Space Interferometry Mission (SIM)

Flight System

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Flight System Engineering
PEM

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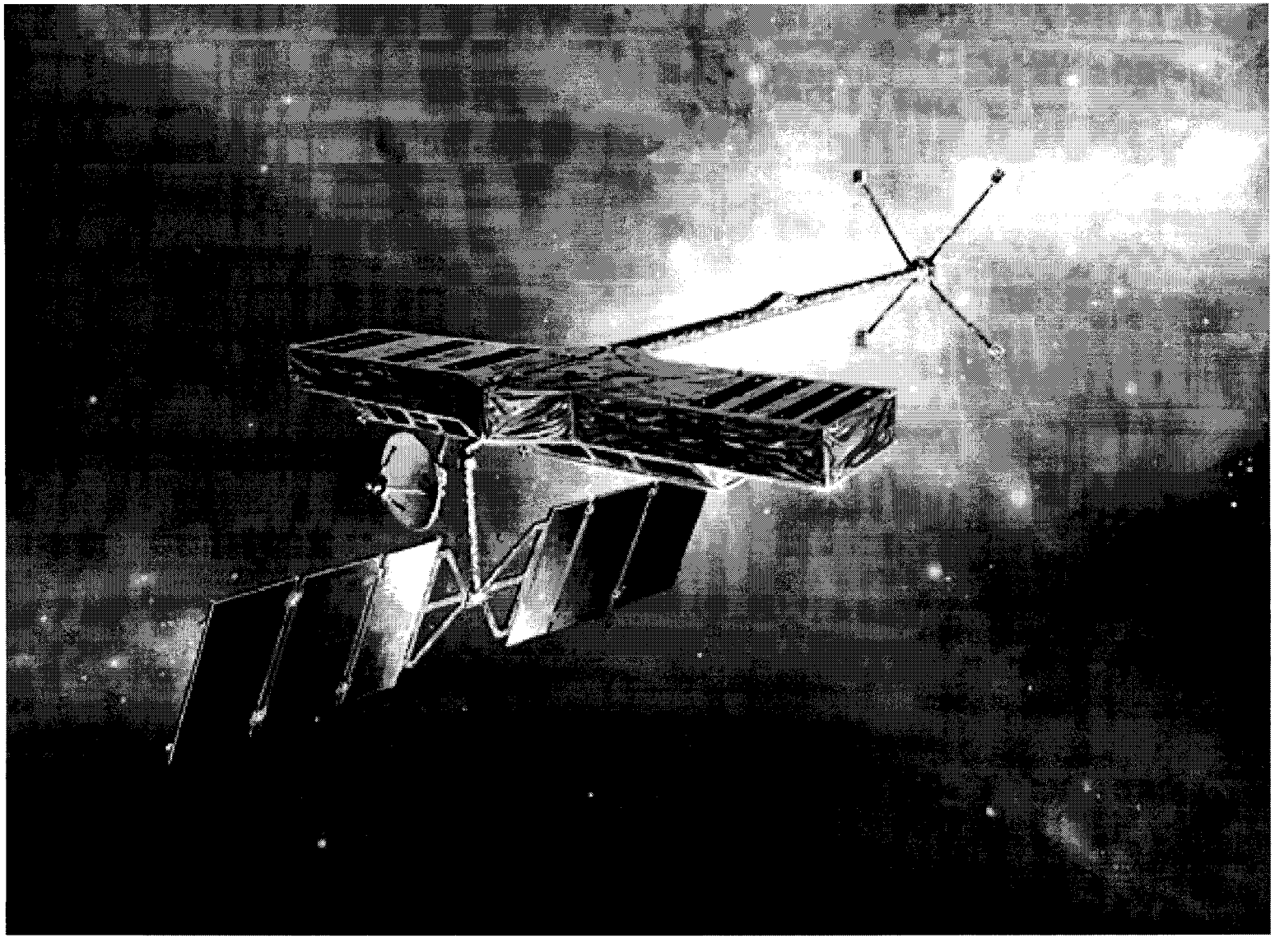
Agenda

- SIM Overview
- How SIM Works
- SIM Flight System Conceptual Design
- SIM Top-Level Requirements
- SIM Technology Testbeds
- System Engineering Process
- Overall Flight System Configuration
- SIM Instrument Subsystems
- Technical Challenges
- Summary

SIM Flight Concept

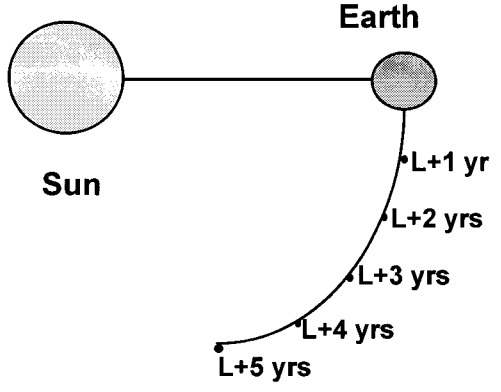


Three collinear interferometers mounted on a 10 meter long structure

Mission Overview

- Precisely measure angles between stellar objects
- 10 meter rigid baseline interferometer
  - Single instrument Flight System
- Flight Environment
  - Atlas V 421 Launch Vehicle => 5307 kg launch capability
  - Earth-trailing orbit - 1 AU
    - Like SIRTF
  - 5 year lifetime

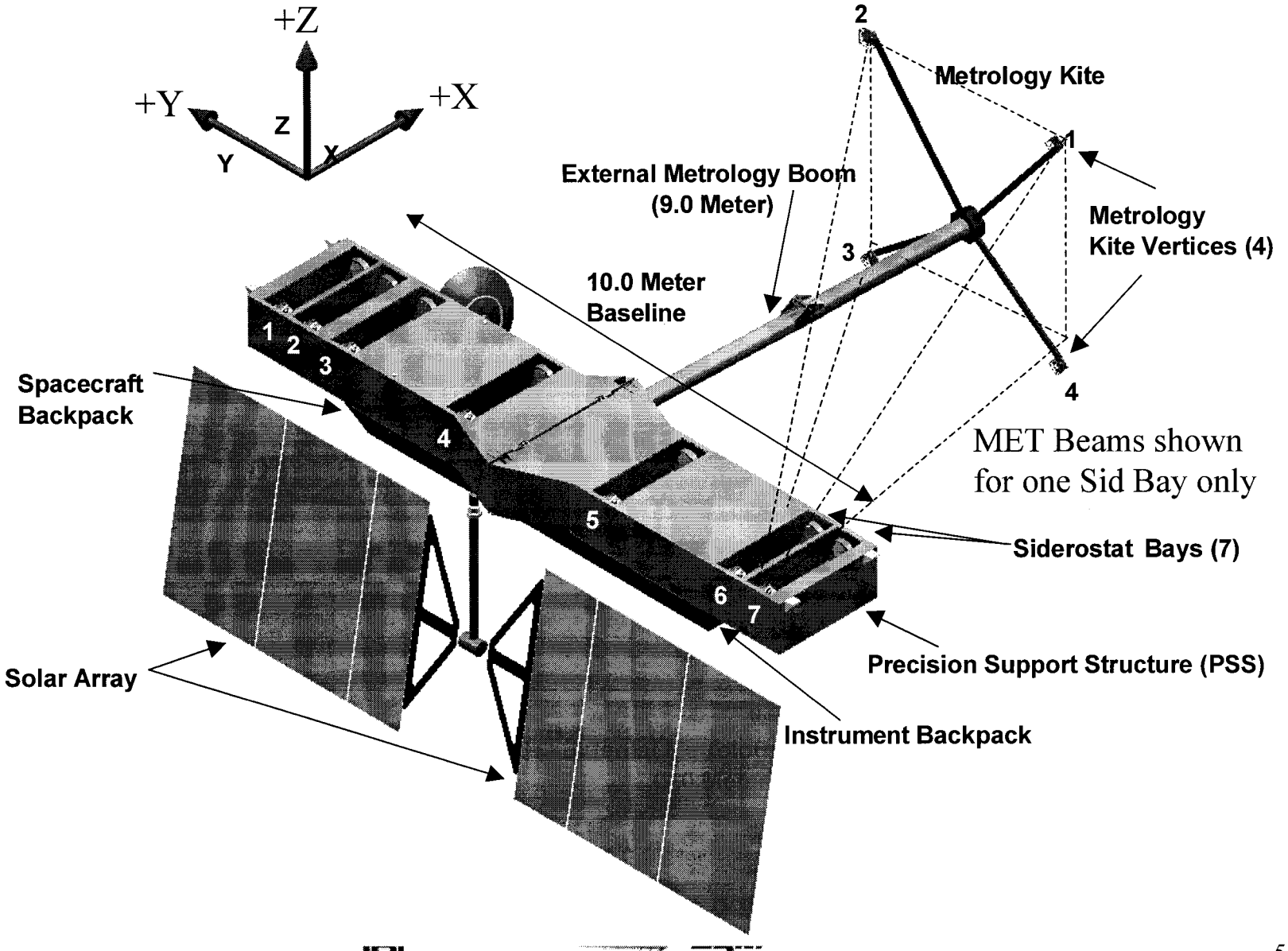
Earth-Trailing Solar Orbit



CHARACTERISTICS

C_3	0.4 km^2/Sec^2
Occultations	None
5.5-yr Radiation Dose	20 Krads
Launch Vehicle	Atlas V 421
RCS System	Mono-Prop
Delta-V Req'd?	No
Orbit Determination	Range/Doppler
Earth-S/C Range	Up to 100 Million Km
Launch Period	June, 2006
Mission Duration	5.5 Years

SIM Configuration

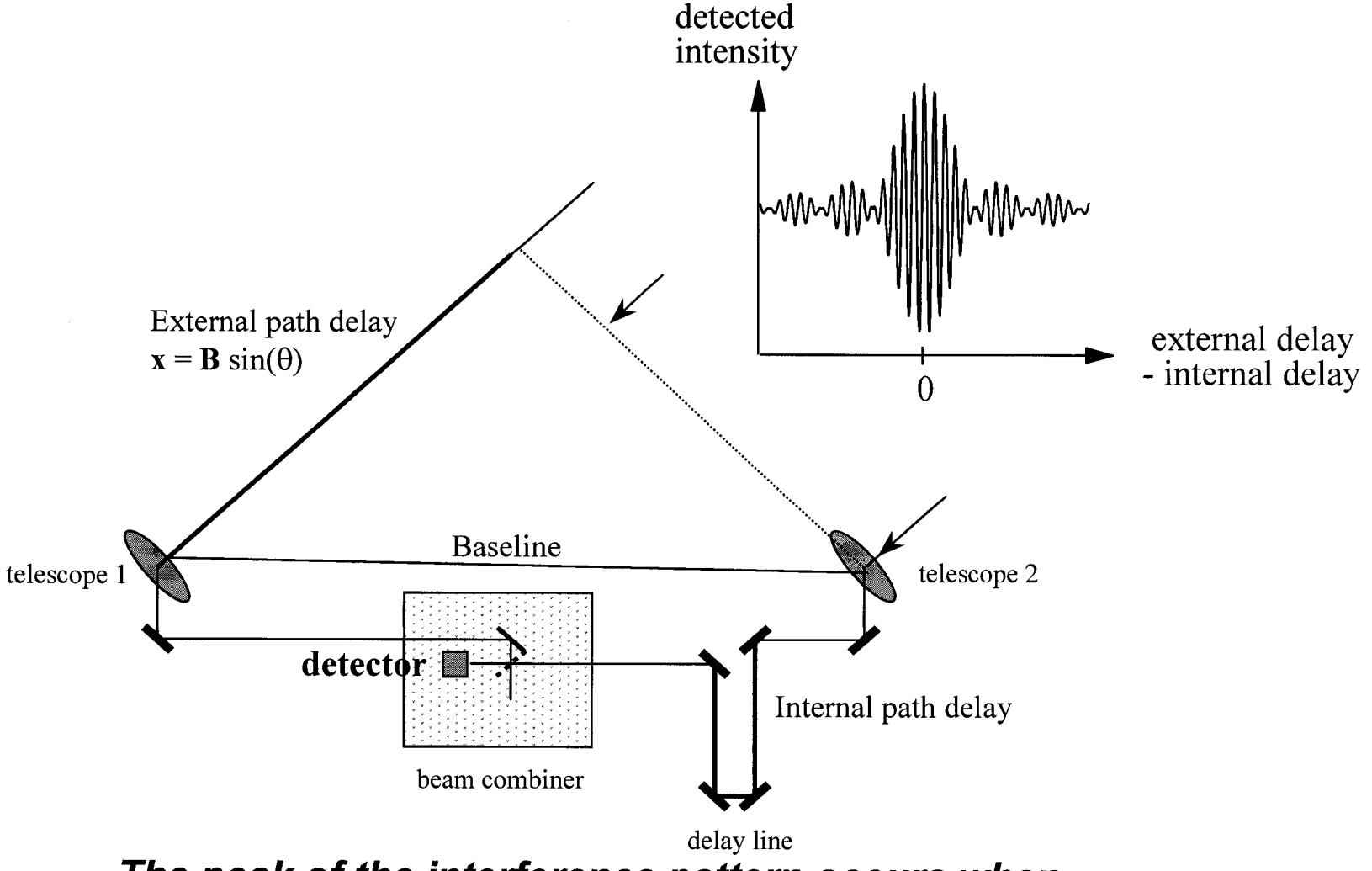


Key Flight System Requirements

- **Science Objectives**
  - **Astrometry**
    - **4 uas wide angle (15 degrees) mission accuracy => 10.5 uas single measurement accuracy**
    - **narrow angle (1 degree) mission accuracy => 1 uas measurement accuracy per hour**
  - **wavelength - 0.4 - 0.9 um**
  - **minimum brightness - 20th mag**
  - **sensitivity => 4 uas for 16th mag in 13.3 hours**

- **Technology Objectives**
  - **Imaging => ~0.5 meter to ~10 meter baselines with "uniform" u-v coverage**
  - **Nulling Technology Demonstration => 10^{-4} null over 5 minutes**

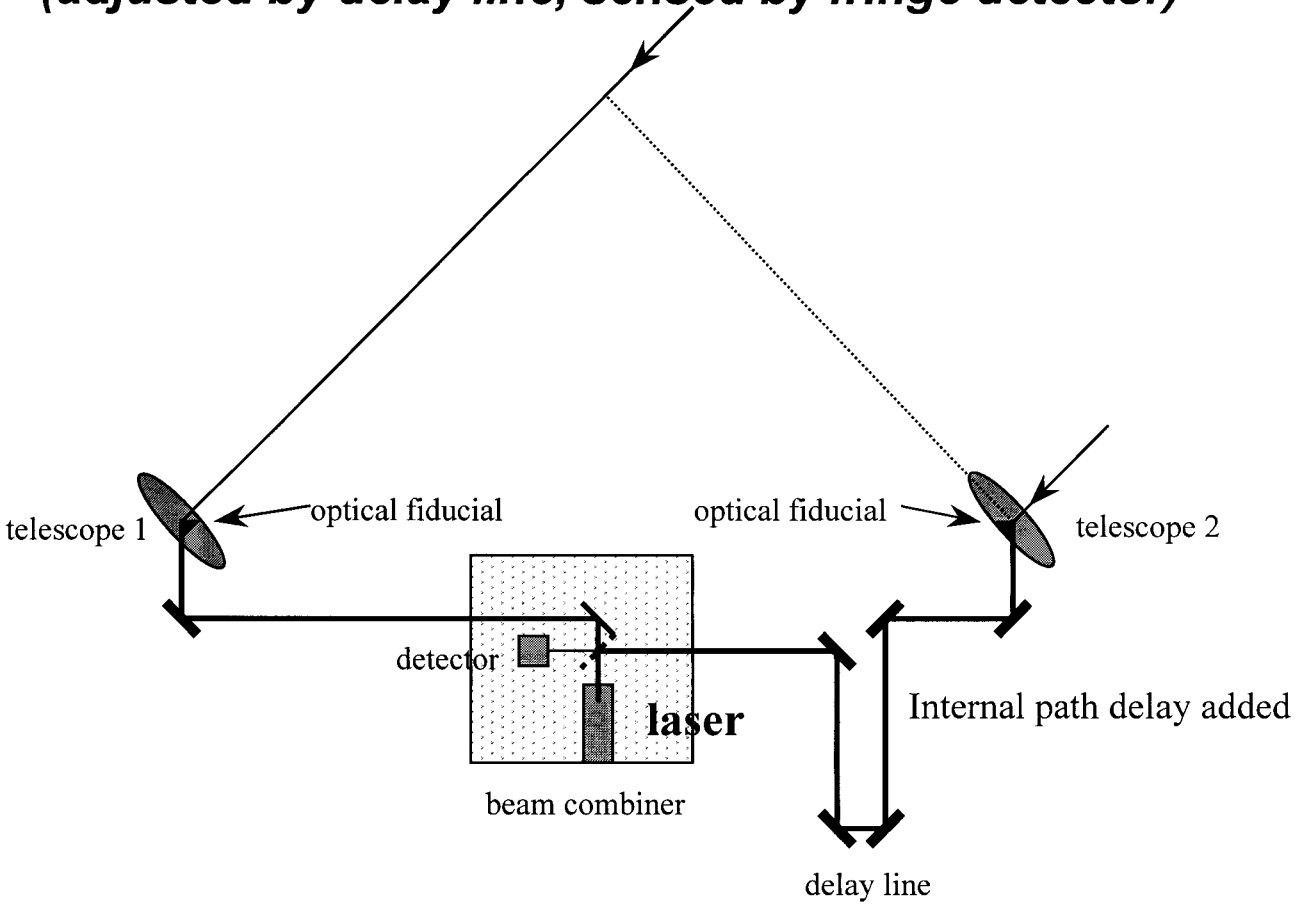
SIM Astrometric Measurement



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

Internal Metrology

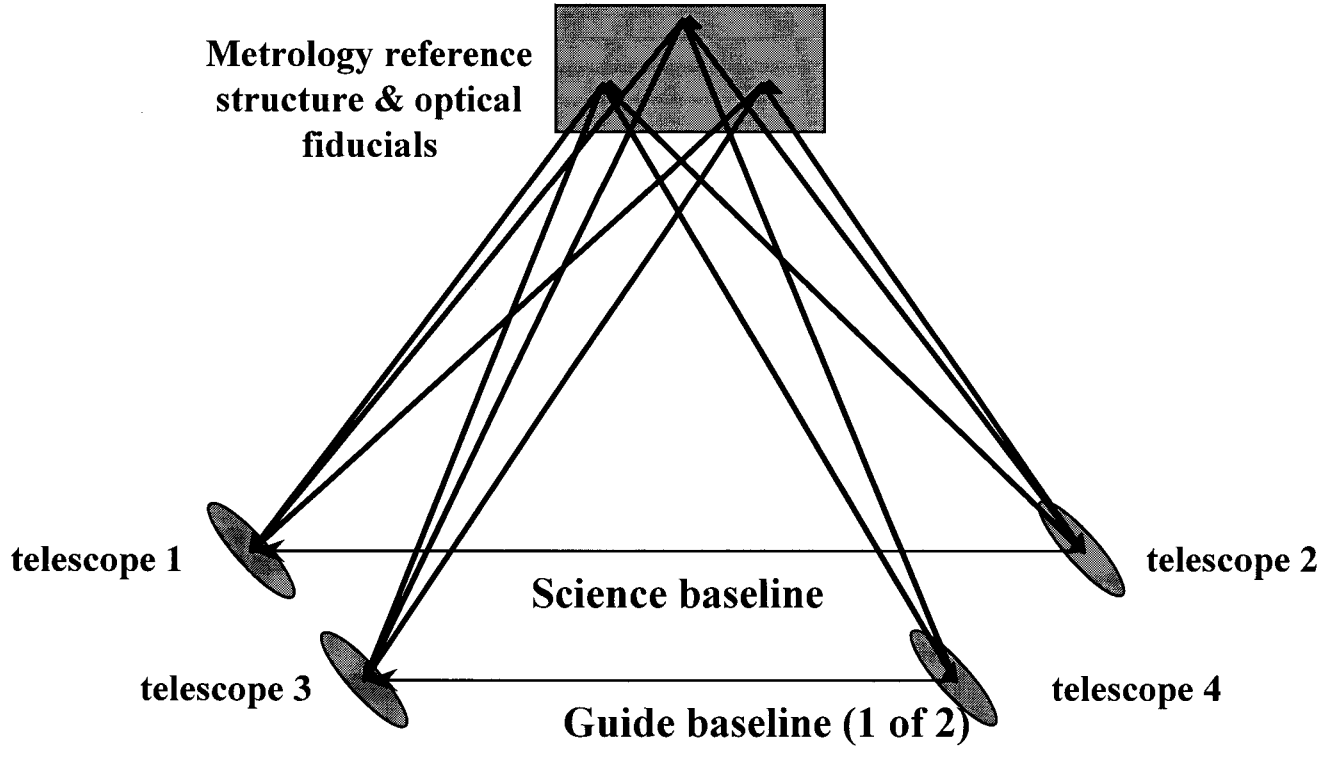
Laser gauge measures internal delay
(adjusted by delay line, sensed by fringe detector)



Laser path retraces starlight path from combiner to telescopes

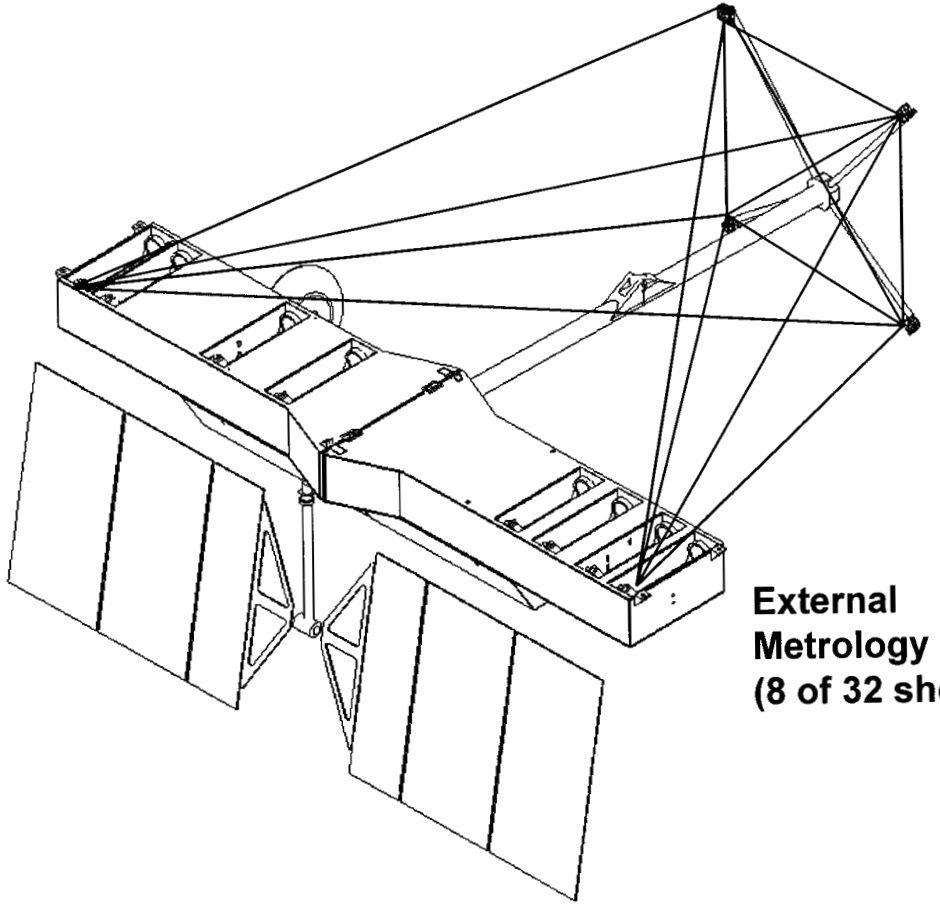
Relationship Between Baselines

Measure baseline B using laser triangulation



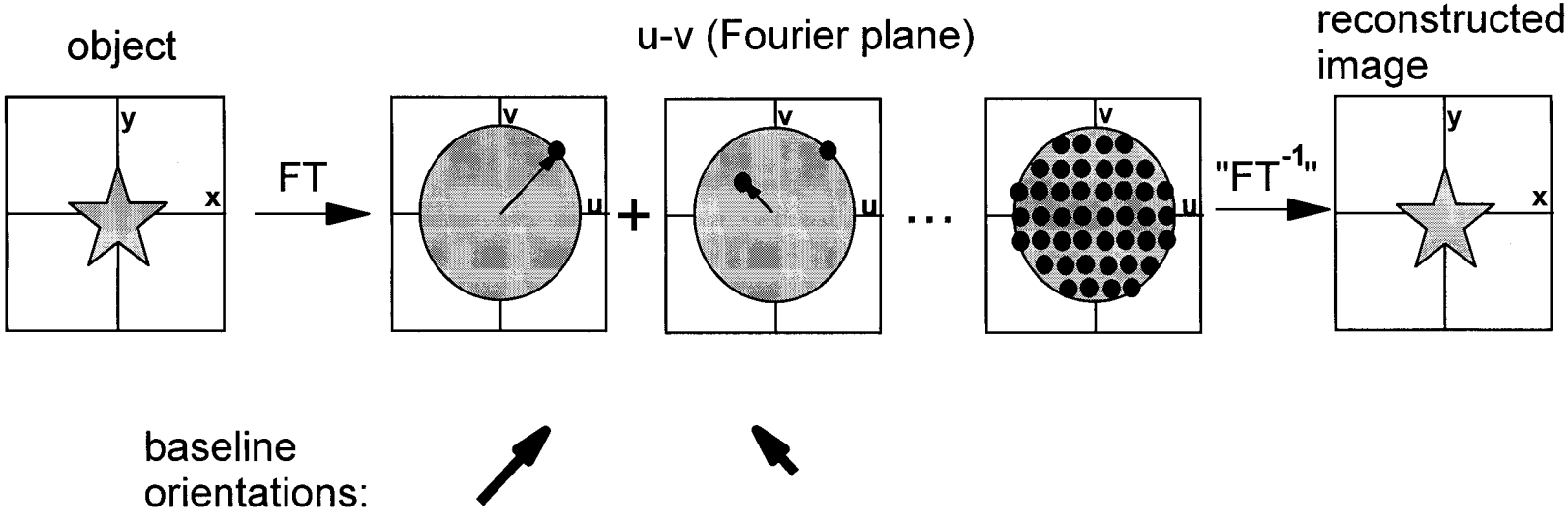
The Guide baseline attitude information is used to stabilize the science interferometer

External Metrology Implementation



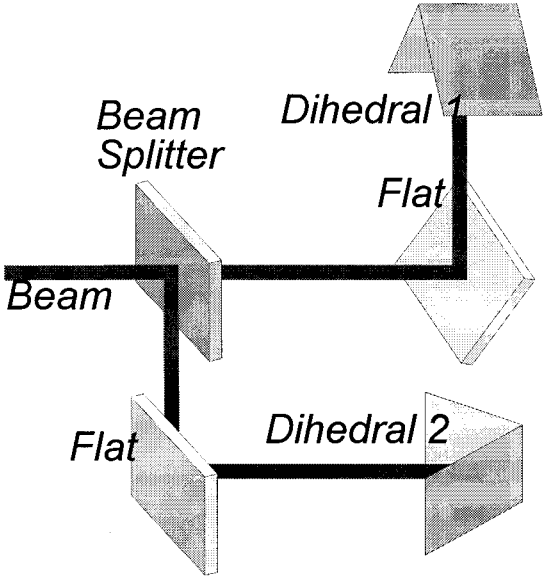
- Measures relative orientation of science and guide baselines
- Allows accurate transfer of attitude information from guides to science interferometer
  - Science interferometer stabilized by commanding its delay line
  - Provides long integration time for faint stars

Imaging with an Interferometer

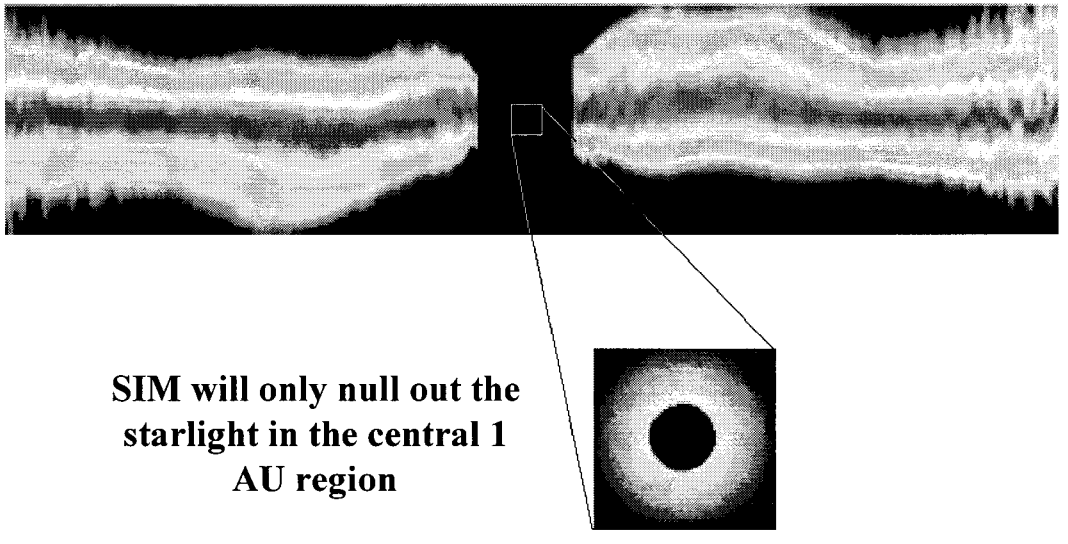


- **The interferometer measures the Fourier transform of the object**
- **Each baseline orientation selects one point in the (u,v) plane**
  - **The data for this point is the fringe visibility and phase**
- **With many baseline orientations, you fill in the (u,v) plane**
- **The image is reconstructed from these Fourier-domain measurements**

How SIM Performs Nulling



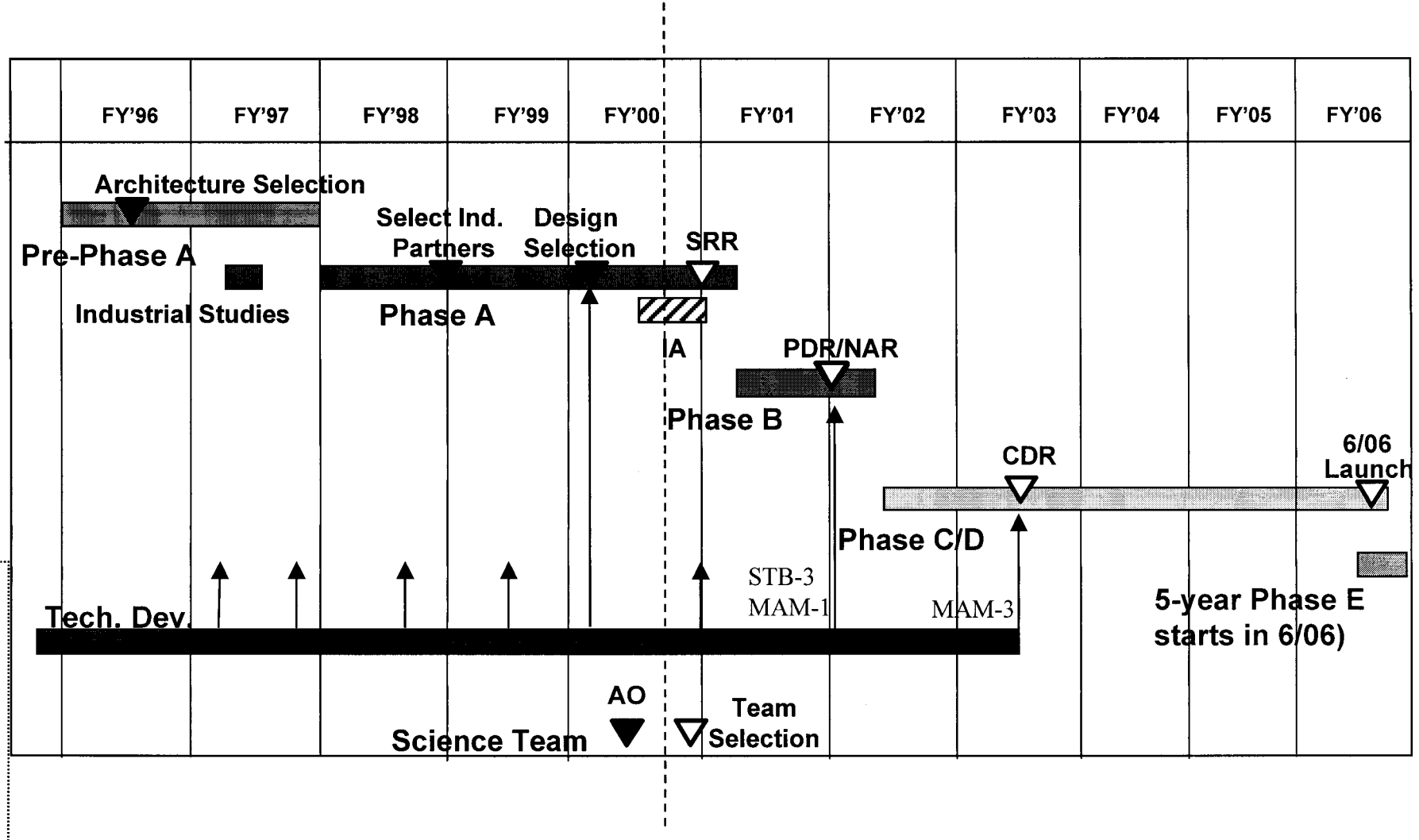
HST image of Beta Pictoris with central region blocked (about 16 AU)



SIM will only null out the starlight in the central 1 AU region

- In the nulling beam combiner, flip the phase of one arm of the interferometer before combining the beams
- Stabilize the null to about 1 nm (pathlength)
- Measure the starlight extinction at the center of the null
- Verify requirements have been met

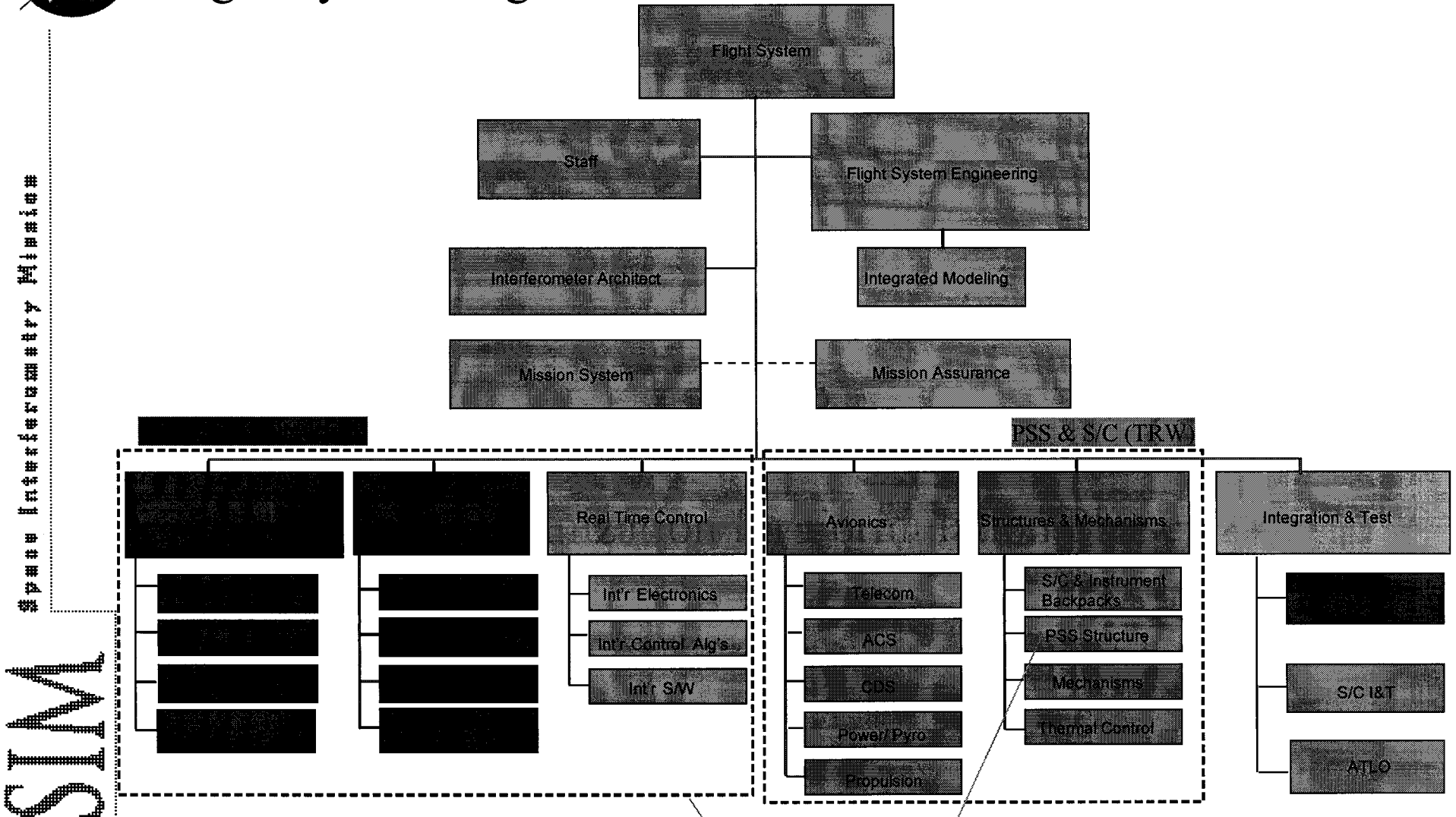
SIM Project Schedule



Programmatic Overview

- Integrated Jet Propulsion Laboratory (JPL) / Industry team
  - Assembled to formulate a reference design
- JPL
  - Leads the overall system development and Real-time Control Subsystem
- Lockheed Martin
  - Responsible for development of the instrument Starlight and Metrology Subsystem and the Interferometer Integration & Test
- TRW
  - Responsible for the Precision Structure, Spacecraft and ATLO (Assembly, Test and Launch Operations)

Flight System Organization for Formulation Phase



Led by JPL
Led by LM
Led by TRW

Instrument + PSS = Interferometer

Flight System Responsibilities

Flight System Engineering (JPL)

- Leads the development and verification of the system and subsystem-level requirements and design

Integrated Modeling (JPL)

- Develops nanometer and picometer level models of the flight interferometer design to predict on-orbit performance

Starlight Subsystem (LM)

- Develops the optics, delay lines, cameras and beam combiners to gather the starlight and interfere the signals from each arm to produce a fringe

Metrology Subsystem (LM)

- Develops the laser source, fiber distribution system, beam launchers and corner cubes to achieve picometer level sensing of the interferometer baseline lengths and starlight pathlength differences

Flight System Responsibilities (Cont'd)

Real Time Control Subsystem (JPL)

- Develops the electronics and software to control the interferometer actuators and sensors

Spacecraft (TRW)

- Develops the spacecraft subsystems (telecom, CDS, ACS, power/pyro, propulsion)

Precision Structure (TRW)

- Develops the precision structure wing and metrology boom, spacecraft and instrument backpacks and deployment mechanisms

Integration and Test (LM/TR W)

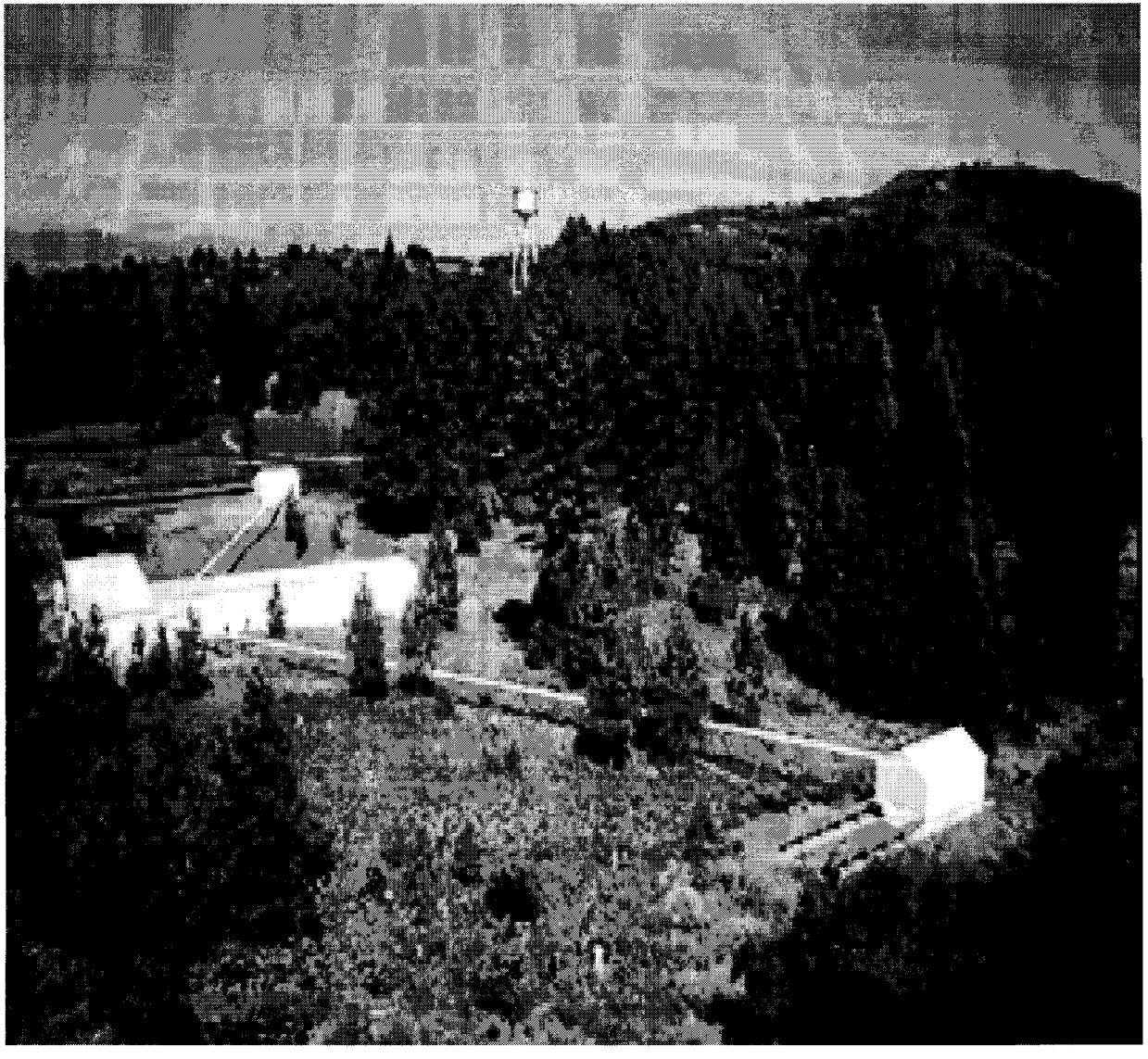
- Integrates and tests the interferometer, spacecraft and flight system. Performs functional, environmental, dynamics & control and astrometric performance tests.

SIM Design Summary

- Three simultaneously operated Michelson interferometers
  - 2 "guide" interferometers used as high precision star trackers
  - 1 Science interferometer
    - 10-meter maximum science baseline
- Switchyard interferes any combination of collectors
  - allows measurements at different baseline lengths
- External Metrology Truss
  - Monitors relative orientation of the three baselines
  - Determines absolute distances between reference fiducials
- Internal Metrology gauging system
  - Measures optical path differences between arms
  - subaperture metrology scheme - metrology only measures central portion of starlight beam
- External and internal metrology share common fiducial

SIM Technology Program - Testbeds

SIM System Ground Testbeds: PTI



Palomar Testbed Interferometer

- Fully functioning 110 m baseline interferometer
- Science data processing

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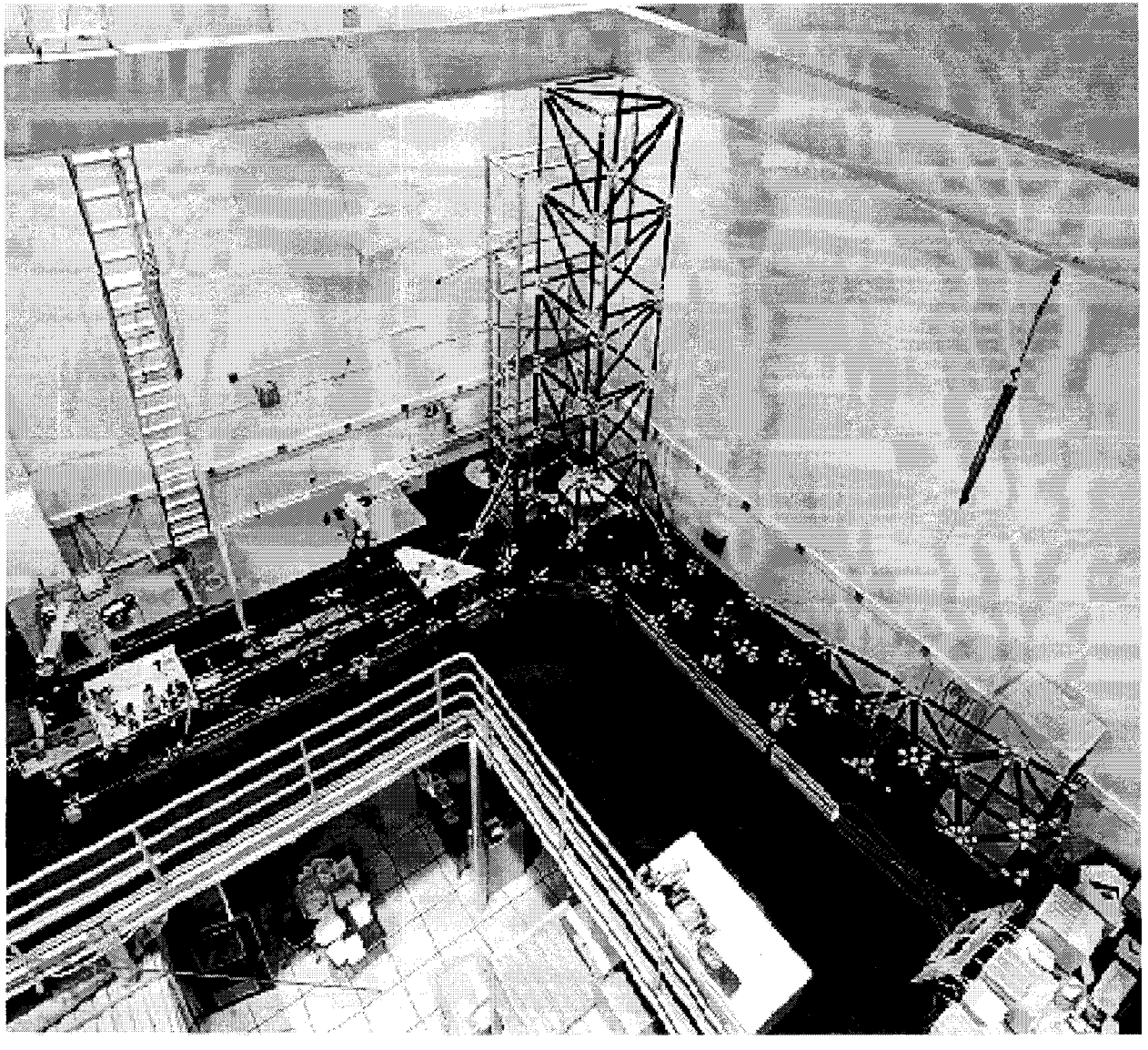
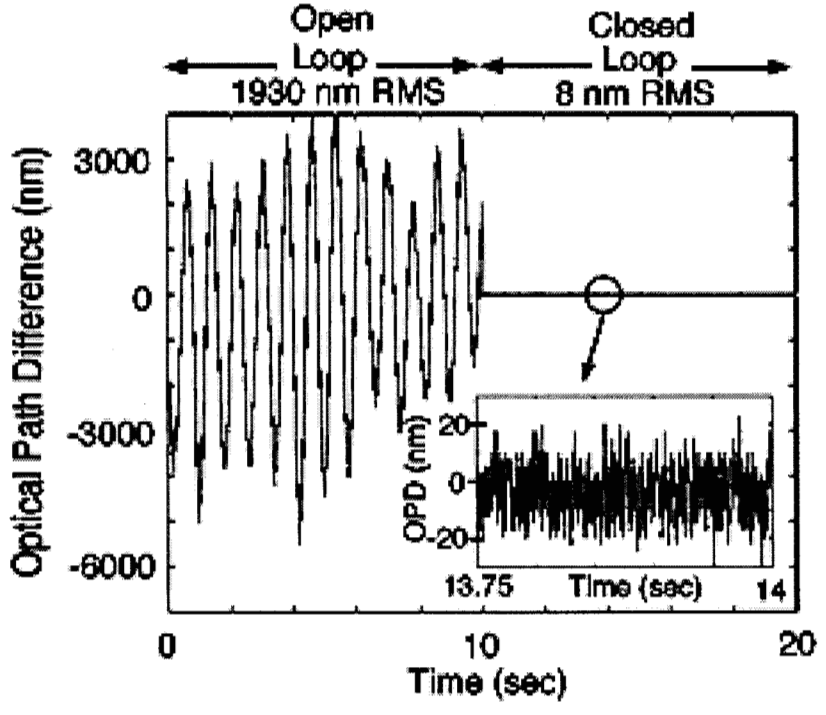
SIM System Ground Testbeds: STB-1



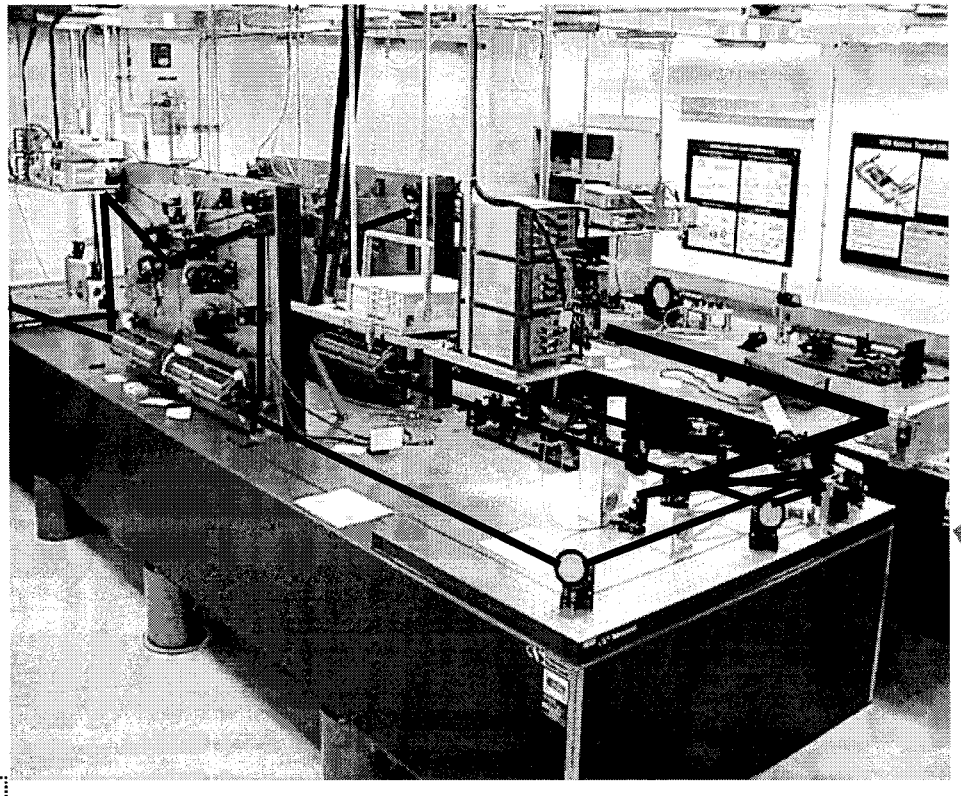
Nanometer stability on a flexible structure

NanometerTestbed Closed Loop Results



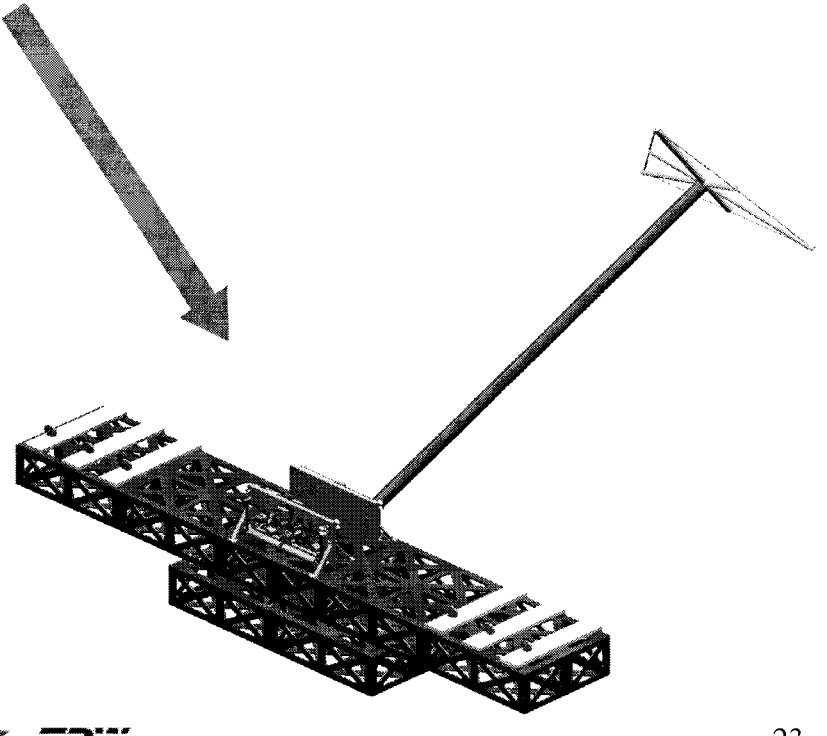
- **Proven positional stability of less than 10 nm in ambient air**
  - **Use to validate predictive modeling techniques**
  - **Induced mechanical disturbances via attitude control system reaction wheels**
    - **Use to characterize interferometer stability and control systems**

SIM System Ground Testbeds: STB-3



SIM System Testbeds

- Nanometer stability on flexible structure
- Full scale
- Full complexity
- Up to Three baselines



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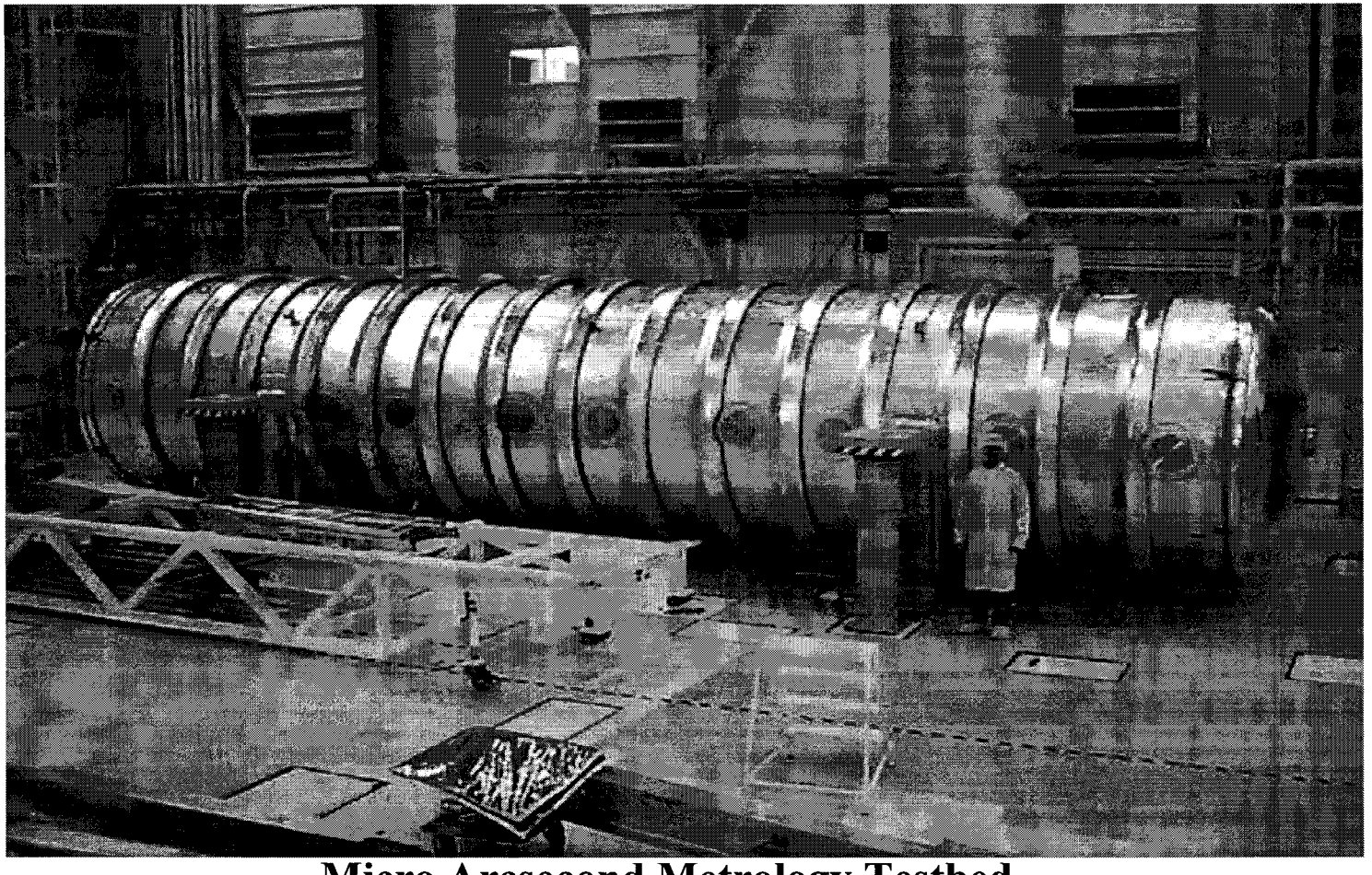
SIM System Ground Testbeds: MAM



Micro Arcsecond Metrology Testbed

- Sub-nanometer metrology
- 1/5 Scale - vibration isolated
- Operation in vacuum
- Demo μ-arcsec measurement

JPL LOCKHEED MARTIN TRW

Mapping of Flight Risk to Technology Program

Prioritized list of key risk items

TRDV Matrix

Milestones	Formulation Phase: Testbeds	Formulation Phase: Modeling	Implementation Phase: I&T	Implementation Phase: Modeling	Implementation Phase: Anal.
1. Guide OPD jitter < 10nm	STB1 STB3	Dynamics Model	X	X	X
2. Starlight path measured to 100pm	MAM	ITOM	X(?)	X	X
.	.	.	.	.	.
.	.	.	.	.	.
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Plans &Requirements for:

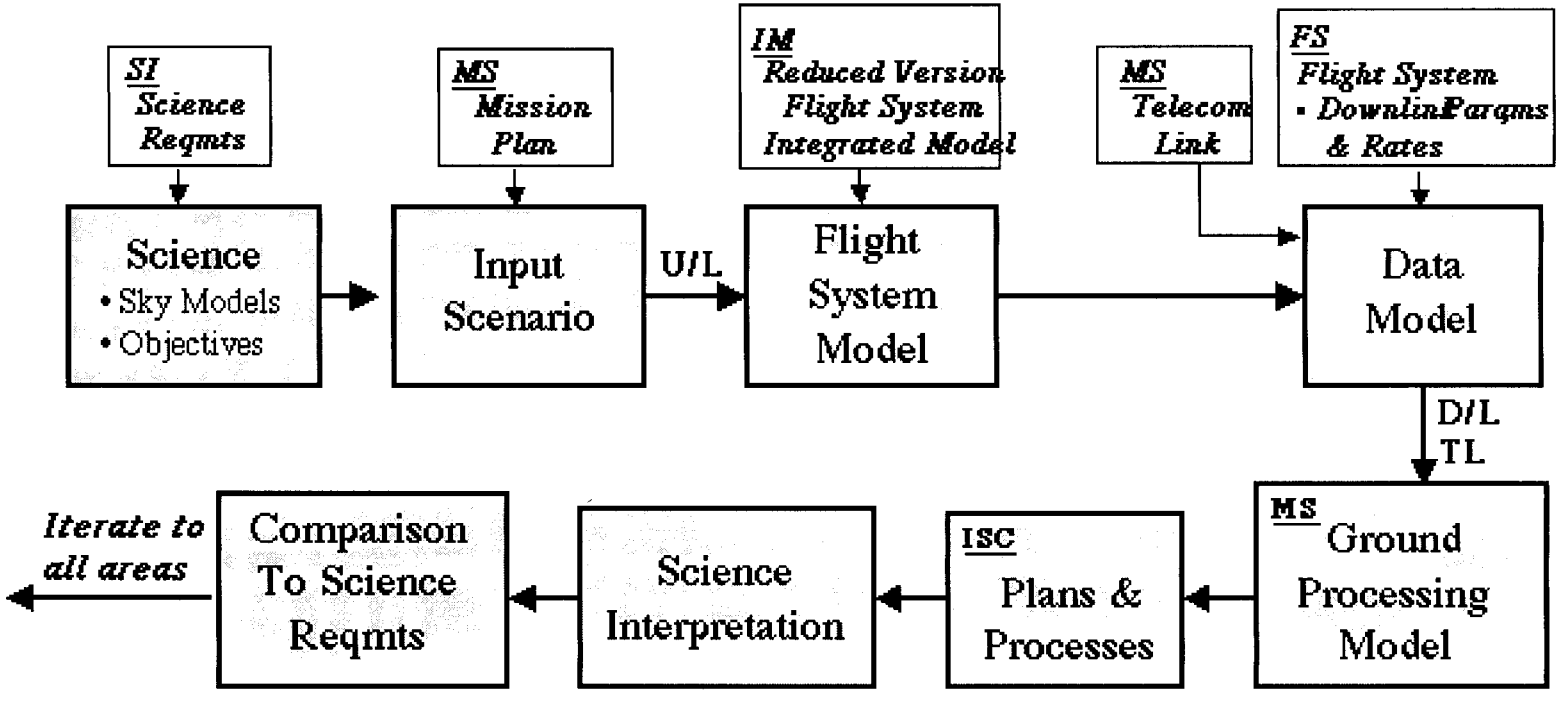
1. *Testbeds*
2. *Integrated Modeling*
3. *Flight I&T*

TRDV = Technology Readiness Design Verification

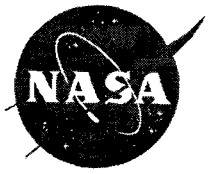
System Engineering Process

- Establish the requirements and design on the mission and instrument
- Allocation of requirements based on key Astrometric and Dynamics & Control Error Budgets
- Utilize a traditional requirements flowdown and design approach
  - Developing a comprehensive set of System and Subsystem requirements
  - Using computerized requirements tracing tool
- Cross-cutting working groups define complex functional interface requirements
- Identify and address Technology risks early
  - Matrix of Flight requirements to technology challenges
    - Technology Readiness Developments Matrix (TRDV)
- Use System Modeling Extensively
  - Flight System integrated Modeling Effort

SIM Simulation Modeling



- System-level modeling approach
- Reduced versions of the integrated Flight System modeling used as input
- Forms basis for the design of the ground processing



JPL

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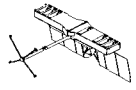

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Flight System Layout

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SIM Configuration

Space Interferometry Mission

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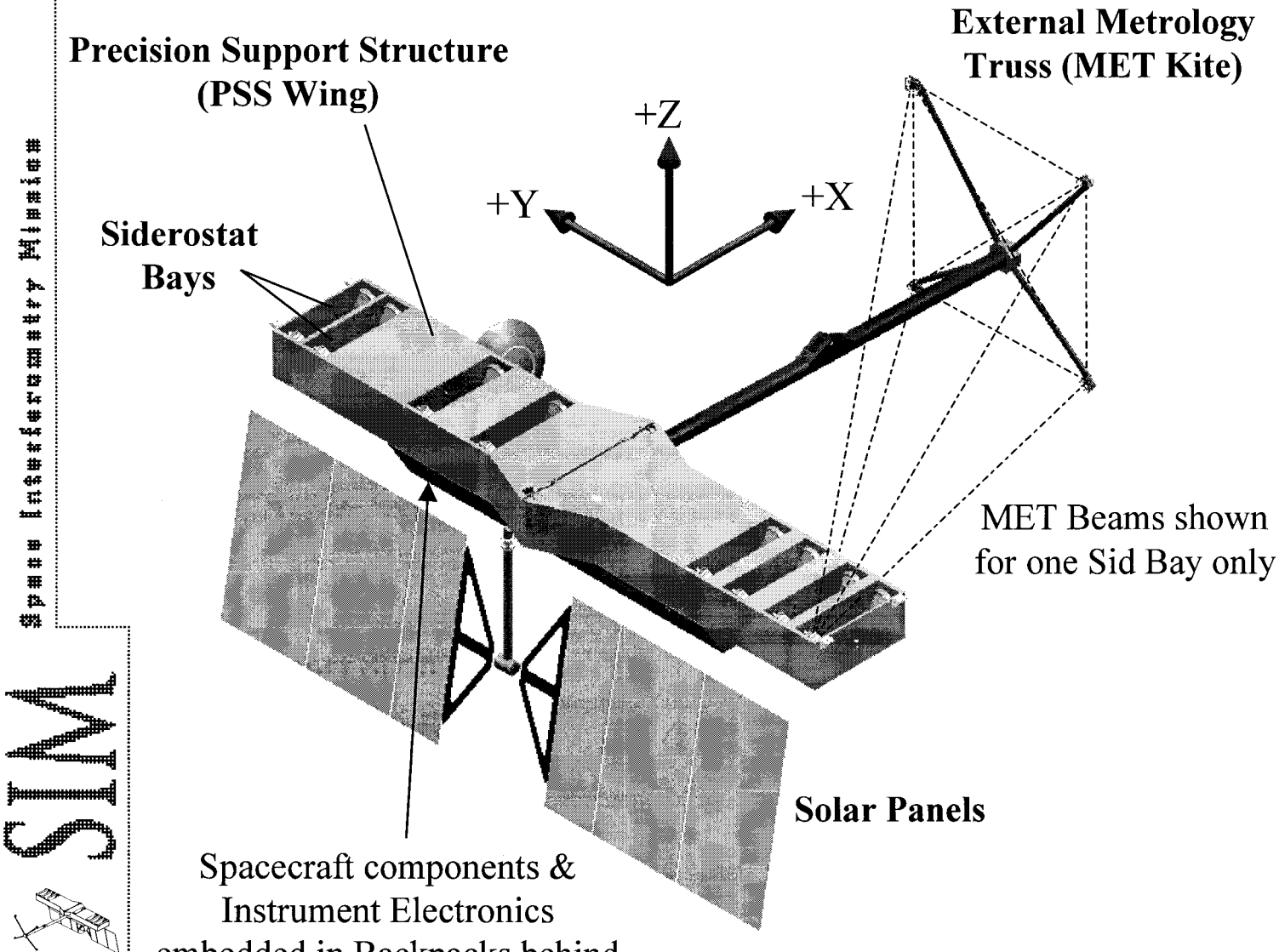
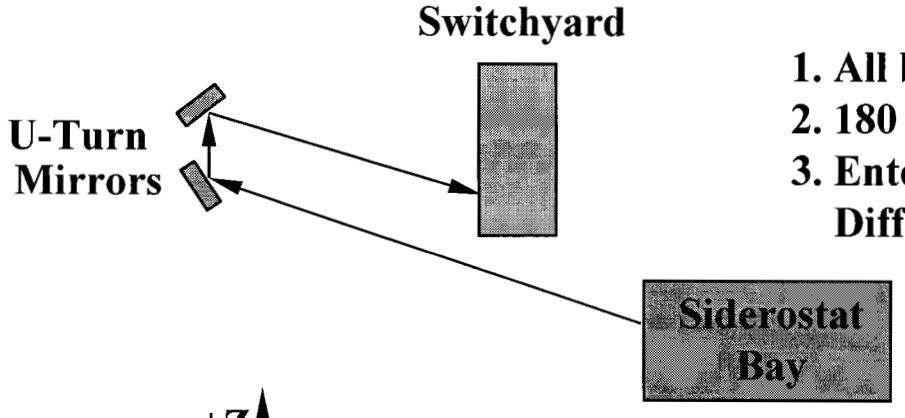
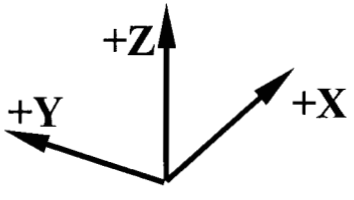


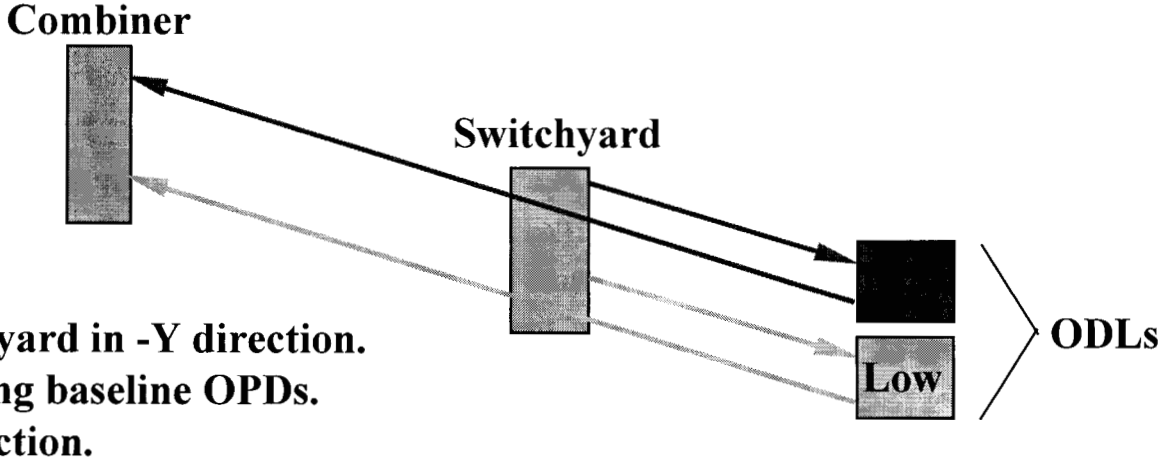
MET Kite stowed

Light Paths Through Instrument



1. All beams exit Siderostat Bays in +Y direction.
2. 180 deg reversal at U-Turn Mirror pairs.
3. Enter Switchyard with zero Optical Path Differences (OPDs).

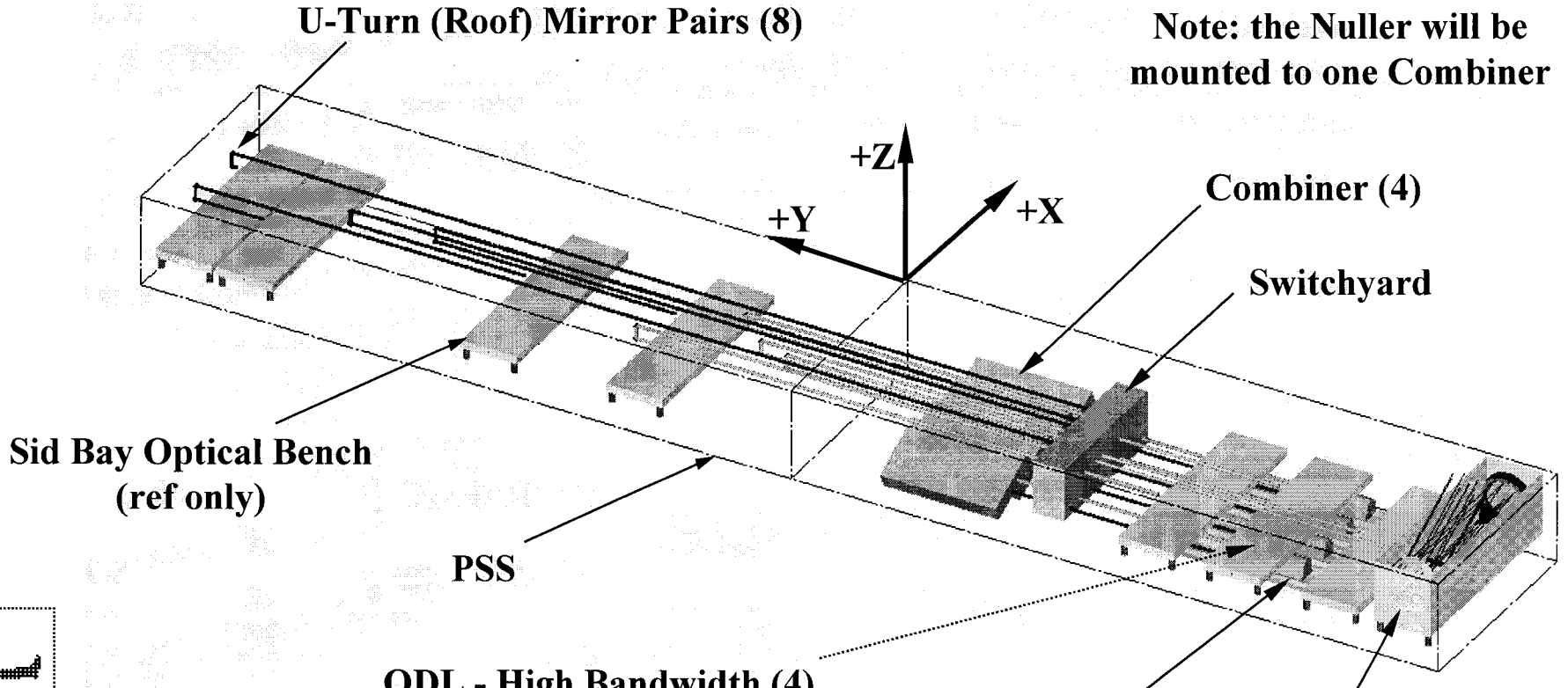




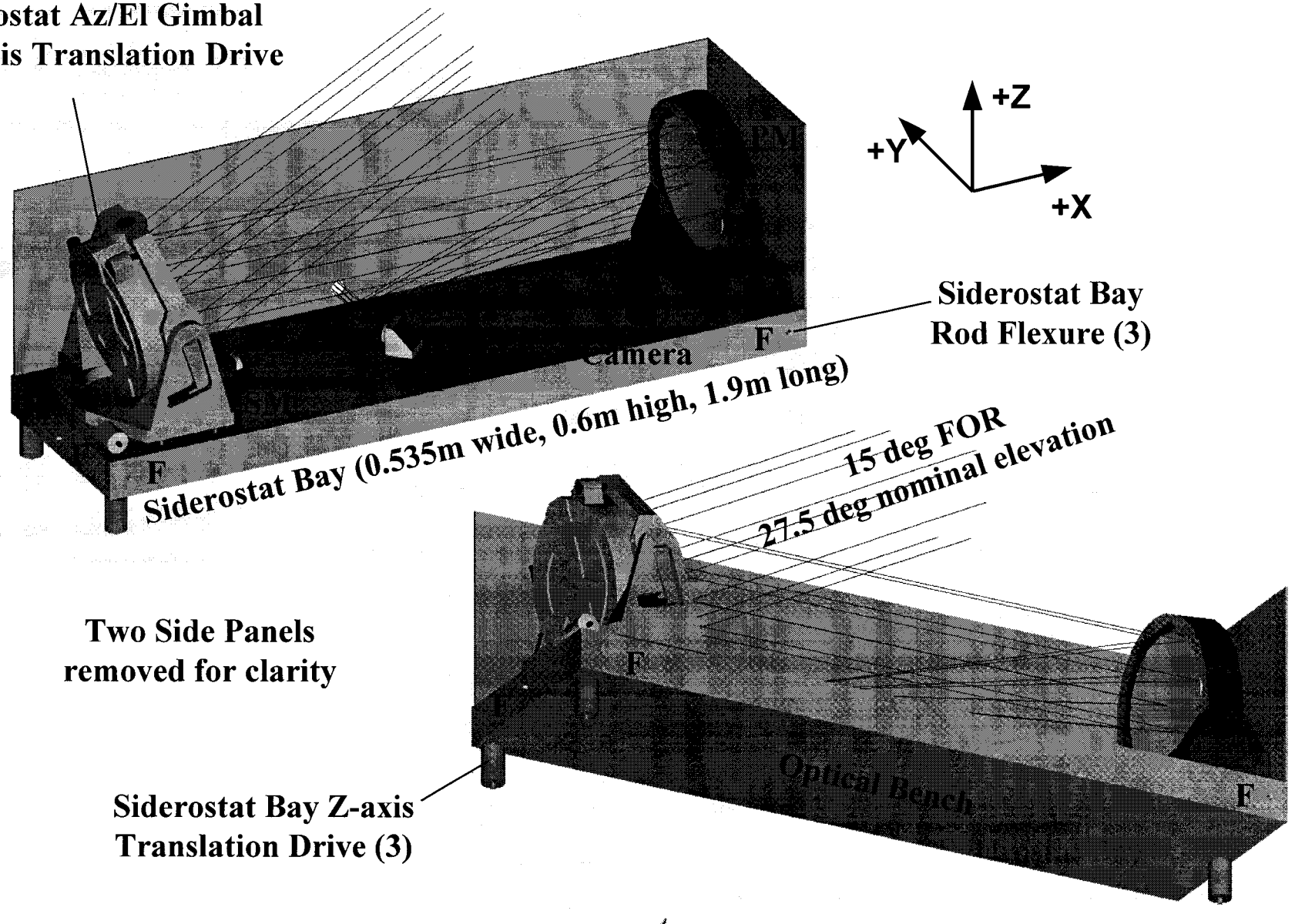
(Optical Delay Lines)

1. All beams exit Switchyard in -Y direction.
2. Enter ODLs, correcting baseline OPDs.
3. Exit ODLs in +Y direction.
4. Pass through Switchyard unvignetted.
5. Enter Combiner.

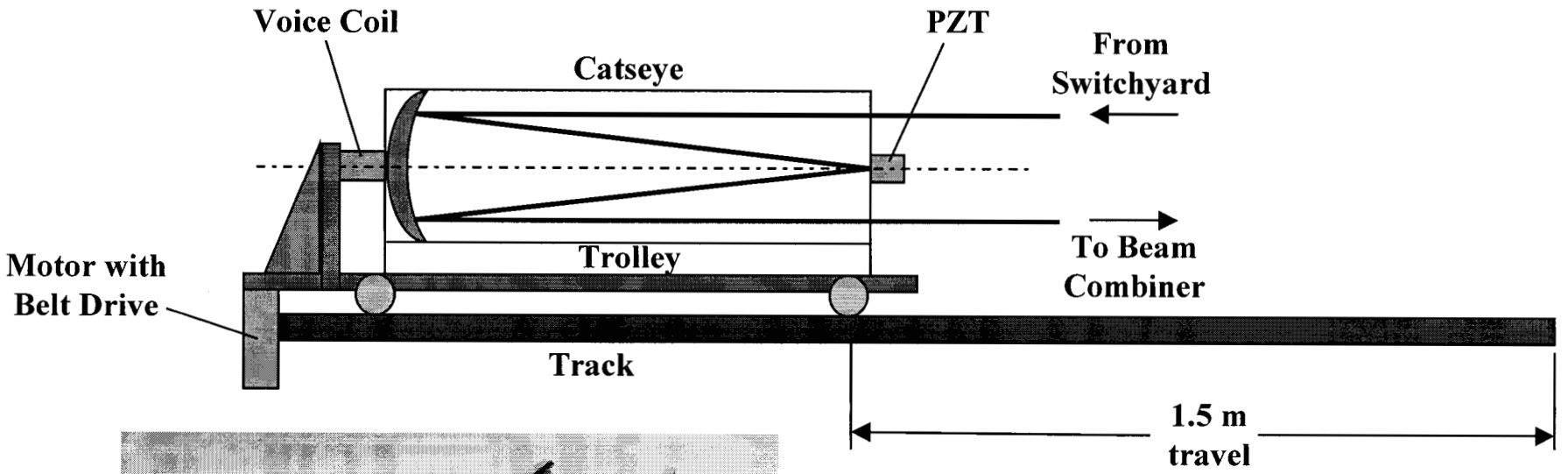
Instrument Layout

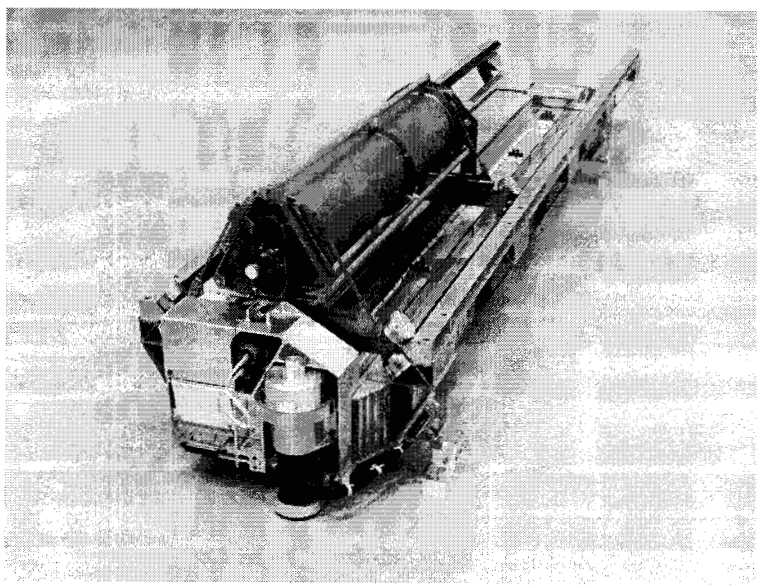


Siderostat Bay Configuration



Optical Delay Line (ODL)

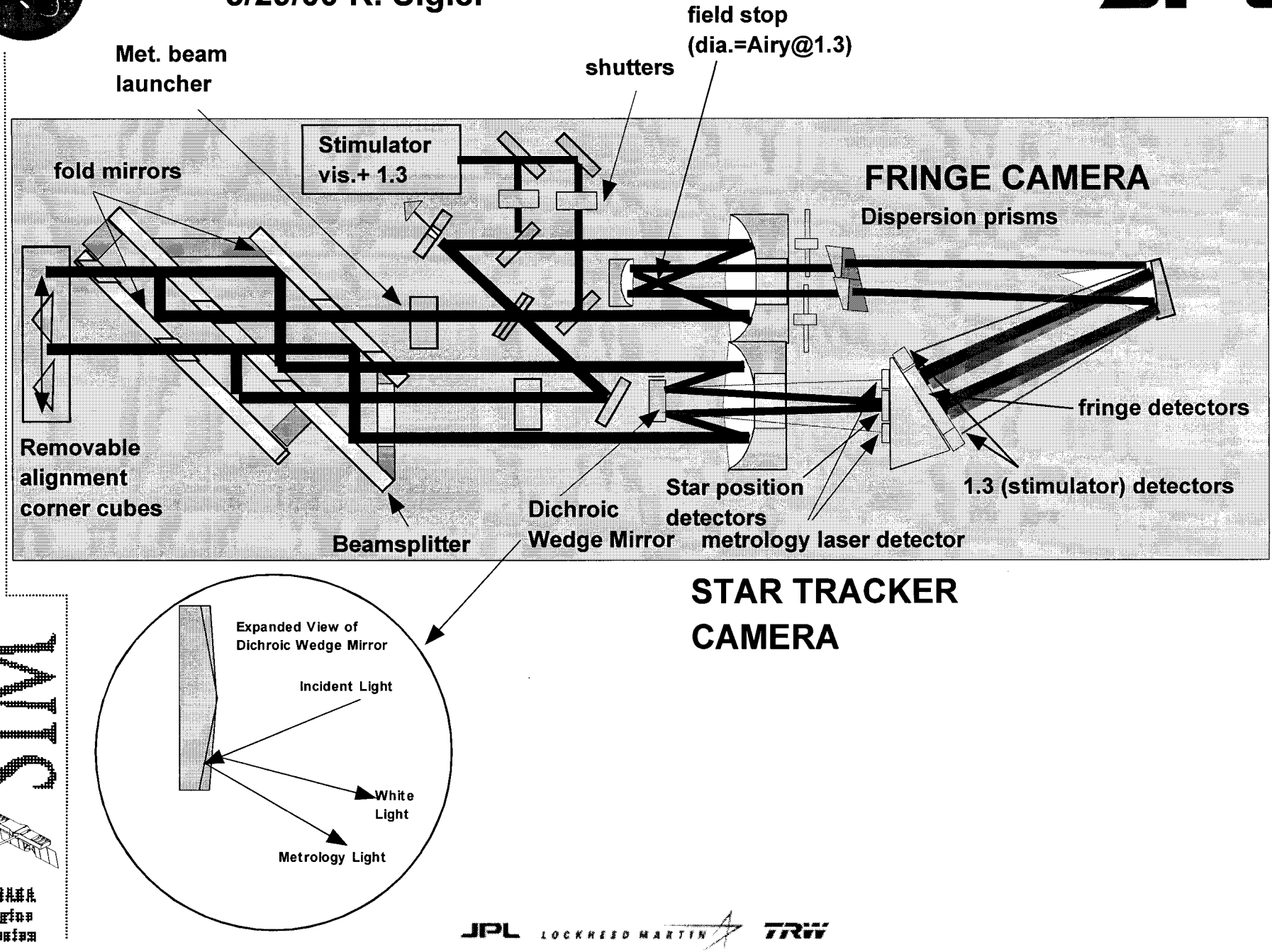




Astrometric Beam Combiner

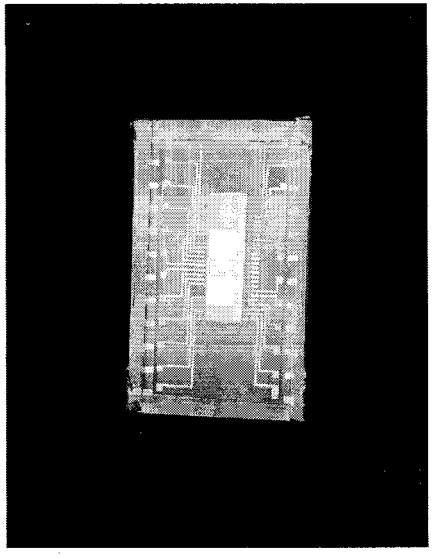
- **ABC Functions**
  - **interferes light from two arms of the interferometer**
  - **provide feedback from the star tracker for pointing control**
  - **measure dispersed white light fringes to determine starlight pathlength differences**
  - **launch point for internal metrology including a common fiducial**
  - **provide internal calibration and alignment (stimulator) including diffraction effects, alignment of starlight path to cameras, and alignment knowledge between the metrology and starlight paths**

ASTROMETRIC BEAM COMBINER vers. 2.2
3/29/00 R. Sigler



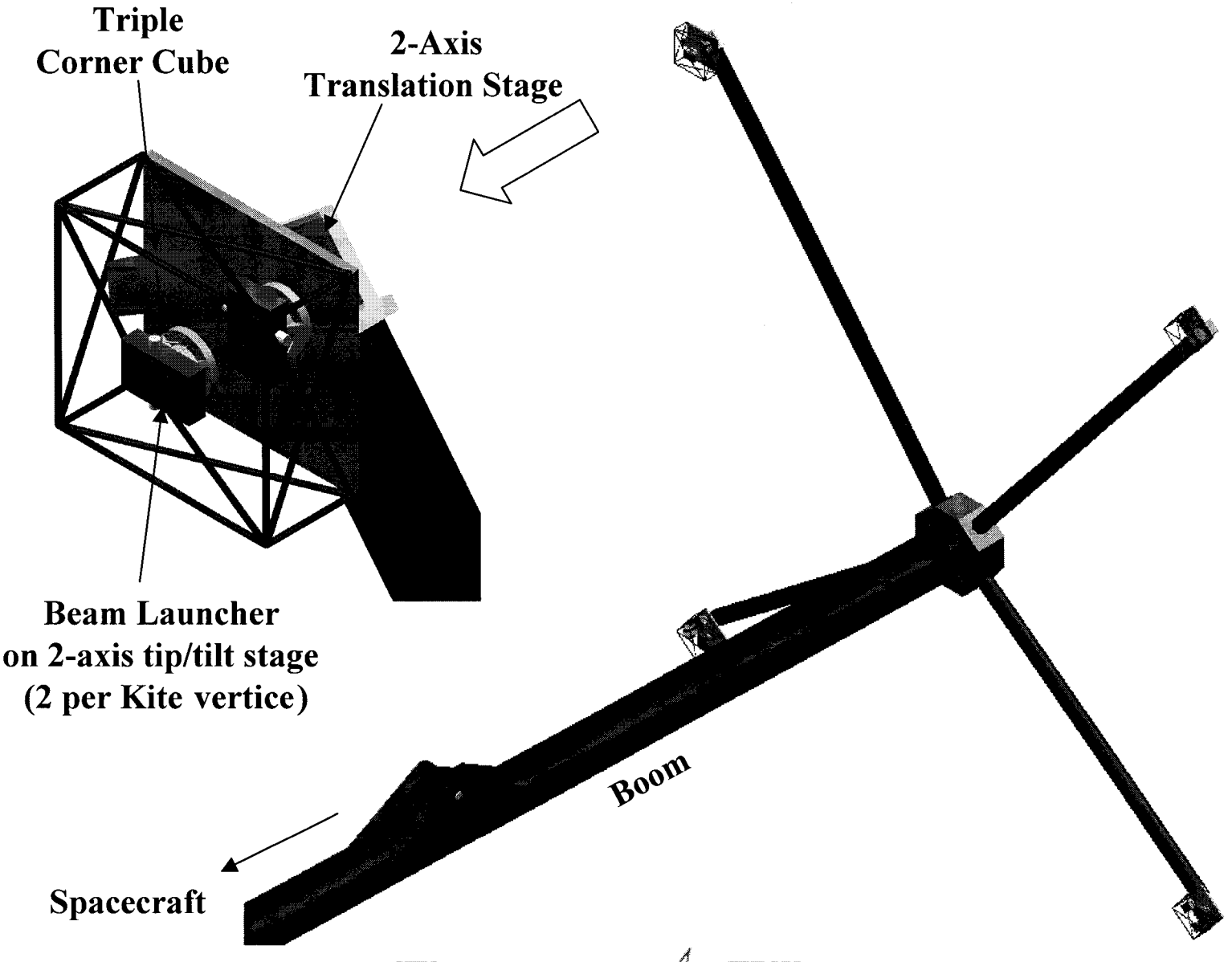
Detectors and Cameras

- **EEV-39 CCD Detector Characteristics**
  - **commercial device**
  - **80 x 80 pixels**
  - **4 quadrants**
  - **1 kHz frame rate**
  - **QE - 0.7**
  - **3 e- readnoise at 50kpix/sec**
  - **region of interest capability**



- **Separate detectors for angle and fringe tracker**
  - **allows different PSF sizes and clocking rates**
- **Fringe tracking detector**
  - **80 channel spectrometer for acquisition and measurement of science fringes**
  - **on-chip binning to suppress read noise on dim stars**

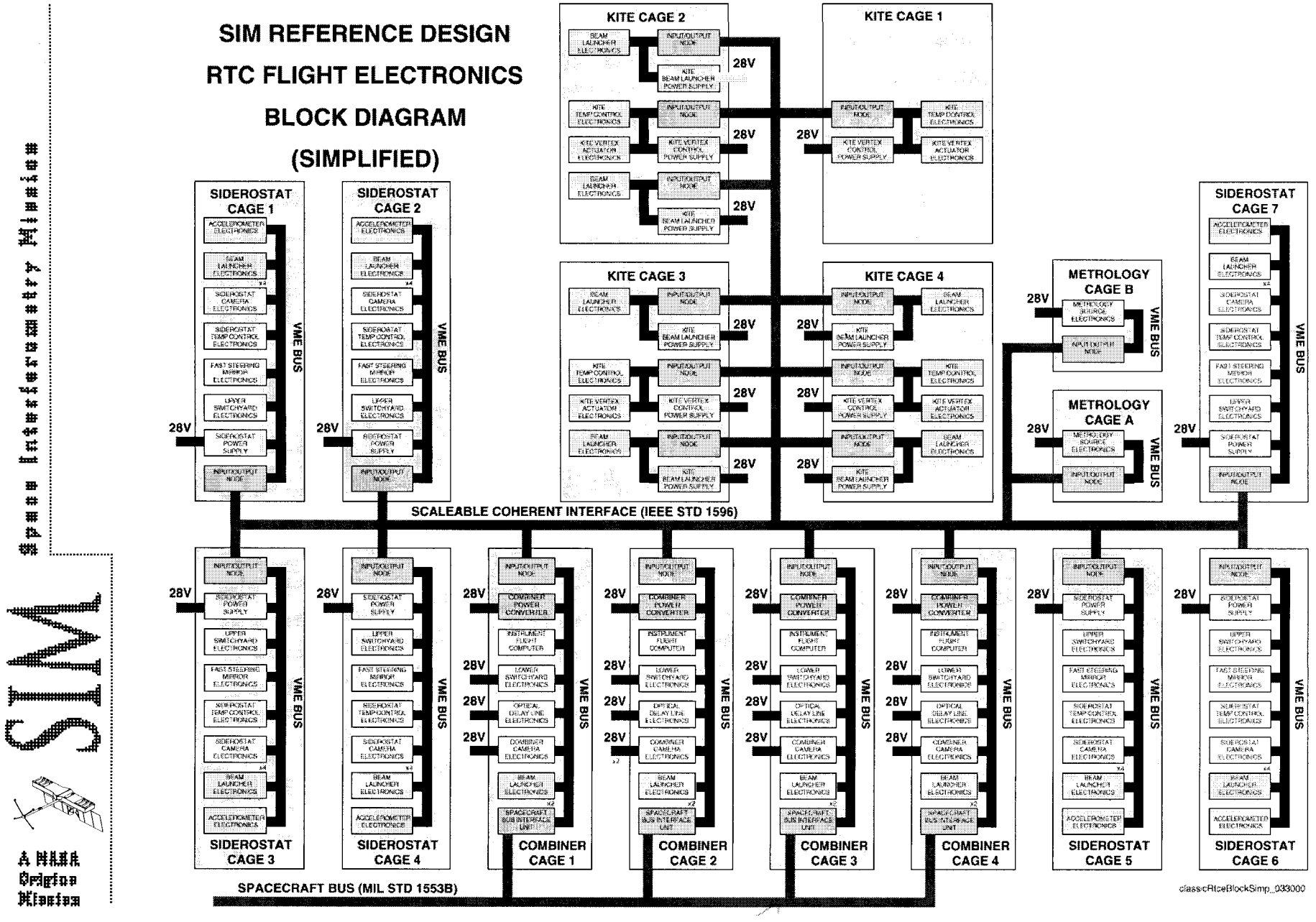
Metrology Kite & Boom



Real-Time Control Subsystem Design

- **Interferometer Electronics and Computers**
  - Instrument Flight Computers (4 @ 500 MIPS ea)
    - Two x2000 PPC750s per IFC
  - Shared-Memory Interconnect
  - Spacecraft bus interface
  - Interconnect I/O Nodes (25)
  - Electronics Cages for Kite (4), Sid (7), Met (1), Combiner (4)
- **Control Algorithms and Testbeds**
  - Interferometer Real Time Control Algorithms
  - Control Analysis Testbed
- **Interferometer Flight Software and Testbeds**
  - Software Simulation Testbed
  - SIM Flight System Testbed
- **RTC Integration Support Equipment H/W, S/W, & Test**

SIM RTC Electronics Block Diagram

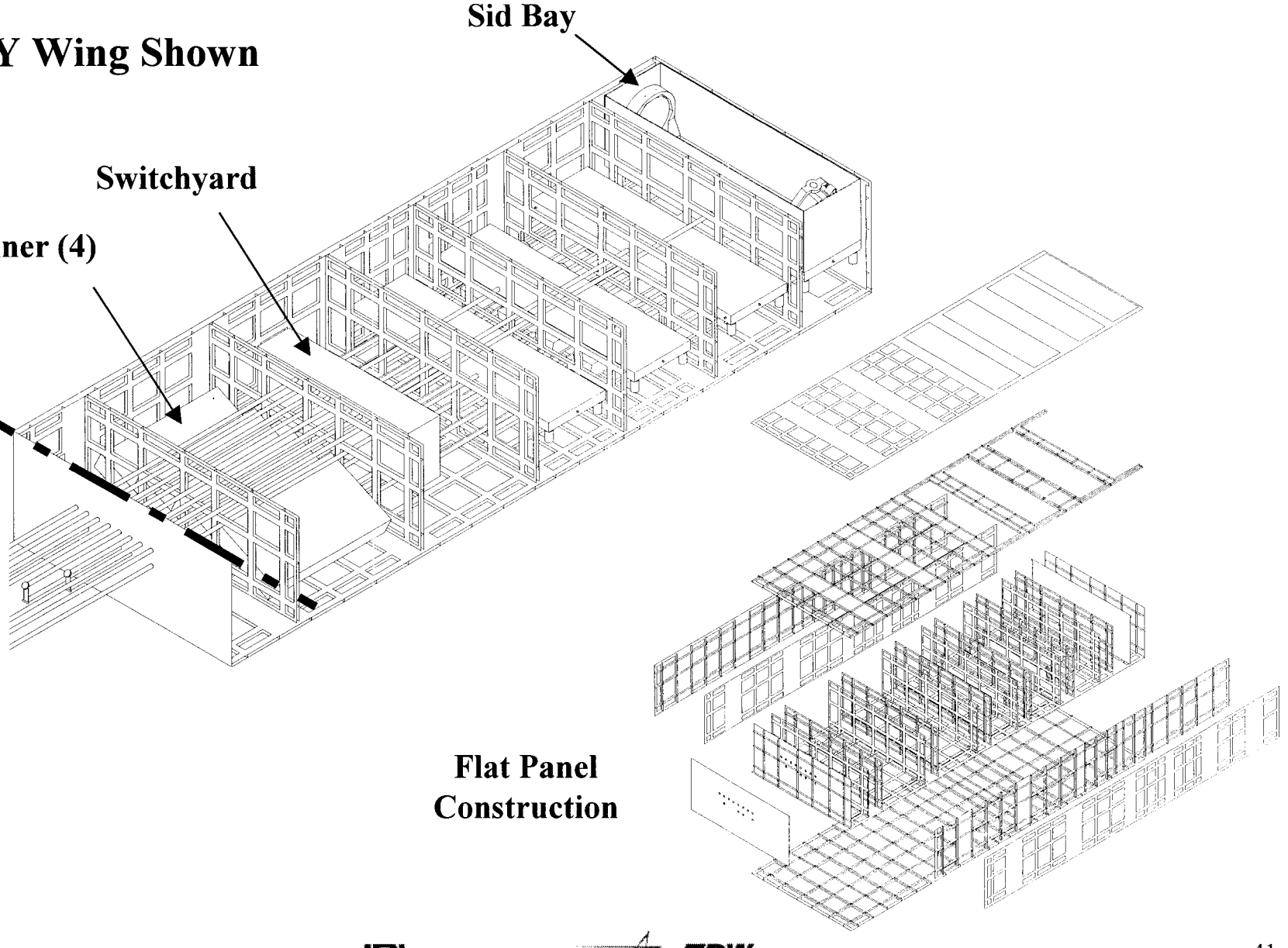


Interferometer Software Implementation

- Software Functionality
  - provides for autonomous sequencing for science observations
  - provides for instrument diagnostics functions
  - provides functionality and servo control for interferometers
  - provides data reduction and compression for downloads
- Software Implementation
  - centralized architecture with exceptions (e.g metrology pointing
  - four CPUs all running same software
  - highly synchronous with hardware
  - VME based
  - written in C++ (w/ possibility of Lisp for sequencer)
- Fault Protection
  - will handle some instrument anomaly condition (e.g. can't see star)
  - for high-level faults will call home
- Critical Design Issues
  - processor throughput
  - bus bandwidth
  - fault protection design

Precision Support Structure Construction

-Y Wing Shown



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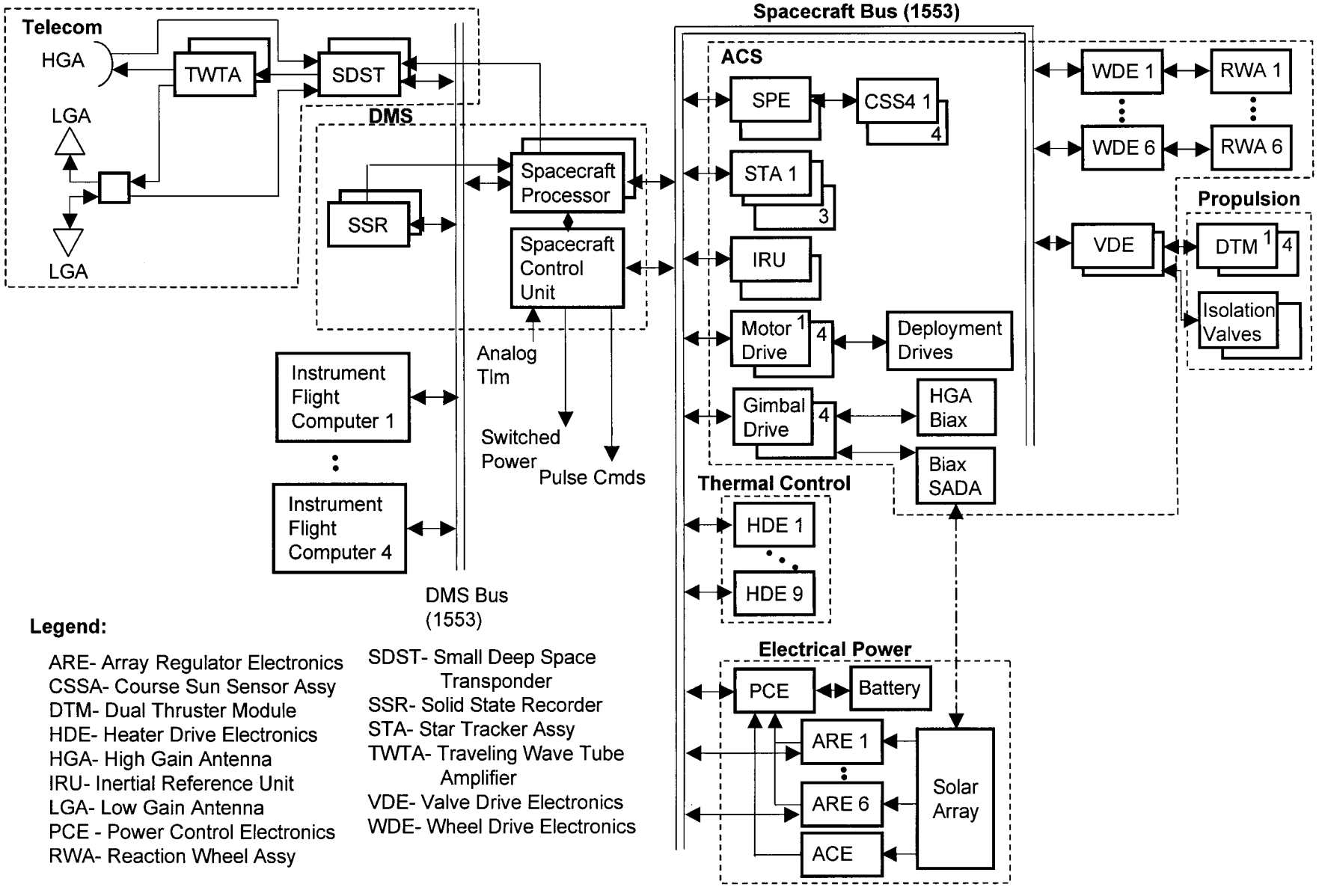
Spacecraft Subsystem Avionics

- All S/C avionics has heritage from flight programs; planned as build-to-print for SIM
  - ACS, Electrical Power, Thermal from EOS
  - DMS from SBIRS-low
  - Telecom from EOS, DS-1
- Instrument interfaces
  - Data interface with Instrument Flight Computers (4) via 1553
  - Switched primary power (36 "wall switches)
  - Survival heaters
- X band telecom fully compatible with DSN

S/C Subsystem Avionics Block Diagram



Legend:

ARE- Array Regulator Electronics
CSSA- Course Sun Sensor Assy
DTM- Dual Thruster Module
HDE- Heater Drive Electronics
HGA- High Gain Antenna
IRU- Inertial Reference Unit
LGA- Low Gain Antenna
PCE - Power Control Electronics
RWA- Reaction Wheel Assy
SDST- Small Deep Space Transponder
SSR- Solid State Recorder
STA- Star Tracker Assy
TWTA- Traveling Wave Tube Amplifier
VDE- Valve Drive Electronics
WDE- Wheel Drive Electronics

Spacecraft Flight Software

- Instrument interfaces
  - Attitude and rate data
  - Pointing requests from instrument
  - Solid state recorder and link management
  - Survival thermal control
  - Coordinated attitude, solar array, HGA slews
  - Data transmission to Ground
- CCSDS capabilities included

JPL

Space Interferometry Mission

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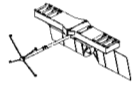
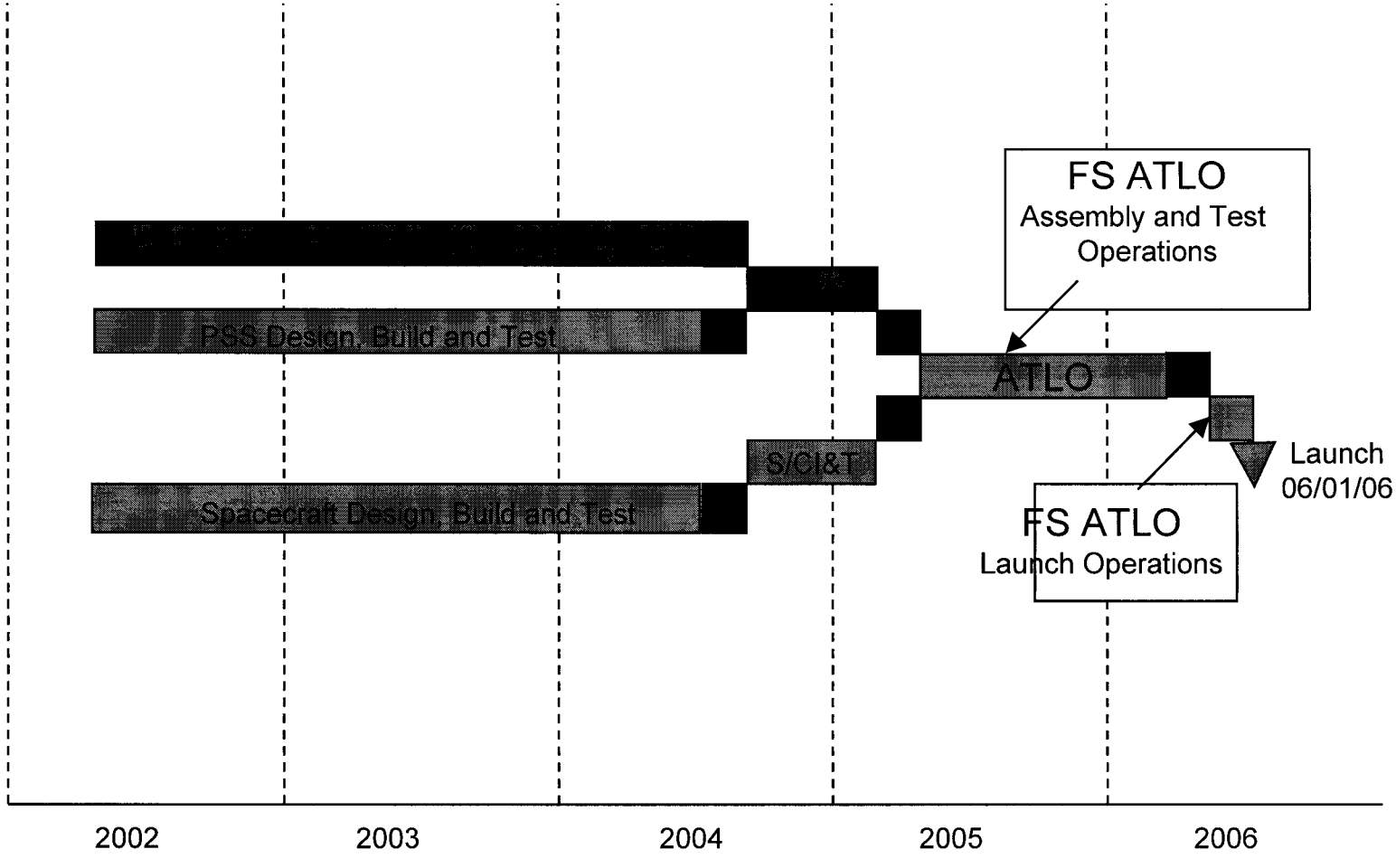


A NASA Origins Mission

SIM Flight System Integration and Test

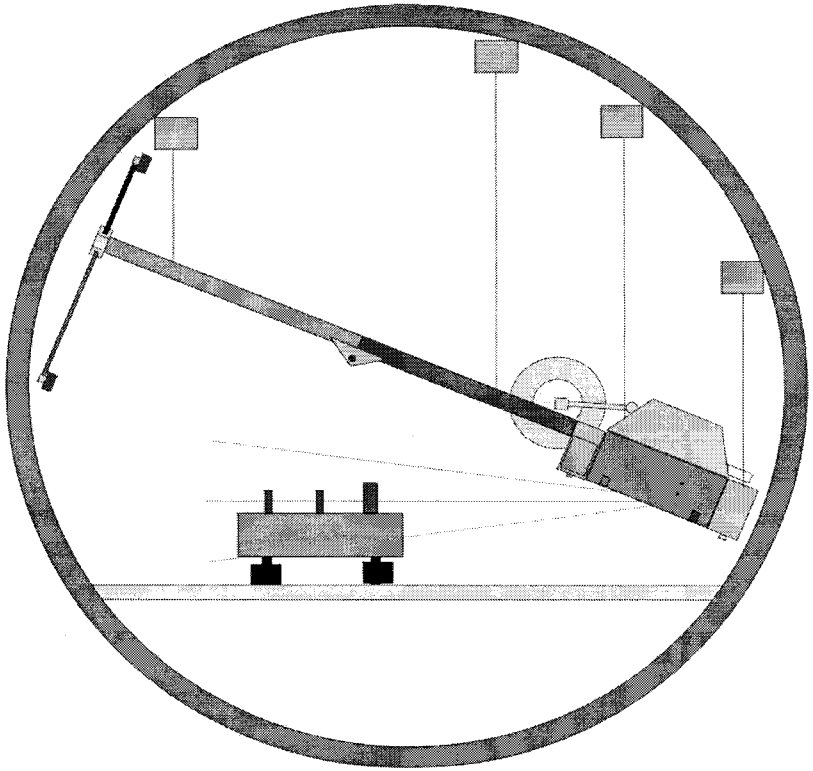
Flight System Development Flow

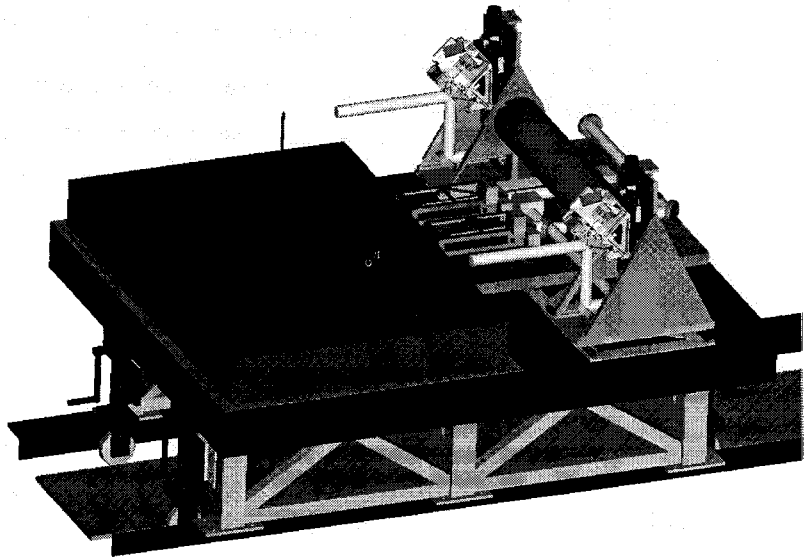


SIM Performance Testing

- Two types of system level performance tests
  - Functional (nanometer control) test
    - test functionality/dynamics&control
    - tests the ability to acquire and track stellar fringes on dim targets
  - Performance (picometer) vacuum test
    - tests the ability to measure the fringe position and metrology at the required levels
    - tests measurement accuracy
    - single baseline test only

Picometer Performance Test





Prototype Picometer Pseudostar

Test Planned for LM Delta TV Chamber (11 m x 24 m)

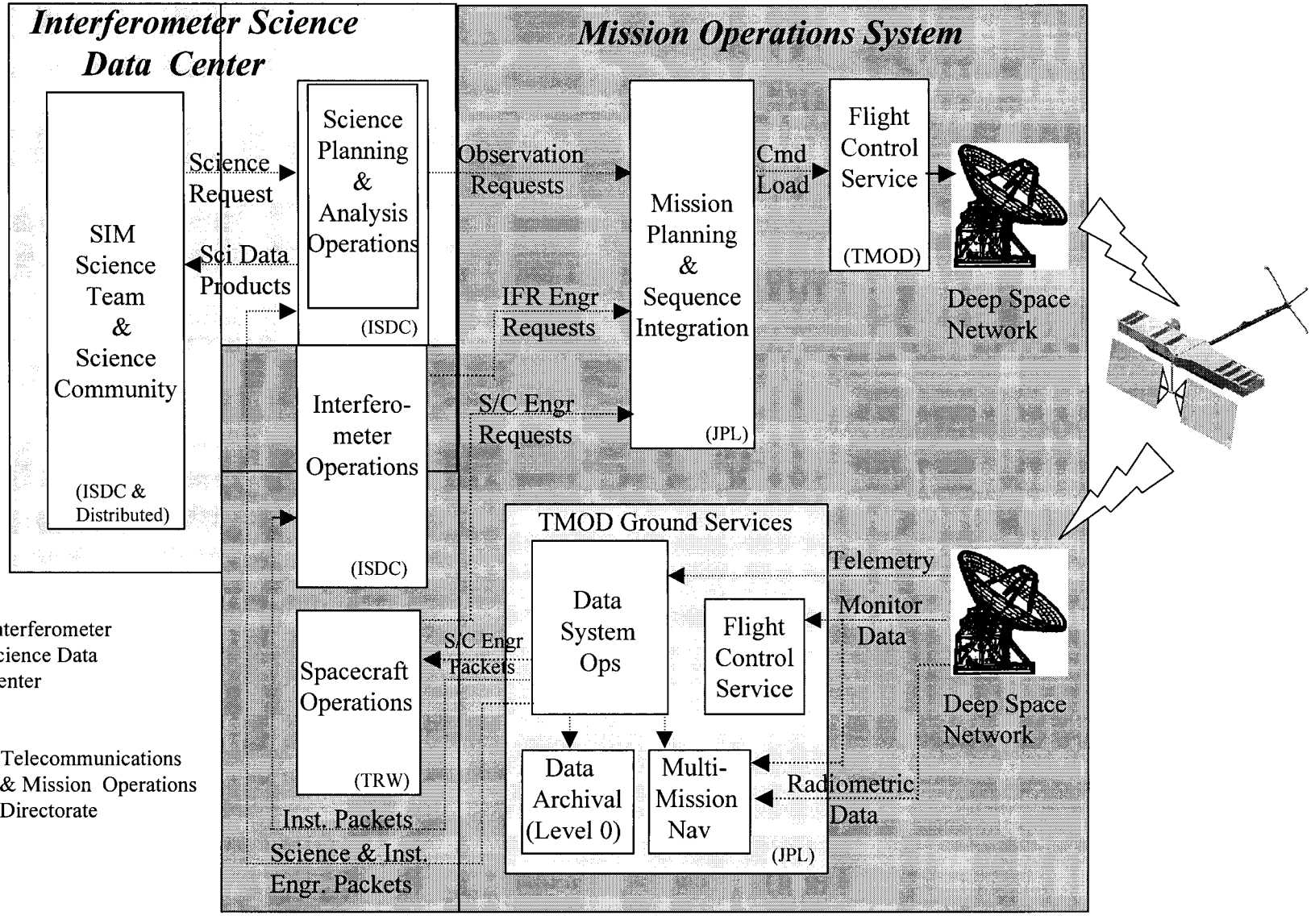
Constraints & Margins - Mass & Power

- SIM Mass (CBE) = ~ 3200 kg
- Launch Vehicle Capability = 5307 kg

- SIM Power (CBE) = ~ 3000 W
- Solar Array Output = 4000W

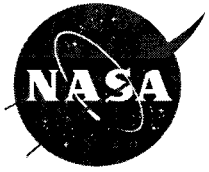
Mission System

Flight Operations Data Flow



ISDC - Interferometer Science Data Center

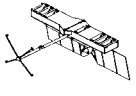
TMOD - Telecommunications & Mission Operations Directorate



JPL

Space Interferometry Mission

SIM



A NASA Origins Mission

SIM Tall Tentpoles

JPL LOCKHEED MARTIN TRW

SIM Interferometer Tall Tentpoles - Nanometer Control

- SIM must have the ability to acquire and measure white light fringes in the presence of multiple disturbance sources
  - ACS drifts
  - RWA jitter
  - Microdynamic events
  - Self induced disturbances (metrology dither, delay line motion)
- Pointing on dim targets
  - less than 30 mas pointing error on guide stars
  - angle feed forward information to science star to produce less than 30 mas pointing error
- Fringe stability on dim targets
  - less than 10 nm OPD jitter on guide stars
  - pathlength feed forward on science star with less than 10 nm OPD jitter

SIM Interferometer Tall Tentpole Thermal Design and Control

- Milli-kelvin stability of starlight optics and optical systems
  - errors arise from subaperture metrology system
  - temperature change and spatial gradients are more important than absolute temperature control
- Milli-kelvin control of metrology beam launchers
  - errors due to OPD changes in launcher optics
  - beam launchers will use an athermalized design
- Sub-kelvin control of PSS wing and metrology boom
  - ~10-100 um mechanical stability of wing and boom
- Traditional thermal issues
  - heat contamination between components
  - methods of heat rejection

SIM Tall Tentpole - System Complexity

- SIM is a complex instrument
  - many actuators
  - many sensors
  - lots of high bandwidth control loops
  - high precision components
  - 5 year lifetime

- Need to demonstrate ability to design, build, and test systems of SIM's complexity
  - How to divide the design job ?
  - How to monitor and manage fabrication ?
  - How to test for system function and performance ?
  - How to maintain performance over mission life ?

Summary

- SIM will increase Astrometric performance nearly two orders of magnitude over current capability
- A technology program suite of testbeds and models
  - Tied to Flight System development
  - Reduce risk
  - Validate that SIM meets on-orbit performance requirements
- SIM is developing state-of-the-art electro-optical devices within a complex instrument configuration
  - Picometer-class metering gauges
  - Precision optics and structures
  - Millikelvin thermal control
- SIM has numerous System challenges ahead
  - Performance
  - Interfaces
  - Complex modeling activities
- Will produce great science results