# Red Pitaya Digital Controller

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# Motivation

- LIGO subsystems require some type of control
- Non-planar ring oscillator laser (NPRO)
- High intrinsic stability
- PZT stabilizes the laser frequency through feedback actuation
- Usable bandwidth is limited by mechanical resonances

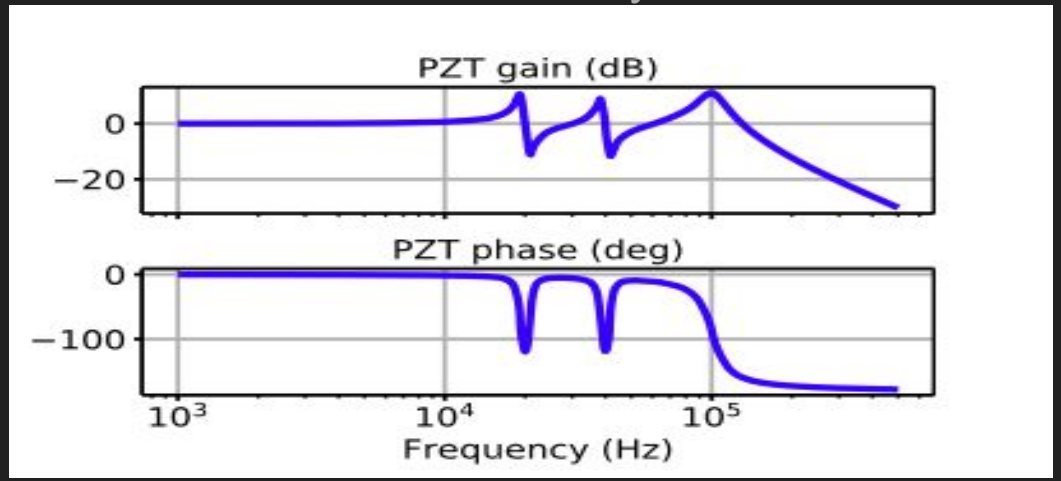
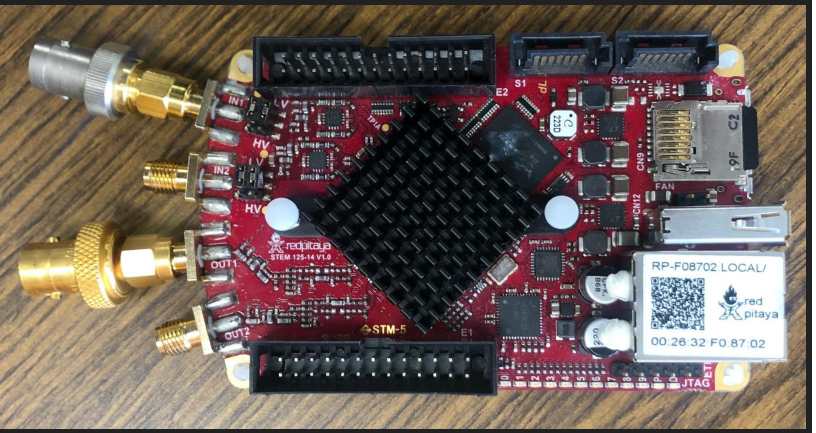


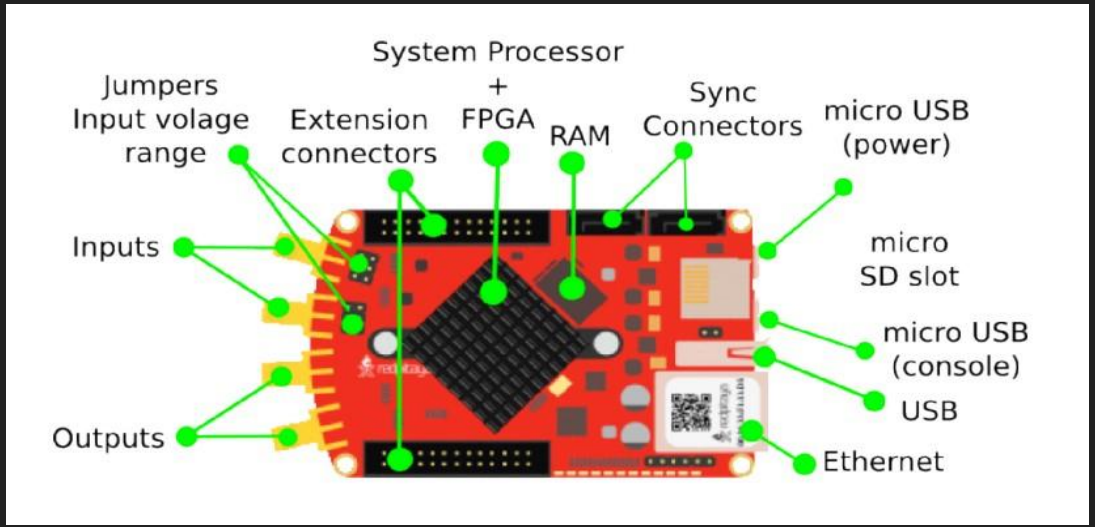

Figure adapted from Okada et al.

# FPGA and Red Pitaya



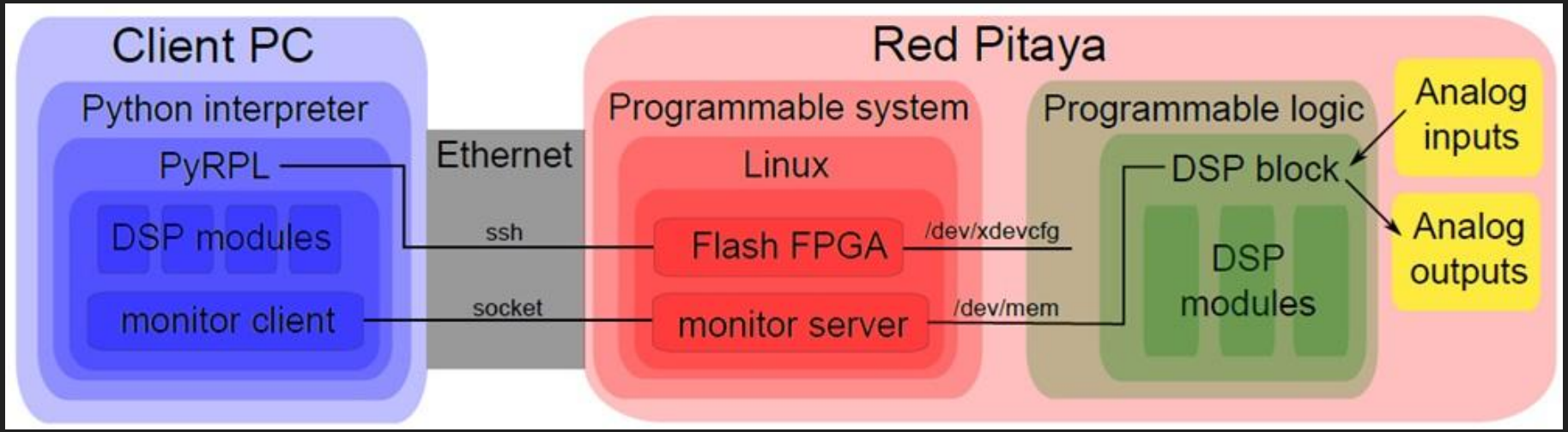
- Field-programmable gate arrays (FPGA):an integrated circuit with programmable interconnects that can be customized for a particular application
- Red Pitaya: electronic board that possesses an FPGA and other useful components (DAC/ADC)



# PyRPL

- Open source python package
- Specifically works with Red Pitaya
- Possesses many useful DSP modules
- Network analyzer and IIR filter module



# Transfer Functions

- Ratio of output to input in Laplace s-domain where initial conditions are set to zero
- To go to the frequency domain: s=jw
- Mathematically,

$$H(s) = \frac{Y(s)}{X(s)} = \frac{\sum_{i=0}^{n} b_i s^{n-i}}{\sum_{i=0}^{m} a_i s^{m-i}}$$

$$H(z) = \frac{Y(z)}{X(z)} = \frac{\sum_{n=0}^{N} b_n z^{-n}}{\sum_{n=0}^{N} a_n z^{-n}}$$

# ZPK Representation

- Useful to write transfer functions in terms of zeroes and poles
- Zeroes: roots of the numerator polynomial
- Poles: roots of the denominator polynomial
- K: the overall gain associated with the transfer function

$$H(s) = K \frac{\prod_{i=1}^{n} (s - z_i)}{\prod_{i=1}^{m} (s - p_i)}$$

# Digital Filter Types

- Finite impulse response (FIR)
- Infinite impulse response (IIR)

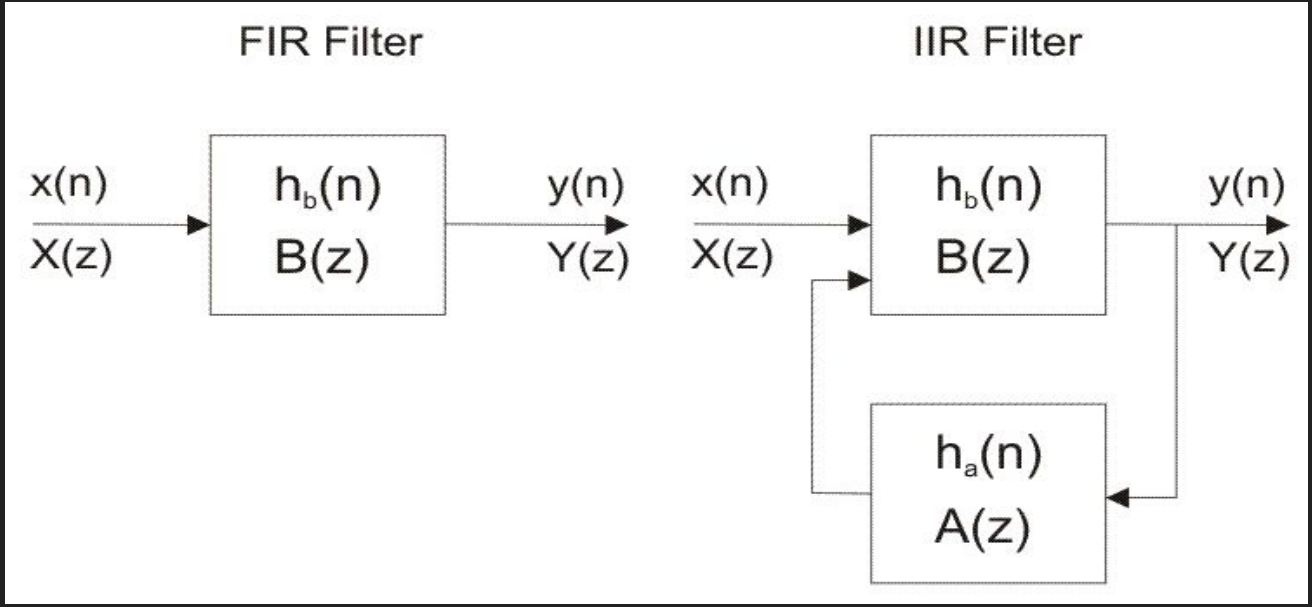
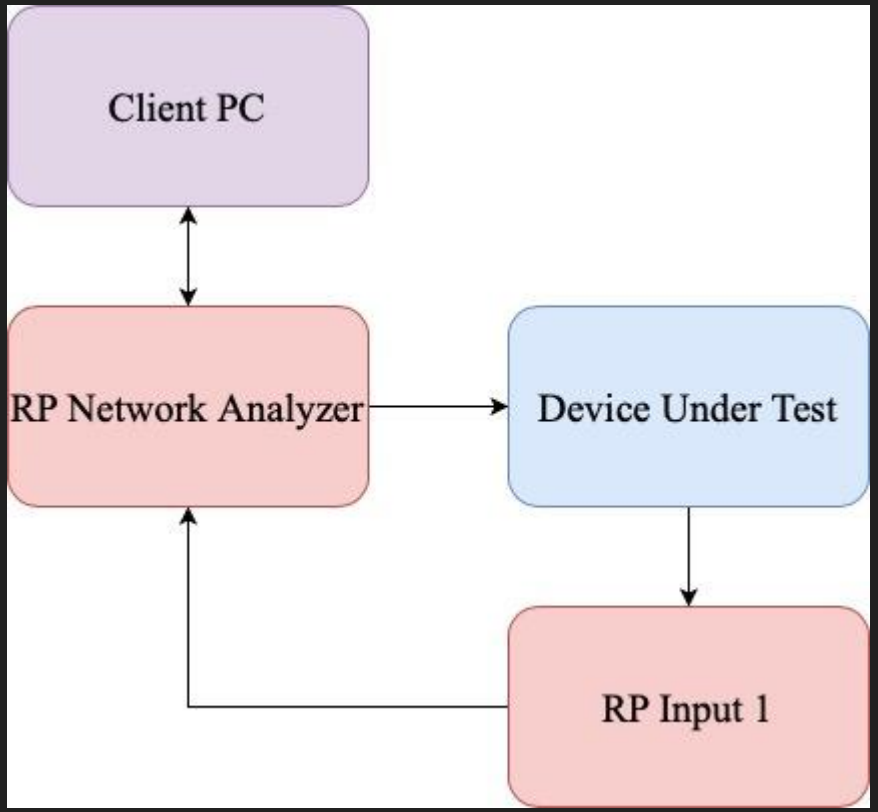


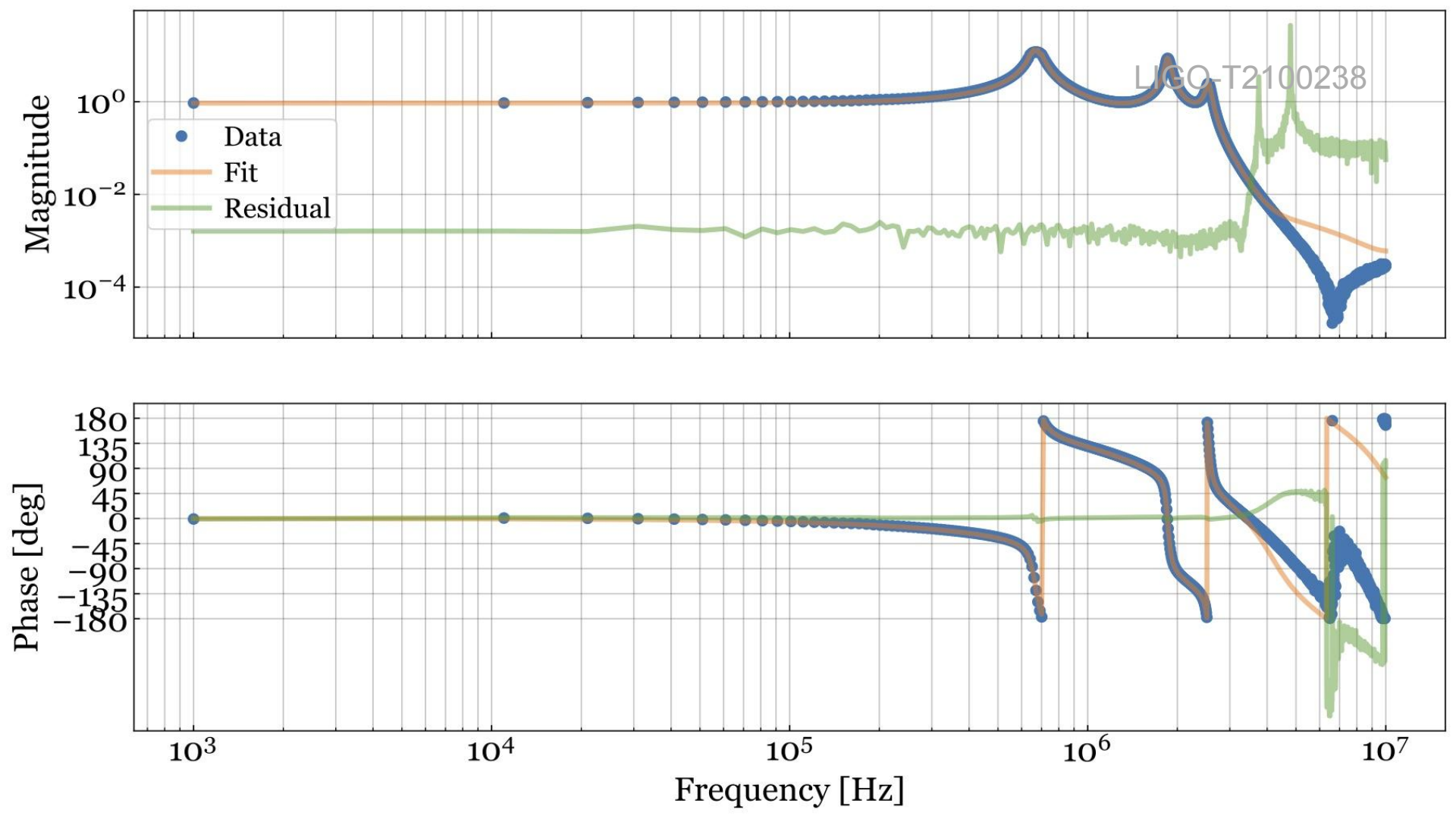

Figure adapted from Milivojevic

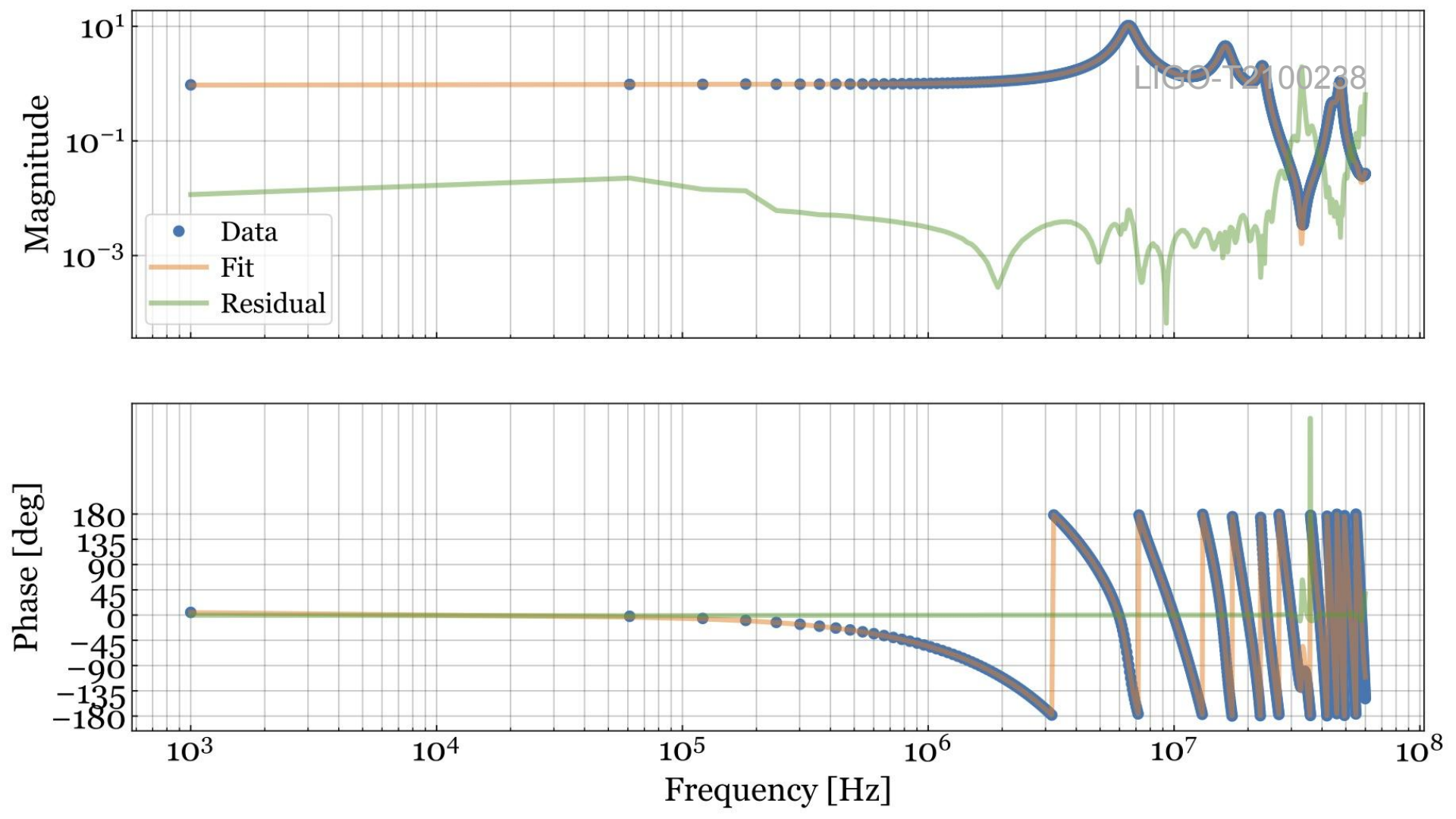
# System Identification

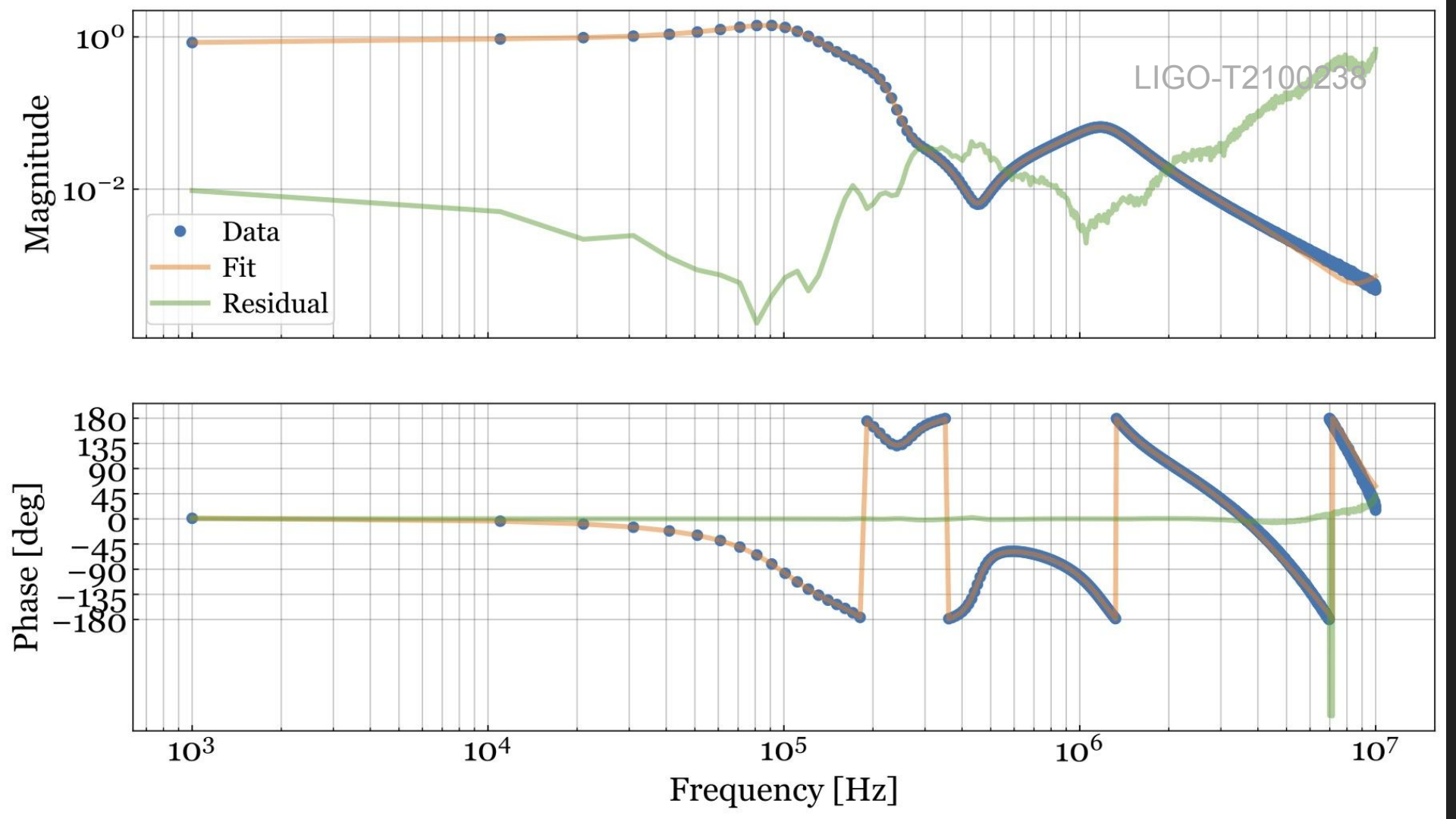
- Network Analyzer
- Vector fitting algorithm (pole-residue form)

$$H(s) = \sum_{m=1}^{N} \frac{r_m}{s - p_m} + d + sh$$




LIGO-T2100238
Magnitude
$10^{0}$
$10^{-2}$
$10^{-4}$
Data
Fit
Residual
Phase [deg]
180
135
90
45
0
−45
−90
−135
−180
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
$10^{7}$
Frequency [Hz]

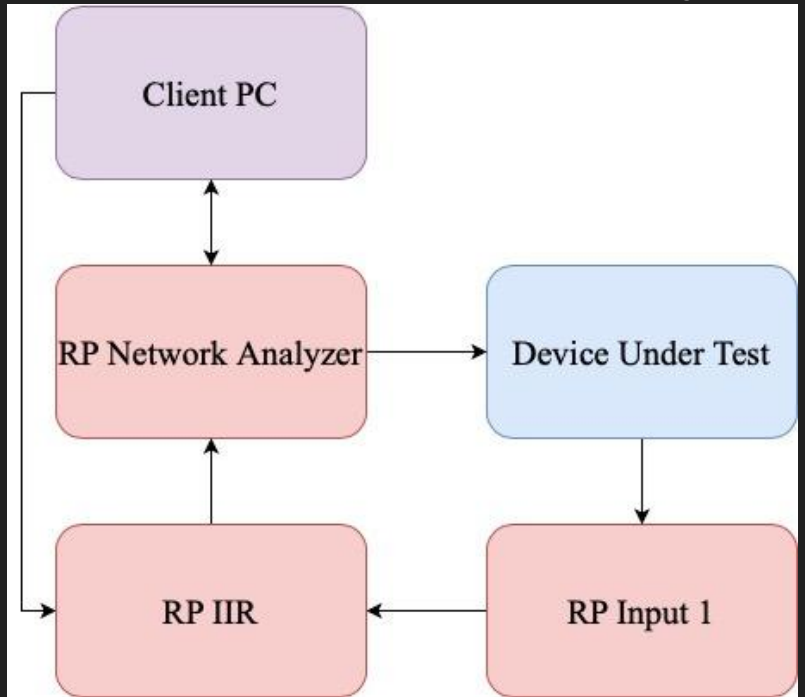

LIGO-T2100238
Magnitude
$10^{1}$
$10^{-1}$
$10^{-3}$
Data
Fit
Residual
Phase [deg]
180
135
90
45
0
−45
−90
−135
−180
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
$10^{7}$
$10^{8}$
Frequency [Hz]

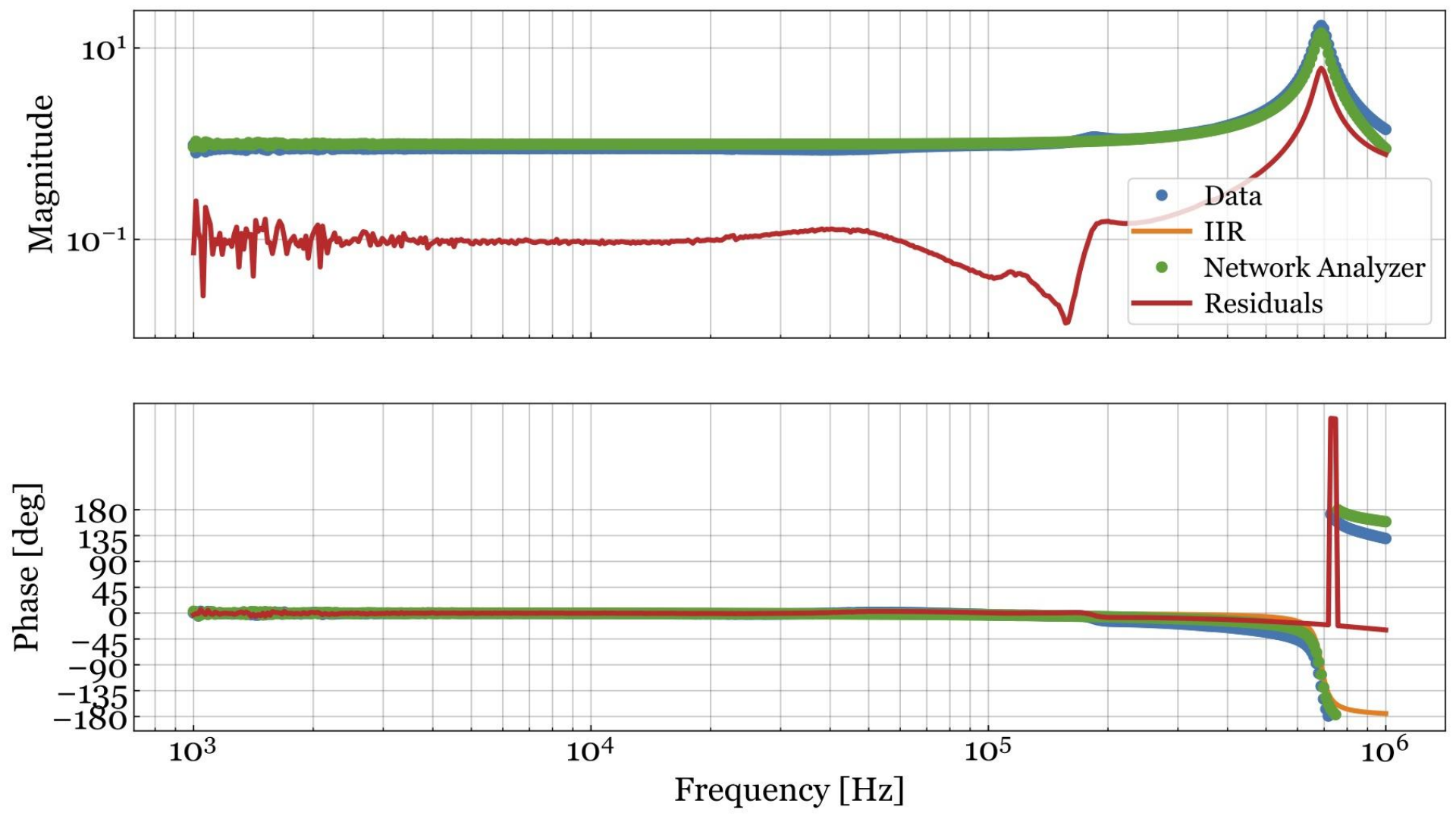

LIGO-T2100238
Magnitude
$10^{0}$
$10^{-2}$
Data
Fit
Residual
Phase [deg]
180
135
90
45
0
−45
−90
−135
−180
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
$10^{7}$
Frequency [Hz]

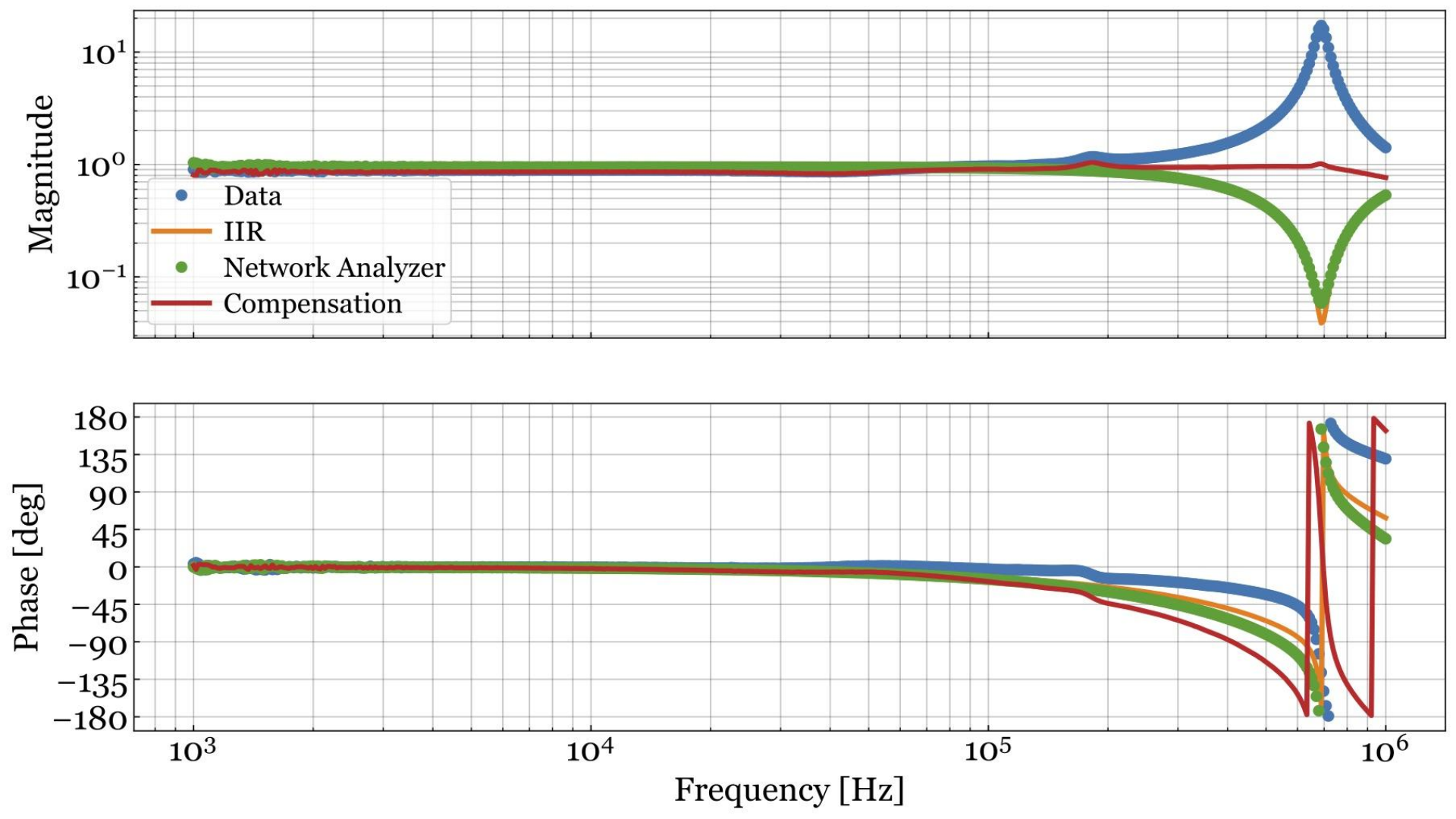
# IIR Filter



- Capable of producing transfer functions with up 16 poles and zeros
- Implemented as 8 parallel biquads
- Can properly simulate transfer functions of physical systems




Magnitude
$10^{1}$
$10^{-1}$
Data
IIR
Network Analyzer
Residuals
Phase [deg]
180
135
90
45
0
−45
−90
−135
−180
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
Frequency [Hz]


Magnitude
$10^{1}$
$10^{0}$
$10^{-1}$
Data
IIR
Network Analyzer
Compensation
Phase [deg]
180
135
90
45
0
−45
−90
−135
−180
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
Frequency [Hz]

# Future Work

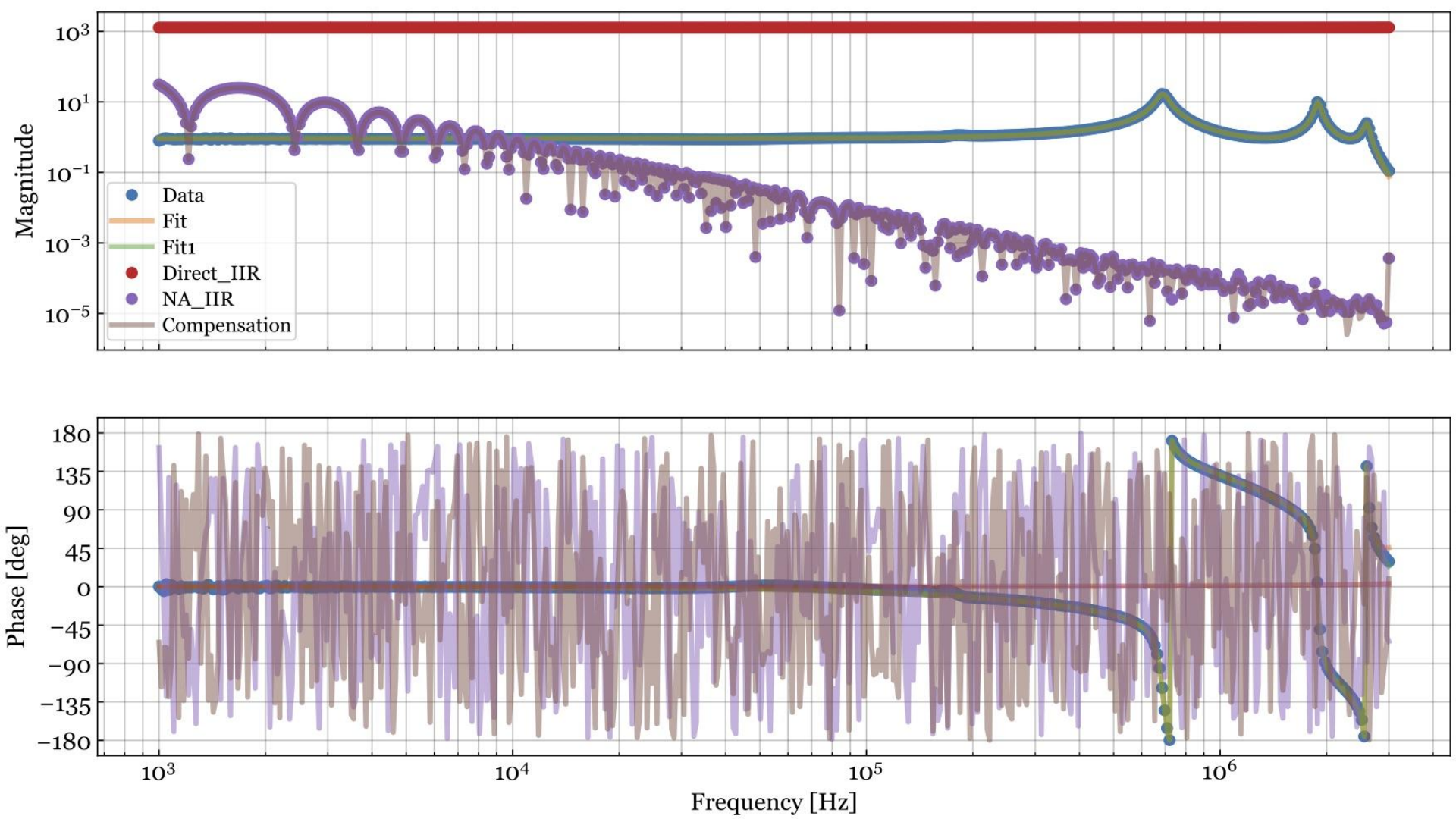
- Improving IIR module
- Better automation of system identification and filtering
- FIR module

# Acknowledgements


- National Science Foundation
- Caltech LIGO SURF




# Questions ?


Magnitude
Phase [deg]
Frequency [Hz]
Data
Fit
Fit1
Direct_IIR
NA_IIR
Compensation