wang
2. External Metrology Corner Cube Model - L D Zhang
3. Internal Metrology Diffraction Model - Josh Hudman
4. External Metrology Diffraction Model - Dan Hoppe
5. Starlight Diffraction Model - Dan Hoppe

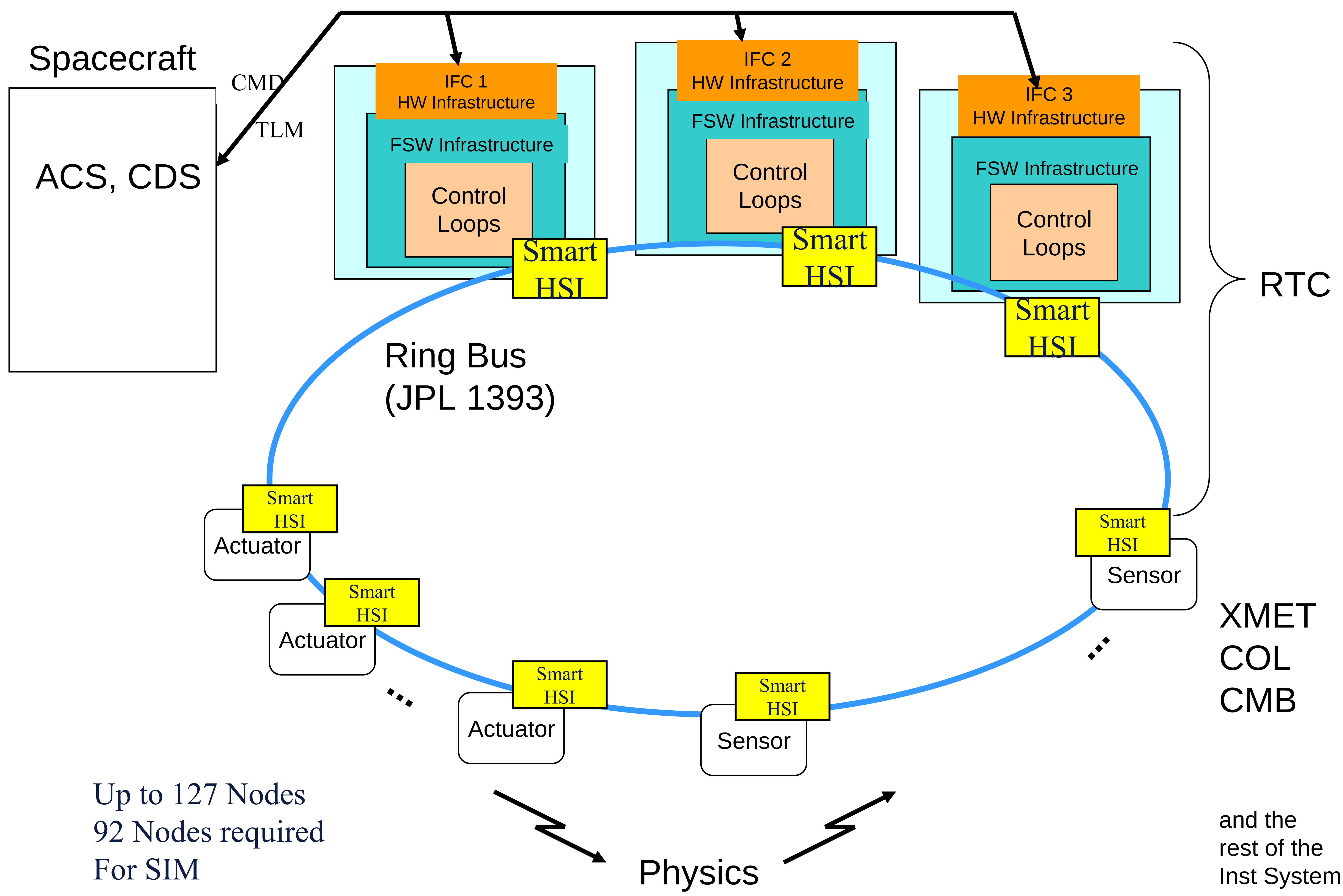
Picometer level optical modeling is beyond state of the art

Width of a human hair = 10,000,000 picometers
Optical design, physics, and processing must all be captured
Estimate field dependent Zernikes 1-15 as part of grid processing

Surface Figure Example

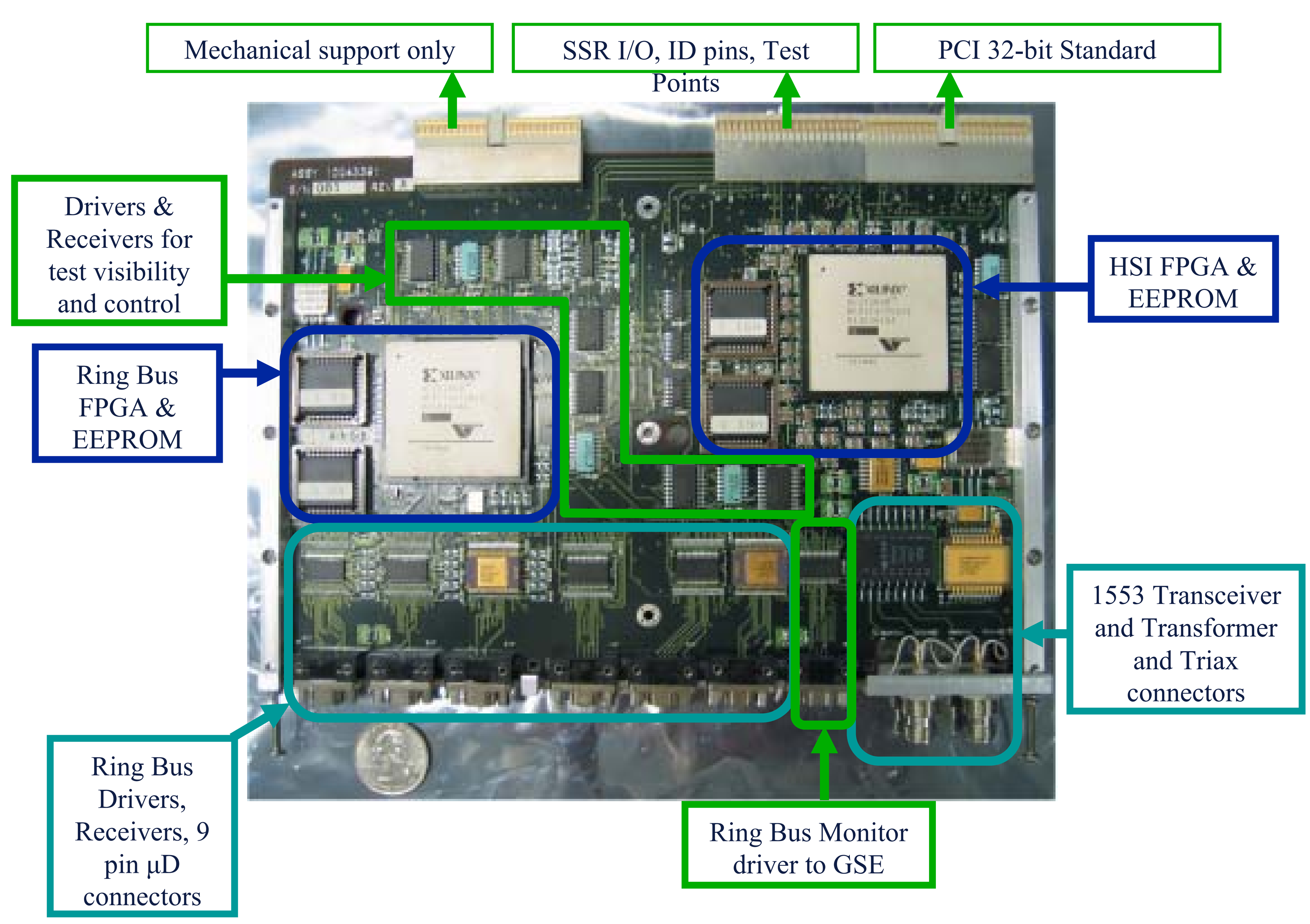


RTC Architectural Context Diagram



High Speed Interface (HSI) Card

- HSI 6U cPCI card
  - Compatible with MSAP
- SIM Instrument has 2 types of Ring Bus nodes
  - "Smart" IFC (HSI Card) using PCI and RAD PPC-750
  - "Dumb" Peripherals - FPGA interface to Ring Bus IC (no processor).
- Status:
  - EM-5 test activities are complete.
  - Data analysis is underway and the final report will be completed by the end of February.



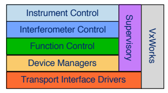
Testing in 2005 included rings of up to 10 Ring Bus ICs/HSI Cards.

Real Time Control (RTC) Flight Software (FSW)

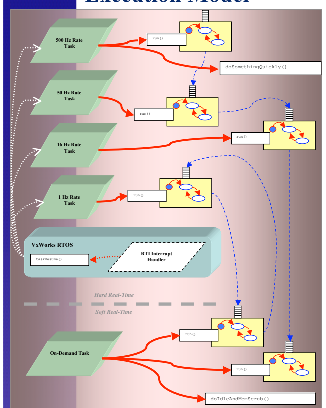
SIM PlanetQuest

Layered Architecture

Levies constraints on modules' interfaces

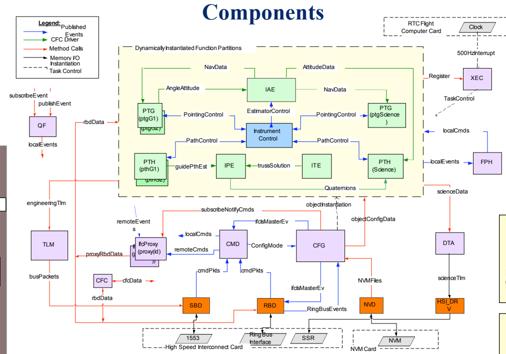


Execution Model



Architecture

Components



Connectors

0 – Registration Pattern for execution, telemetry, and ring bus transfers

- At initialization registration pattern allows for dynamic configuration

1 – Publish and Subscribe Events based on Quantum Framework

- Asynchronous for both commanding and status

2 – Implemented proxy system for inter flight computer event communication

3 – Within functional block, and same rate group, allow direct method calls

4 – Cross Functional Communications Interfaces – high rate

Provides direct method calls when functions on same flight computer

Provides Ring Bus wrappers when functions on remote flight computer

5 – Low priority large data transfers

Special ring bus interface for low priority large volume transfers such that high rate data not held up.

Attributes

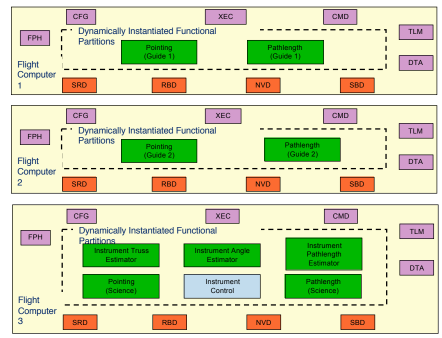
1 - ***Reliability***
- Mission Critical process
- CMMI level 3 processes

2 - ***Performance***
- No semaphores
- Component execution calls grouped into rate task threads

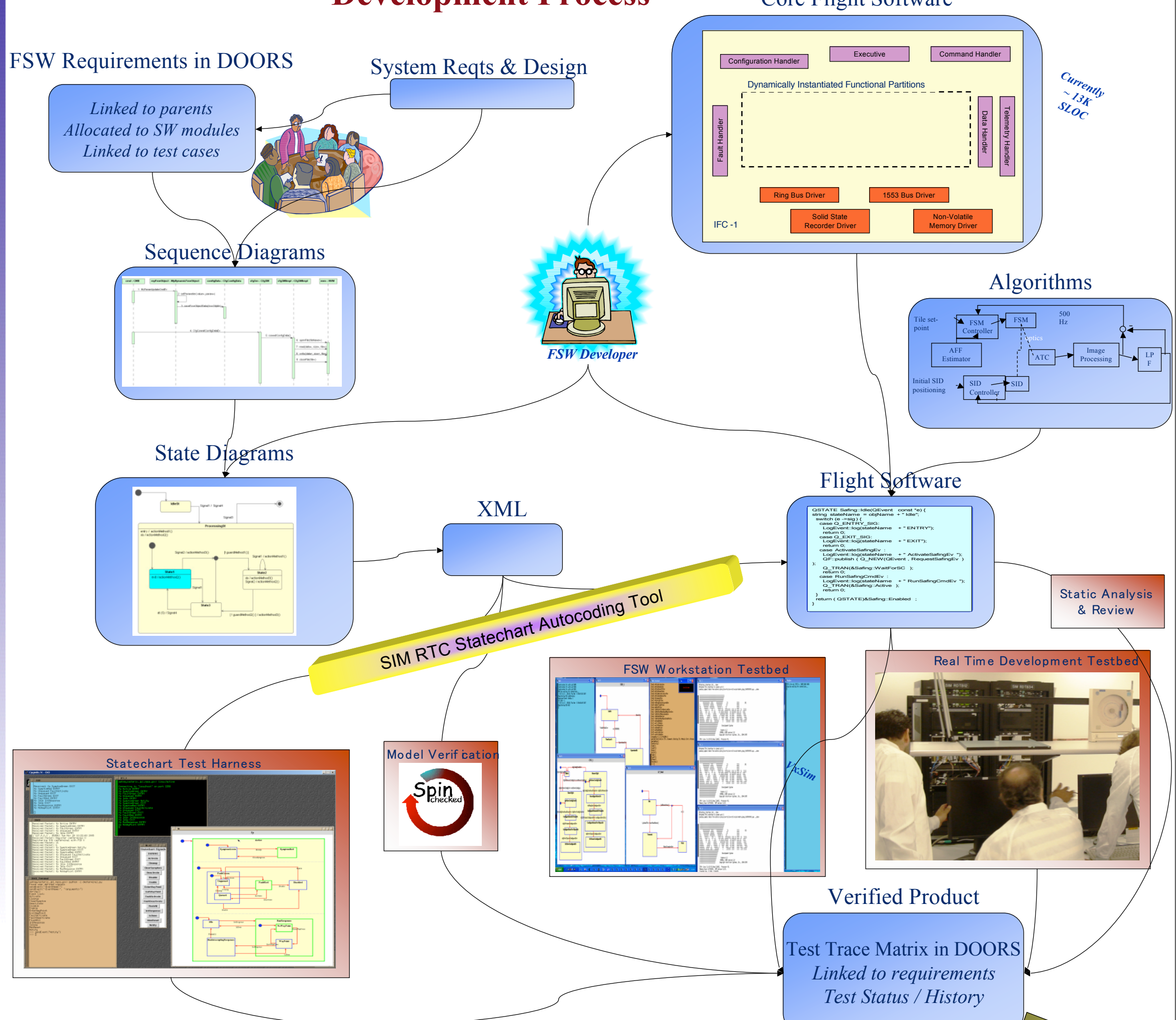
3 - ***Maintainability***
- Object oriented design, UML diagrams
- Embedded C++
- RTOS = VxWorks 6.2 with Workbench
- Single version of FSW for all CPUs

4 - ***Flexibility***
- Table driven approach for configuration
- Table driven (XML) command and Telemetry with auto-coded FSW

Reconfigurable Dynamic Design

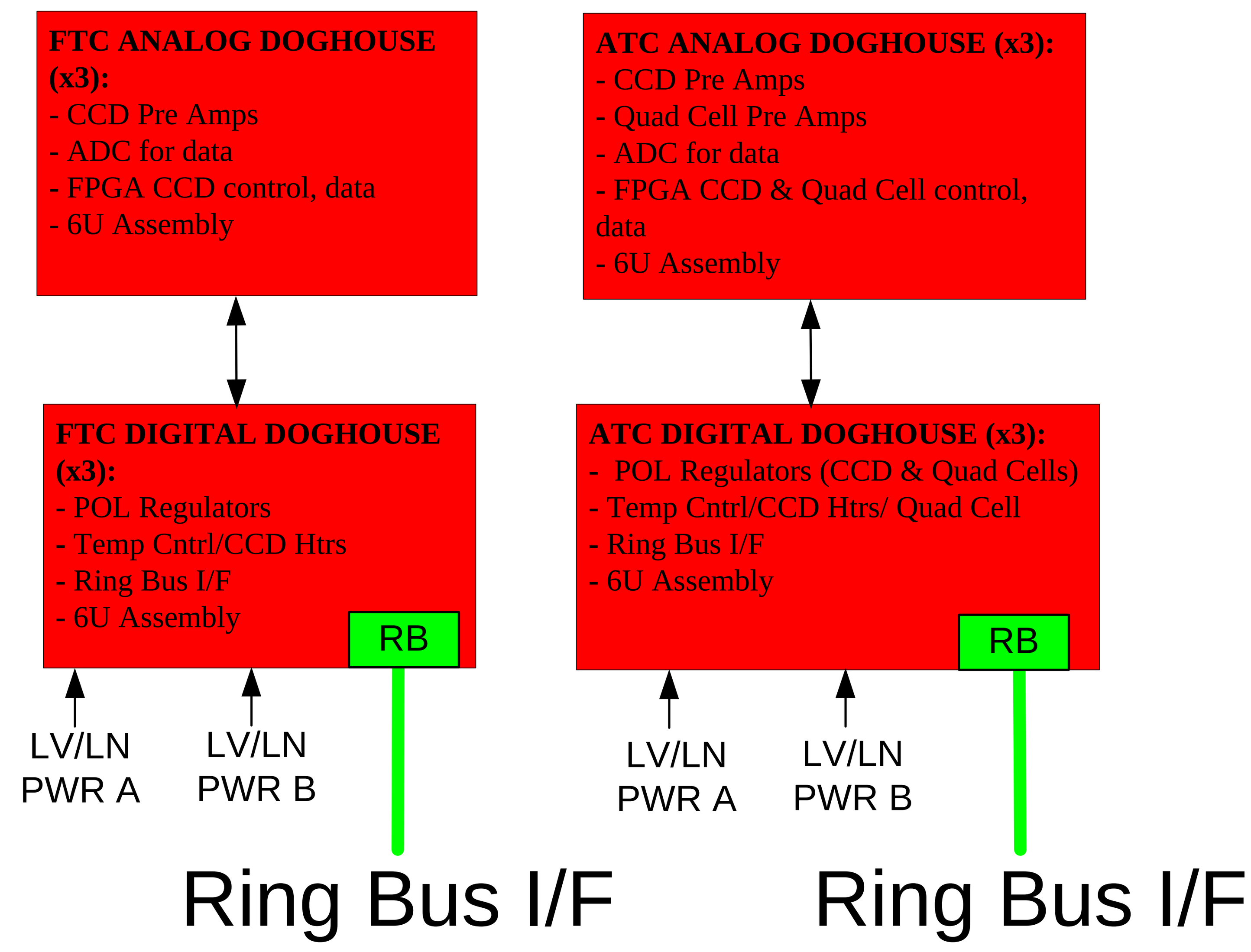


Development Process



NORTHROP GRUMMAN Space Technology · JPL · LOCKHEED MARTIN · CALTECH

Electronics Architecture



- Descriptions
  - Distributed Electronics Architecture
  - Utilize JPL 1393 Ring Bus Interface
  - Adds Flexibility in Electrical Architecture and reduction in system cabling

- Potential Applications
  - Ring Bus Application for future Avionics Architecture

- Design Maturity
  - Ring Bus is Brassboard fidelity
  - ICE Electronics various levels of Maturity from conceptual design to breadboard hardware.

Architecture Contact: Michael Brenner Extension: 4-6985

Ring Bus Contact: Terry Wysocky Extension: 4-0395

What is the JPL 1393 Ring Bus?

- A high-speed data transfer bus based upon IEEE 1393 Standard

  358.4 times faster than 1553B
  Rad Hard & SEU Immune
  Data Packets protected portal-portal
  LVDS for high-speed, low-noise, low-power
  Ease of Electronics Architecture redesign
  Improved Testability

  Scalable up to 126 BIUs
  Utilizes ATM Cells (Asynchronous Transfer Mode) standard of ITU-T, ANSI, ETSI & ATM Forum
  Multiple paths for fault containment regions.
  Allows for partitioning of FSW functions

- Enhanced to meet SIM real-time control system requirements with time and event synchronization.

  High Bandwidth (90+% margin for SIM)
  Time Synchronized

  Low Latency (predictive)
  Event Synchronization (programmable triggers)

- Minimize FSW Intervention

  Few States to Monitor/Manage (4)
  Intelligent Physical Layer

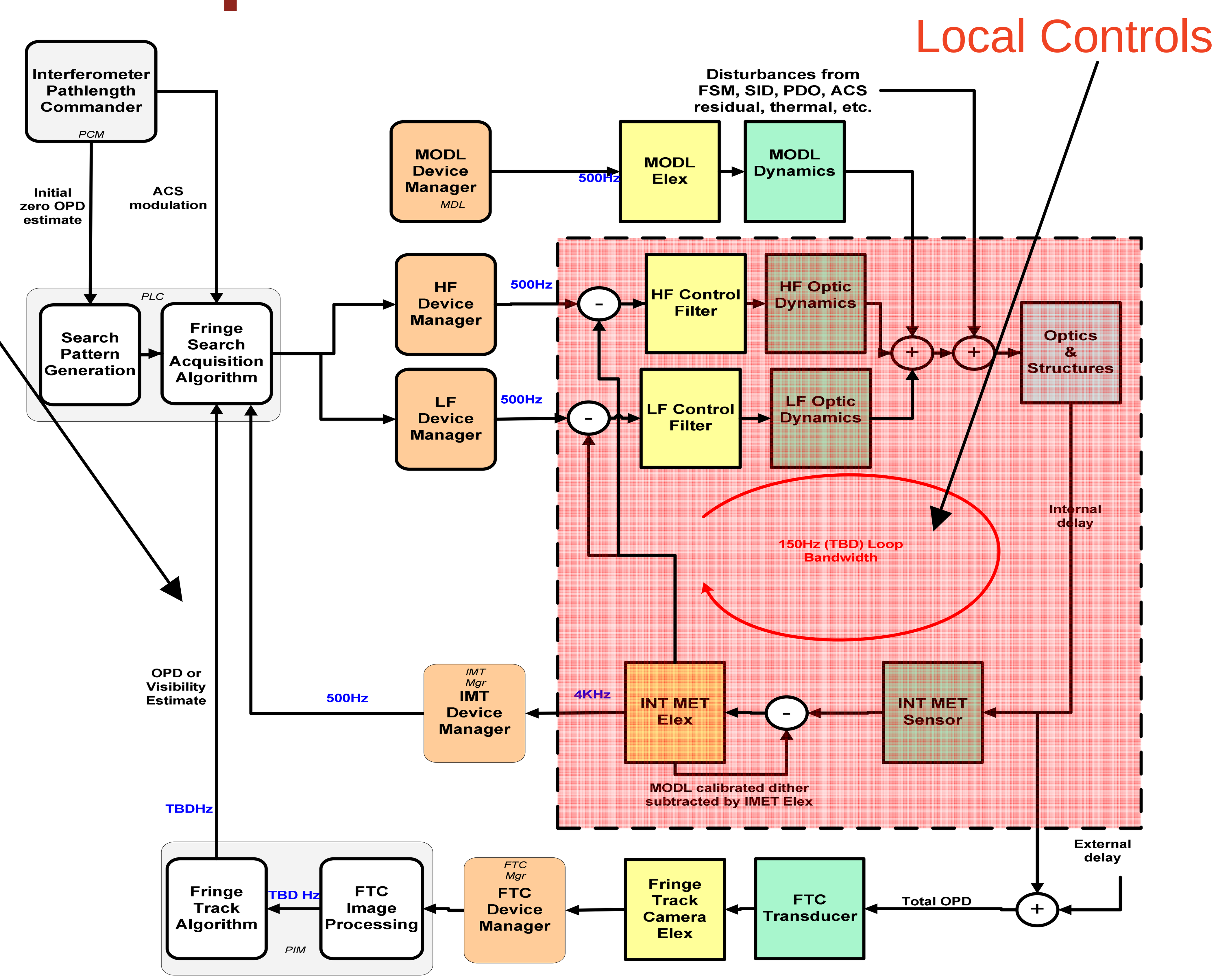
  Built-in Fault Tolerance
  Minimal FSW Intervention

- Additional Features

  JPL 1393 Ring Bus Users Manual
  SIM Ring Bus ICD (D-33135)

SIM Controls Design & Implementation

Global Controls



- **Descriptions**
  - Distribution on Controls into Global and Local Controls
  - Relieve Processor margin
  - Find the right tool for the job
  - Flight Computers for Global Controls
  - Local Controls implemented in Hardware

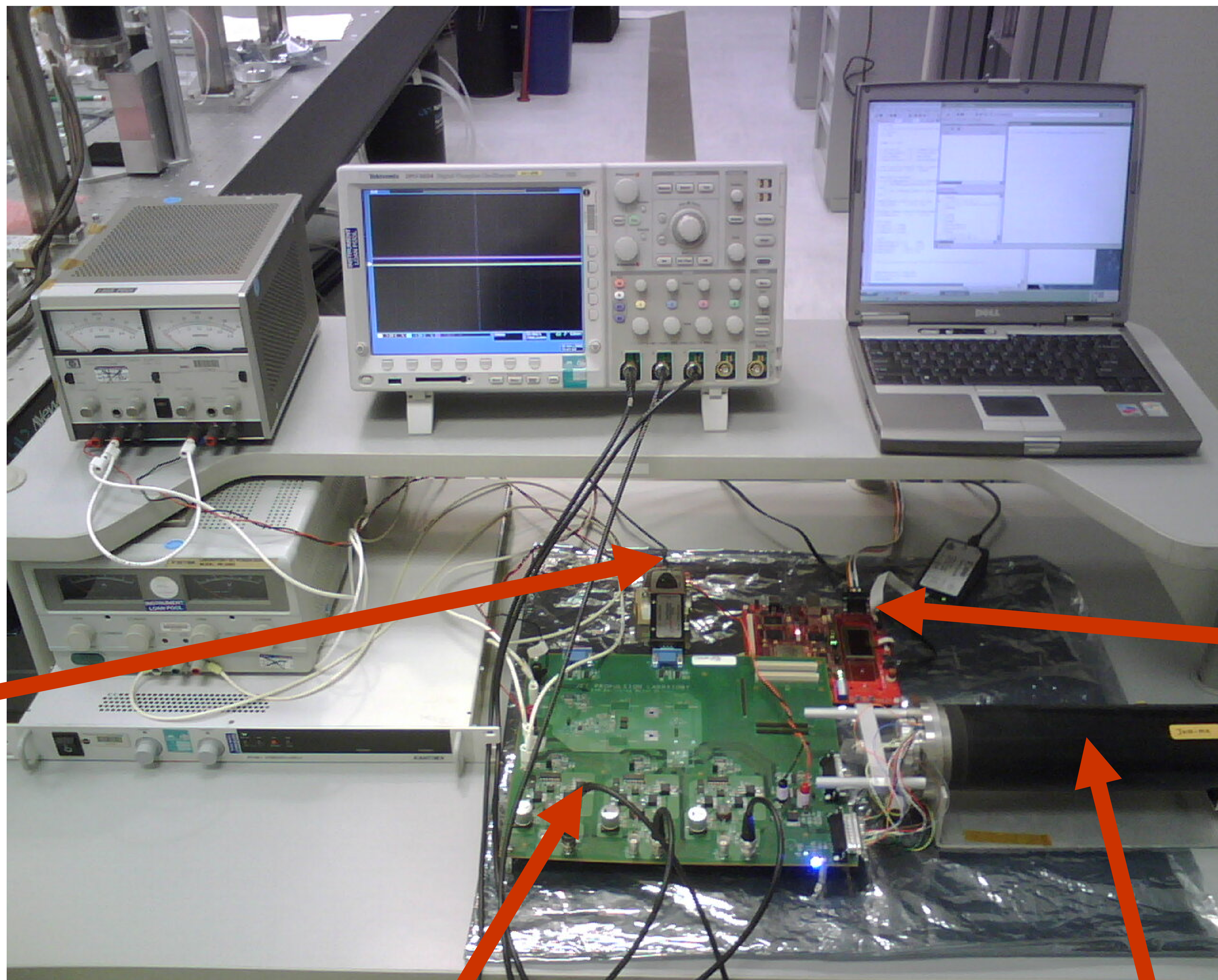
- **Potential Applications**
  - Large Controls Systems
  - Local Controls include Thermal control, Course stage Motor Control, Fine stage PZT positioning control, Local Mechanism Profiling.

- **Design Maturity**
  - Conceptual Design with solid models in UG Software.

Contact: Michael Brenner (4-6985) John Koenig (3-7129)

Siderostat Ballscrew Testbed Electronics

Contact: John Koenig Extension: 3-7129



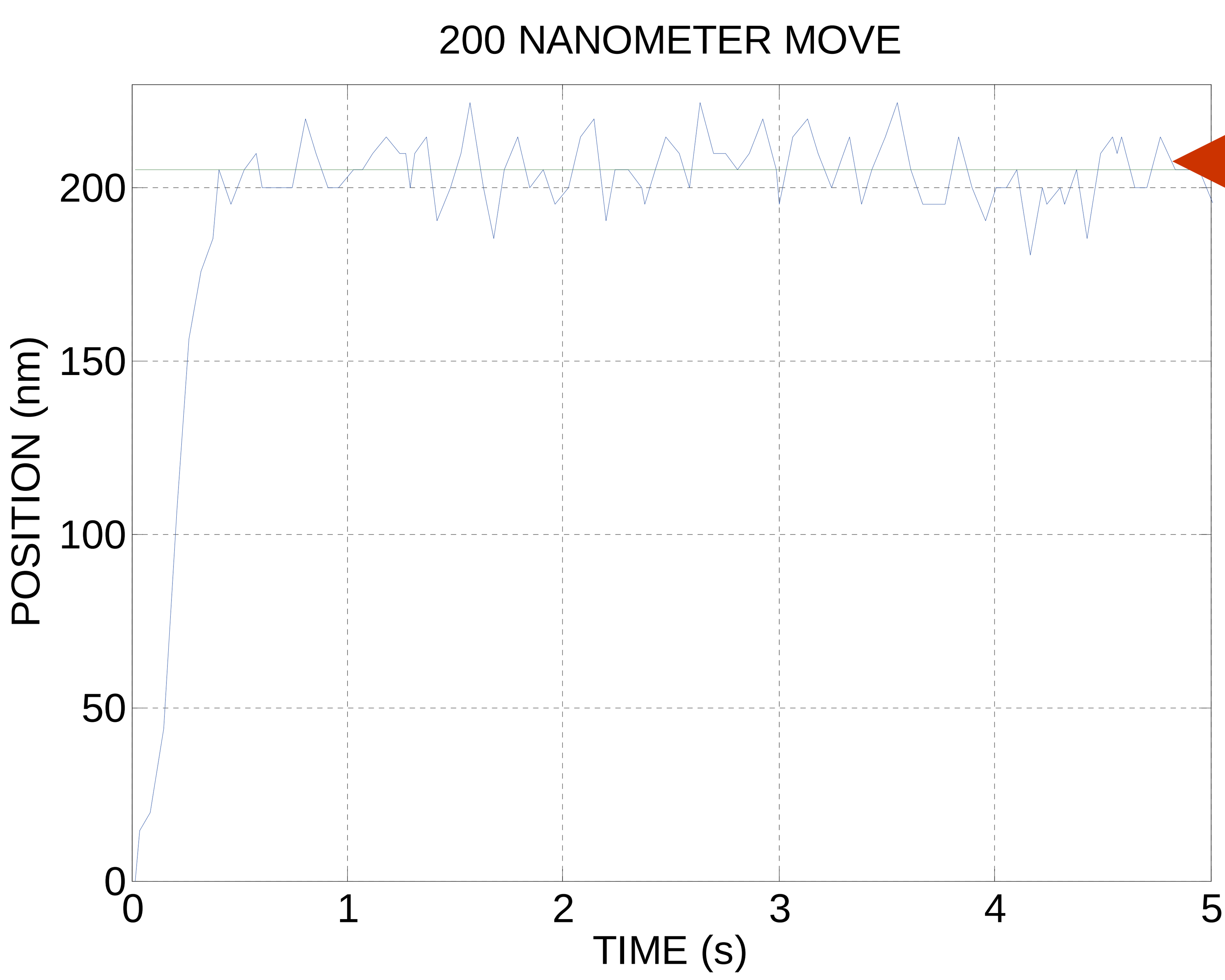
Micro-E Optical Encoder Electronics (5 nanometer resolution)

Commercial FPGA Board (ICE Designed Control Logic)

ICE Designed DC Brushless Motor Driver and Interface Board

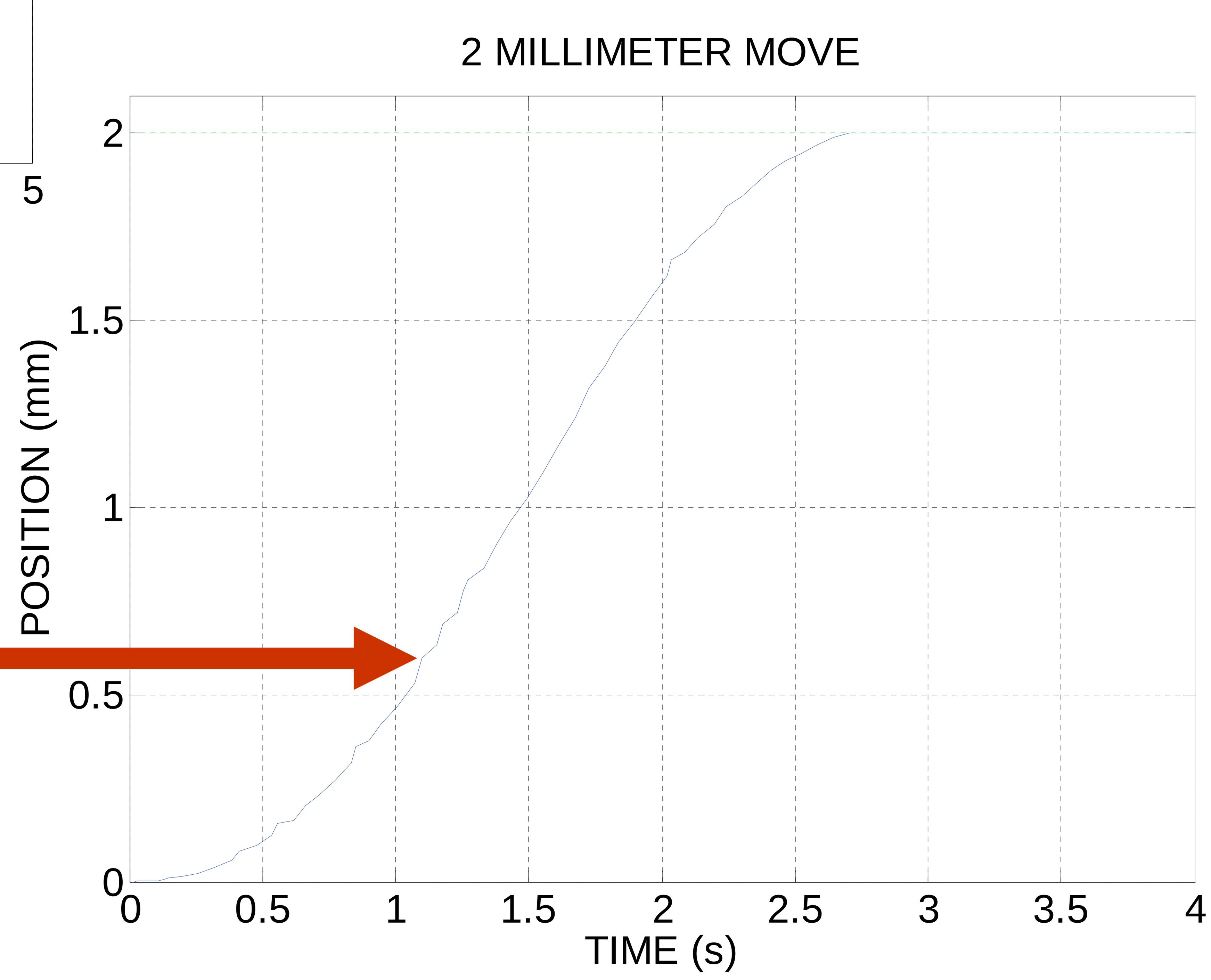
Siderostat Ballscrew Actuator (contains DC Brushless Motor, PZT Brake, and Optical Encoder)

Initial PID Control Results



• Controlling Ballscrew Position to **+/- 20 nanometers** (Level of Sensor Noise)

• Position Control Capability is 50 Times Better Than +/- 1 micron Requirement

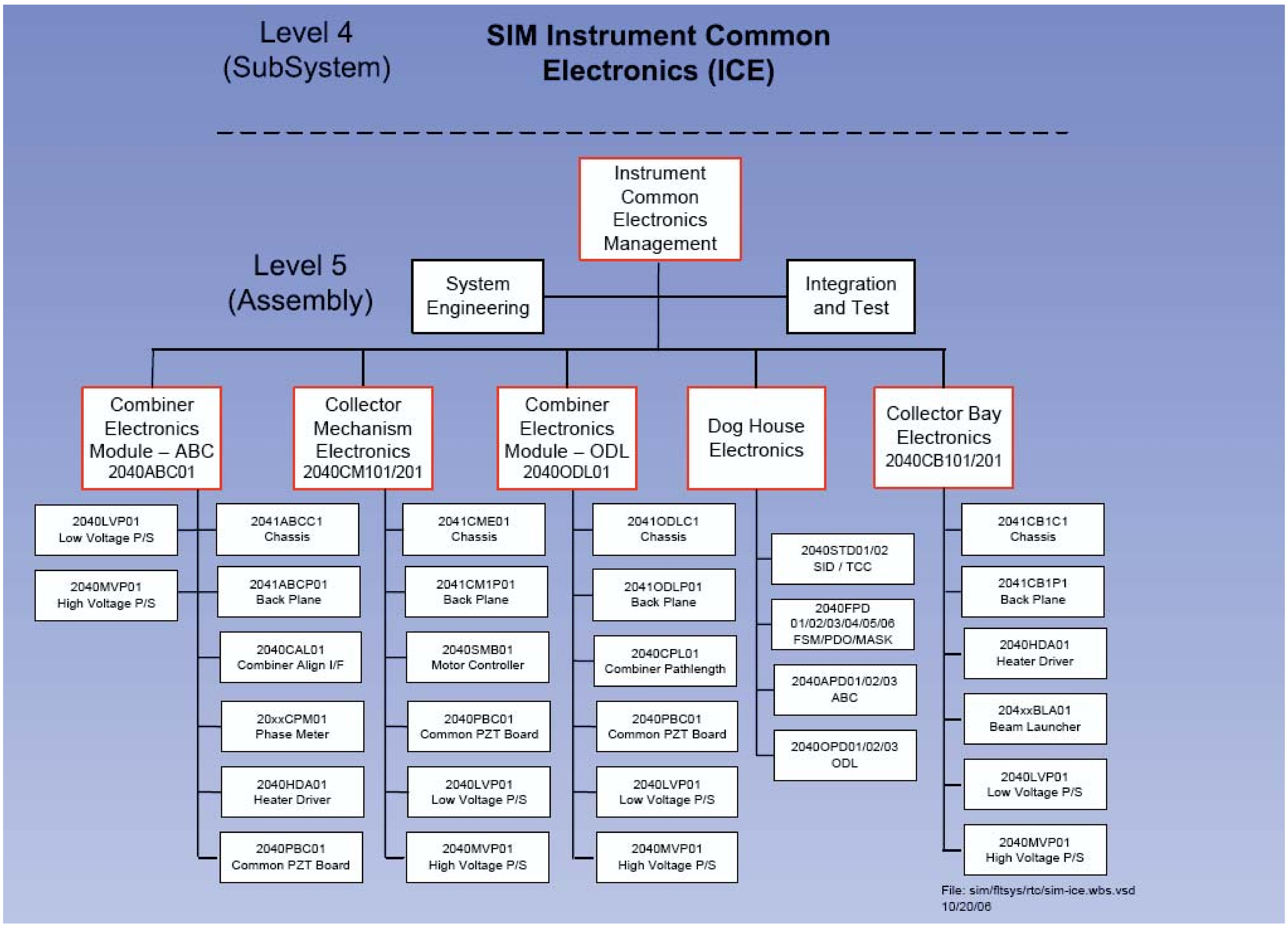


•For Testbed, Large Moves are Profiled Using Constant Rate and Acceleration

•For Flight, the Profile Will Be Programmable via a Lookup Table

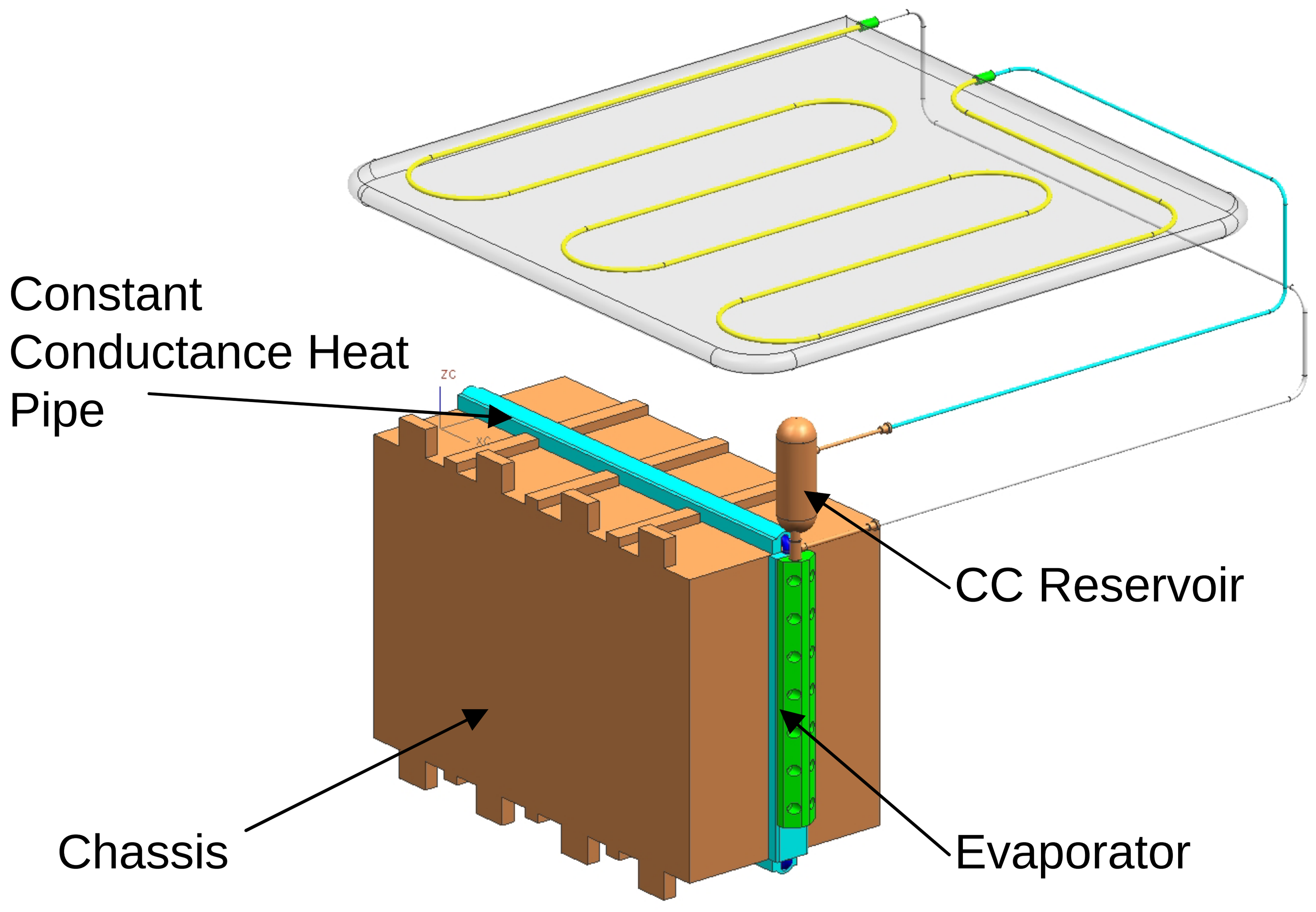
ICE Designs - ESTARs

http://sim-proj.jpl.nasa.gov/fltsys/instrumentcommon8583/sim-ice-wbs.htm



Electronics Mechanical Configuration

- Descriptions
  - Kinematic Mounting to Secondary Support Structure
  - Loop Heat Pipe Interface required for High power Assemblies
  - Adds Flexibility in Electrical Architecture and reduction in system cabling



- Potential Applications
  - Large High Power Avionic and Instrument Electronic Systems in proximity to sensitive Opt-mechanical Systems
  - Electronics are thermally invisible to sensitive Opt-mechanical Systems

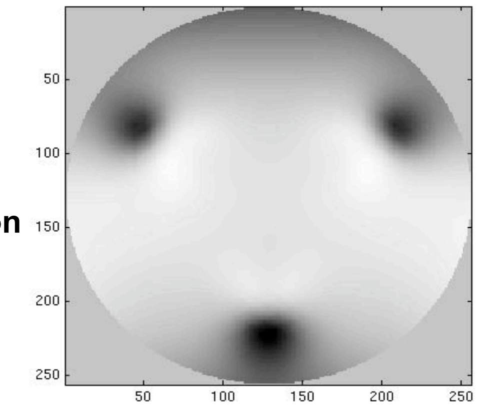
- Design Maturity
  - Conceptual Design with solid models in UG Software.

Contact: Jeff Reed Extension: 34467

Development of Integrated Modeling Capability for SIM Collector Subsystem

- **Descriptions**
  - A MACOS model was constructed for the SIM Collector Subsystem, including optical elements from SID to relay optics.
  - A software interface was developed to enable adding thermal distortions from NASTRAN thermal models to the MACOS optical system model for optical performance (wavefront) analysis.

SIM Collector wavefront map with thermal surface distortion added on M1.



- **Potential Applications**
  - The capability of integrating data from thermal, structural and optical models for an end-to-end system-level analysis is critically important and widely needed in system design and analysis for NASA space missions.
  - The feasibility of performing an integrated modeling and analysis with MACOS is successfully demonstrated by this work.

- **Capability Maturity**
  - A variety of modeling capabilities have been developed for the integrated modeling of SIM optical system, which actually go beyond the Collector Subsystem.
  - It can handle both rigid-body motions and surface distortions of any element in the system, when thermal or structural data are generated by NASTRAN or Cielo.
  - Actuations of elements can be performed to correct beamwalk or minimize wavefront error.

Contact: John Lou   Extension: 4-4870

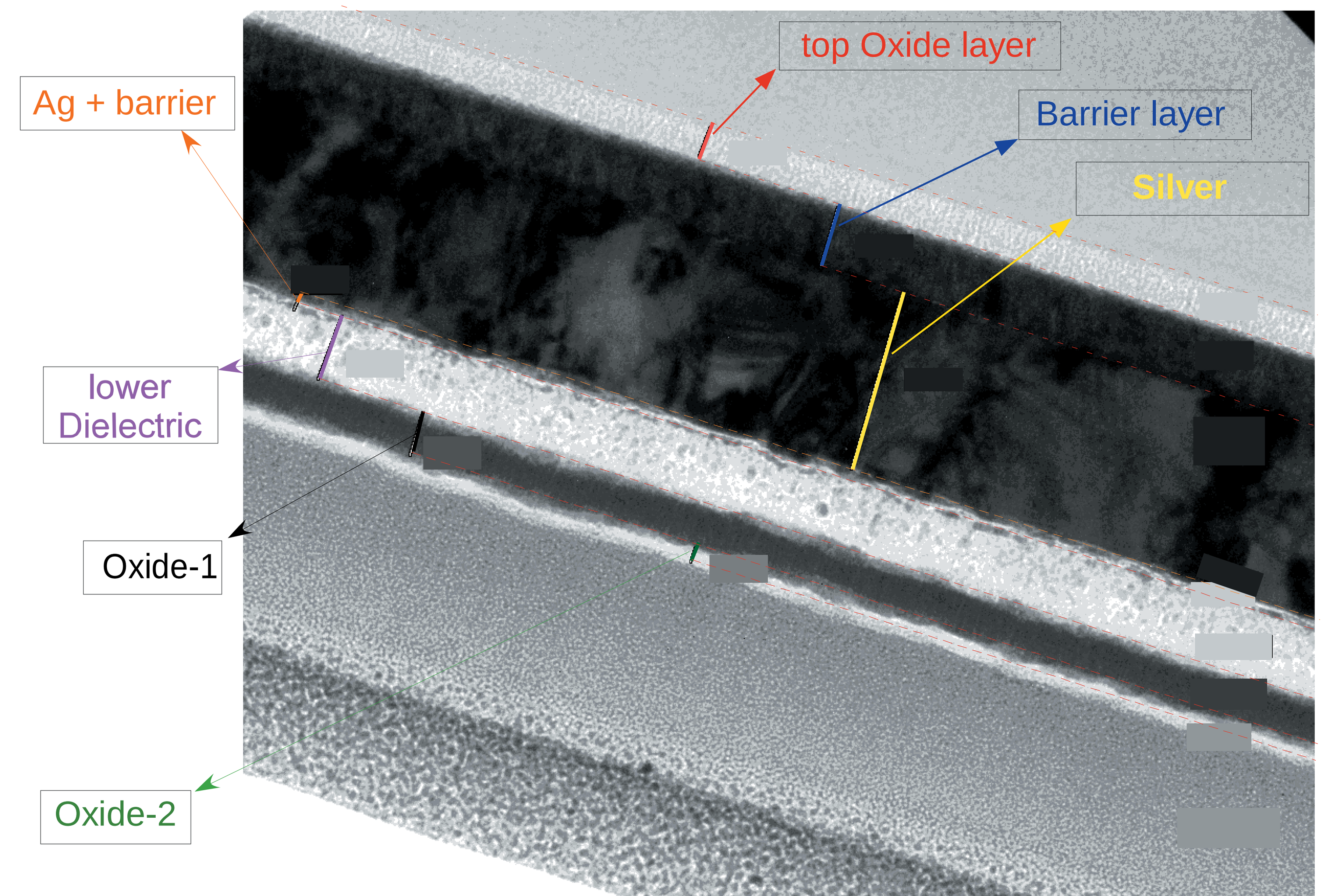
Protected Silver Mirror (PSM) coating an overview

- **Descriptions**

- Based on existing technologies, a special protected silver mirror coating will be developed to meet the SIM environmental and EOM survival requirements.

- Mirror coating modeling tools has been developed to predict mirror performance.

- Environmental test procedures as well as characterization test procedures will be developed to ensure compliance with the EOM mirror performance.



A cross section of a typical protected Ag mirror coating

- **Potential Applications**

- The mirror coating modeling tools can be used to predict the SIM mirrors polarization at any orientation as well as methods to optimized polarization effects.

- If funded, flight witness samples characterization facility can be used for any tailored application of flight optics.

- **Technology Maturity**
  - Analysis
    - **High** (modeling)
  - Environmental test /Characterization
    - ***Low to medium***
  - Existing PSM coating
    - **Low** (environmental)
    - **High** (BOL spectral)
    - **Low** (EOL spectral)
    - **Medium** (polarization)

Contact: Nasrat Raouf, X:4-0085

National Aeronautics and Space Administration

Internal Metrology Beam Launcher

Contact: Feng Zhao Extension: 4-3602

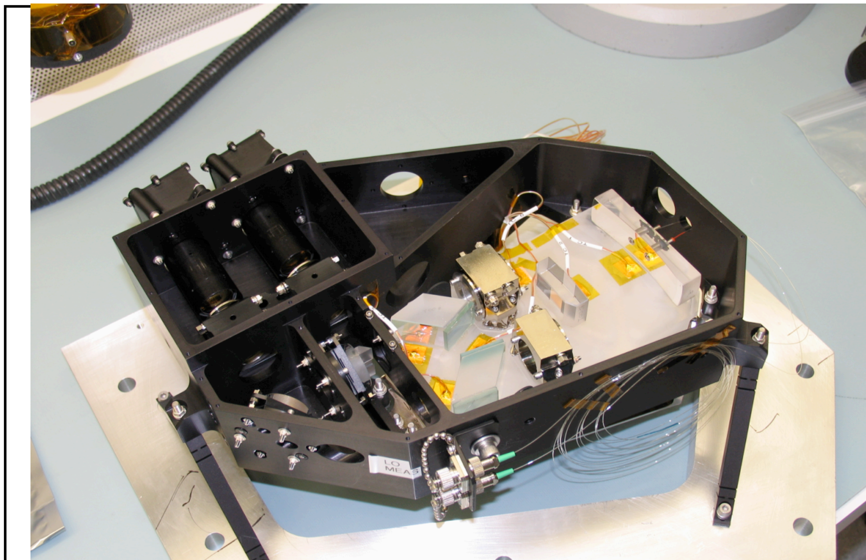
Descriptions

Measure optical path length difference to ultra-high resolution:

< 3.5 pm sensor error (narrow angle case)

Achieve <98dB cross talk (optical and electrical) between two REF and MEAS channels

Long term stability: <500pm over 100hrs



Internal metrology beam launcher brass board

APPLICATIONS

Ultra-high precision measurement of optical path length, structural deformations

Design Maturity

Brass board built using flight requirements (form/fit/function)

Design tools such as picometer optical diffraction analysis, milli Kelvin thermal analysis, etc.

Validate brass board design through tests:

1. System level performance test (MAMTB, SCDU)
2. Environmental tests:
   - 2.1. Thermal test (op and non-op to qual-levels)
   - 2.2. Dynamics test (qual-level)

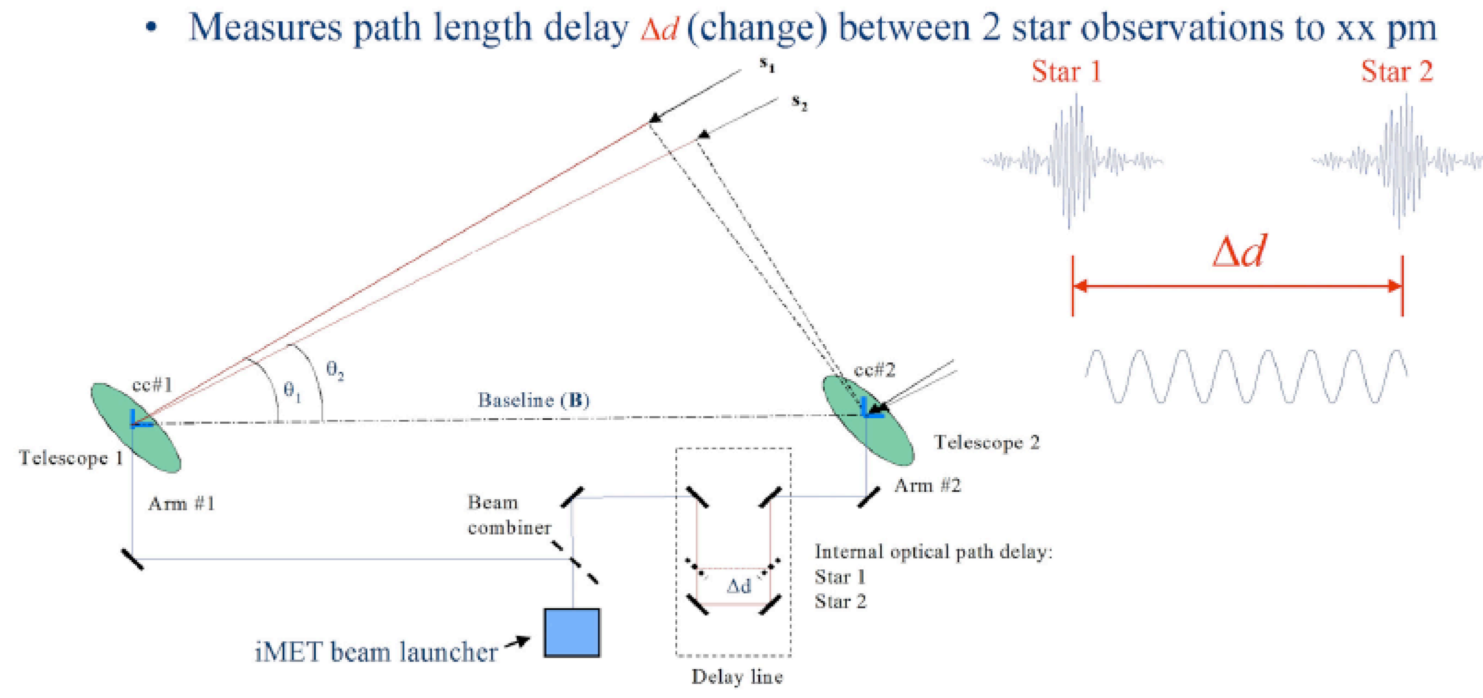
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

SIM Internal Metrology Brass Board Beam Launcher Development

iMET Team
Jet Propulsion Laboratory
November 10, 2006

Internal Metrology in SIM

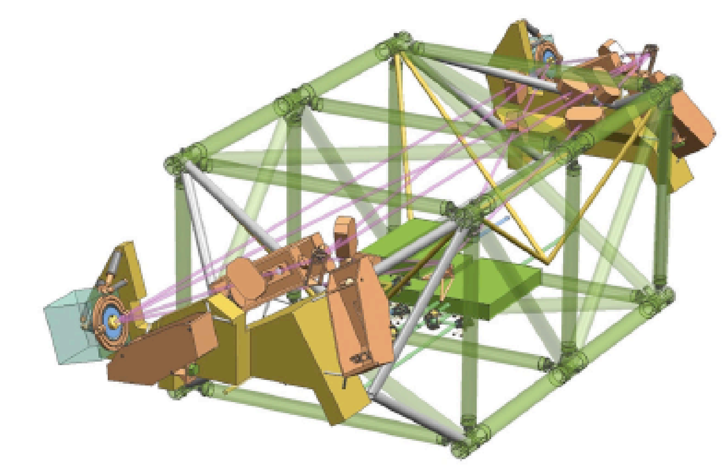
- SIM model in its simplest form: $\Delta d = \vec{B} \bullet (\vec{s}_1 - \vec{s}_2)$
- Δd is measured with Interferometer (both Science and Guide) using:
  - White-light gauge
    - Measures star central fringe to xx pm
  - Laser gauge (Internal Metrology)
    - Measures path length delay Δd (change) between 2 star observations to xx pm



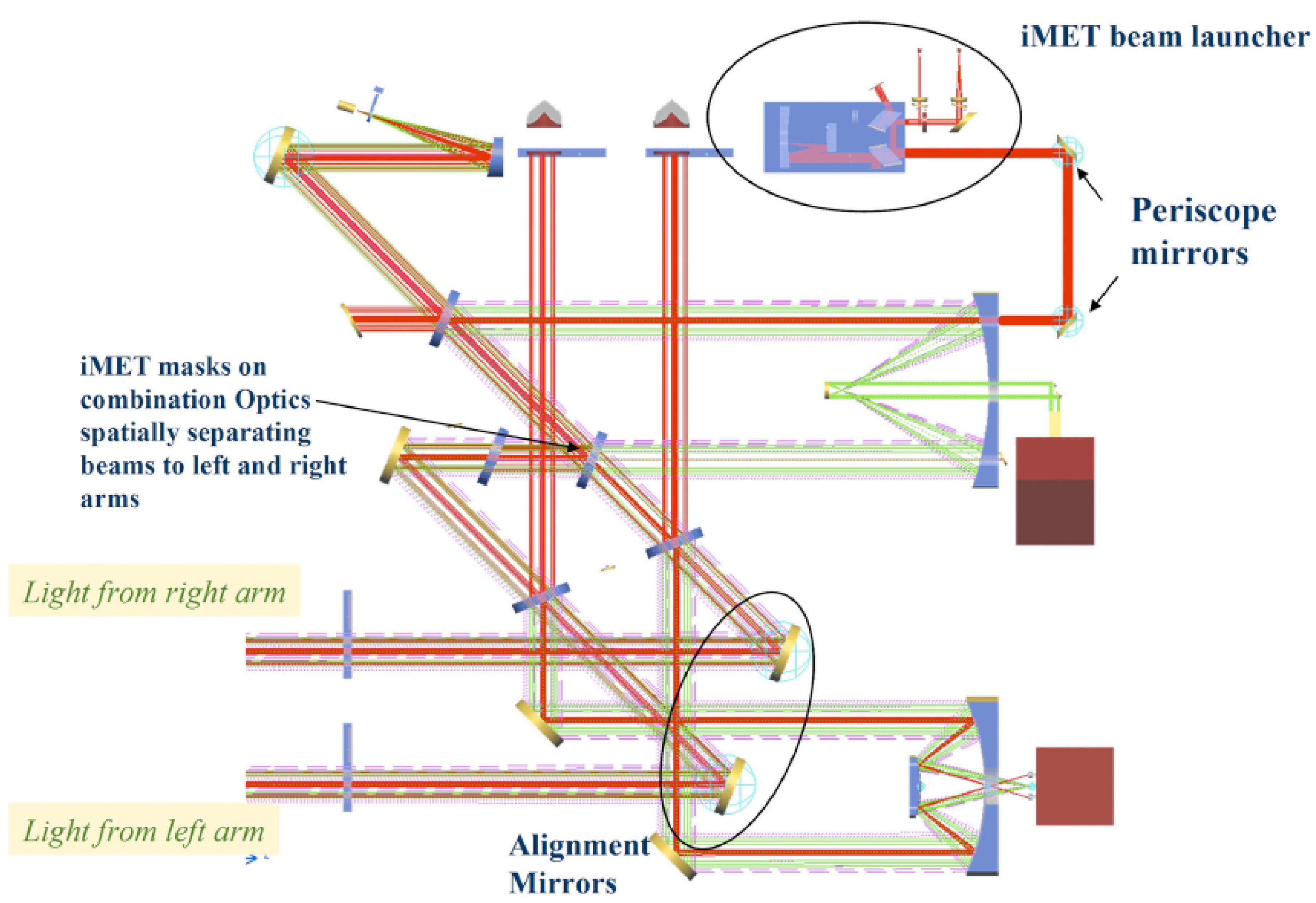
Key and Driving Requirements

	Internal metrology (Δd)	External metrology (B)
Number of gauges	3 total (1 science, 2 guide)	14 total
Fiducial distance	8m	2.5 – 9m
Range of motion	+/-1.2m (ODL)	~100 μm
Velocity	200mm/s while slewing 500 μm/s while observing	~1 μm/s
Accuracy (absolute)	Not needed	3 μm
Accuracy (relative)	3.5pm (90 s), 46pm (1 hr)	3pm (90 s), 46pm (1 hr)
Telemetry rate	16kHz	1kHz

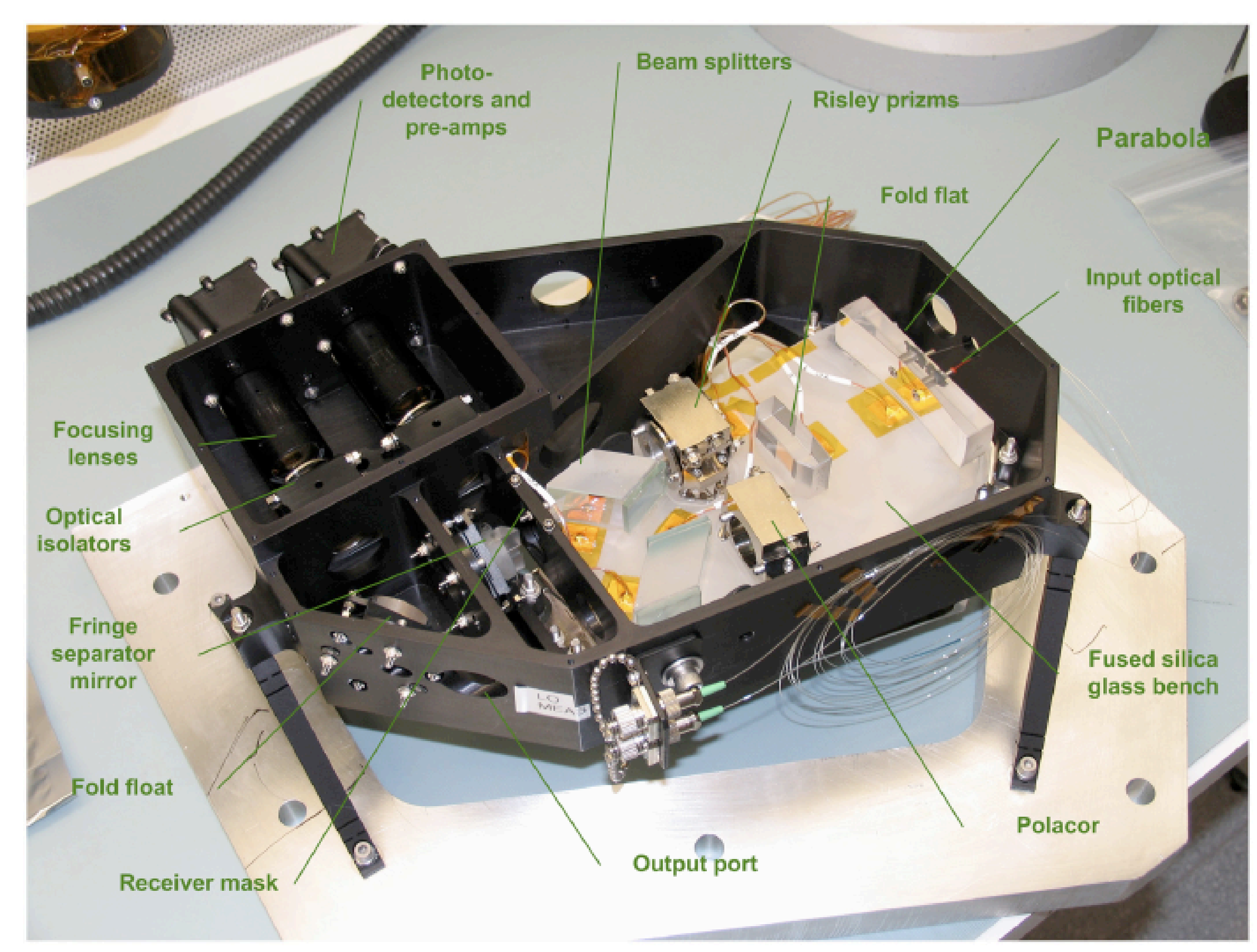
iMet Key &driving requirements



iMET beam launcher in ABC

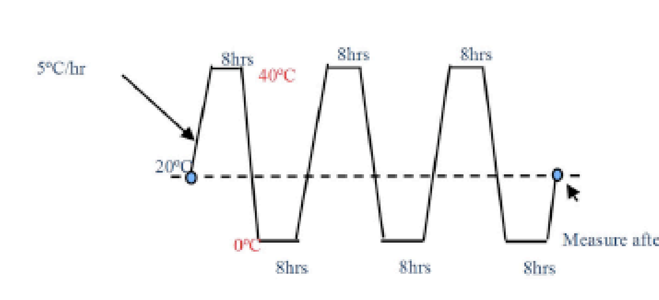


Brass board iMET beam launcher details

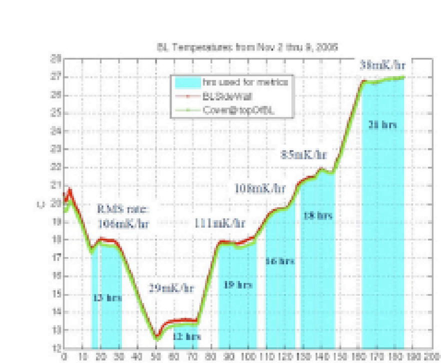


Int-MET Brass-board Milestones (actuals)

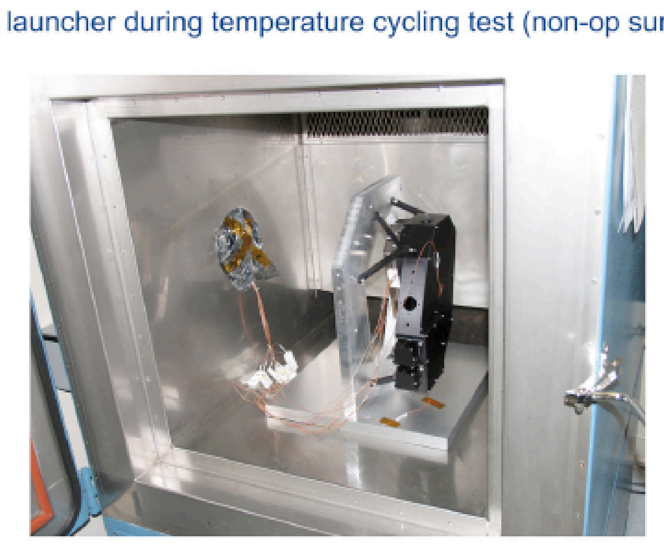
- Int-MET design start: 06/2003
- Lv 5 requirement complete 08/2003
- Brass-board PDR 09/30/2003
- Brass-board long-lead procurement 01/2004
- Brass-board test facility ready 06/2004
- Brass-board bonding test complete 08/2004
- Brass board integration start 10/2004
- 1st brass board beam launcher completed 1/4/2005
- 2nd brass board beam launcher completed 04/2005
- System level pico test in MAM (BB#1) 09/2005 – 03/2006
- Thermal cycling (non-op survival at qual level) 08/2005 – 02/1006
- Vibration test (BB#2 at qual level) 04/2006
- Stand-alone thermal test (operational qual level) 11/2006

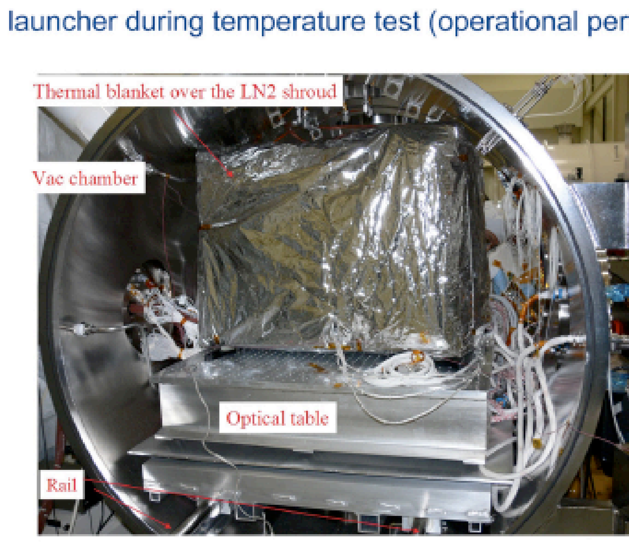


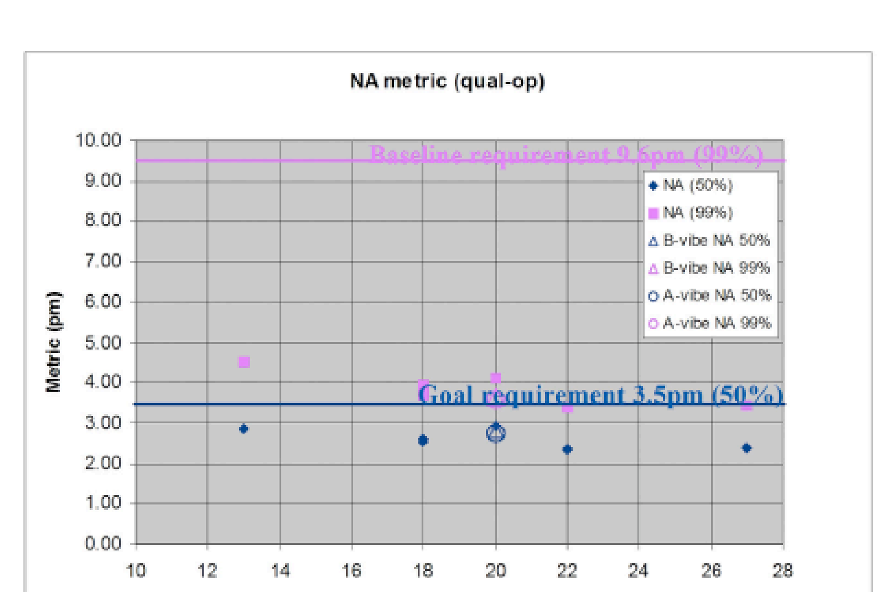
Beam launcher during temperature cycling test (non-op survival)



Beam launcher during temperature test (operational performance)







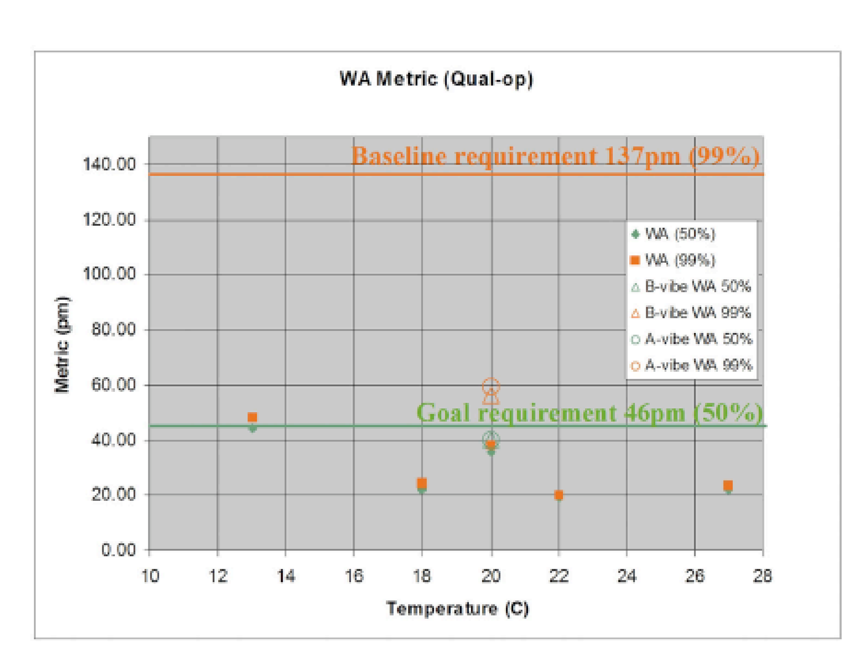
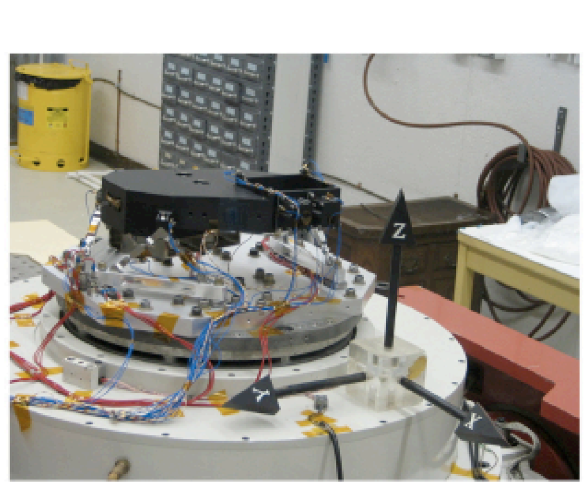


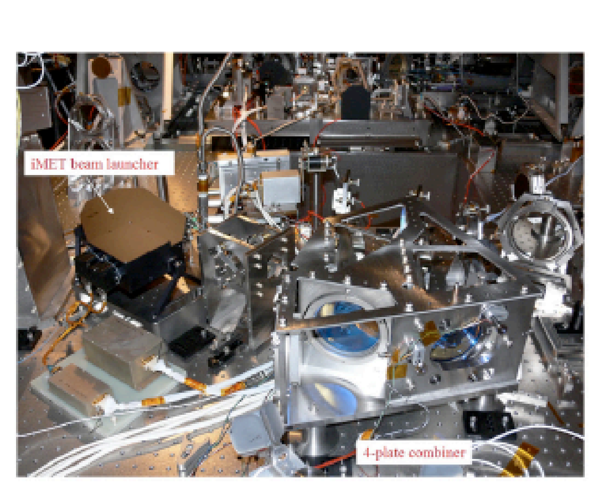
Table 1: Random Vibration Test Spectra

Frequency (Hz)	Qual Level
20	0.032 g^2/Hz
20-50	+3 dB/oct.
50-300	0.08 g^2/Hz
300-2000	-6 dB/oct.
2000	0.0018 g^2/Hz
Overall	6.5 g_{rms}

Duration: 2 min./axis.



Beam launcher during random vibration test



Beam launcher in MAM (system level test)

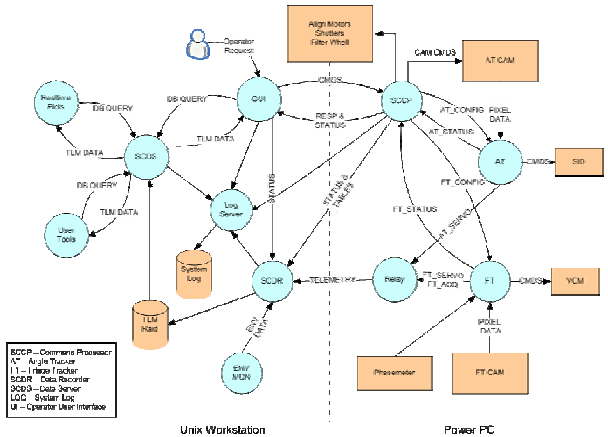
SIM internal metrology beam launcher risk is retired

Requirements	Form	Fit	Function	Process	Temperature (non-op survival)	Temperature (operational)	Random vibration	System level tests
Compliance	Y	Y	Y	Y	Passed Qual/ PF level	Passed Qual/ PF level	Passed Qual/ PF level	Met goal requirements

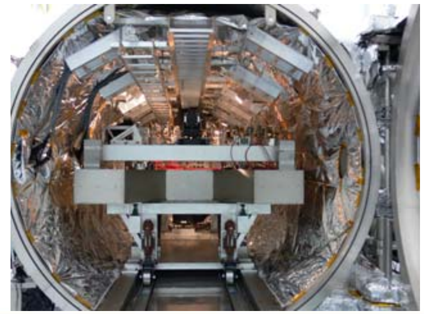
Space Interferometry Mission—PlanetQuest is a stellar interferometer that will carry out astrometry with micro-arcsecond accuracy.

- SIM will measure the phase of a white light fringe over the bandwidth 400—1000 nm with an accuracy of a few tens of picometers.
- Picometer metrology will measure the internal path lengths in both arms of the interferometer.
- From the path lengths and fringe phase measurements the instrument will measure internal delay.

Software Architecture



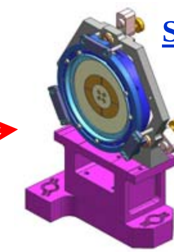
Vacuum chamber

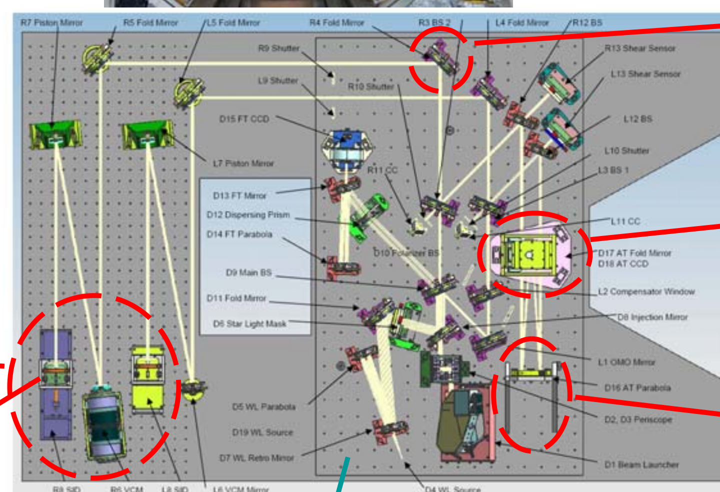


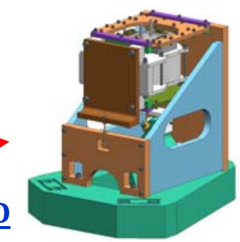
The Spectral Calibration Development Unit (SCDU) is a breadboard being developed for SIM—PlanetQuest.

- The objective of SCDU is the demonstration of wavelength calibration.
- Residual measurement errors must meet SIM Astrometric Error Budget.
- SCDU hardware is a retro-mode propagation Michelson interferometer
  - Internal artificial starlight source
  - Modulated path length in one arm (FTS)
  - Internal metrology in both arms (~3 meter length)
  - Servo control systems will be employed to reduce both
    - Tilt error
    - Fringe drift/modulation error

Stable optical mount

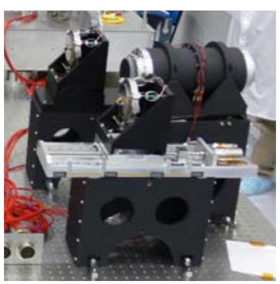


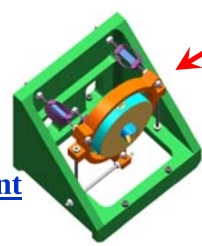




Angle Tracker CCD

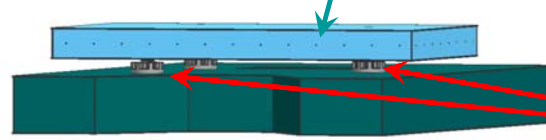
Voice coil and siderostats



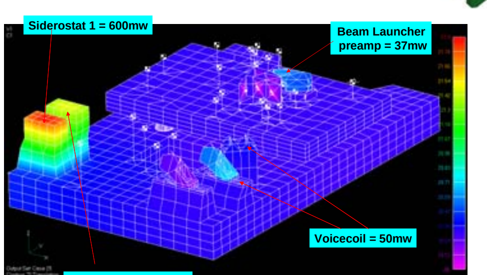


Siderostat 3-axis PZT tilt mount

Angle Tracker parabolic focus mirror



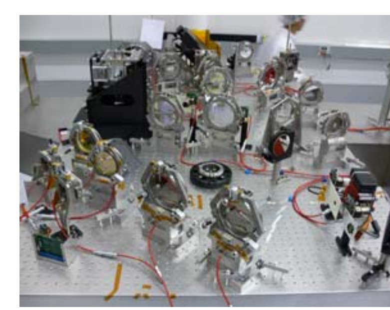
Kinematic flexure mounts x3



Thermo-mech Finite element model

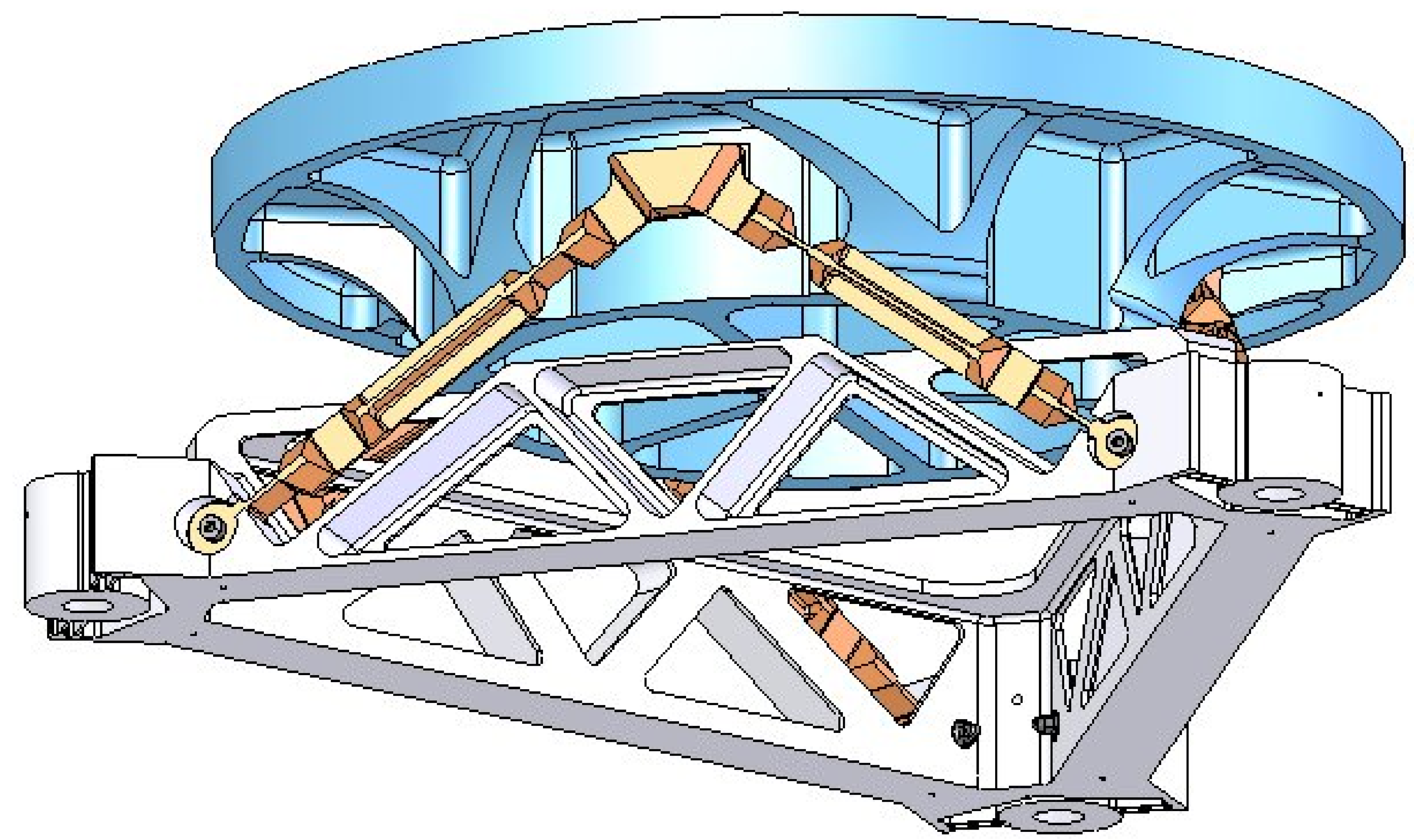
Spectral Calibration in SCDU

- The instrument has wavelength dependent phase due to dispersion in the optics. When the instrument "slews" between two stars of different spectral profiles a wavelength dependent error is introduced. This error must be calibrated to meet fringe measurement requirements.
- To the extent that the instrument drifts over time the wavelength calibration error is time dependent.
- Thermally and mechanically stable hardware and thorough optical design will reduce the wavelength dependent error to tens of nanometers.
- Numerical processing of the fringe measurement will in turn reduce the error to a few picometers.



Low Stress Glass Mounting

- Descriptions
  - Ø343 mm ULE mirror on Invar mount
  - Glass stress ≤ 2 ksi
  - Low thermal distortion: 3 nm rms over AFT



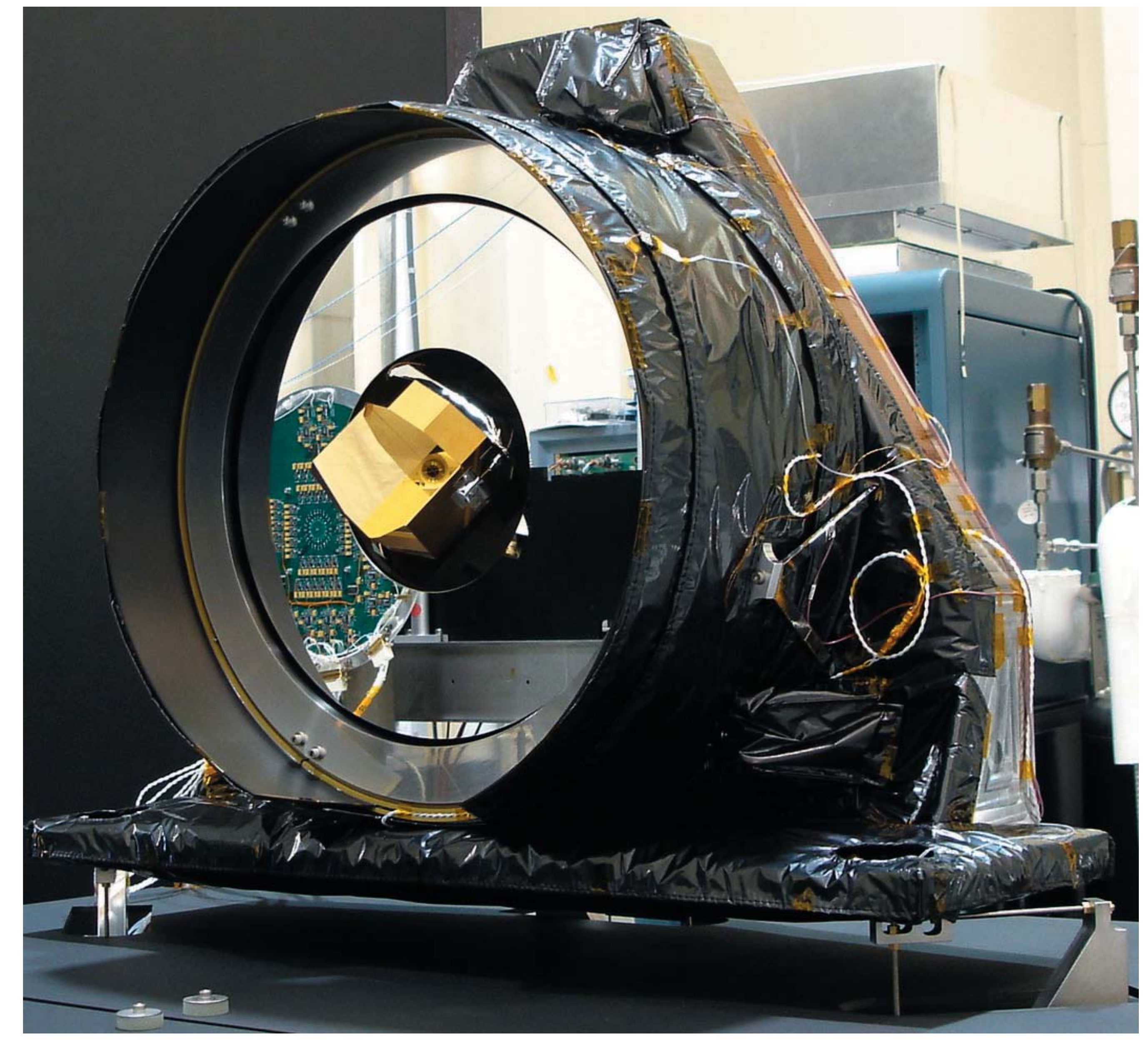
- Potential Applications
  - Precision optical instruments

- Design Maturity
  - Trade study (bondpad size, location, 1 g sag vs. figure distortion & stresses)
  - Analysis (steady-state thermal, static and random vibration)
  - Prototype

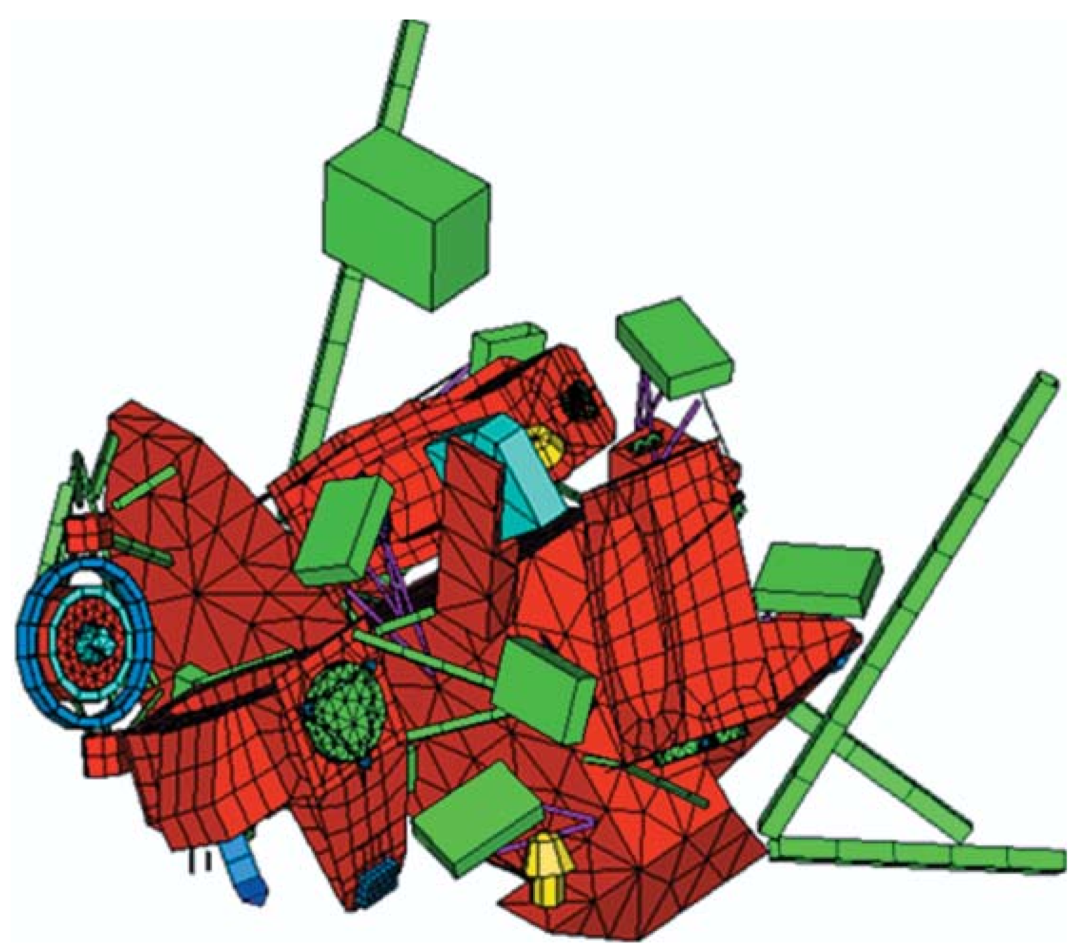
Contact: Jonathan Lam Extension: 4-1196

Millikelvin Temperature Control

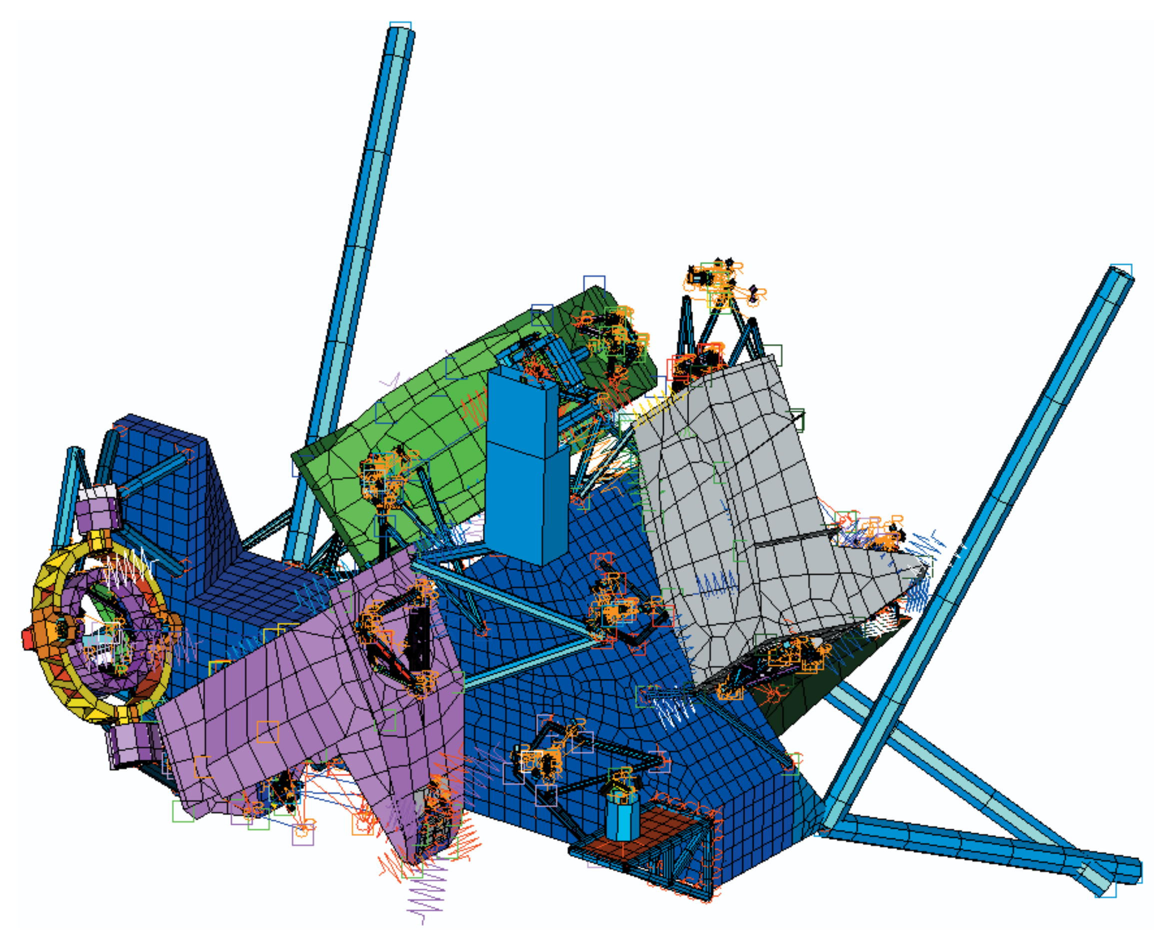
- Design: Several nested stages with active temperature control for isolation from thermal disturbances
- Modeling: Thermal modeling of mK systems with active control
- Hardware: Low CTE materials, Low contamination MLI, spot-bonded heaters



TOM-3 testbed Siderostat with thermal isolation



TMG Thermal Model



IDEAS Structural model

Temperatures generated by a TMG model are mapped onto a IDEAS structural model

- TOM-3 testbed demonstrated temperature control of the collector subsystem
- System-level analysis underway
- SPRINT testbed will demonstrate system-level mK temperature control.

Contact: Mark Lysek Extension: x41190

PZT Life Qualification

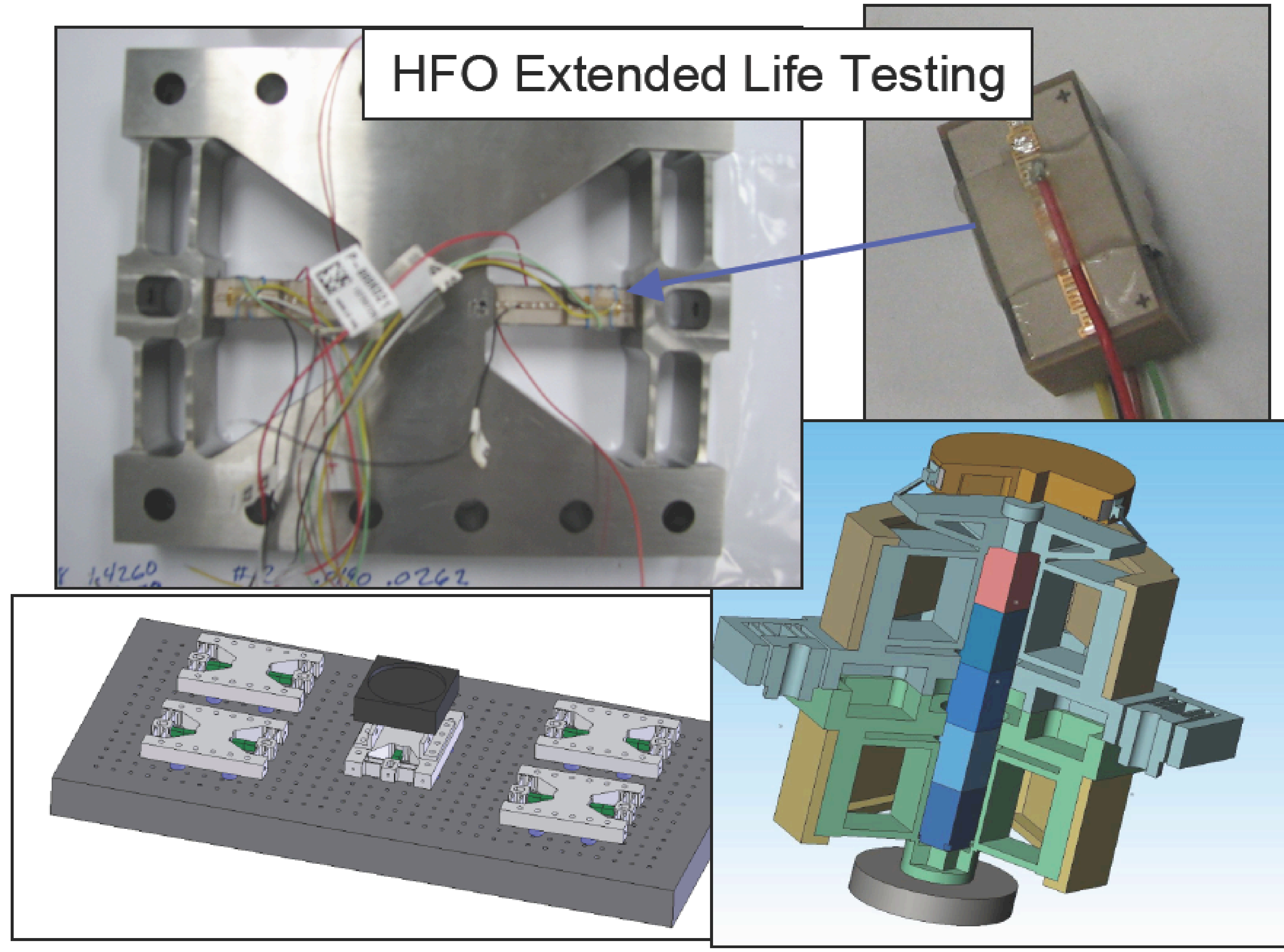
PZT Accelerated Lifetime Testing

- High Frequency Optic (HFO) Extended AC Lifetime Test
  - 2kHz; 0-25VAC; 140Bcycles
- Characterization AC Lifetest
  - 2kHz; 0-60VAC; 4Bcycles plus
- Operational AC/DC Lifetest (TBD)

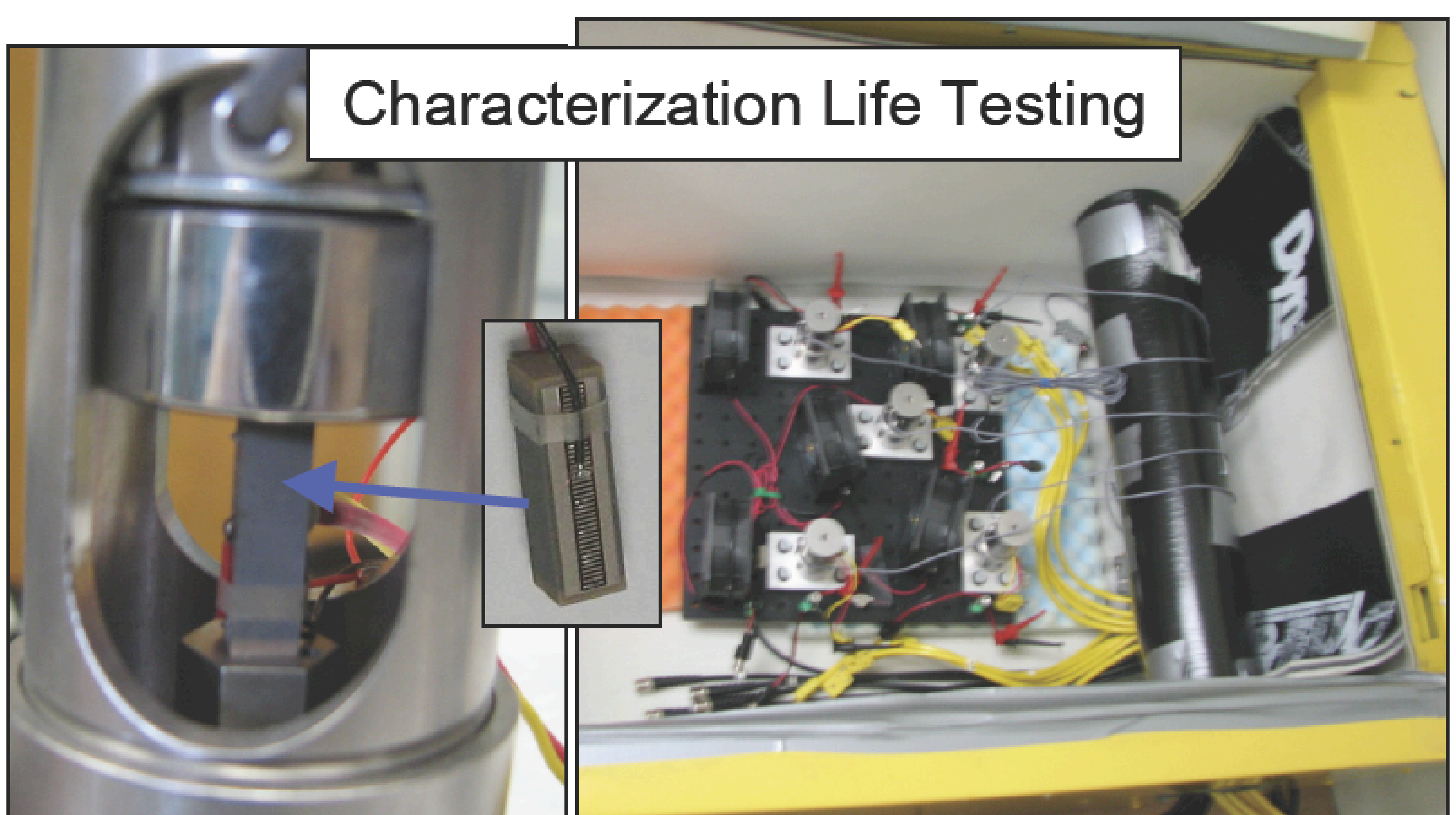
Meet Critical Requirements of Potential Applications:

- HFO Lifetime Requirement
  - 250Hz for 44Bcycles over 5.5yrs.
- FSM Lifetime Requirement
  - Tile-to-tile lifetime operational test (TBD)

HFO Extended Life Testing



Characterization Life Testing



Testing/Design Maturity

- Resolved encountered test/measurement issues in **characterization** test
- In the **characterization** setup preparation 5 stacks reached 7B+ cycles
- HFO flight-like fixtures are being assembled for **Extended Lifetime Test**

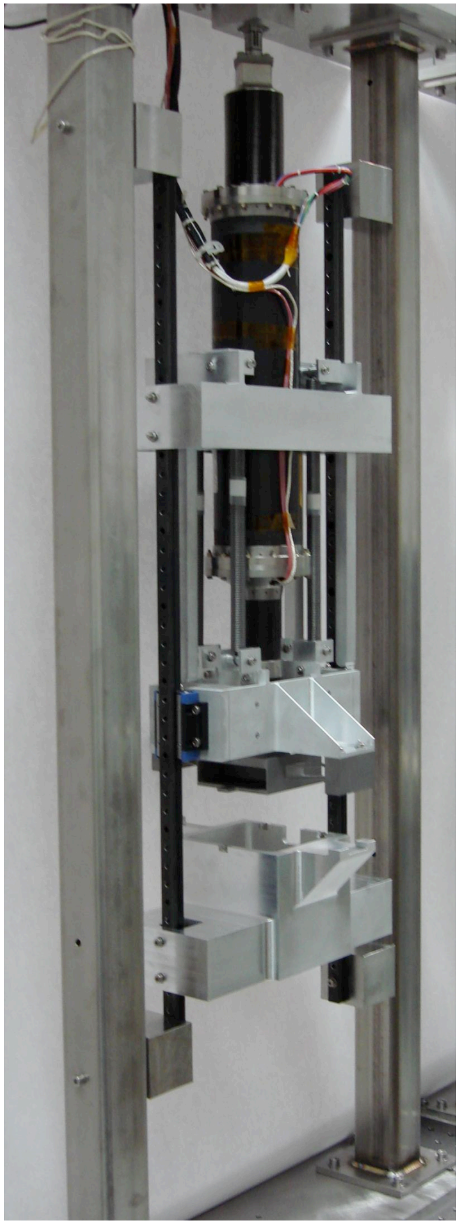
Contact: Bar-Cohen Extension: x4-2610

Precision Ballscrew Testbed

- Features
  - Commercial Ballscrew achieves repeatable incremental step size of 20 nm (1/100,000 revs), beating expectations by 2 orders of magnitude
  - Flight like electronics and control system
  - Direct drive DC motor positions ballscrew utilizing a commercial Micro-E glass scale encoder for 5 nm resolution position feedback

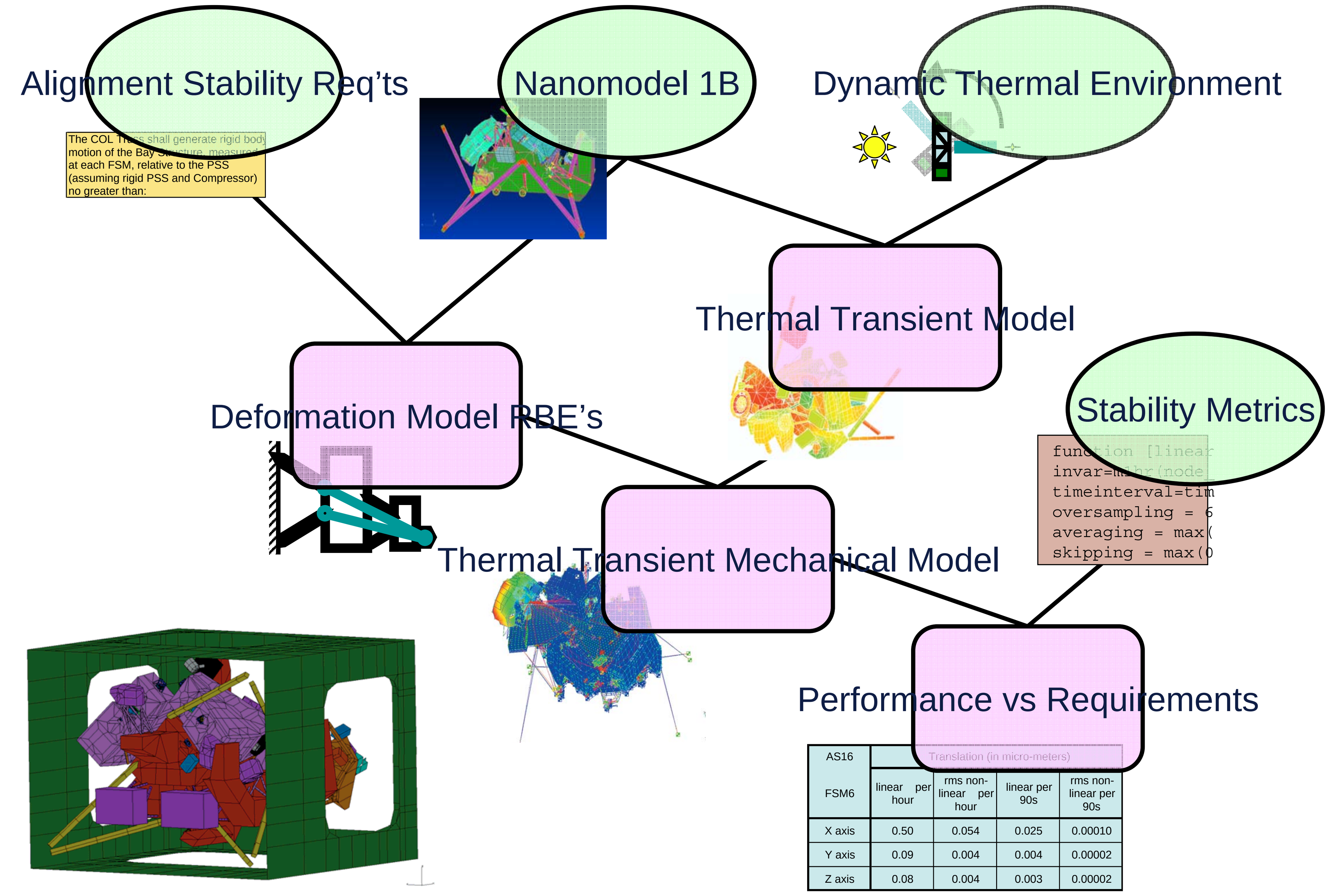
- Brassboard Level Design Maturity
  - Designed/analyzed for flight environments
  - Positive stress margins
  - Min step size is currently limited by the encoder resolution which is easy to improve by a factor of 4
  - Life test of 3 units is nearly underway

- Potential Applications
  - Siderostat Coarse Stage
  - Siderostat Fine Stage
  - Guide FSM Coarse Stage
  - TCC Translation Mechanism



Contact: Brant Cook (3-2661), Dave Braun (4-7284)

SIM Thermal Distortion Modeling (TDM)



COL Bay 2 thermal model

Description:

- Developed an integrated modeling process and toolset to verify thermal-structural-optical design capability against system requirements.
- Serves as a performance analysis tool during design and development.
- Supports instrument system engineering and provides guidance for trade studies.

Potential Applications:

- Complex opto-mechanical instruments with precise pointing and alignment stability requirements.
- Opto-mechanical structures in which the effects of thermal-elastic deformations on optical performance are critical (wavefront error, surface aberrations).

Technology Maturity:

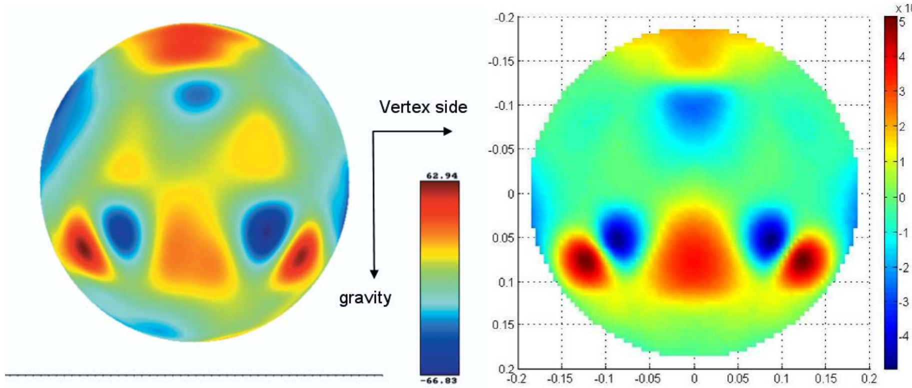
- TDM has been used twice on the SIM Collector Bay 2 (early-'06, late-'06).
- An analytical process and toolset to support preliminary and detailed designs.

Contact: K. Charles Wang   Extension: x3-5270

Optics Manufacturing Fault Investigation

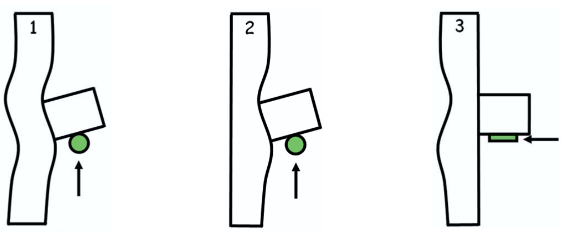
Alfonso Feria, Dave van Buren, Jonathan Lam

The compressor with all mirrors mounted to it was delivered to the TOM3 team, but a significant print-thru on the M1 mirror surface was observed at the fabricator after the mirror was bonded to the JPL bipods and mount. A similar pattern print-thru was also observed on the fully assembled compressor.



M1 Mirror Print-Thru showing 20 nm rms equivalent surface error, 129.8 nm peak-to-valley (P-V) (left). FEA combined case. M1 Mirror Analysis Results including 1 G gravity on bipods. Rms surface error is 14 nm, P-V is 103 nm. (right)

Deformation of mirror surface under metrology fixture loading



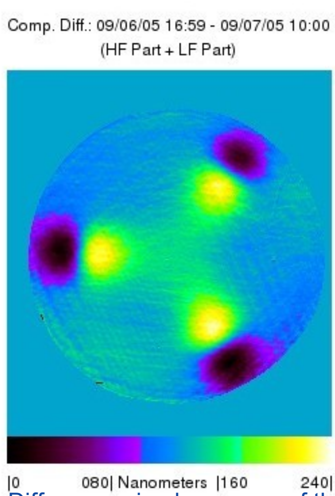
Deforms under pin load, metrology sees bumps

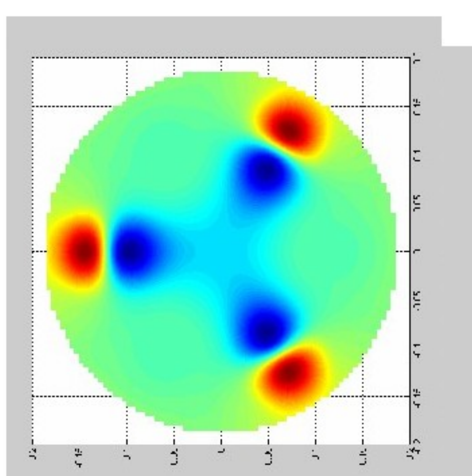
Bumps polished out

Bumps reverse when load is removed

After the study was completed, it was determined that improper fixture support during surface figure measurements led to polished-in dimples. When the mirror was in the test fixture, the mirror deformation affected its surface. A surface map was taken and the information conveyed to the polishing machine. During polishing, the surface was polished with the inherent defect. So, during surface measurement, the mirror would show a perfect surface, but after removing the load caused by the test fixture, the dimples will show up. For a planar or concentric mirror, the manufacturer would rotate the mirror several times to be able to subtract the gravity effect. But since this particular mirror is an offset parabola, rotating the mirror was more complicated because the measuring equipment would have had to be repositioned during the surface map measurements and due to schedule constraints this was not done.

The analysis matched the shapes and amplitude (to the same order) of the measured error. The distortion mechanisms were also reviewed and concurred by the manufacturer. It is estimated that this problem accounted for about 2/3 of total distortion problem. Additionally, it was determined that inadequate mirror mount design also contributed to the overall distortion. Wave front error (WFE) changes during shimming and mounting into the Compressor Bench were also observed. This problem was due to a soft offload ring and stiff supports (bipods, hexapods)





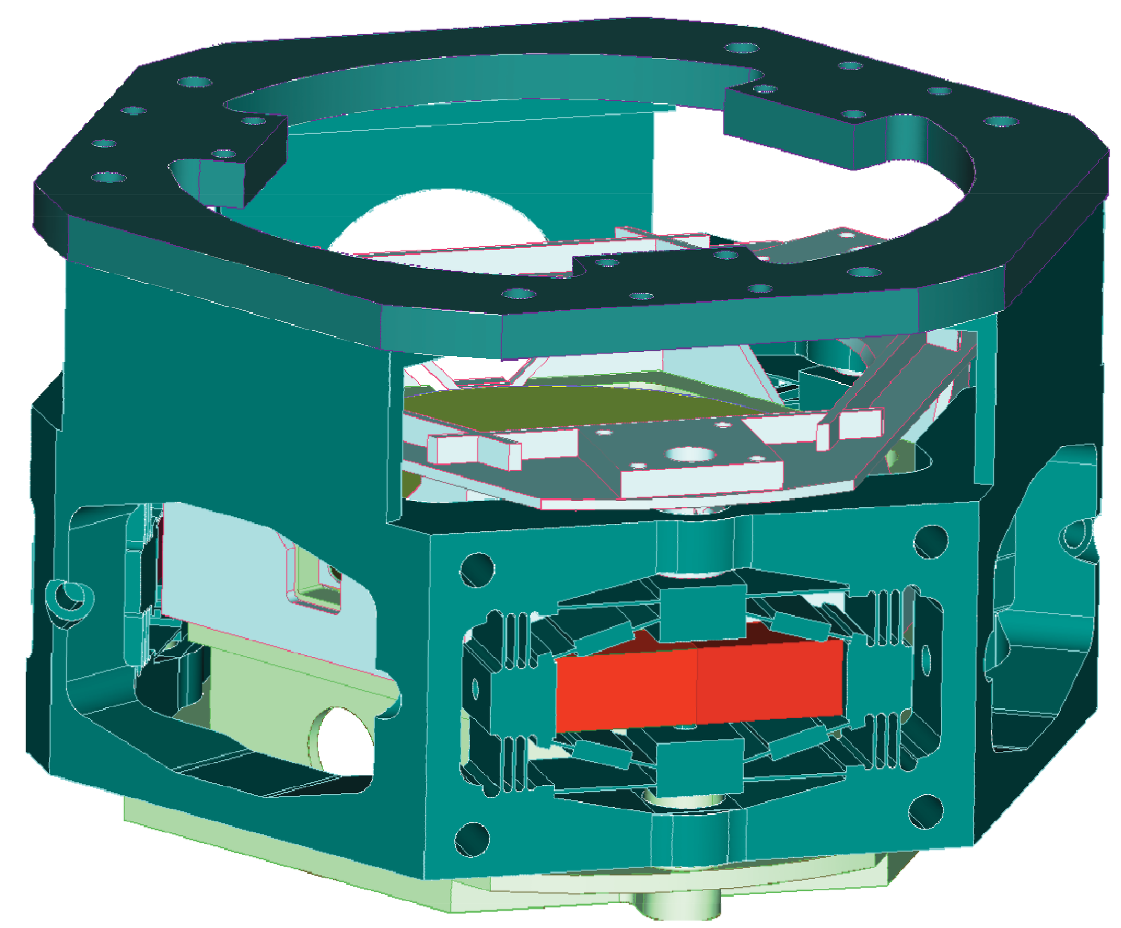
Differences in phase map of the compressor compared to deformation map of the model with a 1ºK delta temperature soak. Distortion of Mirror after a Uniform Temperature Drop 8.4 ºK (measured, left). Uniform Temperature Increase of 1ºK (calculated, right). (Note: Color scales do not match due to the different software used to plot the results)

During the investigation of the M1 mirror print-thru, a delta temperature soak case was also analyzed. During the TOM3 testing a temperature drop case was conducted and it was possible to perform a model correlation of the results. A visual analysis demonstrates an excellent correlation between the measured values and the analytical results. The analytical results obtained with the finite element model showed an RMS value 15% higher than the test results. The P-V analytical results were less than 2% from the test results.

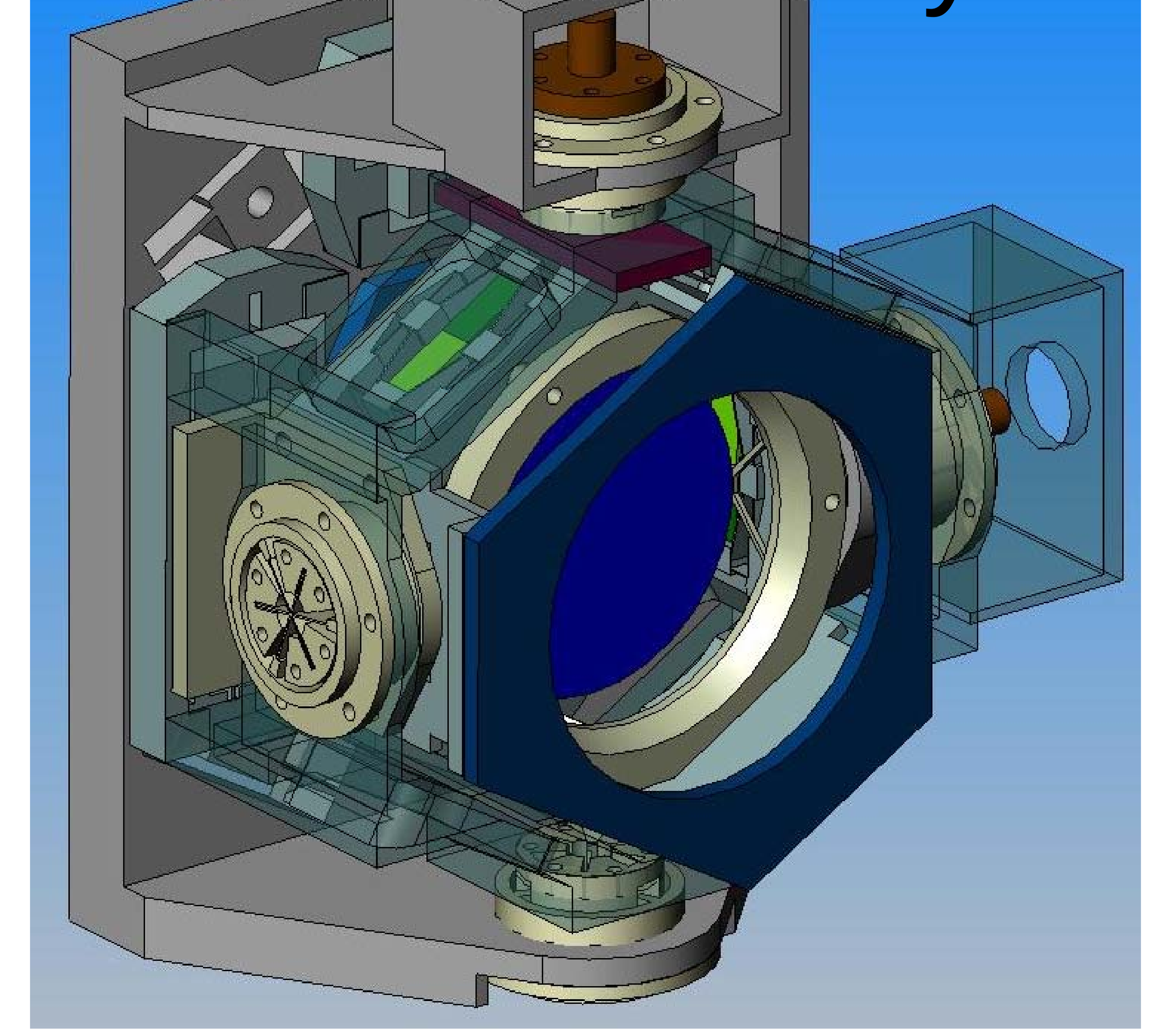
Momentum Compensated Steering Mirror

- Descriptions
  - Large range of motion (up to 10 degrees) with milliarcsecond resolution
  - High frequency response
  - Long life

Fine Stage



Full Assembly



- Potential Applications
  - Precision optical systems
  - Laser targeting systems

- Design Maturity
  - Preliminary structural & thermal analysis completed
  - BB of fine stage built
  - Initial testing verifies model predictions
  - EM build planned late ‘07

Contact: John Carson Extension: 4-5730

Materials and Processes Engineering, HP Invar

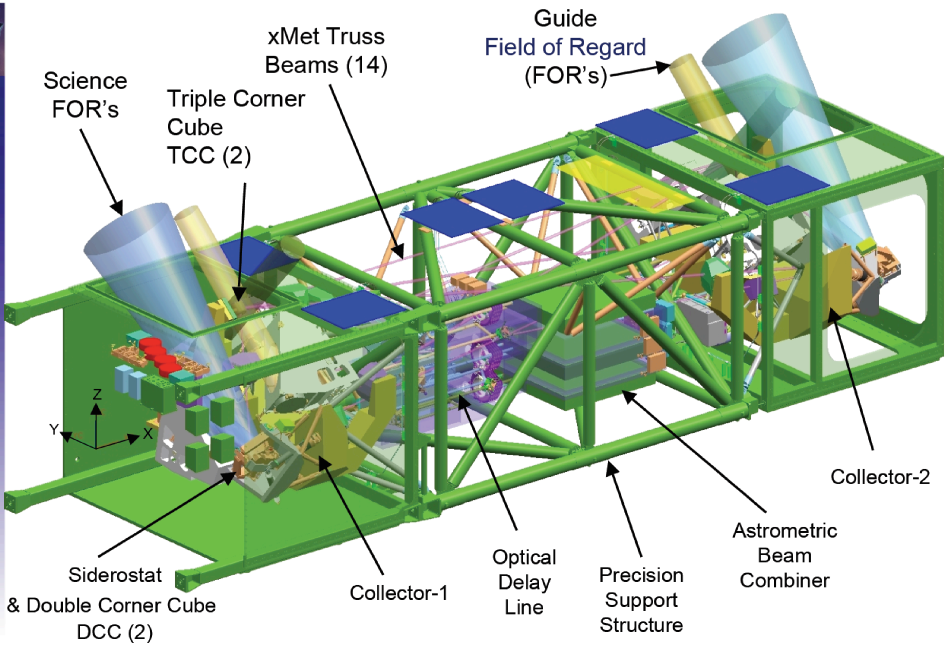
Contacts: Saverio D'Agostino (3-2466) Witold Sokolowski (4-4482)

- High Purity Invar
  - Powder Metallurgy Process
  - Processing and heat treatment optimized for a combination of low CTE and long term temporal stability
- Potential Applications
  - Optic support elements
  - Metrology Beam launcher components
- Design Maturity
  - Process defined, demonstration heat produced
  - Prototype heat treatment defined
  - Initial materials properties measured (table below)
  - TBD's indicate testing still to be done

Heat Treatment	CTE ppm/°C	Temporal Stability ppm/yr.	Microyield (ksi)	Microcreep (ksi)
3-Step	0.91	-0.80	18.5	TBD
2-Step	0.62	-0.73	TBD	TBD

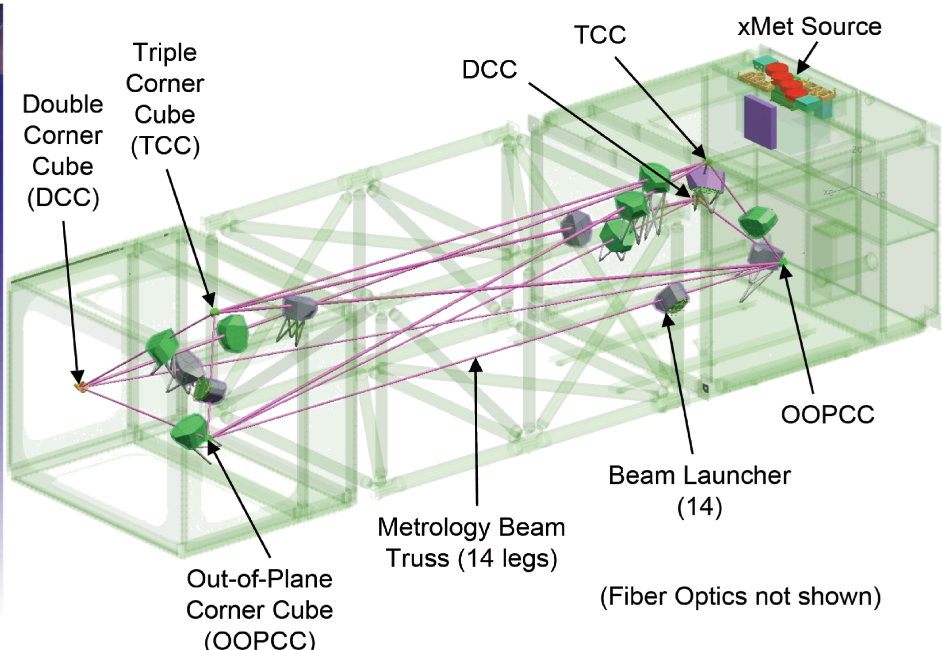
Overall Configuration – Instrument Only

SIM PlanetQuest



SIM Instrument – External Metrology

SIM PlanetQuest



SIM Space Interferometry Mission

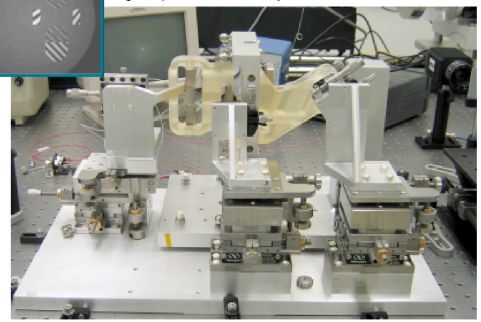
May 2006

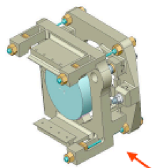
External Metrology (Met) Brassboard (BB) Beam Launchers (BL)

To relate the guide interferometer to the science interferometer, the SIM External Metrology system uses an optical heterodyne interferometer technique to measure displacements of certain fiducials at the picometer level. This external metrology "sensor" consists of a metrology source, fourteen beam launchers (BL), six fiducials forming a truss (see Figure below) and signal processing electronics. To get an acceptable solution to the truss deformation, each BL launches an optical beam towards the fiducials and measures the displacement between them. SIM uses a "racetrack" configuration to measure the roundtrip optical pathlength change, which is twice the displacement between the fiducials.

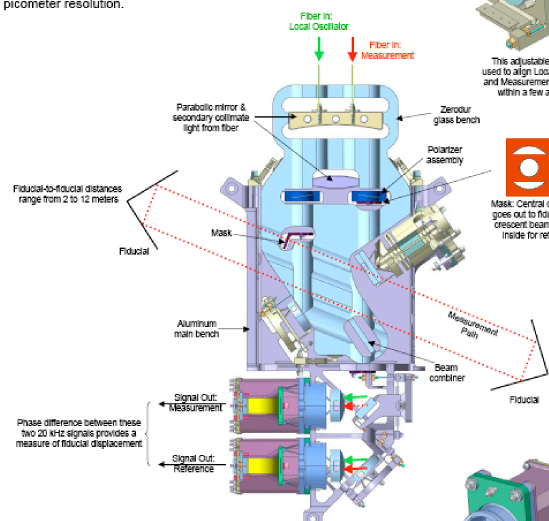
The racetrack beam launchers have quite a bit of history at JPL. The quick-prototype (QP) launchers were built by Lockheed-Martin and tested extensively in the Kite and 2-Gauge testbeds over the last several years. The sub-aperture-vertex-to-vertex (SAVV) BLs were built at JPL and extensively tested in the Micro-arcsecond Metrology (MAM) testbed. To address the risk of low flight heritage, brassboard (BB) beam launchers were designed, fabricated, and underwent both performance and environmental testing. The brassboard BLs were largely based on the lessons learned from past BL work, and were designed to measure distance changes to the required single-digit picometer resolution.

Glass bench in fixture during alignment of collimator components. Inset shows fringes from parabolic mirror and secondary reference surfaces.

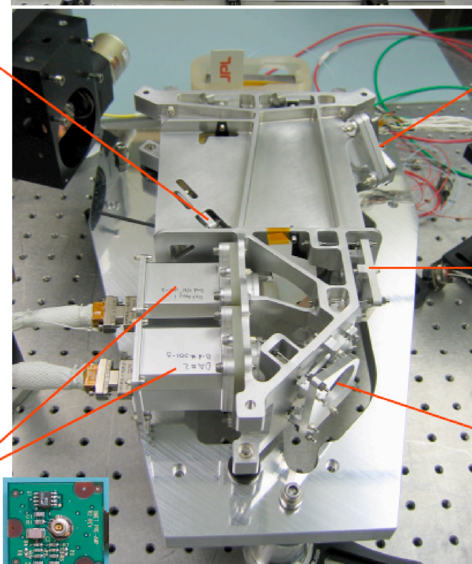




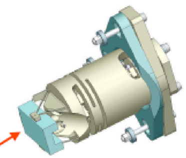
This adjustable mirror is used to align Local Oscillator and Measurement beams to within a few arcsecs.



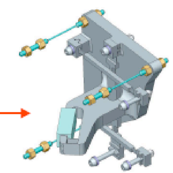
Mask: Central core beam goes out to fiducials and crescent beams remain inside for reference



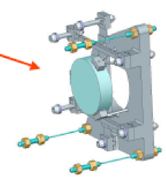
Completed brass board beam launcher assembly (without enclosure) during testing



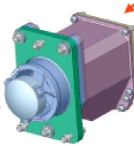
This Titanium dither mechanism holds the reference pick-off mirror (RPM). The RPM is articulated with three piezo transducers to enable pointing of the measurement beam.



The rectangular mirror on this aluminum stage reflects just the core beam towards the signal detector.



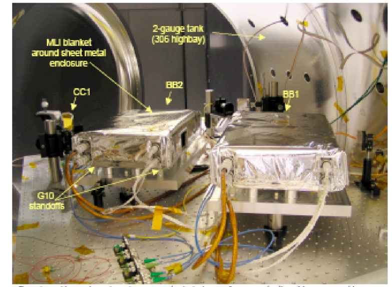
The circular mirror on this aluminum stage reflects the crescent beams toward the reference detector.



Each detector assembly holds a lens and a photodiode/preamplifier circuit board.

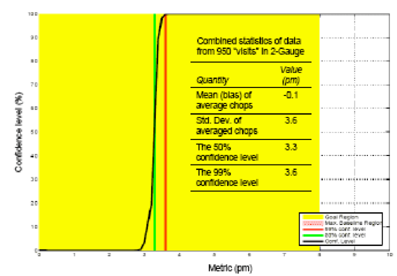
Photodetector & preamplifier board in each detector assembly

Performance testing of beam launchers are conducted via back-to-back consistency tests in the 2-Gauge Testbed using breadboard laser source and electronics. The picture below shows two BB BLs, both covered with thermal enclosure and multi-layer-insulation (MLI) blankets, in 2-Gauge tank. In this configuration, the measurement beams of each BL go through the other BL to interrogate the same pair of fiducials. The BB BL met SIM performance requirement for both Narrow Angle (NA) and Wide Angle (WA) metric.



Brassboard beam launchers in vacuum tank during performance testing. Measurement beams from BB1 and BB2 go through each other, and between corner cubes CC1 & CC2 (not shown).

Criterion	*Performance Requirement* *Goal*	*Baseline*	*Measured in 2-gauge*
Narrow Angle Metric	3.0 pm (50% CL)	8.0 pm (99% CL)	3.3 pm
Grid Wide Angle Metric	42 pm (50% CL)	128 pm (99% CL)	14 pm



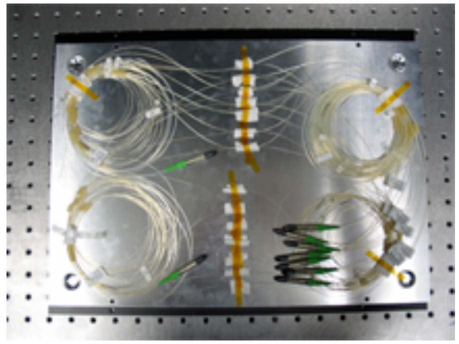
Environmental testing of BB2 consisted of both vibration (shake) and thermal cycling (bake). Shake tests were performed at a peak value of 0.04 g^2/Hz, resulting in 4.6 g_{rms}. Temperature cycling tests were performed between 10 and 45° C. Performance tests conducted pre and post environmental testing indicate no degradation in performance. Measurement of heterodyne efficiency (or visibility) over time – after shake, bake, vacuum cycling, handling and transportation – indicate excellent alignment stability.

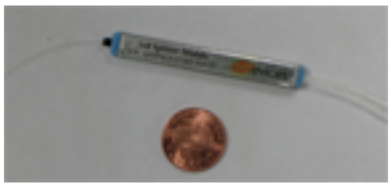
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

NORTHROP GRUMMAN Space Technology
JPL
CALTECH

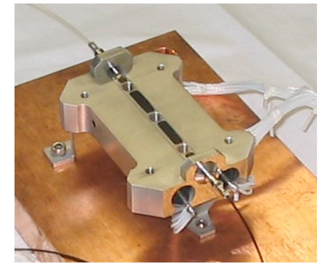
Metrology Source EM3 Subassemblies

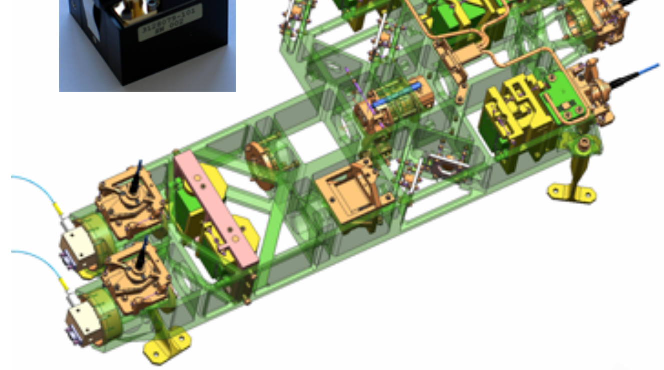
1) Fiber Distribution Assembly brassboard (subset of full FDA)





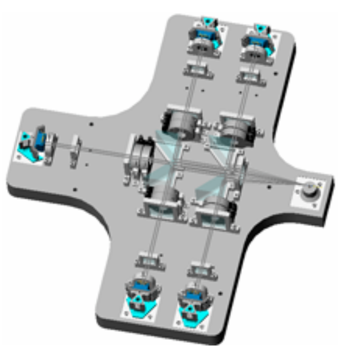
2) Frequency Doubler brassboard.

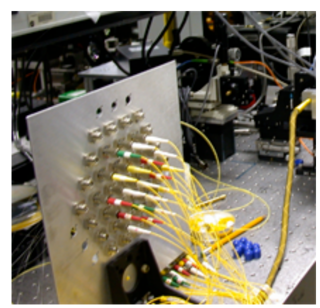


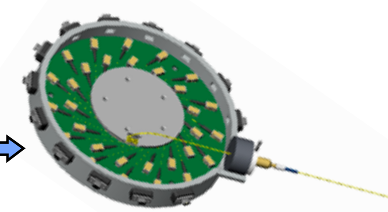


3) Optical Bench brassboard, including Laser Head brassboard, Frequency Shifter brassboard and Optical Switch brassboard

4) Laser Pump Module breadboard

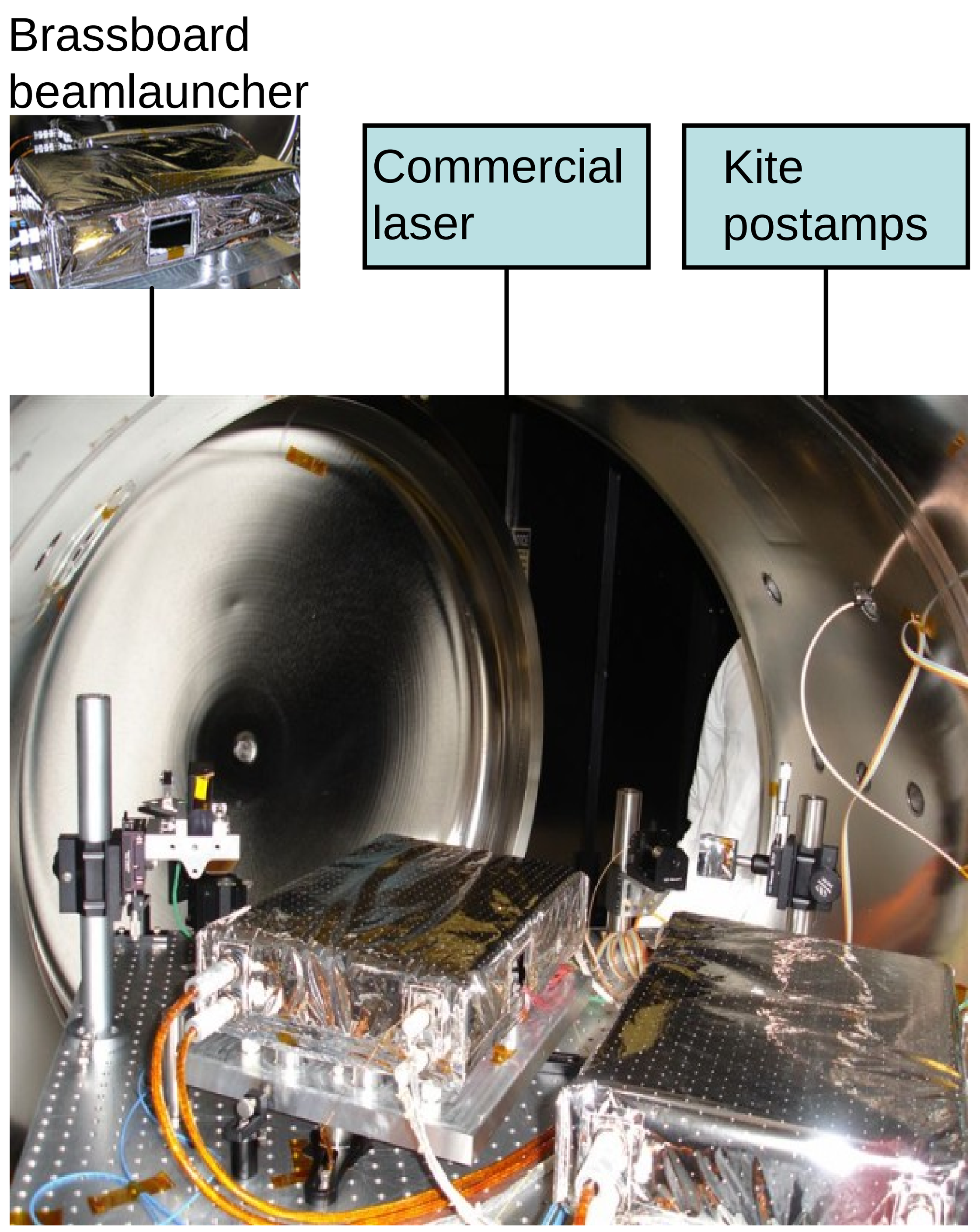






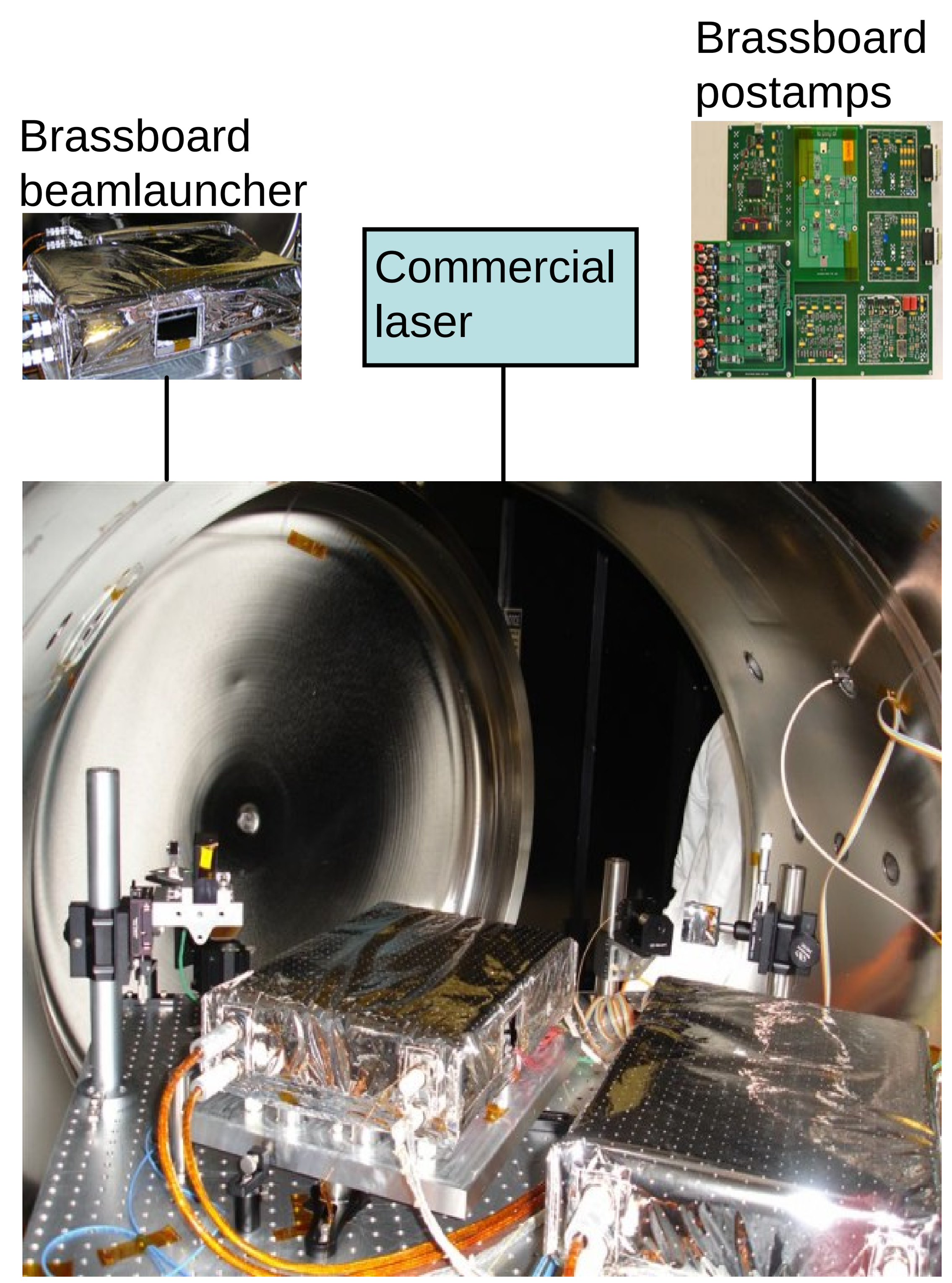
Flight design concept

Two-Gauge Testbed:
Improvement of Narrow-Angle (NA) Metric
Requirement: NA < 2.9 pm, at 50% Confidence Level

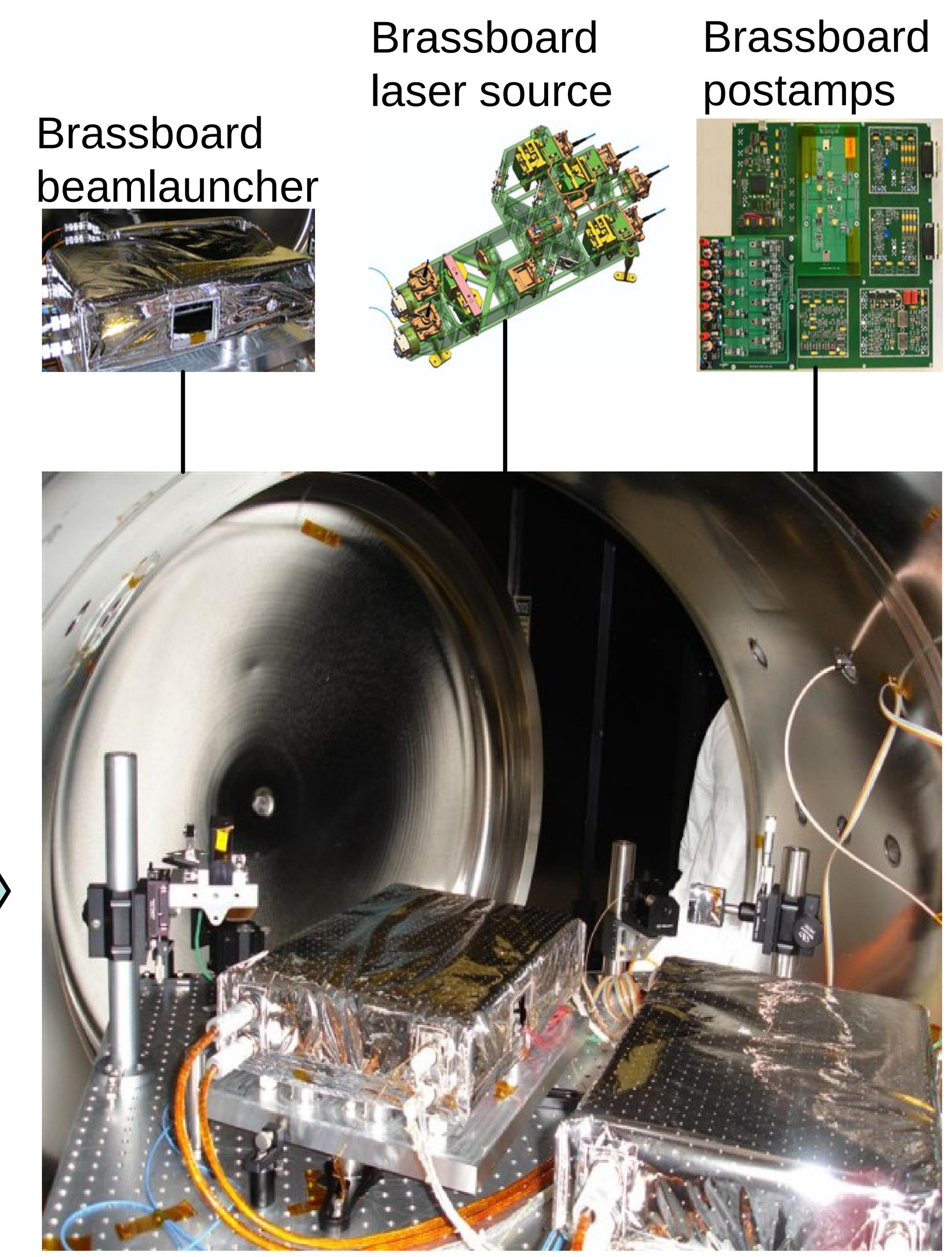


Two brassboard beamlaunchers in the Two-Gauge vacuum enclosure

June 06
NA = 3.5 pm



September 06
NA = 2.4 pm



March 07
NA = 1.8 pm

Contact: Alexander Abramovici Extension: 4-9038

NPRO LASER HEAD DEVELOPMENT FOR SIM METROLOGY

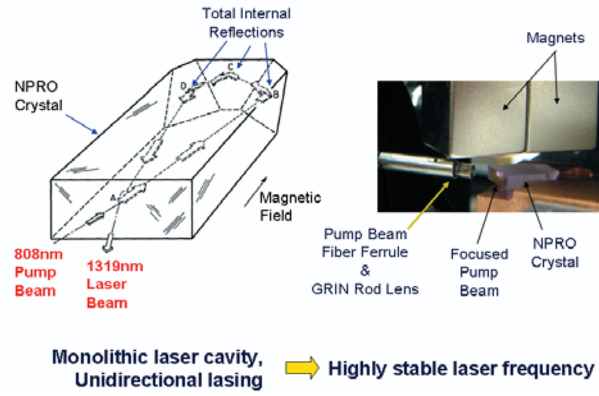
Cognizant Engineer: Duncan Liu

Contributors: Francisco Aguayo, Cheryl Asbury, Charles Cruzan, Serge Dubovitsky, Shannon Jackson, Paul Gelsinger, Andrew Lamborn, George Lutes, Atul Mehta, Amin Mottiwala, Don Moore, Jim Moore, Jerry Mulder, Robert Peters, John Rice, Yueming Qiu

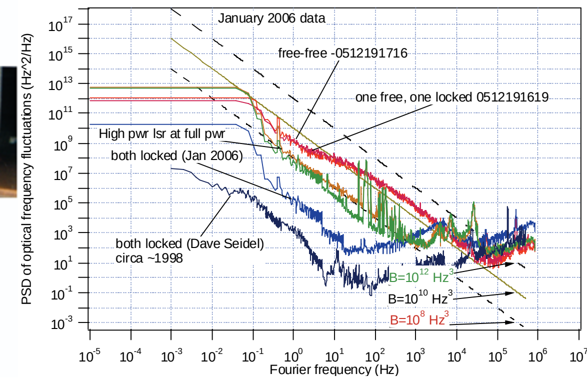
NPRO Laser Description

- A highly stable laser-diode pumped solid-state laser that is capable of providing a stable laser frequency and power for pico-meter-class metrology operation
- Wavelength selected is 1319nm
- Available output power > 300mW
- Narrow line width of <10kHz/ms attributed to the monolithic uni-directional ring laser cavity design
- Long term frequency stability < 50MHz/hour
- Coherent length > 1km
- PSD (power spectral density) ~ 1x10^7 Hz^2/Hz
- Thermally tunable 30 GHz

Nd:YAG Non-Planar Ring Oscillator (NPRO)



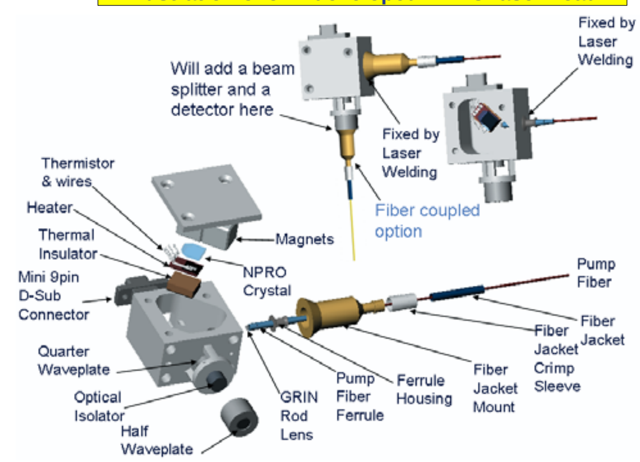
PSD of a free-running NPRO laser



Approach

- The pump beam is delivered with a multimode fiber attached to the laser head by laser welding
- The output beam is coupled into a single-mode polarization maintaining fiber attached to the laser head by laser welding
- Fiber coupled pump beam delivery isolates pump module from laser head and leads to a more robust and long lifetime pump module to be designed and a more stable thermal environment for the NPRO laser crystal
- Laser welding provides a stronger bonding for fiber attachment and a more repeatable attachment process than epoxy or soldering; it is the industrial standard for fiber attachment in various high-reliability photonics devices

Illustration of JPL developed NPRO laser head



SIM Metrology Laser Head Development History

1996

- Down-selected 1319nm fiber-coupled NPRO laser
- Worked with Lightwave Electronics to redesign the Model 125 laser to be flight-qualifiable

1997

- Redesgned Model 125 laser brass board tested and passed both random vibration and thermal tests (-20C to 50C, limited by epoxy used in fiber attachment)

1998

- Out of concern with fiber attachment by epoxy, laser welding was proposed to be used to attach the fiber
- Proposed fiber-delivered pump beam scheme
- A conceptual laser head designed based on 4-axis Newport laser welding fiber-attachment system
- JPL packaging section and SIM project procured a Newport Model 4000 laser welding system.

1999

- Produced the first NPRO laser head; two more laser head produced later
- Passed vibration tests
- Passed thermal tests for -20C to 50C; failed 70C test due to fiber jacket not removed on the fiber in the large inner diameter ferrule; problem solved with the new ceramic/metal ferrule design

2004

- Fiber-pumped free-space output NPRO laser head was baselined for SIM metrology subsystem

2005

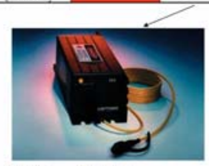
- Two fiber-pumped, free-space output NPRO laser heads delivered to SIM Metrology source bench brass board development team

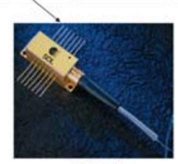
2006

- NPRO laser heads in SIM Metrology source bench brass board passed random vibration and thermal vacuum tests

Laser Technology Down-Select

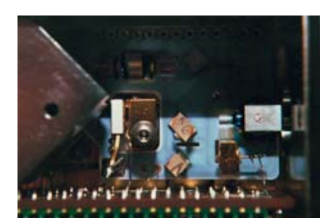
	Requirements	Diode Pumped Nd:YAG NPRO (Lightwave)	Semiconductor DFB Laser Diode (SDL)	Diode Pumped Microchip Laser (Micracor)	Fiber Ring laser (MBPT)
Wavelength	> 1.1 µm	1.319 µm	1.3 – 1.55 µm	1.319 µm	1.54 µm
Linewidth	Low	5 kHz	150 kHz	500 kHz	<60 kHz
Freq. Fluct. (hr)	Low	50 MHz	500 MHz	50 MHz	50 MHz
Freq. Control	> Linewidth	Yes	Maybe	Maybe	Yes
Rel Int. Noise	TBD	-165	-130	-130	-150
Output Power	100 – 200 mW	200 mW	100 mW	10 mW	10 mW
Size & Weight	Small	Medium	Small	Medium	Large
Reliability and Space Qualifiability	Launch+5yrs	Medium	Very good	Potentially Good	Poor



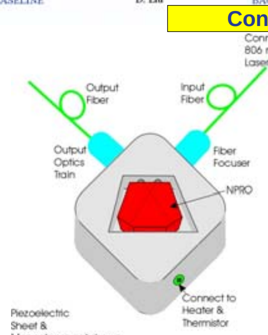


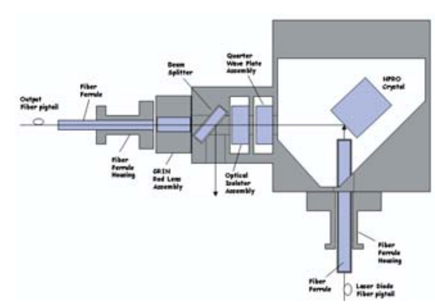
3/9/2007 BASELINE D. Liu BACKUP

Modified Model 125 NPRO Laser

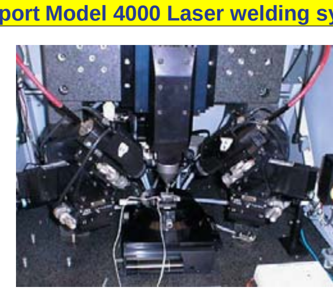


Conceptual and preliminary design

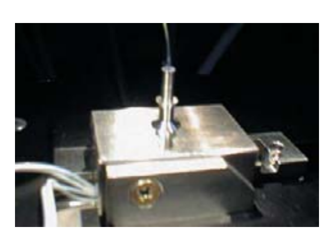


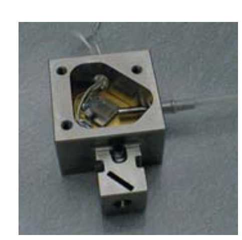


Newport Model 4000 Laser welding system



Pump-beam fiber attached to NPRO laser head





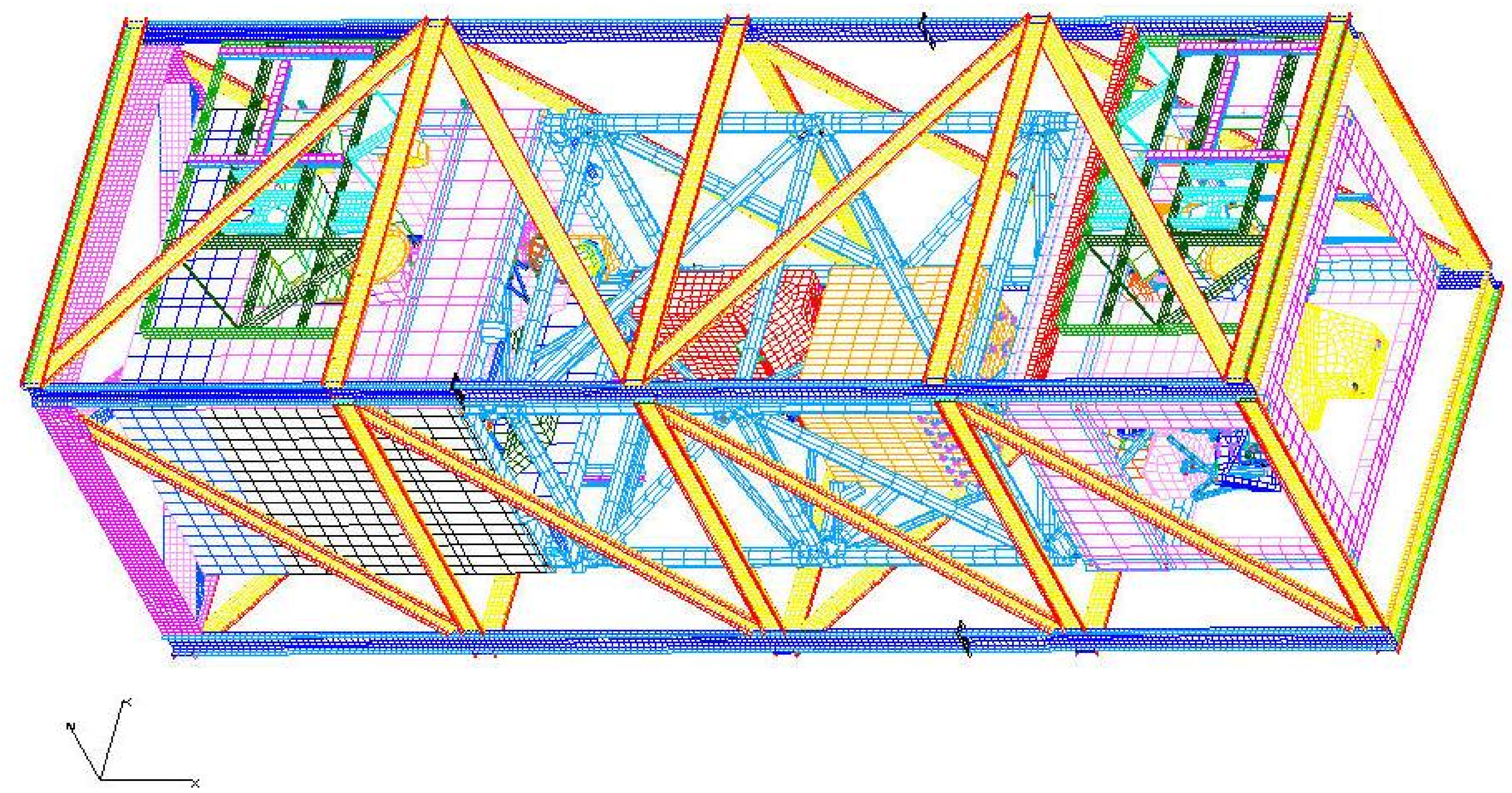
First NPRO Laser Head Built at JPL 1999

Fiber-pumped, free-space output, NPRO Laser Head Built at JPL 2005

Jet Propulsion Laboratory
California Institute of Technology

Astrometric Pseudostar System

- **Astrometric Pseudostar**
  - SIM instrument is 1 microarcsec level space observatory
  - Instrument has to be tested on the ground without a real star
  - The pseudostar star system provides the unprecedented capability of testing the SIM instrument to the required picometer level OPD



- **Potential Applications**
  - Large, precision structure thermal distortion test
  - Spaceborne starlight interferometer performance test
  - Sun heat load simulations for spacecrafts and instruments
  - Stable optical platform with large moving optics

- **Design Maturity**
  - Completed integration of instrument and pseudostar TVAC frame/IR lamp model
  - Completed multi-disciplined analysis: Thermal + Structural + Optical
  - Analysis showed the required picometer level stability
  - Finished a concept design of the pseudostar relay optics subsystem

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