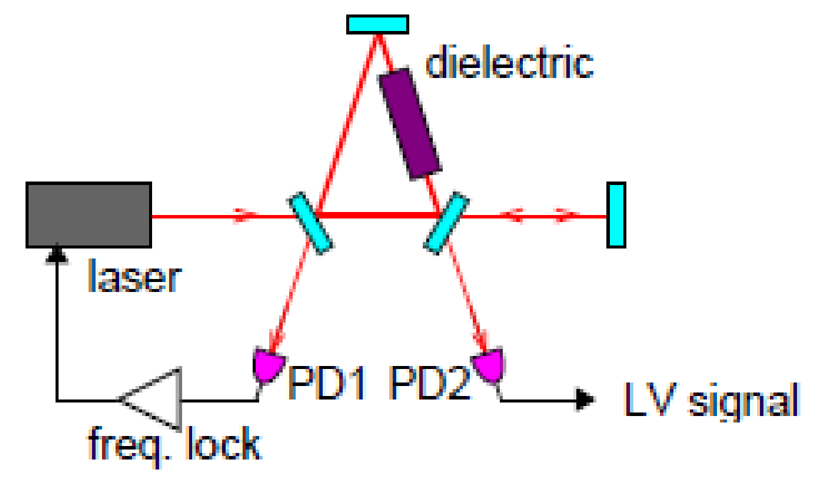
Jake Guscott

Anisotropy in the Speed of Light

Introduction

- Special Relativity formulated upon two postulates
  - Laws of Physics are invariant in all inertial reference frames
  - Speed of light (in vacuum) is the same for all observers
- Special Relativity proposes Lorentz invariance
  - Supported by all previous experiments
  - Required for General Relativity and The Standard Model
  - Formulations of theories of Dark Matter and beyond the standard model predict Lorentz invariance may only be approximate
  - Our experiment tests the limits of Lorentz invariance

Experimental Setup



(Diagram Michimura, Y 2014, Tests of Lorentz Invariance with an Optical Ring Cavity, Ph.D thesis, The University of Tokyo)

Experimental Setup

- Rotate setup
  - Once every 12 seconds
  - Sensitive to fluctuations at this frequency
- If there is anisotropy we expect fluctuations in the Lorentz violation signal at the frequencies
  - 1/12Hz
  - 1/12Hz ±1/day Hz
  - 1/12Hz ±1/day Hz ±1/year Hz
- Need to have low noise at these frequencies
  - All very close to 1/12Hz

Improvement on Previous experiment

- Wireless Operation
  - Allows Continuous rotation
    - Previously had to rotate 400° in one direction and then reverse to avoid tangled wires
  - Allows recording of data for longer
    - Increases frequency resolution
- Optical Axis (OA) closer to monolithic breadboard
  - Increase Common Mode Rejection Ration
  - New setup OA ½" inch above breadboard
  - Old setup OA 1.93" inch above breadboard

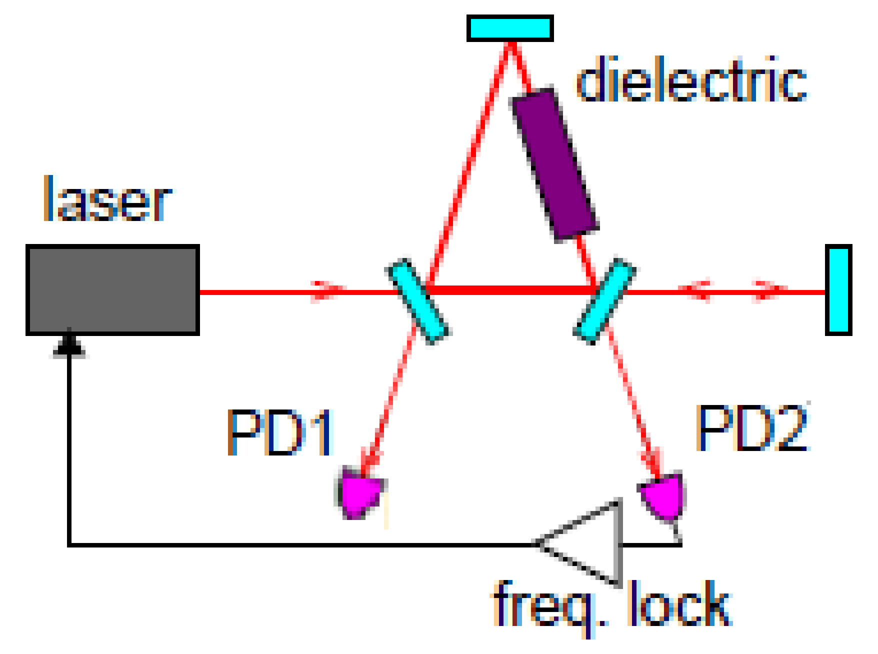
Further Alterations

- New laser
  - Koheras Basik
    - More compact
    - Larger operational piezo range (can hold lock over a larger range)
    - Lower intensity noise
    - Previously used Koheras AdjustiK

- New insulating material
  - 1cm thick white insulating material on top and 4 walls
    - Should also decrease sound and thermal noise from external sources
  - Previously used black rubber to insulate system from external light sources

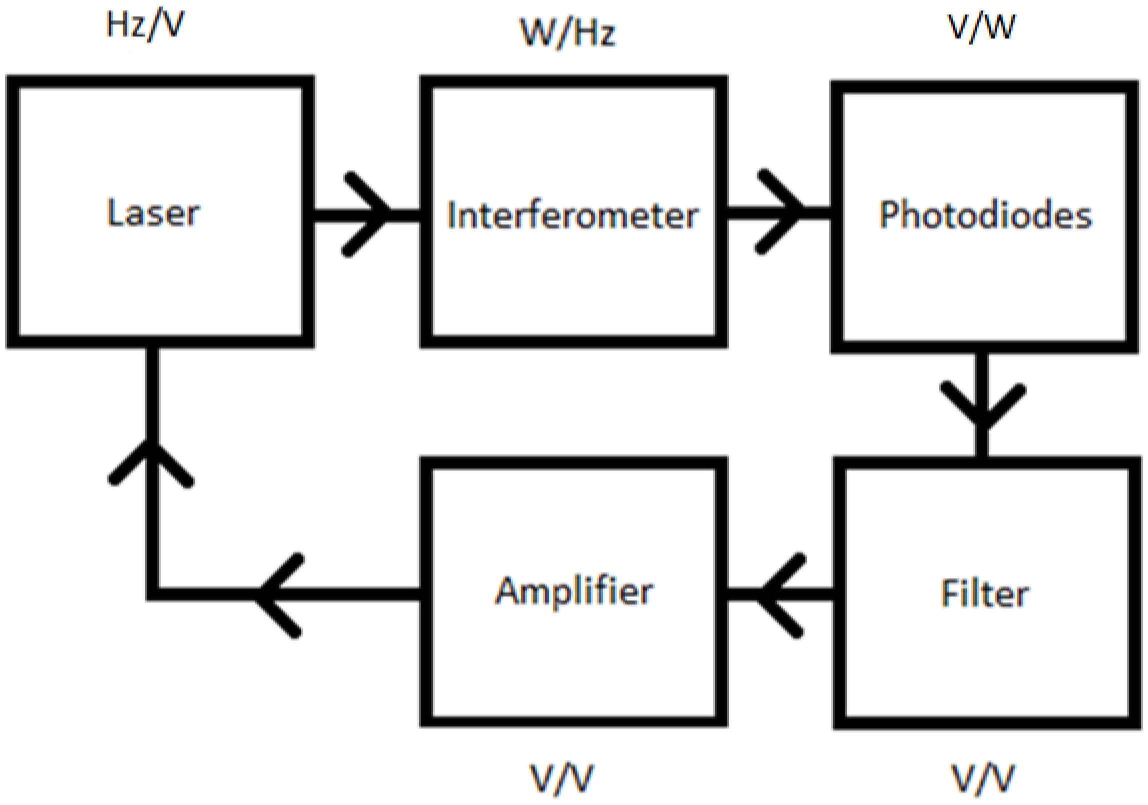
Calibration

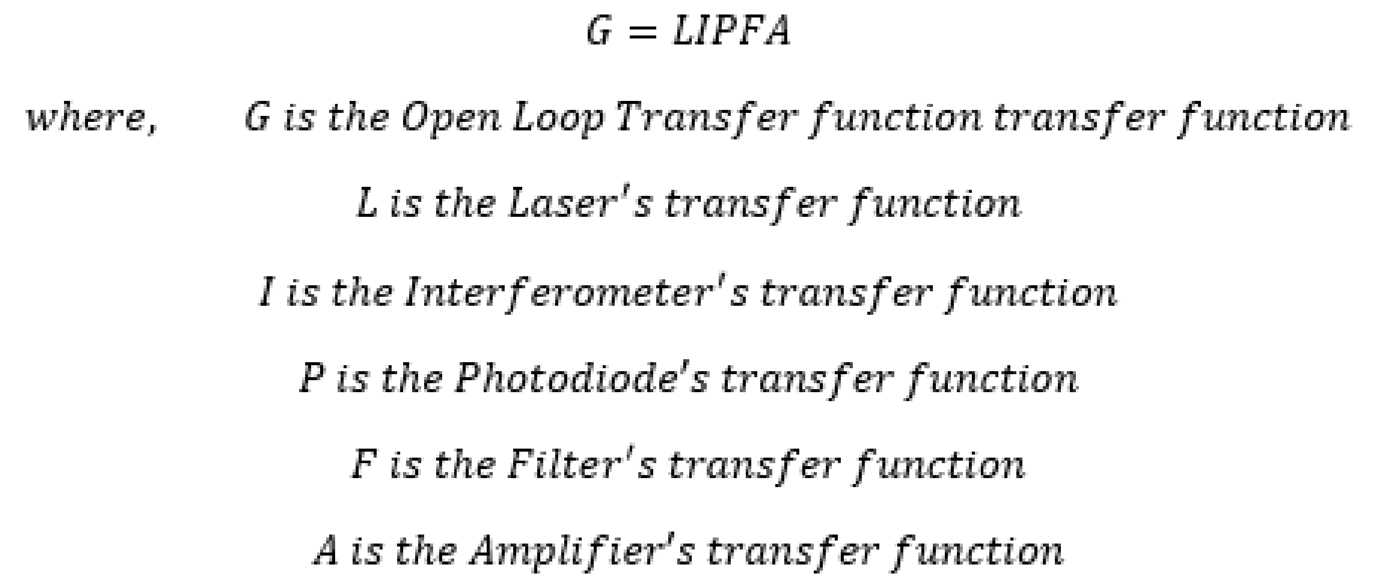
- Lorentz Violation signal measured as output from photodiodes
  - Units are Volts per root Hertz
- Needs to be converted to fractional frequency noise
  - Equivalent to input to Interferometer
  - Units are reciprocal of root Hertz



(Diagram Michimura, Y 2014, Tests of Lorentz Invariance with an Optical Ring Cavity, Ph.D thesis, The University of Tokyo)

Servo Diagram





$$G = LIPFA$$

where, G is the Open Loop Transfer function transfer function

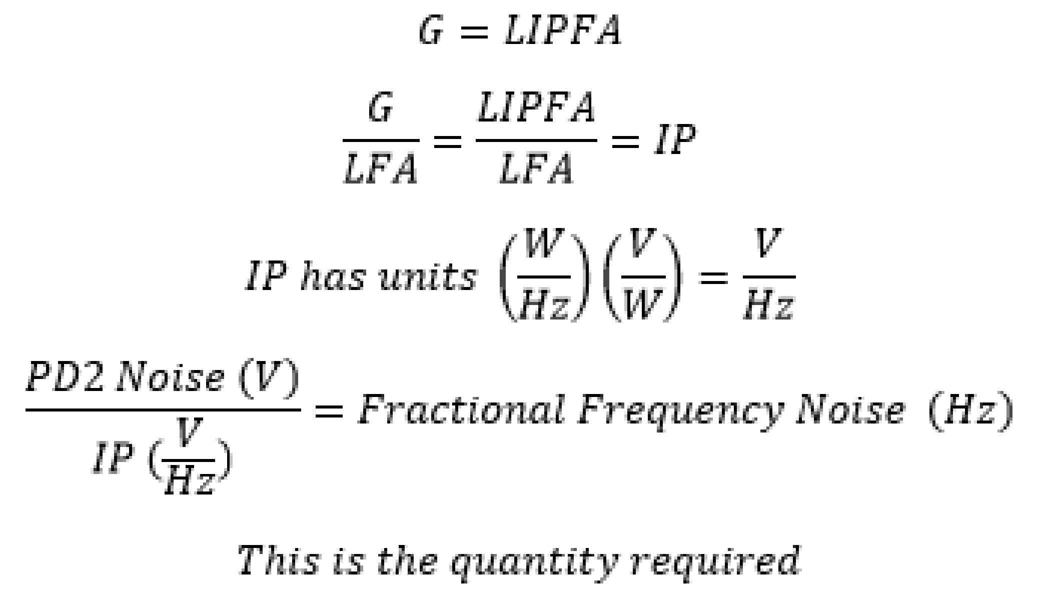
L is the Laser's transfer function

I is the Interferometer's transfer function

P is the Photodiode's transfer function

F is the Filter's transfer function

A is the Amplifier's transfer function



$$G = LIPFA$$

$$\frac{G}{LFA} = \frac{LIPFA}{LFA} = IP$$

$$IP \text{ has units } \left(\frac{W}{Hz}\right)\left(\frac{V}{W}\right) = \frac{V}{Hz}$$

$$\frac{PD2\ Noise\ (V)}{IP\ (\frac{V}{Hz})} = Fractional\ Frequency\ Noise\ \ (Hz)$$

This is the quantity required

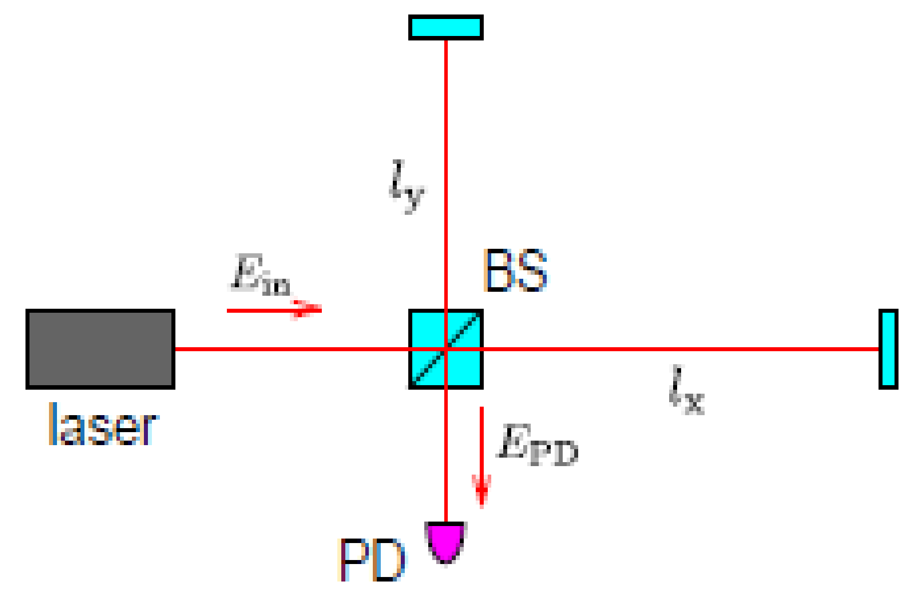
Calibration

- Need to Obtain IP
- Measure

Open Loop Transfer Function	G
Filter Transfer Function	F
Amplifier Transfer Function	A
Laser Transfer Function	L

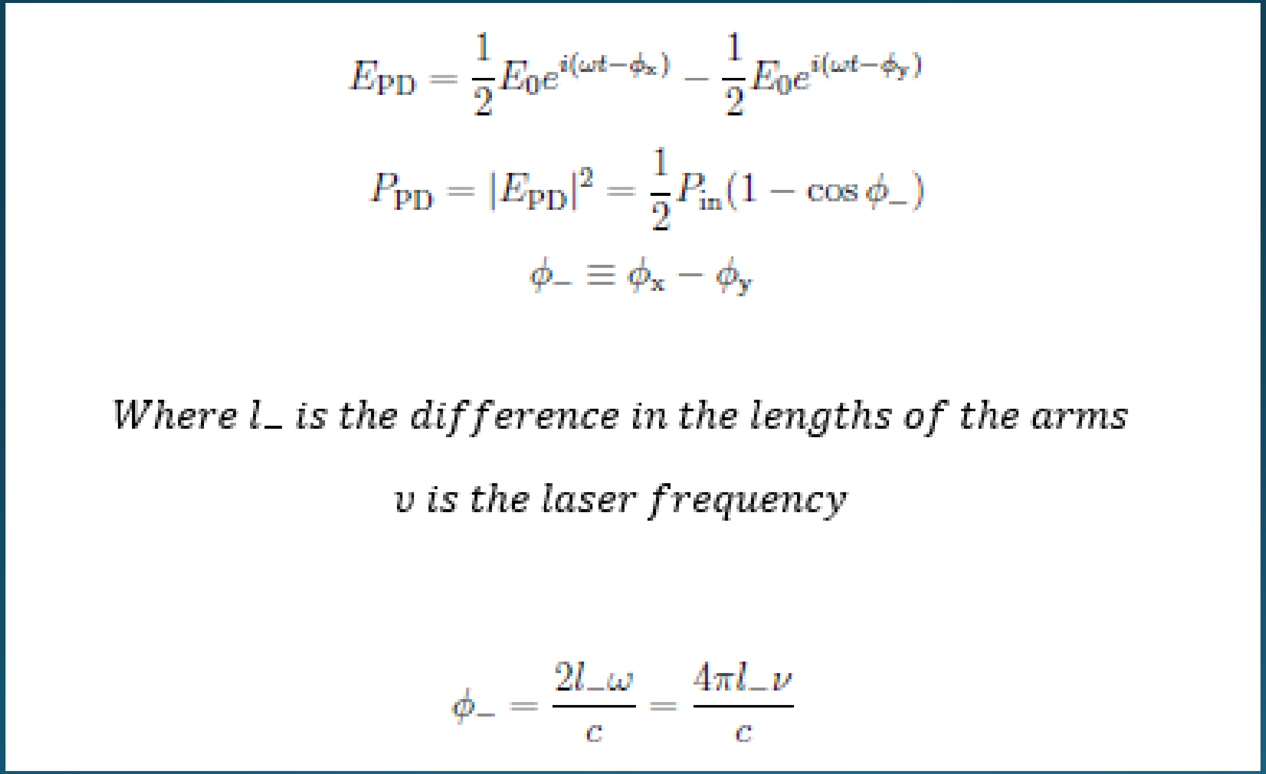
- G,F can be easily measured
- L requires supplementary experiment

Asymmetric Michelson



(Diagram Michimura, Y 2014, Tests of Lorentz Invariance with an Optical Ring Cavity, Ph.D thesis, The University of Tokyo)

Laser Transfer Function



$$E_{\mathrm{PD}} = \frac{1}{2}E_0 e^{i(\omega t - \phi_{\mathrm{x}})} - \frac{1}{2}E_0 e^{i(\omega t - \phi_{\mathrm{y}})}$$

$$P_{\mathrm{PD}} = |E_{\mathrm{PD}}|^2 = \frac{1}{2}P_{\mathrm{in}}(1 - \cos\phi_-)$$

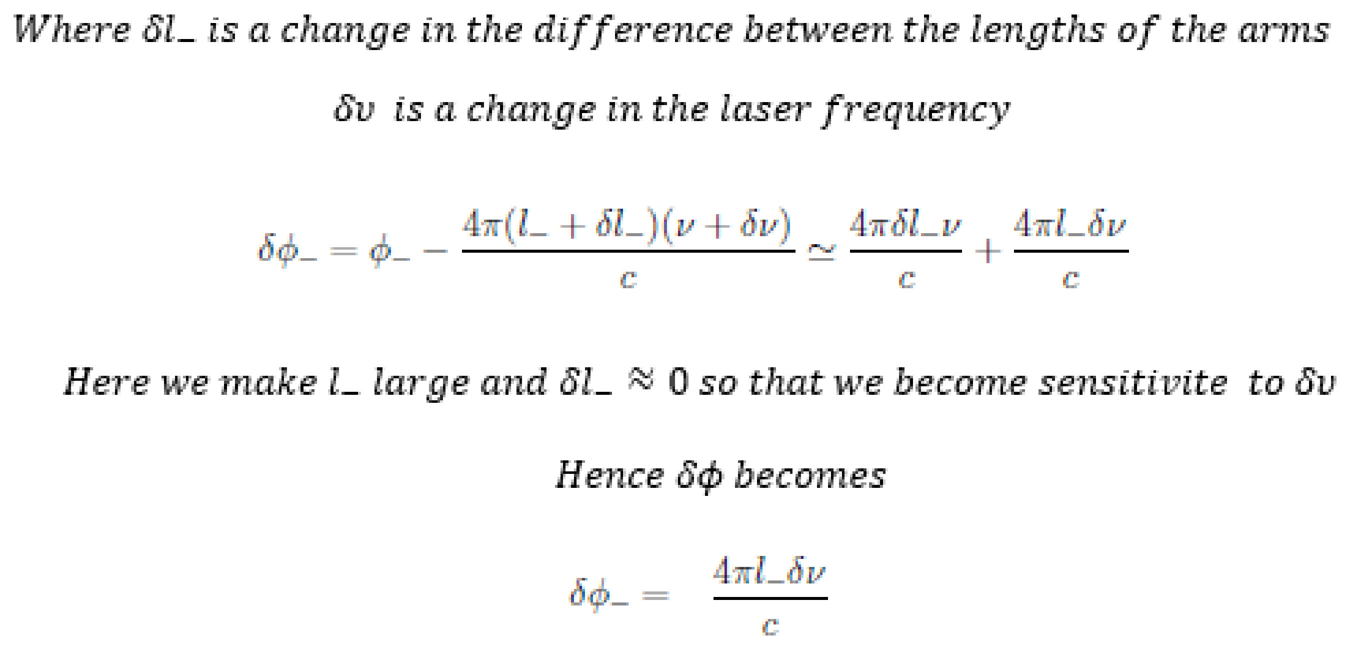
$$\phi_- \equiv \phi_{\mathrm{x}} - \phi_{\mathrm{y}}$$

Where l_- *is the difference in the lengths of the arms*

v *is the laser frequency*

$$\phi_- = \frac{2l_-\omega}{c} = \frac{4\pi l_-\nu}{c}$$

Laser Transfer Function



Where δl_- is a change in the difference between the lengths of the arms

δv is a change in the laser frequency

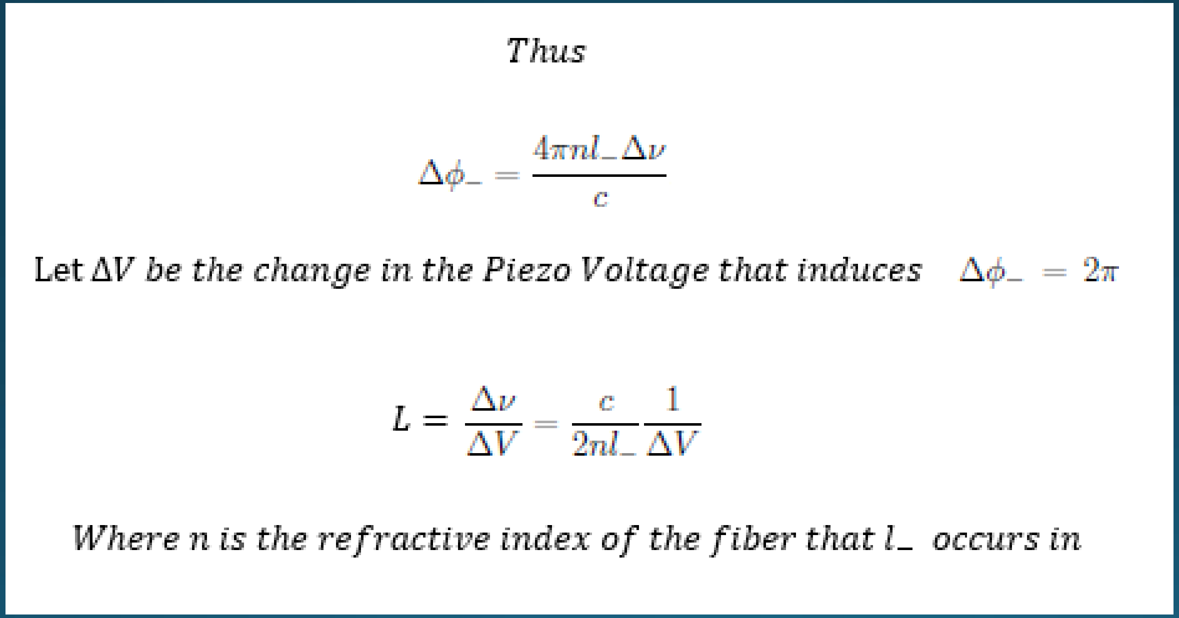
$$\delta\phi_- = \phi_- - \frac{4\pi(l_- + \delta l_-)(\nu + \delta\nu)}{c} \simeq \frac{4\pi\delta l_- \nu}{c} + \frac{4\pi l_- \delta\nu}{c}$$

Here we make l_- large and $\delta l_- \approx 0$ so that we become sensitivite to δv

Hence $\delta\phi$ becomes

$$\delta\phi_- = \frac{4\pi l_- \delta\nu}{c}$$

Laser Transfer Function



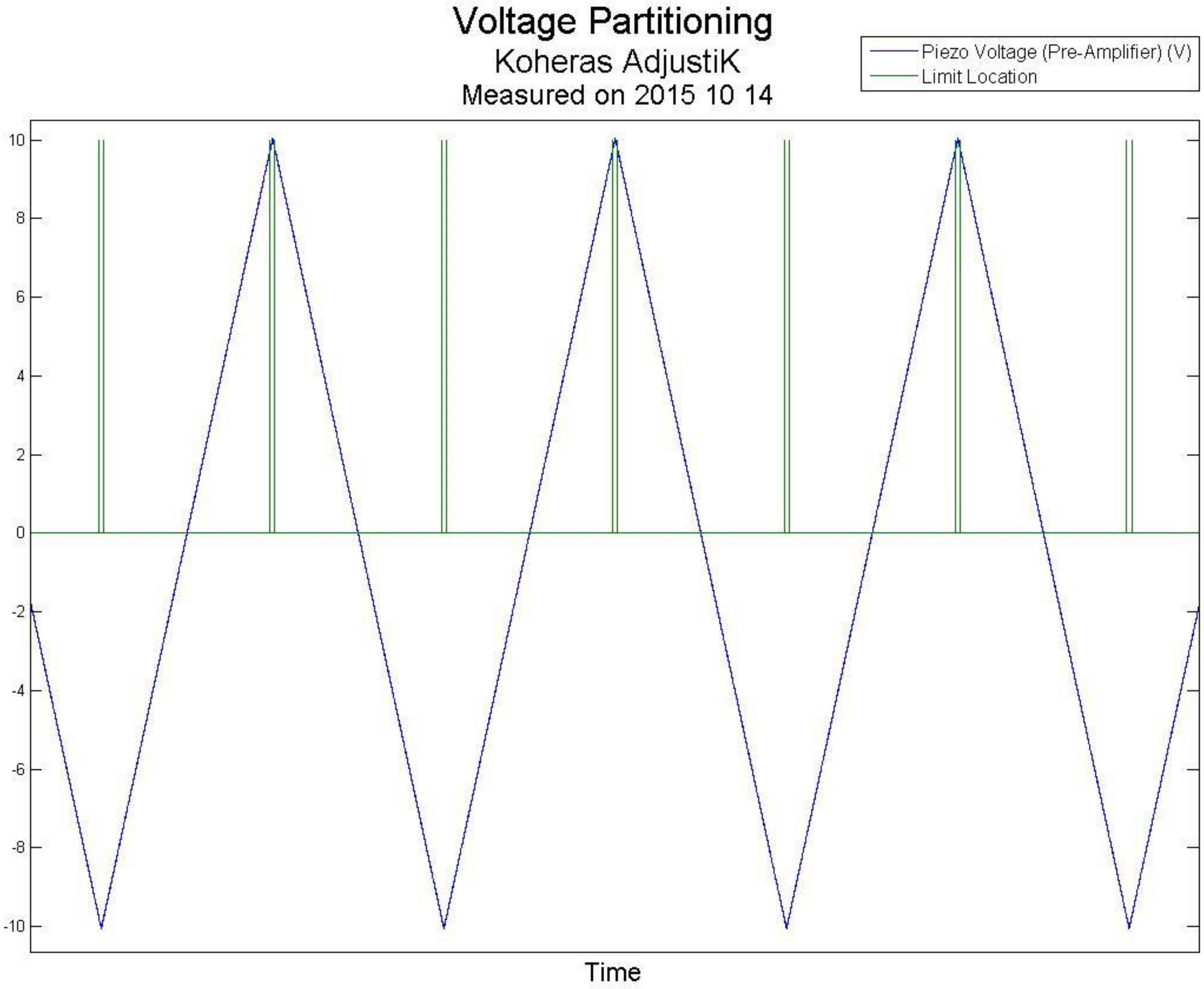
Thus

$$\Delta\phi_- = \frac{4\pi n l_- \Delta\nu}{c}$$

Let ΔV *be the change in the Piezo Voltage that induces* $\Delta\phi_- = 2\pi$

$$L = \frac{\Delta\nu}{\Delta V} = \frac{c}{2nl_-}\frac{1}{\Delta V}$$

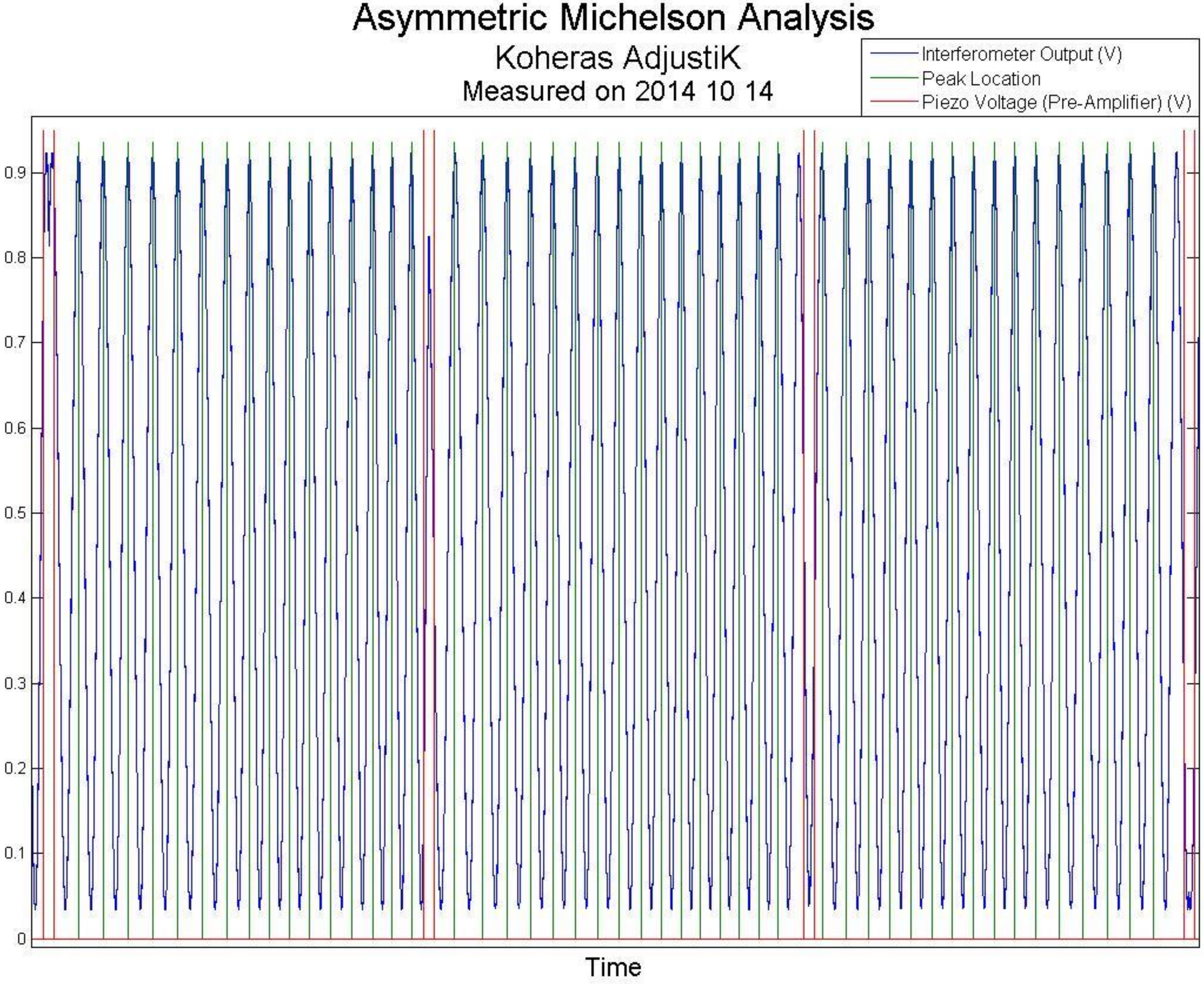
Where n *is the refractive index of the fiber that* l_- *occurs in*



Voltage Partitioning

Koheras AdjustiK

Measured on 2015 10 14



Asymmetric Michelson Analysis

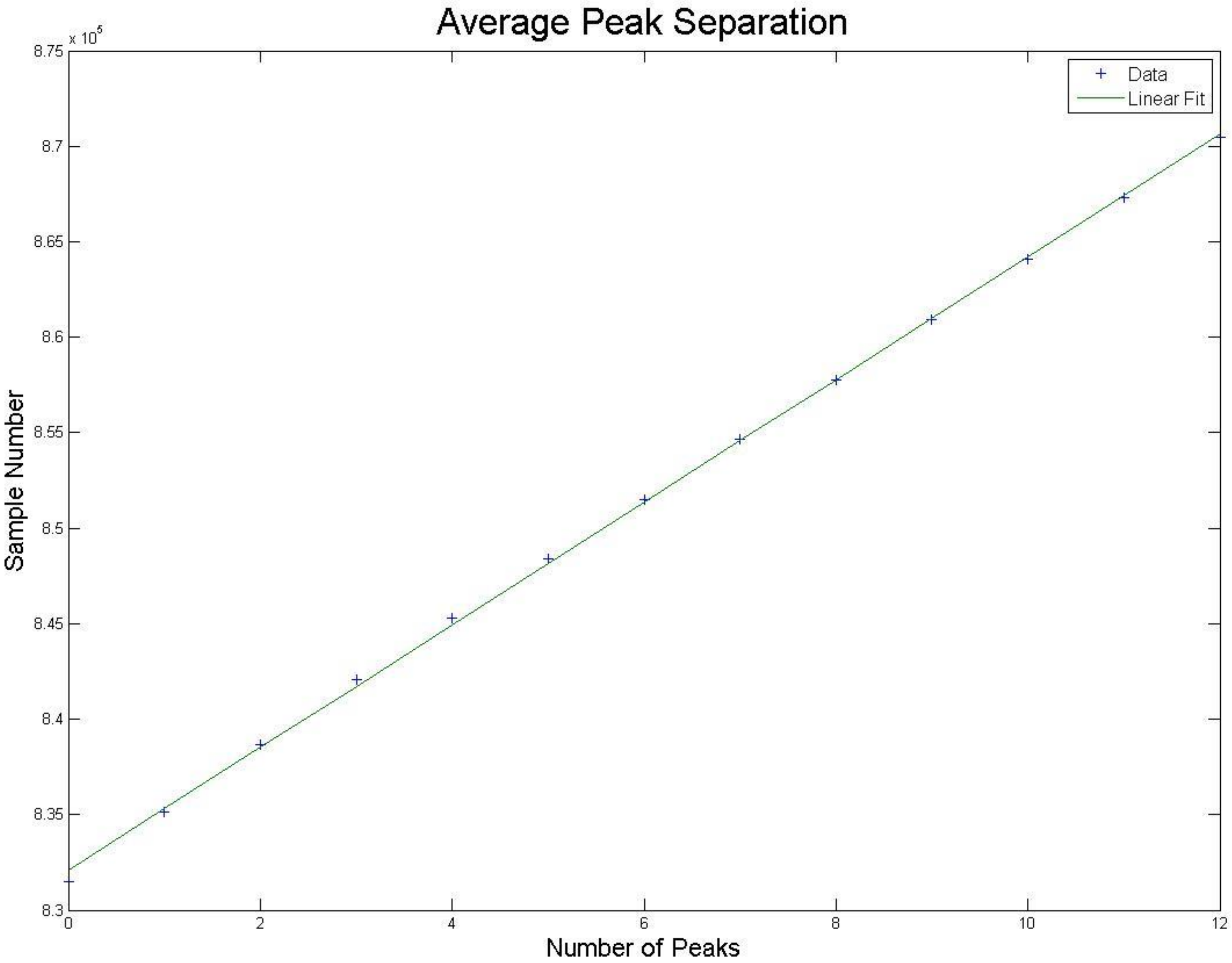
Koheras AdjustiK

Measured on 2014 10 14

$$\frac{(x_2 - x_1) + (x_3 - x_2) + (x_4 - x_3) + (x_4 - x_5)}{4}$$

$$\frac{(\cancel{x_2} - x_1) + (\cancel{x_3} - \cancel{x_2}) + (\cancel{x_4} - \cancel{x_3}) + (\cancel{x_4} - x_5)}{4}$$

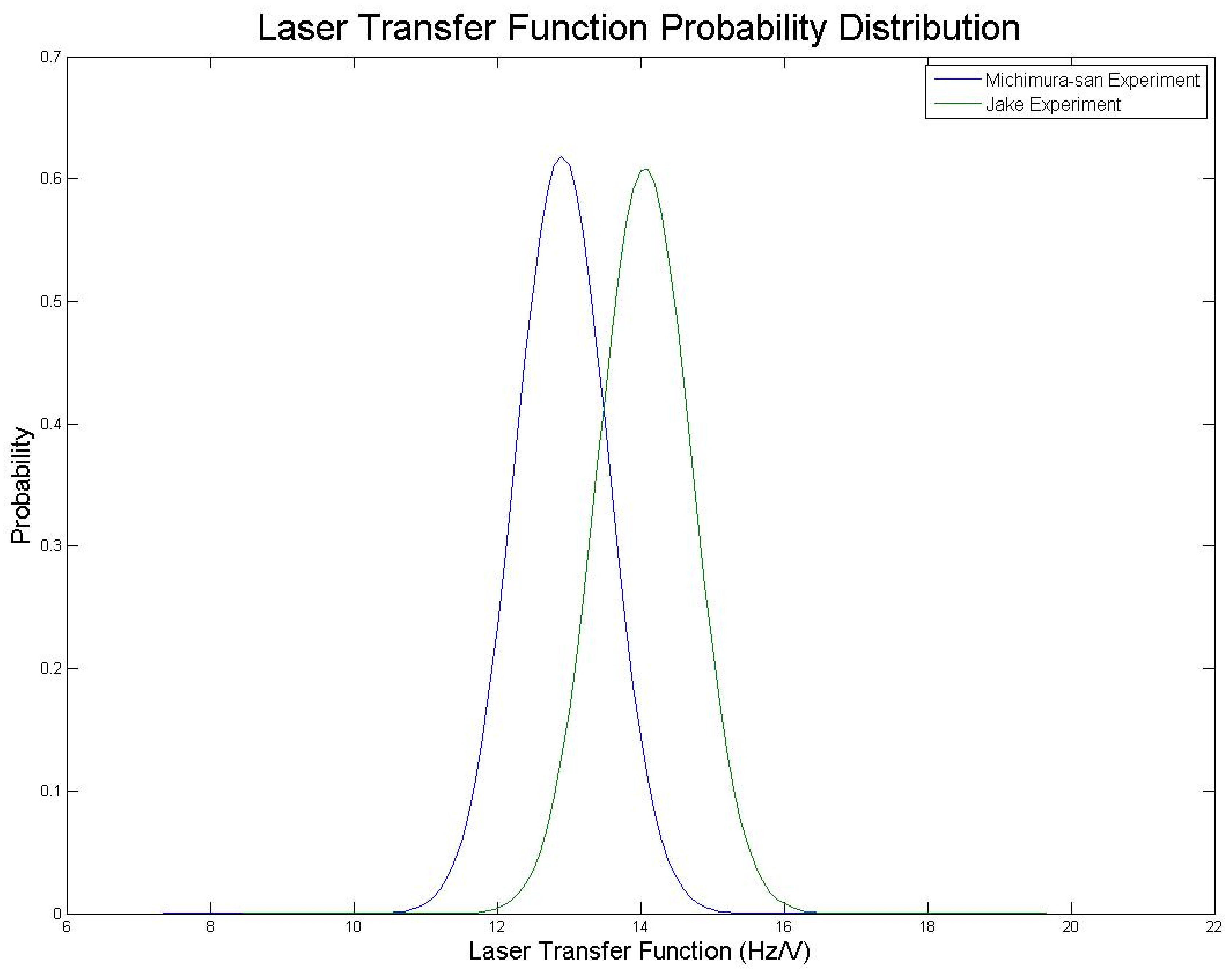
$$\frac{x_1 - x_5}{4}$$


Average Peak Separation
x 10^5
8.75
8.7
8.65
8.6
8.55
8.5
8.45
8.4
8.35
8.3
Sample Number
0
2
4
6
8
10
12
Number of Peaks
Data
Linear Fit

Calibration Analysis

- Koheras AdjustiK
  - $L = 14.1 \pm_{stat} 0.6 \pm_{sys} 0.02\ MHz/V$
    - Upon numerical simulation becomes $L = 14.1 \pm 0.7\ MHz/V$

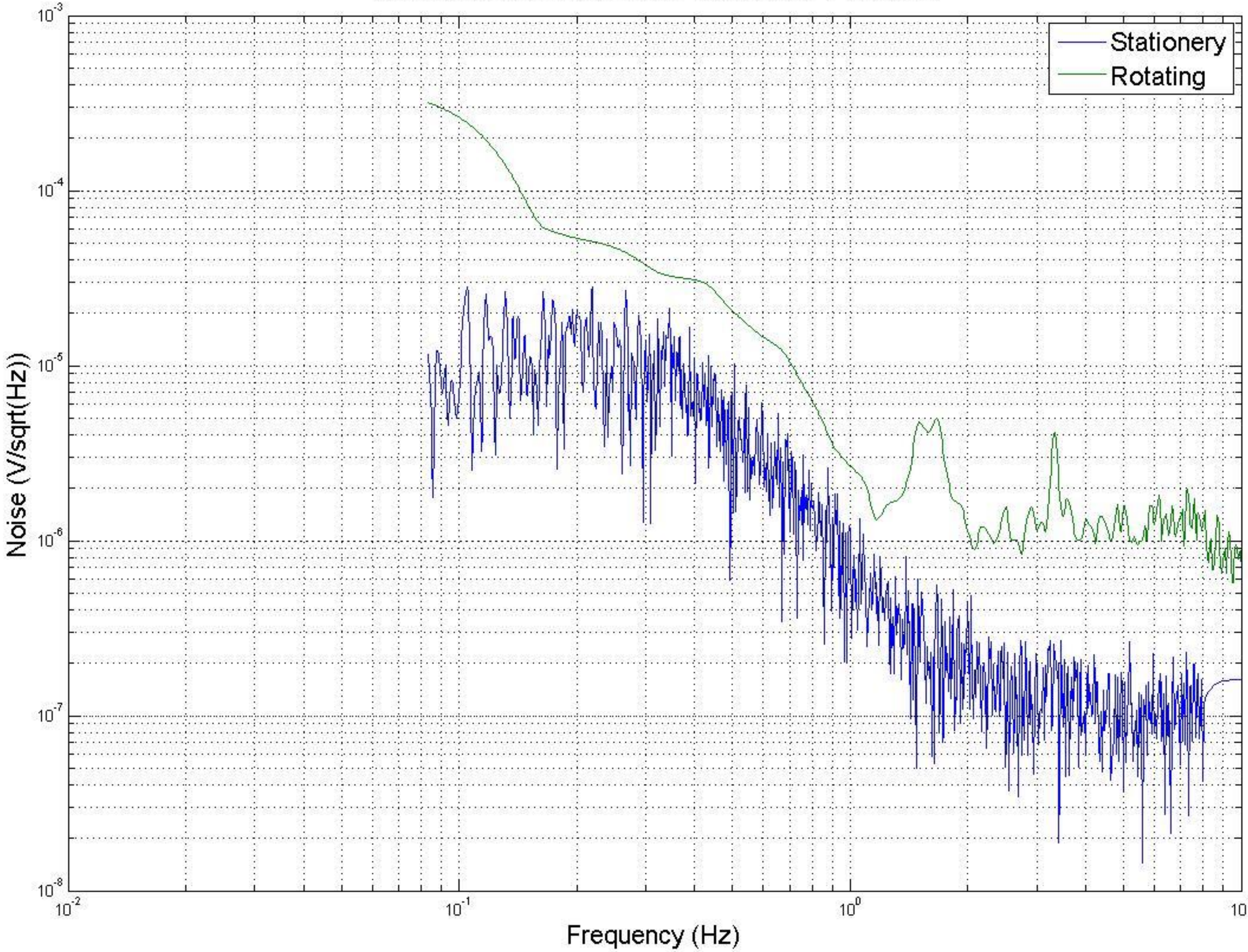
  - Previously determined to be $L = 12.9 \pm 0.6\ MHz/V$
  - Overlap Region has 19% probability

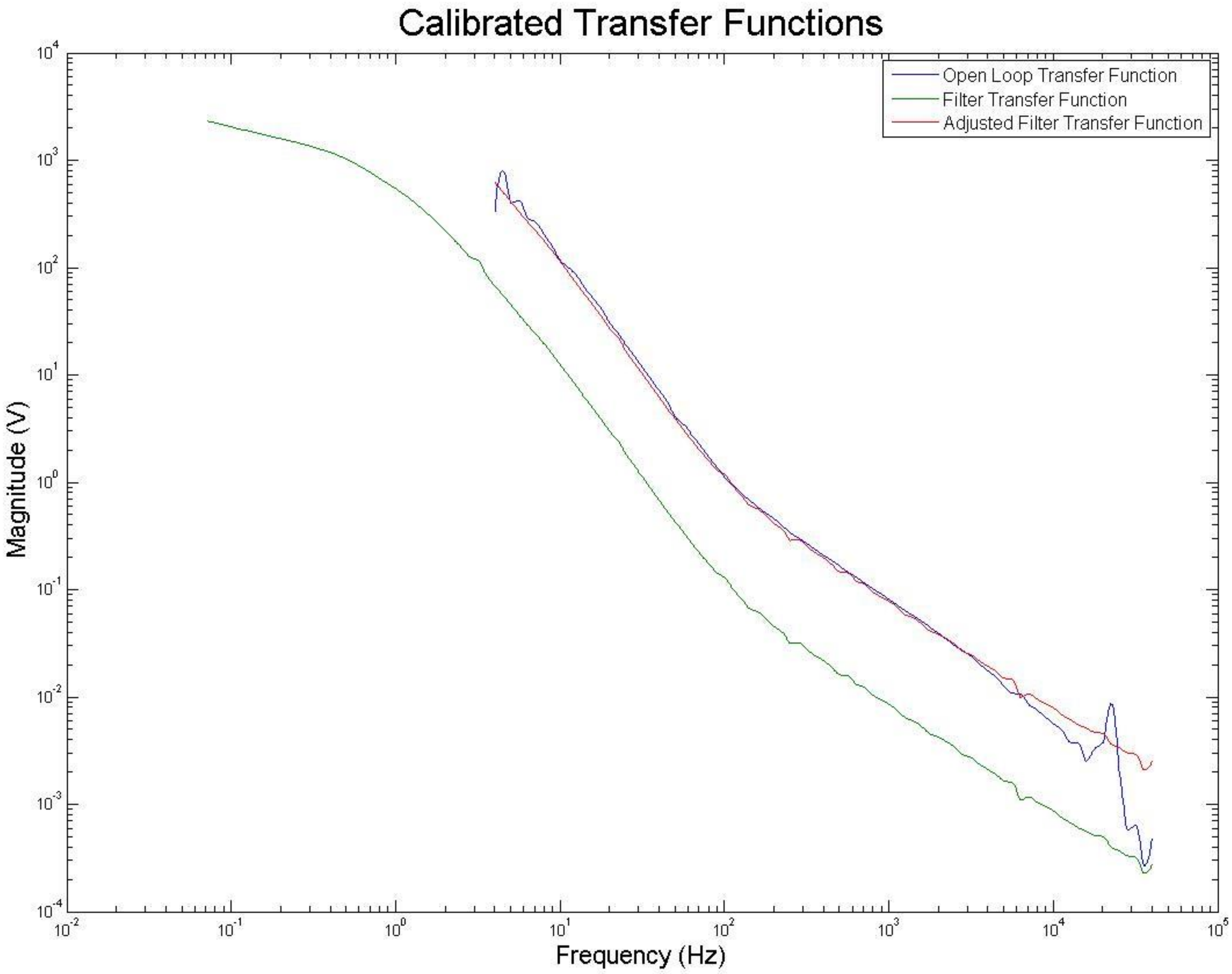

Laser Transfer Function Probability Distribution
Michimura-san Experiment
Jake Experiment
Probability
Laser Transfer Function (Hz/V)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
6
8
10
12
14
16
18
20
22

Calibration Analysis

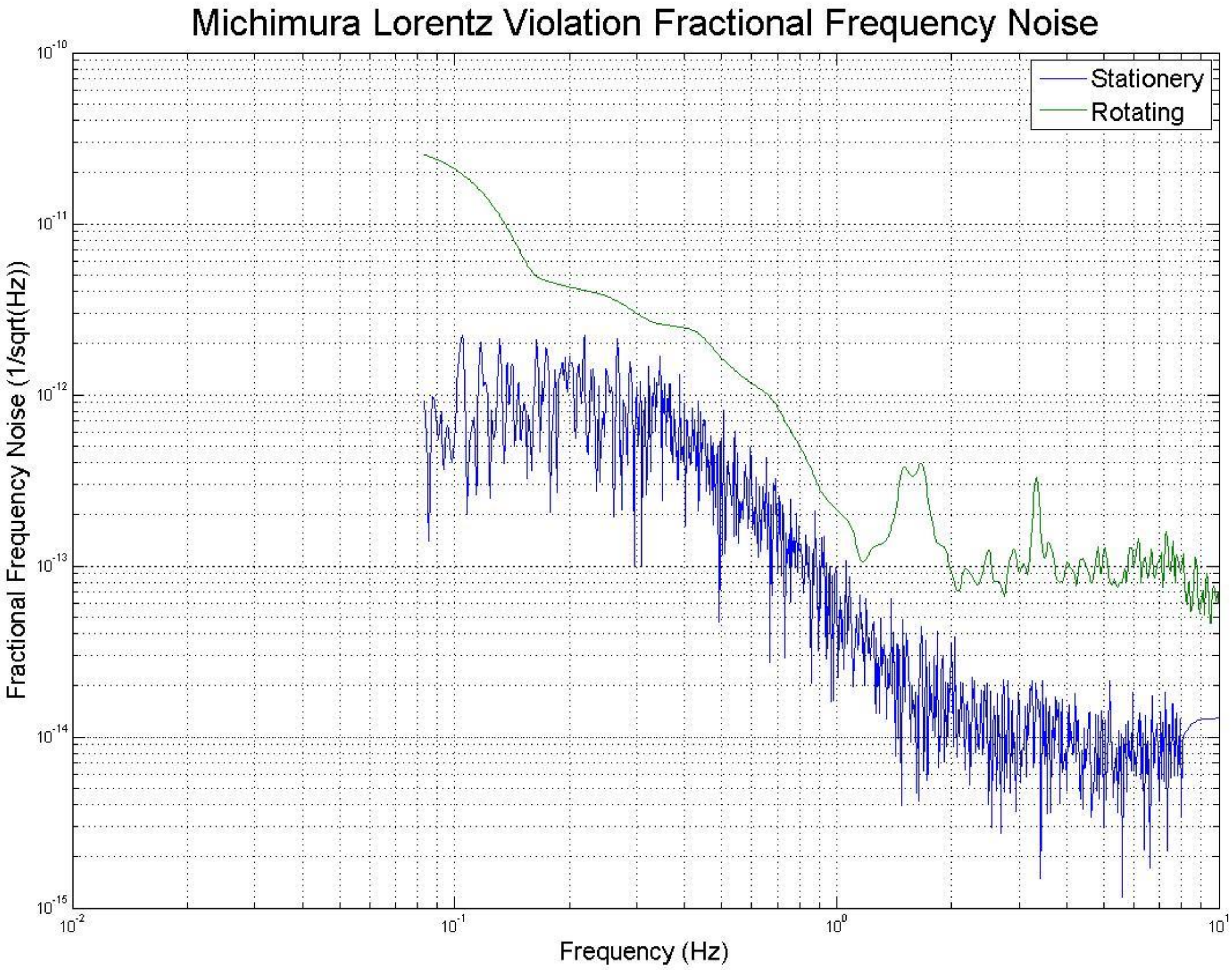
- Koheras BasiK
  - $L = 12.6 \pm_{stat} 0.6 \pm_{sys} 0.02\ MHz/V$
    - Upon numerical simulation becomes $L = 12.6 \pm 0.6\ MHz/\mathrm{V}$

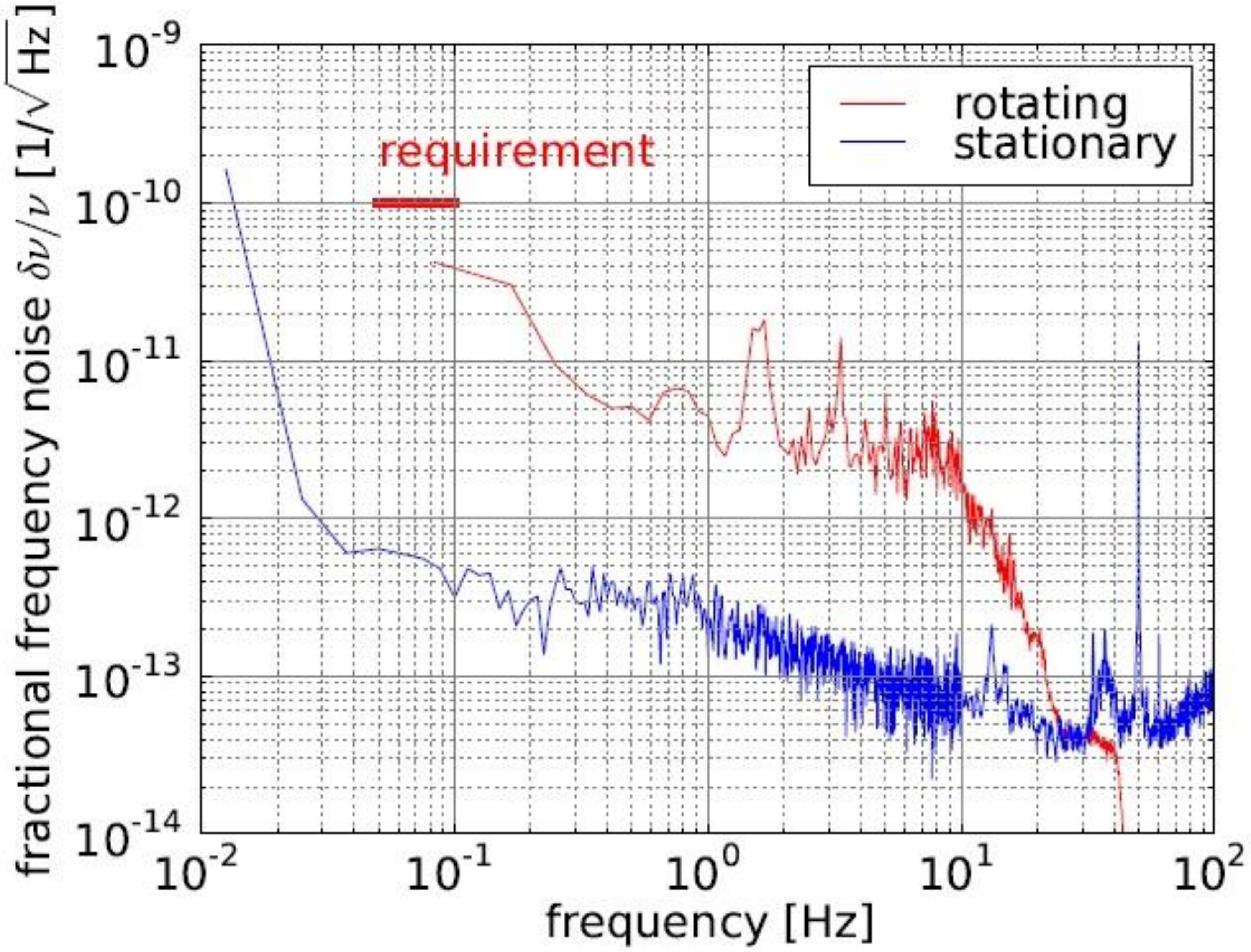
Michimura Lorentz Violation Noise





New Analyser

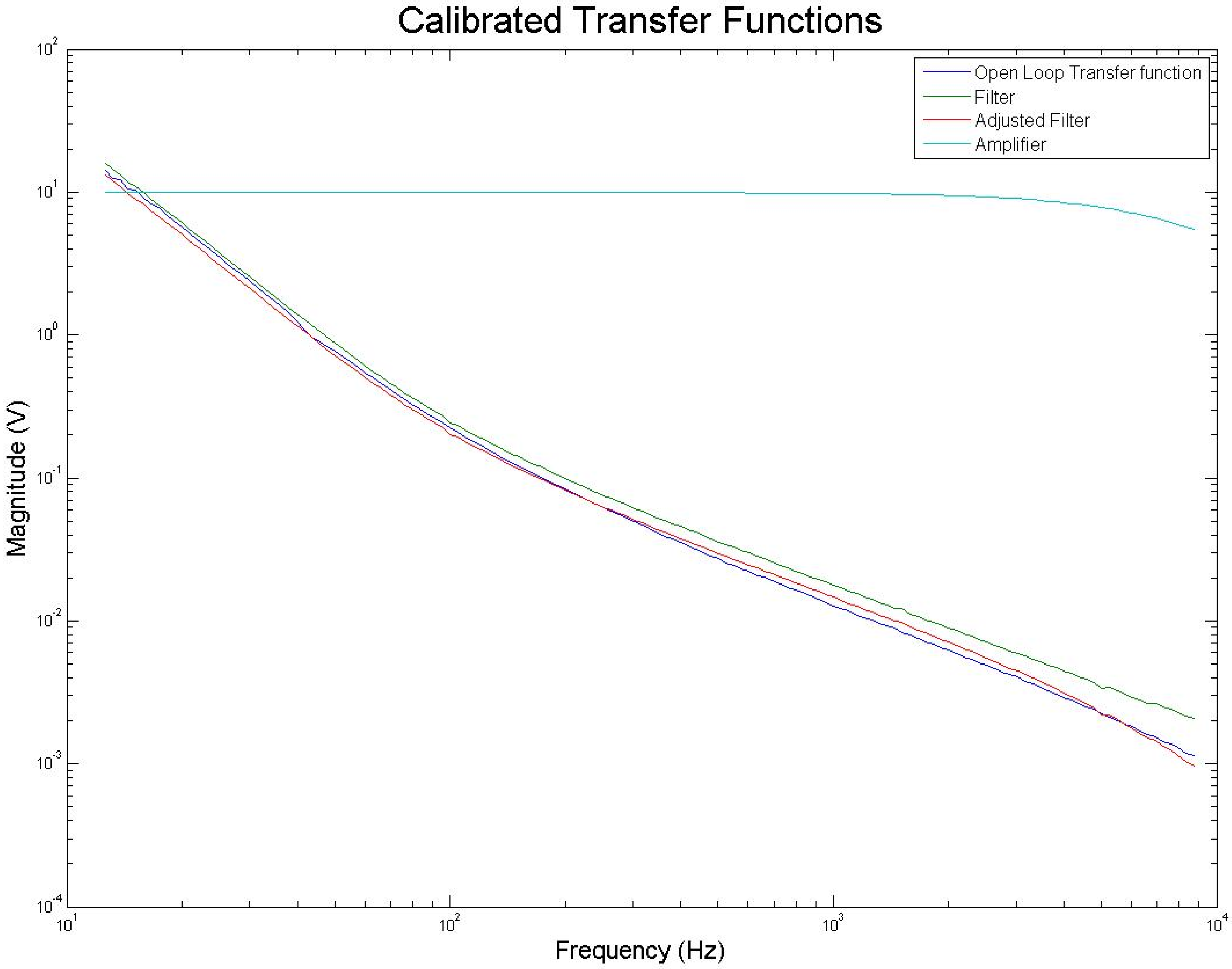

Michimura Lorentz Violation Fractional Frequency Noise
Stationery
Rotating
Fractional Frequency Noise (1/sqrt(Hz))
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)



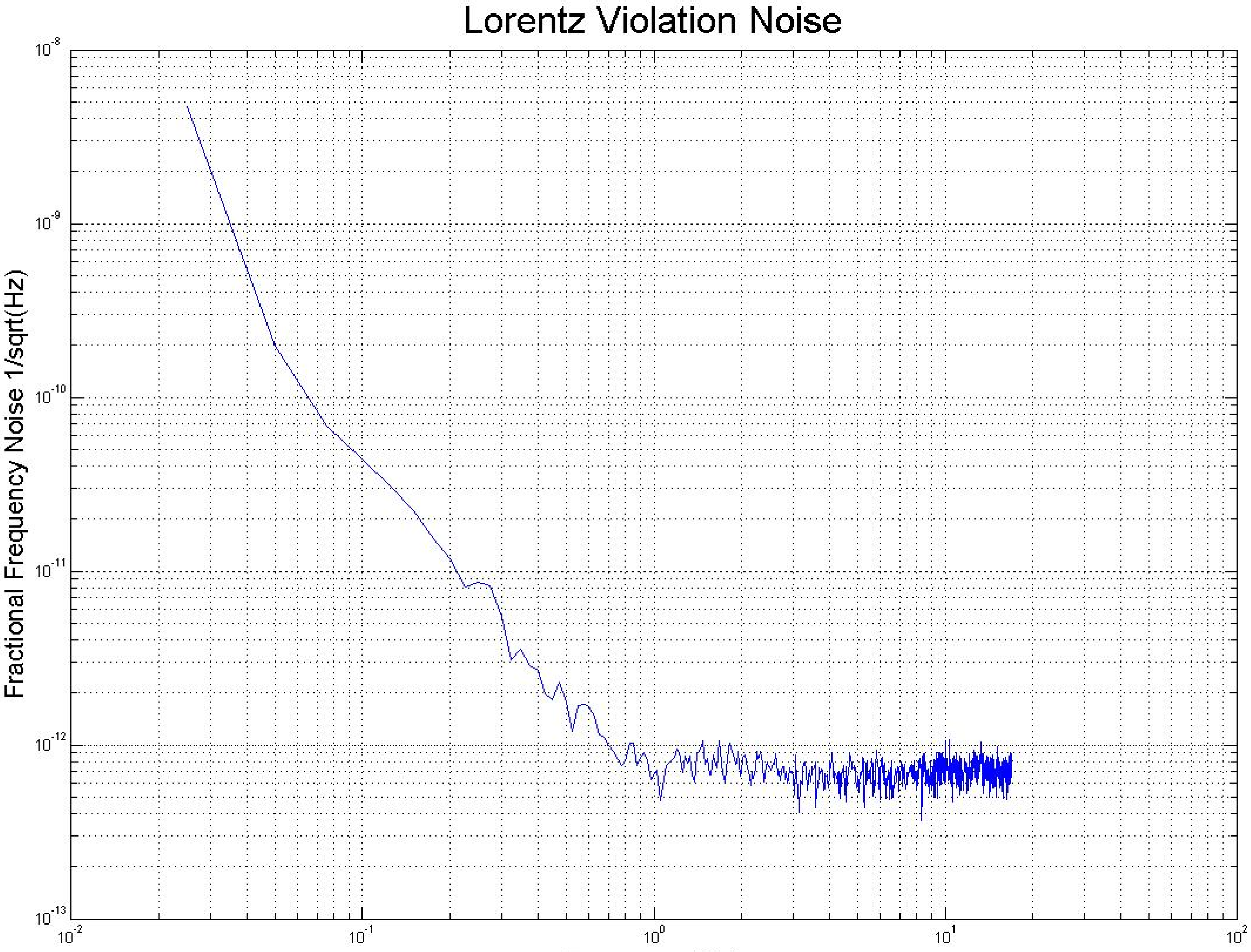
fractional frequency noise $\delta\nu/\nu$ [$1/\sqrt{\mathrm{Hz}}$]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
frequency [Hz]
requirement
rotating
stationary

New Setup

- Koheras AdjustiK

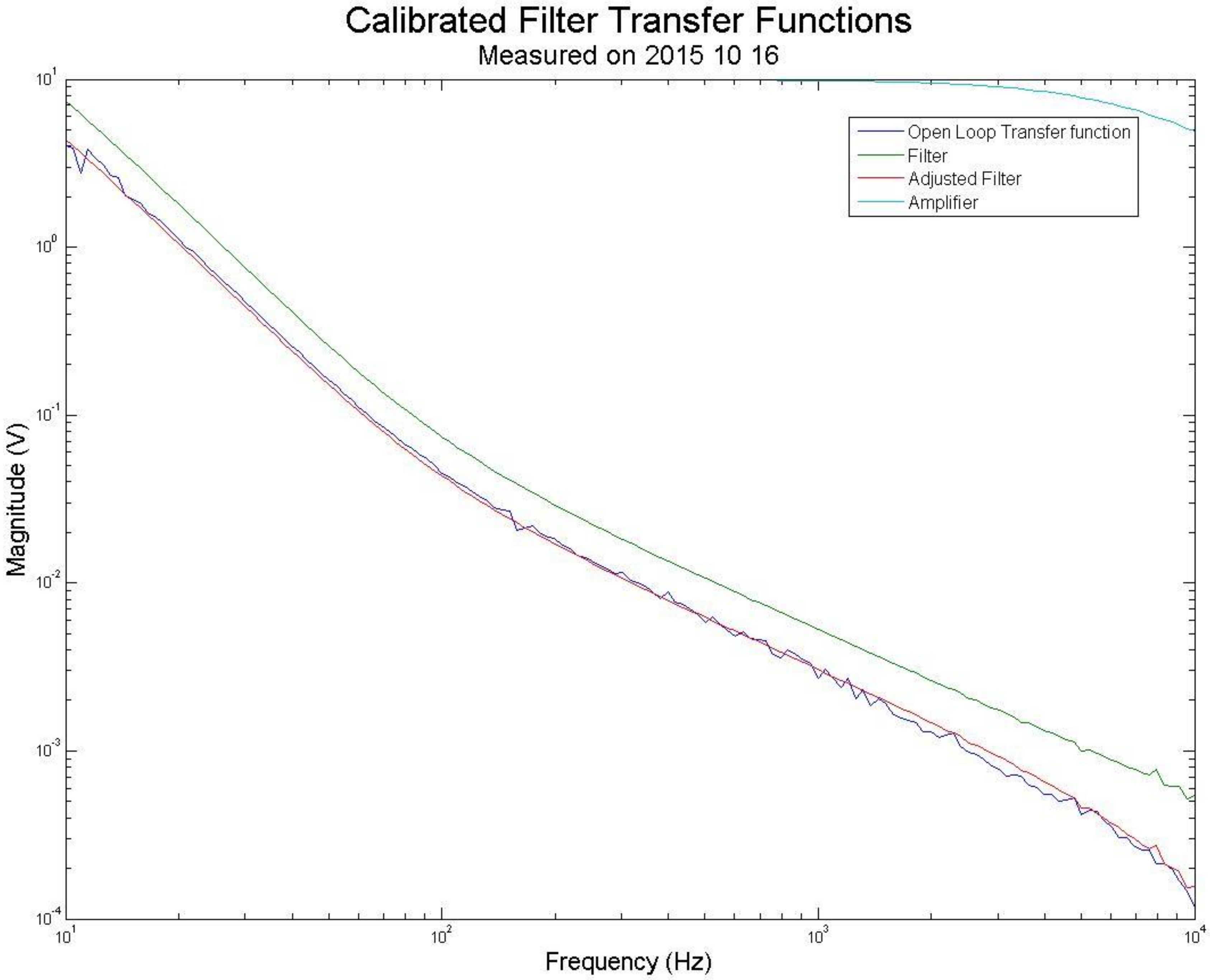


New Analyser



Old Analyser

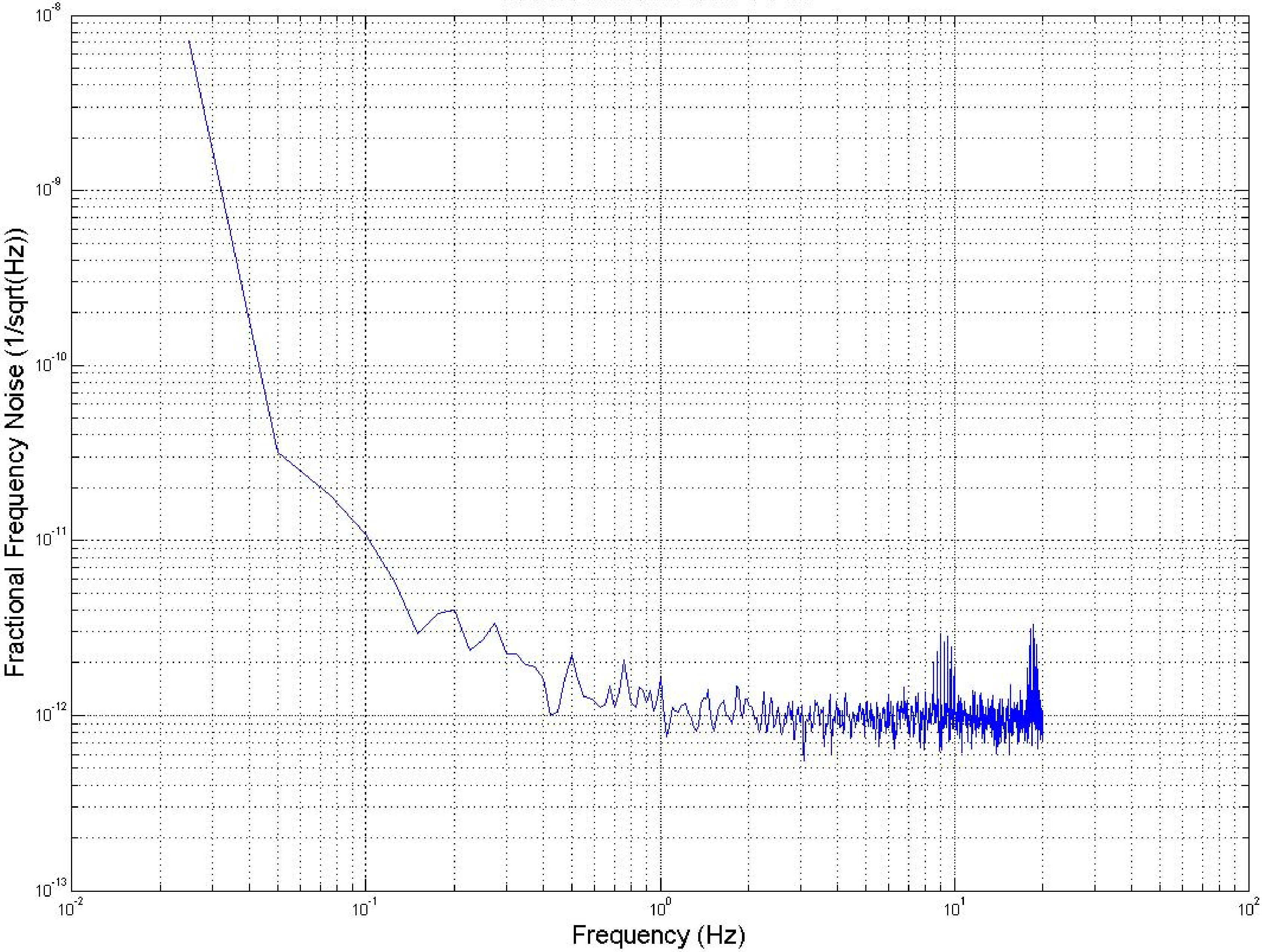
Koheras BasiK



New Analyser

Stationery Lorentz Violation Fractional Frequency Noise

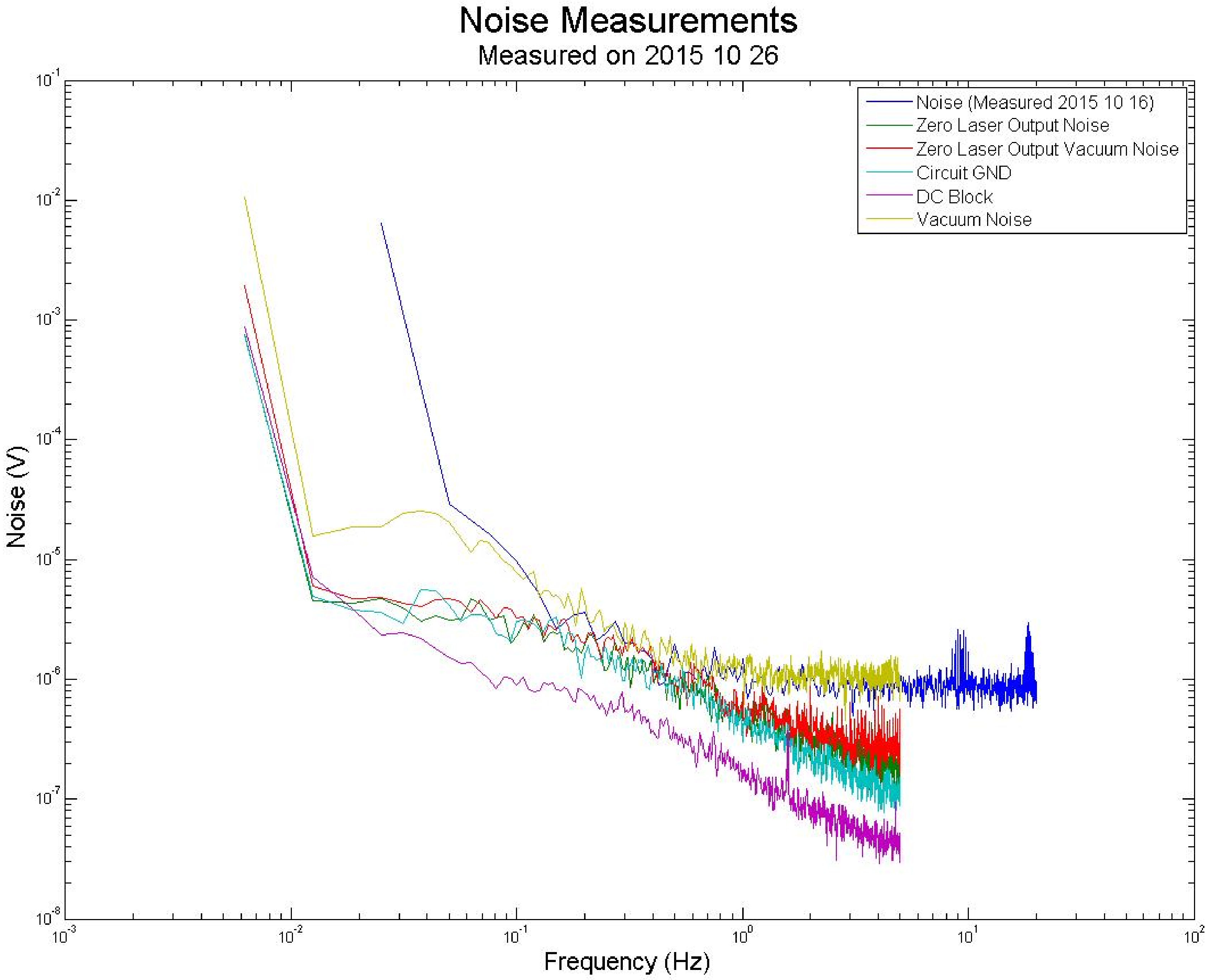
Measured on 2015 10 16



Old Analyser

Noise Evaluation

- Stationery noise of new assembly is higher than stationery noise of old
- Need to what noise is limiting the system



Old Analyser

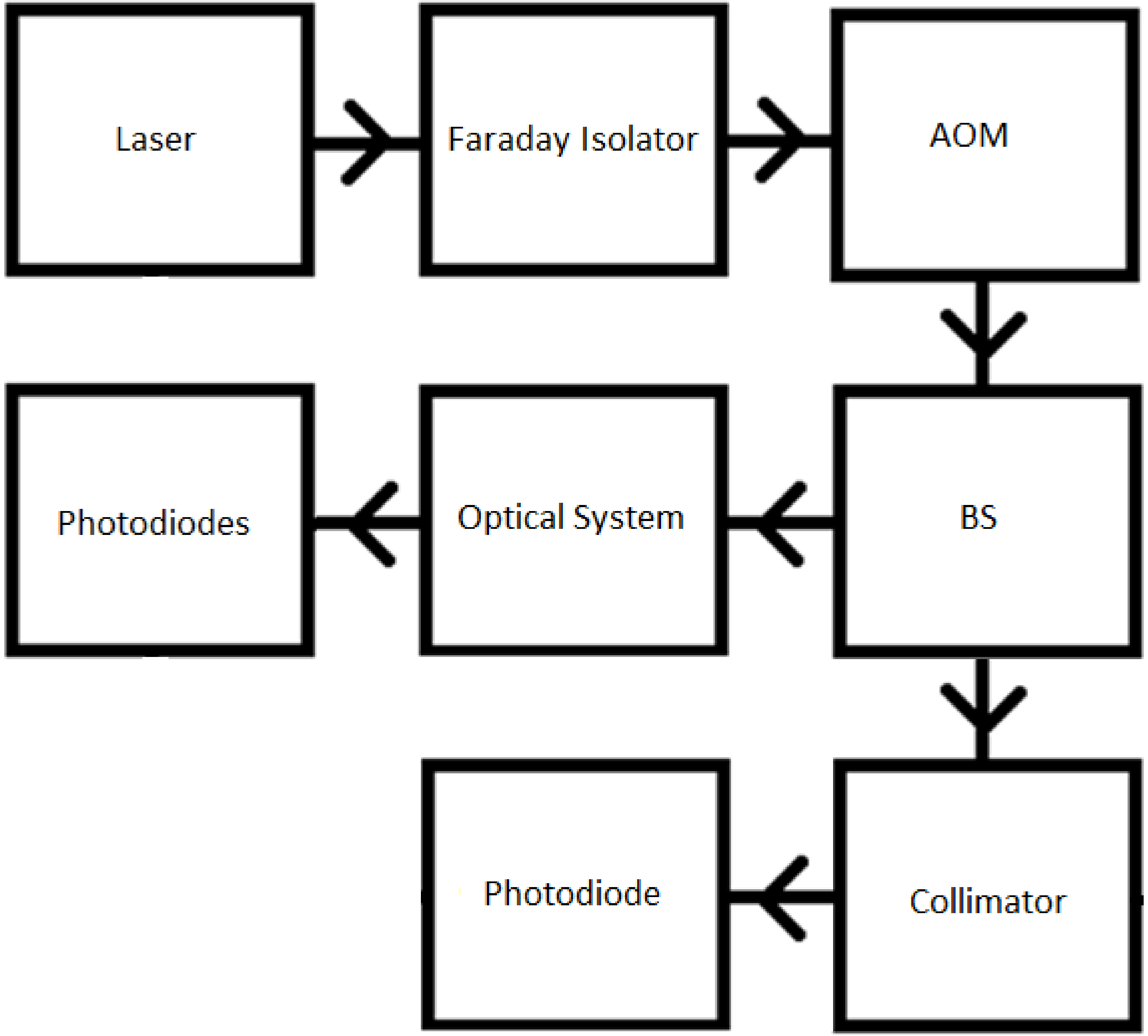
Noise Evaluation

- Not Limited by the following in the frequency region of interest
  - DC Block Noise
  - Circuit Noise
  - Zero Laser Output Noise
  - Zero Laser Output Noise
- Therefore possible Noise sources are
  - Intensity Noise
  - Light Scattering

Check Intensity Noise Limitation

- Need to check if intensity noise limits the system
  - Introduce an AOM to modulation laser intensity
    - Requires introduction of a BS
  - Measure Lorentz violation signal and intensity noise
  - Use the modulation peak to calibrate the intensity noise spectrum

Intensity Noise Check Flow Diagram



Laser

Faraday Isolator

AOM

BS

Optical System

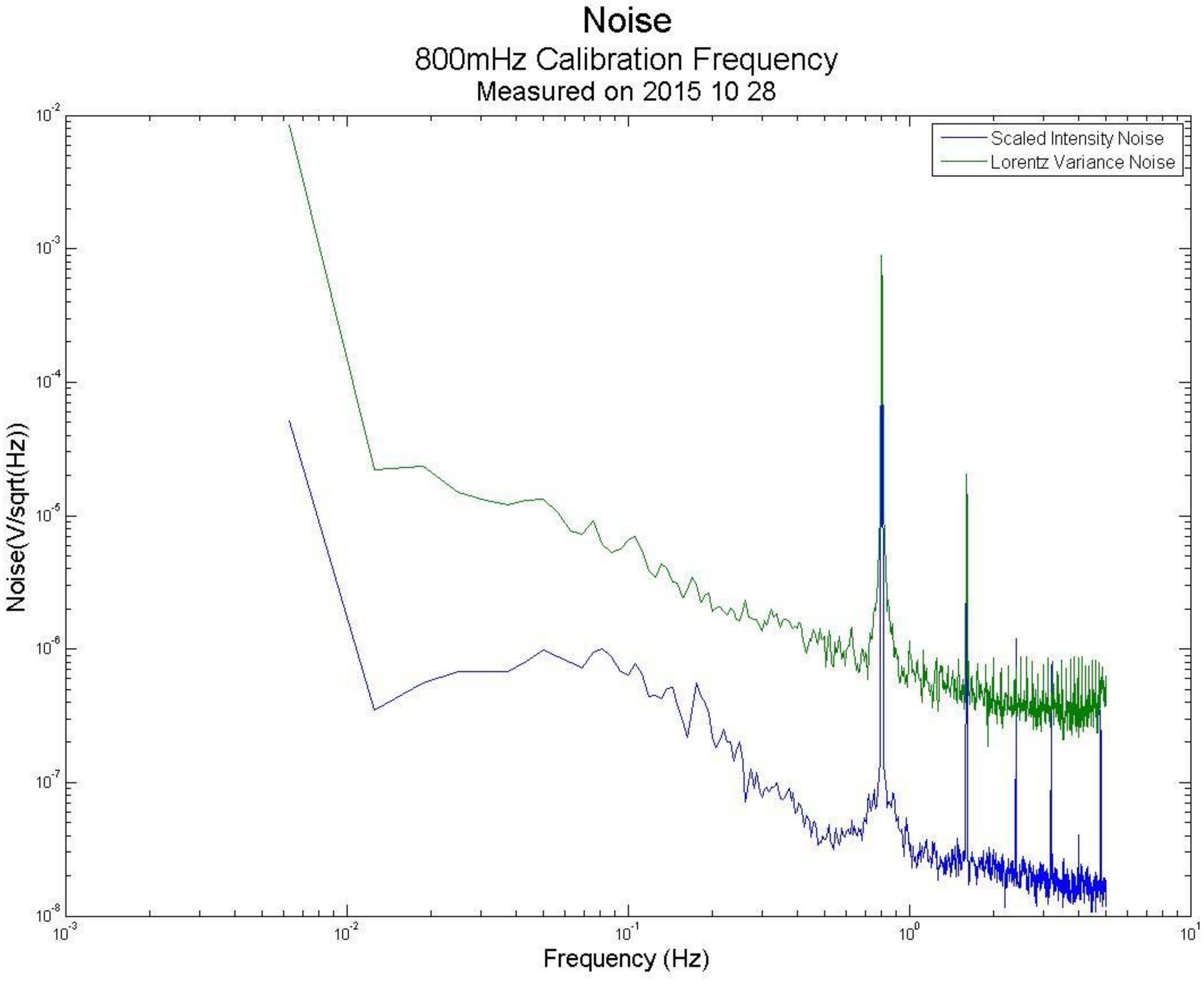
Photodiodes

Collimator

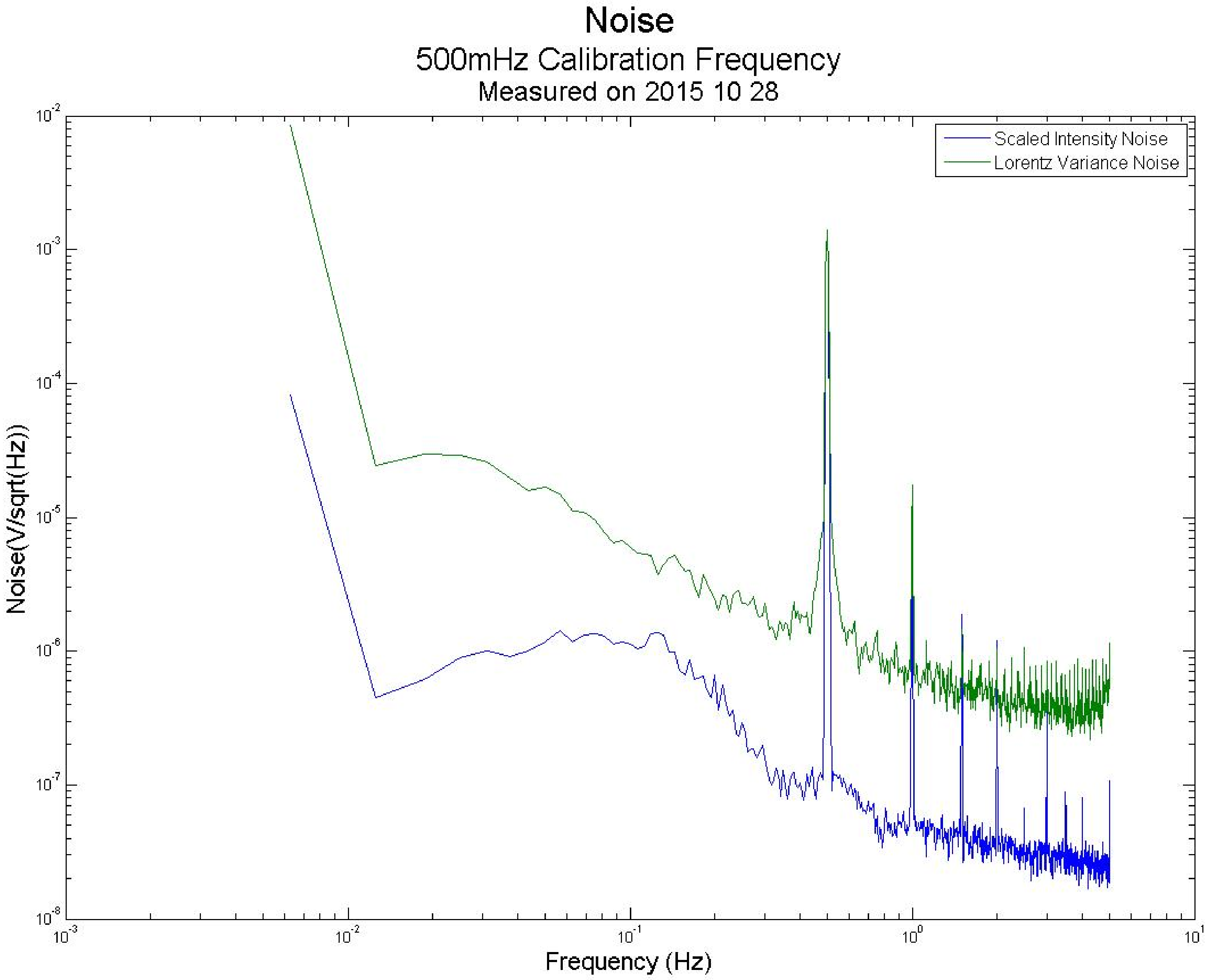
Photodiode

Check Intensity Noise Limitation

- Possible Drawbacks
  - The AOM and BS may introduce additional noise
  - If Lorentz violation signal is intensity noise limited need to rule out AOM and BS noise limiting the test system
  - If not the system is not intensity noise limited

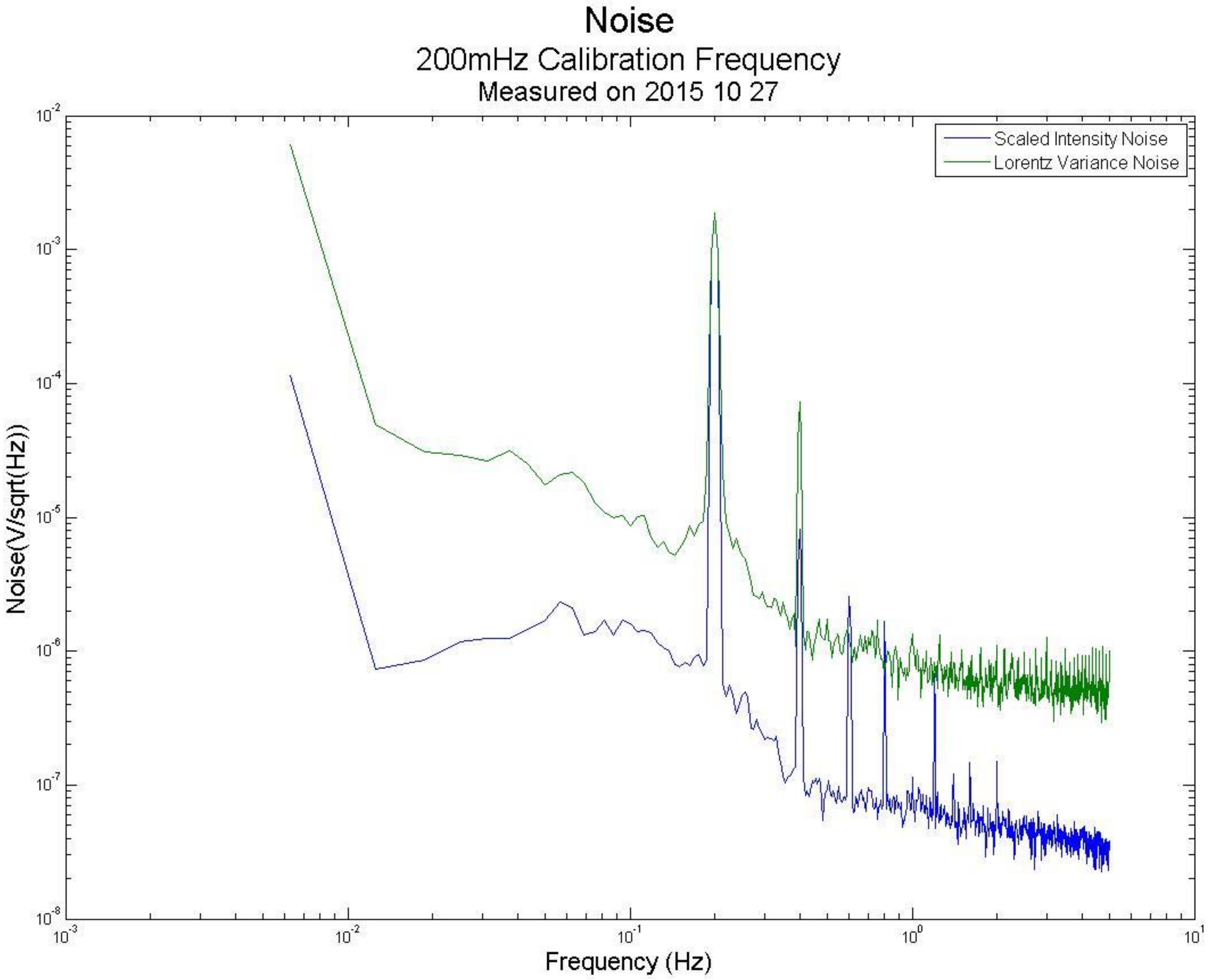


Old Analyser



Noise
500mHz Calibration Frequency
Measured on 2015 10 28

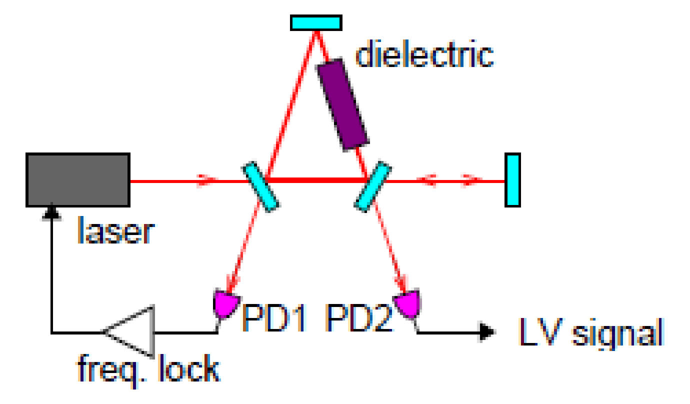
Old Analyser



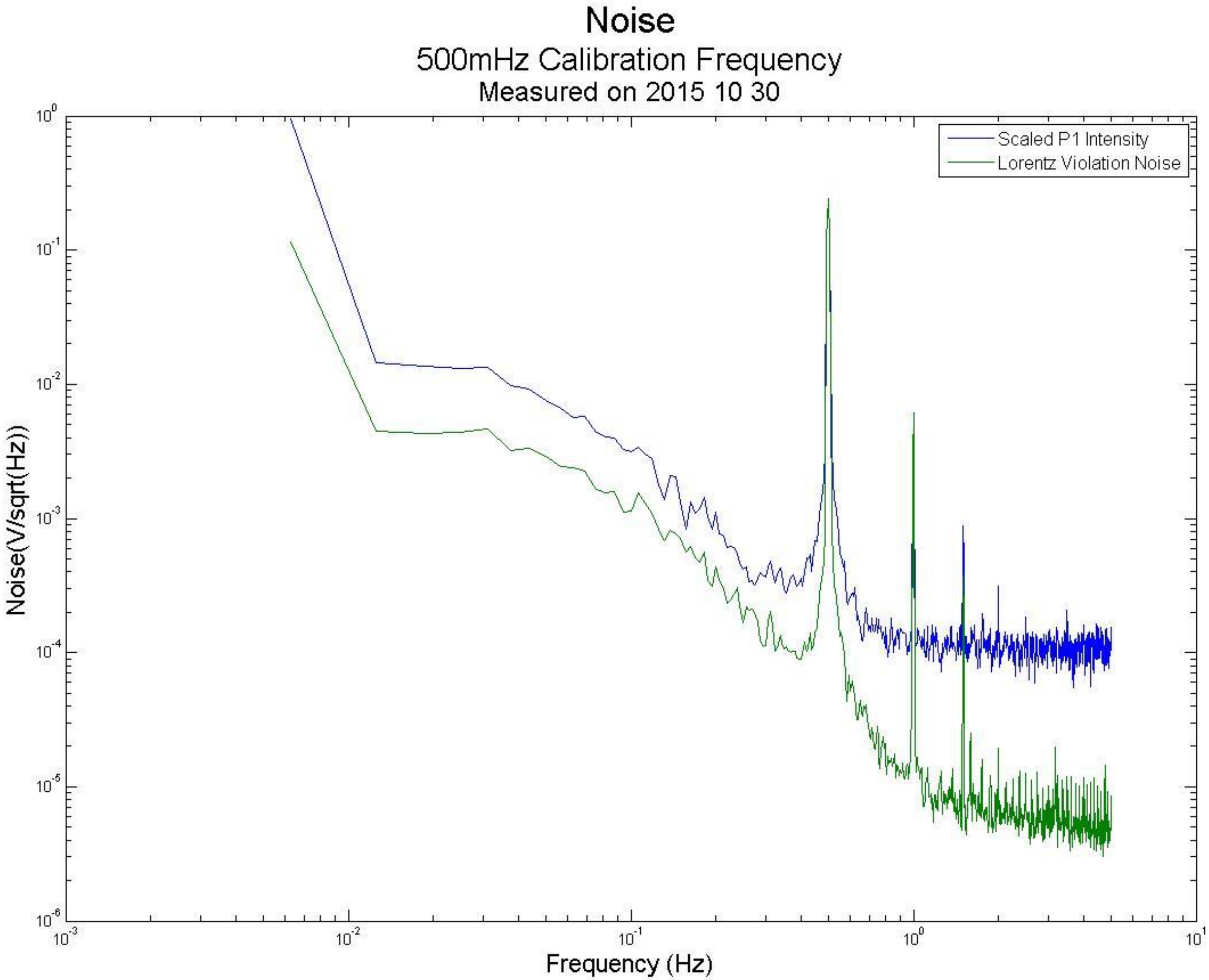
Old Analyser

Check Intensity Noise Limitation

- System is not intensity noise limited
- Possible Light scattering is limiting system
  - Compare Lorentz violation noise with PD1 noise
    - Calibrate with same procedure



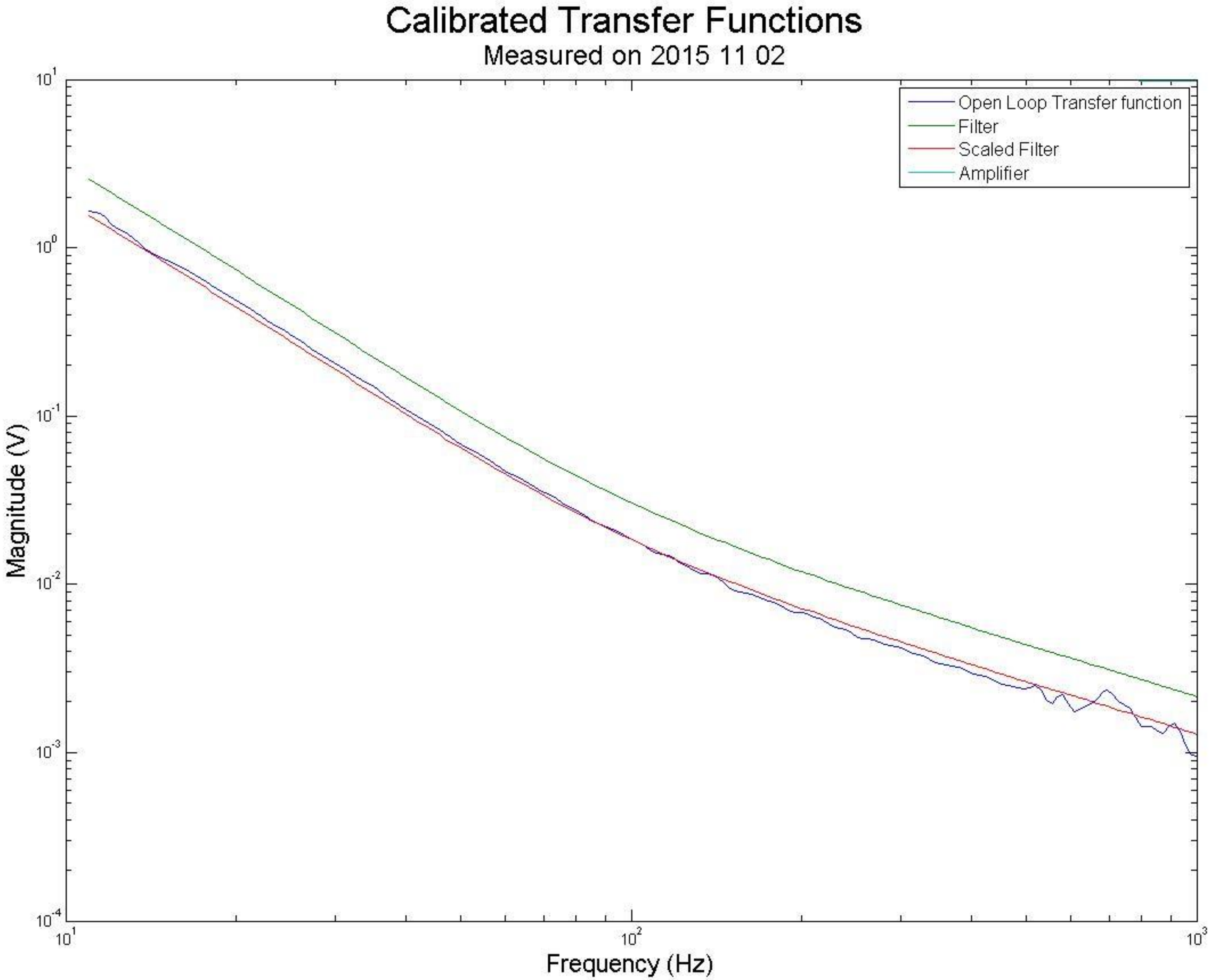
(Diagram Michimura, Y 2014, Tests of Lorentz Invariance with an Optical Ring Cavity, Ph.D thesis, The University of Tokyo)



Old Analyser

Lorentz Violation Signal

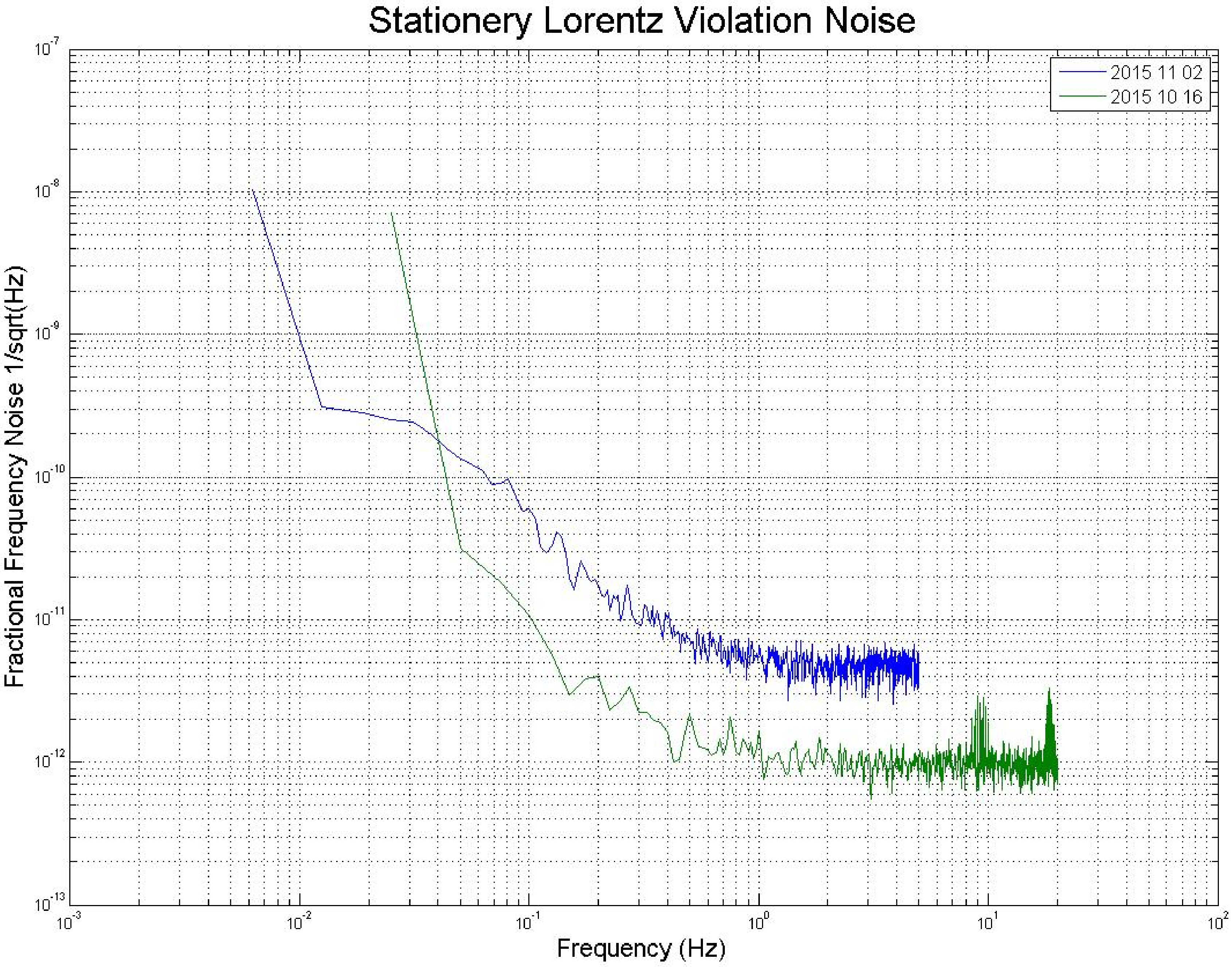
- Scattering that occurs before PD1 output does not limit system
- Several days had passed since calibration and fractional frequency noise measurement
- Repeat this process to check consistency



Calibrated Transfer Functions

Measured on 2015 11 02

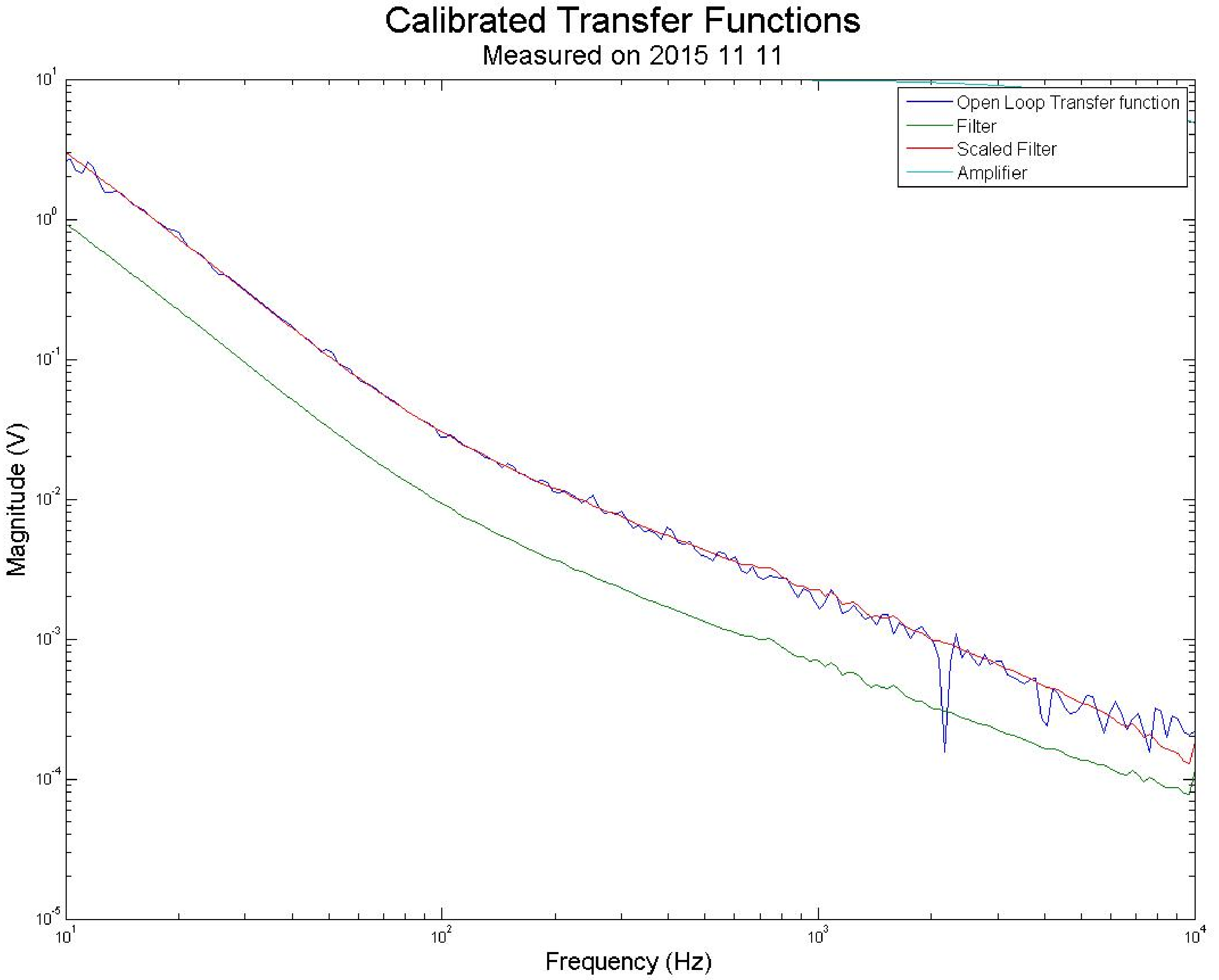
New Analyser



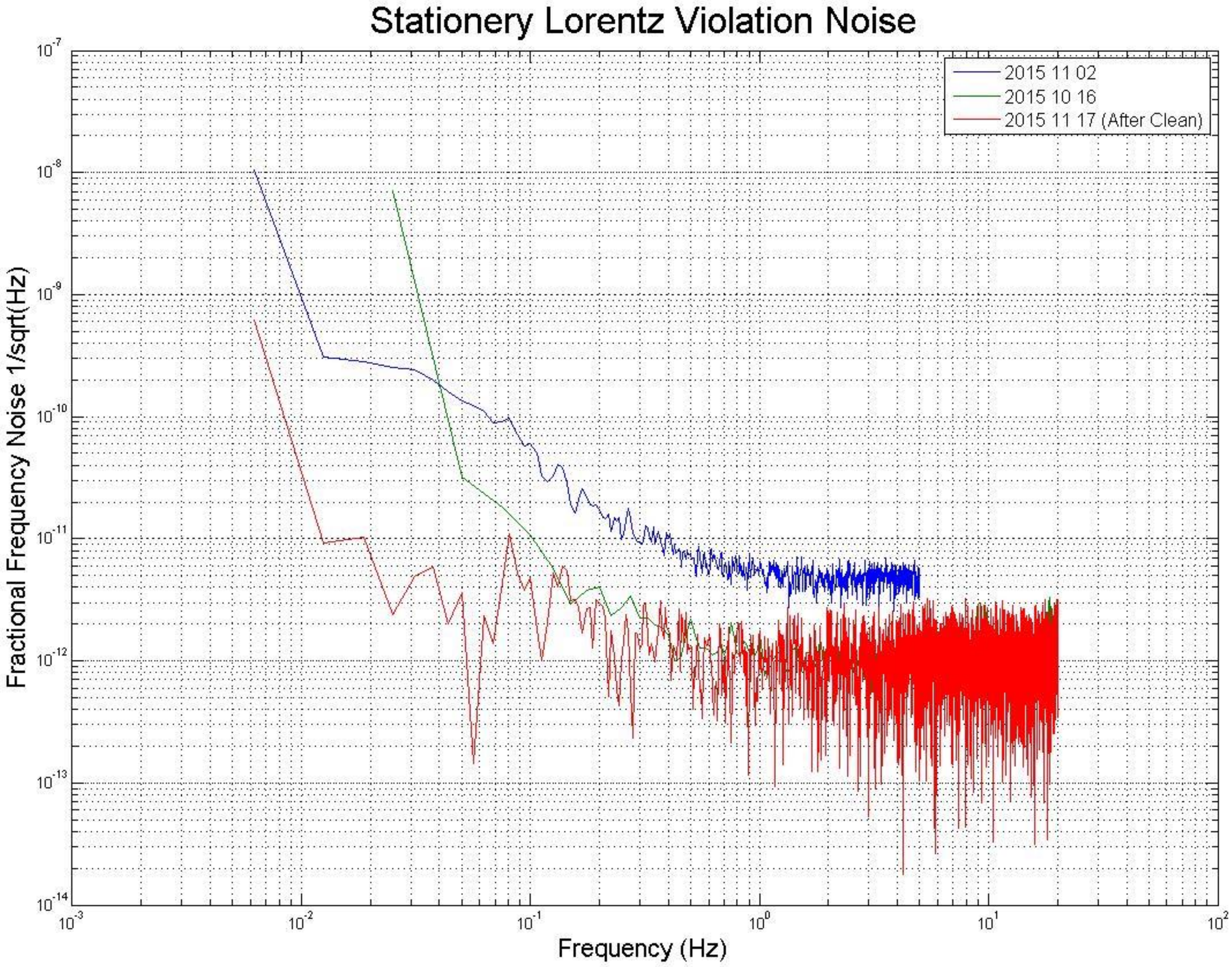
Old Analyser

Cleaning

- Increase of noise compared to initial Assembly
  - Spectrum has arc that is similar to that from scattering
  - Assume Increase is due to scattering
    - System has become dirty



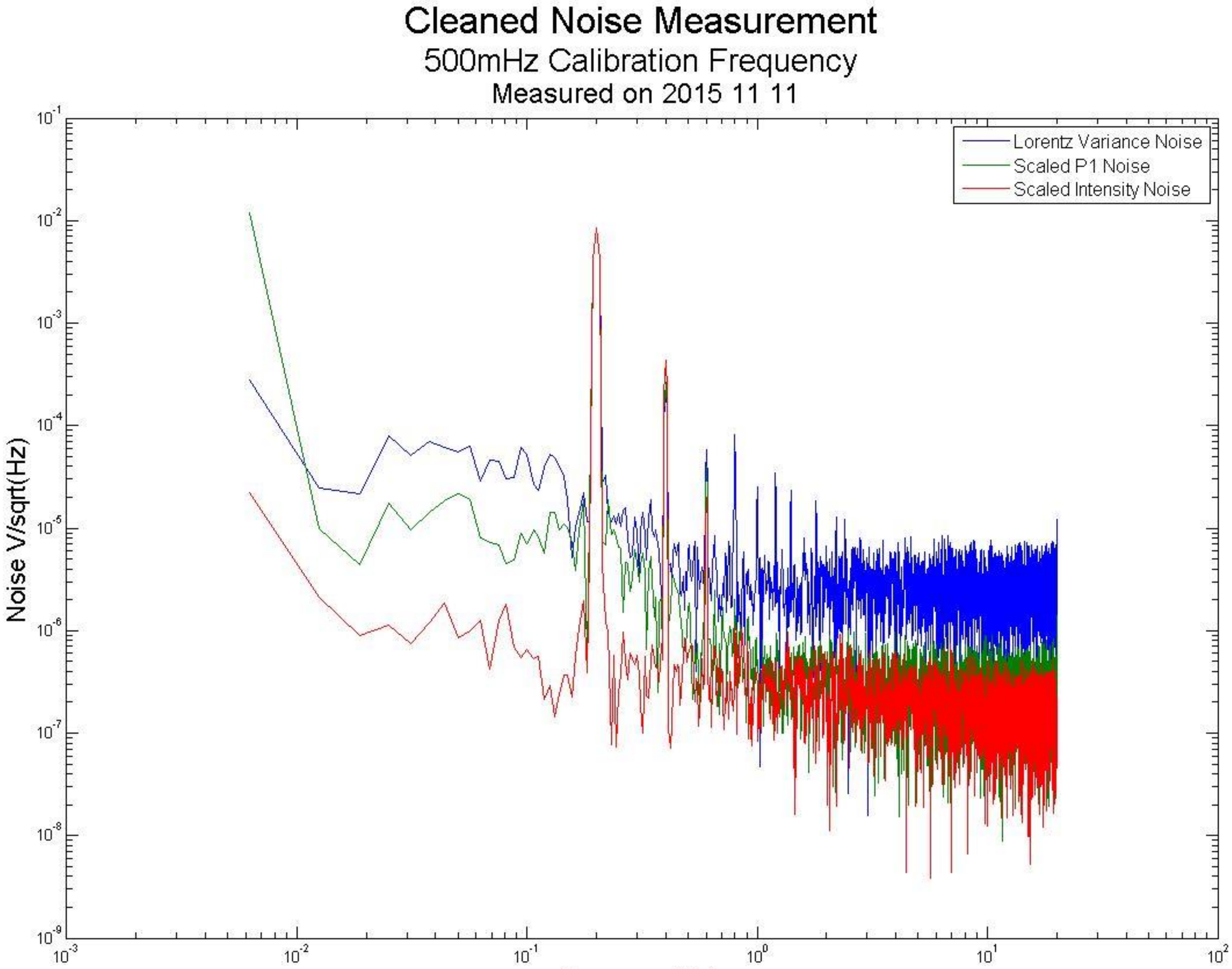
New Analyser



New Analyser

Cleaning Successful

- Cleaning process reduced noise
  - Achieved lower noise level than initial set up
- Still higher than stationery noise measured by Michimura-san experiment
- Check Intensity noise limitation and PD1 noise limitation
  - Same as previous explanation



New Analyser

Check Intensity Noise Limitation

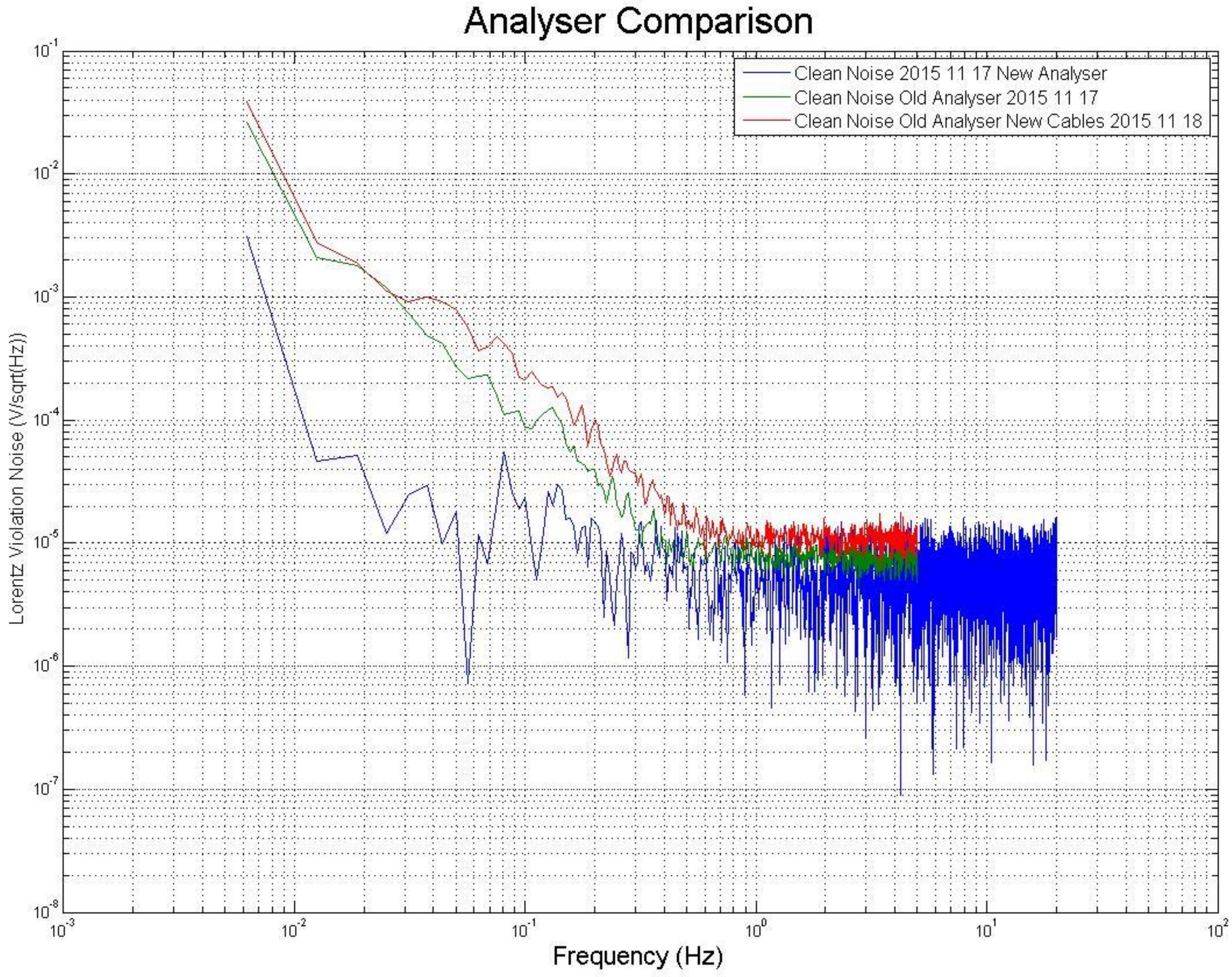
- Not limited by Intensity noise
- Not limited by noise at PD1

Future Prospects

- Measure the rotational noise
  - New setup designed to have increased common mode rejection ratio
    - Rotational noise may be lower than previous set up
- Continue to try to reduce stationery noise
  - M1 has a small scratch, but doesn't appear to be limiting system
    - Would be present in PD1 noise
  - Other scattering sources
    - Fibres dropping from the new insulating material may increase scattering
- Numerically evaluate the quality of the calibration agreement

Analyser Analysis

- Noticed a discrepancy between the two spectrum Analysers
    - Older Analyser produces higher Noise measurement
    - Neither analyser is limited by Ground Noise
- Example measurements on following slide measured consecutively


Analyser Comparison
Clean Noise 2015 11 17 New Analyser
Clean Noise Old Analyser 2015 11 17
Clean Noise Old Analyser New Cables 2015 11 18
Lorentz Violation Noise (V/sqrt(Hz))
Frequency (Hz)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}