THE SEARCH FOR ORIGINS

The Role of Integrated Modeling in the Design and Verification of the James Webb Space Telescope

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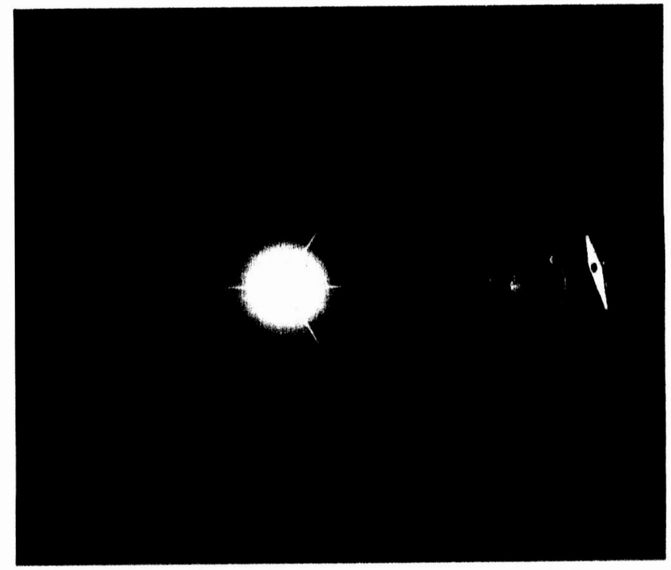
Presentation Outline

- **JWST Mission Overview**
  - Science Objectives
  - Baseline Architecture
  - Key Requirements
  - Performance Budgets as Drivers for Modeling Activities
- **Integrated Modeling Methods and Results for Current Baseline**
  - IM Working Group
  - Thermal Distortion Analysis
  - Jitter Analysis
- **Model Validation and Optical Verification**
  - Discipline Model Validation
  - Role of Integrated Modeling in Optical Verification
- **Future Work and Summary**

JWST Mission-at-a-Glance

- Mission Objective
  - Detailed study of the birth and evolution of galaxies
  - Optimized for near infrared wavelength (0.6 –28 μm)
- Organization
  - Mission Lead: Goddard Space Flight Center
  - International collaboration with ESA & CSA
  - Prime Contractor: Northrop Grumman Space Technology
  - Instruments:
    - Near Infrared Camera (NIRCam) – Univ. of Arizona
    - Near Infrared Spectrometer (NIRSpec) – ESA
    - Mid-Infrared Instrument (MIRI) – JPL/ESA
    - Fine Guidance Sensor (FGS) – CSA



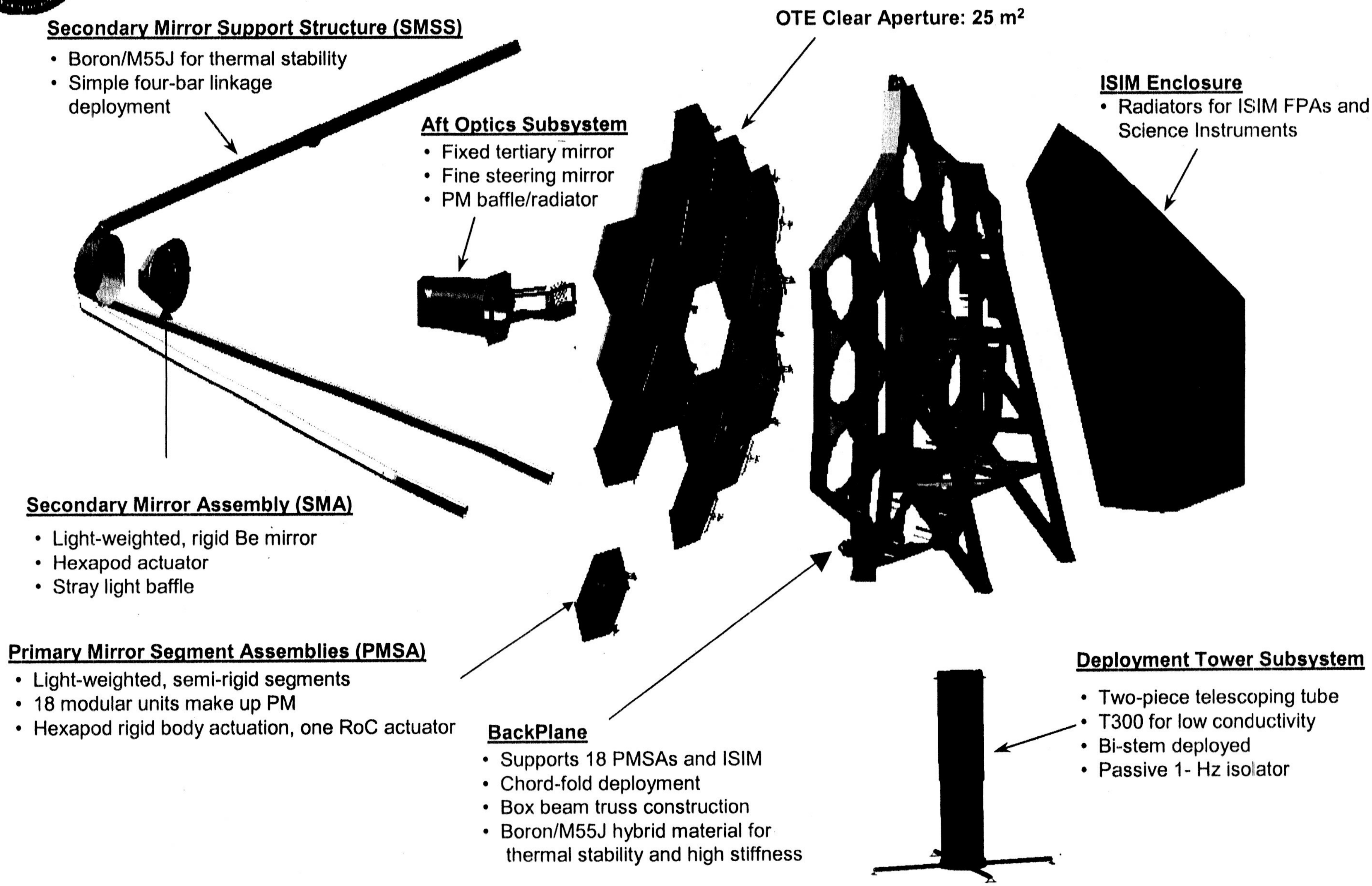
- Description
  - Approx. 6 m diameter deployable, active optics, primary mirror
  - Launched by Ariane 5 from Kourou, French Guiana, direct insertion to L2 orbit
  - Integrated Science Instrument Model (ISIM) consisting of 3 science instruments and a guider
- Website
  - www.JWST.nasa.gov

FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
Formulation Phase (A/B)							Implementation Phase (C/D)					
				Select Prime ▽	SRR ▽	NAR ▽	PDR ▽	CDR ▽		MOR ▽		Launch Timeframe ▼

Observatory Architecture

- Telescope and instruments are passively cooled to ~40K (dewar for detector cooling to 8K)
- Segmented (18 hex), 6.5 m diameter primary mirror
- Periodic control of optical alignment and figure (7-dof per primary mirror segment, 5-dof secondary mirror) using image-based wavefront sensing
- Passive, two-stage vibration isolation of reaction wheels
- Fine pointing performance (~7 mas) using two-axis steering mirror with fine guidance sensor instrument

OTE Architecture



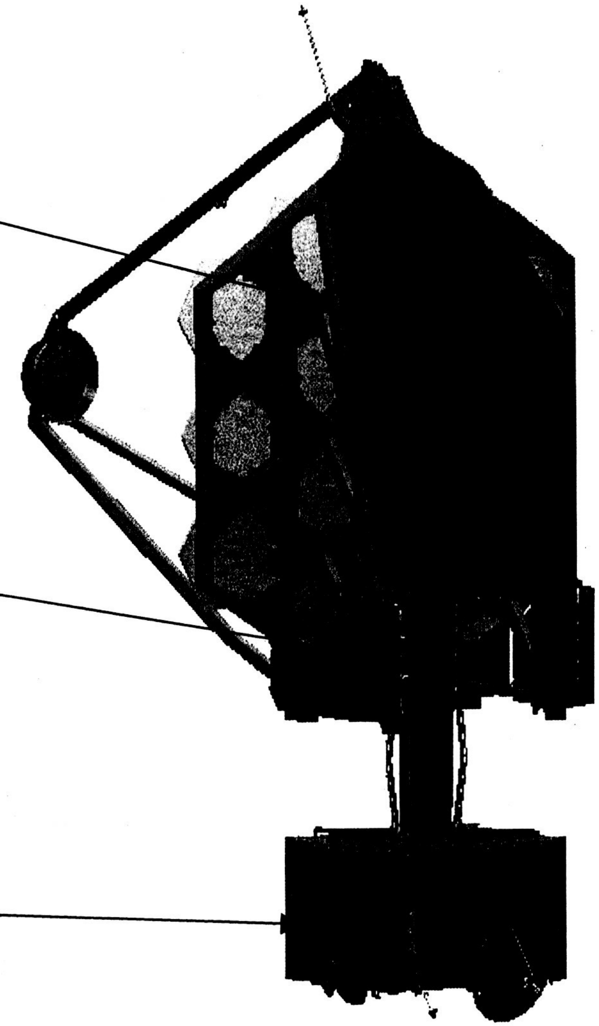
ISIM/Bus Architecture

Region 1
Science Instrument Optics Assemblies
- ***Near Infra-Red Camera (NIRCam)***
- ***Near Infra-Red Spectrometer (NIRSpec)***
- ***Mid Infra- Red Instrument (MIRI), & Dewar***
- ***Fine Guidance Sensor (FGS)***
- ***FGS Tunable Filter Instrument (FGS/TF)***

Radiators and support structure

Region 2 (approximately 290 K)
Focal Plane Electronics (FPE)
Instrument Control Electronics (ICE), MCE,DCE
Fine Steering Mirror (FSM) Differential Impedance Transducer (DIT)

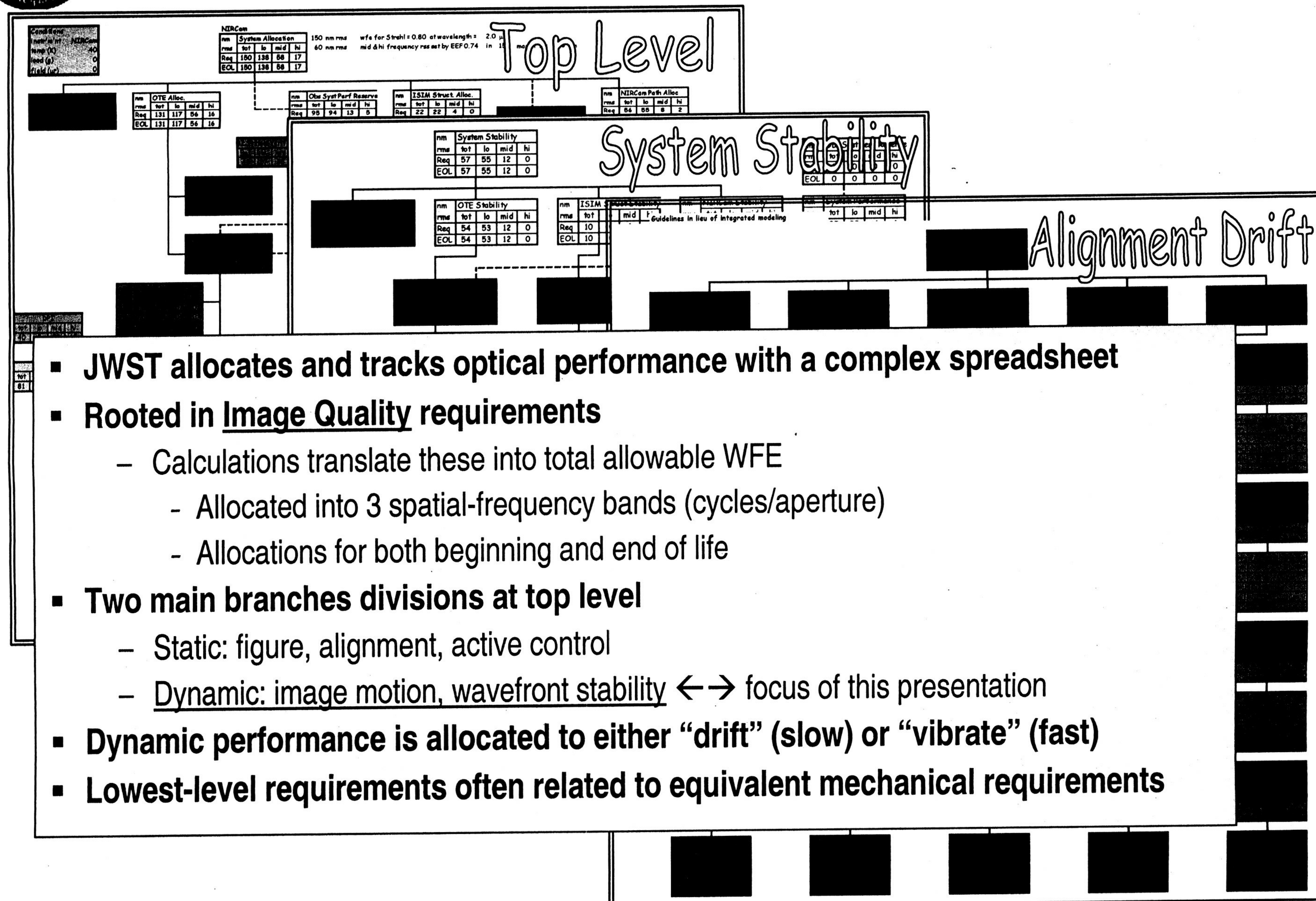
Region 3
ISIM Command & Data Handling (C&DH) Electronics
FGS C&DH Electronics
Avionics, Power, etc.



Requirements Driving the Integrated Modeling Activities

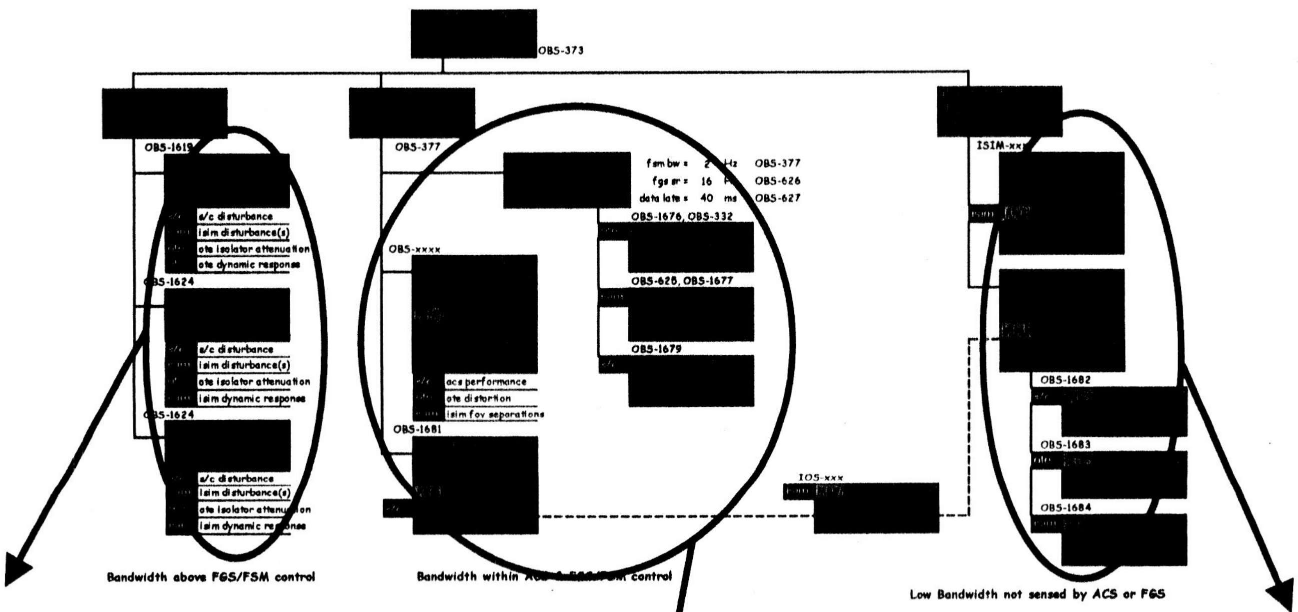
- Image Quality ←→ **focus of this presentation**
  - Strehl Ratio: ≥ 0.8, $\lambda = 2\ \mu m$ (caps total wavefront error at 150 nm rms)
  - Encircled Energy: 74% at R = 150 mas, $\lambda = 1\ \mu m$ (constrains mid-spatial frequency wavefront errors)
  - PSF Anisotropy: $\leq 5\%$ variation in orthogonal axes (constrains asymmetric wavefront errors)
  - EE must be stable over short (24 hours) and long (~30 days) periods
  - Similar requirements for MIRI, but at longer wavelengths
- **Sensitivity (SNR of 10 for faint sources, as functions of λ and $\Delta\lambda/\lambda$)**
  - Sets requirements on stray light, thermal emissions, detector noise
- **Precision Offset Pointing**
- **Field Distortion**
- **Moving Target Tracking**
- **Operational Efficiency**
- **Sky Coverage**

Wavefront Error Performance Budget



- JWST allocates and tracks optical performance with a complex spreadsheet
- Rooted in Image Quality requirements
  - Calculations translate these into total allowable WFE
    - Allocated into 3 spatial-frequency bands (cycles/aperture)
    - Allocations for both beginning and end of life
- Two main branches divisions at top level
  - Static: figure, alignment, active control
  - Dynamic: image motion, wavefront stability ←→ focus of this presentation
- Dynamic performance is allocated to either "drift" (slow) or "vibrate" (fast)
- Lowest-level requirements often related to equivalent mechanical requirements

Image Motion Performance Budget



Jitter Analysis

Analysis performed by Integrated Modeling

Frequency domain analysis of LOS jitter due to disturbances from reaction wheels.

Fine Guidance & Attitude Control Simulation

Analysis performed by ACS

High fidelity simulation of Fine Guidance & Attitude Control performance.

Thermal Induced Alignment Shift

Analysis performed by Thermal and Structural subsystems of ISIM, OTE, and SV

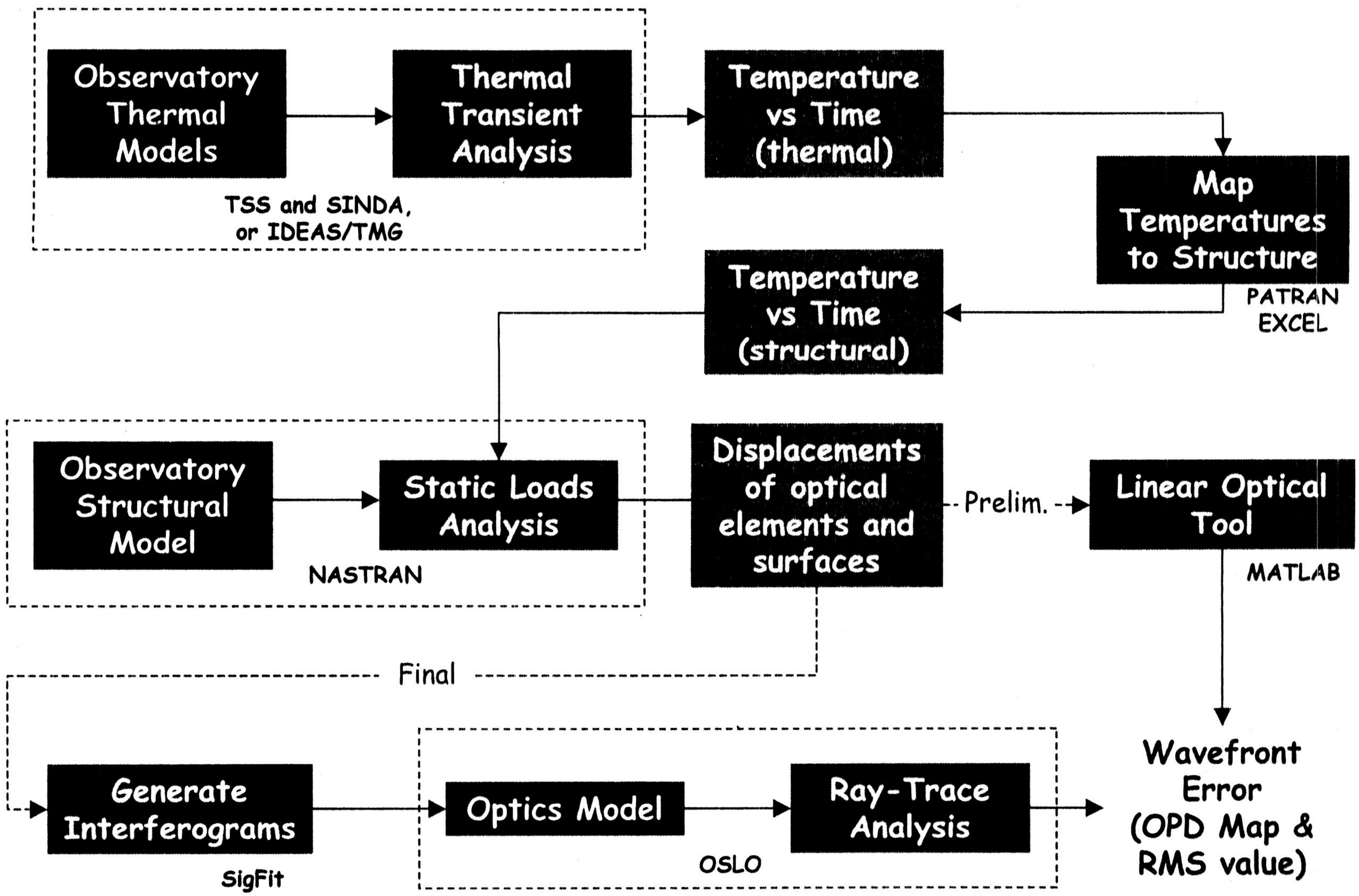
Thermal gradient stability analysis

Structural deformation due to thermal gradient

Contributions grouped left-to-right in descending order by bandwidth

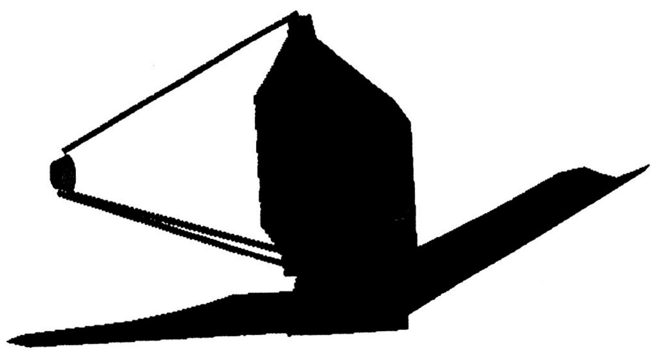
Integrated Modeling Methods and Results for Current Baseline

Structural-Thermal-Optical (STOP) Analysis

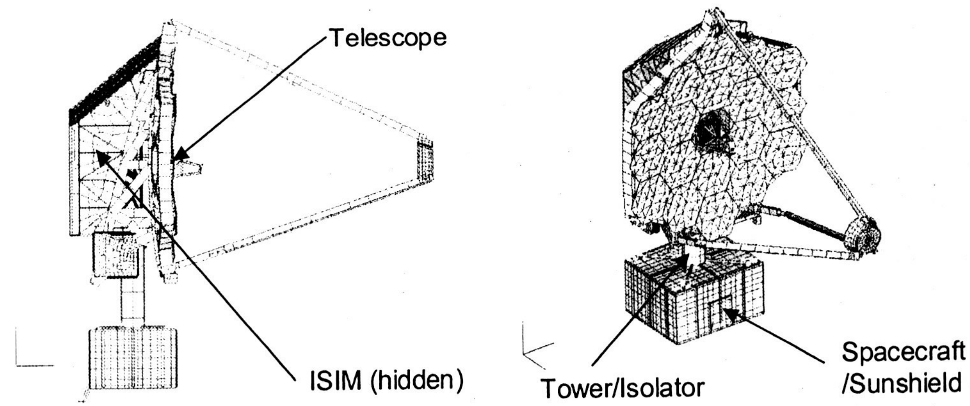


STOP Model Configuration

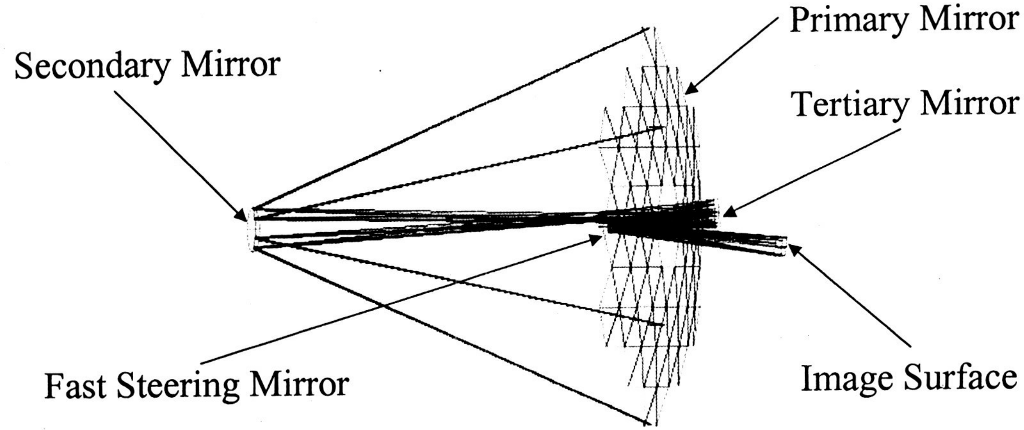
(a) Thermal Model



(b) Structural Model

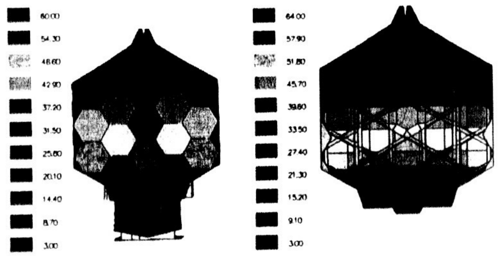


(c) Optical Model

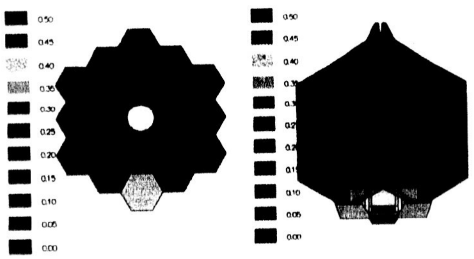


Baseline STOP Performance

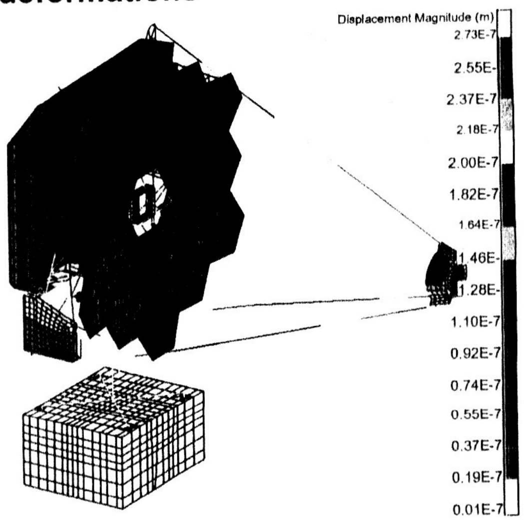
(a)Hot case temperatures



(b)Hot-to-cold temperature change

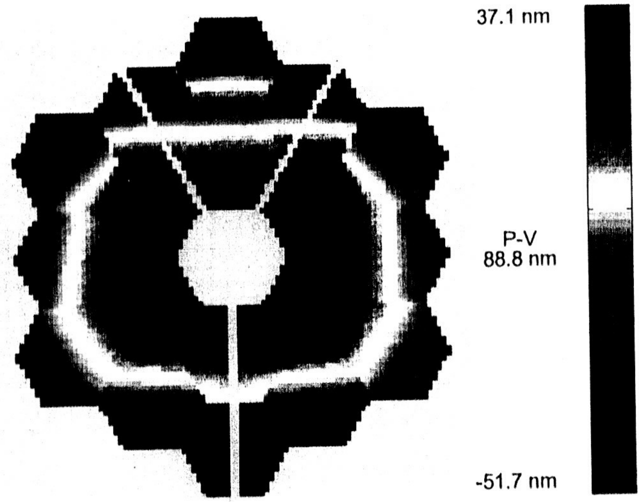


(c) Structural deformations



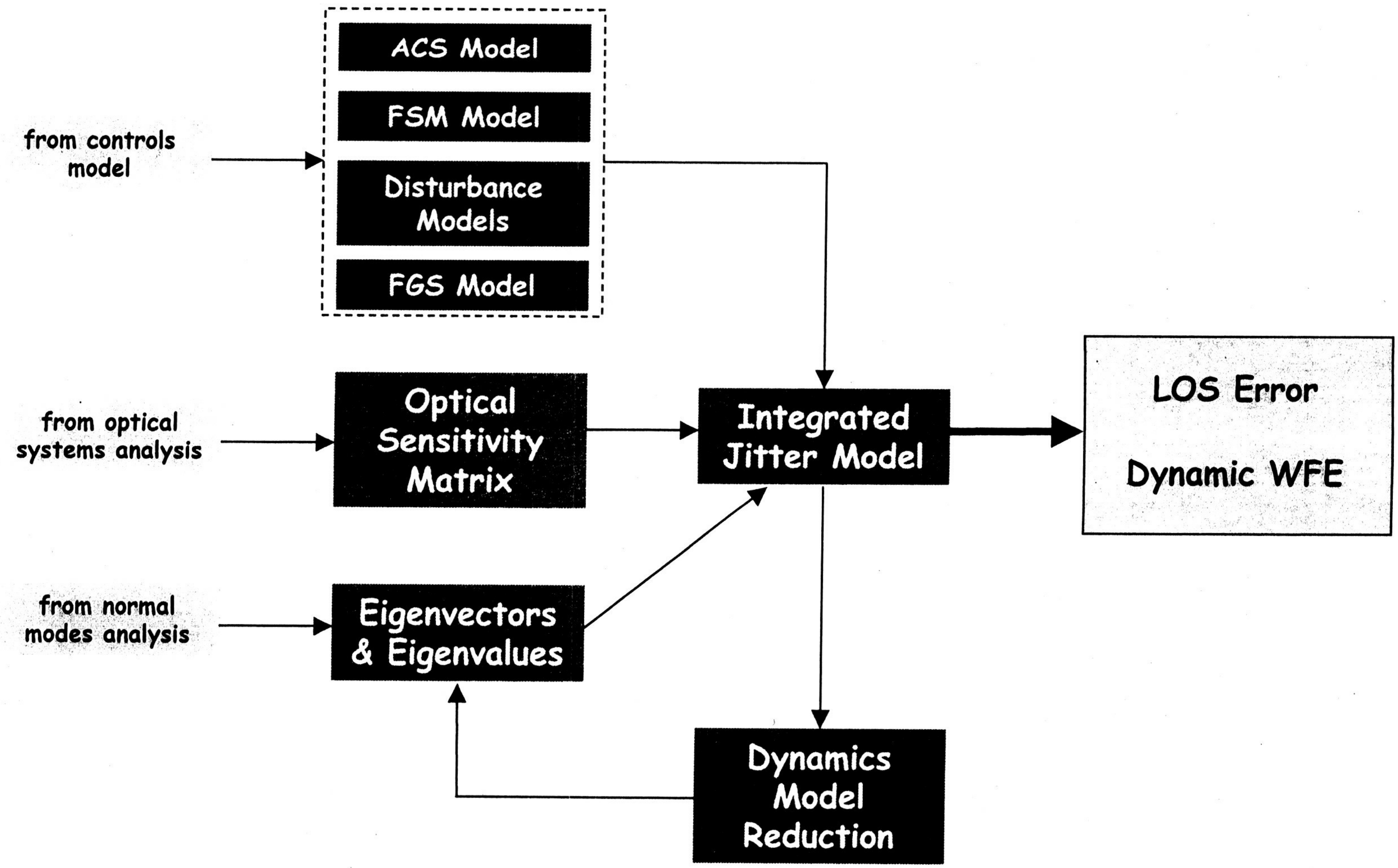
(d) OPD Map

Frequency Content:
<5 c.p.a. - 17.8 nm
5-35 c.p.a. - 6.0 nm
>35 c.p.a. - 2.0 nm



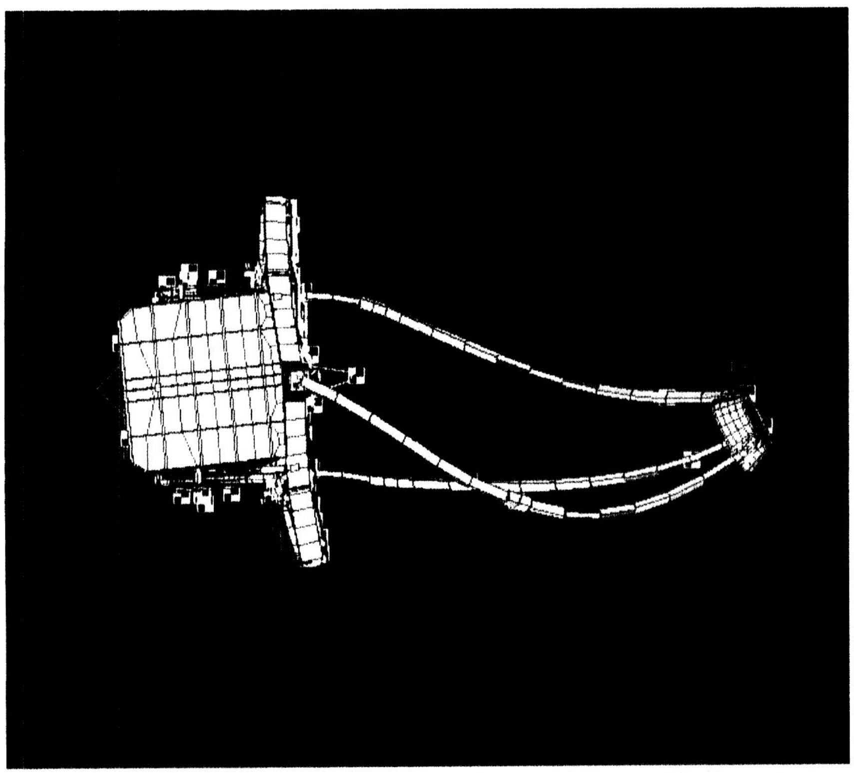
18.2 nm, RMS WFE

Image Motion/Jitter Analysis

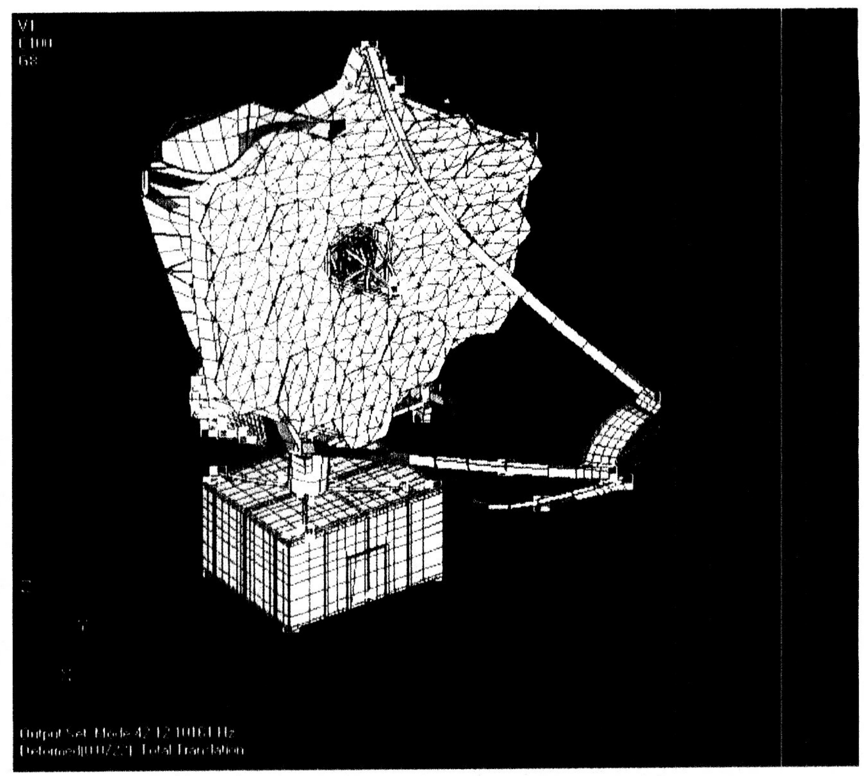


Jitter Analysis – some key mode shapes

Secondary Mirror Support Structure Bending Mode @ 8 Hz

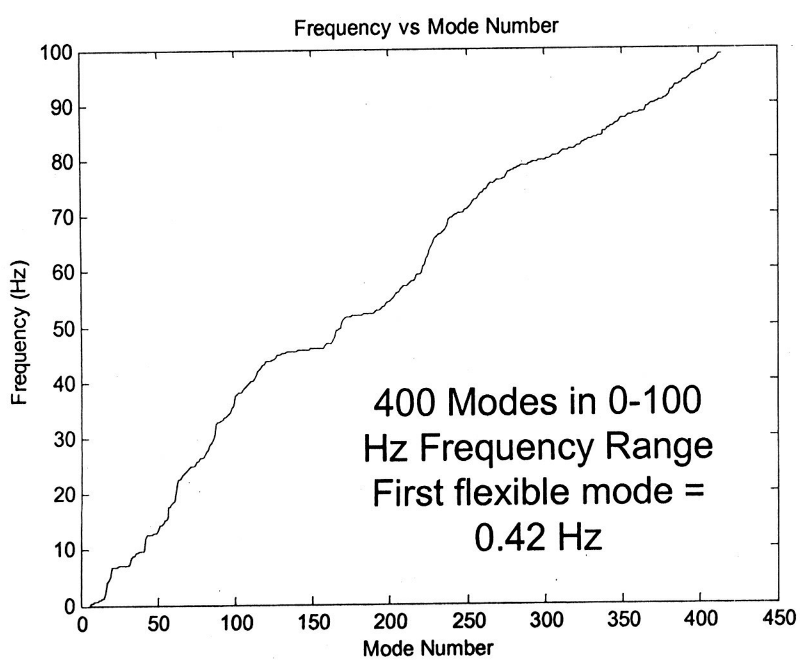


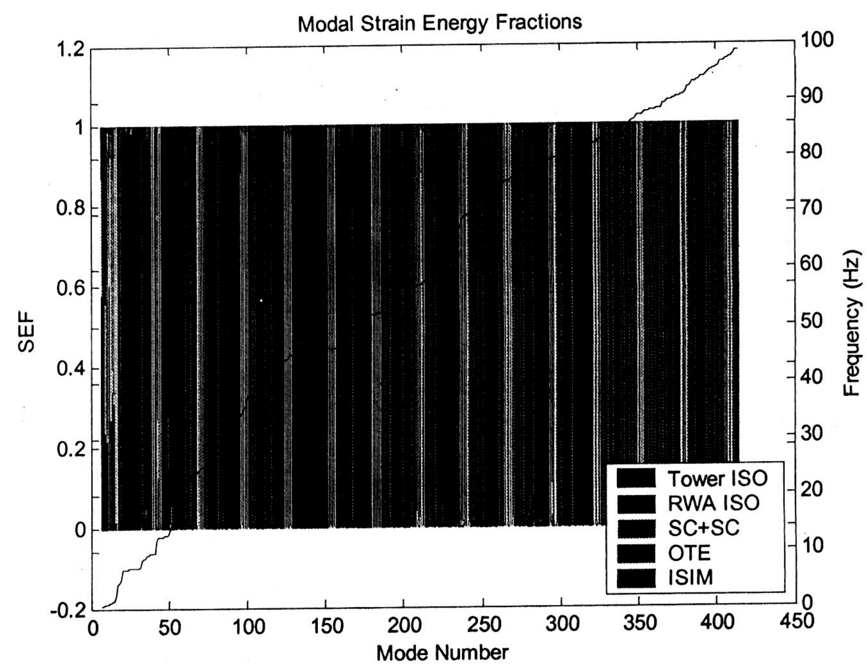
Backplane Twisting Mode @ 12 Hz



Jitter Analysis – modes and damping

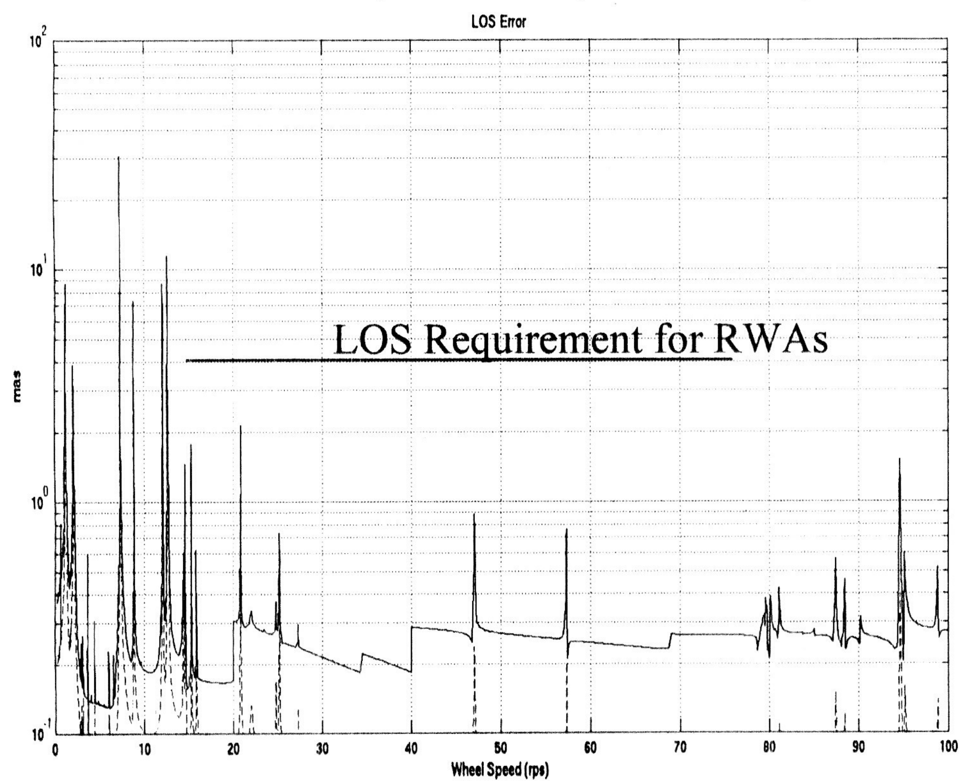
- **The structures discipline provides frequencies, mode shapes, and modal damping values for use in integrated modeling (IM) and attitude control system (ACS) studies:**
  - Mode shapes (mass normalized) are partitioned based on DOF corresponding to predefined reference points (optics, RWAs, etc).
  - Modal damping values are either:
    - Uniform
    - Variable (Based on group participation determined using modal strain energy fractions)

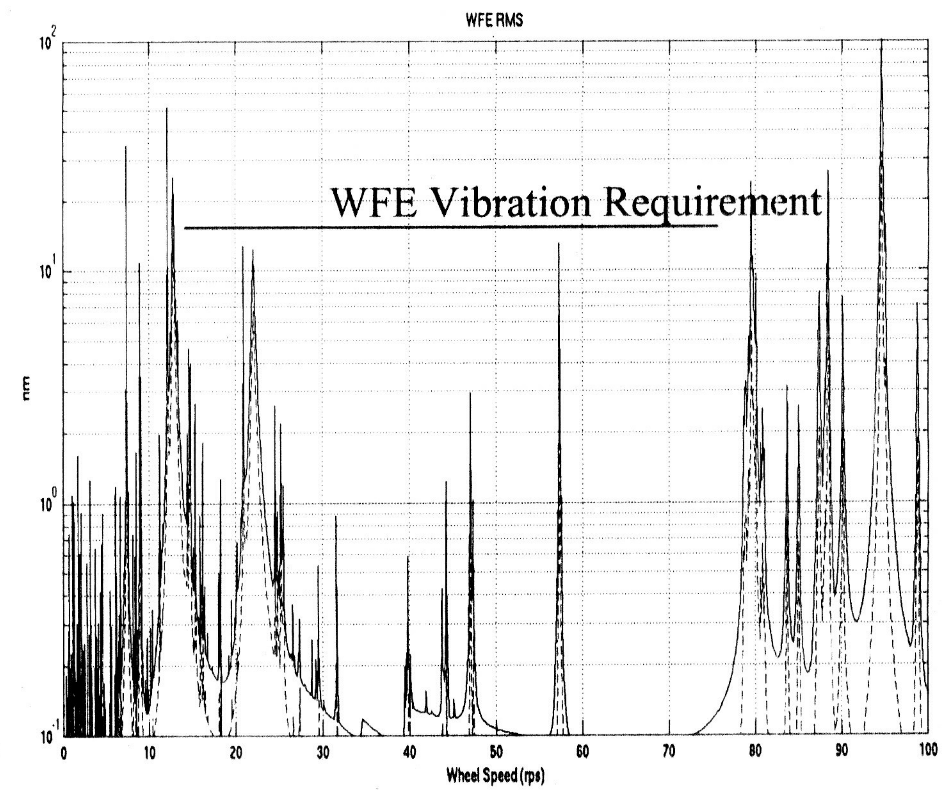




Jitter Analysis – baseline performance

- **Reaction Wheel Assemblies (RWAs) are largest jitter disturbance source:**
  - Harmonic disturbances
  - Excite spacecraft and telescope structural modes when the RWA spin speed or harmonics align with the lightly damped structural modes
  - Use Model Uncertainty Factors (MUFS) to adjust transfer functions and damping as functions of component/subsystem maturity

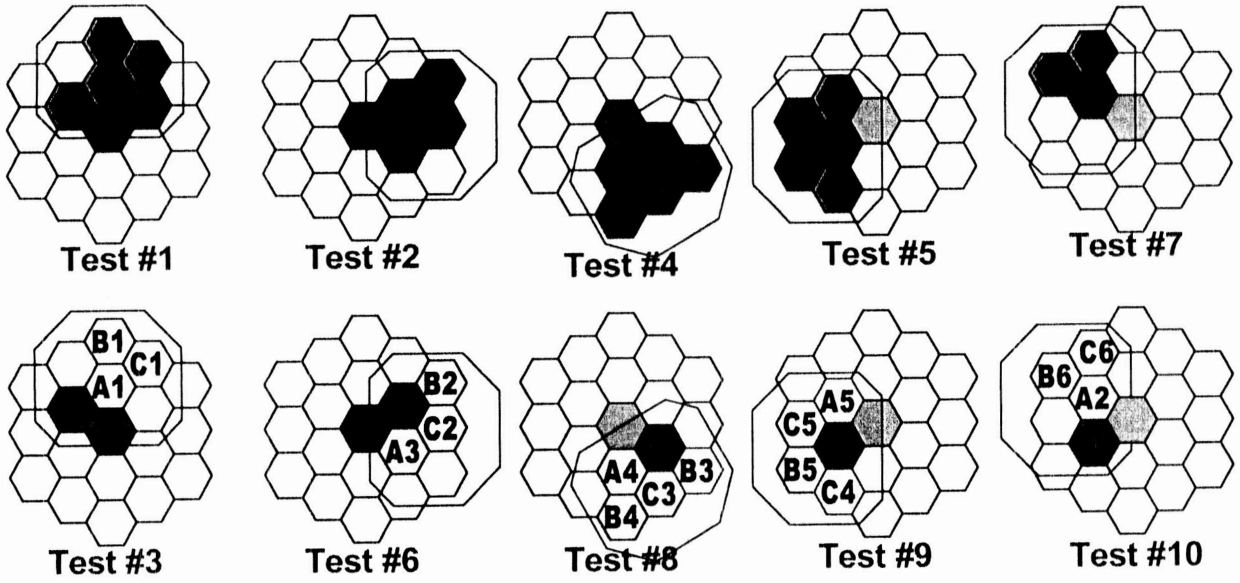




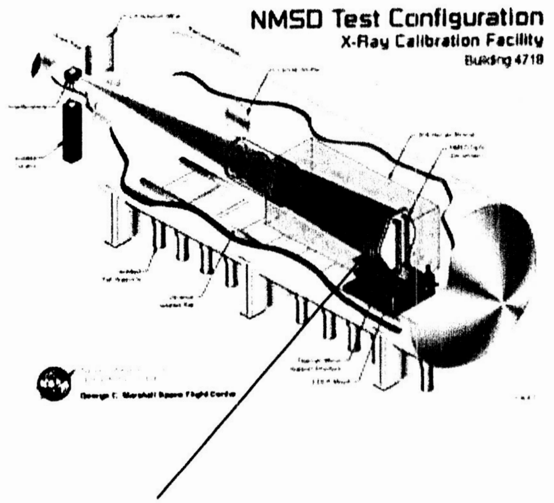
Model Validation and Optical Verification

Optical Model Validation: Component Level

- **e.g., PMSA measurements**
  - Tested at operational temperatures in XRCF
  - Measured pre- and post-coating
  - Measured in batches on surrogate backplane
  - Reference optics used to link tests together & ensure RoC matching
  - Mirrors measured at rotated orientations relative to gravity to back out 1-g effects



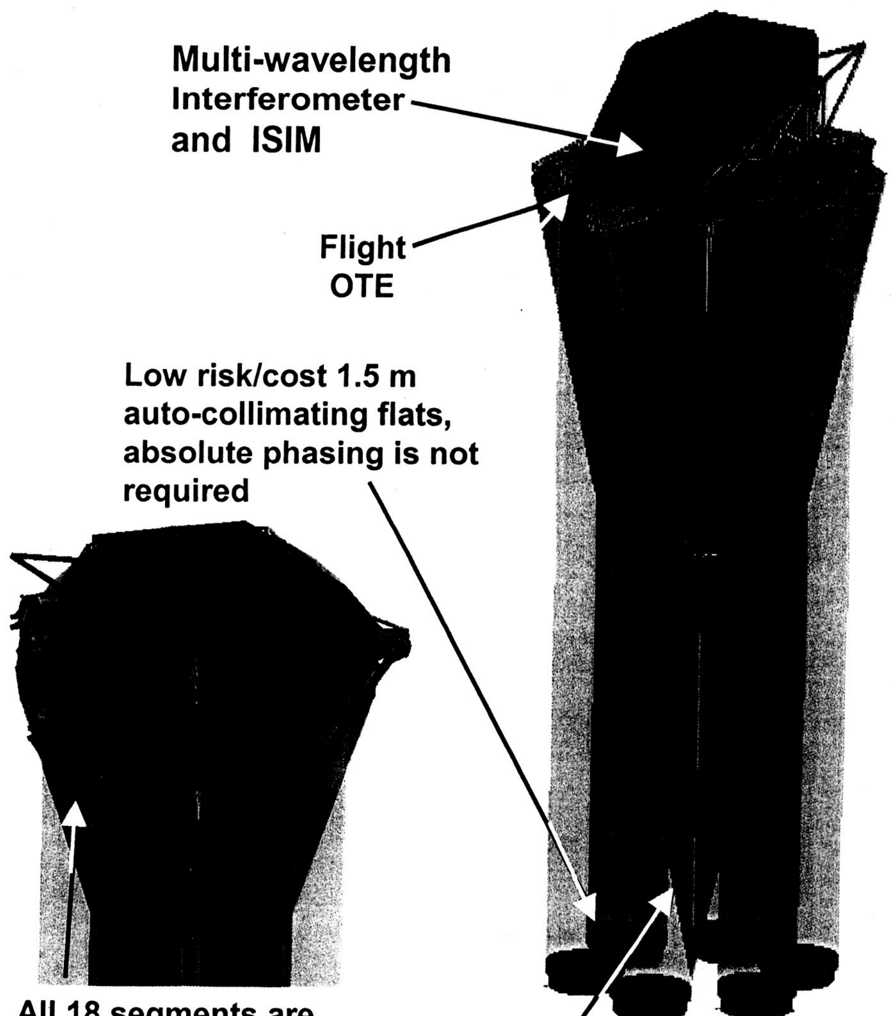
X-ray Calibration Facility (XRCF)
MSFC



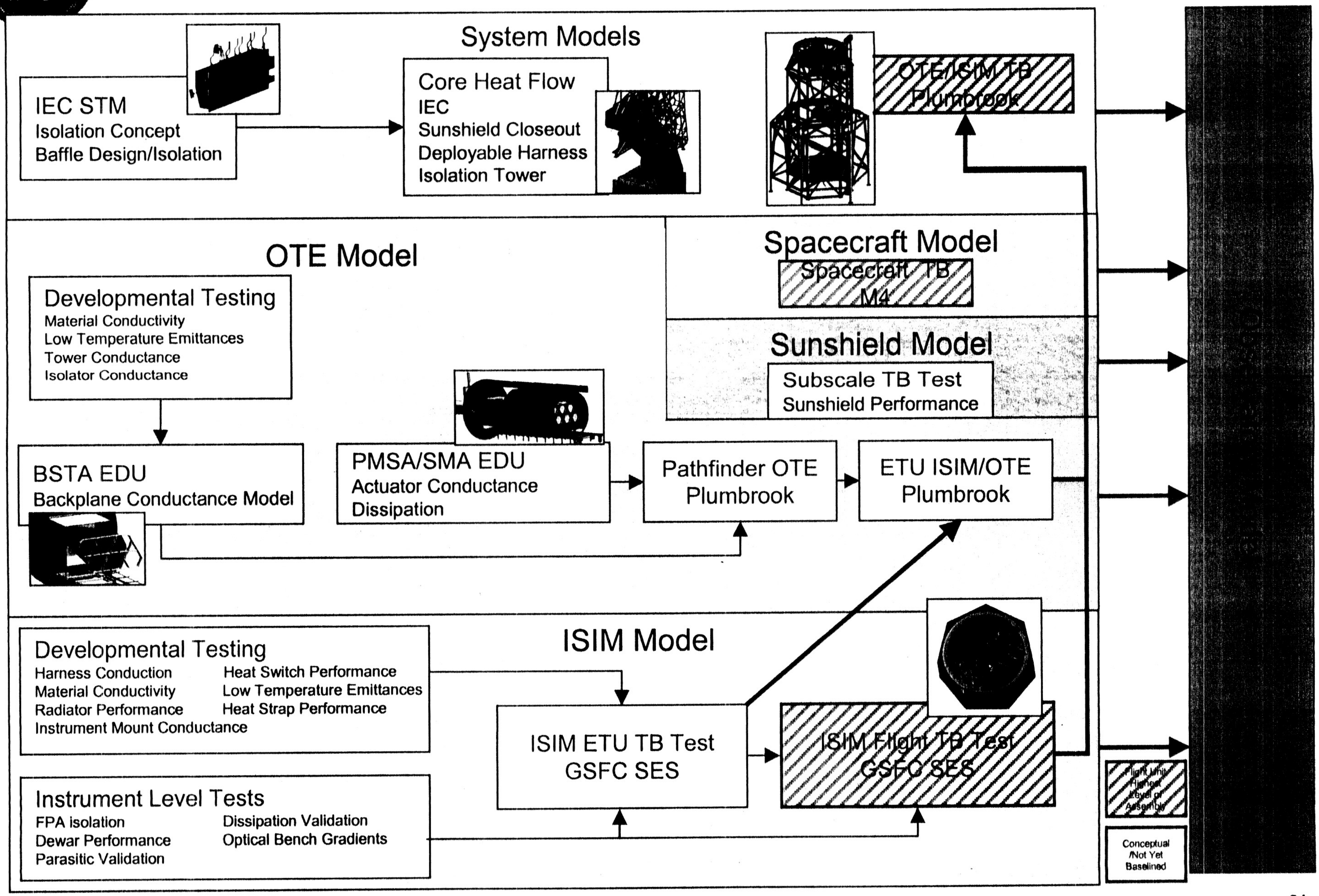
Test setup similar to NMSD, SBMD, and AMSD testing

Optical Verification at Plumbrook

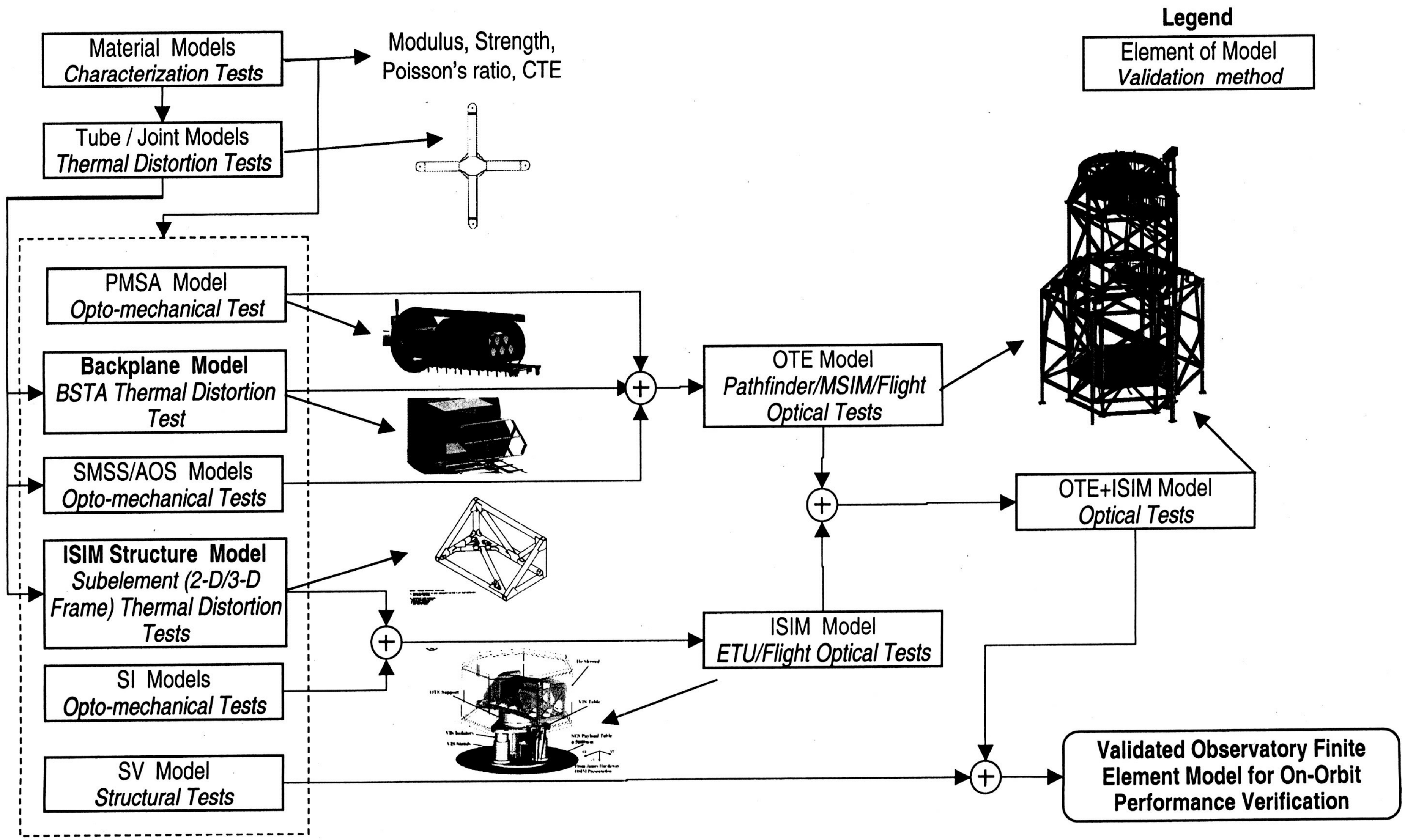
- **Three independent measurements confirm performance**
  - 1) Primary mirror performance using Center of Curvature (CoC) test
    - Senses filled PM aperture except for small central obscuration
  - 2) OTE optical performance using sampled full aperture and Double Pass Interferometer (DPI)
    - All optical segments and every actuator sensed
  - 3) Concurrent verification using NIRCam
    - Includes ISIM and FPA/FPE
    - Recovers sampled aperture phase map
    - Demonstrates WFS&C process and algorithms
- **Multiple wavelength interferometers provide absolute phase knowledge**
- **Full aperture CoC test and sampled full aperture test occur simultaneously**
  - Complete, instantaneous insight into Observatory performance



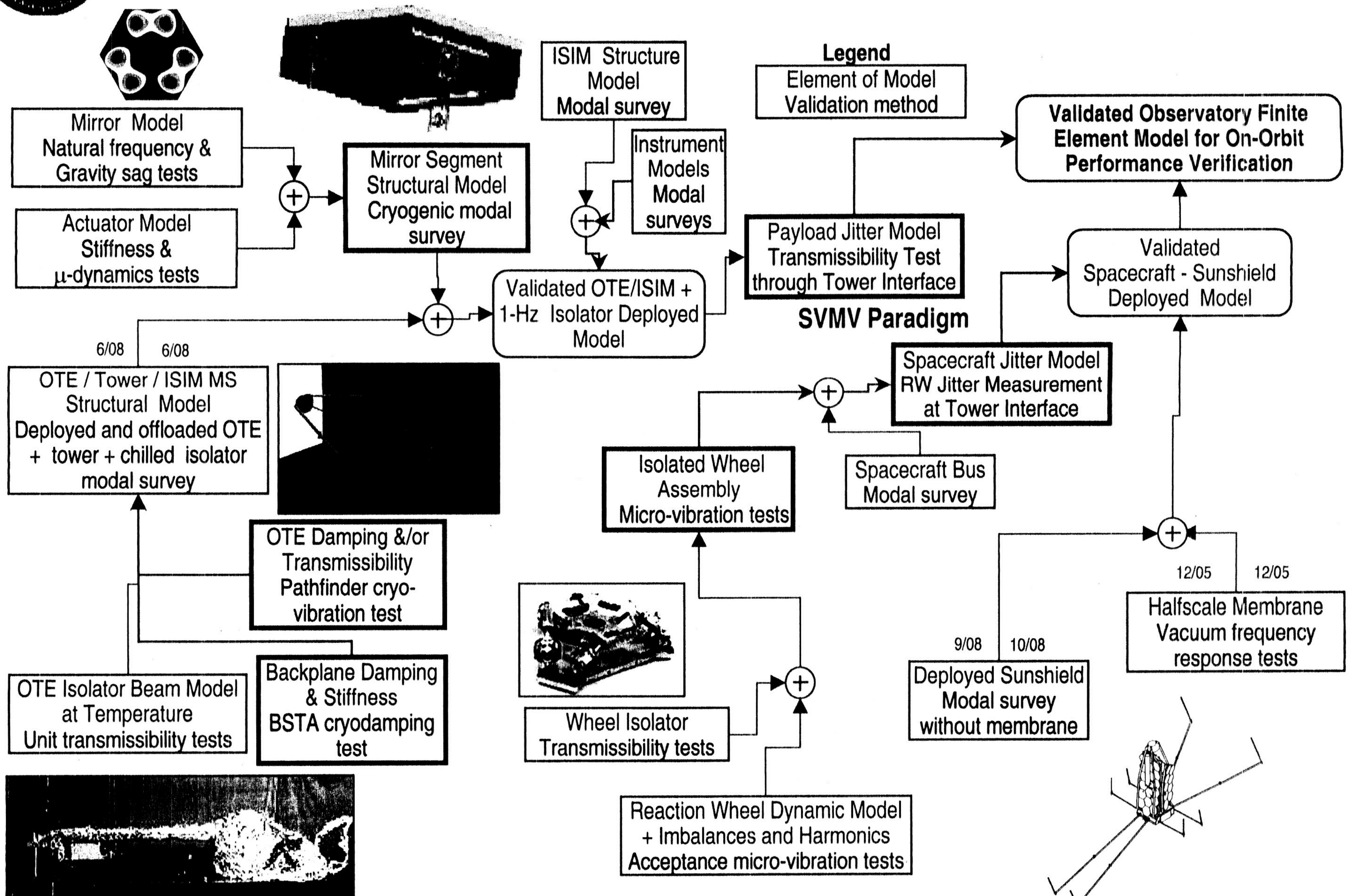
Thermal Model Validation



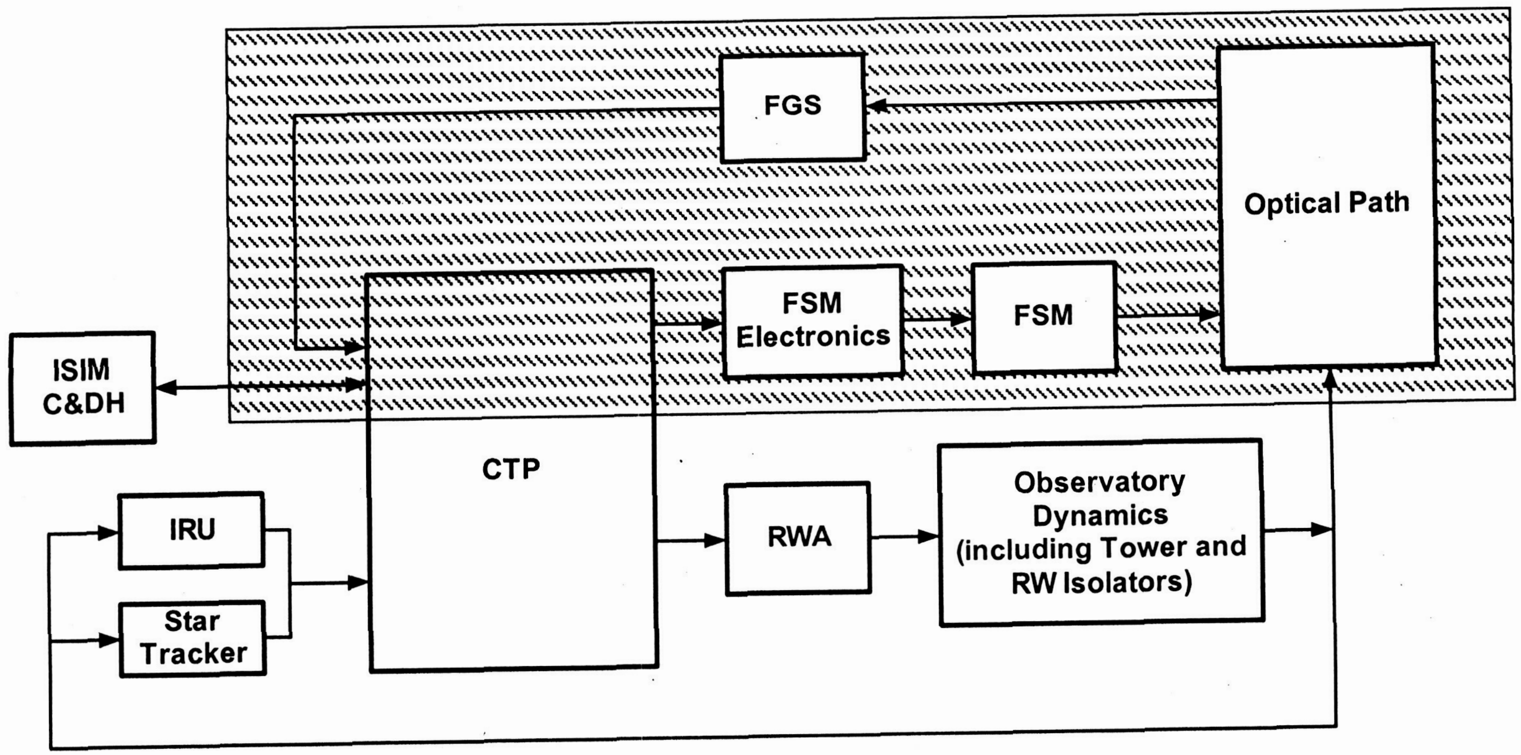
Structural (Static) Model Validation



Structural (Dynamic) Model Validation

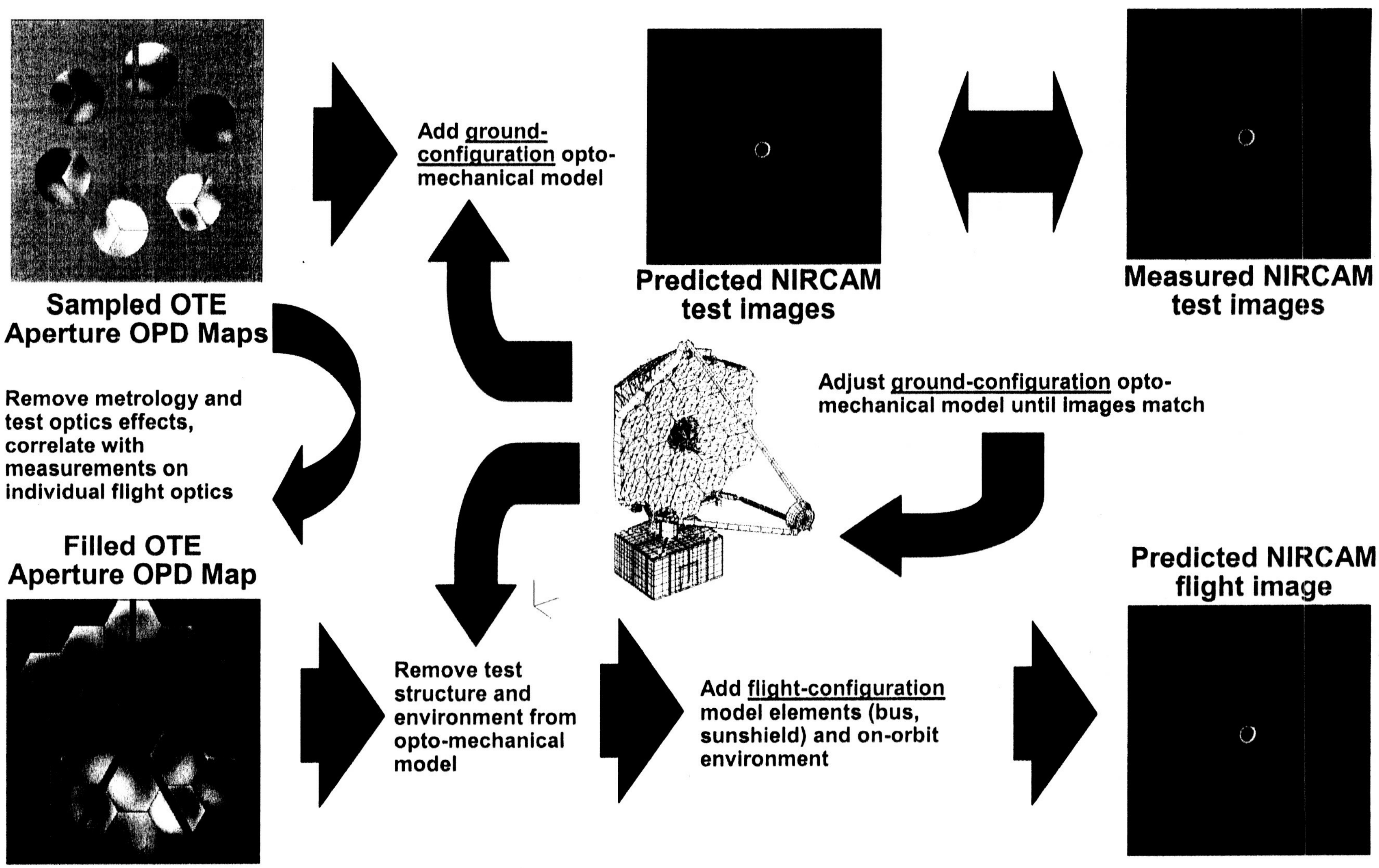


ACS/FSM/FGS Model Validation



- Performance of hardware (including Tower Isolator and RW Isolator) verified at unit level acceptance/protoflight test
- FGS/FSM loop verified at Plumbrook
- System verified by analysis & simulation

Sampled Aperture Images Anchor Filled Aperture Predicted Images



Lessons Learned, Future Challenges

- **Near-term, model validation is by cross-check, but key trade decisions require accurate performance predictions for point designs**
  - model uncertainty factors, margins
- **Need to move beyond nominal (or "worst-case") performance predictions for point designs**
  - sensitivity of results to variations in model parameters (e.g. material properties)
  - uncertainty analysis (range of expected performances)
- **Requirements for model accuracy need to be established early, drives test program (types and accuracy of measurements) and modeling level of effort**
- **Constant pressure exists to create accurate, detailed models while keeping run times tolerable:**
  - Need for high-fidelity (multi-million DOF solid element) structural model anticipated for CDR thermal distortion analysis.
  - Superelement approaches under investigation
- **The plans for model validation and final optical verification are concepts – much detailed modeling and simulation is required to validate the processes**
- **This is the future – similar and even bigger observatories are on the way!**