Free-flight experiments in LISA Pathfinder

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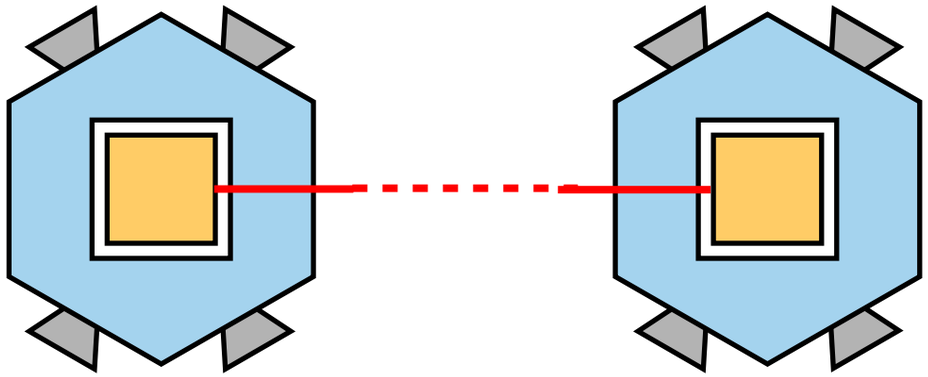
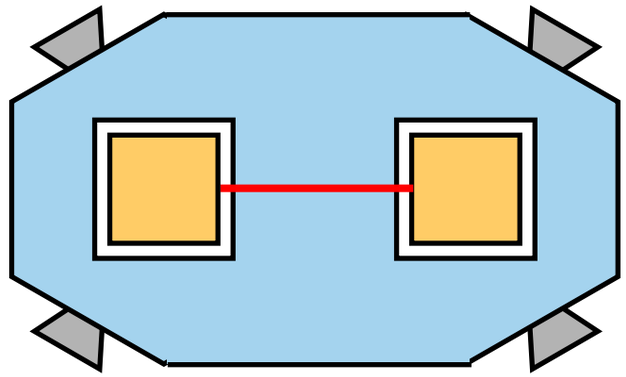
Qualitative Motivation

LISA



- Actuate SC1 to maintain TM1 free-fall
- Actuate SC2 to maintain TM2 free-fall
- $\delta\tilde{a}_{12} \equiv \delta\tilde{a}_1 - \delta\tilde{a}_2 \approx \sqrt{2}\delta\tilde{a}_1$

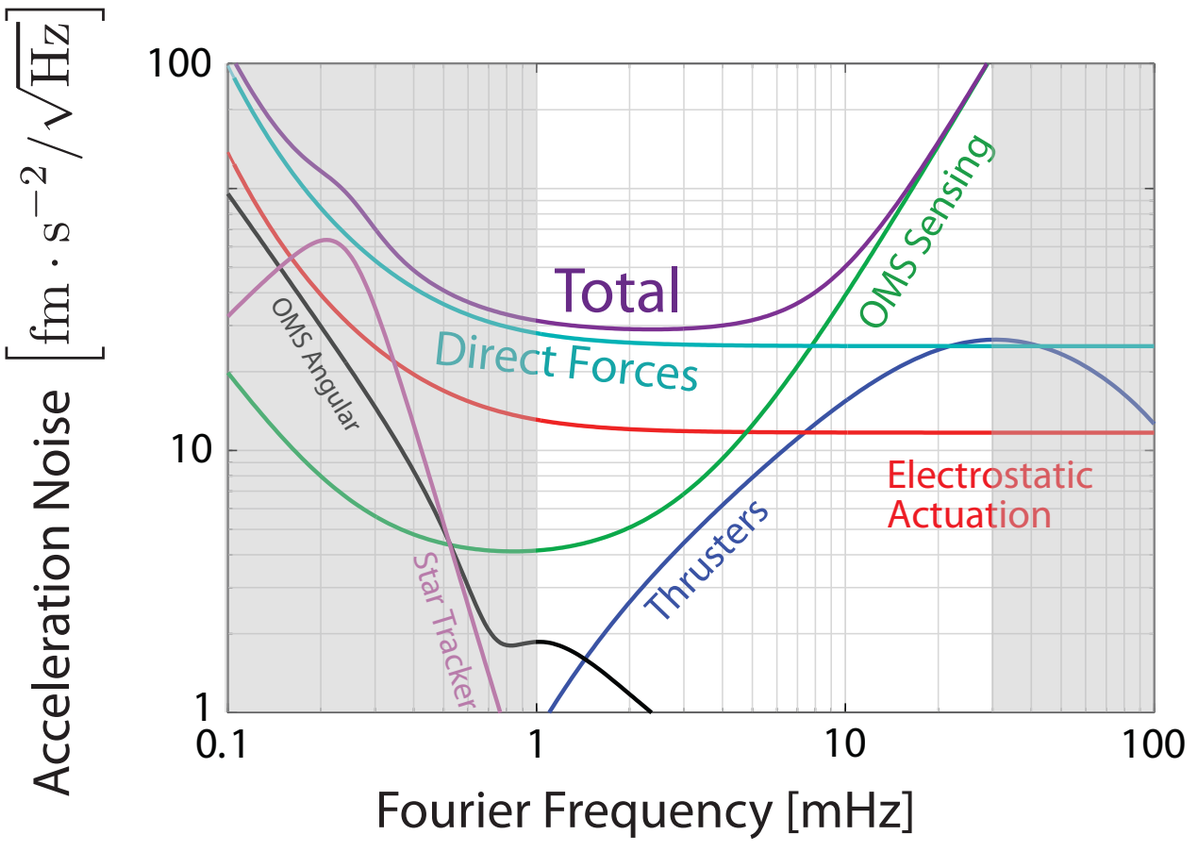
LPF



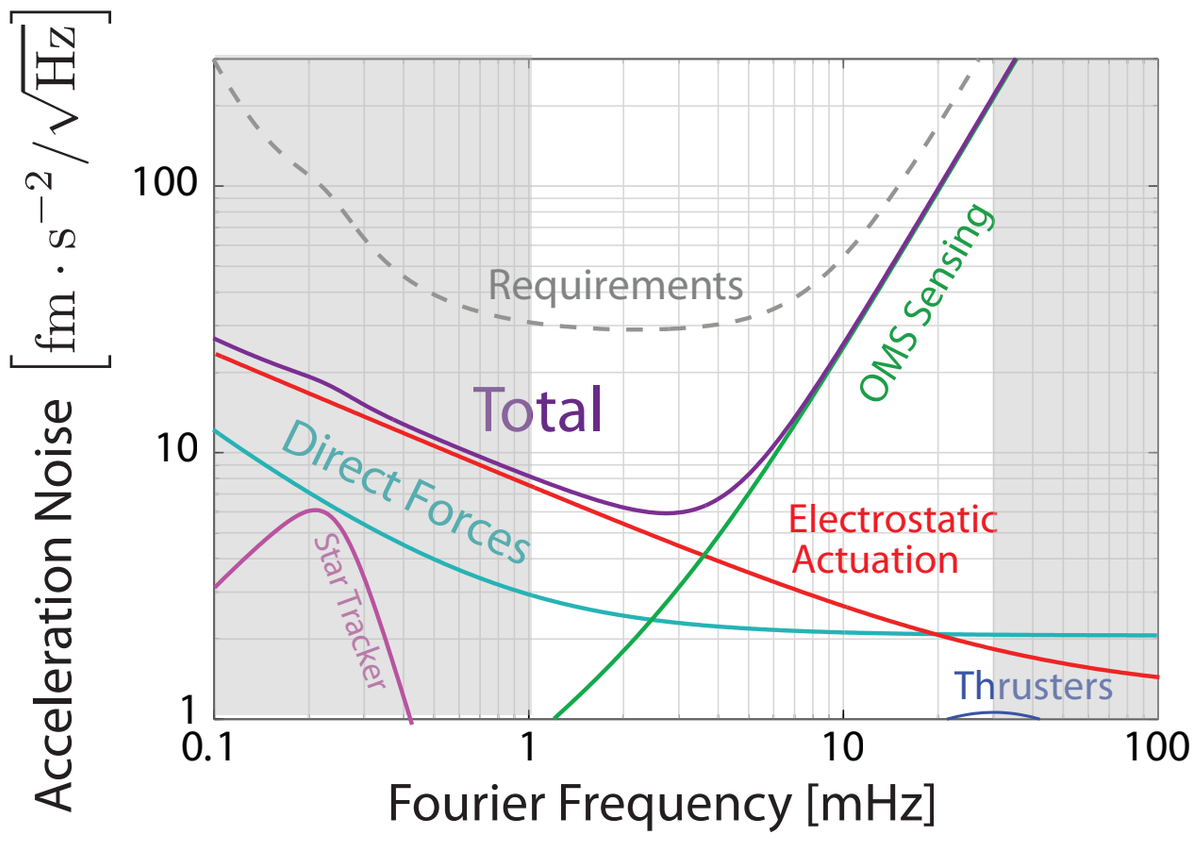
- Actuate SC to maintain TM1 free-fall
- Actuate TM2 to follow TM1 (or SC)
- $\delta\tilde{a}_{12} \equiv \delta\tilde{a}_1 - \delta\tilde{a}_2 \neq \sqrt{2}\delta\tilde{a}_1$
- $\delta\tilde{a}_2 \gg \delta\tilde{a}_1 \rightarrow \delta\tilde{a}_{12} \approx \delta\tilde{a}_2$

Quantitative Motivation

Design Requirements



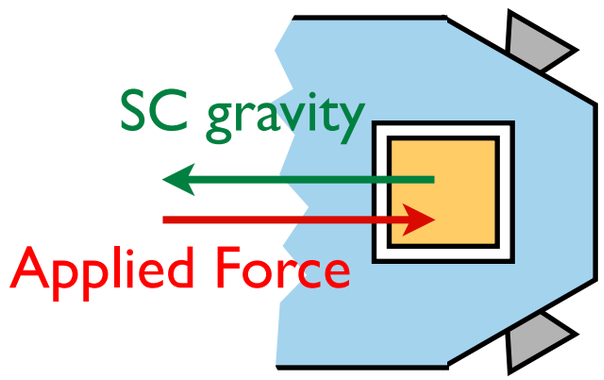
Best Estimate



- Electrostatic actuation noise may limit our ability to measure forces on the TM

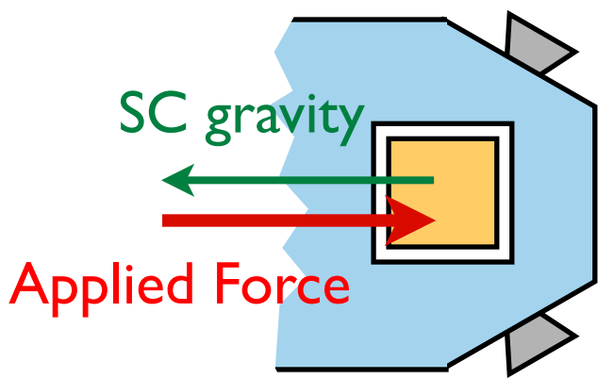
Drift Mode Concept

Standard Science Mode

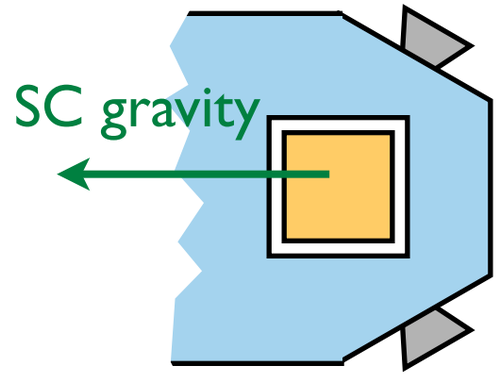


"Constant" Applied Force

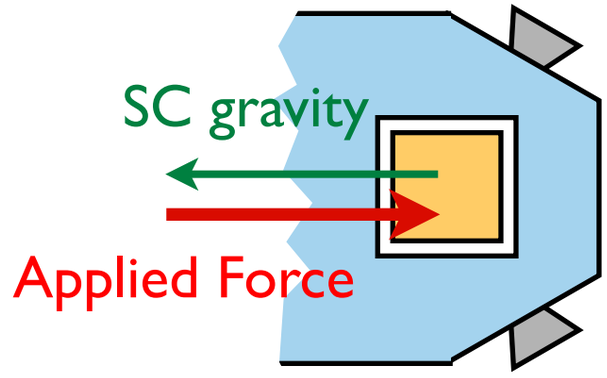
Drift or Free-Flight Mode



Discrete "Kick"

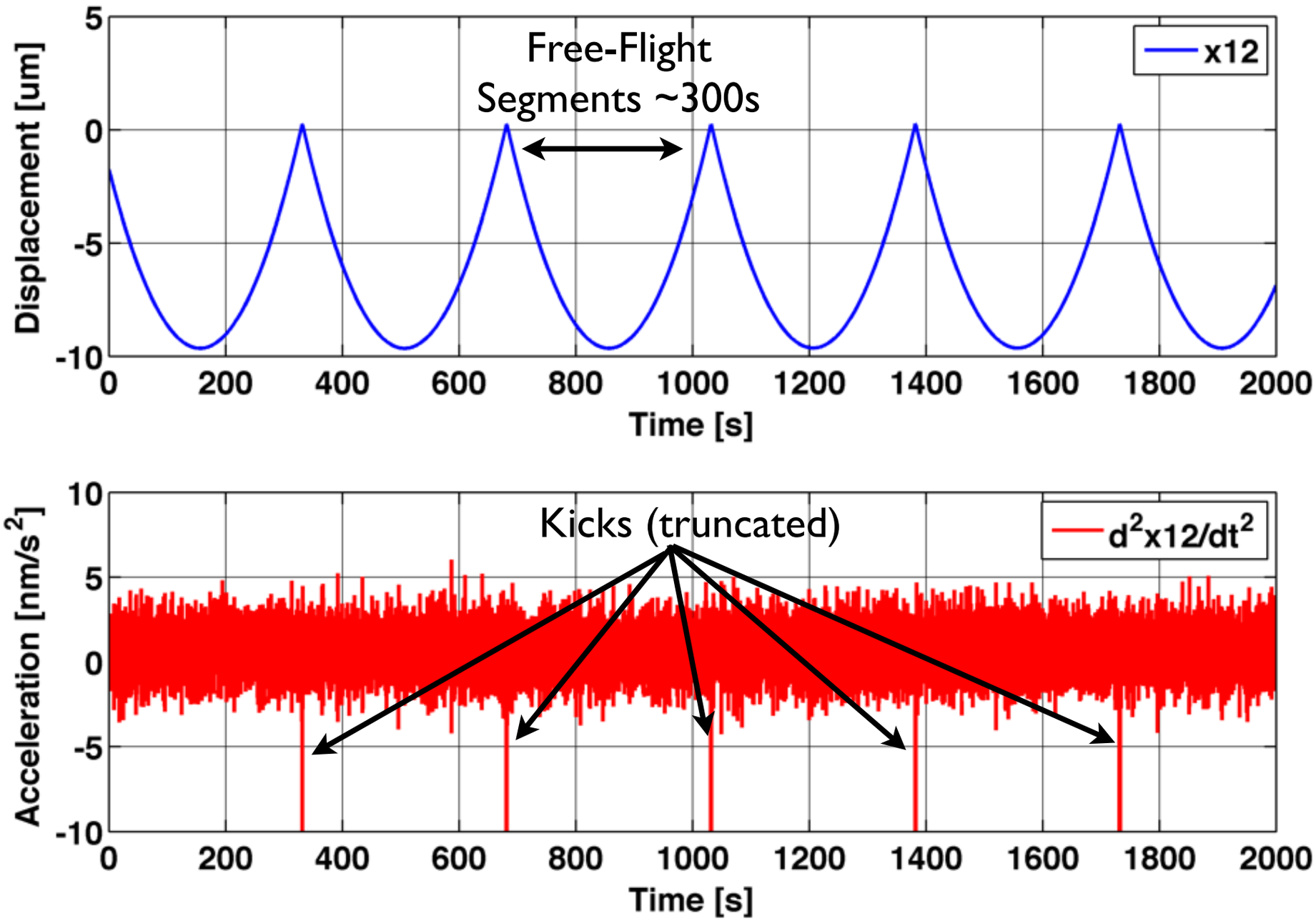


Free Fall



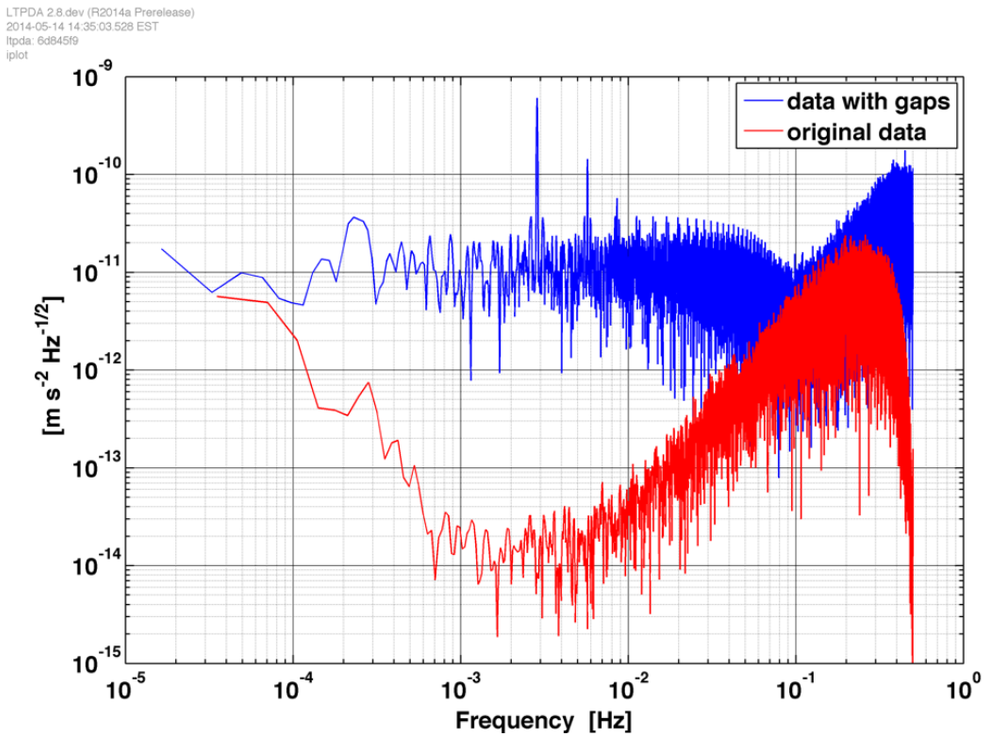
Discrete "Kick"

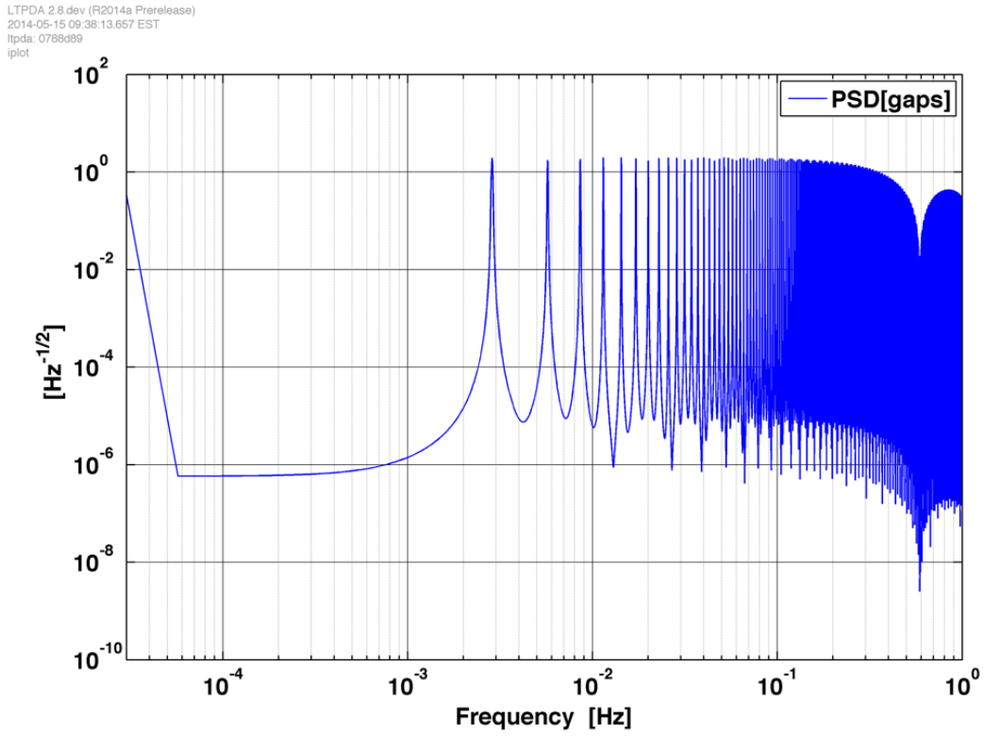
Example Data



Data Analysis Challenges

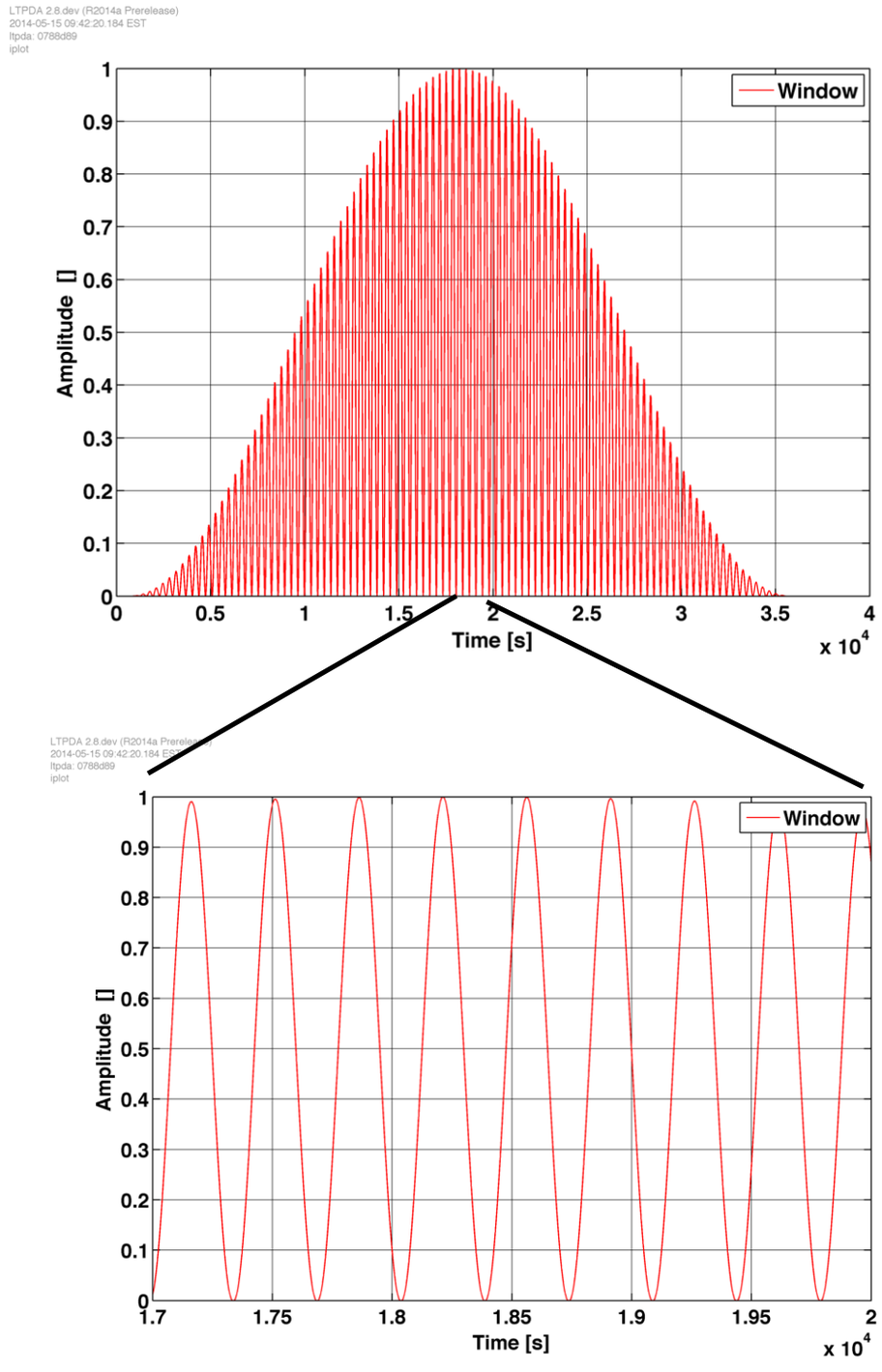
- Excise kicks
- Estimate acceleration noise below kick frequency
  - longest free-flight is ~300s or 1/(3mHz)
  - Want acceleration noise at 1mHz or even 0.1mHz
- Remove large free-fall trajectory (~10um) with sufficient accuracy
  - small residuals are aliased by "gap transfer function"

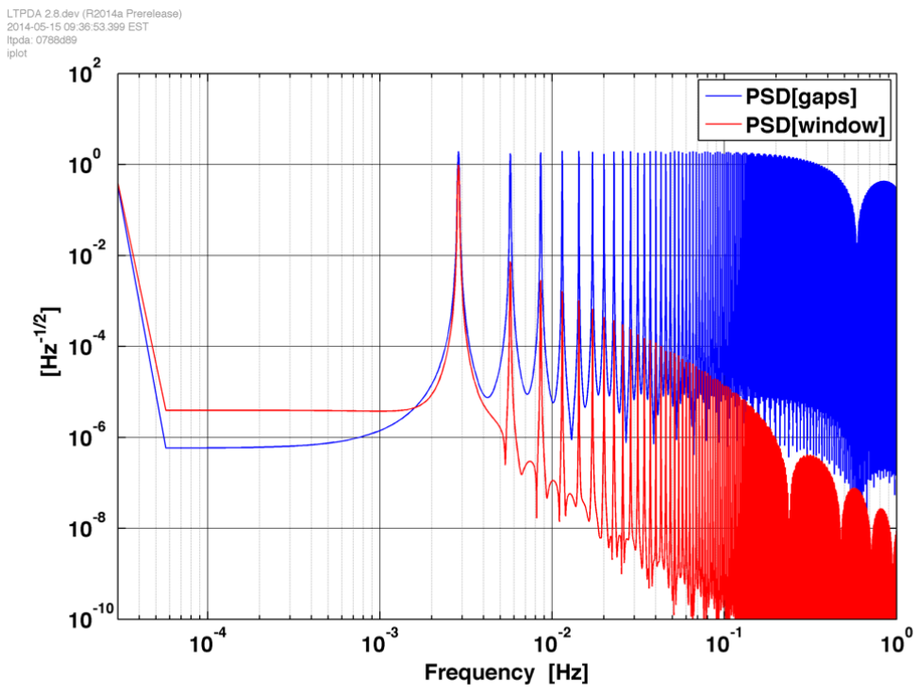




Windowed Approach

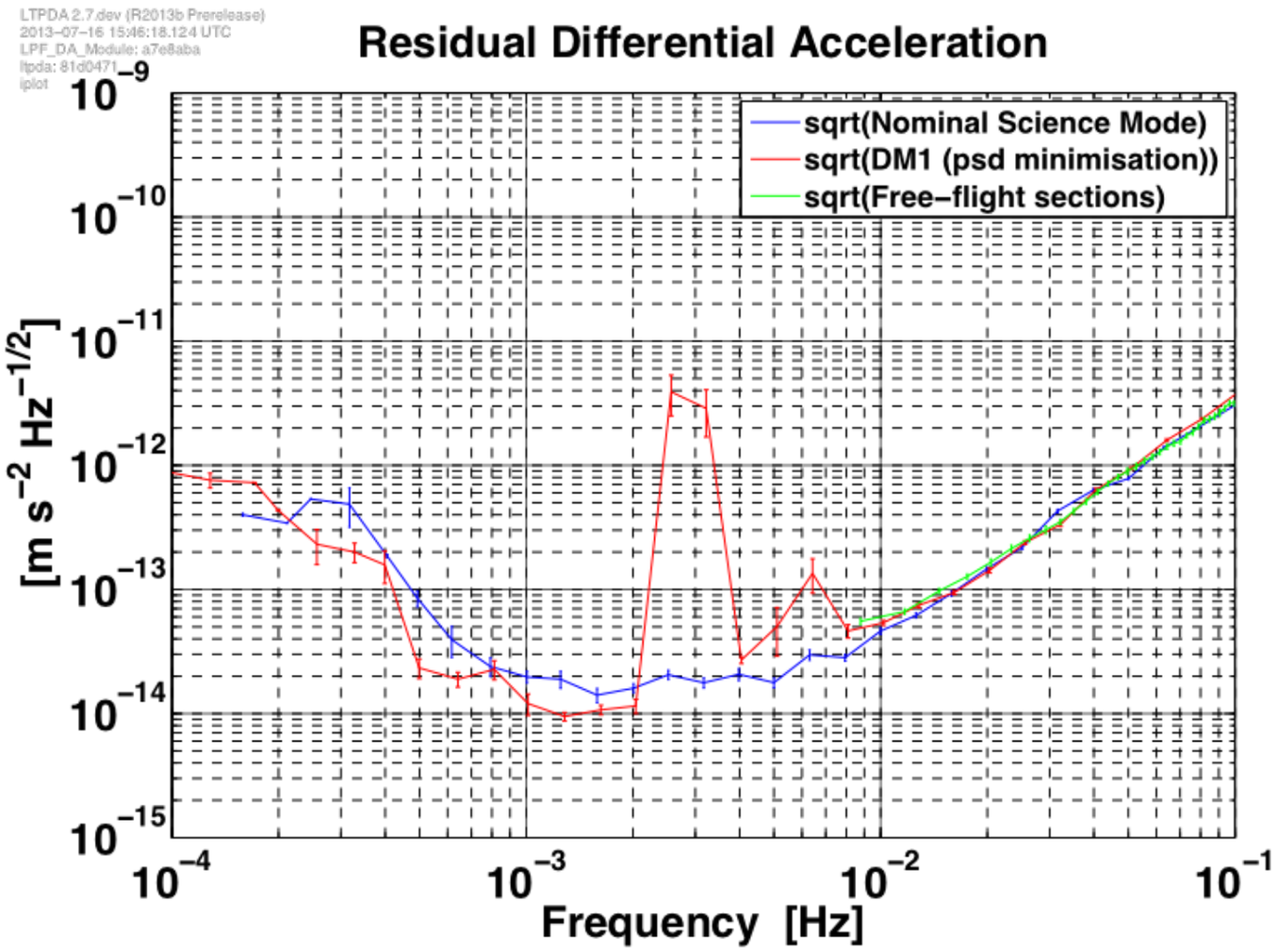
- Approach
  - Build a customized window that smoothly goes to zero at each gap location (suppress gap transfer function)
  - Apply normal PSD estimation techniques





Windowed Approach Results

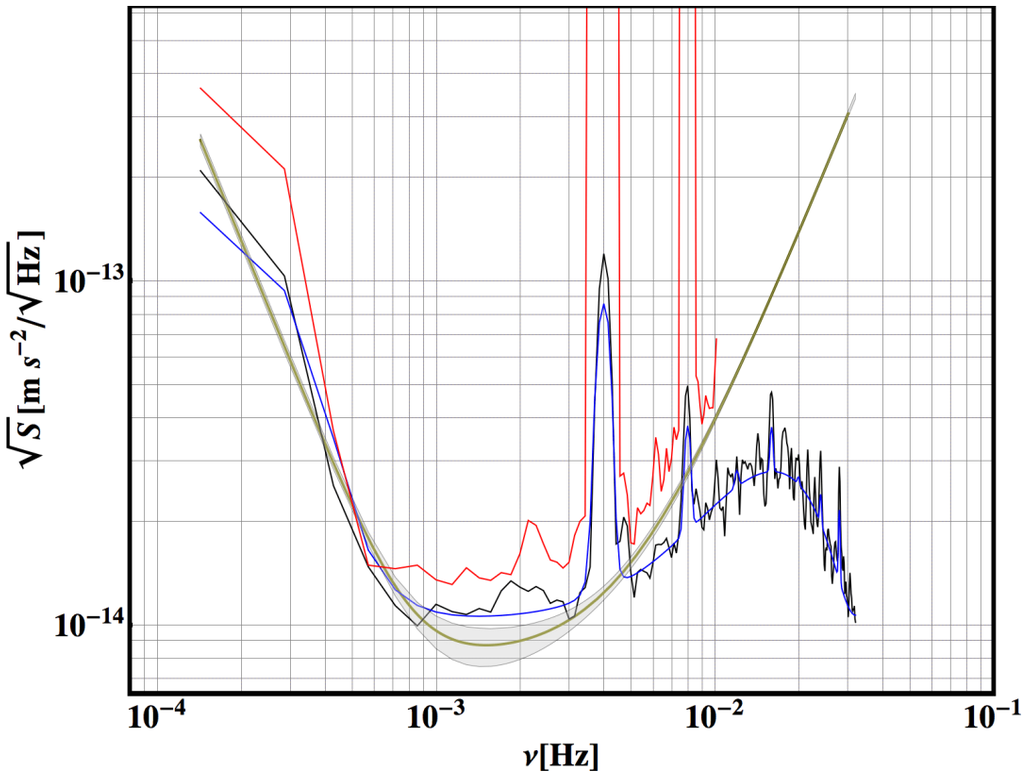
- results from STOC Sim #3: Able to recover performance near science mode performance and perhaps below.
- Not clear if noise floors in OSE simulator were configured properly, may not have been actuation noise limited



Credit: M. Hewitson

Spectral Leakage Suppression Method

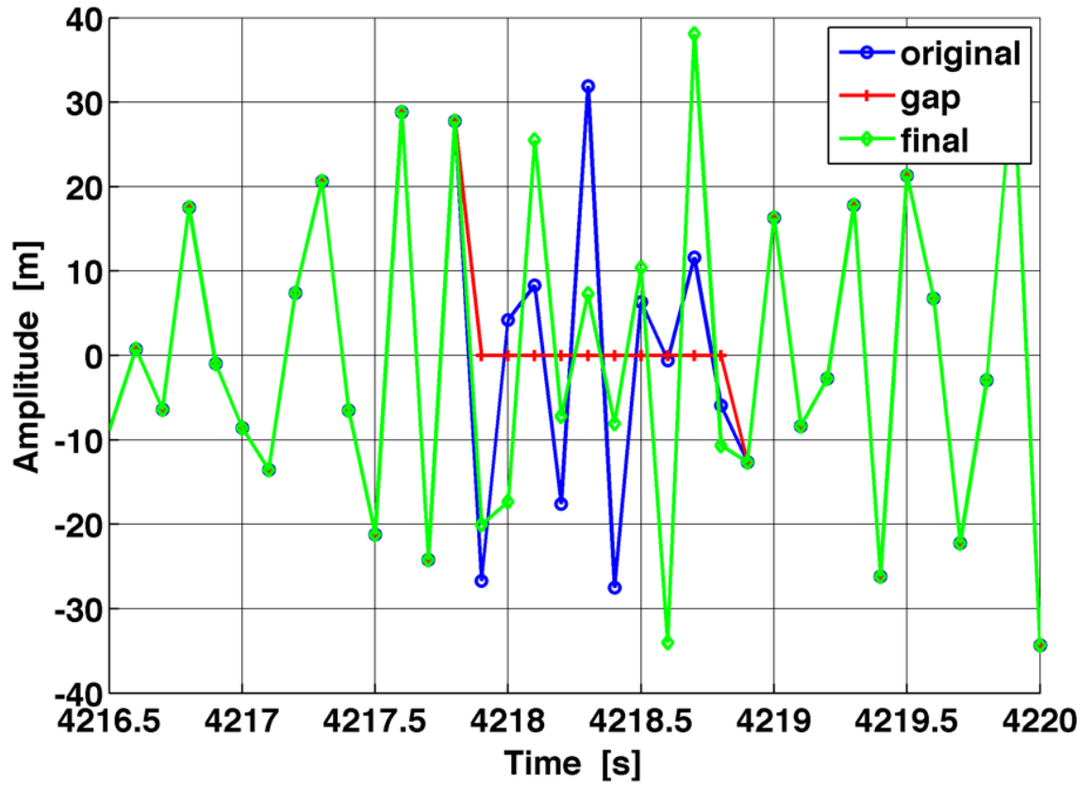
- Approach
  - apply low-pass filter and detrend data between gaps
  - Fit analytic model to resulting spectrum
  - Compute transfer function of gap process
  - Apply "inverse gap transfer function" to model spectrum
- Results (noise only)
  - Significant improvement over simple gap filling (e.g. straing lines, splines, etc.)
  - Some bias introduced at low frequencies



Credit: S. Vitale

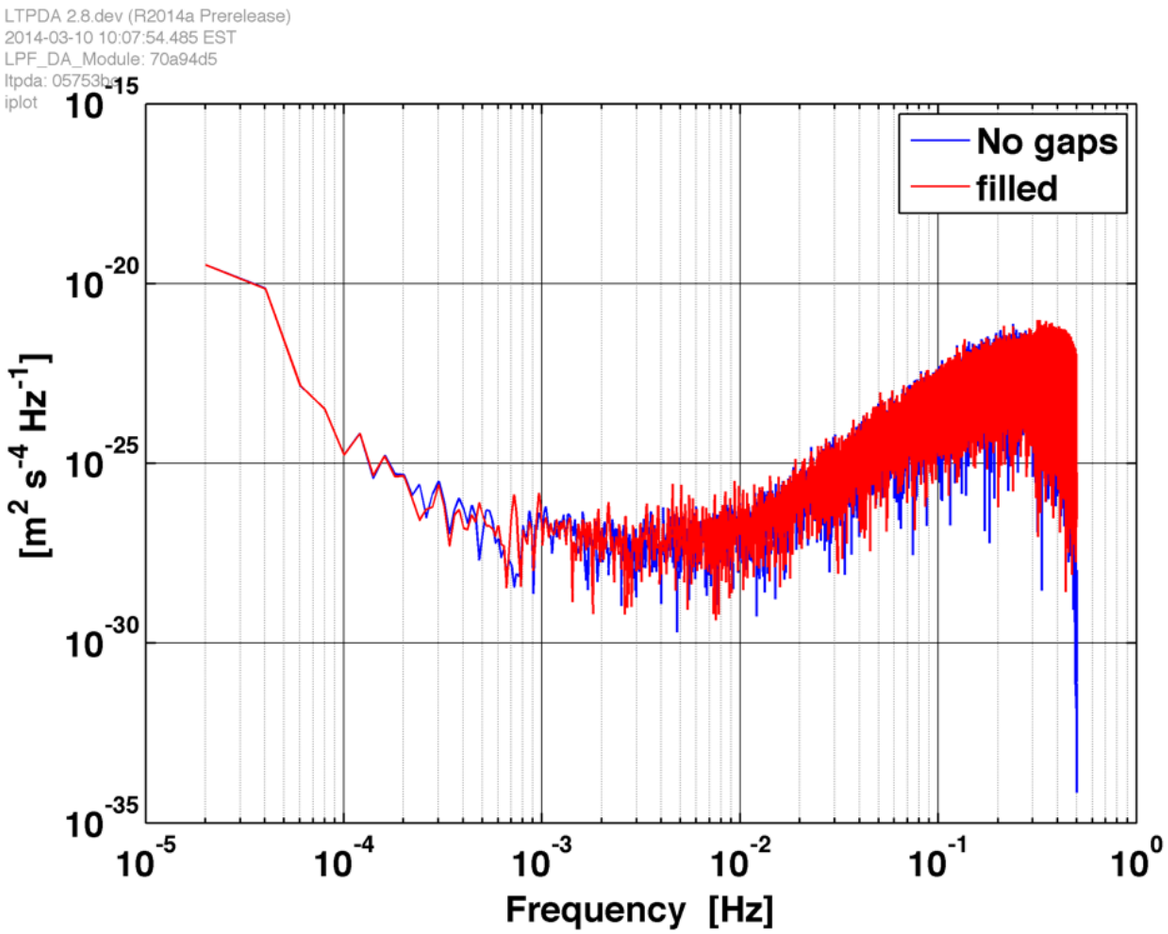
Gap-filling Approach

- Approach
  - Fill gaps with random data generated from an assumption of an underlying noise spectrum
- Algorithm
  - Create two-point function from model spectrum
  - draw zero-mean random samples matching that distribution
  - use data adjacent to gaps and two-point function to adjust mean of random samples
  - Update spectral model and iterate if necessary

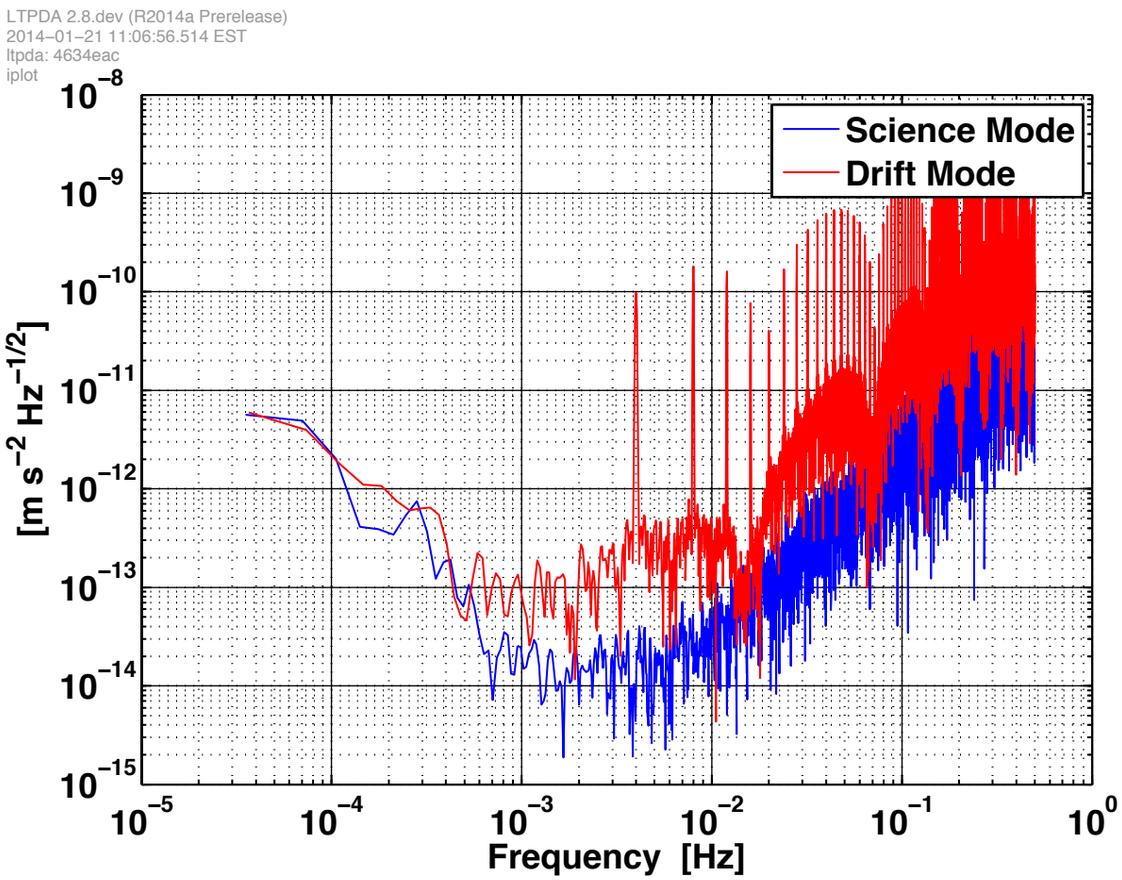


Gap-Filling Results

Noise Only Test



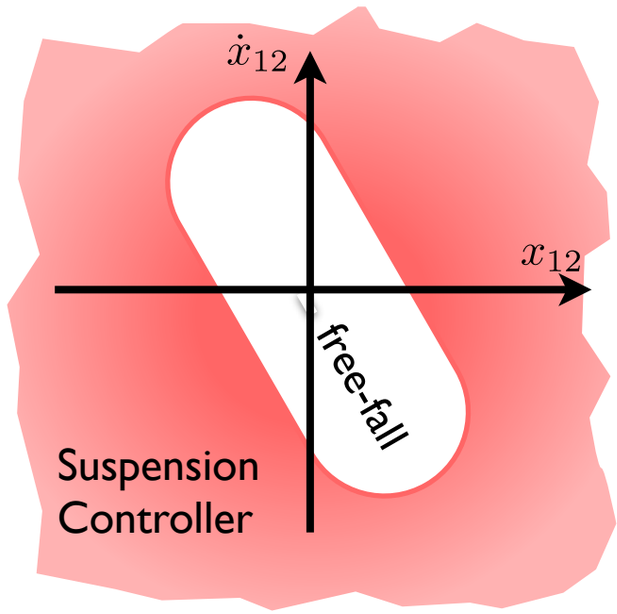
Complete Problem

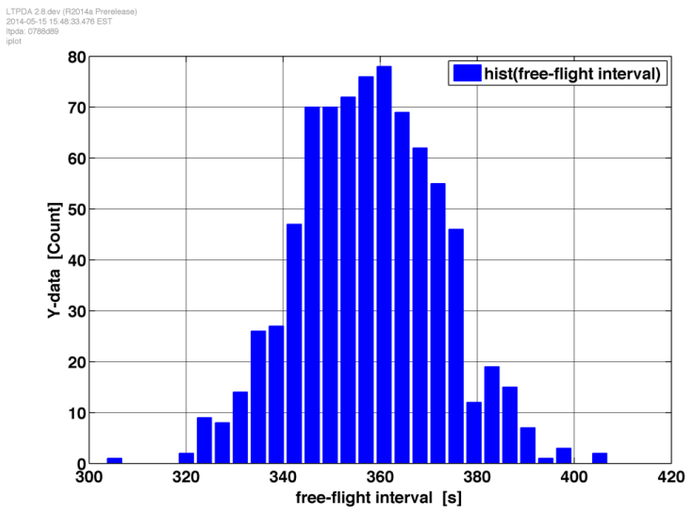


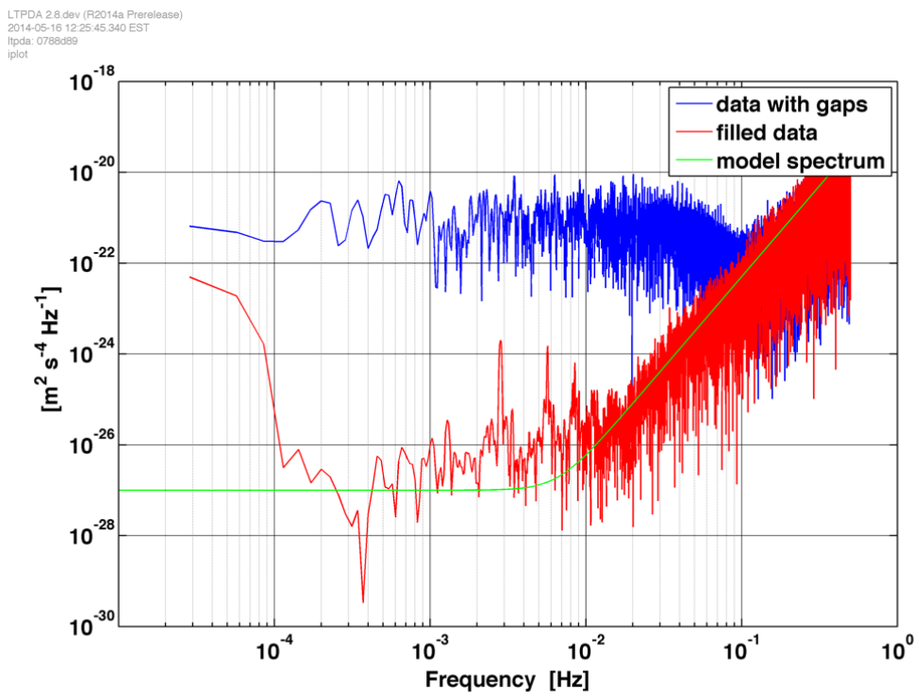
- Gap filling technique works well, but is *slow*
- Residuals from imperfect subtraction of parabolic flight corrupt spectrum in full problem

Drift Mode for ST7?

- Alternate Control Design
  - Use existing validated controller modes
  - Select mode based on instrument state variables
- Features
  - Automatic compensation of changes in gravity gradient, noise levels, etc.
- irregular gap intervals (possible advantage for data analysis)

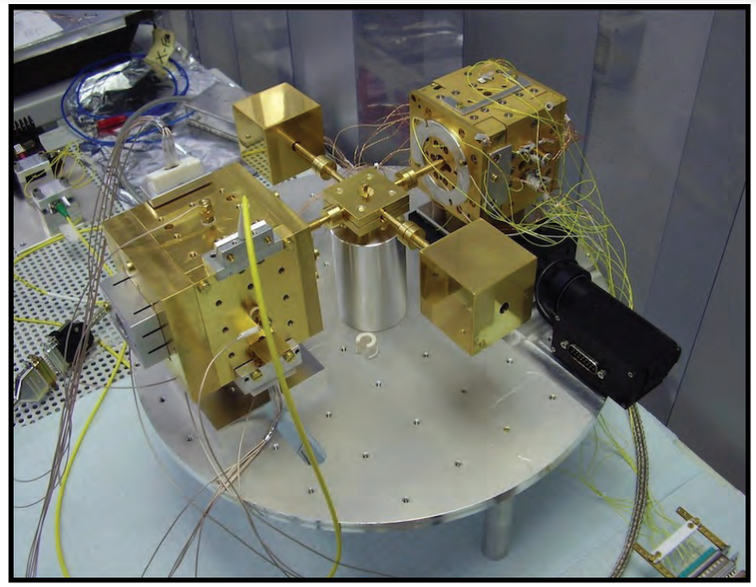


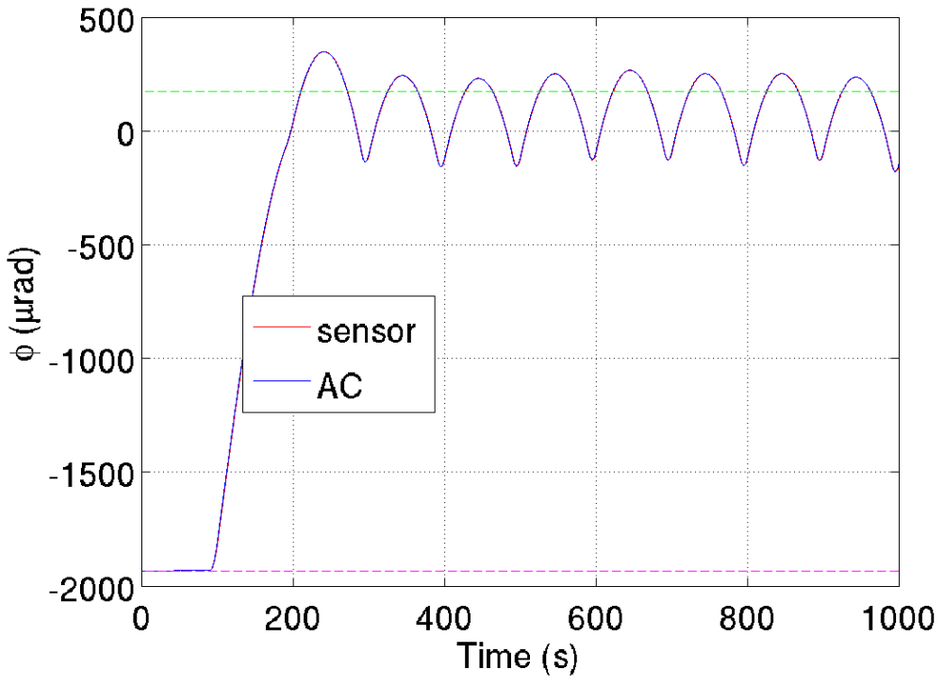




Drift Mode in the Lab

- U. Trento Torsion Pendulum Experiment
  - Apply external torque to mimic LPF gravity gradient
  - "Suspend" test mass with kick-controlled torque to recover nominal angular position
  - Measure noise in kicked case as compared to zero-gradient case
  - accelerations of $6 \times 10^{-10} m/s^2$, free flights of ~225s, impulses of ~25s
- AEI Interferometry Readout
  - Mimic TM motions in drift mode with piezo mirrors, check how IFO tracks motion
- UF Torsion Pendulum Experiments





Credit: W. Weber

Conclusions

- Free-flight experiments allow validation of drag-free flight in the presence of actuation noise
- Multiple data analysis strategies have been developed, all with some success
- Work remains to finalize and validate analysis pipelines in preparation for operations
- Experimental work will generate data with more realism, providing further tests for the DA pipelines