# Global control issues for Advanced LIGO Quad Suspensions

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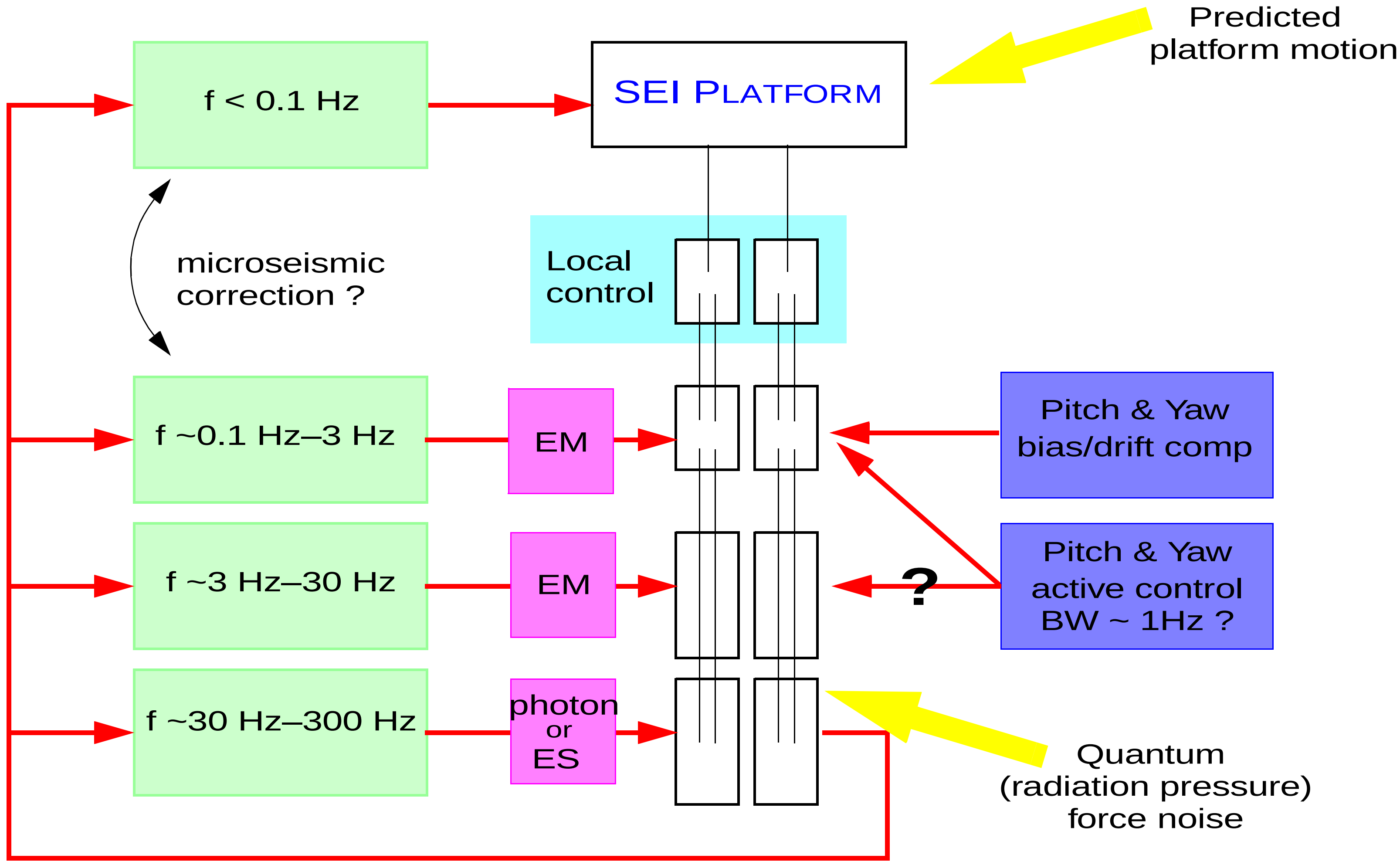
# Points of Discussion

- Longitudinal control – arm differential mode
  - follow up on K Strain's original global control example, incorporating expected active seismic isolation (from SEI)
  - new information about instability of the optical plan (Buonanno & Chen); minimum bandwidth for this channel
- Considerations for angular control
- Noise implications
  - actuator driver electronics noise
  - actuator coupling to environmental electromagnetic noise

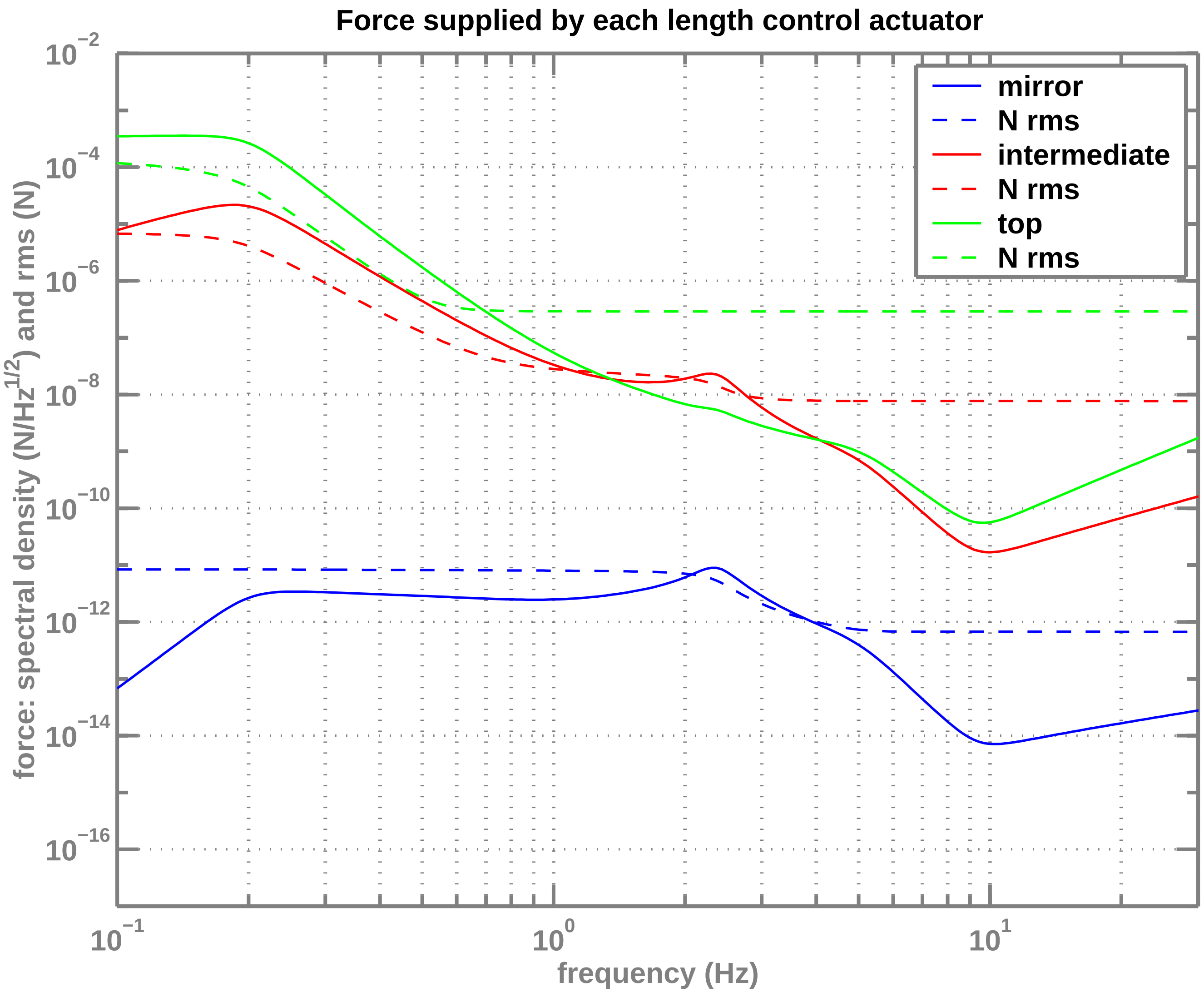
# Control Hierarchy



# CONTROL ALLOCATION CONSIDERATIONS

- Signal/noise ratio at each stage: $F_{max}/F_{noise}$
  - maximum force determined by the input fluctuations (seismic, quantum, etc) and the frequency band over which each stage has dominant control
  - noise determined by electronics noise in actuator driver, or a noise property of the actuator itself
- Overall servo bandwidth (differential mode)
  - gain required at ~100 Hz to stabilize optical dynamics
  - residual rms not really a driver
  - BW constrained at high-f end by mechanical modes (suspension fiber violin resonances, test mass modes)

# LONGITUDINAL CONTROL




No feedback to seismic platform in this example

At each stage, $F_{max} = 10xF_{rms}$

1 mN

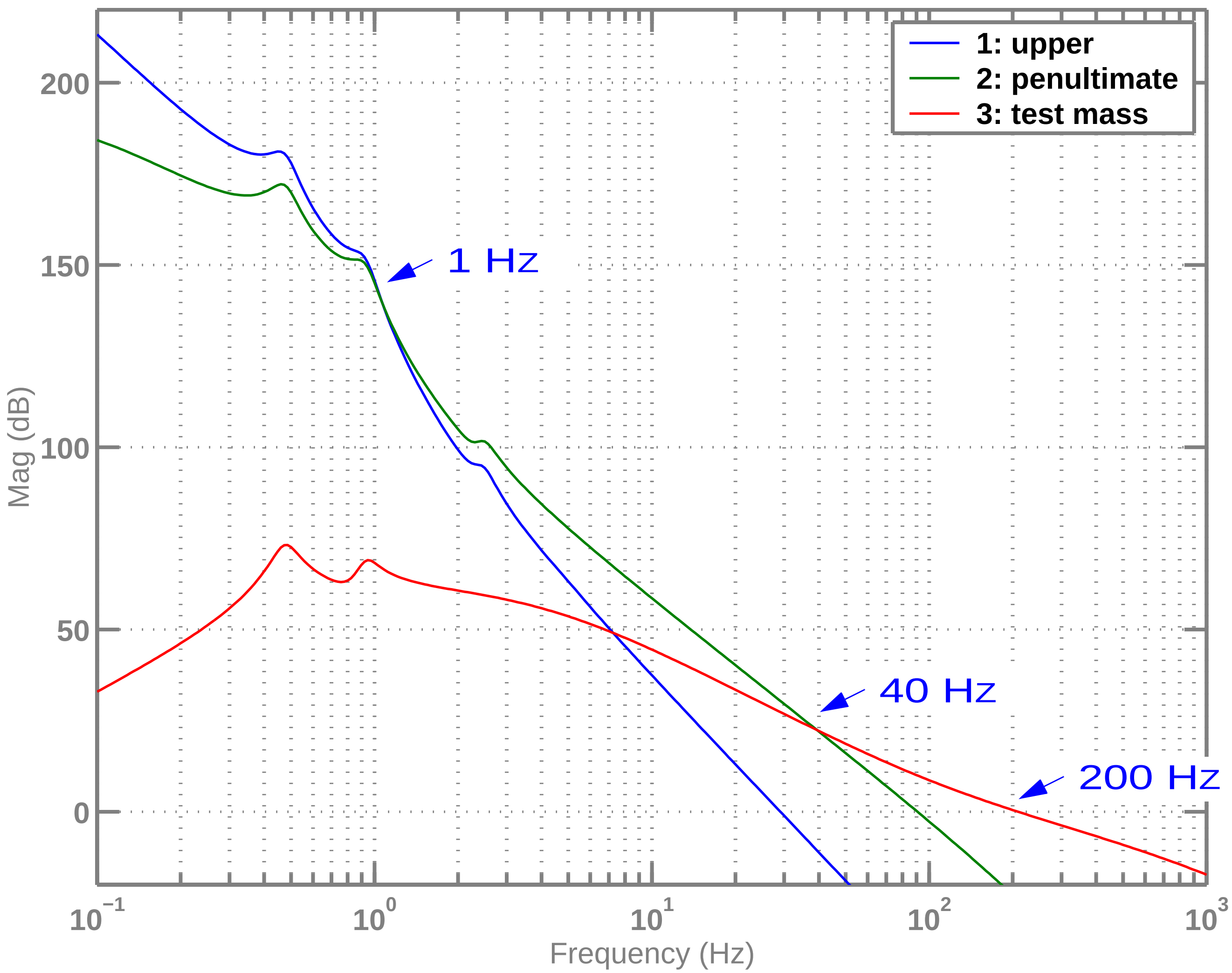
↓

0.1 mN

↓

0.1 nN

# Open loop gains



# EM ACTUATORS: B-FIELD COUPLING

- Magnetic field fluctuations limit magnet size
  - Environmental B-field fluctuations (fields produced by ifo equipment must also be considered):

$$B(f) \sim 10^{-11}\left(\frac{10\ \text{Hz}}{f}\right)\ \text{T}/\sqrt{\text{Hz}}$$

  - Force on ‘magnetized’ mass: $F \sim \mu B \varepsilon / l \sim \mu B$
  - Feedthru to test mass (current quad susp model):

$$x_{TM}(10) = F_2 \cdot 2\times10^{-8} \text{ (penultimate mass)}$$

$$= F_1 \cdot 5\times10^{-10} \text{ (upper control mass)}$$

  - $x_{TM}$ required to be < $10^{-20}$ m/rtHz at 10 Hz
    - B-field coupling falls off as $1/f^5$ or faster

# EM ACTUATORS: MAX STRENGTH

- Max magnetic moment from B-field coupling, divide by factor of 10 for additional margin?
  - 0.05 A-m$^2$, penultimate mass (x0.1 ?)
  - 2 A-m$^2$, upper control mass (x0.1 ?)
  - LIGO I magnets: 0.007 A-m$^2$
- Coils
  - assume LIGO I style coils, ~2.5 cm OD, 400 turns
  - F = 2.2 N/A x ($\mu$/1 A-m$^2$)
  - maximum current, ~ 0.1 A
- $F_{max}$
  - 1 mN for penultimate mass ($\mu$=0.005 A-m$^2$)
  - 40 mN for upper control max ($\mu$=0.2 A-m$^2$)

# Pitch & Yaw Bias Range

- Types of misalignment
  - Initial alignment errors (surveying errors, adjustment resolution)
    - LIGO experience: ~ 20 cm error over 4 km →25 μradian
  - Long term drift: little experience, less than 10 μradian over a week or more
  - Dynamic fluctuations: less than 0.1 μradian (guess)
- Require ±0.25 mrad of pitch & yaw bias range
- Applied at stage 1 (upper control mass) of quad suspension
  - must apply pitch bias here; might as well do yaw also
  - force required: 50 mN
    - compare to 1 mN required for longitudinal control

# SUMMARY OF FORCE & NOISE REQ. FOR EACH STAGE

| Stage | Pitch & Yaw bias | Long. lock | Actuator Noise, $N/Hz^{1/2}$ | Dynamic Range ($Hz^{1/2}$) | Max force |
|---|---|---|---|---|---|
| upper control mass | 50 mN | 1 mN | $2 \times 10^{-11}$ | $5 \times 10^{7}$ | 40 mN |
| penultimate mass | | 0.1 mN | $5 \times 10^{-13}$ | $2 \times 10^{8}$ | 1 mN |
| test mass | | 0.1 nN | $2.5 \times 10^{-15}$ | $4 \times 10^{4}$ | |

- Comparison dynamic range examples:
  - LIGO I ADC/DAC: ~$10^{6}$ √Hz
  - LIGO I suspension controller: ~5 x $10^{9}$ √Hz
  - low-noise op-amp: ~$10^{10}$ √Hz

# Photon actuation on Test Mass

- $F_{max} = 10x\ F_{rms} = 10^{-10}$ N
  - $F_{max} = P/c \rightarrow P_{min} = 30$ mW
  - Go for P = 1 W (still small laser; no multiple bouncing needed)
- $F_{noise} < 2.5 \times 10^{-15}$ N/rtHz
  - $\frac{\delta P}{P} < 2\times10^{-7}/\sqrt{\mathrm{Hz}}$, shot noise in a 50 μW beam

# To DO

- ❑ Include unstable optical resonance
- ❑ Include wire resonances
  - crossover between penultimate and test mass actuations
  - important for test mass actuation as well
  - Virginio S making a model with MSE
- ❑ Auxiliary degrees-of-freedom
  - required bandwidth probably only ~1 Hz
  - don’t need actuation on test mass; maybe not even on penultimate mass ?
- ❑ Lock acqusition