Newtonian Noise Simulation and Suppression for Advanced Gravitational-Wave Interferometers

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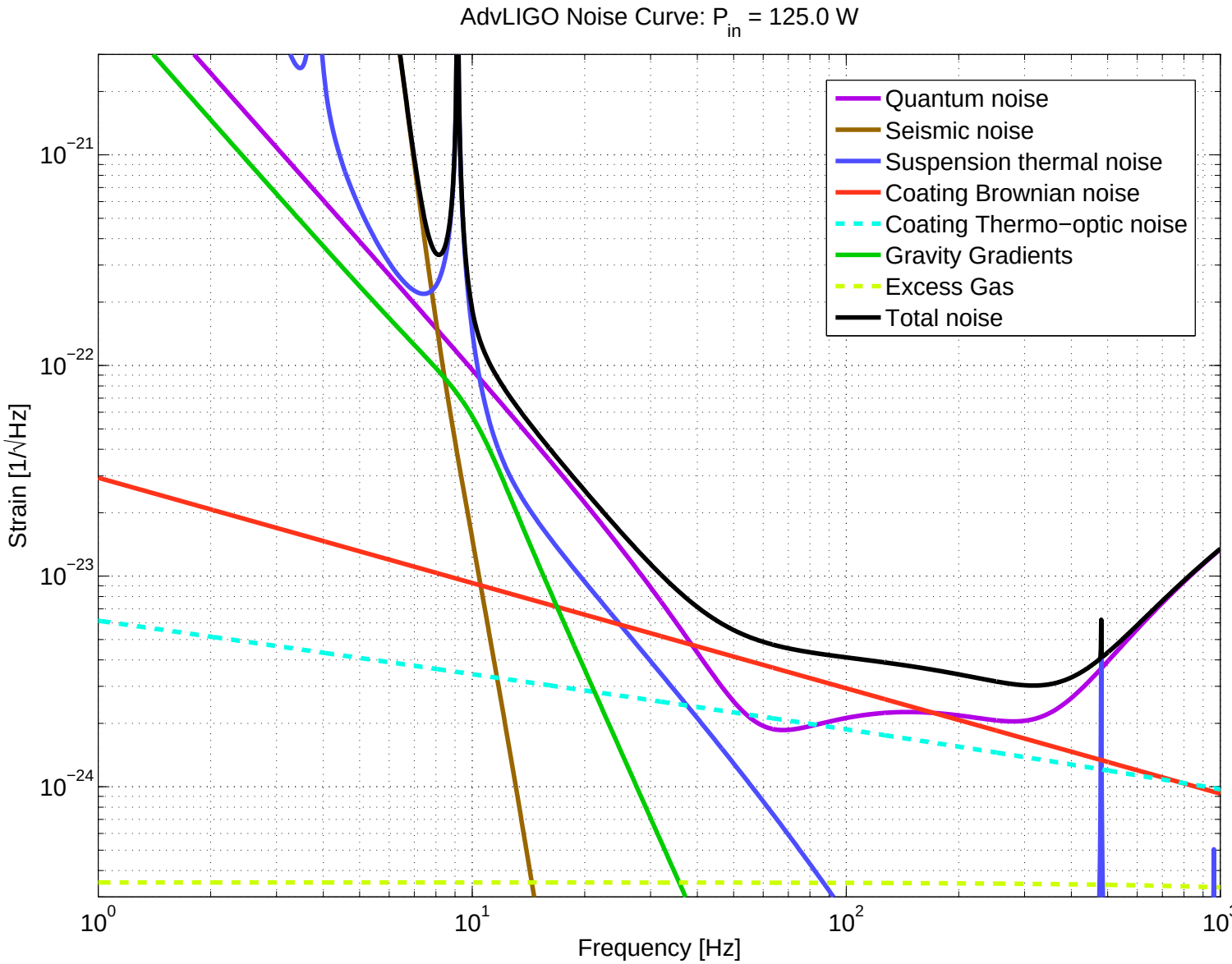
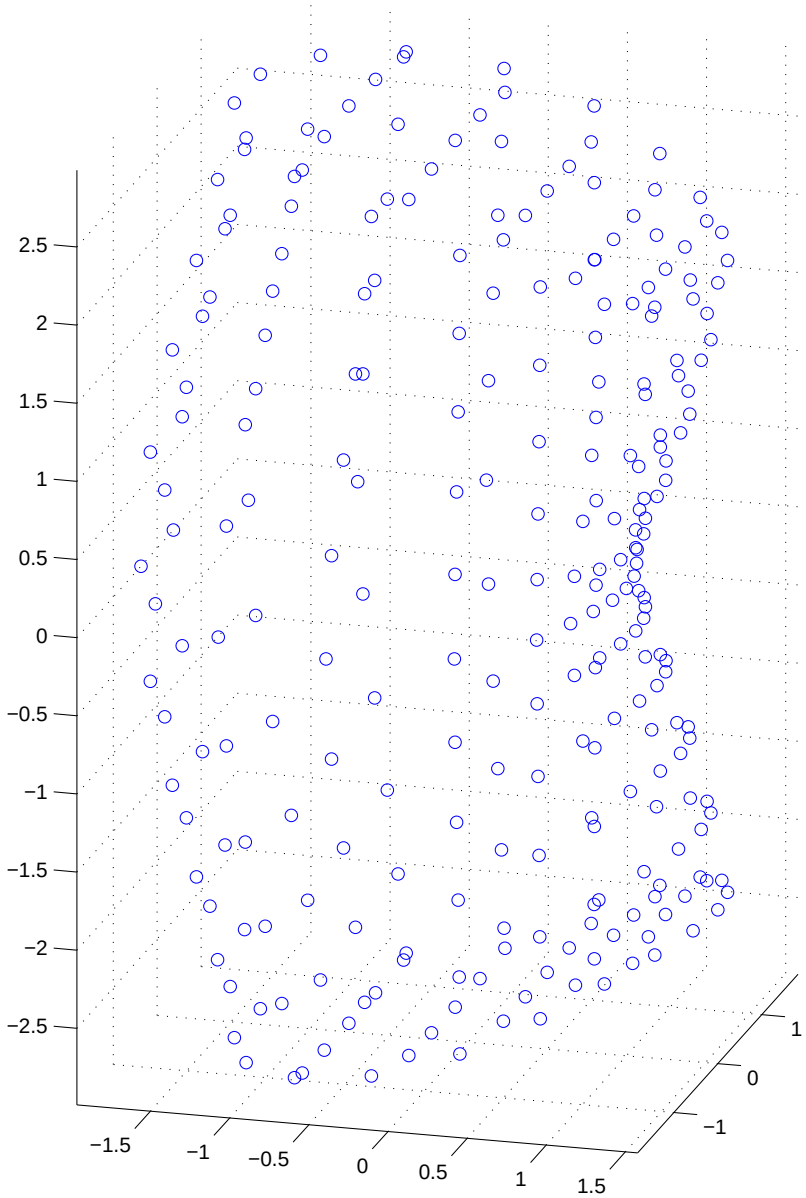
Newtonian noise

- Massive black hole mergers and stochastic background are expected to be observed in the 10 Hz region, where Newtonian noise is a problem.
- Direct gravitational coupling "short-circuits" seismic isolation system.
- Gravitational force cannot be shielded, so passive isolation is impossible.
- Active noise cancellation is the way!

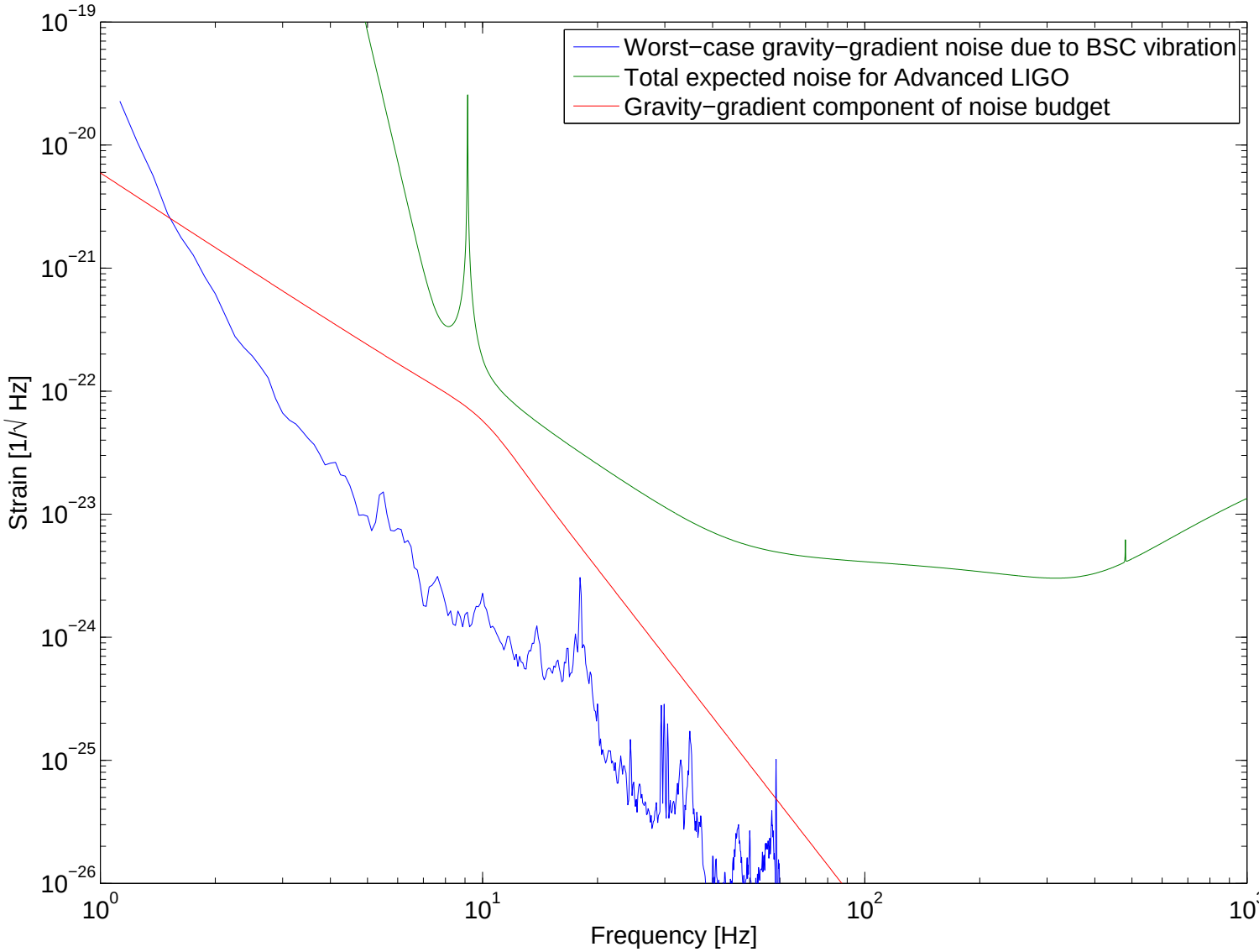

AdvLIGO Noise Curve: P_in = 125.0 W
Quantum noise
Seismic noise
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Gravity Gradients
Excess Gas
Total noise
Strain [1/√Hz]
10^−21
10^−22
10^−23
10^−24
10^0
10^1
10^2
10^3
Frequency [Hz]

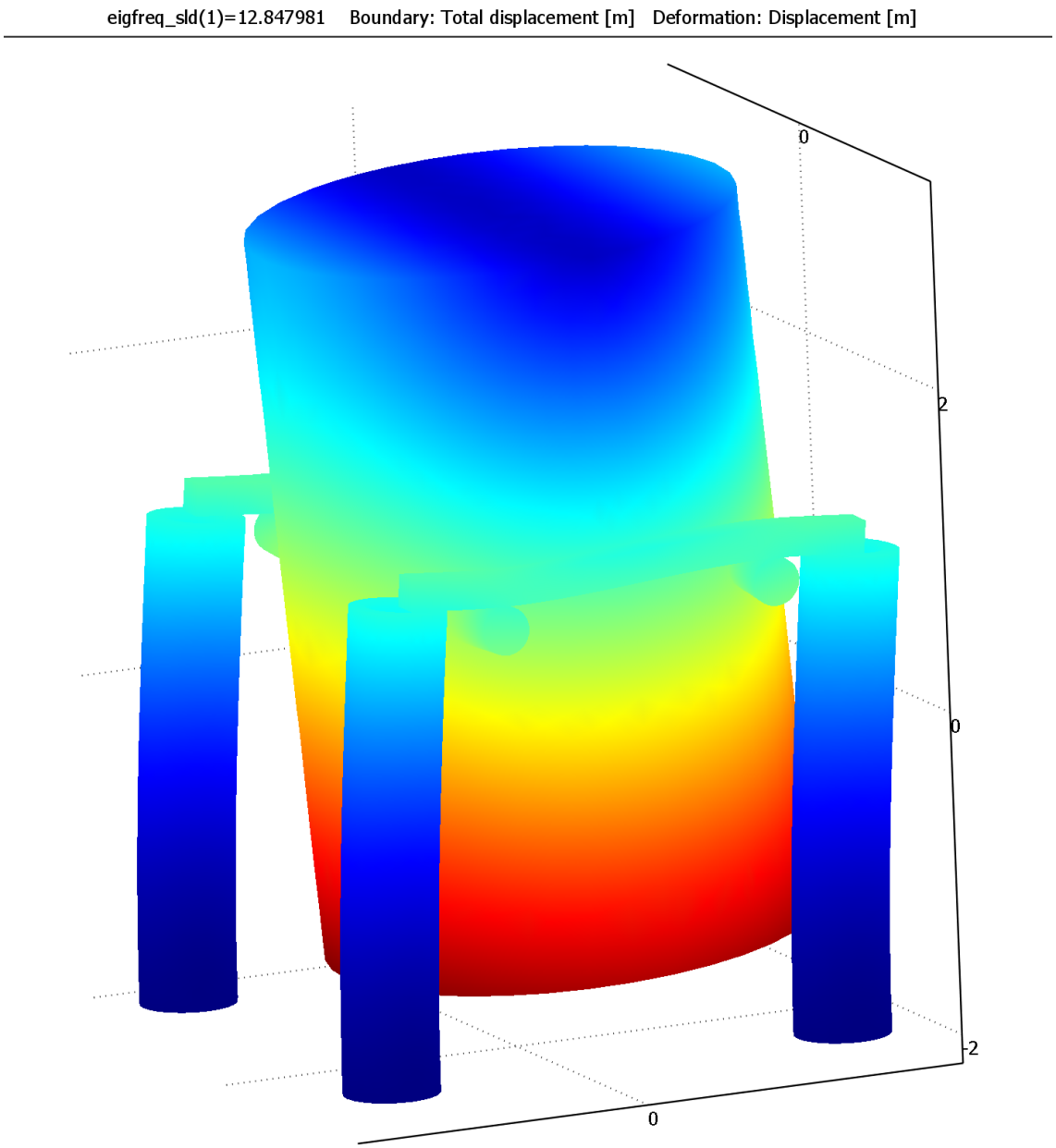
Modeling the BSC

- Many possible modes of vibration — which should be modeled?
- Assume the worst: Each point moves so as to maximize the gravitational force along the beam axis.

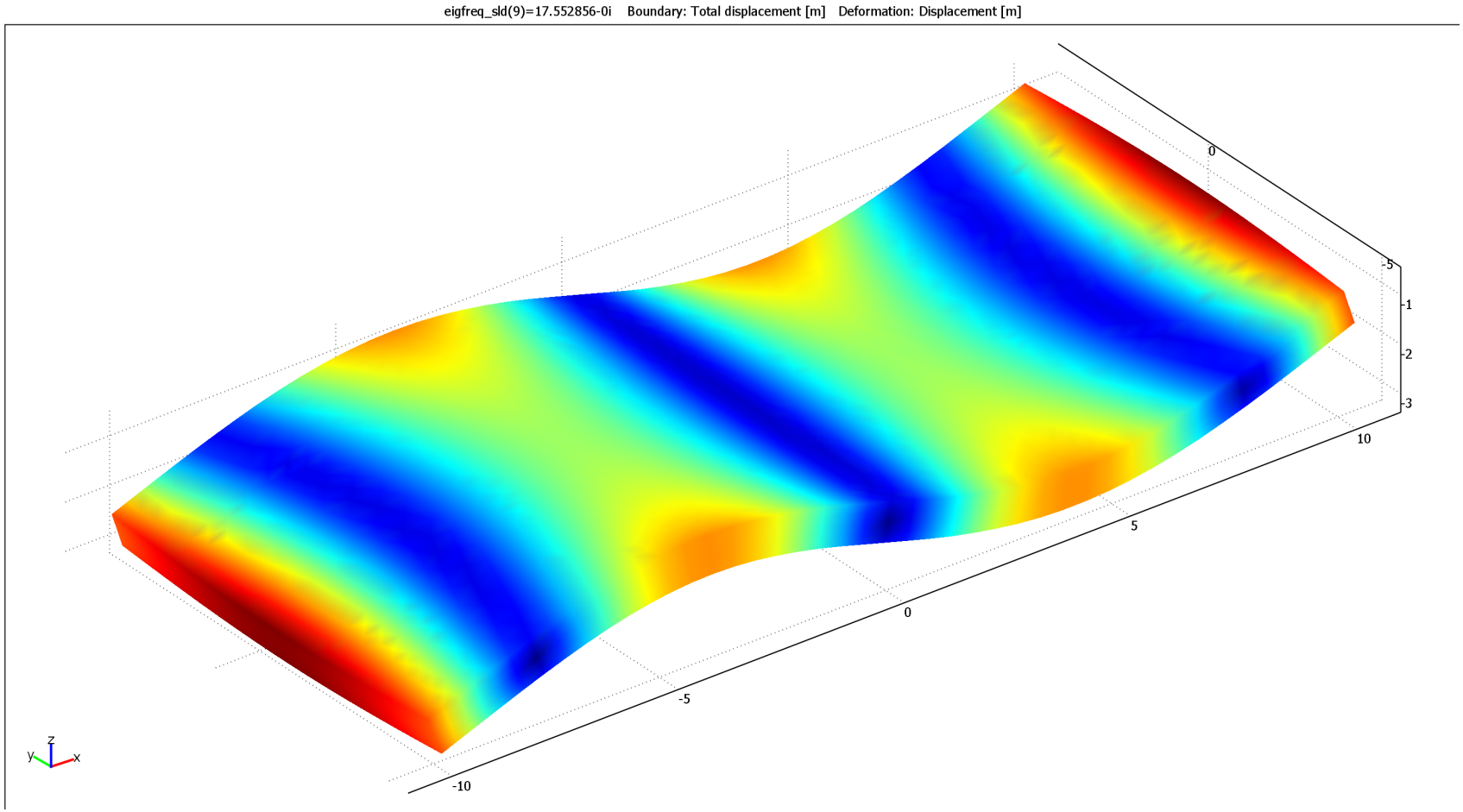


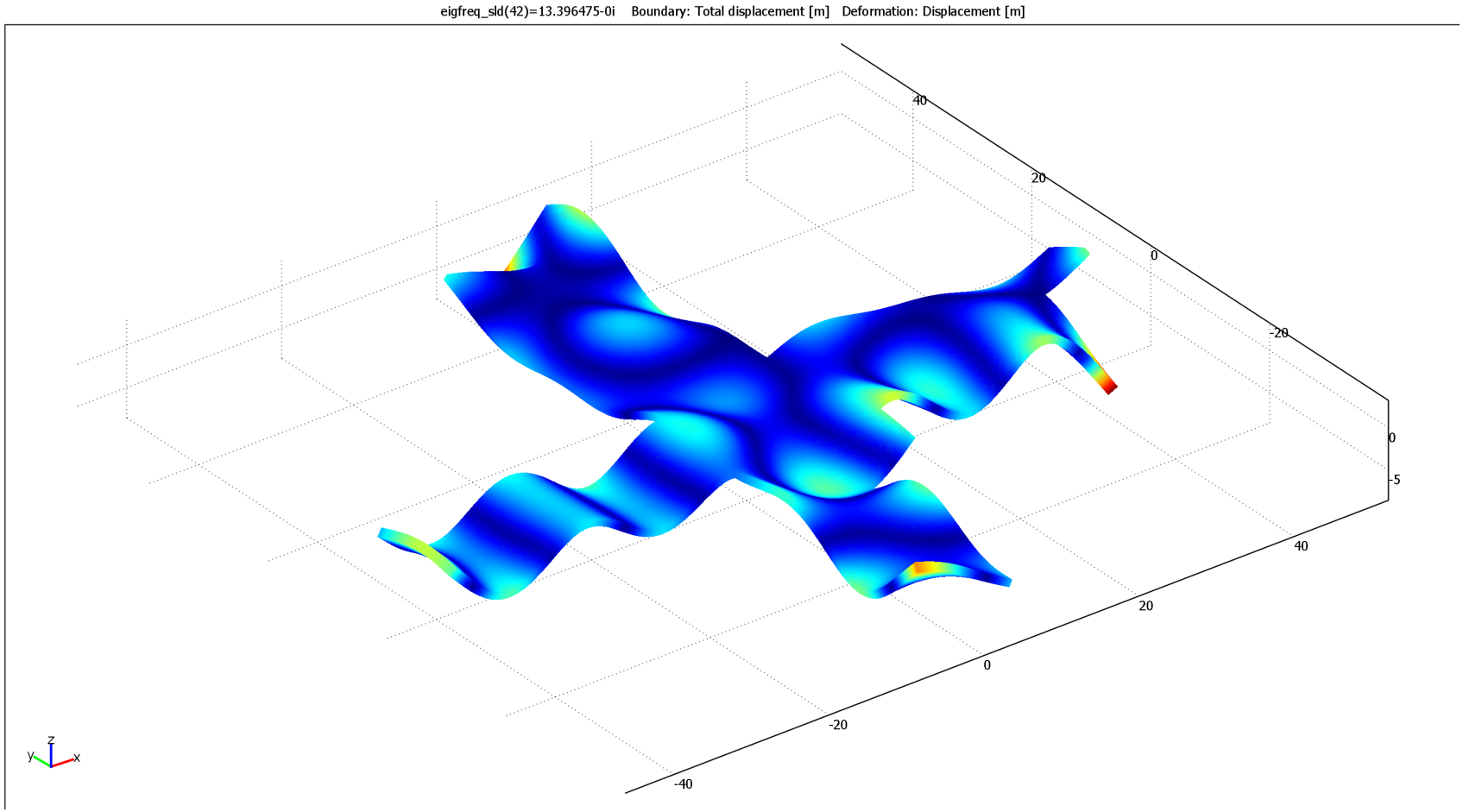
- Not a physically reasonable mode of vibration (although similar to a folding mode), but a limiting case.
- Mass of 8 tonnes results in gravity coefficient of 10^{-7} s^{-2}, i.e., for every micron of deflection, the acceleration of the test mass changes by 10^{-7} microns per second squared.


Worst−case gravity−gradient noise due to BSC vibration
Total expected noise for Advanced LIGO
Gravity−gradient component of noise budget
Strain [1/√ Hz]
Frequency [Hz]
10^−19
10^−20
10^−21
10^−22
10^−23
10^−24
10^−25
10^−26
10^0
10^1
10^2
10^3



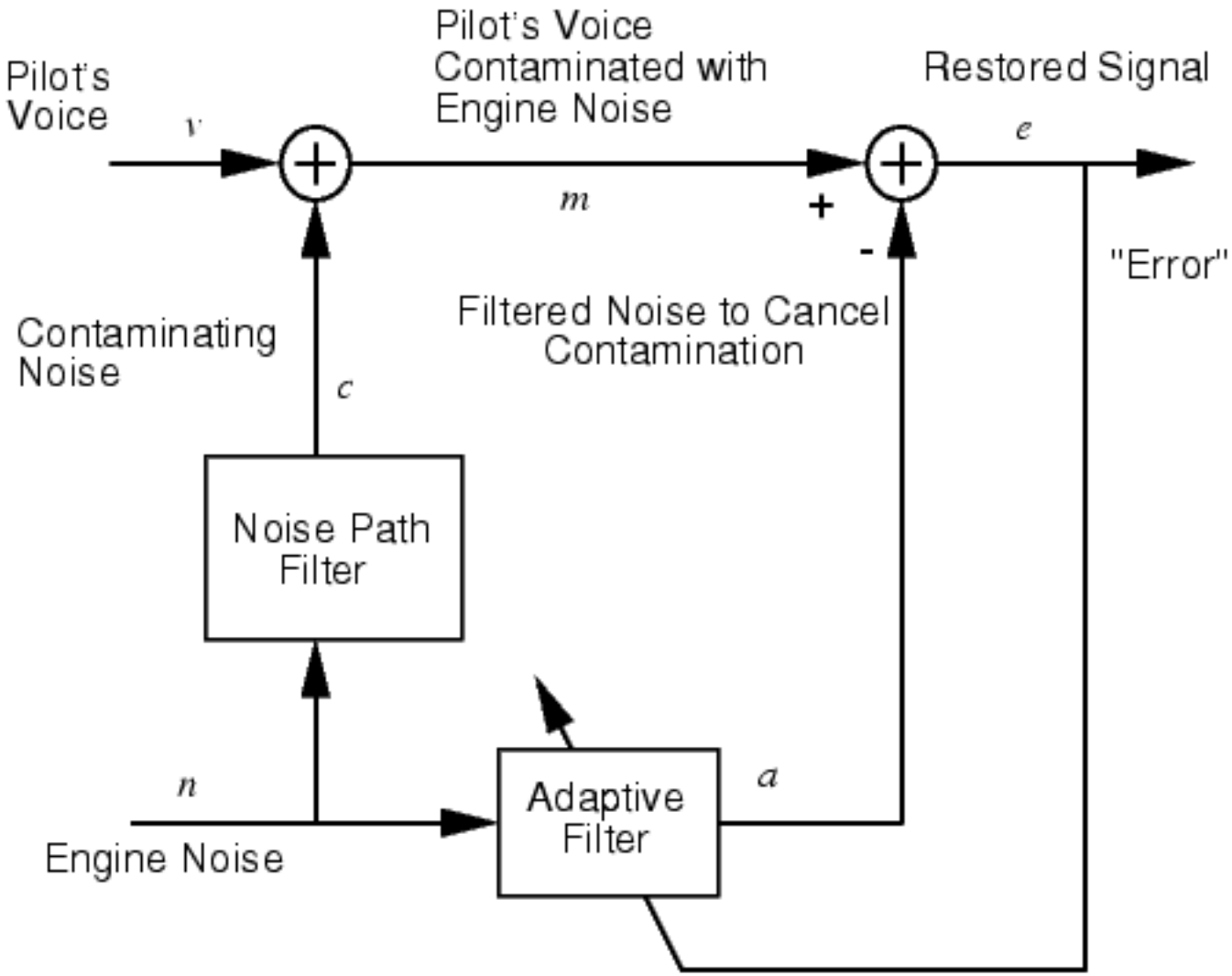
- Swinging mode predicted at 13 Hz
- Gravity coefficient 1.5×10^{-8} s^{-2} (compare to 10^{-7} s^{-2} for worst case model, 1.8×10^{-7} s^{-2} for both following slab modes)


eigfreq_sld(9)=17.552856-0i Boundary: Total displacement [m] Deformation: Displacement [m]
0
-5
-1
-2
-3
10
5
0
-5
-10
z
y
x


eigfreq_sld(42)=13.396475-0i Boundary: Total displacement [m] Deformation: Displacement [m]
40
20
0
-20
-40
-20
0
20
40
0
-5
z
y
x

Cancelling the noise

- Cannot simply subtract accelerometer data from suspension data, because it is filtered through an unknown transfer function.
- To approximate this transfer function, we can use an optimal filter.
- This approach is also used in acoustic applications, e.g. noise cancelling headphones.



Adaptive Filter Adjusts to Minimize Error.
This removes the engine noise from contaminated signal, leaving the pilot's voice as the "error."

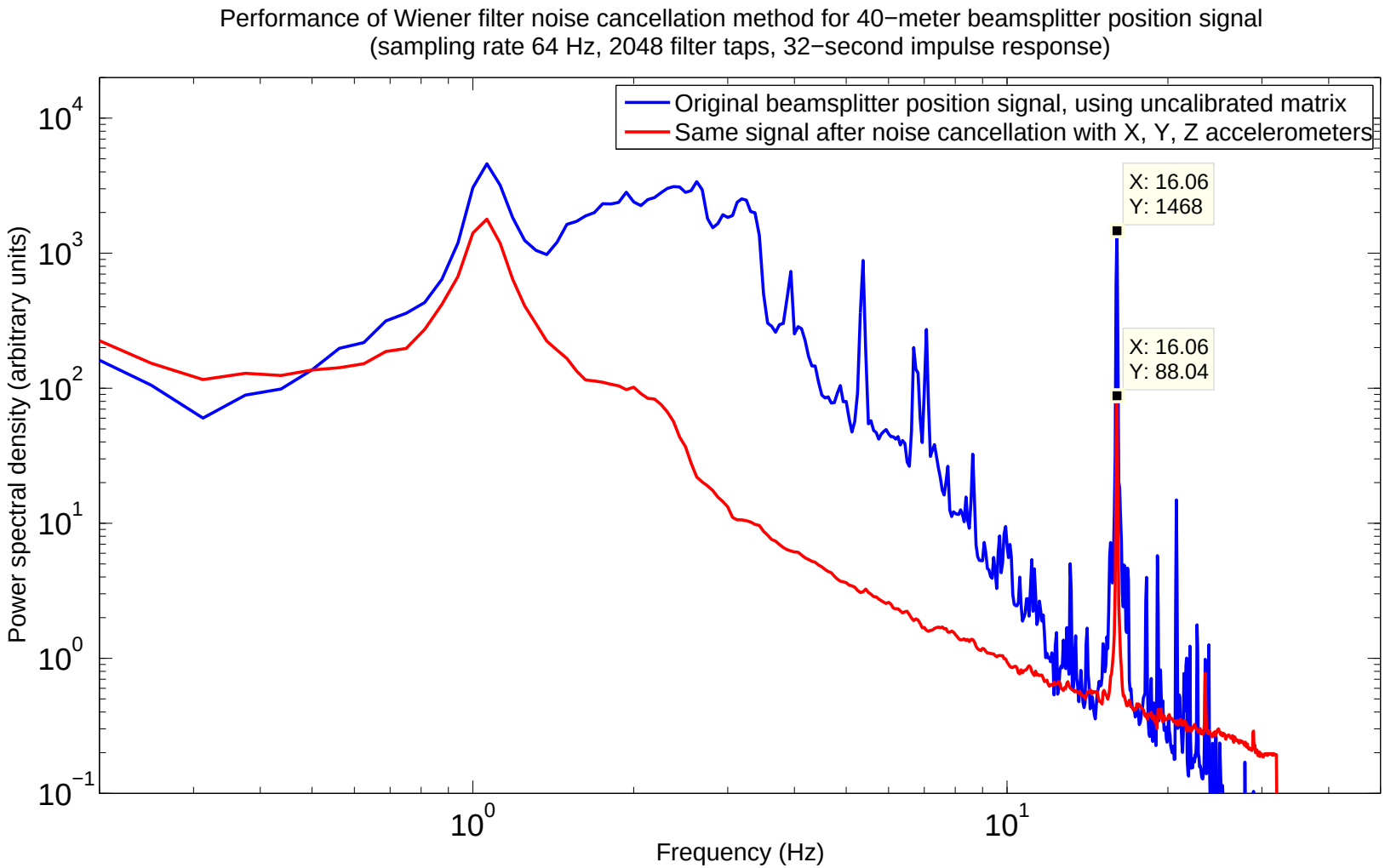
Comparison of static and adaptive filters

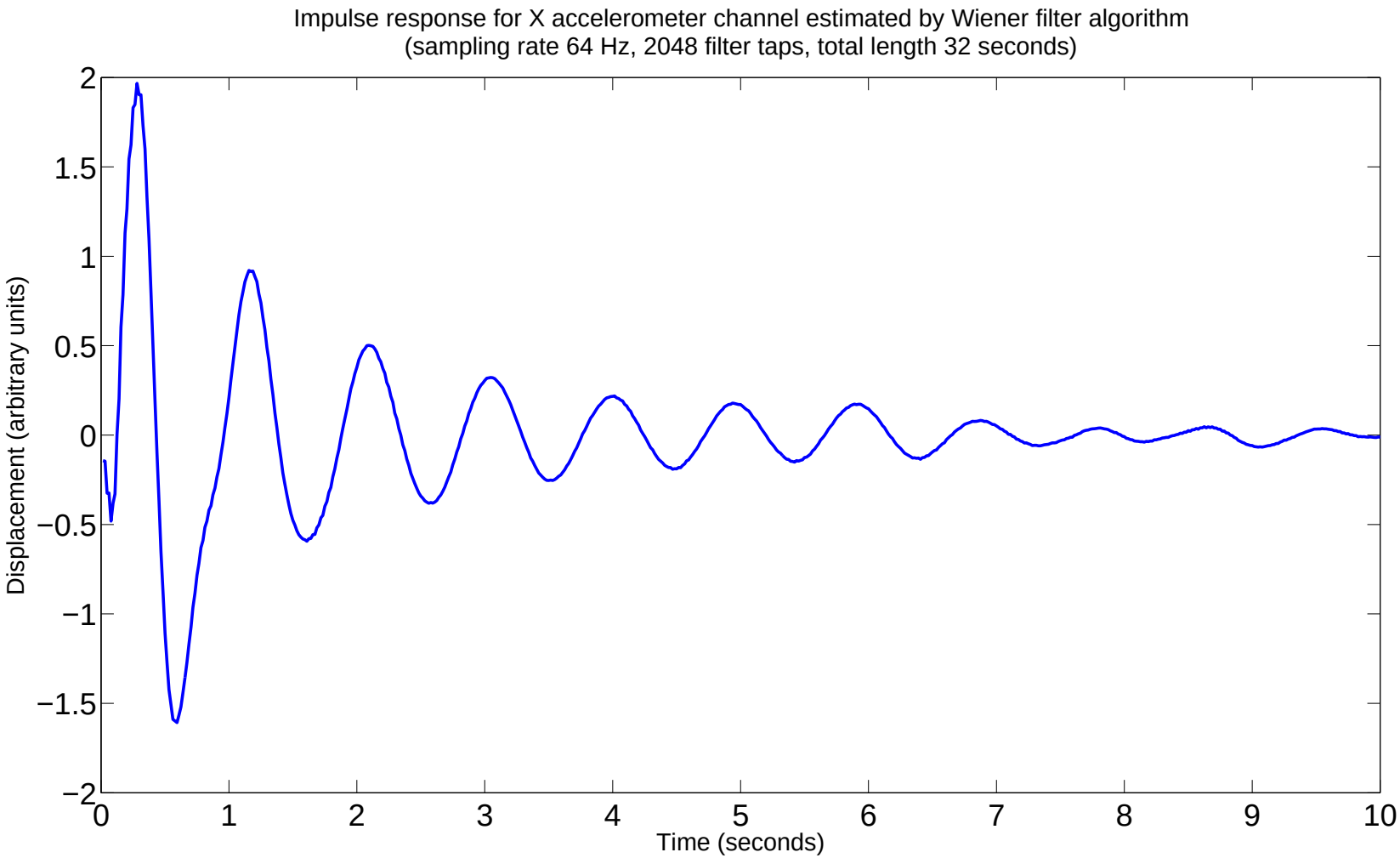
Static filters	Adaptive filters
Static coefficients	Dynamically updated
Stationary signals	Non-stationary signals
Require representative data	Can be started anywhere
Hard to construct, easy to apply	No separate construction phase
FIR Wiener, IIR Wiener	LMS, NLMS, RLS, Kalman...

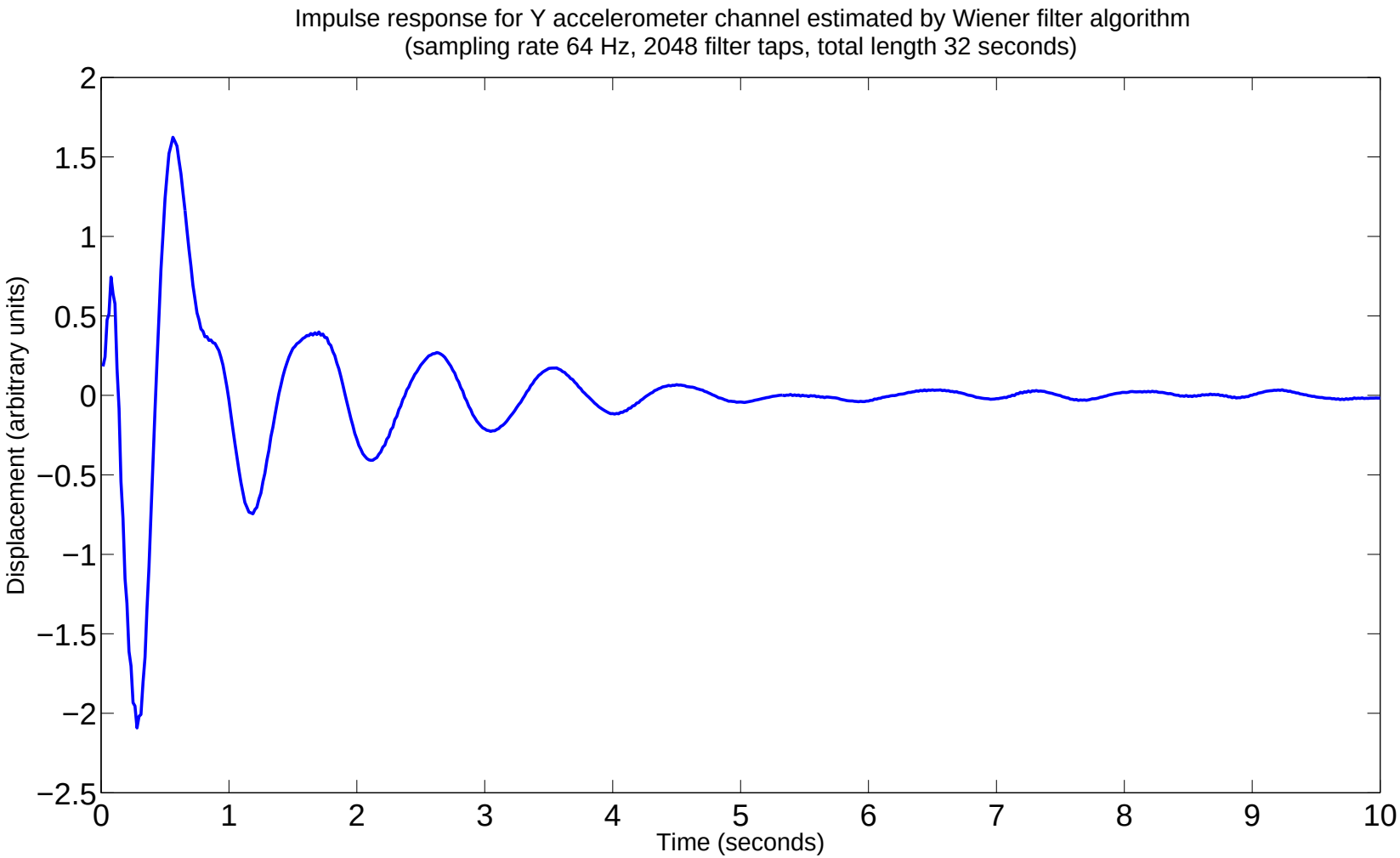
- Adaptive IIR filters are tricky (slow or not guaranteed to converge, susceptible to local minima) and not yet well understood, but they may be particularly useful for low-frequency noise cancellation.

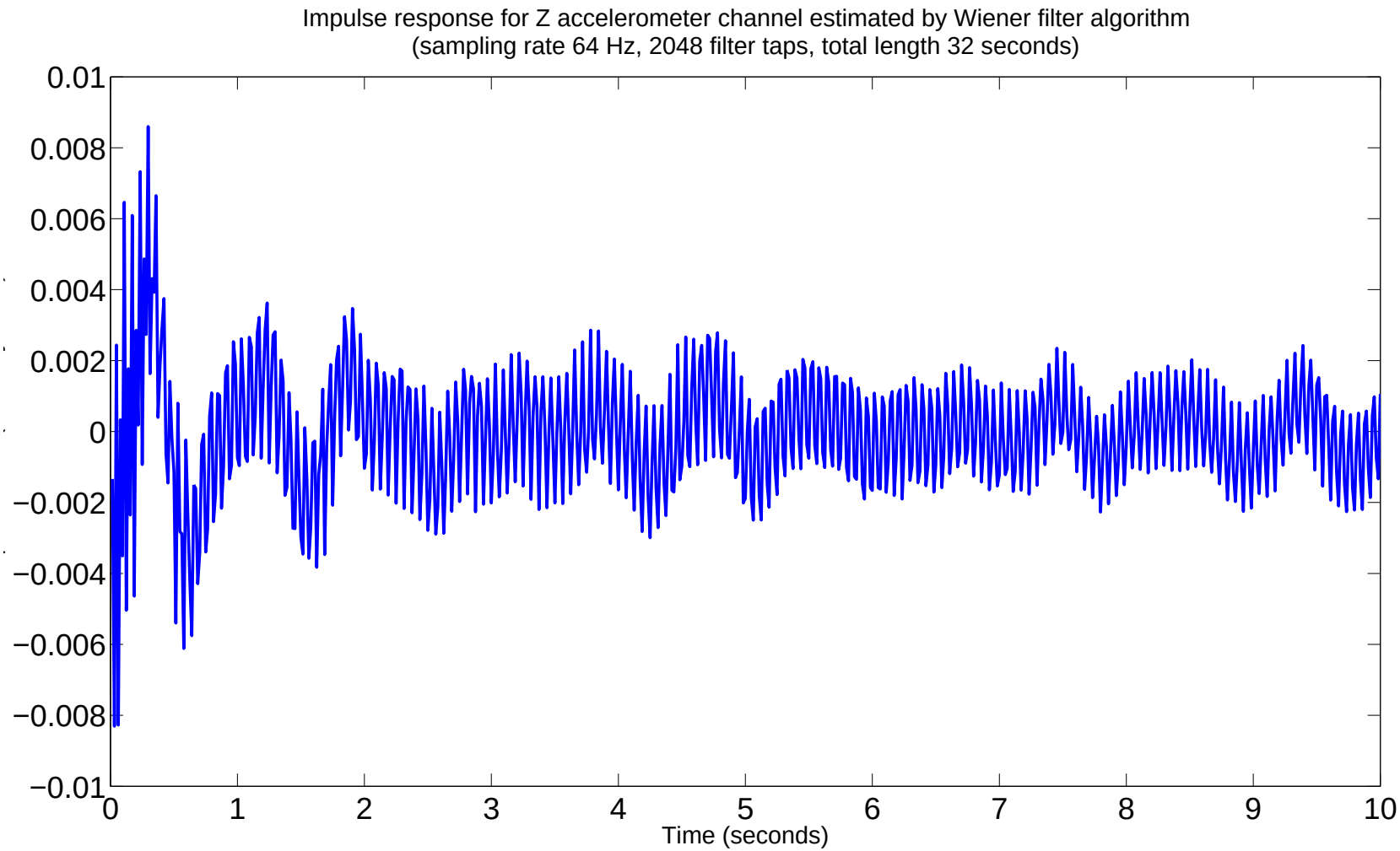
Progress so far

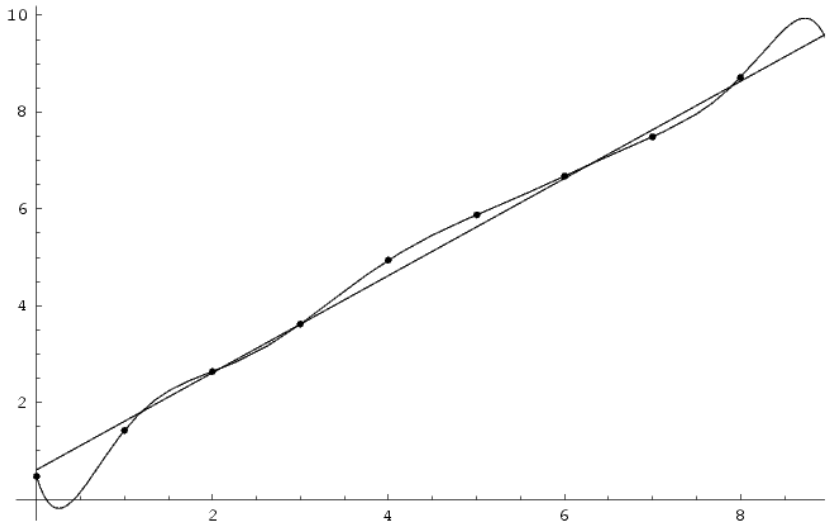
- MATLAB has built-in functions for many single-input single-output (SISO) filters, but none for multiple-input (MISO or MIMO) filters.
- I have implemented my own MISO FIR Wiener filter in MATLAB, which agrees with the built-in "firwiener" function for the special case of one input channel.
- SISO adaptive filters have been applied to one input channel (X, Y, or Z accelerometer), but this is not a good indicator of their performance in general, so these results are not presented in this talk.


Performance of Wiener filter noise cancellation method for 40−meter beamsplitter position signal
(sampling rate 64 Hz, 2048 filter taps, 32−second impulse response)
Original beamsplitter position signal, using uncalibrated matrix
Same signal after noise cancellation with X, Y, Z accelerometers
X: 16.06
Y: 1468
X: 16.06
Y: 88.04
Power spectral density (arbitrary units)
Frequency (Hz)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}

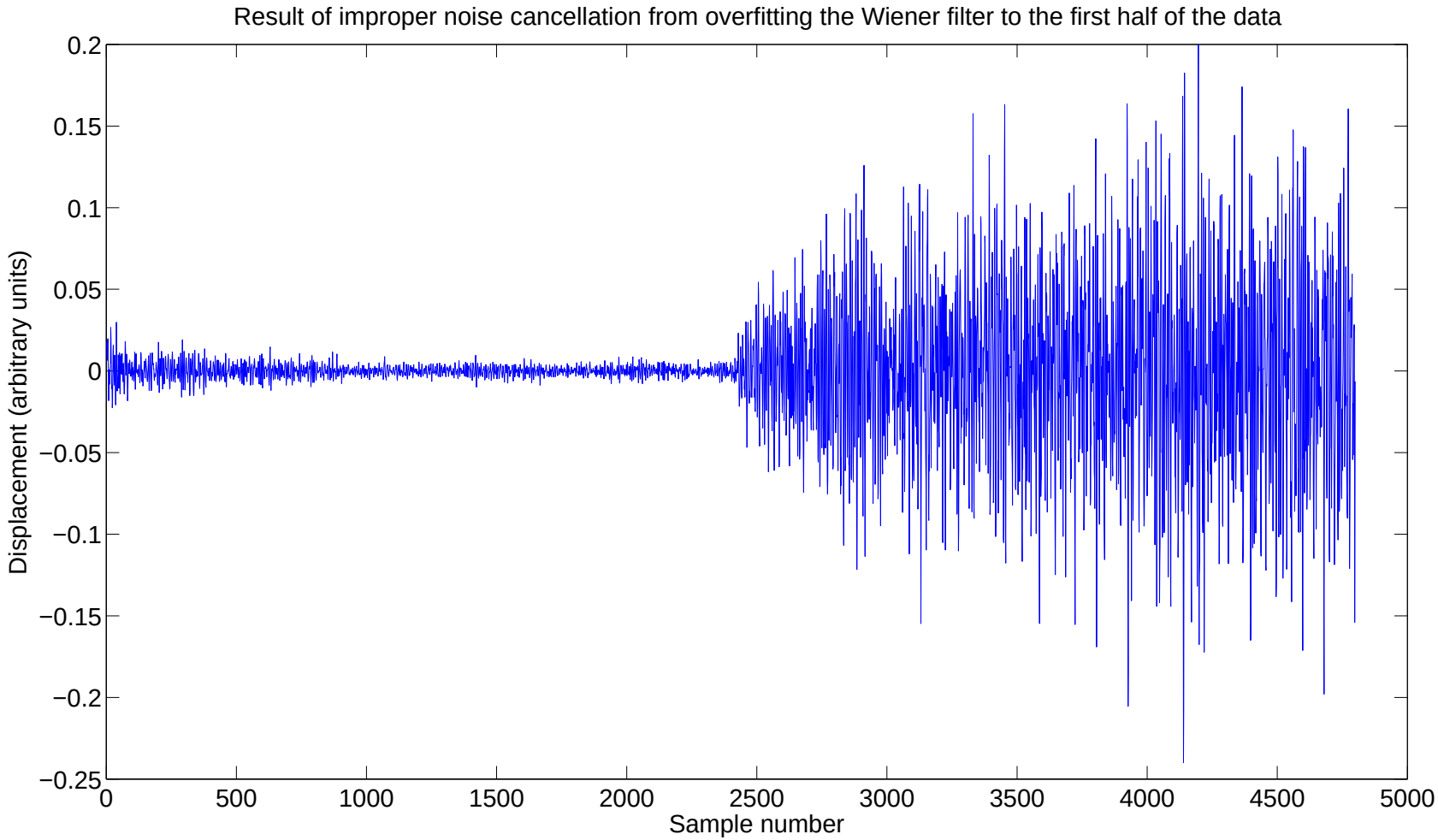

Impulse response for X accelerometer channel estimated by Wiener filter algorithm
(sampling rate 64 Hz, 2048 filter taps, total length 32 seconds)
Displacement (arbitrary units)
Time (seconds)
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
0
1
2
3
4
5
6
7
8
9
10


Impulse response for Y accelerometer channel estimated by Wiener filter algorithm
(sampling rate 64 Hz, 2048 filter taps, total length 32 seconds)
Displacement (arbitrary units)
Time (seconds)
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
0
1
2
3
4
5
6
7
8
9
10


Impulse response for Z accelerometer channel estimated by Wiener filter algorithm
(sampling rate 64 Hz, 2048 filter taps, total length 32 seconds)
0.01
0.008
0.006
0.004
0.002
0
−0.002
−0.004
−0.006
−0.008
−0.01
0
1
2
3
4
5
6
7
8
9
10
Time (seconds)



- Overfitting results when a model has too many parameters and not enough data.
- For example, when an FIR filter has almost as many taps as input samples.


Result of improper noise cancellation from overfitting the Wiener filter to the first half of the data
Displacement (arbitrary units)
Sample number
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

Ideas for future research

- Find out how to inject realistic noise into COMSOL model and use virtual accelerometers to evaluate strategies (how many do we need, where should we put them...).
- Implement different adaptive filter algorithms and compare their performance.
- Investigate adaptive IIR filters.