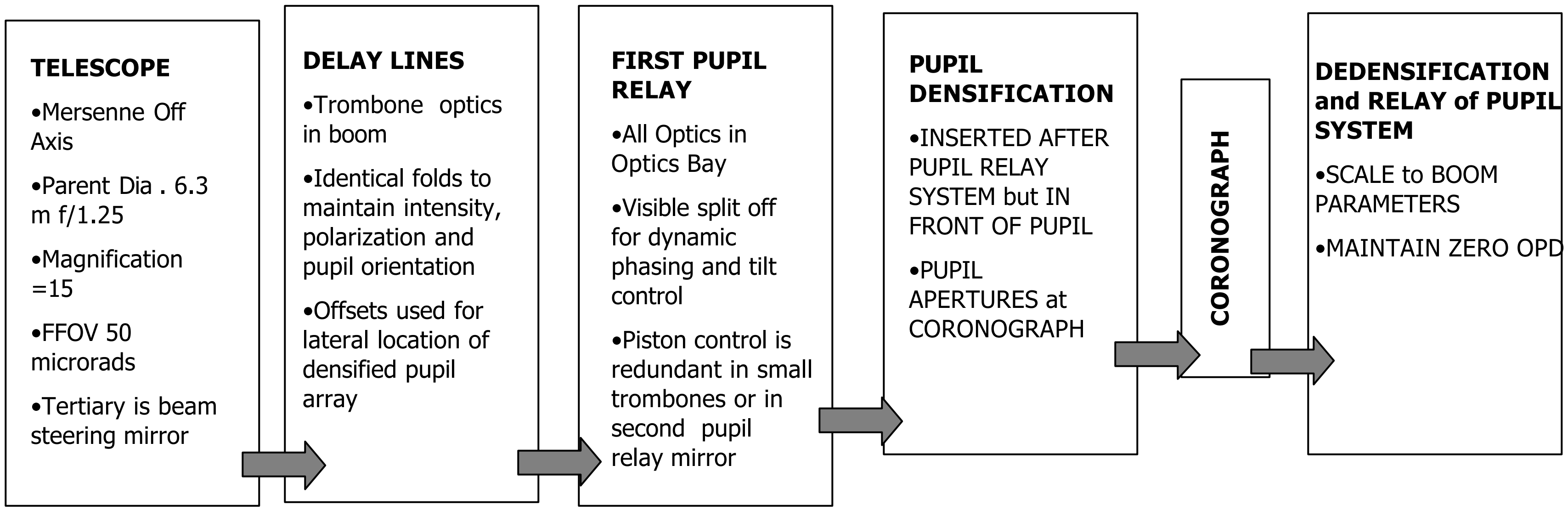
NRLA Technical Appendix

Supporting Material

NRLA compared to other TPF concepts

- Most TPF concepts use one of the following 2 techniques for planet detection/characterisation :
  - Nulling : the light of the central star is partially cancelled by destructive interferences (TPF blue book, Darwin concept etc...)
  - Imaging : the light of the planet is decoupled (spatially) from the light of the bright central star on the detector array (ASA)
- The NRLA concept uses both techniques : the phase mask coronagraph provides an efficient null while aperture synthesis separates the planets' photons from the residual central star photons.
- The spatial decoupling of photons becomes less efficient when the number of apertures is small. The NRLA concept is especially efficient, compared with other nullers, with more than 5 apertures.

Block Diagram of NRLA Optical System



TELESCOPE

- Mersenne Off Axis
- Parent Dia . 6.3 m f/1.25
- Magnification =15
- FFOV 50 microrads
- Tertiary is beam steering mirror

DELAY LINES

- Trombone optics in boom
- Identical folds to maintain intensity, polarization and pupil orientation
- Offsets used for lateral location of densified pupil array

FIRST PUPIL RELAY

- All Optics in Optics Bay
- Visible split off for dynamic phasing and tilt control
- Piston control is redundant in small trombones or in second pupil relay mirror

PUPIL DENSIFICATION

- INSERTED AFTER PUPIL RELAY SYSTEM but IN FRONT OF PUPIL
- PUPIL APERTURES at CORONOGRAPH

CORONOGRAPH

DEDENSIFICATION and RELAY of PUPIL SYSTEM

- SCALE to BOOM PARAMETERS
- MAINTAIN ZERO OPD

NRLA Optical Design Features (2)

- First densified pupil: circular array of 7 apertures, each 40 mm within a circle that is 90 mm diameter. The first pupil mask is located here.
- The second pupil is imaged on to the second pupil mask and after it has been de-densified.
- Some tuning of sub-pupil locations possible with thermal control of ECC's
- Adjustment of the paths to remove piston errors accomplished by tilt of the extended corner cubes
- Final imaging optic is a strip from a long off axis asphere 50 mm x 1350 mm long.
- Intermediate sub-aperture size of 40 mm diameter chosen as a compromise between:
  - Avoiding a second pupil relay between coronograph and de-densified array
  - Keeping extended corner cubes to "manufacturable" size
  - Maintain throughput to coronograph with FFOV of 50 microrads
- Seven sub-apertures arrayed around a circle with 20 mm between each subaperture, and no sub-aperture in center

Likely Size of the Optical Components in NRLA

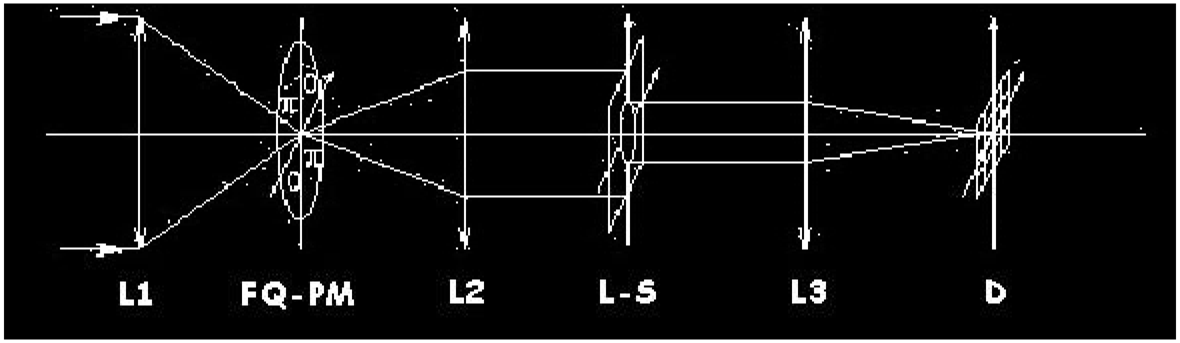
OPTIC	QUANT	DESCRIPTION	DIAMETER (mm)
PRIMARY Parent Dia 6600	7	OAP	3000
SECONDARY Parent Dia 440	7	OAP	200
Tertiary & BSM1	7	FLAT	320
TROMBONE (Q-2)	14	FLATS	320
BEAM STEER	14	FLAT	320
Pupil Relay 1.1	7	OAP	320
pupil relay 1.2	7	ASPHERE	50
Pupil relay 1.3	7	ASPHERE	125
FS Mirror	7	FLAT	60
F TROMBONE (Q2)	14	FLATS	60
PUPIL MASK (Q7)	1	MASK	100
CORONOGRAPH M1	1	OAP	100
CORONOGRAPH	1		
CORONOGRAPH M2	1	OAP	100
EXTENDED CORNER CUBES	7	SET OF 3 FLATS	600X800
DEDENSIFIED PUPIL MASK	1	MASK	1333
IMAGING MIRROR	1	OAP	50X1400

Coronagraph Simulation

- Models the phase mask nulling coronograph, dedensification, and rotational aperture synthesis to construct the image
- Parameters and settings in definition file:
  - The planetary system is described via locations of point sources
  - Mechanical vibrations are coupled via phase error mask files
- Current model is set for 7 telescopes and takes 160 snapshots (can be changed)
- Written in C for Linux, then modified to work in Windows
  - Run either from command lines or using scripts
- Additional Matlab programs display & analyze the resulting images.

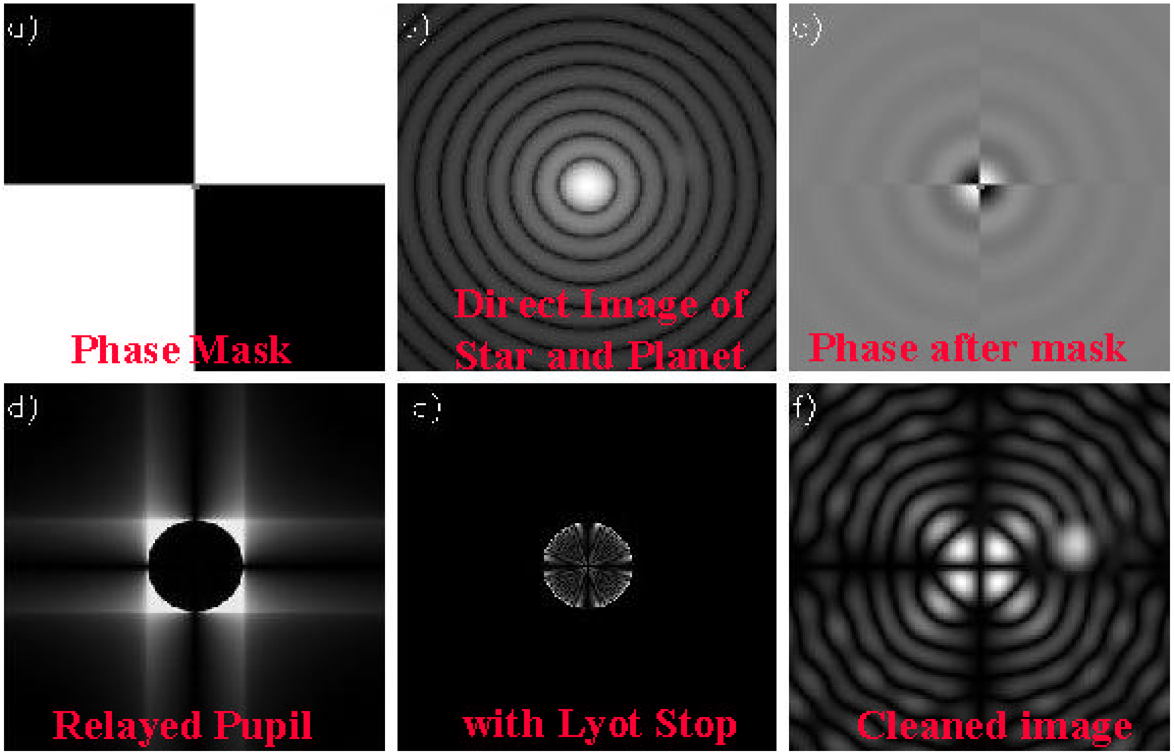
Four Quadrant Coronagraph

Optical layout



- Four quadrant phase-mask in the focal plane (Rouan 2000)
- High dynamic range ? 20mag. (with perfect optics)
- Resolution unaffected
- Broad-band operation with achromated phase mask requires a circularized pupil affected by guiding errors (null width ? ?^{2})
- Pupil obscuration up to 10% tolerable

(Rouan et al., 2000, Riaud et al, in preparation)



Residual Star Suppression

-- Record multiple exposures at different telescope rotations

-- Rotate exposures to register the sky and compute the image median
  - this is the static PSF

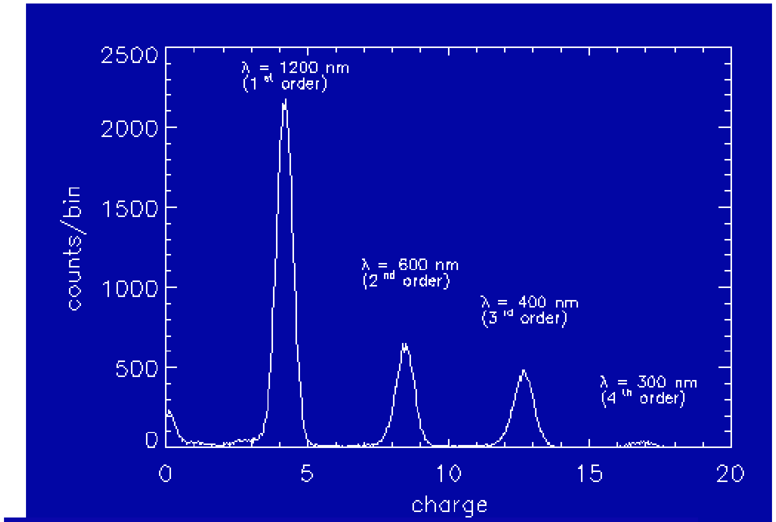
-- Subtract stellar residual from each frame

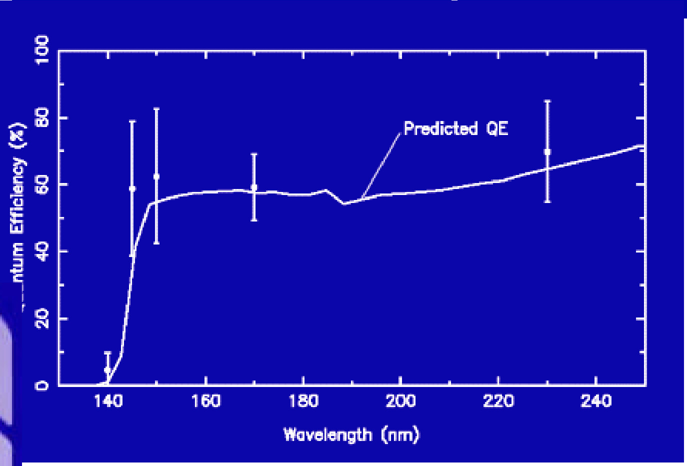
-- Rotate and sum star-subtracted frames

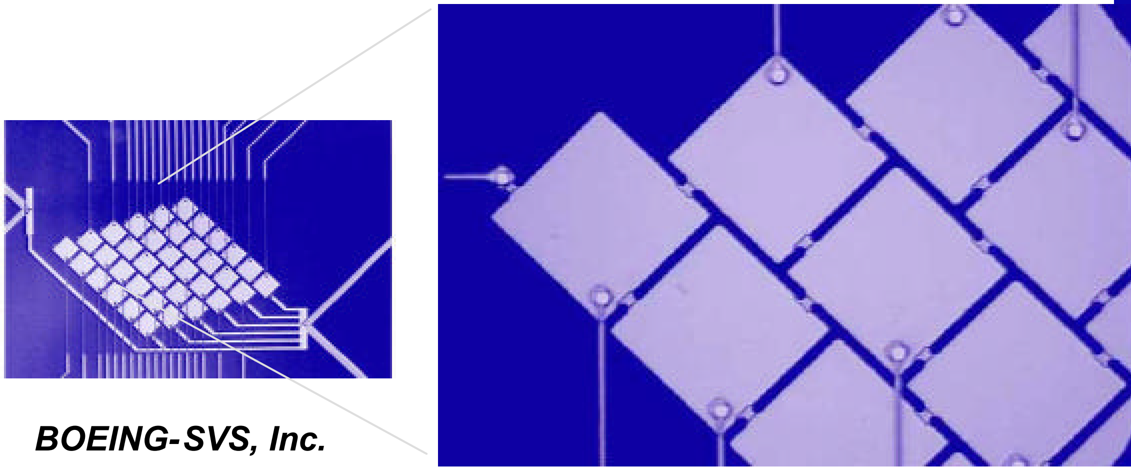
Wavelength-discriminating Detector Arrays

- Superconducting Tunneling Junction detectors

  -- Operational in laboratory environment
  -- Good QE but responsive out to NIR only at present
  -- Operational temperature < 1K
  -- Few pixels
  ✍ Resolves spatially and spectrally with one array
  -- Prototype Ta-based camera developed for ground-based astronomy (S-CAM)
  6x6, 25 micron pitch





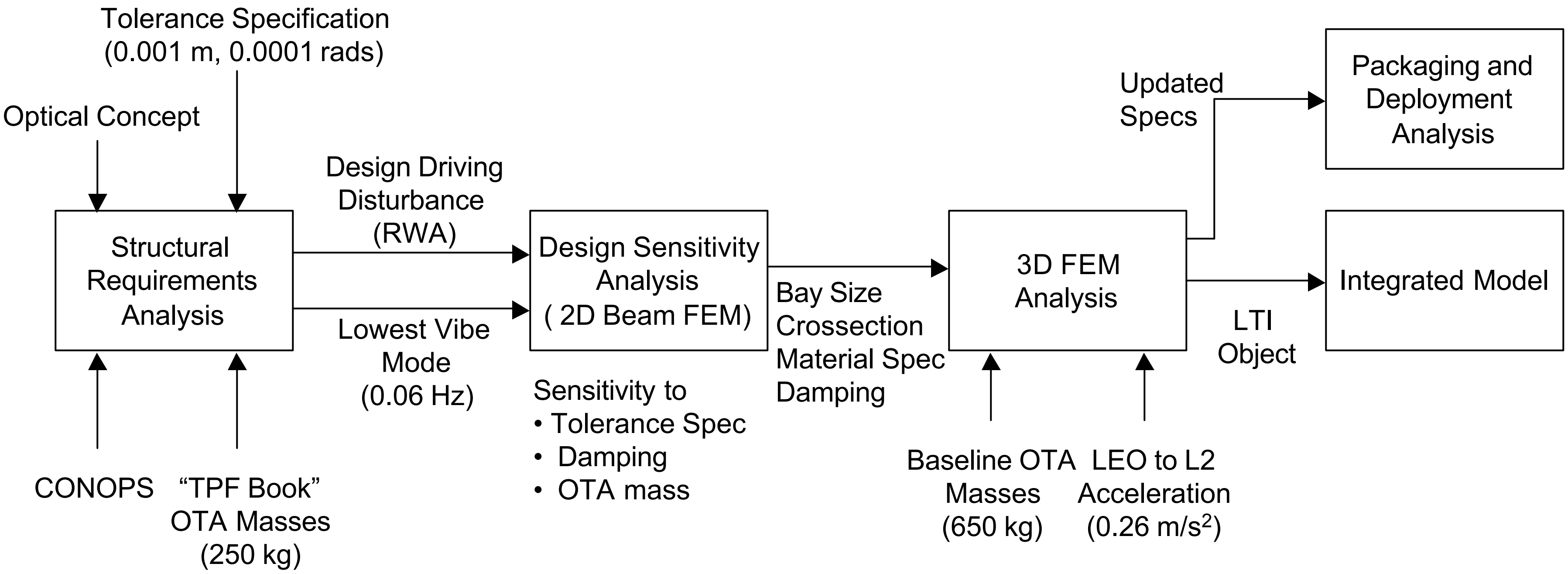


BOEING-SVS, Inc.

Superconducting Tunnel Junctions (STJs)

- STJs are photon-counting devices. Each detected photon produces a macroscopic charge in the junction. Measuring this charge leads to an estimate of the incoming photon's wavelength
- The current STJs are sensitive from the UV to the near-infrared (~up to 2 microns)
  - The spectral resolution is about 10
  - Extending the wavelength range towards the infrared requires new choices of supraconducting materials
  - A 6x6 pixels array of STJs has been successfully built and used for ground-based astronomical observations (Rando et. al., Experimental Astronomy, 10, 499, 2000)
- STJs arrays are the ideal detectors for the NRLA concept. The image is reconstructed in each wavelength "bin" without additionnal observing time. It offers a simple and robust solution for spectroscopy (no additionnal optics).
- Bigger arrays of STJs should be built in the coming years. It would be highly desirable to extend the long-wavelength end of the sensitivity of STJs to >10 microns, and develop coolers to support them.

NRLA Boom Structural Design Process



Tolerance Specification
(0.001 m, 0.0001 rads)

Optical Concept

Structural Requirements Analysis

CONOPS

"TPF Book"
OTA Masses
(250 kg)

Design Driving
Disturbance
(RWA)

Lowest Vibe
Mode
(0.06 Hz)

Design Sensitivity Analysis
(2D Beam FEM)

Sensitivity to
- Tolerance Spec
- Damping
- OTA mass

Bay Size
Crossection
Material Spec
Damping

3D FEM Analysis

Baseline OTA
Masses
(650 kg)

LEO to L2
Acceleration
(0.26 m/s^2)

Updated
Specs

Packaging and Deployment Analysis

LTI
Object

Integrated Model

BOEING

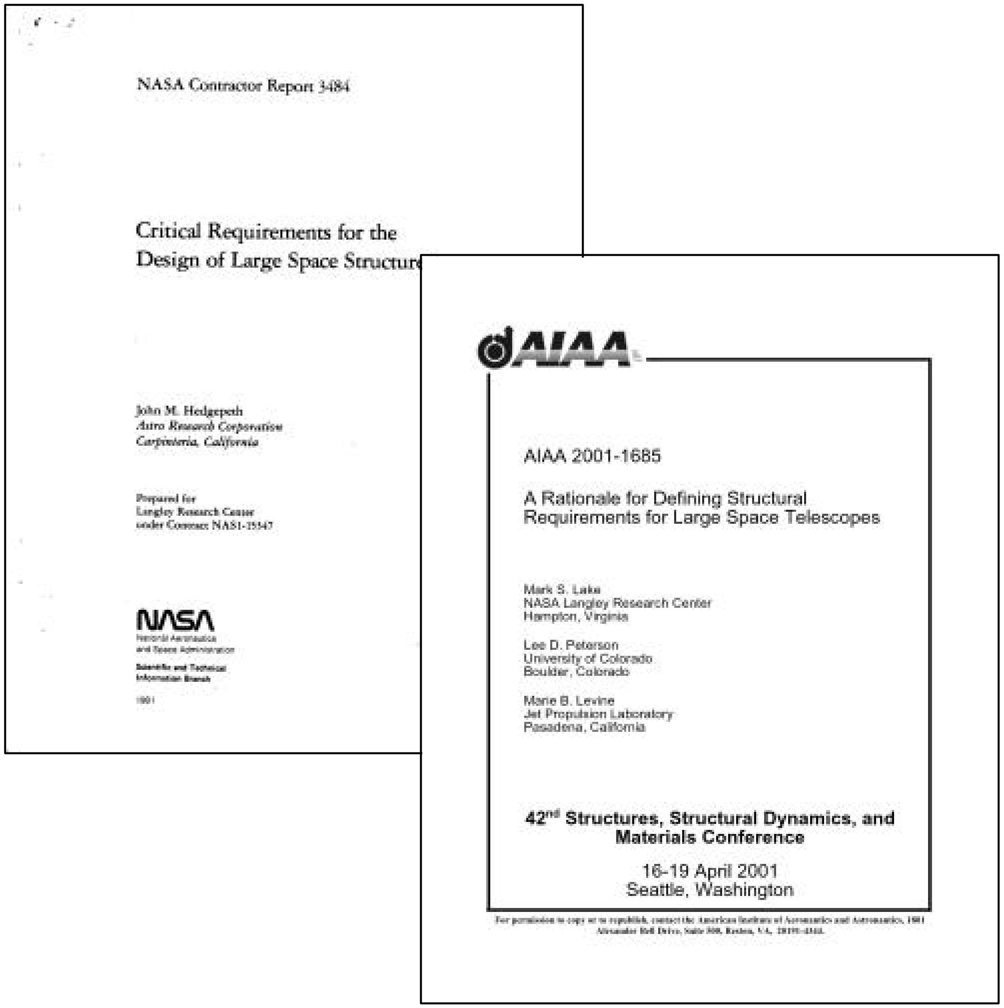
Structural Conceptual Design Process Uses Relationships Between Inertial Load Stiffness and Vibration Frequency

- Many different design drivers can be related to constraints on the lowest vibration frequencies of the structure
- Generally

$$u ? ? \frac{a}{4?^2 f_0^2}$$

- Depending on mode shape and the projection of the load onto the mode

$$? ? 1$$



NASA Contractor Report 3484

Critical Requirements for the
Design of Large Space Structure

John M. Hedgepeth
Astro Research Corporation
Carpinteria, California

Prepared for
Langley Research Center
under Contract NAS1-15347

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

AIAA

AIAA 2001-1685

A Rationale for Defining Structural
Requirements for Large Space Telescopes

Mark S. Lake
NASA Langley Research Center
Hampton, Virginia

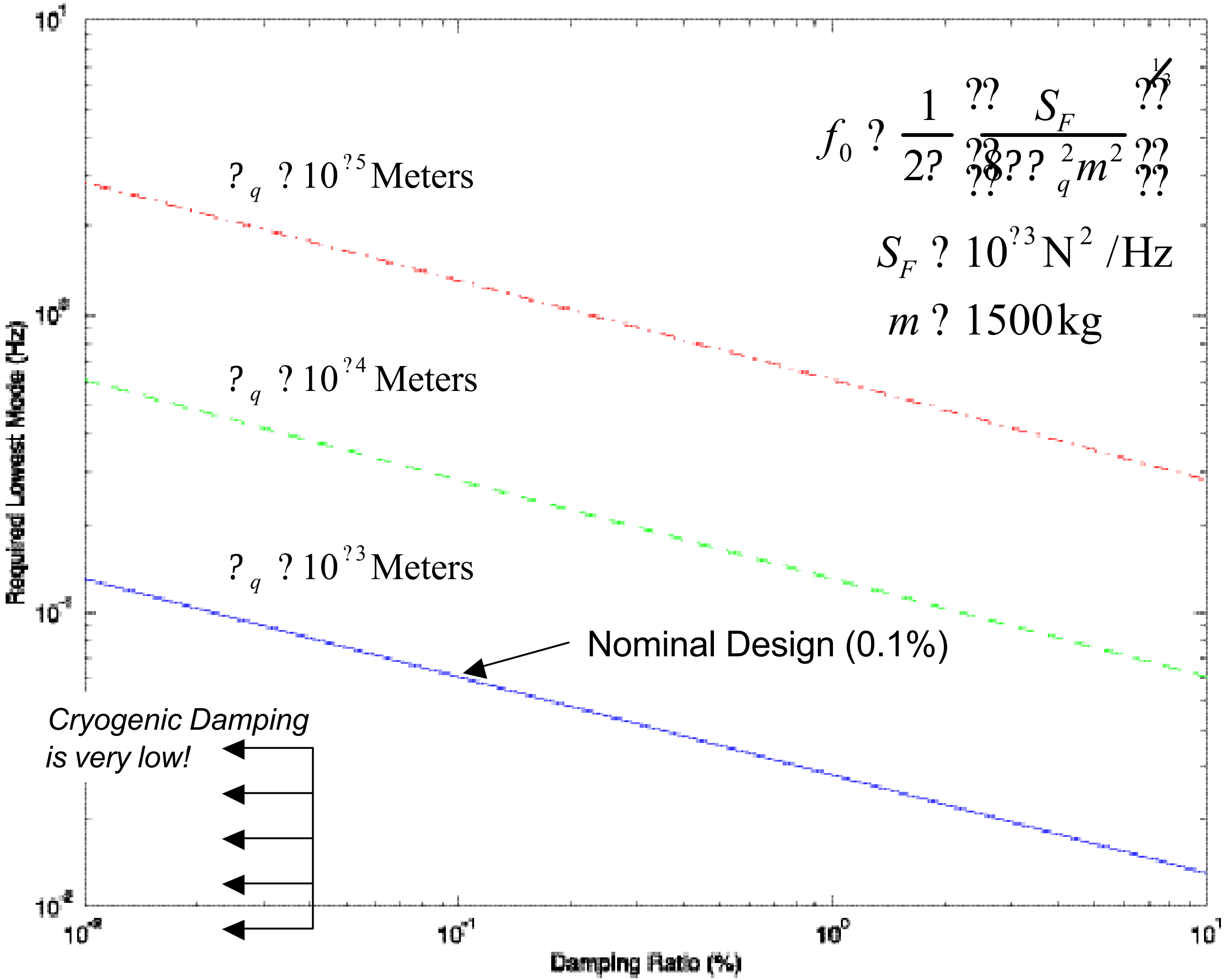
Lee D. Peterson
University of Colorado
Boulder, Colorado

Marie B. Levine
Jet Propulsion Laboratory
Pasadena, California

42nd Structures, Structural Dynamics, and Materials Conference

16-19 April 2001
Seattle, Washington

Required Frequency Depends on Damping Ratio and Structural Requirement



$$f_0 ? \frac{1}{2?}\left(\frac{S_F}{8? ?_q^2 m^2}\right)^{1/3}$$

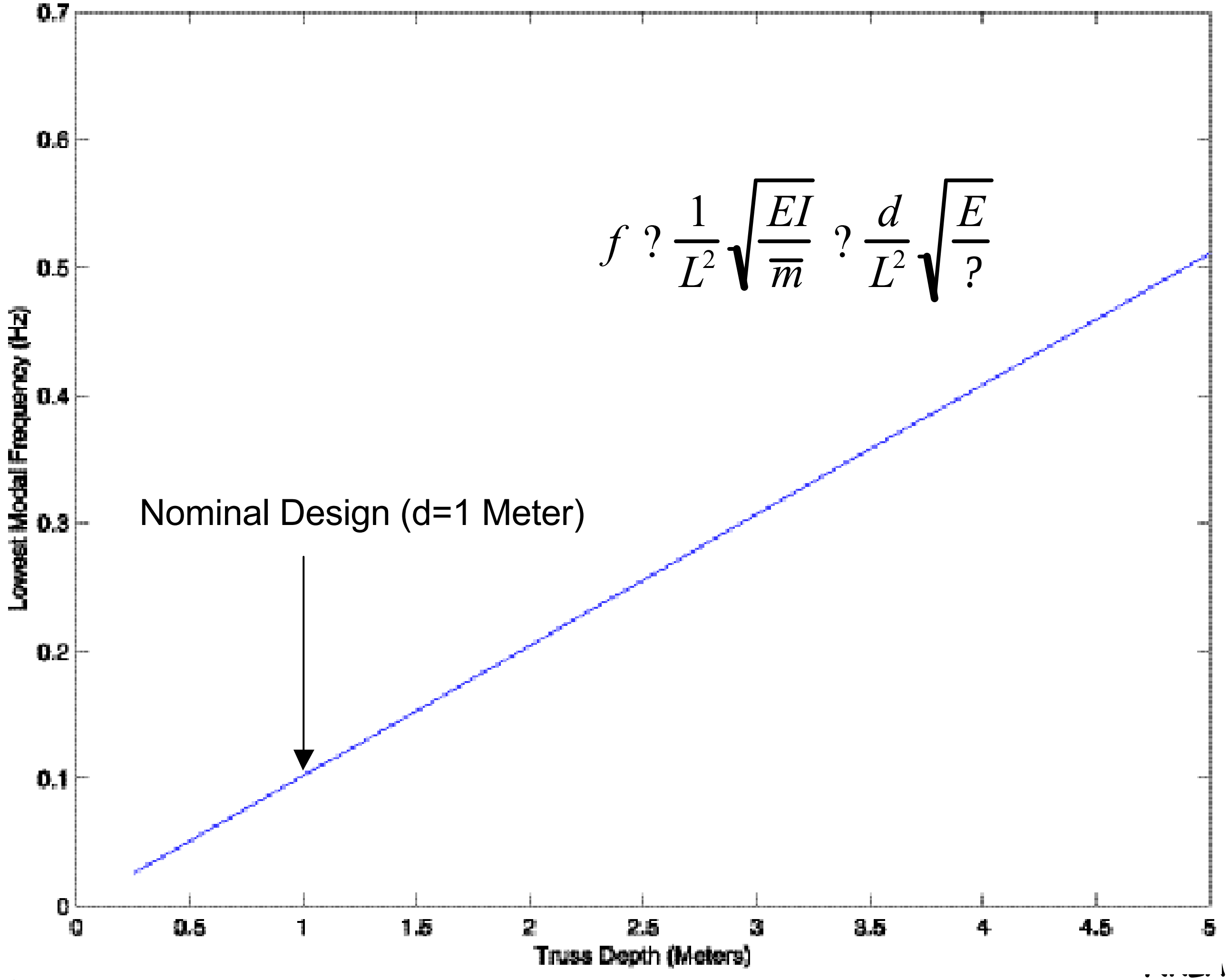
$S_F ? 10^{?3}\,\mathrm{N}^2/\mathrm{Hz}$

$m ? 1500\,\mathrm{kg}$

Nominal Design (0.1%)

Cryogenic Damping is very low!

How Frequency Depends on Structural Depth



$$f \; ? \; \frac{1}{L^2}\sqrt{\frac{EI}{\overline{m}}} \; ? \; \frac{d}{L^2}\sqrt{\frac{E}{?}}$$

Nominal Design (d=1 Meter)

Optical Telescope Assemblies

- Total of 7 OTA's
- Position

$$x \; ? \; ?\,?50 \quad ?32.4 \quad ?20.6 \quad 2.9 \quad 38.2 \quad 44.1 \quad 50\,?\,\text{Meters}$$

$$y = 0$$

$$z = 0$$

- Model as rigid bodies

$$m \; ? \; 650\,\text{kg}$$

$$I_{xx} \; ? \; I_{yy} \; ? \; 260\,\text{kg}\,\text{Meters}^2$$

$$I_{zz} \; ? \; 429\,\text{kg}\,\text{Meters}^2$$

- Geometric Tolerances

$$u_x, u_y, u_z \; ? \; 10^{?3}\ \text{Meters}$$

$$?_x, ?_y, ?_z \; ? \; 10^{?4}\ \text{Radians}$$

Spacecraft Characteristics

- Position

$$x \; ? \; 0$$
$$y = 4.3$$
$$z = -5$$

- Model as a rigid body

$$m \; ? \; 2500\,\mathrm{kg}$$
$$I_{xx} \; ? \; I_{yy} \; ? \; I_{zz} \; ? \; 2500\,\mathrm{kg\,Meters}^2$$

Optics Bay Characteristics

- Position

$$x ? 0$$
$$y = 4.3$$
$$z = -3$$

- Model as a rigid body

$$m ? 1100\,\mathrm{kg}$$
$$I_{xx} ? I_{yy} ? I_{zz} ? 1100\,\mathrm{kg\,Meters}^2$$

Centrifugal Loading Due to the Nominal Rotation Rate

- 1 rev/3hrs

$$\omega = 2\pi/(3 \times 3600) = 5.8 \times 10^{-4} \text{ Radians/Second}$$

- Constraint on lowest axial vibration frequency to meet deformation requirement

$$f_0 = \sqrt{\frac{L\omega^2}{8\pi^2 u_y}} = \sqrt{\frac{100 \times \left(5.8 \times 10^{-4}\right)^2}{8\pi^2 0.001}} = 0.021\text{Hz}$$

Slew and Retargeting

- Ramp-up/Ramp-down with an angular acceleration of

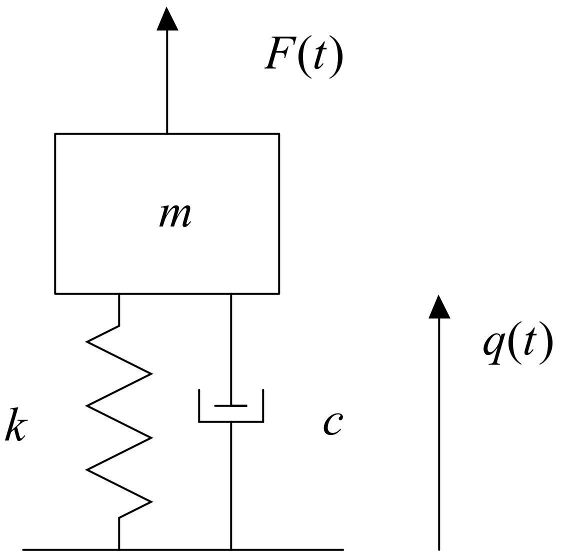
$$? \; ? 10^{?7} \, \text{Radians/Second}^2$$

- Assume slew profile is shaped to avoid dynamic overshoot (factor of 2)
- Constraint on lowest bending vibration frequency to meet deformation requirement

$$f_0 \; ? \; \sqrt{\frac{L?}{8?^2 u_y}} \; ? \; \sqrt{\frac{100 \, ? 10^{?7}}{8?^2 0.001}} \; ? \; 0.011\text{Hz}$$

- Note: If this vibration frequency requirement is met, the vibration damping required to settle need not be considered

Stochastic Response of Single DOF to Random Loading

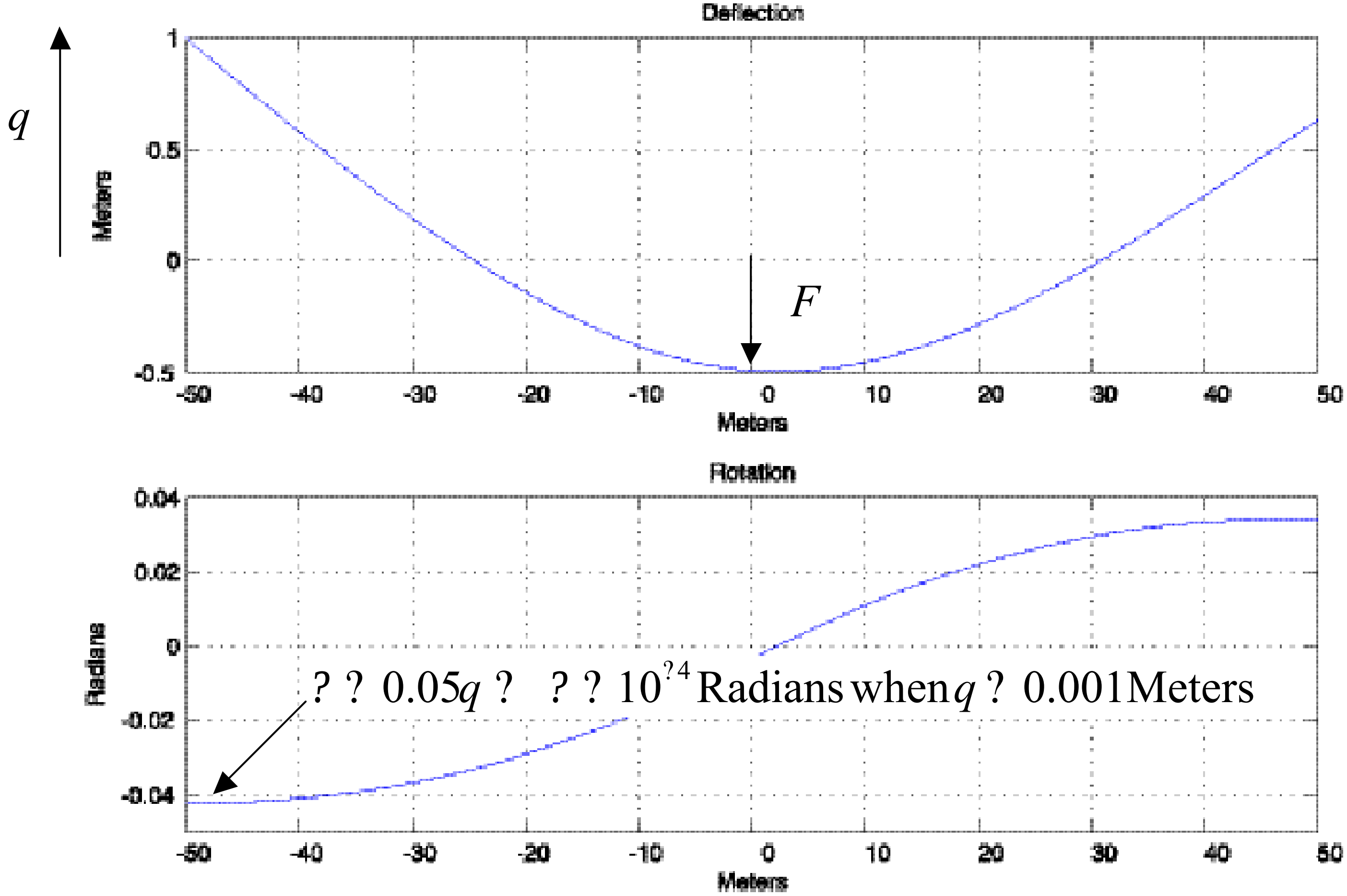


$$\mathrm{RMS}(q) ? ?_q ? \sqrt{\frac{S_F}{8??^3 m^2}}$$

$$? ? \sqrt{\frac{k}{m}}$$

$$? ? \frac{c}{2? m}$$

First Mode Shape is Nearly Symmetric



? ? 0.05q ?   ? ? $10^{?4}$ Radians when q ? 0.001Meters

Convert Equations of Motion Using Mass Normal Modes to Get Correct Modal Mass

- EOM $M\ddot{x} ? Kx ? F$

- Eigenanalysis for the first mode yields

$$\ddot{?}? ? ^2? ? ?$$

$$?^T M? ? I, \quad ?^T K? ? ?^2$$

$$? ? ?^T F$$

- Write in terms of q and F

$$q ? ?_q ?, \quad ?^T F ? ?_F F$$

$$\frac{1}{?_q ?_F}\ddot{q} ? \frac{?^2}{?_q ?_F} q ? F ? \quad ?_q ? \sqrt{\frac{S_F}{8??^3 m^2}}, \quad m ? \frac{1}{?_q ?_F} ? 1587\text{kg}$$

Example Result
(Nominal Conceptual Design)

- Express bending frequency constraint as a bound:

$$f_0 \geq \frac{1}{2\pi}\left(\frac{S_F}{8\zeta\sigma_q^2 m^2}\right)^{1/3}$$

$$S_F = 10^{-3}\,\mathrm{N}^2/\mathrm{Hz}$$

$$\zeta = 0.001$$

$$\sigma_q = 0.001\,\mathrm{Meters}$$

$$m = 1500\,\mathrm{kg}$$

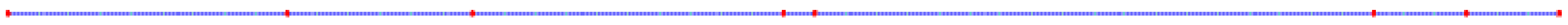
$$\Rightarrow \quad f_0 \geq 0.061\,\mathrm{Hz}$$

Beam Finite Element Model
Used for Conceptual Design Analysis

- Assumed material properties
  - Generic CFRP (graphite epoxy)

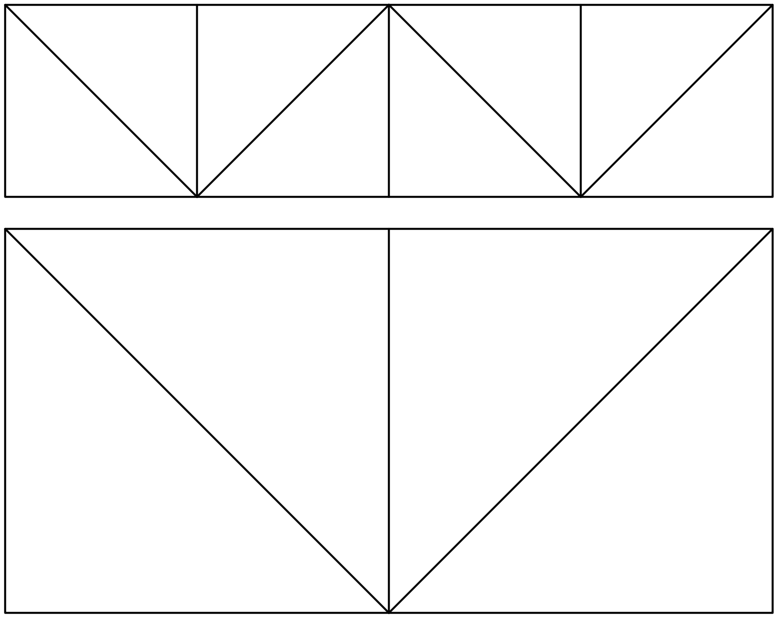
- Truss member dimensions
  - Diameter: 1 cm
  - Solid crossection

$$\left.\begin{array}{l} E\ ?\ 97\text{GPa} \\ ?\ ?\ 1600\,\text{kg}/\text{m}^3 \end{array}\right\}\ \text{Fairly weak CFRP}$$

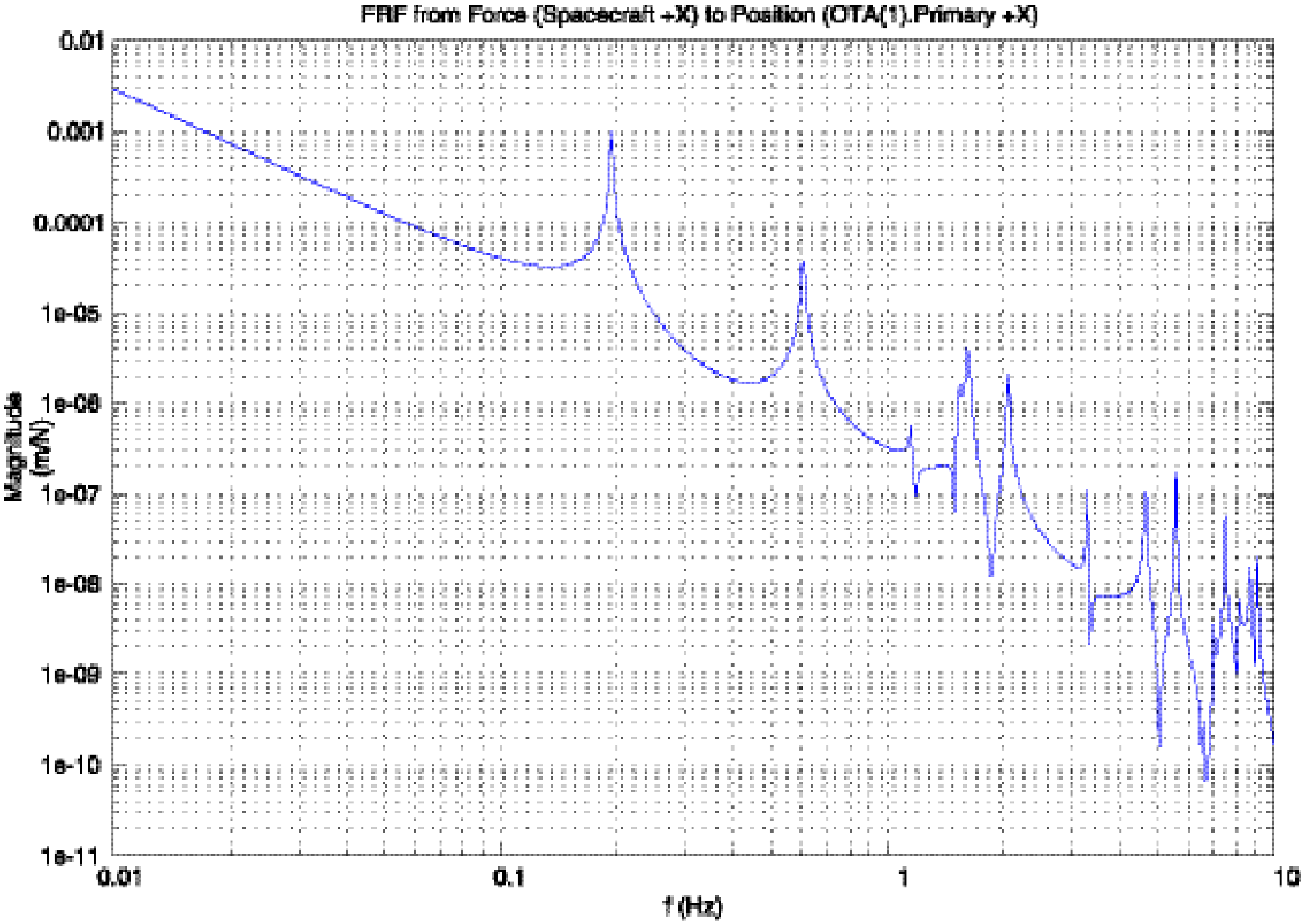


Structural Mass Does Not Vary with Depth (to first order)

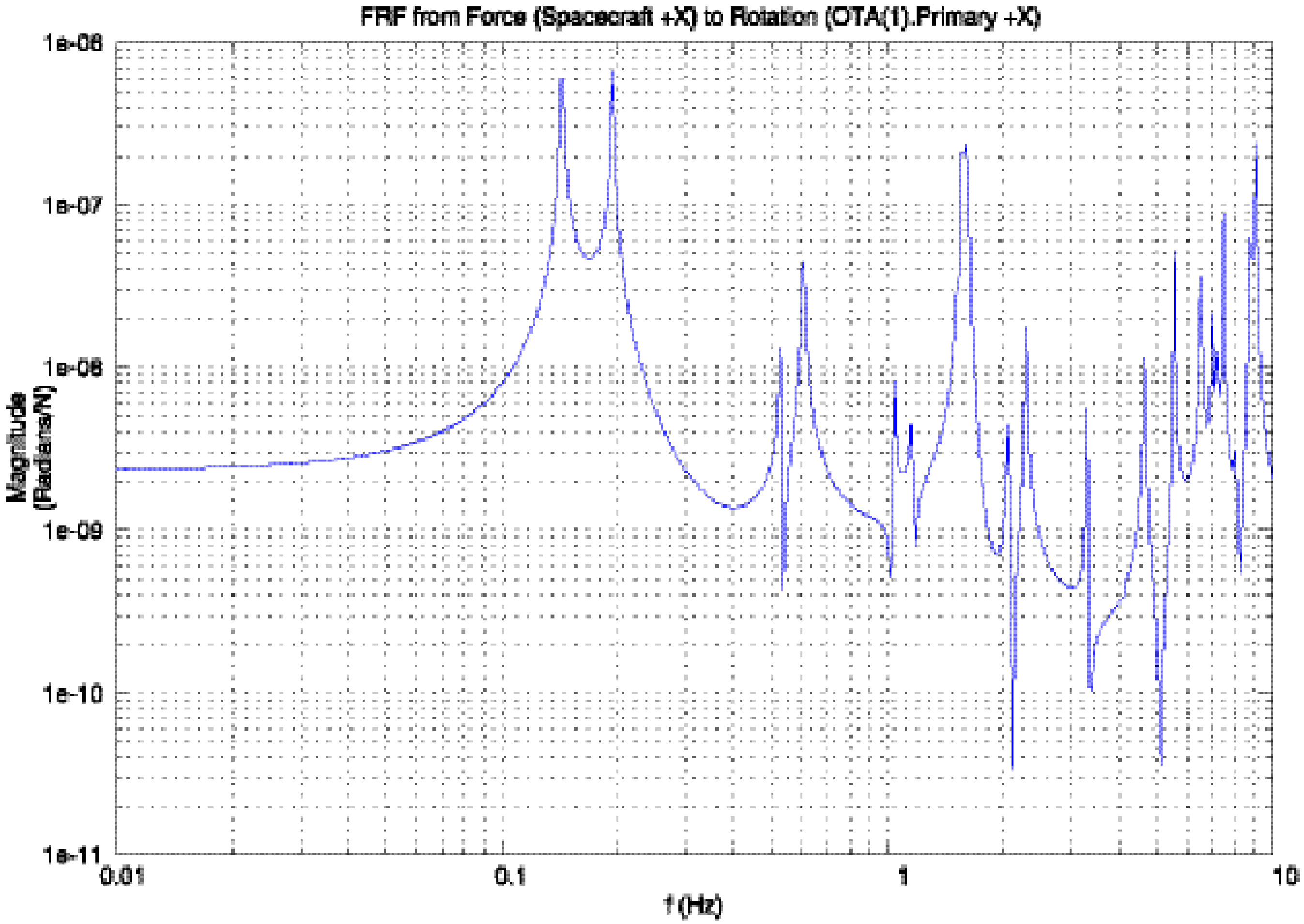
- Longerons, diagonals and battens all have the same crossection
- To first order, the mass does not vary with depth



LTI Bode Plots: X Force to OTA-1 Primary X Displacement



LTI Bode Plots: X Force to OTA-1 Primary X Rotation



What About "Microdynamic" Effects?

- Nonlinear instabilities due to
  - Joint friction and microslip
  - Material microplasticity
- Experience to date indicates
  - Spontaneous vibrations can be generated by the release of internal strain energy
    - Due to mechanical or thermal loads
  - Bounding (energy) analysis of these effects partially developed
    - Links joint microslip requirements and overall structural modal and kinematic properties to microdynamic vibration amplitudes
  - Active control of these instabilities has not been demonstrated in published literature
    - But likely to require increased controller bandwidth to include structural modes (perhaps high frequency local modes)
- Very likely to be a "design issue" not a "feasibility issue" for TPF boom

What About Separated Spacecraft / Connected Structure Trade?

- This study baselined a connected structure
  - Did not consider separated spacecraft (e.g. the TPF Book design)
- Prior studies of this trade should be reexamined
  - Should not rely on scaling of prior “historical” deployed boom canister masses
    - For example: “SRTM” boom by AEC-ABLE
    - Boom in that case was 29% of total Boom+Canister mass
    - SRTM boom designed for LEO loads and Shuttle req’ts
  - Current structural technology under development will likely (greatly) reduce the required canister mass
  - Human/robotic assembly eliminates the canister mass
    - Require minor mass allotment for launch hardware

L2 Environment

- Environment for Operation of the Telescope
- No stressing issues – designs can meet environment

Area of Concern	Sources and Values
Thermal	Solar constant for heating at L2 is in a range from 1291 - 1421 W/m^2
Plasma	Energy from ions ~ 10 eV
	Energy from electrons ~ 50 eV
Meteroids	1e-4 cm diameter, 162 impacts/m2/year
	1 cm diameter, 6.3e-8 impacts/m2/year
Solar Pressure	1360 W/m^2
Magnetic Fields	Magnetic field of magnetotail ranges from 2 - 10 nT.
	Magnetic field of interplanetary field is ~5 nT.

Link Budget

- X-band
  - Perhaps Ka-band Depending on Regulatory and Technology Issues
  - 40-W TWTA With 1.0-m Diameter High Gain Antenna on 2-DOF Gimbal
  - Data Rate = 2Mbps (8 Hr Downlink Per Week)

  - Downlink Budget

LINK	**Data Rate (Mbps)**	**Data Channel Margin 3? (dB)**	**Carrier Channel Margin (dB)**
Imaging Telemetry to DSN 34m ground station	2.0	18.0	49.1
Imaging Telemetry to commercial 11m ground station	2.0	6.9	37.8

C&DH

- Spacecraft Processor
  - Spacecraft Monitoring
  - Need to Run Attitude Control Algorithms
  - Need to Run Navigation Algorithms for L2 Dynamics
  - No Formation-Flying Algorithms
  - Separate Processor in Optics Bay for Image Processing
- Data Bus
  - Average Data Collection Rate = 1Gb Per Day
    - Demand Less Than 1 Mbps, Which Is Currently Available With MIL-STD-1553B
- Data Storage
  - Requirement of 3 Weeks Worth of Data
  - 168 Gb Recorder (Solid State), EOL
    - Not Unreasonable Considering Time Frame

Spacecraft Disposal

- Assuming NASA Safety Standard 1740.14 Still in Effect.
- Spacecraft Should Be Moved Out of L2 Halo Orbit
- Chaotic Dynamics at Quasi-stable L2 Very Useful
  - Small ? V (Burn to Depletion) to Remove Assembly From L2 Into Heliocentric Disposal Orbit

Biomarker Report – Recommended Bands

FEATURE	BAND LIMITS [microns]	MEAN ? ?microns?	? ? ?microns?	R
H_2O	6.67 – 7.37	7.00	0.7	10
CH_4	7.37 – 7.96	7.65	0.59	13
CH_4	7.37 – 8.70	7.98	1.33	6
Continuum	8.16 – 9.24	8.67	1.08	8
CO_2	9.07 – 9.56	9.31	0.49	19
O_3	9.37 – 9.95	9.65	0.58	17
CO_2	10.10 – 10.75	10.42	0.65	16
Continuum	10.14 – 12.44	11.17	1.3	5
CO_2	13.33 – 17.04	14.96	3.71	4