



Radio Frequency Noise Reduction in the LIGO Hanford Observatory

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2019 Caltech SURF Program

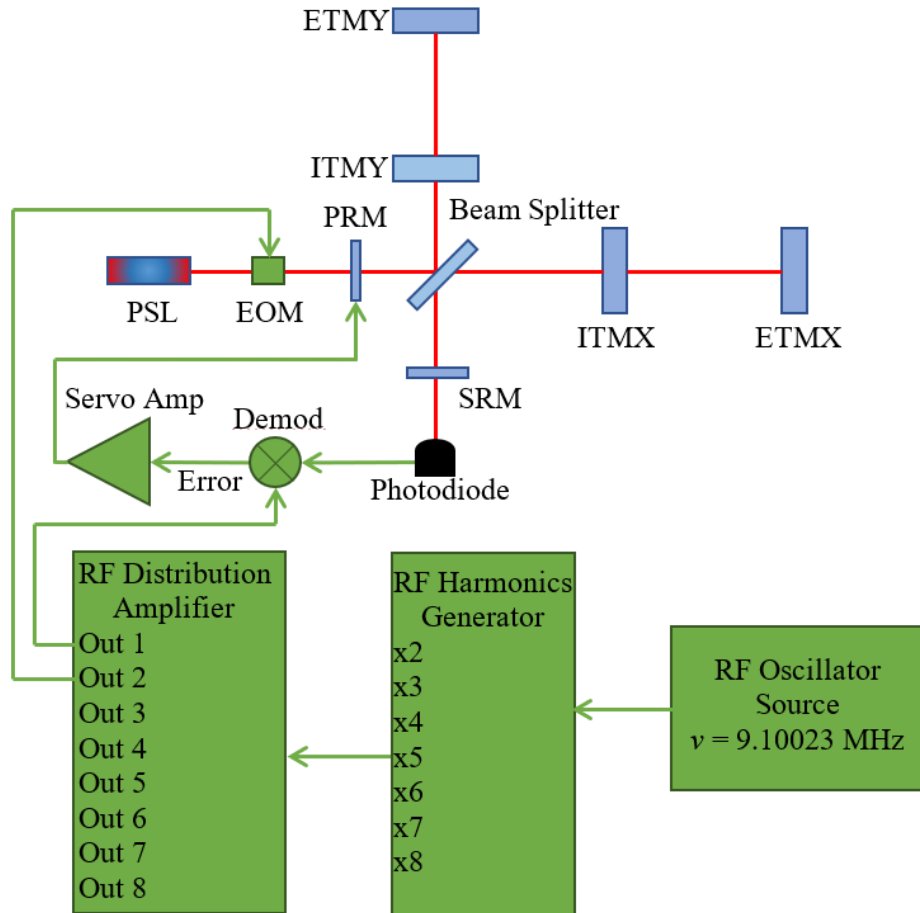
Mentors: Dick Gustafson and Keita Kawabe

Overview

- RF Distribution System Overview
- Investigation: Mapping RF Cable Noise to DARM
 - » Intro to RF Cable Shield Noise
 - » Mapping Methodology
 - » Experiment #1: Cable Characterization
 - » Experiment #2: RF Noise Injections
 - » Experiment #3: Cable Noise Profile Collection
- Further Improvements
 - » Adjusting Mapping Equation for Non-Flat Transfer Function
- Future Work

RF Distribution System Overview

RF Signal Generation for Servo Control Loop

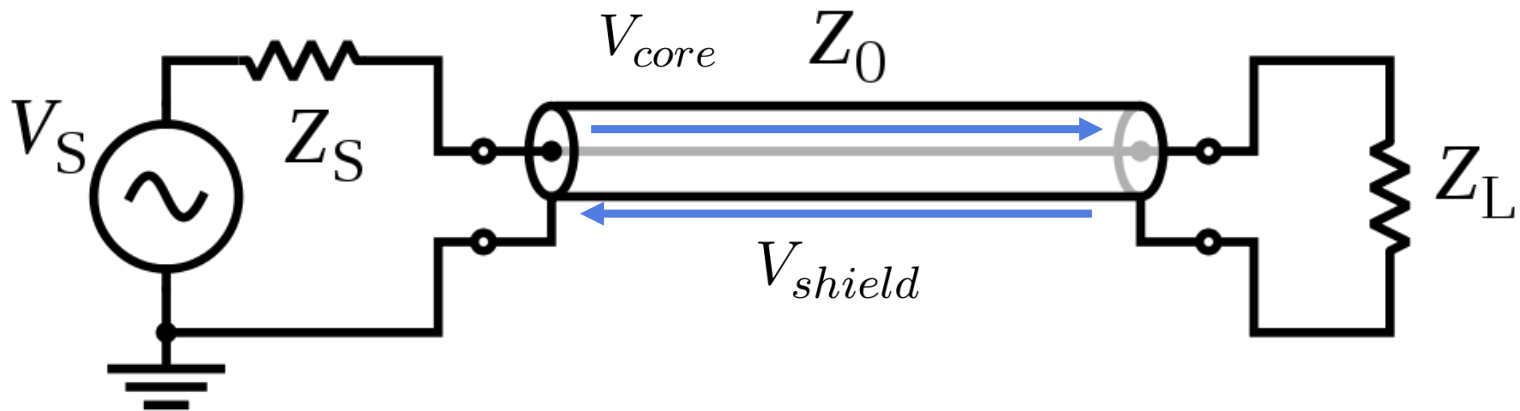


PSL = Pre-Stabilized Laser
 EOM = Electro Optic Modulator
 PRM = Power Recycling Mirror
 SRM = Signal Recycling Mirror
 ITMX = Input Test Mass X
 ETMX = End Test Mass X
 ITMY = Input Test Mass Y
 ETMY = End Test Mass Y

Mapping Cable Noise to DARM

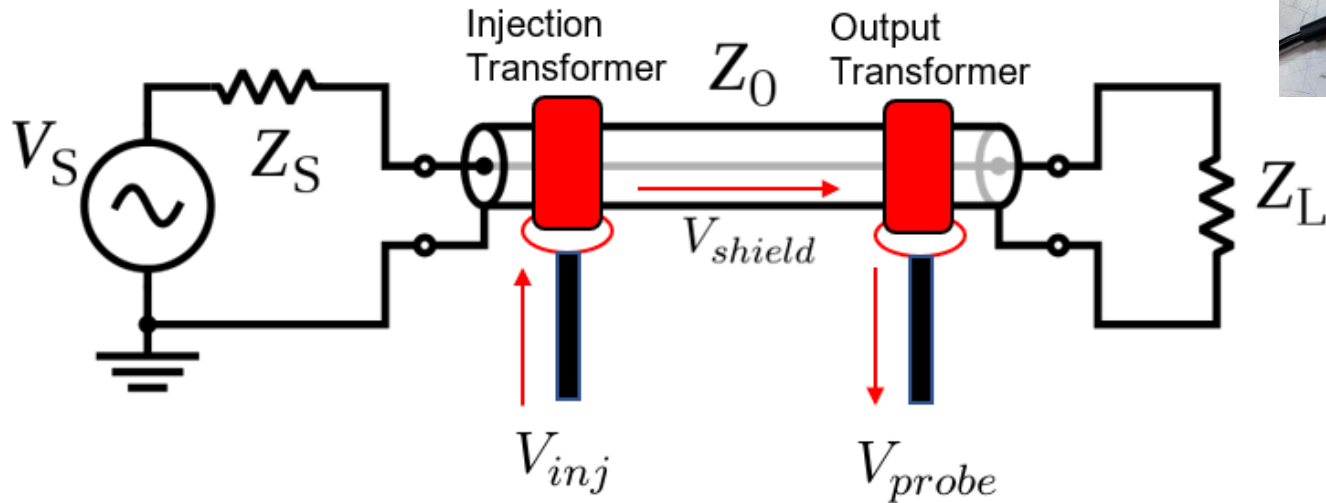
Shield Noise Overview

- » Shield Noise = Any unwanted RF signal (V_{shield}) on the shield of a transmission cable



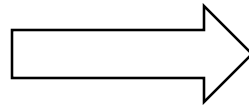
Mapping Cable Noise to DARM

Measuring and Exciting Shield Noise



$$V_{shield} = aV_{inj}$$

$$V_{probe} = bV_{shield}$$

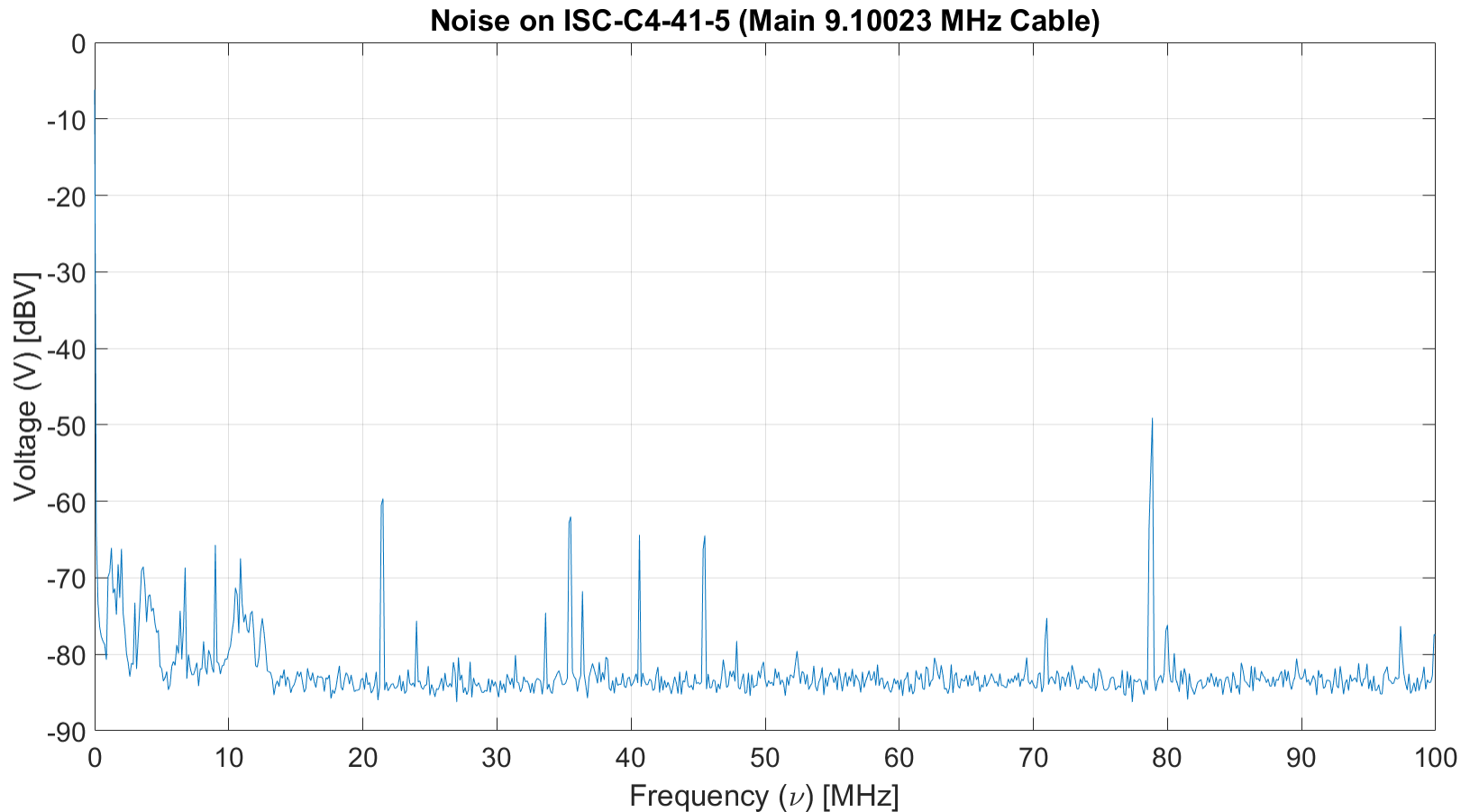


$$V_{shield} = \frac{V_{probe}}{b}$$

$$ab = \frac{V_{probe}}{V_{inj}}$$

Mapping Cable Noise to DARM

□ Sample Shield Noise Profile

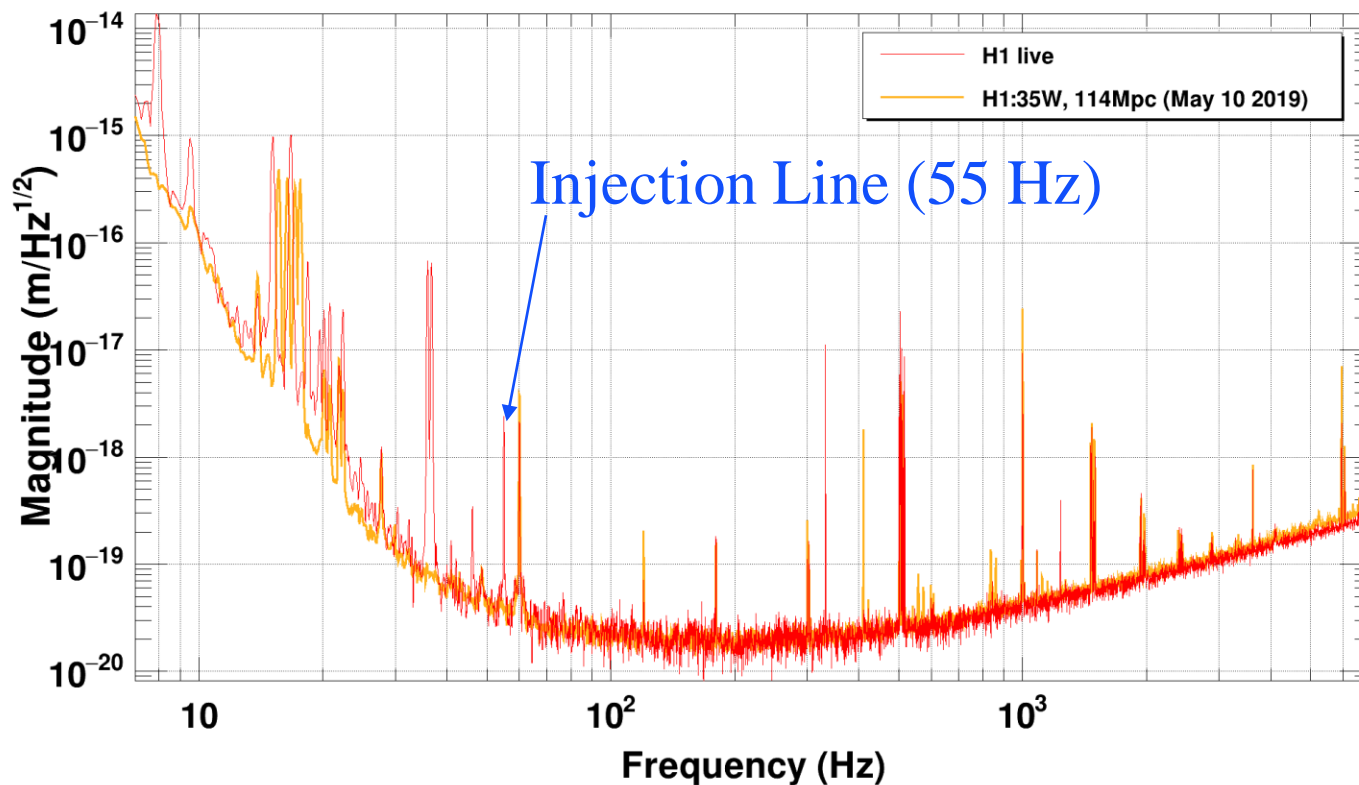


Mapping Cable Noise to DARM

□ DARM Response of March 2019 RF Signal Injection

H1 DARM during 9.100285 MHz Injection on Main 9.10023 MHz Line

$$V_{inj} = V_{core} \text{ [MHz]} \pm V_{offset} \text{ [Hz]}$$



*T0=15/03/2019 20:50:45

Avg=5/Bin=5L

BW=0.187493

LIGO-T1900364-v5

Mapping Cable Noise to DARM

□ Mapping Methodology:

$$\frac{\text{ASD}(D)}{\text{ASD}(V_{shield})} = \frac{D_{inj}}{V_{shield,inj}}$$

$$\text{ASD}(D) = \frac{D_{inj}}{aV_{inj}} \text{ASD}(V_{shield})$$

$$\text{ASD}(D) = \frac{1}{ab} \frac{D_{inj}}{V_{inj}} \text{ASD}(V_{probe})$$

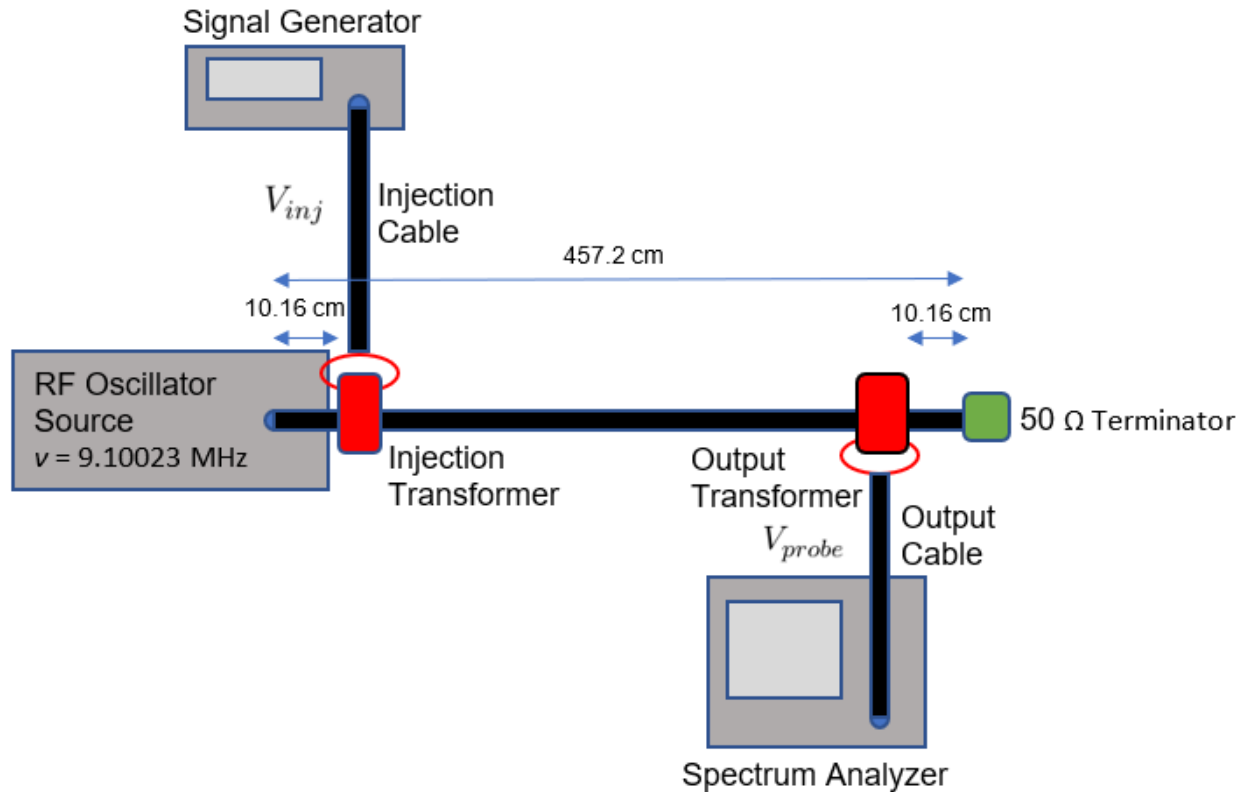
Experiment #1: Cable Characterization

Experiment #2: RF Noise Injection

Experiment #3: RF Noise Profile Collection

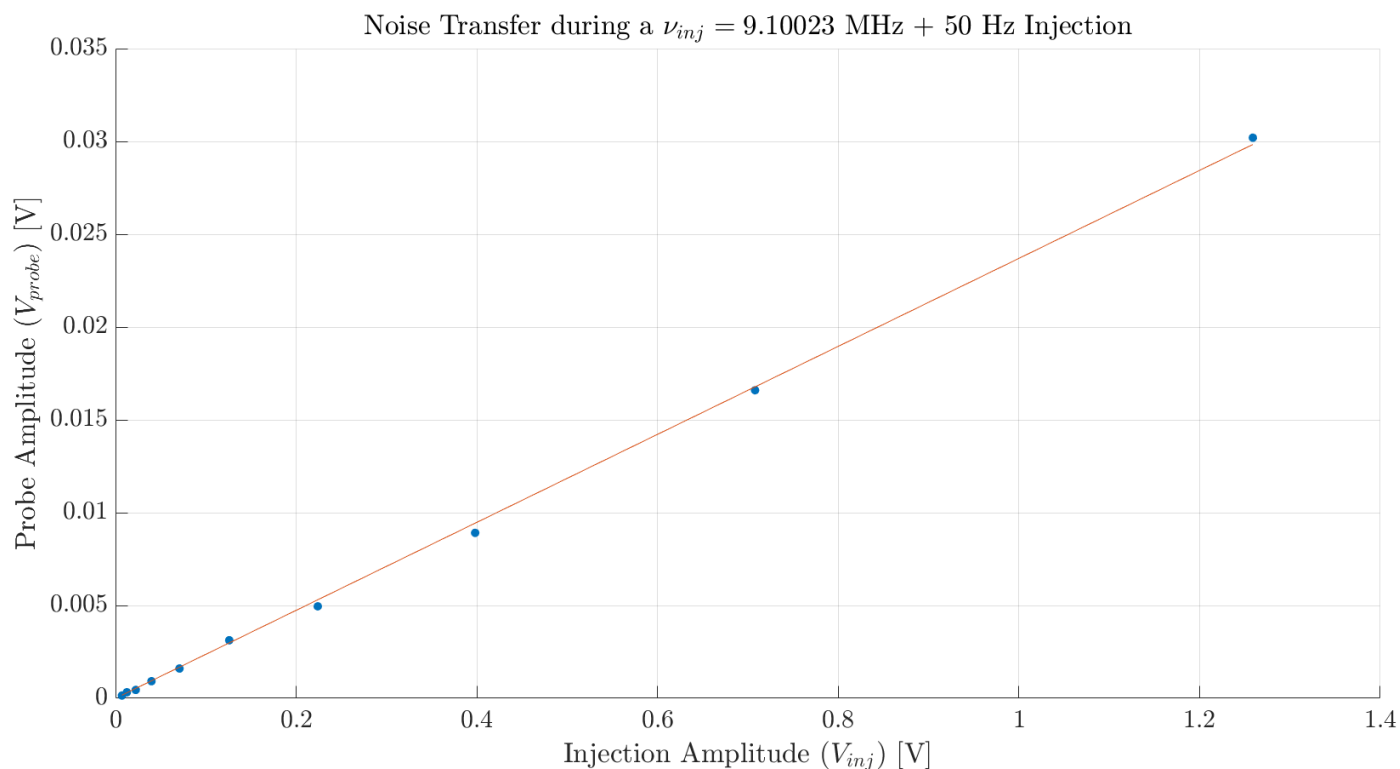
Mapping Cable Noise to DARM

□ Experiment #1: Cable Characterization - Setup



Mapping Cable Noise to DARM

□ Experiment #1: Cable Characterization - Results



$$ab = 0.0237$$

Mapping Cable Noise to DARM

□ Mapping Methodology:

$$\frac{\text{ASD}(D)}{\text{ASD}(V_{shield})} = \frac{D_{inj}}{V_{shield,inj}}$$

$$\text{ASD}(D) = \frac{D_{inj}}{aV_{inj}} \text{ASD}(V_{shield})$$

$$\text{ASD}(D) = \boxed{\frac{1}{ab} \frac{D_{inj}}{V_{inj}} \text{ASD}(V_{probe})}$$

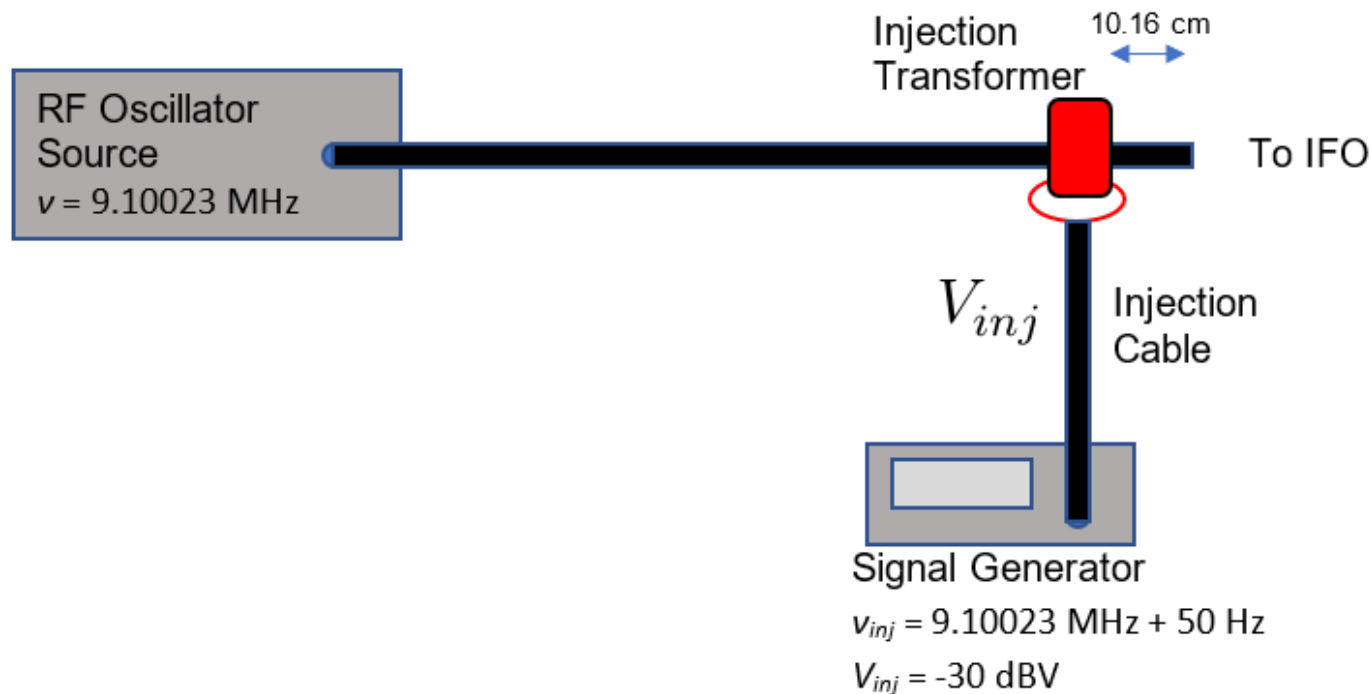
Experiment #1: Cable Characterization

Experiment #2: RF Noise Injection

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Mapping Cable Noise to DARM

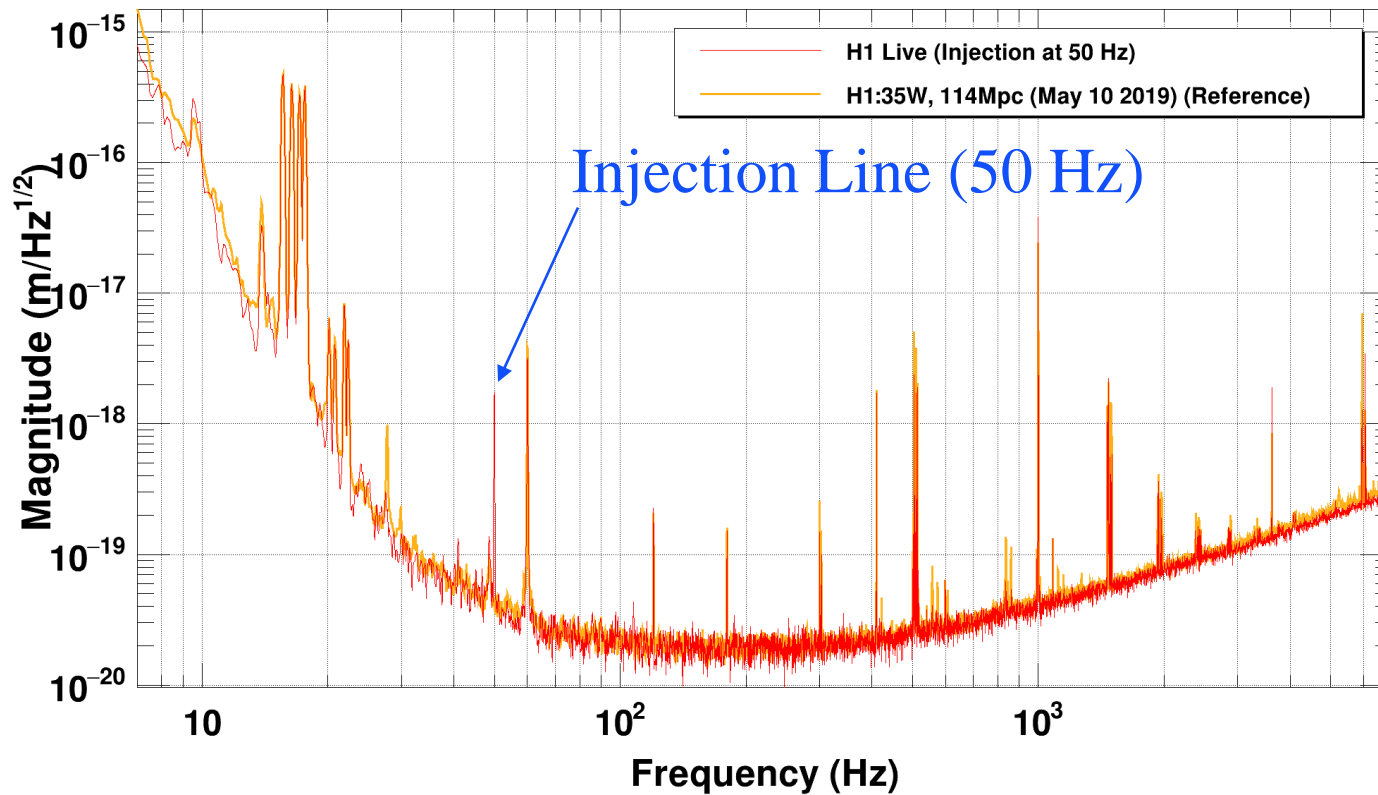
Experiment #2: Noise Injections - Setup



Mapping Cable Noise to DARM

Experiment #2: Noise Injections - Results

9.10023 MHz + 50 Hz Injection on ISC-C4-41-5 (Main 9.10023 MHz Line)



*T0=30/07/2019 15:57:00

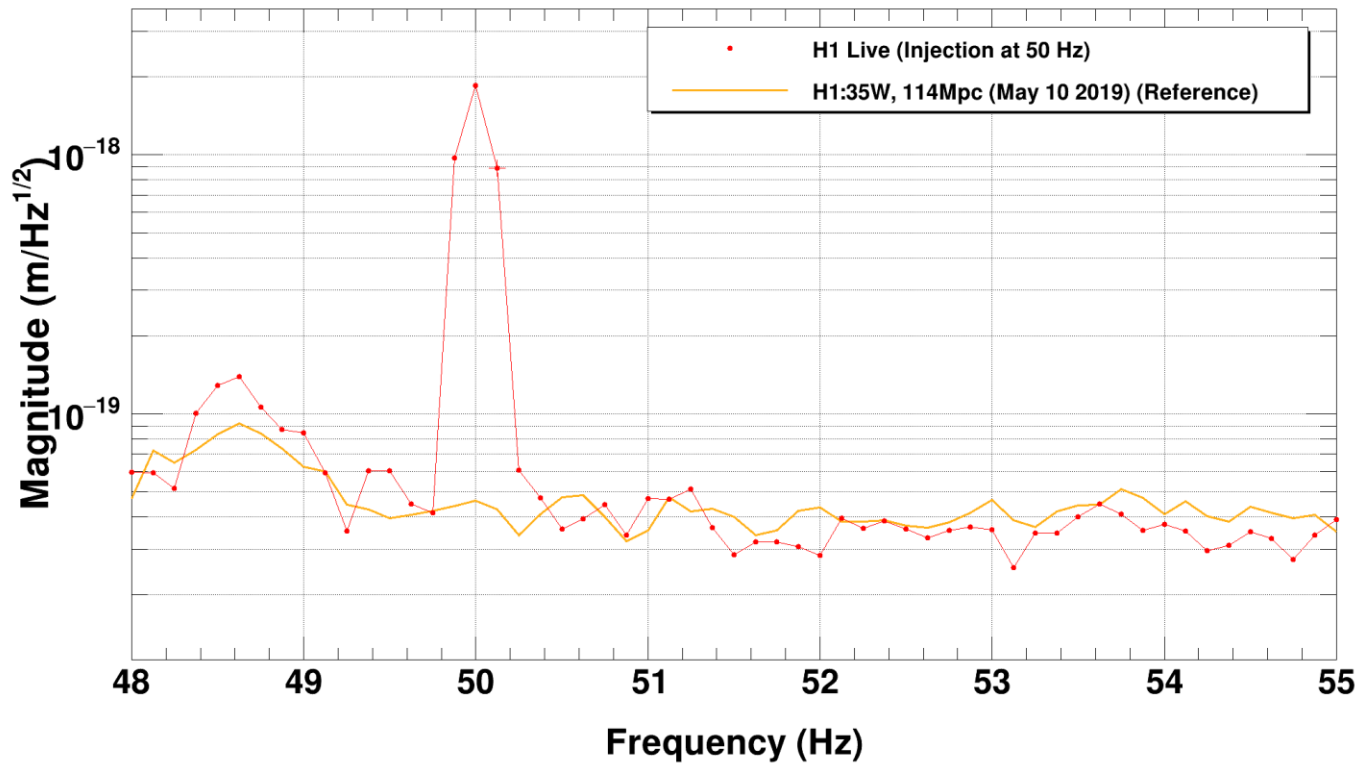
Avg=10/Bin=5L

BW=0.187493

Mapping Cable Noise to DARM

Experiment #2: Noise Injections - Results

9.10023 MHz + 50 Hz Injection on ISC-C4-41-5 (Main 9.10023 MHz Line)



$$D = \sqrt{\left(\sum_i d_i^2\right) BW}$$

$$= 5.77 * 10^{-19} \text{ m}$$

*T0=30/07/2019 15:57:00

Avg=10

BW=0.187493

Mapping Cable Noise to DARM

□ Mapping Methodology:

$$\frac{\text{ASD}(D)}{\text{ASD}(V_{shield})} = \frac{D_{inj}}{V_{shield,inj}}$$

$$\text{ASD}(D) = \frac{D_{inj}}{aV_{inj}} \text{ASD}(V_{shield})$$

$$\text{ASD}(D) = \boxed{\frac{1}{ab} \frac{D_{inj}}{V_{inj}} \text{ASD}(V_{probe})}$$

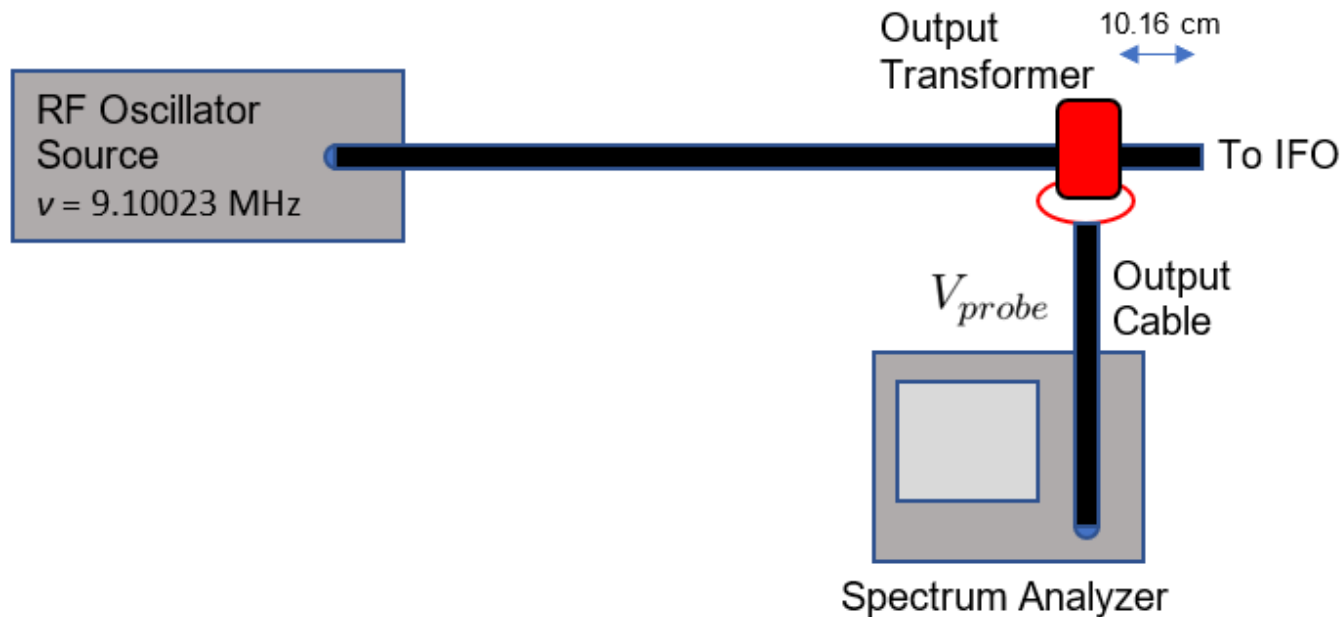
Experiment #1: Cable Characterization

Experiment #2: RF Noise Injection

Experiment #3: RF Noise Profile Collection

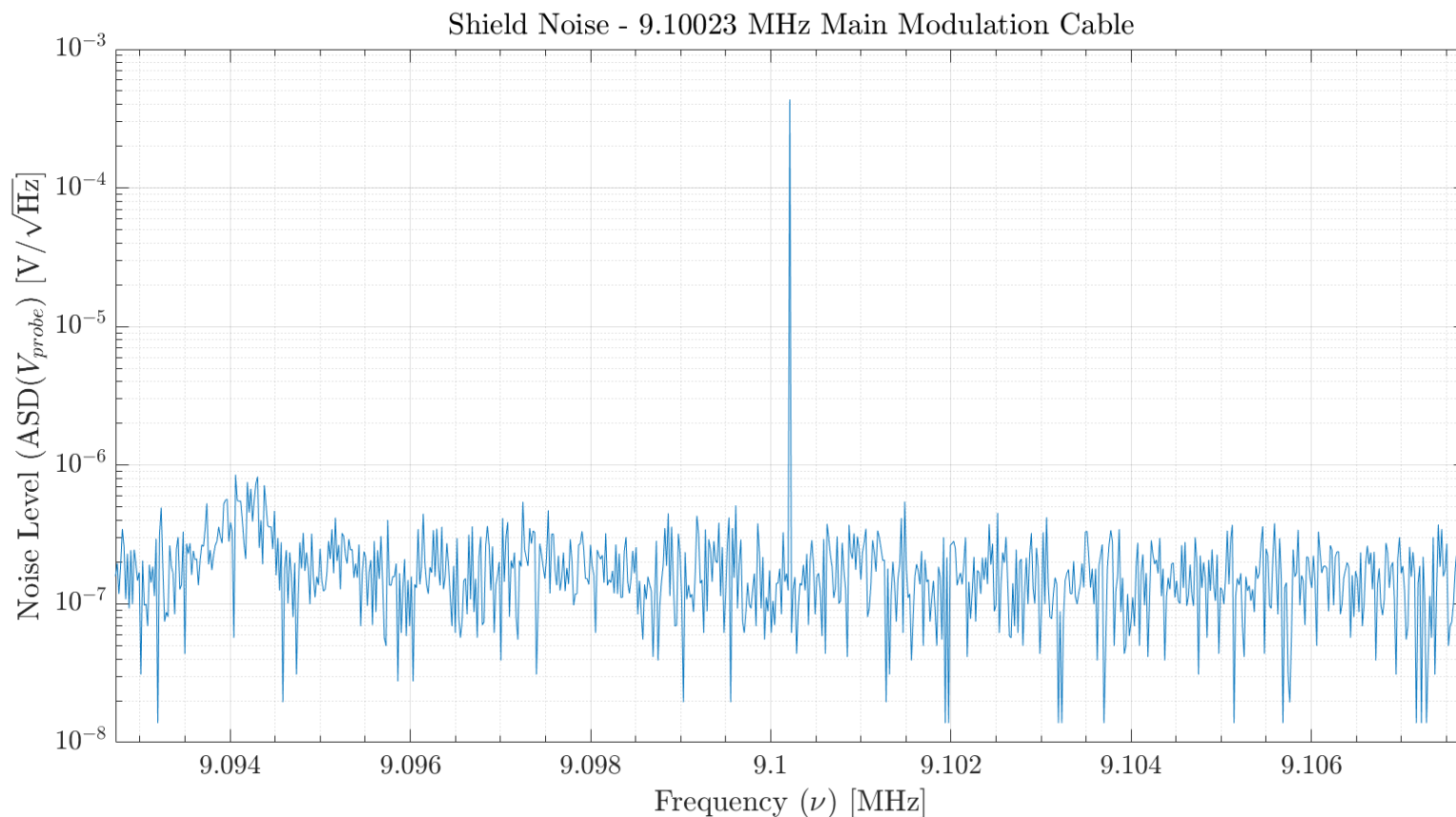
Mapping Cable Noise to DARM

- Experiment #3: RF Noise Profile Collection - Setup



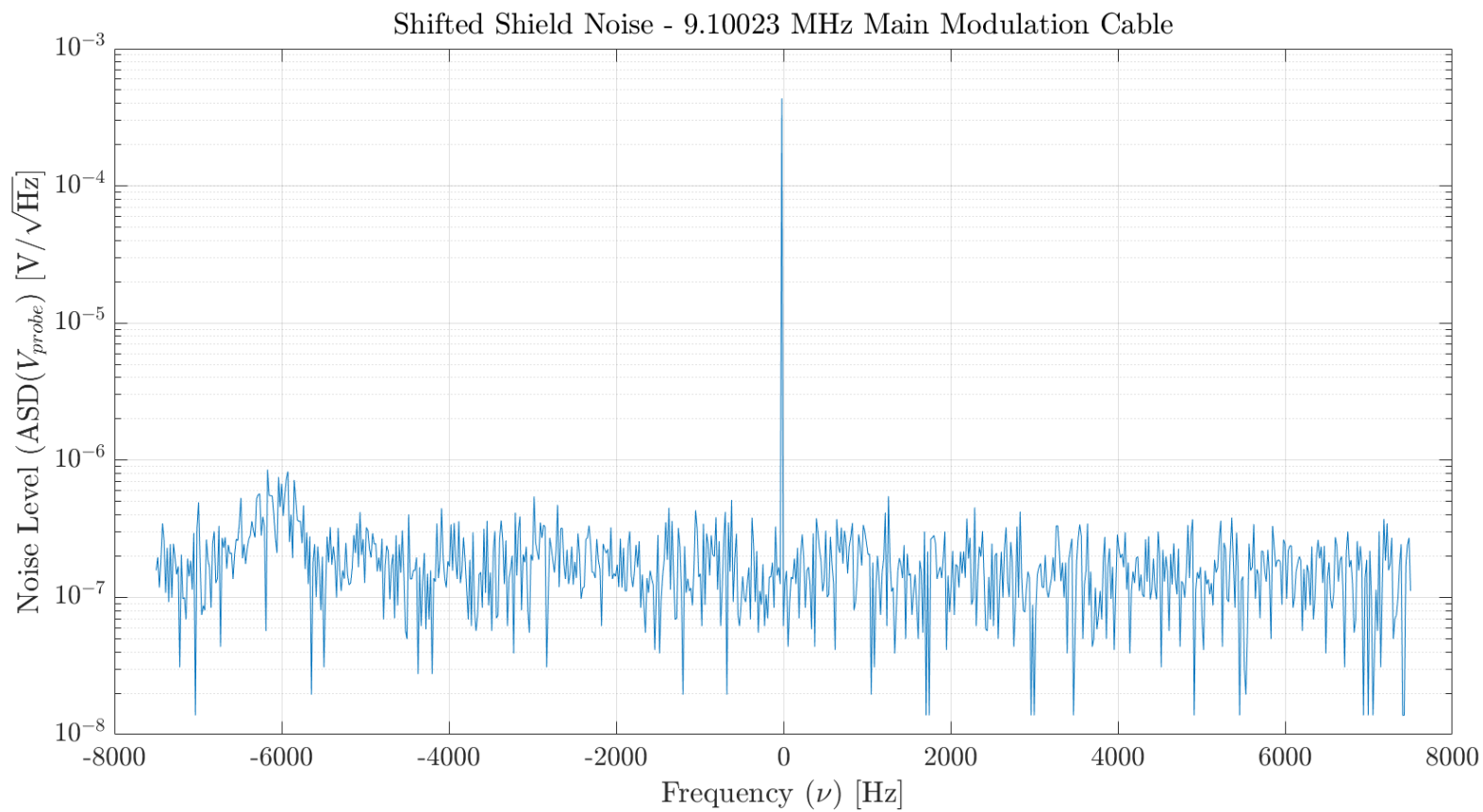
Mapping Cable Noise to DARM

Experiment #3: RF Noise Profile Collection – Data Prep

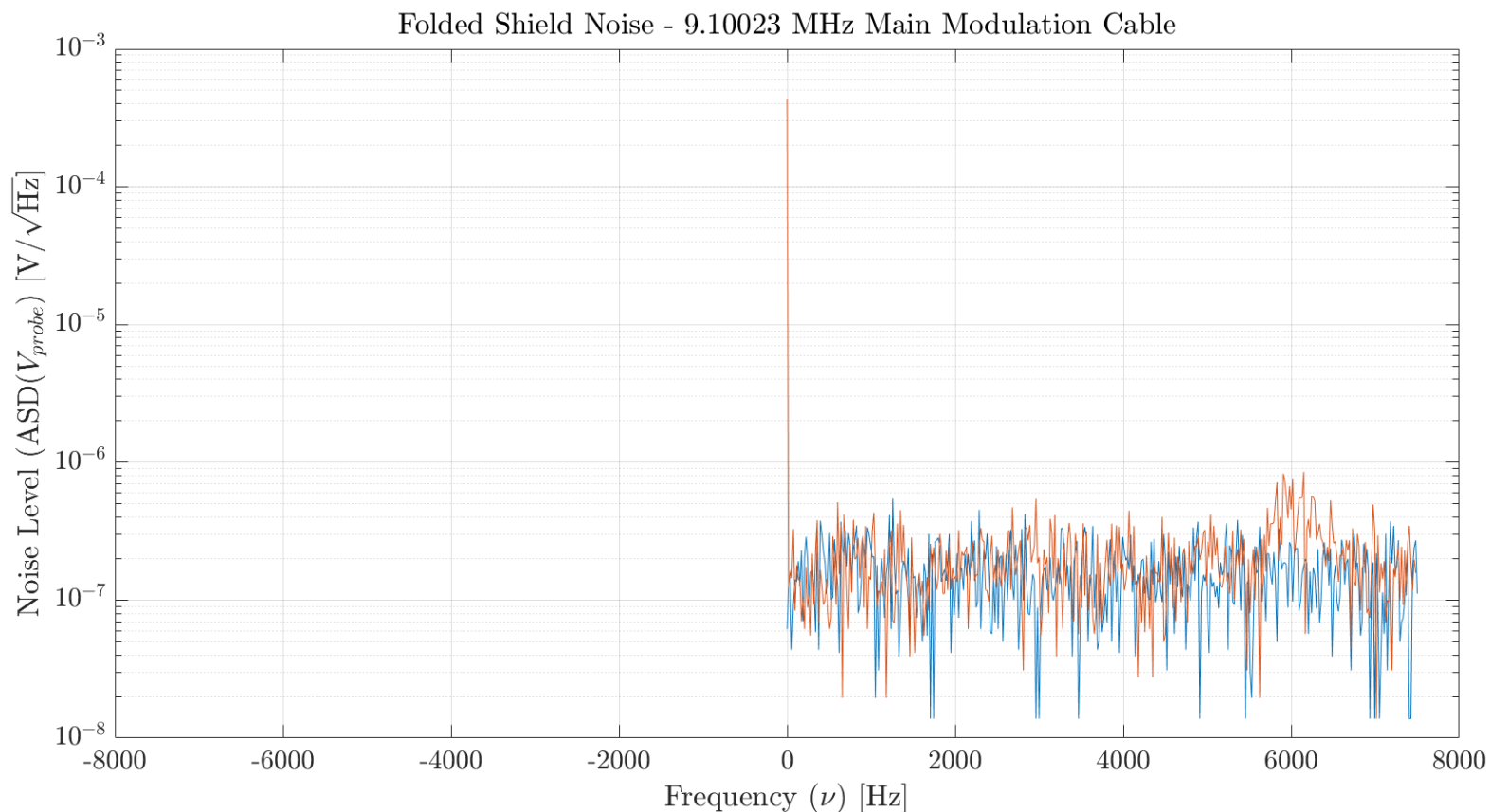


Mapping Cable Noise to DARM

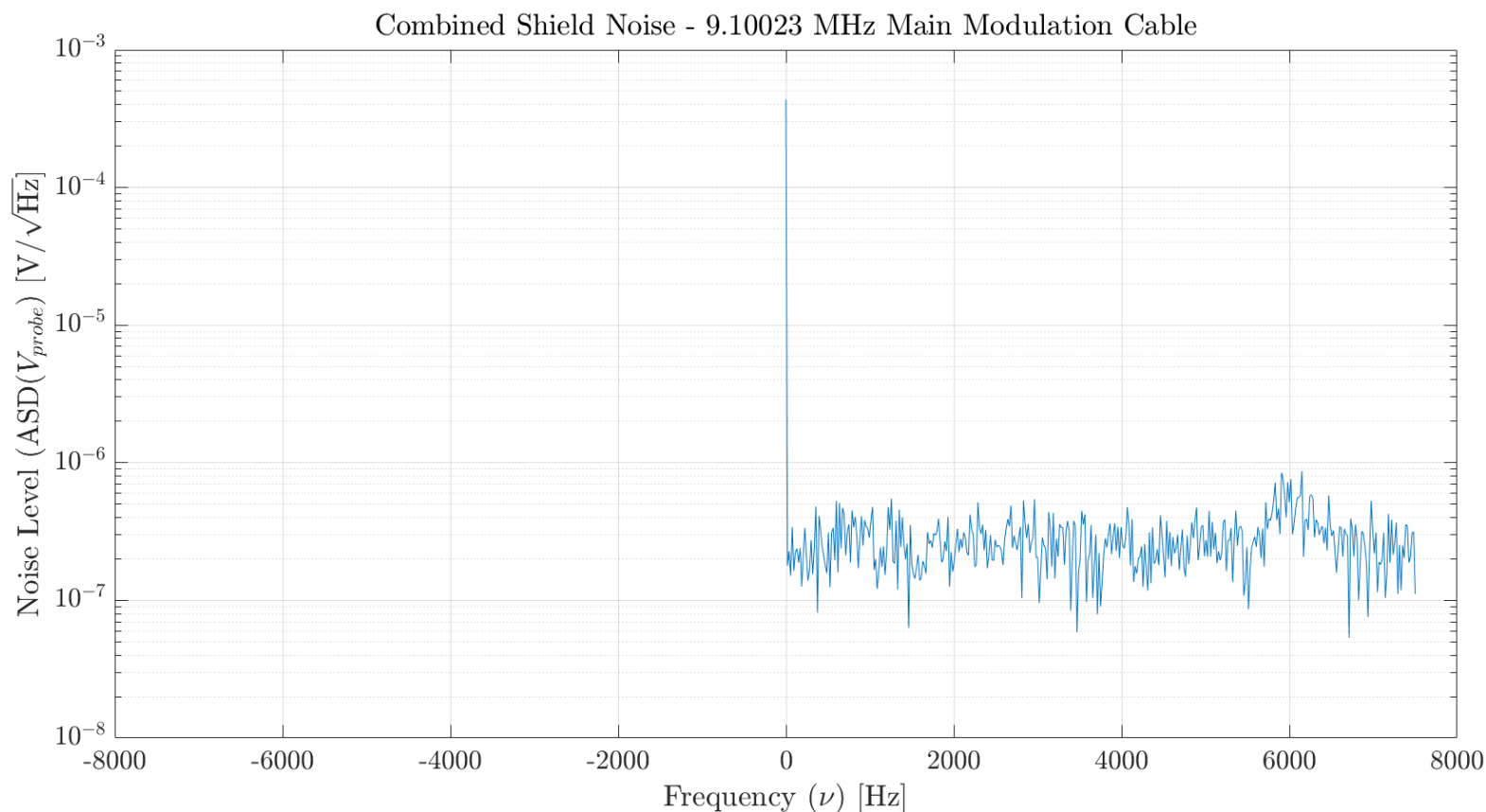
Experiment #3: RF Noise Profile Collection – Data Prep



Experiment #3: RF Noise Profile Collection – Data Prep



Experiment #3: RF Noise Profile Collection - Results



Mapping Cable Noise to DARM

$$\frac{\text{ASD}(D)}{\text{ASD}(V_{shield})} = \frac{D}{V_{shield}}$$

$$\text{ASD}(D) = \frac{D}{aV_{inj}} \text{ASD}(V_{shield})$$

$$\text{ASD}(D) = \frac{1}{ab} \frac{D}{V_{inj}} \text{ASD}(V_{probe})$$

Experiment #1: Cable Characterization

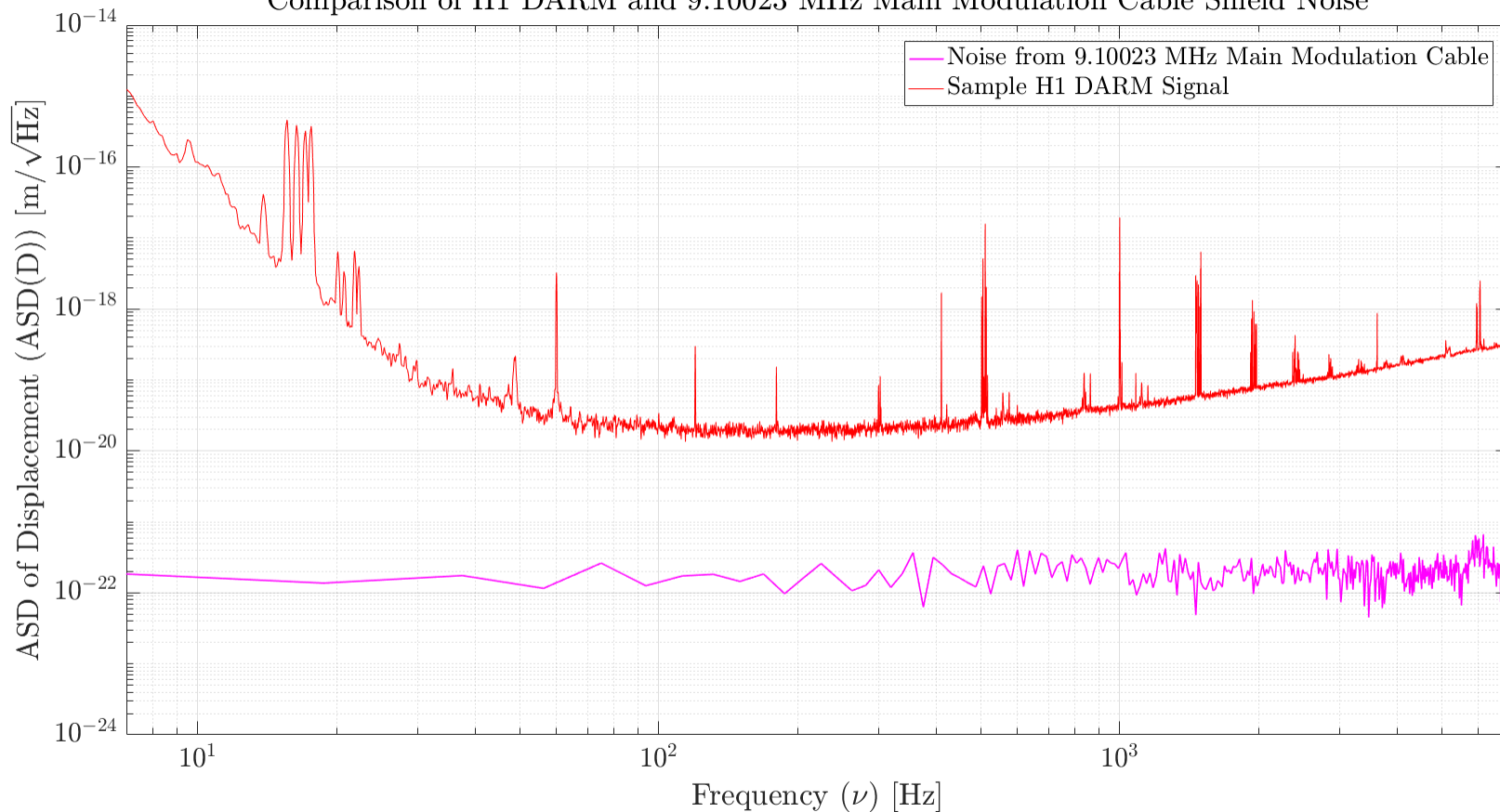
Experiment #2: RF Noise Injection

Experiment #3: RF Noise Profile Collection

Mapping Cable Noise to DARM

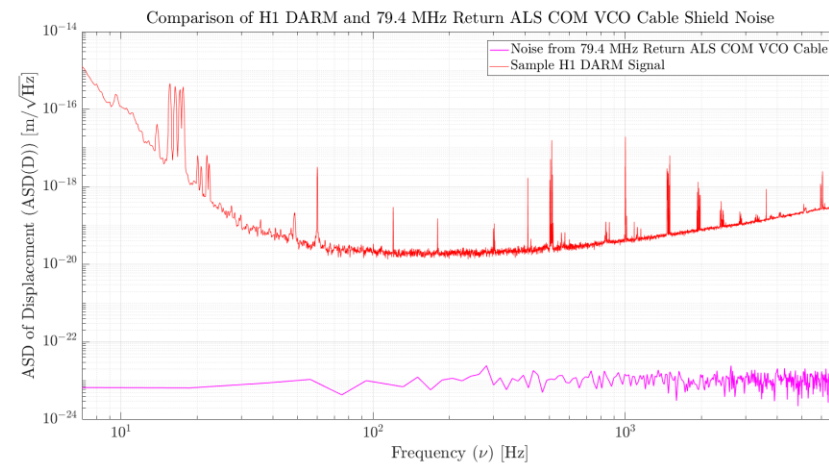
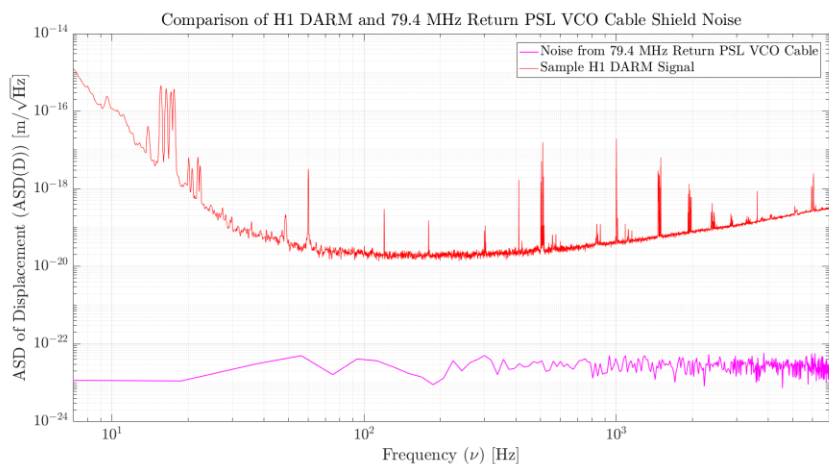
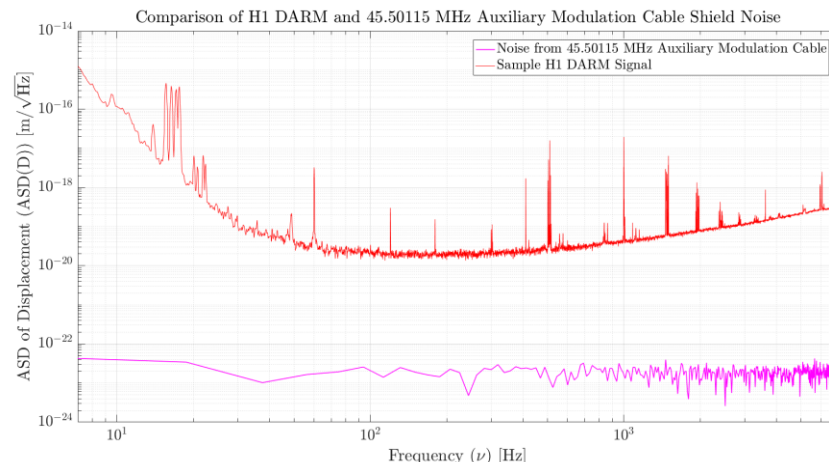
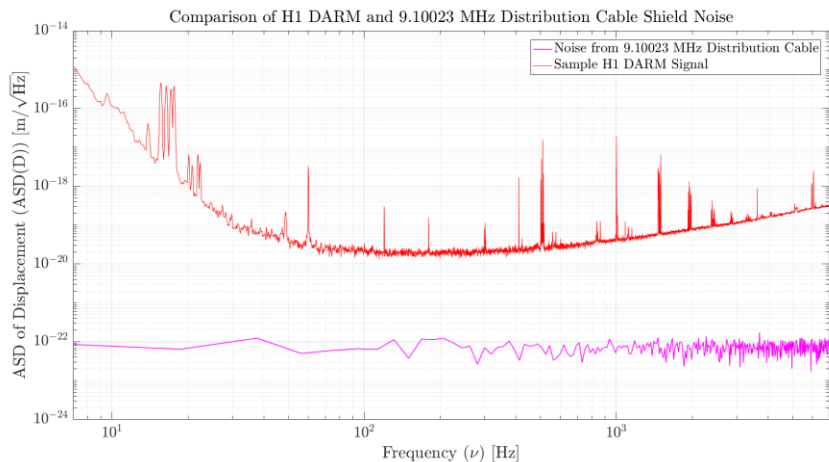
Final Results: 9.10023 MHz Main Modulation Cable

Comparison of H1 DARM and 9.10023 MHz Main Modulation Cable Shield Noise



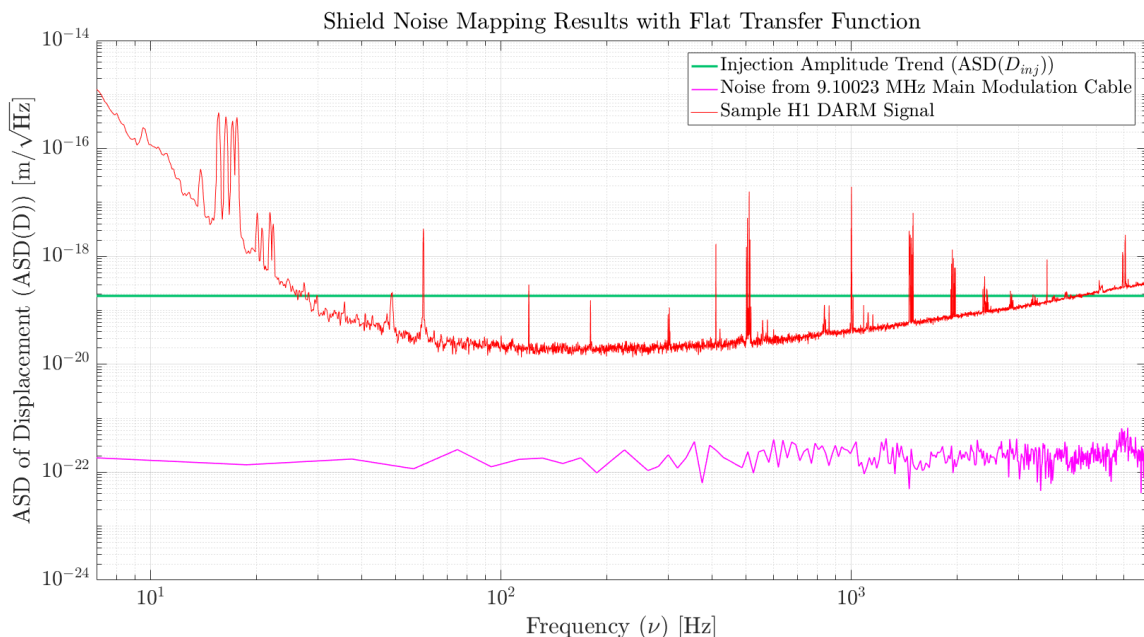
Mapping Cable Noise to DARM

Final Results: Other Cables



Further Improvements

- Original Equation Assumes Flat Transfer Function between Cable Noise and DARM Noise



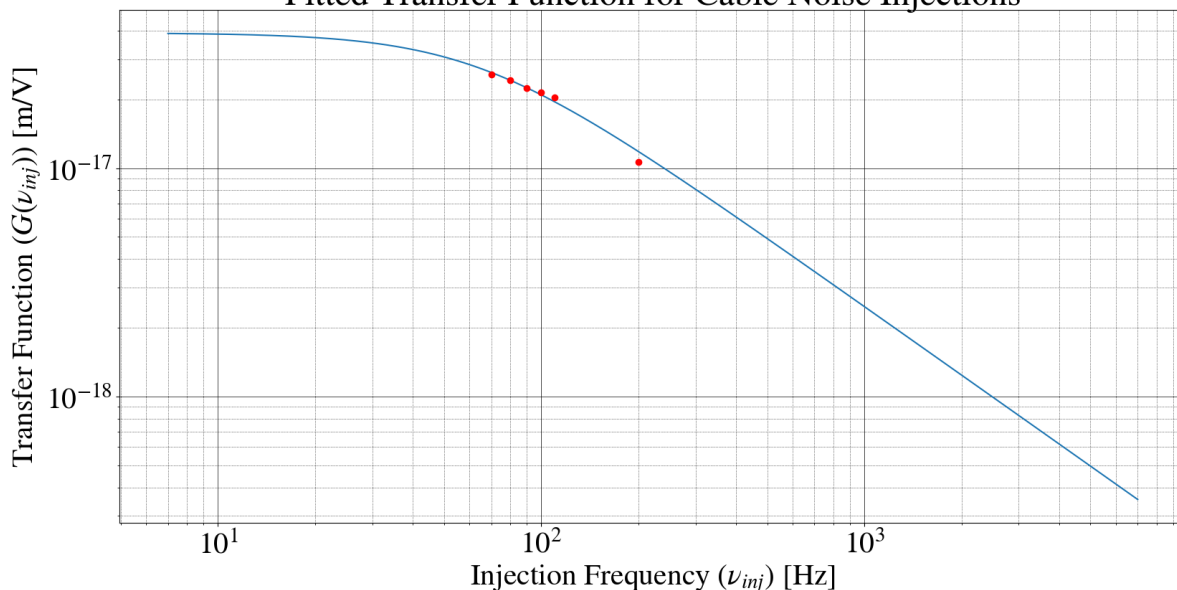
$$ASD(D) = \frac{1}{ab} \frac{D_{inj}}{V_{inj}} ASD(V_{probe})$$

$$H(\nu_{inj}) = \frac{D_{inj}}{V_{inj}} = \text{constant}$$

Further Improvements

- Recently Acquired Data Suggests a Non-Flat Transfer Function -> Try 1-pole Transfer Function

Fitted Transfer Function for Cable Noise Injections



$$H(\nu_{inj}) = K \frac{1}{1 + i \frac{\nu_{inj}}{\nu_0}}$$

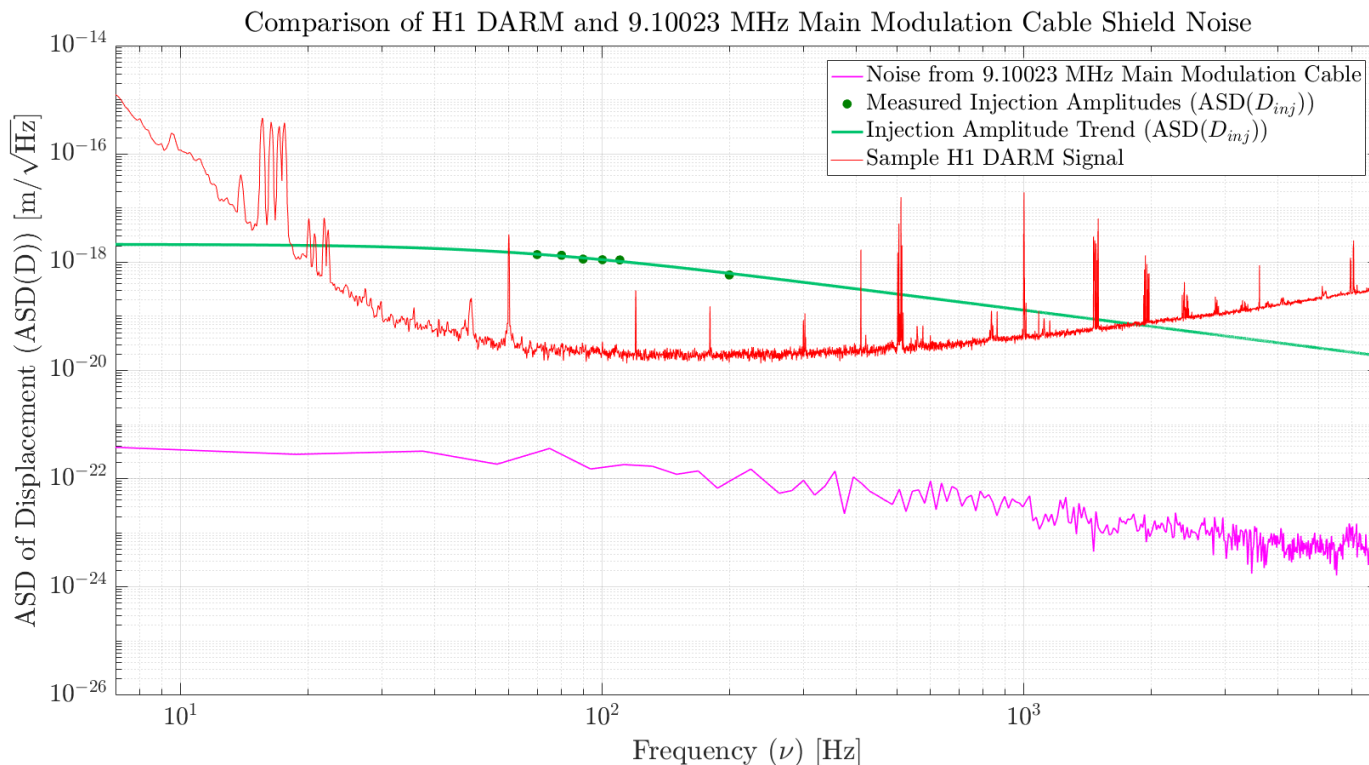
$$K = 3.91 * 10^{-17} \frac{\text{m}}{\text{V}}$$

$$\nu_0 = 63.3 \text{ Hz}$$

Further Improvements

□ Mapping Equation with Single Pole Transfer Function

$$ASD(D) = \frac{1}{ab} \frac{K}{1 + i \frac{\nu_{inj}}{\nu_0}} ASD(V_{probe})$$



Future Work

- Perform more injections across the aLIGO DARM frequency band to verify our choice of a 1-pole transfer function
 - » Improve fit values or select new transfer function template as necessary
- Use new mapping equation to model noise on 45.50115 MHz and 79.4 MHz cables

Acknowledgements

- Special Thanks Goes to the Following Individuals for their Contributions to the Project
 - » Mentors: Dick Gustafson and Keita Kawabe
 - » EE Lab Staff: Marc Pirello and Filiberto Clara
 - » National Science Foundation and the Caltech SURF Program