A New Large Vibration Test Facility Concept for the James Webb Space Telescope

28th Space Simulation Conference
November 3-6, 2014
James Webb Space Telescope (JWST)

**Mission Objective**
- Study the origin and history of galaxies, stars and planetary systems
  - *Optimized for infrared observations (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 Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA

**Description**
- Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch on an ESA-supplied Ariane 5 ECA rocket to Sun-Earth L2
Need for a New Facility

- Goddard is assembling the OTE and ISIM Elements of JWST
  - Together the **OTE** + **ISIM** is called OTIS
  - OTIS is the cryogenic portion of JWST that is launched at ambient temperature
- The OTIS needs to be subjected to a sine vibration test
  - Qualification test for the low frequency spectrum of launch environment
  - Verify workmanship
- Current vibration facilities are inadequate because:
  - Predicted dynamic overturning moment during axial test due to OTIS lateral cg offset exceeds current facility capabilities
  - OTIS physical size
    - 131”x131” shaker mounting interface
    - Issues with current test cell access and hook height
Critical Requirements

- **Test article size**
  - OTIS envelope: 8’-5” x 7’-10” x 28’-3”
  - OTIS mass: 8,686 lbs
  - Fixture mass: 6,200 lbs

- **Cross-axis motion**
  - Bare Table: <10%
  - OTIS Payload: <40%

- **Overturning moment capacity**
  - Must react moments simultaneously

<table>
<thead>
<tr>
<th>Axis</th>
<th>Frequency (Hz)</th>
<th>Test Level (zero to peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>5-50</td>
<td>1.00 g</td>
</tr>
<tr>
<td></td>
<td>50-80</td>
<td>1.25 g</td>
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<tr>
<td></td>
<td>80-100</td>
<td>1.00 g</td>
</tr>
<tr>
<td>V2</td>
<td>5-50</td>
<td>1.00 g</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>1.50 g</td>
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<tr>
<td></td>
<td>60-80</td>
<td>1.00 g</td>
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<tr>
<td></td>
<td>80-100</td>
<td>1.50 g</td>
</tr>
<tr>
<td>V3</td>
<td>5-20</td>
<td>1.50 g</td>
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<tr>
<td></td>
<td>20-40</td>
<td>0.75 g</td>
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<td></td>
<td>40-60</td>
<td>1.25 g</td>
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<td></td>
<td>60-100</td>
<td>1.00 g</td>
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<table>
<thead>
<tr>
<th>Axis</th>
<th>Horizontal</th>
<th>Vertical</th>
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<tbody>
<tr>
<td>Pitch</td>
<td>3.50e6 in-lbf</td>
<td>1.30e6 in-lbf</td>
</tr>
<tr>
<td>Roll</td>
<td>180,000 in-lbf</td>
<td>400,000 in-lbf</td>
</tr>
<tr>
<td>Yaw</td>
<td>50,000 in-lbf</td>
<td>300,000 in-lbf</td>
</tr>
</tbody>
</table>
Dual Shaker Systems

- **Horizontal system**
  - T-film slip table system
  - Single ED shaker
  - Excite V1 & V2 axis

- **Vertical System**
  - Patented inertial mass guidance
  - Dual ED shakers
  - MIMO control
  - Excite V3
Horizontal Vibration System

• Design Concept: T-Film slip table with high rotary inertia reaction base
  – Expansion of standard Team T-Film Table to accommodate extremely large overturning moments

• Design Components:
  – Electrodynaminc Shaker
    • Single 50,000 lbf shaker
    • Air isolated trunnion mount
  – T-Film Table
    • Hydrostatic Bearings
    • Couples overturning moments into reaction base
  – Reaction Base
    • High rotary inertia
    • Air isolated
    • High density concrete masses
Horizontal System – Hydrostatic Bearings

- **T-Film Bearings**
  - Fundamental element in Team slip tables
  - Reacts roll and pitch moments
  - Placed in load path from OTIS to reaction base

- **Yaw Bearings**
  - Reacts yaw moment
  - Guides slip plate in shaker axial direction

- **Filler Elements**
  - Static load support
  - Do not react moments

- **5-degrees of control**
Horizontal System – Moment Factor of Safety

- Rated dynamic load of Team bearings:
  - T-Film Bearings: 19,500 lbf
  - Yaw Bearings: 16,000 lbf
- Pitch and Roll overturning moments are reacted by T-Film bearings
- Yaw moment reacted only by Yaw bearings
- LVTS simultaneous moment requirement:
  - Pitch: 3.5e6 in-lbf
  - Roll: 180,000 in-lbf

<table>
<thead>
<tr>
<th></th>
<th>Moment Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>13.0e6 in-lbf</td>
</tr>
<tr>
<td>Roll</td>
<td>10.7e6 in-lbf</td>
</tr>
<tr>
<td>Yaw</td>
<td>1.89e6 in-lbf</td>
</tr>
</tbody>
</table>

\[ M_{ratio} = \frac{M_{P,app}}{13e6} + \frac{M_{R,req}}{10.7e6} < 1.0 \]

\[ M_{ratio} = \frac{3.5e6}{13e6} + \frac{180,000}{10.7e6} = 0.286 \]

\[ N_{roll-pitch} = \frac{1}{M_{ratio}} = 3.5 \]

\[ N_{yaw} = \frac{M_{y,all}}{M_{y,req}} = \frac{1.89e6}{500,000} = 3.8 \]
Horizontal System – Electrodynamic Shaker

- Single Data Physics LE-5022 – 50,000 lbf shaker
- Air isolated trunnion mount
  - Low natural frequency (1.7-2.0 Hz)
- Shaker Body Mass = 14,535 lbm
- Shaker body provides sufficient reaction mass
- Mounted to horizontal reaction base
Horizontal System – Shaker Force – V1 & V2 Axes

- Otis payload & fixture mass
- Incorporates force limits as notches in test profile near OTIS modes
- Plots FEM force vs. frequency
- Peak shaker force ~ 22,000 lbf
- Approximate margin of 2 on shaker force
Horizontal System – Cross Axis Motion w/ OTIS

- Driving Both orientations
- Ratio of lateral and vertical acceleration relative to axis being driven
- Measured at four OTIS interface nodes
- Response down to 1 Hz
  - Accounts for air isolators
- Peak response inside required bandwidth is below 24% & 27% for driving V1 & V2, respectively
Vertical Vibration System

- **Design Concept: Inertial Mass Guided Head Expander**
  - Expansion of a patented system delivered to Orbital Sciences in support of the Dawn Program
  - Reduced Cross-Axis motion from 250% down to 14%
  - US Patent 7,267,010 B2

- **Design Components:**
  - **Electrodynami c Excitation**
    - Dual 50,000 lb shakers
  - **Guided Head Expander**
    - Transmits energy from shaker to test article
  - **Inertial Masses**
    - React moments generated by test article
  - **Hydrostatic bearings**
    - Provides short, stiff load path into masses
  - **Air Isolated Supports**
    - Isolates vibration system from building
Vertical System – Guidance Mechanism

- Inertial masses located close to head expander
  - Minimizes dynamics of restraining structure
  - Inertial masses located on two sides of the head expander
  - Independent masses – NO precision aligning required
  - Each mass constrains 3-DOF – together constrain 5-DOF
- Head expander coupled to masses via pad bearings
  - Three pad bearings per inertial mass – define a vertical plane
- Pad bearings provide a stiff connection to masses
  - Each constrain 1-DOF, allow 5-DOF (3 rotations & 2 lateral translations)
- Pad bearings require an external preload
- Preload actuator and spherical couplings pull head expander against pad bearings and masses
- Dual spherical couplings act as ball & socket joints on each end
- Preload actuator acts as constant force, low stiffness spring
- Spherical couplings allow for vertical motion
- Low spring stiffness of actuator allows for slight axial motion required due system geometry & kinematics
- **End result** – 1-DOF guided head expander with extremely low cross-axis motion
Vertical System – Pad Bearing & Preload Actuator Configuration

- Yaw Restraint
- Roll Restraint
- Pitch Restraint
Pad capacity is defined by applied preload – pad must remain in compression
Upper pad bearing preload: 24,200 lbf each – two upper pads
Lower pad bearing preload: 48,400 lbf
Each mass reacts either Roll ($M_1$) or Pitch ($M_2$)
Both masses react Yaw ($M_3$)
$M_1$ & $M_2$ single axis capacity: 2.90e6 in-lbf
$M_3$ single axis capacity: 3.17e6 in-lbf
Simultaneous moments
Factor of Safety: 1.84

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<tr>
<th>Axis</th>
<th>Capacity</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>$M_1$ (Roll)</td>
<td>2.9e6 in-lbf</td>
<td>1.3e6 in-lbf</td>
</tr>
<tr>
<td>$M_2$ (Pitch)</td>
<td>2.9e6 in-lbf</td>
<td>400,000 in-lbf</td>
</tr>
<tr>
<td>$M_3$ (Yaw)</td>
<td>3.17e6 in-lbf</td>
<td>300,000 in-lbf</td>
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</tbody>
</table>
Vertical System – Electrodynamic Shaker

- Dual Data Physics LE-5022 50,000 lbf shakers – 100,000 lbf total
- Rigid trunnion mount, each shaker
- Shaker Body Mass = 22,500 lbm (each)
- Additional mass required to reduce body motion and remain within shaker stroke limits
- Common shaker base
Vertical System – Shaker Force – V3 Axis

- Dual shaker FEM results
- Incorporates force limits as notches in test profile near OTIS modes
- Plots FEM force vs. frequency
- Peak shaker force $\sim 38,000$ lbf
- Approximate margin of 2.6 on shaker force

Sine Test Profile with Notching
Vertical System – Cross Axis Motion V1/V3

- Vertical FEM cross axis motion
- Percent cross-axis motion for both lateral directions, relative to average vertical response
- Plots response at head expander corners – both lateral directions
- Peak response: 40% – @ OTIS modes
Questions?