THE AIR FORCE RESEARCH LABORATORY
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RF APERTURE ARCHITECTURES

11 Nov. 08

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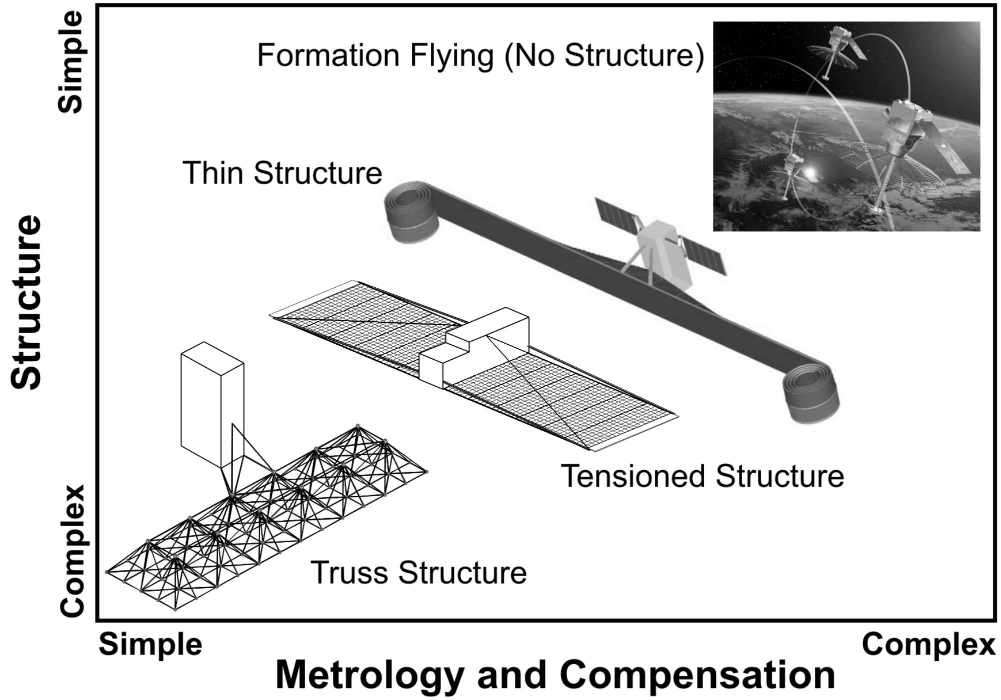
Mitigating Structural Deformations



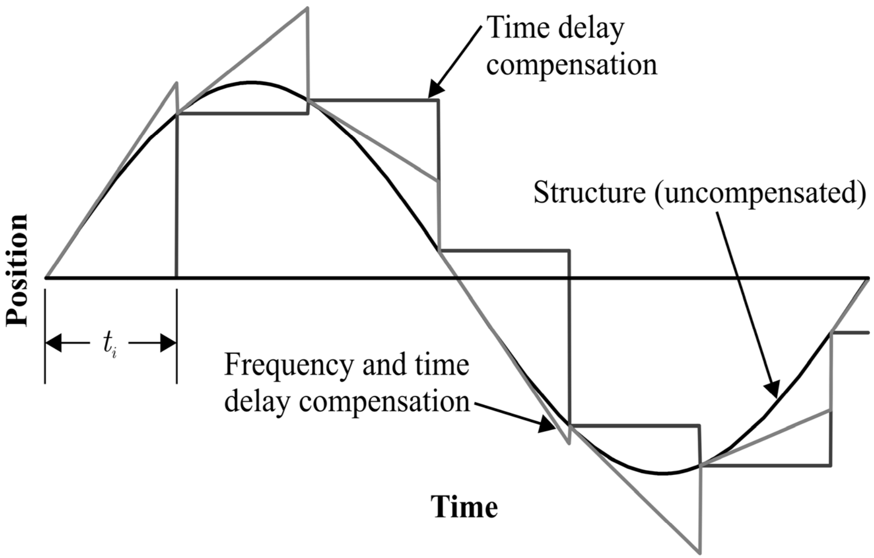
- **Mitigating structural deformations in large apertures:**
  - **There is always a trade between *ACTIVE TECHNOLOGIES* (shape correction, metrology and electronic compensation, etc.) and PASSIVE STRUCTURAL TECHNOLOGIES (structural hierarchy, material dimensional stability, deployment)**
  - **This trade is a specific function of how electromagnetic energy behaves and what about it is being sensed**
  - **It is not always as simple as "keep RMS surface errors less then $\lambda/30$"**
- **This presentation investigates this relation and derives RF system architecture development recommendations from it**

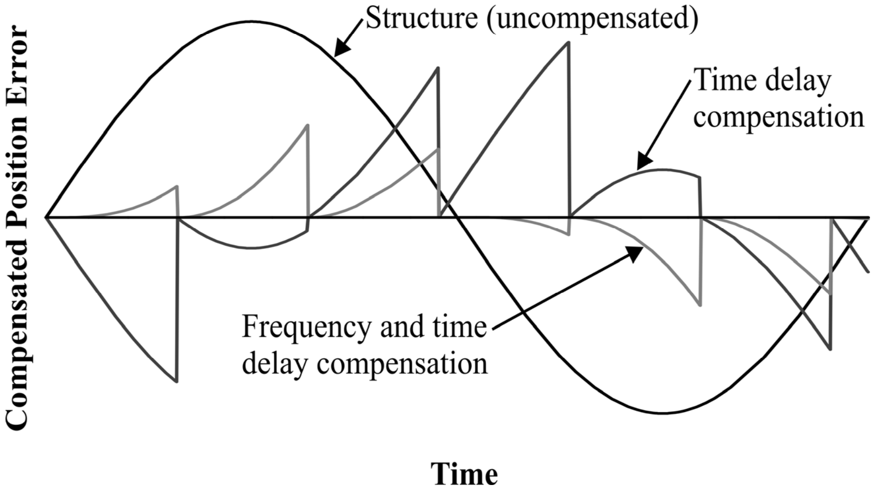
Scope

- Developed for multi-element RF systems that transmit and receive (phased arrays, phased arrays with reflectors)
  - Radar
    - Imaging, tracking, 3D terrain
  - Communications
- Applicable to receive only systems as well
- Many sources of system errors
  - Thermal stability, dynamic stability, electronic stability
- Under consideration here:
  - Only structural dynamic deformations
  - Only one dimensional apertures
- Infinite knowledge of structural deformations is assumed when needed
  - Challenges of obtaining this information through metrology or other techniques are not addressed here.

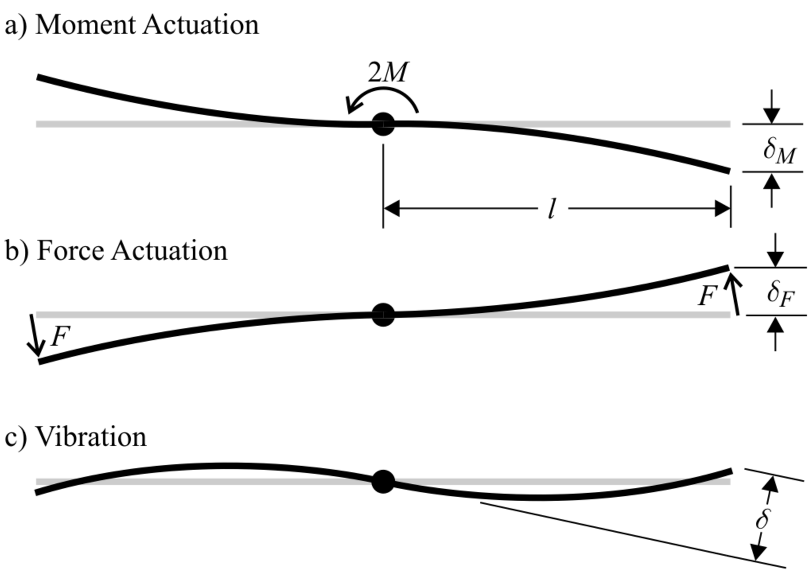
Phase Measurement

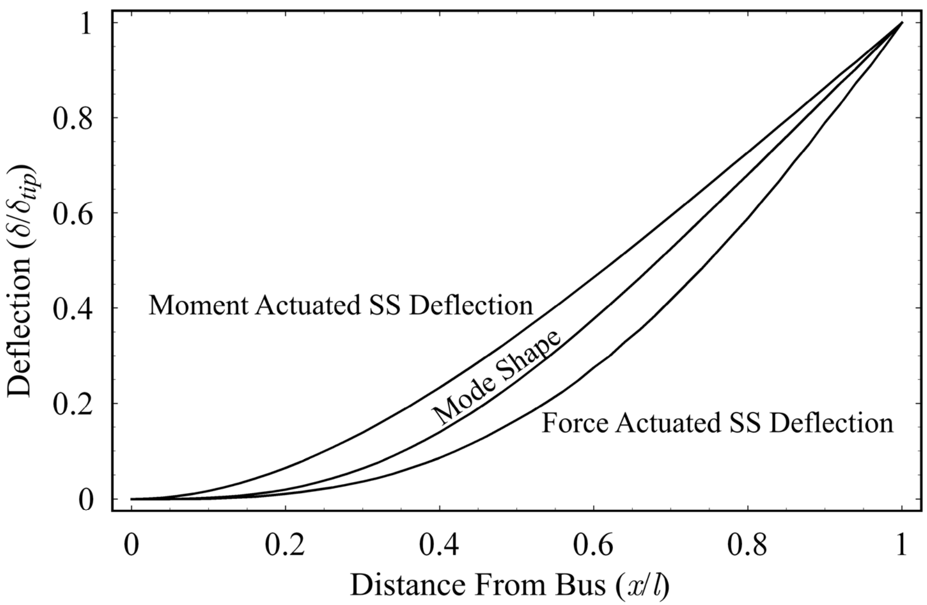
- Goal is to adjust phase of incoming/ outgoing radiation over entire aperture for coherent beam
  - Assume the sensor (or some element in the optical path) is moving and changing the phase (time delay) of the radiation
  - Assume the motion is sinusoidal (derived from vibrations due to low order structural mode)
  - Consider three levels of phase shift (time delay) adjustment of the sensor to correct for the motions
    - 1) No change
    - 2) Adjust time-delay, updated regularly
    - 3) Also adjust rate of change of time-delay (equivalent to frequency shift), updated regularly
- Can this be translated into structural requirements?
- Can structural requirements be translated into deployable structure architectures?





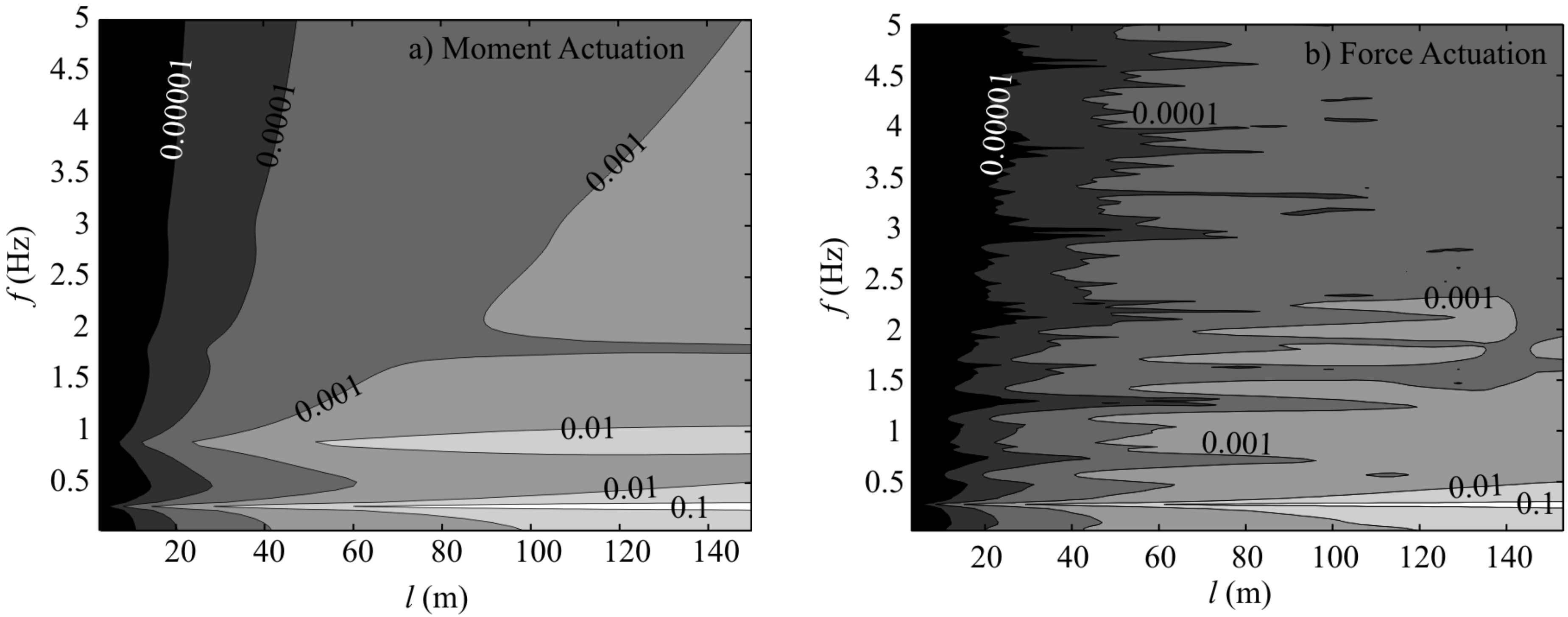
Structural Dynamic Excitations





- **Two excitation methods**
  - **Structure is torqued by CMG or reaction wheel placed at center of aperture**
  - **Forces from thrusters placed at ends of aperture**
- **Moment actuation, force actuation and vibrations all have similar though not identical shapes**
- **Bang-bang control scheme employed to slew system 90 degrees**
  - **Actuators turned on to accelerated aperture, reversed to decelerate it, no coasting period**

Actuation Methods Only Excite a Single Mode



- Power spectral density plots for post actuation vibrations along aperture length
  - Normalized so that maximum is 1
- Mode described in last slide is only mode significantly excited
  - Not the first mode
  - Force actuation spreads energy among modes more significantly, but most is still in one mode

Estimate Stiffness and Deformation

- **Excited structural mode frequency:** $$f = \frac{\lambda^2}{2\pi l^2}\sqrt{\frac{EI}{m}}, \qquad \lambda = 3.9266$$
- **Rotational acceleration due to moment and force actuation:**
$$\alpha = 3\frac{M}{ml^3} \qquad \alpha = 3\frac{F}{ml^2}$$
- **Quasi-static deflection due to constant rotational acceleration:**
$$\delta_M = \frac{11}{120}\frac{\alpha m l^5}{EI} \qquad \delta_F = \frac{Fl^3}{3EI} - \frac{11wl^4}{120EI}, \; w = 3\frac{F}{l}$$
$$\delta_M = \frac{11}{480\pi^2}\frac{\alpha l \lambda^4}{f^2} \qquad \delta_F = \frac{7}{1440\pi^2}\frac{\alpha l \lambda^4}{f^2}$$
- **Observations:**
  - **Equations can be used to determine minimum stiffness for a maximum deformation requirement**
  - **Force actuation results in 4.7 times less structural deformation**
  - **Deflections decrease with the square of frequency**

Deformation Speed and Acceleration

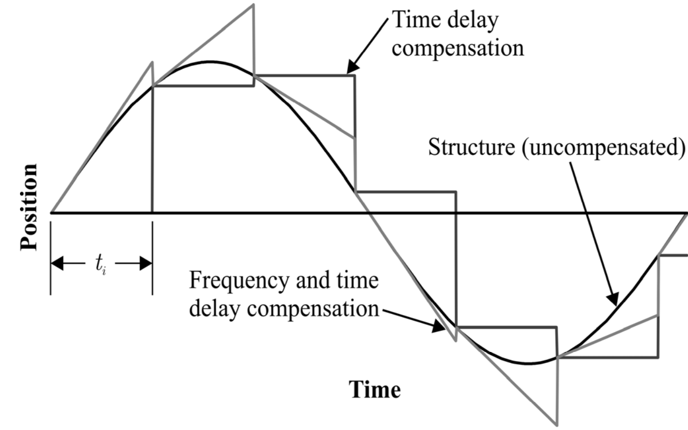
- **Based on the amplitude and frequency of deformations, the maximum speed of the aperture tip is:**

$$v_{M,\max} = u_D \frac{11}{120} \alpha \lambda^2 l^3 \sqrt{\frac{m}{EI}} \qquad v_{F,\max} = u_D \frac{7}{360} \alpha \lambda^2 l^3 \sqrt{\frac{m}{EI}}$$

- **And the maximum acceleration of the tip is:**

$$a_{M,\max} = u_D \frac{11}{120} \alpha l \lambda^4 \qquad a_{F,\max} = u_D \frac{7}{360} \alpha l \lambda^4$$

Three Compensation Strategies



1) No compensation

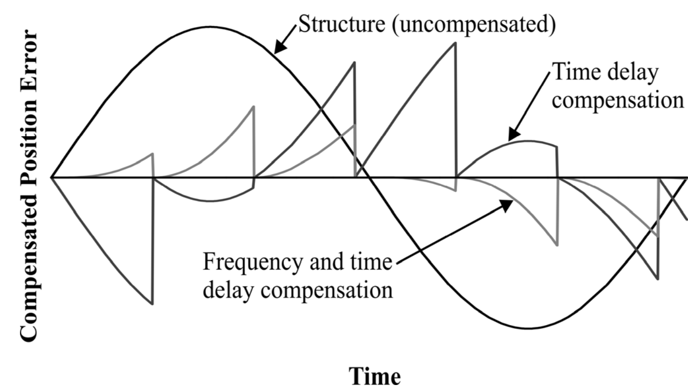
- Deformations must be less than some fraction of wavelength
- Stiffness requirement derived from quasi-static deflection
- δ < coherence requirement

$$EI = u_D \frac{11}{120}\frac{\alpha m l^5}{\delta_M} \qquad EI = u_D \frac{7}{360}\frac{\alpha m l^5}{\delta_F}$$

2) Adjust time-delay, updated regularly

- Element must not move more than the allowable coherence error between updates
- Reduces to a velocity requirement
- Deformation Speed < (coherence requirement)/(update interval)

$$v_{M,\max} = u_D \frac{11}{120}\alpha\lambda^2 l^3\sqrt{\frac{m}{EI}} \qquad v_{F,\max} = u_D \frac{7}{360}\alpha\lambda^2 l^3\sqrt{\frac{m}{EI}}$$



3) Also adjust rate of change of time-delay (equivalent to frequency shift), updated regularly

- Difference between true element position and position predicted by constant velocity assumption must be less than coherence requirement

$$\Delta_M = u_D \frac{11\alpha m l^5}{60EI}\sin^2\left(\frac{t_i\lambda^2}{2l^2}\sqrt{\frac{EI}{m}}\right) \qquad \Delta_F = u_D \frac{7\alpha m l^5}{180EI}\sin^2\left(\frac{t_i\lambda^2}{2l^2}\sqrt{\frac{EI}{m}}\right)$$

3) Time Delay and Frequency Compensation

$$\Delta_M = u_D \frac{11\alpha m l^5}{60EI} \sin^2\left(\frac{t_i \lambda^2}{2l^2}\sqrt{\frac{EI}{m}}\right)$$

$$\Delta_F = u_D \frac{7\alpha m l^5}{180EI} \sin^2\left(\frac{t_i \lambda^2}{2l^2}\sqrt{\frac{EI}{m}}\right)$$

$$\Delta_{M,\max} = \lim_{EI\to 0} \Delta_M = u_D \frac{11}{240} \alpha l t_i^2 \lambda^4$$

$$\Delta_{F,\max} = \lim_{EI\to 0} \Delta_F = u_D \frac{7}{720} \alpha l t_i^2 \lambda^4$$

$$\Delta_{\max} = \frac{1}{2} a t_i^2$$

$$a_{\max} = \frac{2\Delta}{t_i^2}$$

$$a_{M,\max} = u_D \frac{11}{120} \alpha l \lambda^4$$

$$a_{F,\max} = u_D \frac{7}{360} \alpha l \lambda^4$$

$$\alpha_M = \frac{240}{11} \frac{\Delta}{u_D l t_i^2 \lambda^4}$$

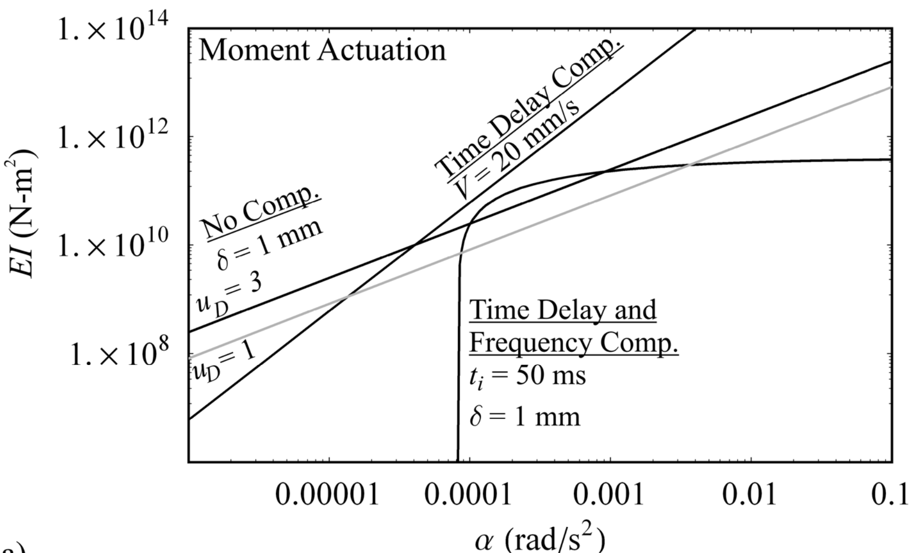
$$\alpha_F = \frac{720}{7} \frac{\Delta}{u_D l t_i^2 \lambda^4}$$

- **Error asymptotes to a limit as stiffness decreases**
  - **Structures with extremely small stiffness perform just as good as a very stiff structures, below a specific rotational acceleration**
  - **Allows definition of a maximum rotational acceleration, below which any structure will suffice**

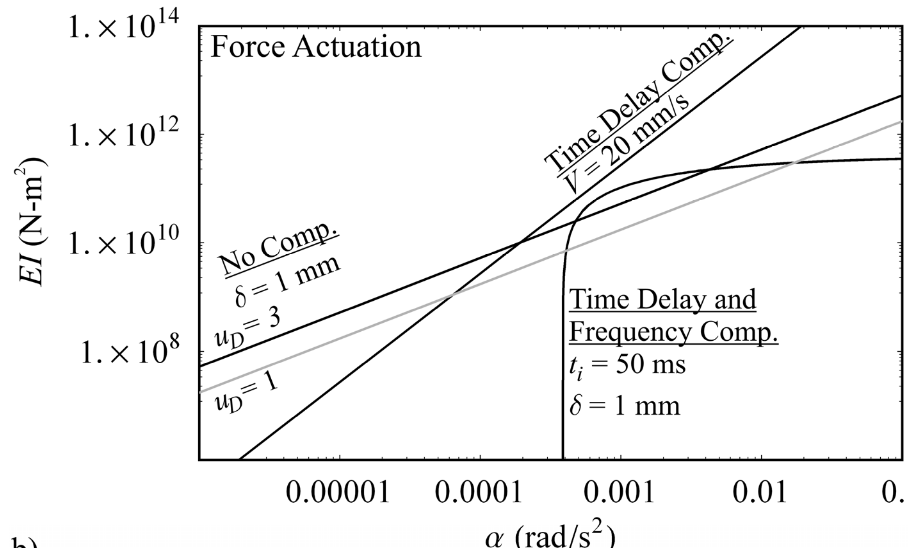
ISAT GRD

- Innovative Space-based Radar Antenna Technology (ISAT) Program
  - DARPA Funded, AFRL Executed, ended early 2007
  - Program for 300 m deployable radar system with 100:1 compaction ratio
- Government Reference Design (GRD)
  - Used for analytical calculations in this presentation
  - Three longeron tubular truss structure with bending stiffness of EI=7.546·107 N-m2 and linear mass of 1.841 kg/m
  - X-band radar panels with a linear mass of 10.0 kg/m were distributed evenly along the length of the truss for a system linear mass of m=11.841 kg/m
  - The bus and center of gravity were coincident and located at the mid length of the antenna. While the total antenna length is 300 m, the half length of the system, l=150 m, is used in all equations
  - Bus inertia is neglected because it is much smaller than the antenna inertia (the bus rotational inertia is 0.023% of the antenna)
  - Half system rotational inertia is 13.32·106 kg-m^2
  - Vibration mode excited by a slew has a frequency of 0.2753 Hz (3.632 s period). 1% of critical damping is assumed and implemented as material damping in Abaqus.
- Slew maneuver:
  - The model was subjected to a 90 deg yaw maneuver actuated with either a 300 N-m (M=150 N-m) moment applied to the system center of gravity or F=1 N tip thrusters for force actuation
  - Both actuation methods result in the same actuation moment, acceleration (1.126·10-5 rad/s^2) and time to slew (12.45 min)

Stiffness Results for GRD



a)



b)

Estimate Bending Loads

- **Loads are due to steady-state and vibrations deformations:**

$$M_M = M_{ss,M} + u_D M_{vib,M} \qquad M_F = M_{ss,F} + u_D M_{vib,F}$$

- **Steady-state deformations are:**

$$M_{ss,M} = \frac{\alpha m}{6}\left(2l + x\right)\left(l - x\right)^2 \qquad M_{ss,F} = \frac{\alpha m}{6} x\left(l + x\right)\left(l - x\right)$$

- **Maximum moment is not always at root:**

$$M_{ss,F,\max} = \frac{1}{9\sqrt{3}}\alpha m l^3 \qquad \frac{x}{l} = \frac{1}{\sqrt{3}} = 0.577$$

Estimate Bending Loads

- **Vibration mode shape is:**

$$M_{vib} = \frac{\delta EI}{l^2} \frac{\lambda^2 \left(\cos\phi - \cosh\phi - \sigma\sin\phi + \sigma\sinh\phi\right)}{\lambda\sigma\cos\lambda - 2 + \lambda\left(\sigma\cosh\lambda + \sin\lambda - \sinh\lambda\right)}, \ \phi = \lambda\left(1 - \frac{x}{l}\right), \ \sigma = 1.000777$$

- **Substitute in deflection and stiffness relations:**

$$M_{vib,M} = \frac{11}{120}\alpha m l^3 \frac{\lambda^2 \left(\cos\phi - \cosh\phi - \sigma\sin\phi + \sigma\sinh\phi\right)}{\lambda\sigma\cos\lambda - 2 + \lambda\left(\sigma\cosh\lambda + \sin\lambda - \sinh\lambda\right)}$$

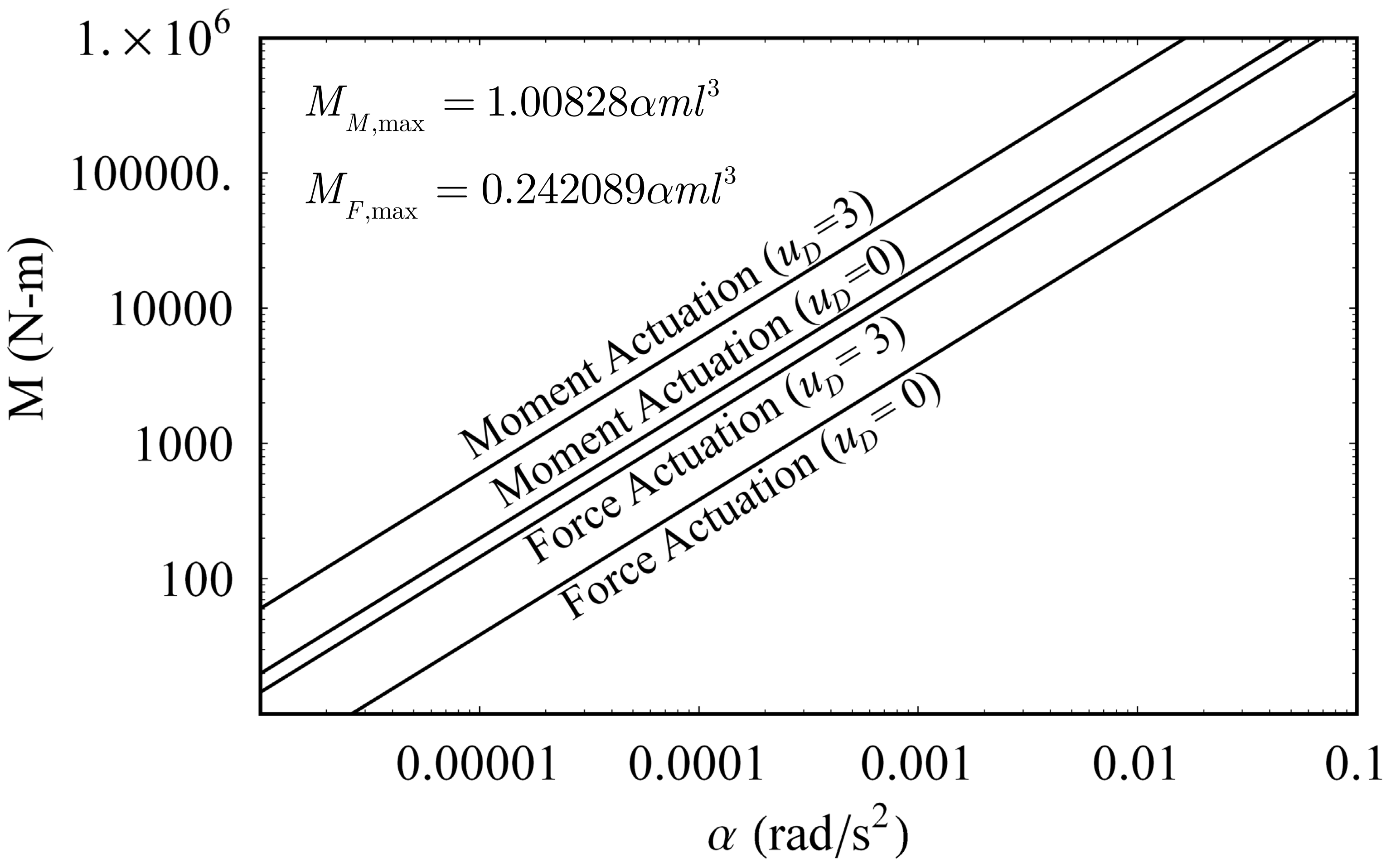
$$M_{vib,F} = \frac{7}{360}\alpha m l^3 \frac{\lambda^2 \left(\cos\phi - \cosh\phi - \sigma\sin\phi + \sigma\sinh\phi\right)}{\lambda\sigma\cos\lambda - 2 + \lambda\left(\sigma\cosh\lambda + \sin\lambda - \sinh\lambda\right)}$$

- **With amplification factors of 3 (due to actuator reversal), maximum moments are:**

$$M_{M,\max} = 1.00828\alpha m l^3 \quad \text{at} \quad \frac{x}{l} = 0.38261$$

$$M_{F,\max} = 0.242089\alpha m l^3 \quad \text{at} \quad \frac{x}{l} = 0.44666$$

Bending Strength



Truss Structural Performance

- Bending stiffness and strength per mass requirements drive structural architecture choices
  - Extremely stiff and low mass requirements lead to extreme mechanical complexity to achieve increased hierarchy
  - Relaxed stiffness and mass requirements lead to simpler deployable structures
  - This relationship can be investigated with structural performance metrics
    - Important to consider both strength and stiffness

Truss Structural Performance Metrics

Require-
ments

Bending Strength

Bending Stiffness

Geometry Indices
-Truss architecture
-Longeron architecture
-Number of longerons

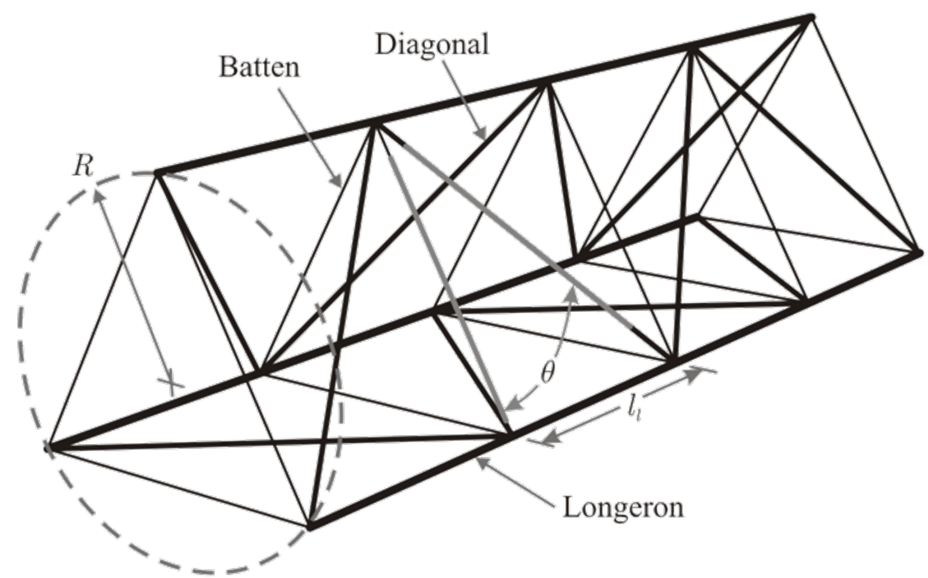
$$\mu = \frac{\left(EIM^2\right)^{1/5}}{w} = \frac{\pi^{4/5}}{2^{3/5}}\,\mu_m\,\overbrace{\mu_t\,\mu_l\,\mu_n}$$

Mass Per Length

Material Index

Specific Structural Performance

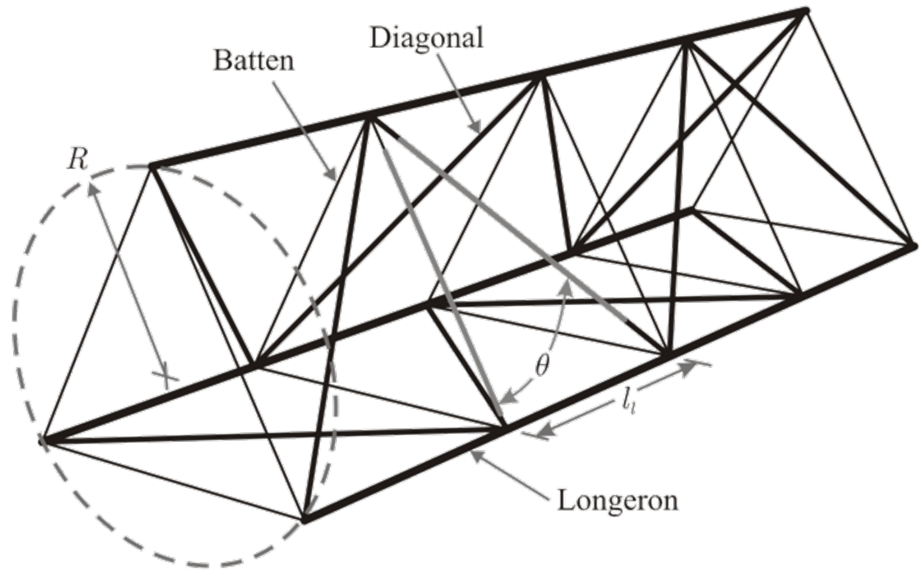
- **Two ways to increase structural performance:**
  - **Materials**
  - **Hierarchy (geometry)**



Murphey, "Chapter 1: Booms and Trusses" in *Recent Advances in Gossamer Spacecraft*, Ed. Jenkins, AIAA 2005

Truss Structural Performance Metrics

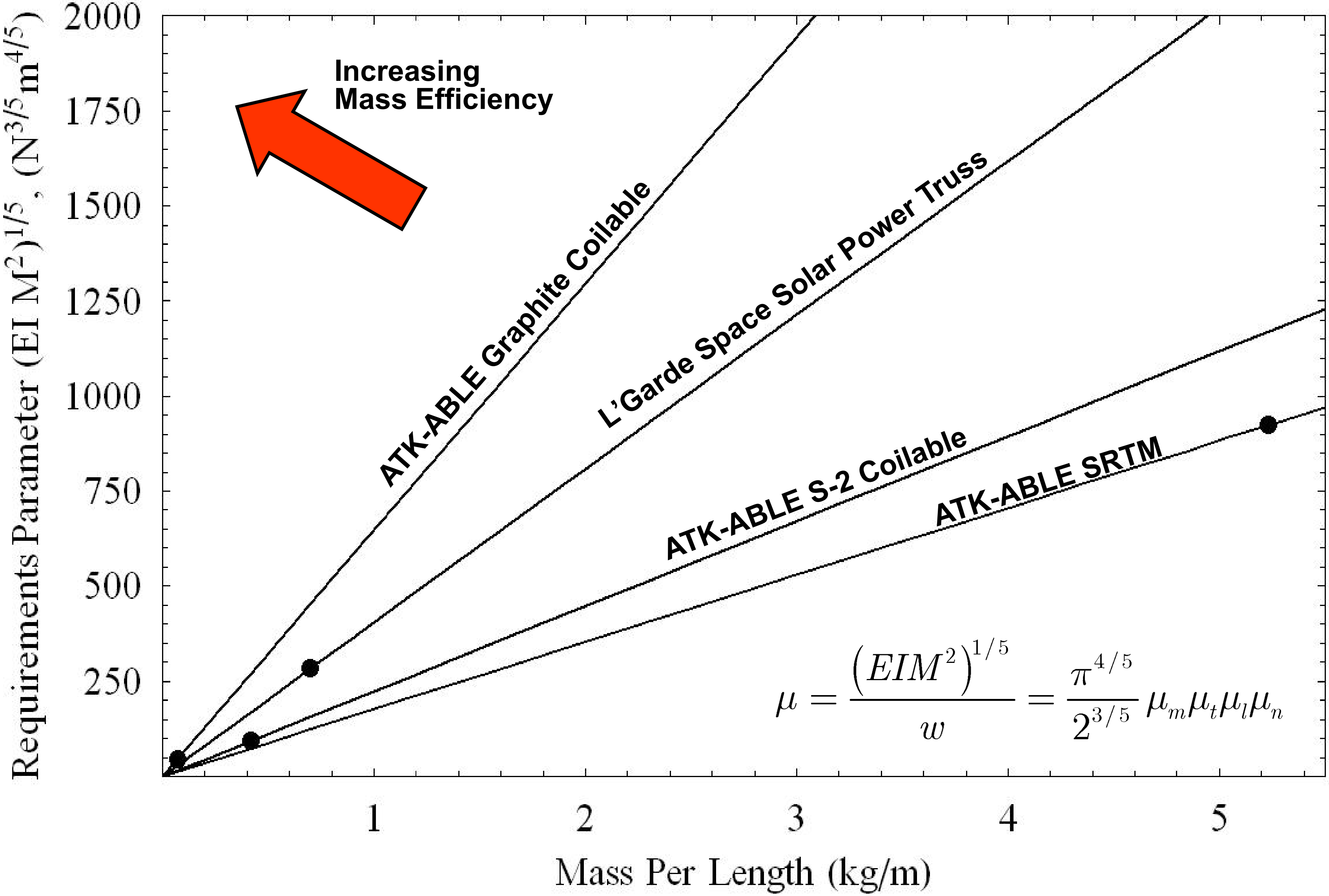
$$\mu = \frac{\left(EIM^2\right)^{1/5}}{w}$$



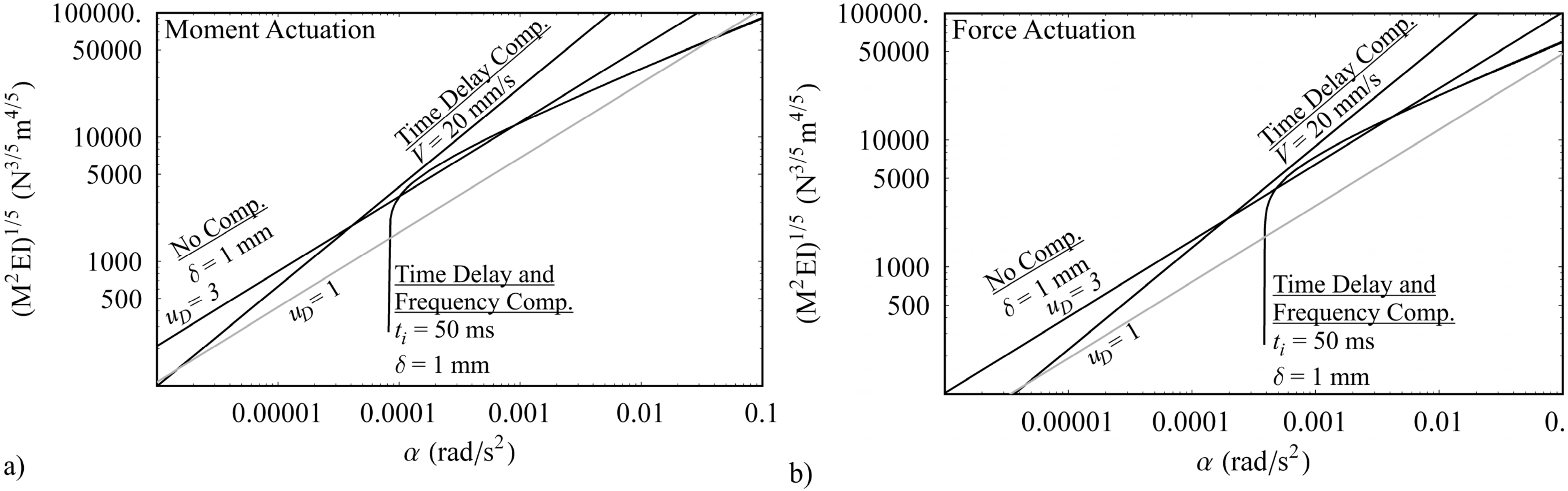
- Metric captures both stiffness and strength requirement
- 1/5 and 2 powers correctly mass normalize metric
  – Mass does not scale linearly or the same with stiffness and strength
- Correctly captures constant mass trade between stiffness and strength
  – As truss radius (R) is increased without changing strut cross sections, stiffness increases while strength decreases

Murphey, "Chapter 1: Booms and Trusses" in *Recent Advances in Gossamer Spacecraft*, Ed. Jenkins, AIAA 2005

Steeper slope represents increased performance per mass

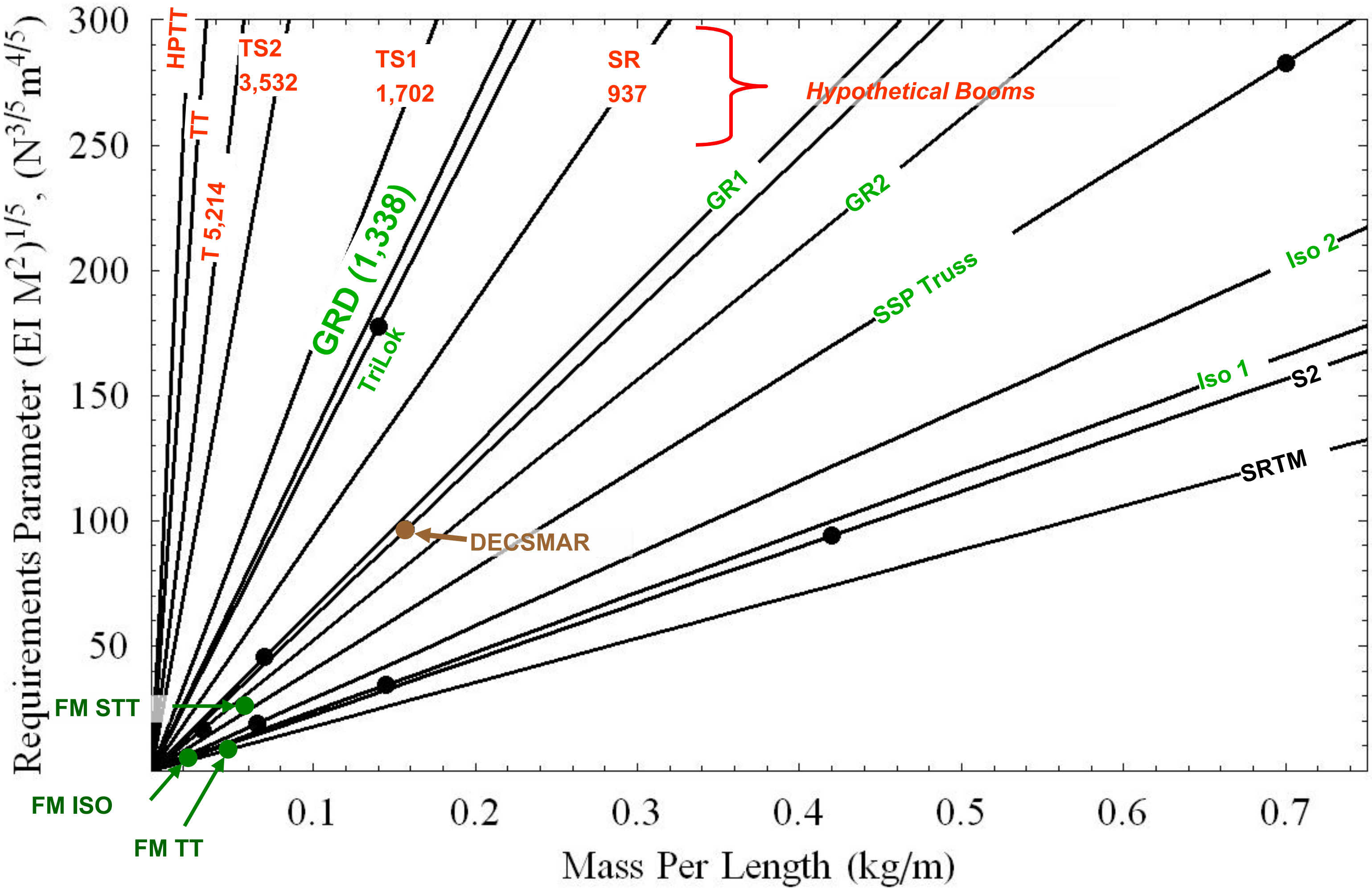


Combined Stiffness and Strength Requirements



- **Requirements plummet below a certain rotational acceleration**
- **Above this limit:**
  - **Limiting total deformations is nearly as good as time delay and frequency compensation**
  - **Better to forgo active systems for passive structural stability in high dynamic excitation systems**
- **Below this limit:**
  - **Time delay and frequency compensation allow extremely low requirements**
  - **Time delay compensation has significantly lower requirements than no compensation**

Comparing Architectures



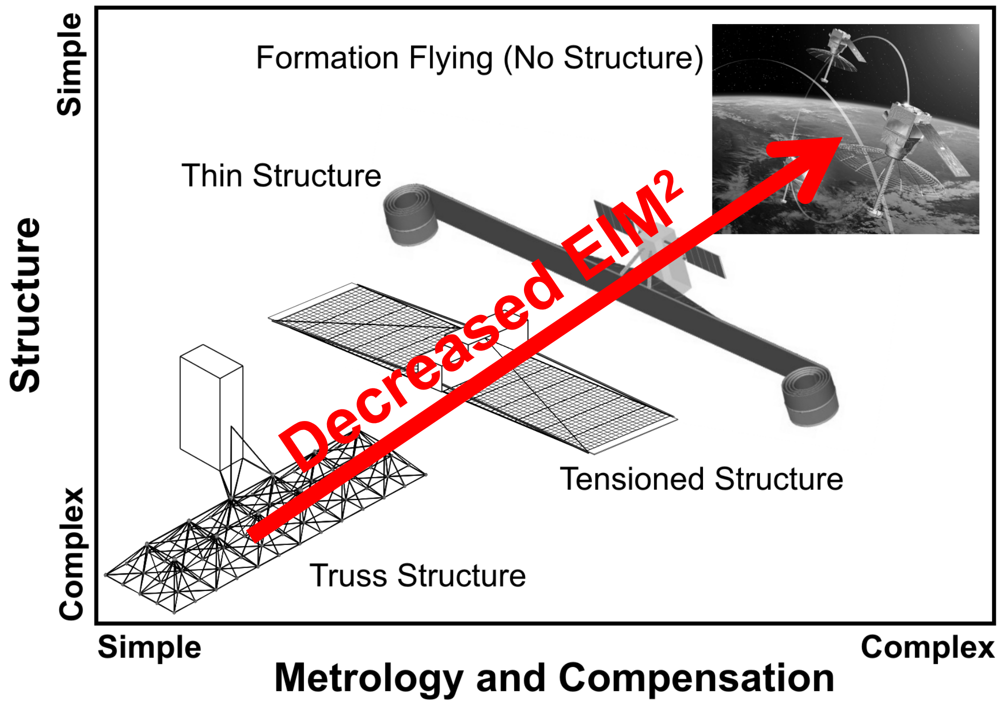
Development of RF Systems

- **Ideal case is when both time delay and frequency compensation are feasible**
  - **Stiffness requirement can be greatly reduced**
  - **Caution: deformations become very large and still impose significant design constraint**
  - **Update rate must increase to allow more precision operations**

$$t_i = \sqrt{\frac{240}{11} \frac{\Delta}{u_D \alpha_M l \lambda^4}}$$

  - **Some operational modes may require integration times much larger than t_i**
    - **Electronics/processing/software technology development may be required to enable updates during integration period**

Structural Architectures



- **Assertion: tensioned structures require the same structural stiffness as bending based architectures**
- **Tensioned architectures offer fewer benefits when the structural requirements are extreme**
- **When structural requirements can be reduced, through time-delay and frequency compensation, tensioned architectures are most advantageous**

Comments on Tensioned Architectures

- Tension adds stiffness to a structure through two mechanisms
  - Tensioned element axial stiffness (k=EA/L)
    - Approach of ‘tension truss’ architectures
  - Tension induces transverse stiffness (k=T/L)
    - Approach of blanket solar arrays, ‘tension aligned’ architectures
- Bending structures rely purely on material stiffness and stability
- Extremely different material requirements
  - General tension truss and aligned structures: Material must be stiff, able to support loads for extended periods of time without stress relaxation and able to be packaged and deployed without length changes
    - Aperture shape depends on internal stress distribution. Stress relaxation /dimensional changes alter the stress distribution and antenna shape
  - Flat tension aligned structures
    - Material stiffness and dimensional stability requirements greatly reduced
    - Aperture flatness does not depend material stability, aperture stiffness depends on element tension, not stiffness
    - Large phased array architectures are easier than large shaped apertures
  - Bending structures
    - Material must be stiff, but does not necessarily need to carry constant loads over time (not sensitive to creep)

Closing Remarks

- The relationship between antenna deformation compensation methods and structural requirements was investigated
- Shown that time-delay and frequency compensation, when performed at a sufficiently high rate, can dramatically reduce structural requirements
- Reduced structural requirements allow new structural architectures
  - Flat tensioned architectures (appropriate for phased arrays) are very promising

- Most of this material has been submitted for publication in:
  - T. W. Murphey, E. M. Cliff, and S. A. Lane, *"Matching Space Antenna Deformation Electronic Compensation Strategies to Support Structure Architectures,"* Submitted for publication in IEEE Transactions on Aerospace & Electronic Systems