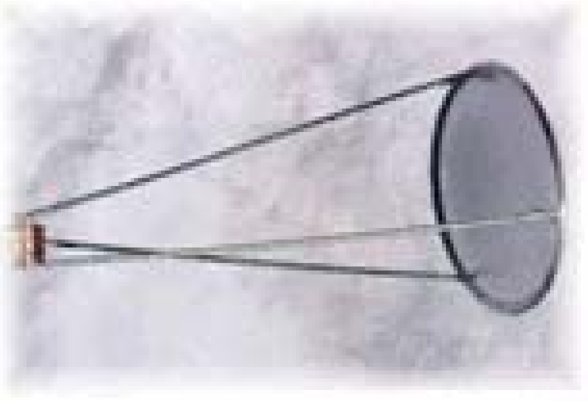
Structures in Space Systems

- Roles
  - Shielding
    - Thermal, radiation, glint
  - Maintaining System Geometry
  - Carrying Loads
- Applications
  - Power and thermal management
  - Aperture forming
  - Spacecraft backbone
- Issues
  - Light-weighting
  - Structural dynamics
  - Thermal distortion

- Technologies
  - Multifunctional Structures
  - Deployment and geometry maintenance
    - Deployable booms
    - Mesh antennas
    - Membrane structures
    - Inflatables
    - Tethers
    - Formation Flight (virtual structure)

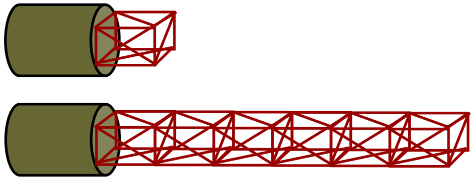
Deployment and Geometry Maintenance

- Deployable Membranes
  - Used for solar arrays, sunshields, decoys
  - Being researched for apertures starting at RF and eventually going to optical
- Inflatables
  - First US satellite was inflated (ECHO I)
  - Enables a very large deployment ratio
    - = deployed over stowed dimension
  - Membranes stretched across an inflated torus
  - Outgassing and need for gas replenishment has led to ultra-violet cured inflatables that rigidize after being exposed to the UV from the Sun.



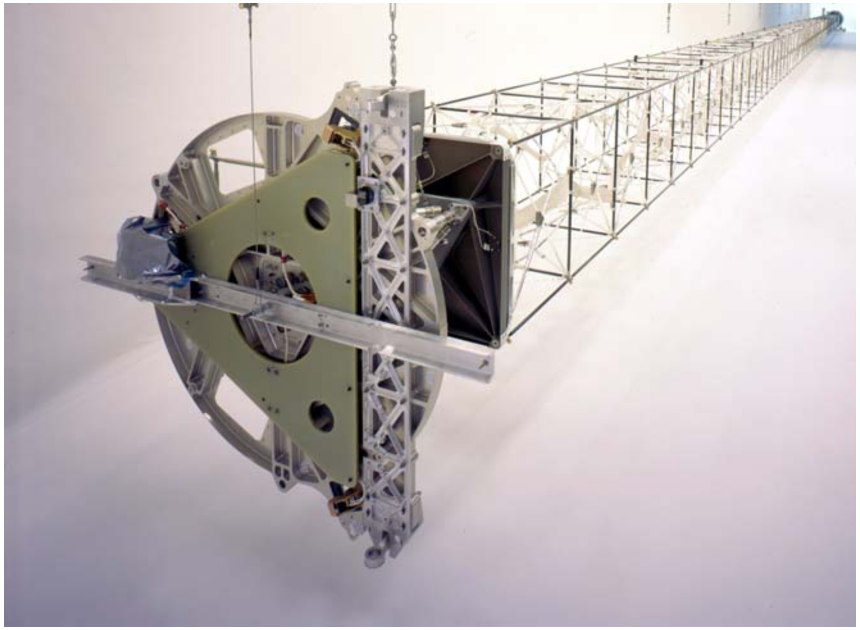
Deployment and Geometry Maintenance

- Truss Structures
  - High strength to weight ratio due to large cross-sectional area moment of inertia



$$Moment = EI\frac{\partial^2 w}{\partial x^2}$$

- Deployable Booms (ABLE Engineering)
  - A bearing ring at the mouth of the deployment canister deploys pre-folded bays in sequence
  - EX: SRTM mission on Shuttle



Handout gives key relationships between I, EI and:

•truss diameter

•total system mass

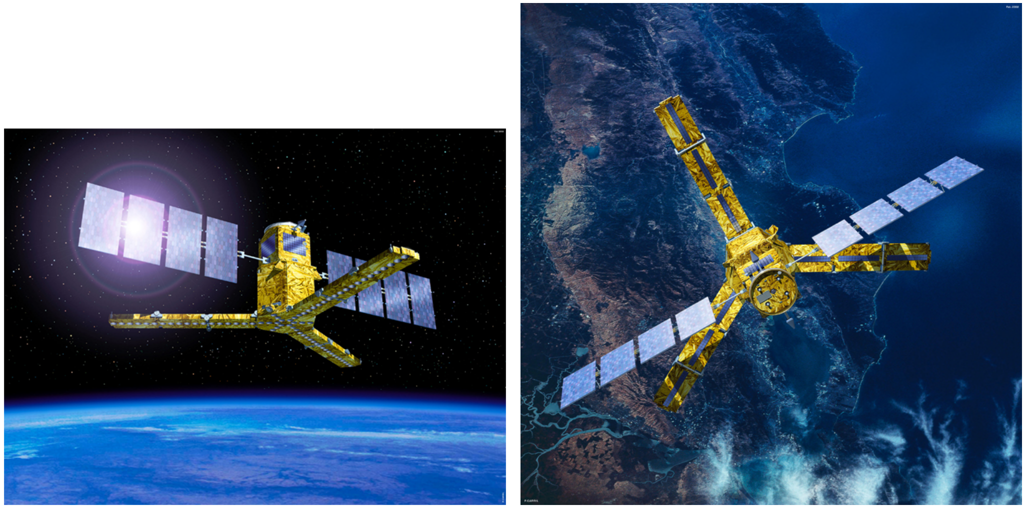
•canister mass fraction

Deployment for Aperture Maintenance

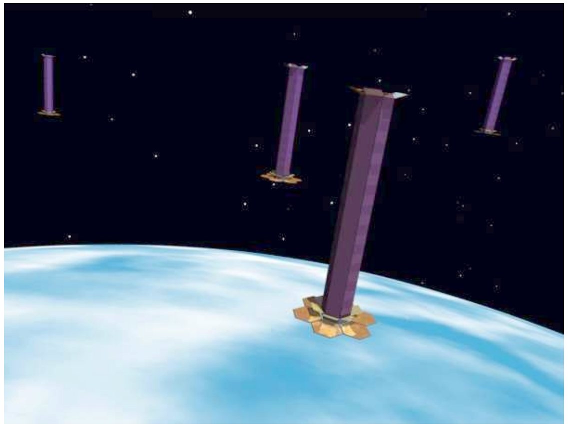
- Aperture physics requires:
  - large dimensions for improved angular resolution

$$\theta_r = 1.22\frac{\lambda}{D} = \frac{\lambda}{B}$$

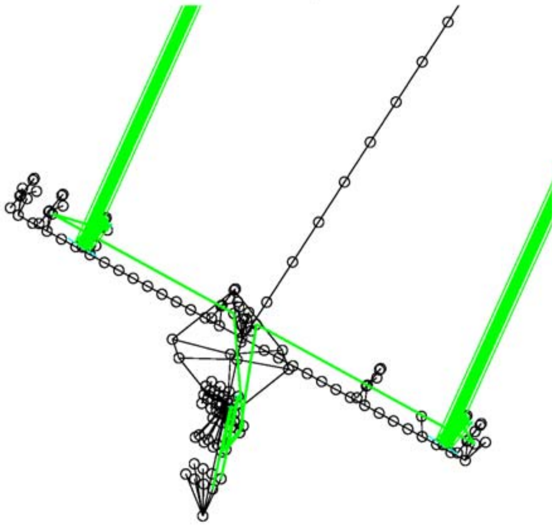
  - Large area for good sensitivity (SNR)
- Options include:
  - Filled Apertures
    - Deployed membranes
    - Deployed panels
  - Sparse Apertures
    - Deployed booms
    - Formation flown satellites

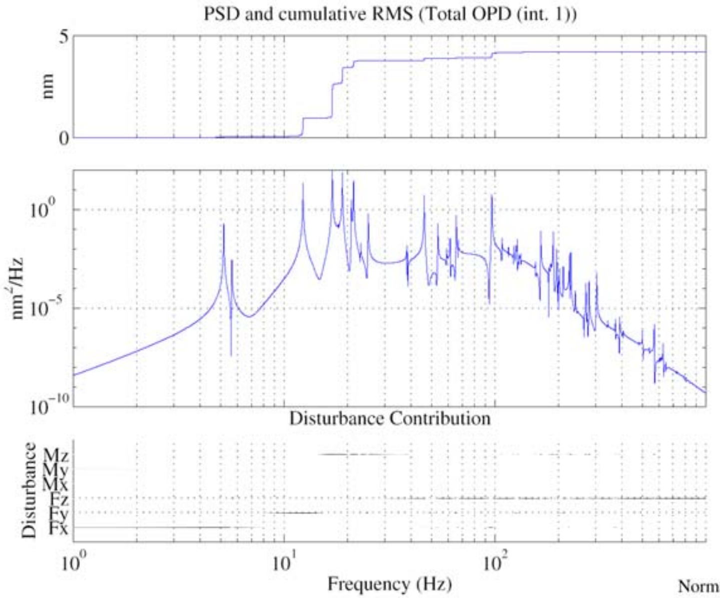


(Courtesy of the European Space Agency. Used with permission.)

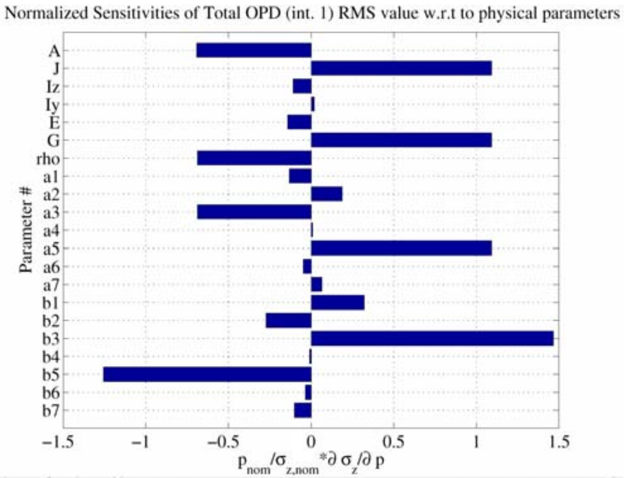


Origins Telescope Dynamics and Controls



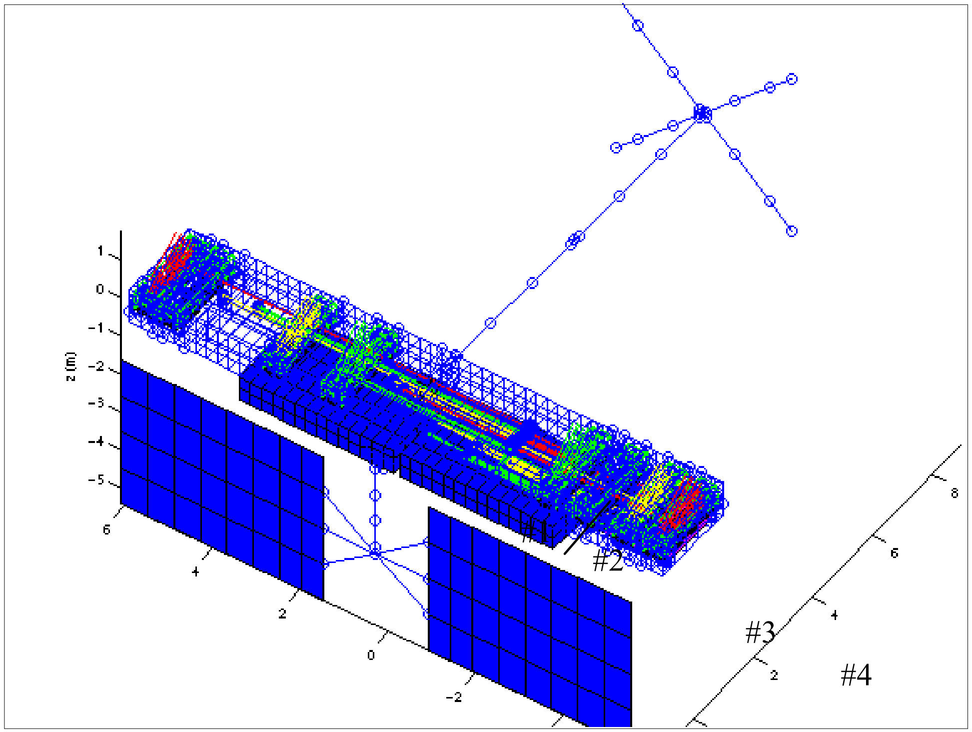


PSD and cumulative RMS (Total OPD (int. 1))

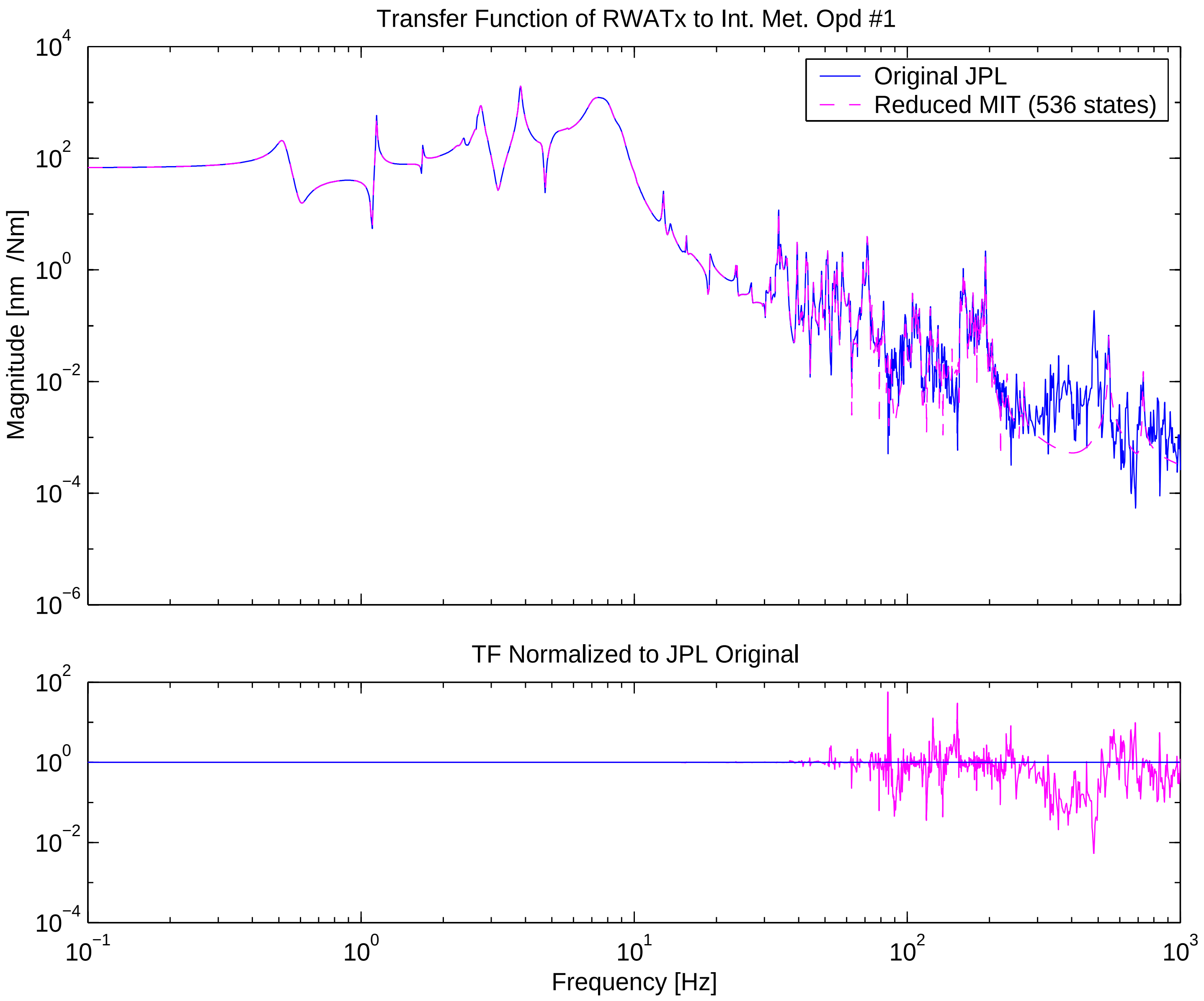


Normalized Sensitivities of Total OPD (int. 1) RMS value w.r.t to physical parameters

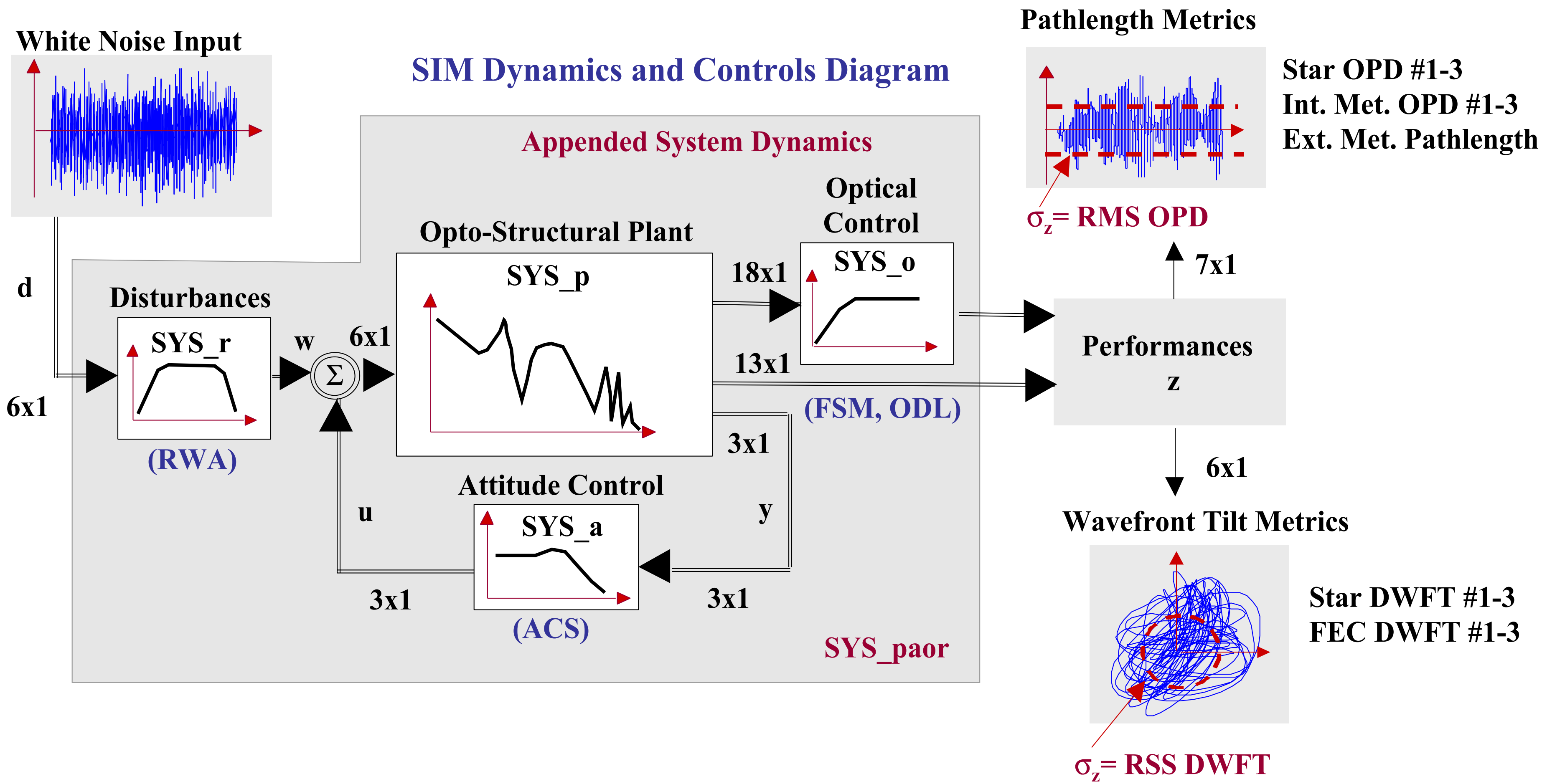
Integrated Model



Example Transfer Function
RWA Tx to Internal OPD #1 : Reduced



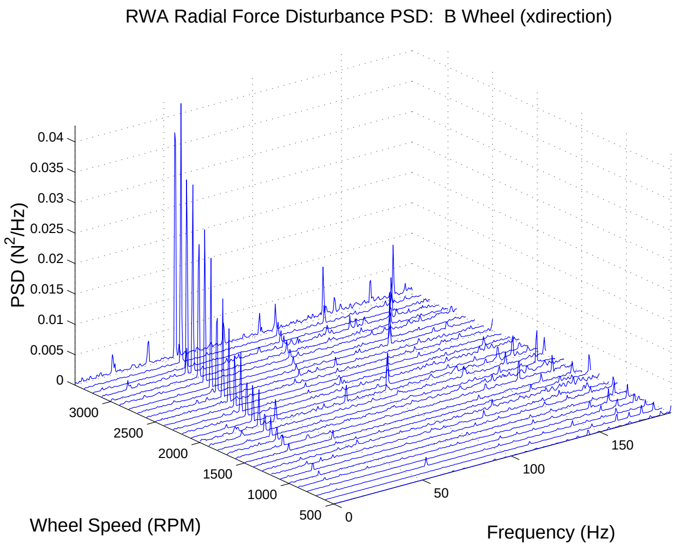
SIM Dynamics and Control Block Diagram



Assume continuous time LTI system.
RWA are the only disturbance source at this point.

Dynamic Disturbance Sources

- Reaction Wheel Assemblies (RWAs) are comprised typically of four wheels
  - Applying torque to the wheels creates equal and opposite torques on the spacecraft
  - As a result, the wheels spin
  - Static and dynamic imbalances in wheels cause 6-DOF forces/torques to be imparted on the structure at the frequency of the wheel RPM.
  - Typically place on isolators and operate in frequency regions where structural response is low
- System design requires careful trade between wheel balancing, isolator corner frequency, vibration control, etc.



Ithaco RWA's (www.ithaco.com/products.html)

Dynamic Disturbance Sources

- Cryocoolers
  - Mechanical compressors-expanders undergo thermodynamic cycles (e.g., Sterling cycle) to cool detectors (cameras). Sometimes called "cold fingers."
  - The moving piston induces vibration

- Fluid Slosh
  - Liquid propellants and cryostats (liquid Helium for cooling detectors) can exhibit fluid slosh
  - Difficult to model these dynamic resonances since
    - gravity stiffens the fluid in 1-g
    - Surface tension stiffens in 0-g

Disturbance Analysis (Open Loop)

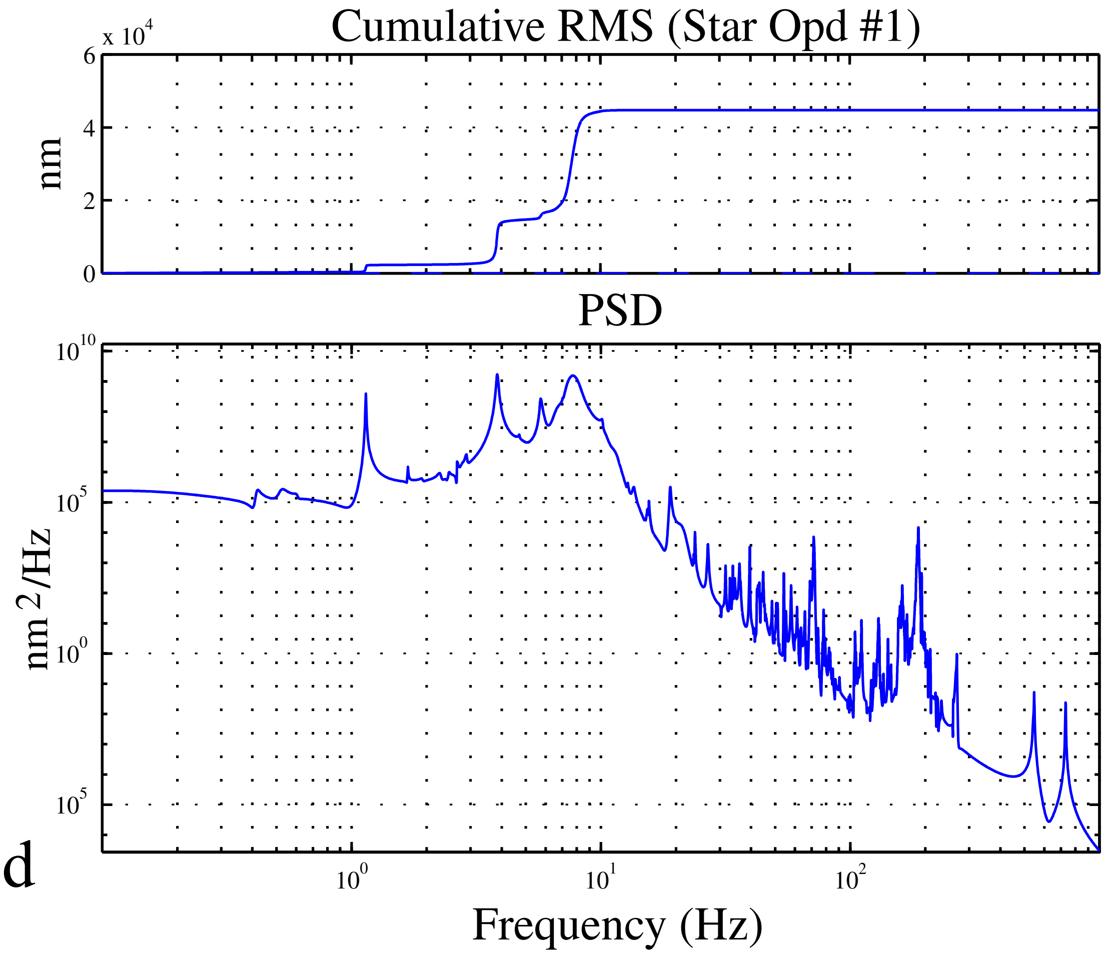
Disturbance Analysis computes performance PSD and RMS

Starlight OPD#1

(top)
Cumulative RMS

(bottom)
PSD plot

Predicted RMS is 4.474×10^{4} [nm]. Most of the error is accumulated between 3-10 Hz.



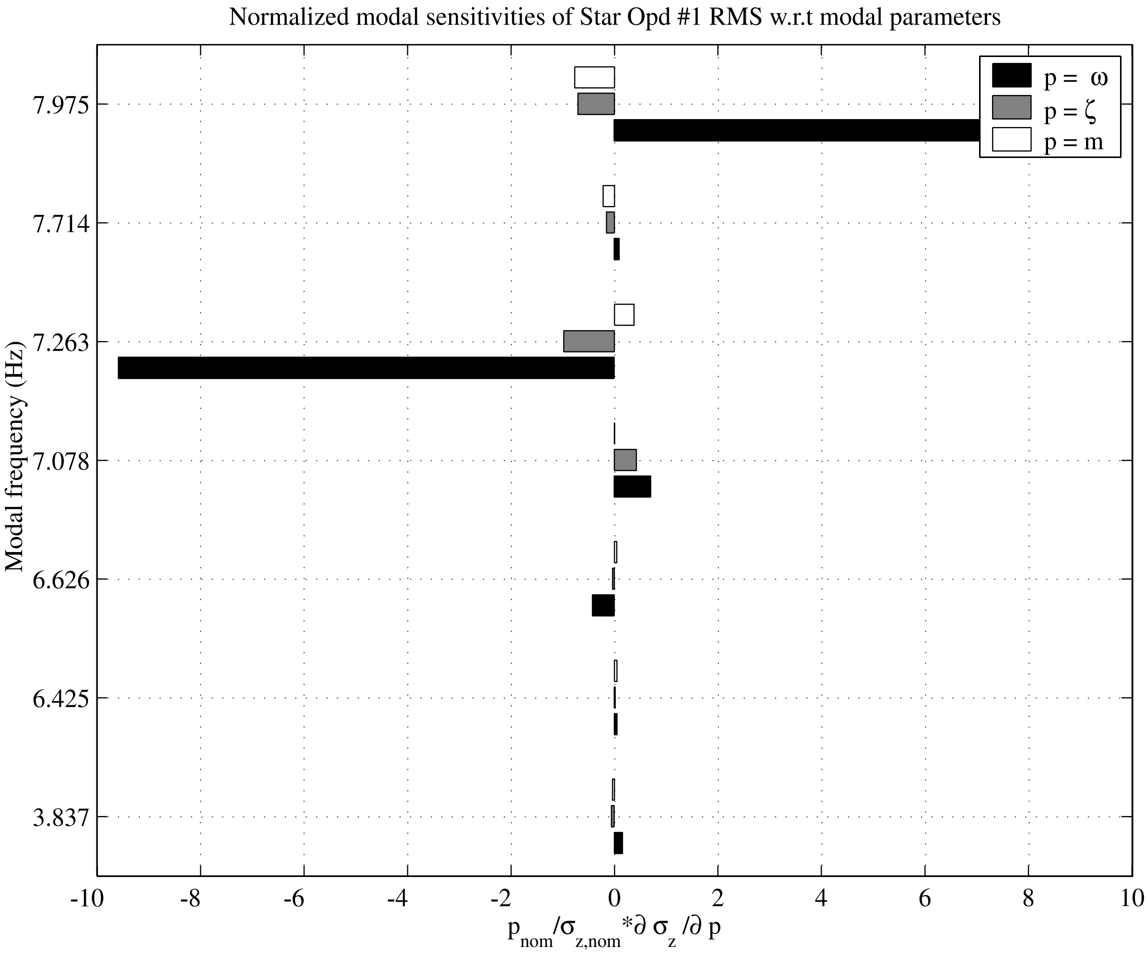
Modal Sensitivity Analysis (1)

Sample Results for:

Starlight OPD#1 (Open Loop)

Conclusion:
Some modes are significantly more sensitive than others.

Big contributors are generally sensitive !



Sensitivities at 7.263 and 7.975 Hz are very large.

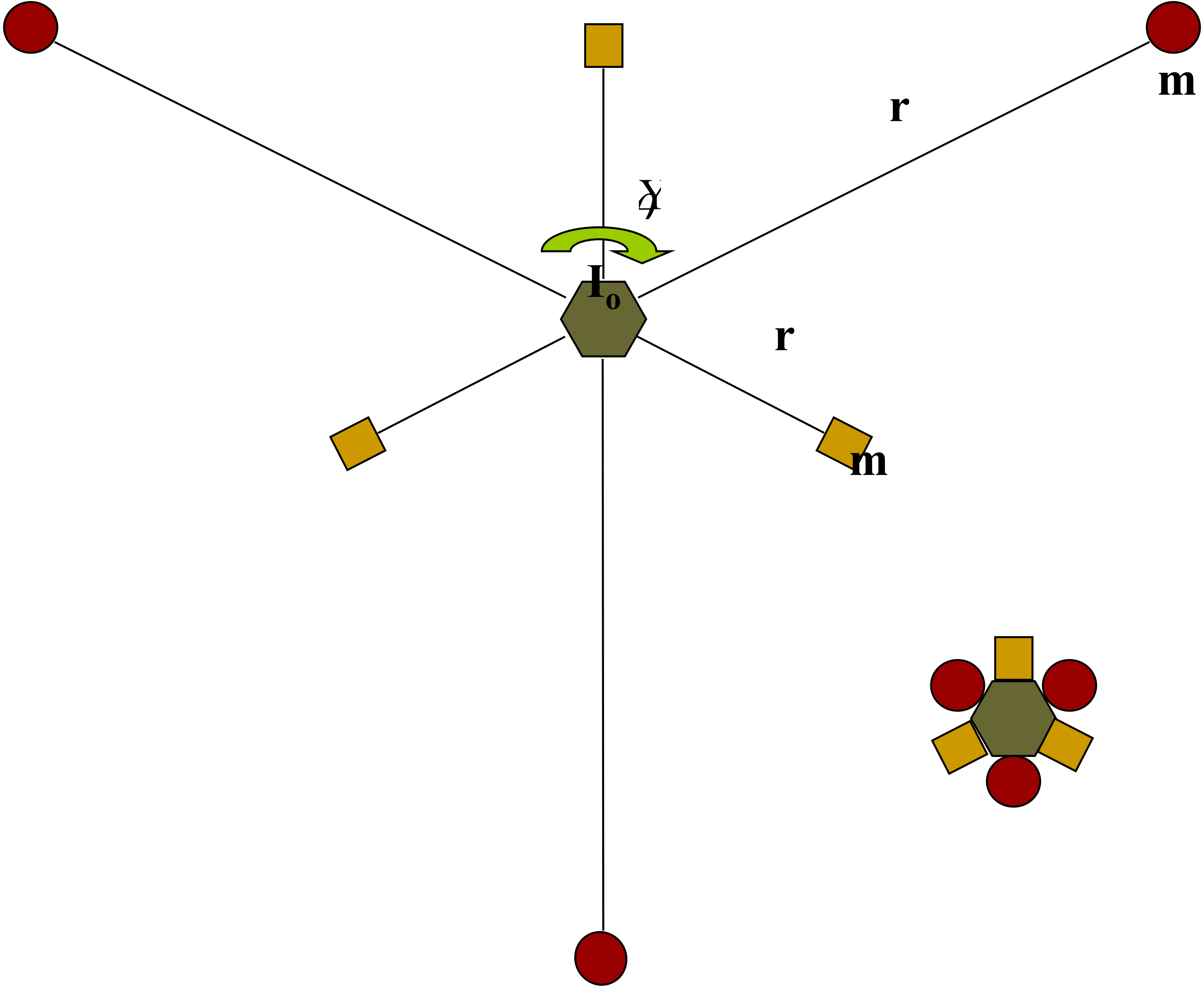
Thermal Issues with Structures

- Sunshields
  - To observe in the thermal infrared requires cold optics and detectors
  - Sunshields are used to block sunlight from heating these elements
  - Need to be large and lightweight
- Thermal Snap
  - The heat load into a structure can change due to Earth eclipse in LEO or due to a slew of the S/C
  - Nonzero or differential coefficient of thermal expansion (CTE) can cause stresses to build
  - Friction joints in deployment mechanisms can eventually slip causing an impulsive input
  - This high frequency vibration can disturb precision instruments
- Thermal Flutter
  - Differential thermal expansion can cause a portion of the structure to curve and reduce its exposure to a heat source
  - The structure then curves back thereby increasing its heat load
  - This can lead to a low frequency instability (flutter)
- Thermal Distortions
  - Differential thermal expansion in optics and optical mounts can dramatically degrade performance
  - Kinematic mounts ensure that only only 6-DOF loads are applied thereby holding the optic's 6-DOF in place without applying bending and shearing loads

Control-Structure Interaction

- If the bandwidth (maximum frequency at which control authority is significant) of a control loop is near the resonances of a flexible structural mode, detrimental interaction can occur: instability
  - Conventional practice is to limit the frequency where the open loop transfer function has dropped by 3 dB to less than one-tenth the first flexible mode in the system.
  - Advanced controls have proven to be effective well beyond this frequency if the structural dynamics are properly considered.

SPECS Geometry



[D] Tether Vibration Control

- Tether vibrations can disturb the stability of the optical train and therefore need to be controlled.
- One option for controlling tether vibration is impedance matching.
- Tether vibration is fundamentally governed by the wave behavior of a string under tension.
- For each tether, motion can be decomposed into leftward and rightward propagating waves.
- A transformation between physical and wave states in the tether can be derived.
- As these waves propagate and interfere with each other, they induce detrimental motion into elements attached to the tether.

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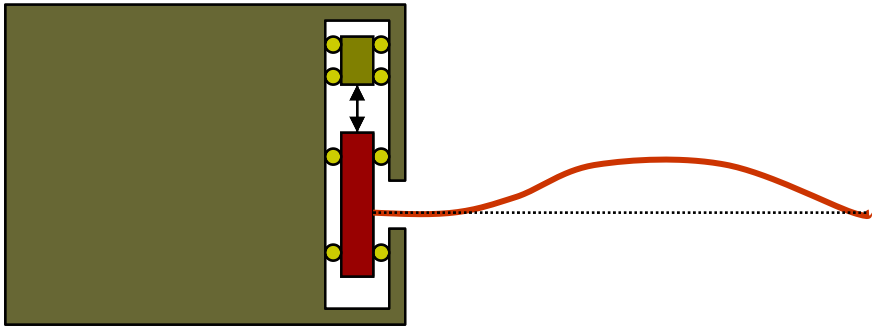
[D] Impedance Matched Tether Termination

- Consider a sliding tether boundary condition with a re-actuated transverse force shown below.
- The boundary ODE, when transformed to wave coordinates, gives the input-output condition.
- The first term is the scattering (reflection) coefficient.
- The second term is the product of the wave generation coefficient and force actuator.

$$m \quad \partial$$



[D] Impedance Matched Tether Termination

$$F = (m\omega^2 + ikT$$

- Setting the outgoing wave to zero gives the force in terms of the incoming wave.
- Transforming back to physical coordinates gives the feedback law.
- Vibrations in the tether are absorbed by the matched termination
- The collector spacecraft is undisturbed since the control force is generated by reacting against the extra mass.
- The control effort is finite since the vibration energy is finite.
- The control law is only dependant on local tether and junction properties.

Advanced Structures

- Multi-Functional Structures (MFS)
  - Conventional design uses structure to support avionics card cages, antennas, wire bundles, etc. Structure usually accounts for ~15% of spacecraft bus mass
  - MFS build circuitry directly into the structure, etch antenna patterns into the surface, etc thereby eliminating need for a considerable amount of support structure
  - Imagine computer boards mounted together to form the spacecraft bus
- Launch Load Alleviation
  - Most of the structural strength (and mass) comes from the need to survive the dynamic (>60g) and acoustic loads (160 dBa)during the eight minute launch
  - Advanced topics include:
    - Launch isolators and active acoustic blankets
    - Self-Consuming Structures: use this extra structure as on-orbit maneuvering propellant

Smart Materials and Composites

- Undergo mechanical strain when subjected to electromagnetic fields and vice versa
  - Piezoelectrics, PVDF, electrostrictives: electric field induces strain
  - Magnetostrictives: magnetic field induces strain
  - Shape Memory Alloys: switches between different strain states depending upon temperature
- Composites
  - Graphite fibers embedded in epoxy matrix allows material strength to be supplied in directions desired and not in others. More mass per strength efficient than metals
  - Difficult to build into complex geometries, significant out-gassing of the epoxy, etc.
  - Advanced topics include:
    - Active Fiber Composites: piezoelectric fibers embedded in composite material
    - Metal matrix composites
    - Snap together, pre-formed composite panels (Composite Optics, Inc)