Integrated Modeling for the James Webb Space Telescope (JWST) Project: Structural Analysis Activities

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May 6, 2004
Overview

● JWST Overview

● Observatory Structural Models

● Integrated Performance Analysis:
  ■ Performance Budget
  ■ Linear Optical Analysis
  ■ Structural-Thermal-Optical
  ■ Optical jitter dynamics

● Future Work and Challenges
Science Requirements

- Measure the luminosities, morphologies, and environments of galaxies within the spectral band 0.6 – 10 µm
- Measure the spectra of 2500 galaxies over the redshift range 1 < z < 5
- Obtain a total observing time of at least 1.1x10^8 seconds.

JWST is designed for at least a 5-year lifetime.

Science Instruments

- **NIR Imaging Camera [NIRCam]**
  - 8 square arc minutes field of view
  - Spectral resolution R (λ/Δλ) = 100
  - Wavelength range 0.6-5 µm

- **Multi-object spectrograph [NIRSpec]**
  - Observing > 100 objects/observatory pointing
  - 9 square arc minutes field of view
  - R ~1000 over wavelengths 1-5 µm
  - R ~100 over wavelengths 0.6-5 µm

- **MIR instrument [MIRI]**
  - Imaging and spectroscopy
  - 2 square arcminutes field of view
  - R ~1500 spectroscopy over wavelengths 5-28 µm.

Constraints

- Launch by 2011
- Cost capped
- Significant International Contributions
- Spacecraft from Prime Contractor (IRT Finding)
- Use existing Launch Vehicle Capabilities

Key Mission Trades

- Orbit, Method to Orbit
- Launch Vehicle/Shroud Configurations
- Filled vs Partially-Filled Apertures
- Thermal Management
- Instrument Packaging
- Sky Coverage
- Communications Strategy
Observatory Structural Model
Integrated Performance Analysis

● Overview
  ■ Multi-disciplinary analysis
    • Thermal, Optical, GN&C, and Structural
    • Tight requirements drive the project toward more integrated analysis
  ■ Performance budget
    • Northrup-Grumman Space Technology (NGST) has adopted a very detailed optical performance budget allocating wavefront error
    • Seek to place the project in a position to intelligently comment on this budget as the contractors estimate the telescope’s performance
  ■ Linear optical model
    • MATLAB-based tool to allow non-optical engineers to estimate wavefront error

● Baseline Analyses:
  ■ STOP
  ■ Jitter
Performance Budget

- NGST allocates and tracks optical performance with a spreadsheet
- Rooted in project Strehl ratio and Encircled Energy 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
  - Active control
  - Stability
- Geometry errors of optics divided into “figure” and “alignment”
- Temporal performance is allocated to either “drift” or “vibrate”
- Lowest-level requirements often related to equivalent mechanical requirements
Linear Optical Analysis

- Provides accurate estimate of OPD wavefront error for perturbed systems (within the limits of the model)

- Coefficients created by ray-tracing runs in OSLO
  - 10nm (nrad) motion introduced in each of optical DOF
  - 100x100 array showing OPD at exit pupil generated in MATLAB for each optical perturbation

- Arrays scaled and summed in MATLAB based on actual motion in each of the 132 DOF
  - Displacements multiplied by appropriate array
  - OPD maps summed
  - FSM manipulated to minimize RMS wavefront error
  - Results are reported as “Best Fit Plane” with global piston offset removed
Linear Model Accuracy

Expected RMS deviation from raytraced RMS wavefront Error

\[ y = p_1x^1 + p_2 \]

Coefficients:
\[ p_1 = 5.214 \times 10^{-5} \]
\[ p_2 = 2.9636 \times 10^{-5} \]

Norm of residuals = 0.0024956

STD DEV of XYZ decenter error (units = 10 nm)

STD DEV of ABC tilt error (units = 10 nm)
Structural-Thermal-Optical (STOP) Analysis

- **Observatory Thermal Models**
  - TSS and SINDA, or IDEAS/TMG

- **Thermal Transient Analysis**

- **Temperature vs Time (thermal)**
  - Map Temperatures to Structure

- **Temperature vs Time (structural)**

- **Displacements of optical elements and surfaces**
  - Prelim.
  - Linear Optical Tool

- **Observatory Structural Model**
  - NASTRAN

- **Static Loads Analysis**

- **Generate Interferograms**
  - SigFit

- **Optics Model**
  - OSLO

- **Ray-Trace Analysis**

- **Wavefront Error (OPD Map & RMS value)**

6/15/2004
STOP Analysis – WFE Predictions

- **STOP analysis of slew maneuvers requires pairs of linear statics runs**
  - Calculate delta between displacements of two room to operational thermal-loaded runs
- **Most STOP analyses use linear optical tool for WFE prediction**
  - Current generation thermal models rarely include PM segment details
  - Beryllium PM segments not expected to develop substantial gradients

![Best-fit Plane of Transient Case (All Optics)](image)
Optical Jitter Dynamics (Jitter) Analysis

- ACS Model
- FSM Model
- Disturbance Models
- FGS Model

from controls model

Optical Sensitivity Matrix

from optical systems analysis

Eigenvectors & Eigenvalues

from normal modes analysis

Integrated Jitter Model

Dynamic WFE

LOS Error

Jitter Model Validation

Validation Results & Documents

Dynamics Model Reduction
Jitter Analysis – Modal Analysis 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)

40 Modes in 0-100 Hz Frequency Range
First flexible mode = 0.42 Hz
Jitter Analysis: Mode Shapes

Secondary Mirror Support Structure
Bending Mode @ 8 Hz

Backplane Twisting Mode @ 12 Hz
Jitter Analysis – LOS and WFE Predictions

- 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.
Challenges and Future Work

Future Work:

- Program plans on following a schedule of analysis cycles:
  - STOP/Jitter/Launch analyses
  - First such cycle is underway (6 month duration)
- Need to verify budget allocations by means of integrated modeling
- Government team performs independent modeling analysis to validate prime contractor
  - Performance predictions
  - Requirements placed on subcontractors/partners

Challenges:

- 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 distortion analysis.
  - Superelement approaches under investigation
- Need to understand sensitivity of results to variations in material properties
- Need to expand linear optical tool to calculate WFE at multiple field points and FOV locations