Quantization Noise in Advanced LIGO Digital Control Systems

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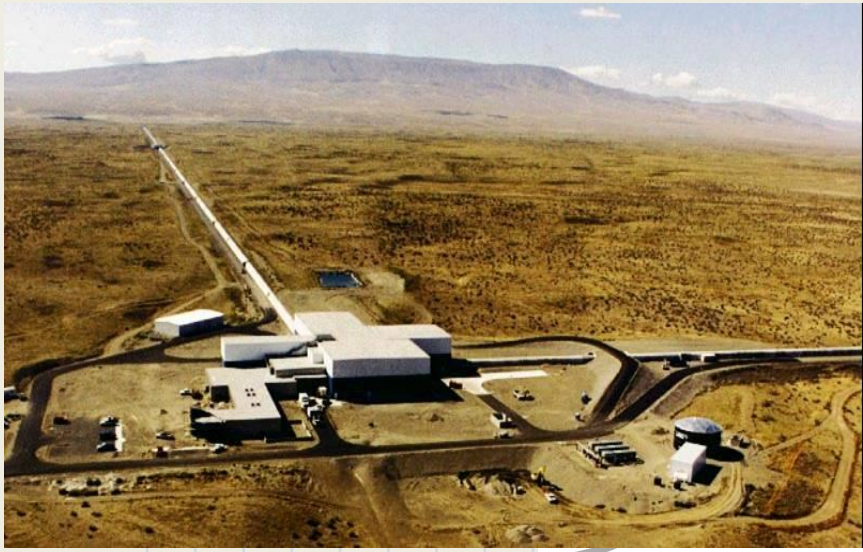
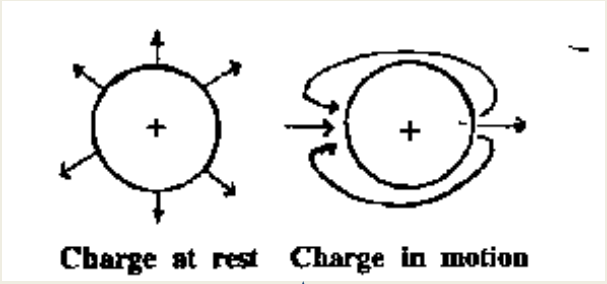
What is LIGO

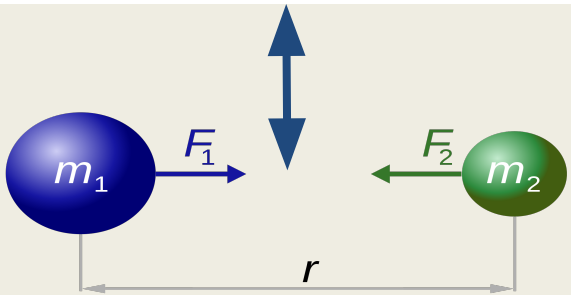
Laser Interferometer Gravitational Wave Observatory



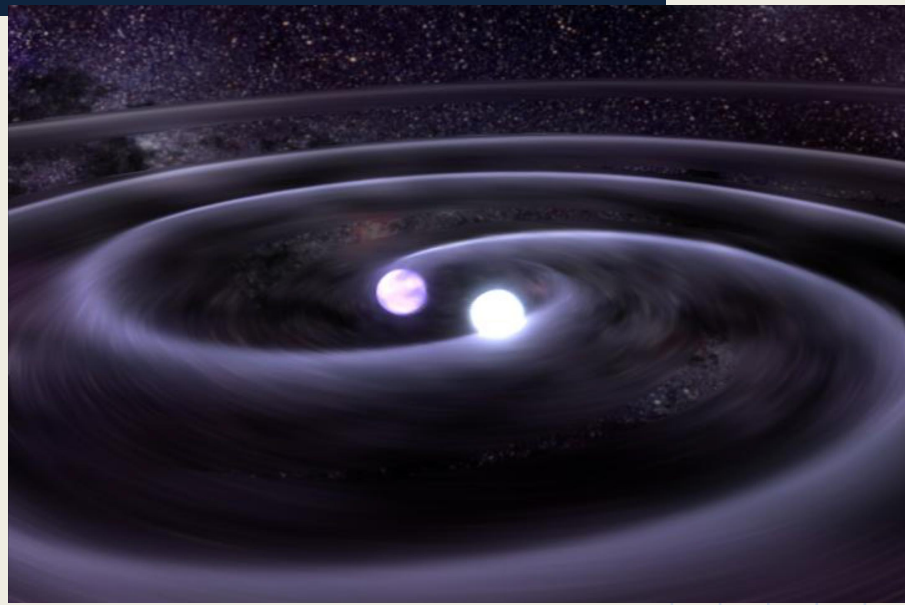
Gravitational Waves

Analogous to EM Waves





$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$



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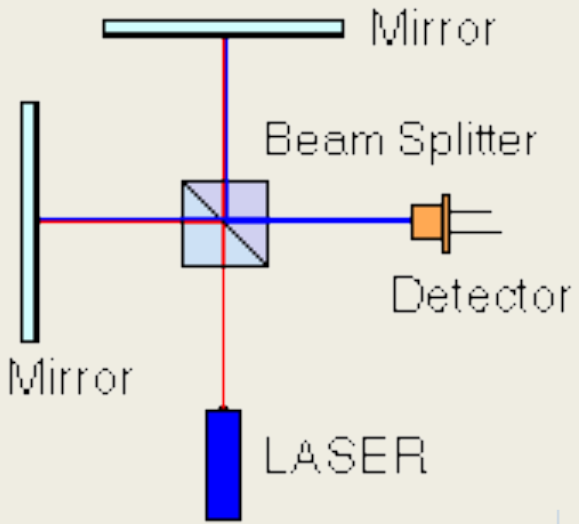
Laser - Interferometer

- Design : Not so simple!
  - 4km Length
  - L-shaped
- Strain Measurement
  - 10^{-19}m
- Noise to Signal?



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Seismic Noise

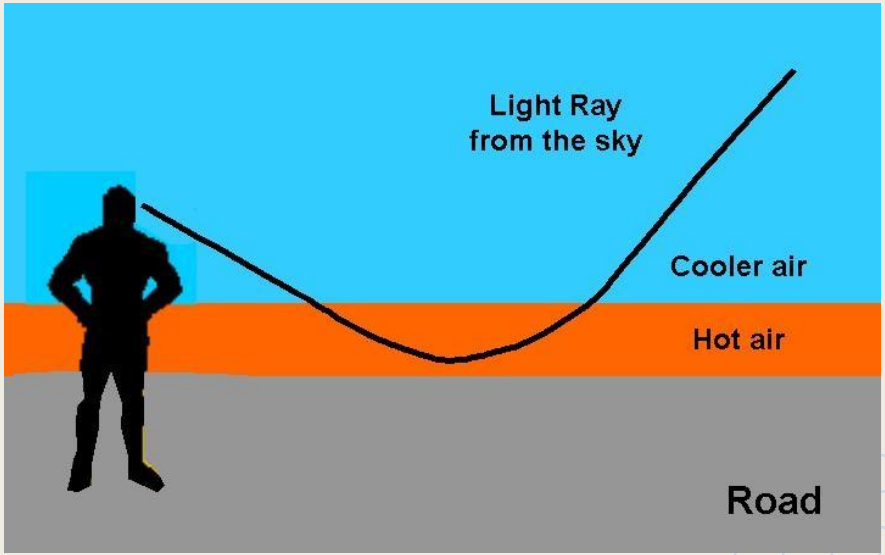
- Earthquakes
- Tree logging
- Traffic

Solutions

- Passive Seismic Isolation
  - Pendulum (Demo!)
  - Magnets
- Active Seismic Isolation
  - Seismometers
  - Accelerometers

Bending of Light

Laser Bends! (Refraction)



Solution: Vacuum Chambers

LIGO Vacuum:

- Ultra-High Vacuum
  - (8x of space)
- Strongest Sustained Vacuum Ever
- 10^{-12} atm pressure in a 8000 m^3 cavity.

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More and More Noise

Winds and Air Currents

Tidal Force

Temperature and Thermal Effects
Quantization Noise (Digital Noise)

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Quantization Noise

In Analog: 1.25 + 2.34500000199999 = 3.59500000199999

In double precision computer,
(1.25) + (2.34500000199999) = 3.5950000012

Quantization Noise = (approximately) 10^{-12}

Similarly, two (B+1) bit numbers, on multiplication give a (2B+1) number which then needs to be truncated for a B+1 precision computer

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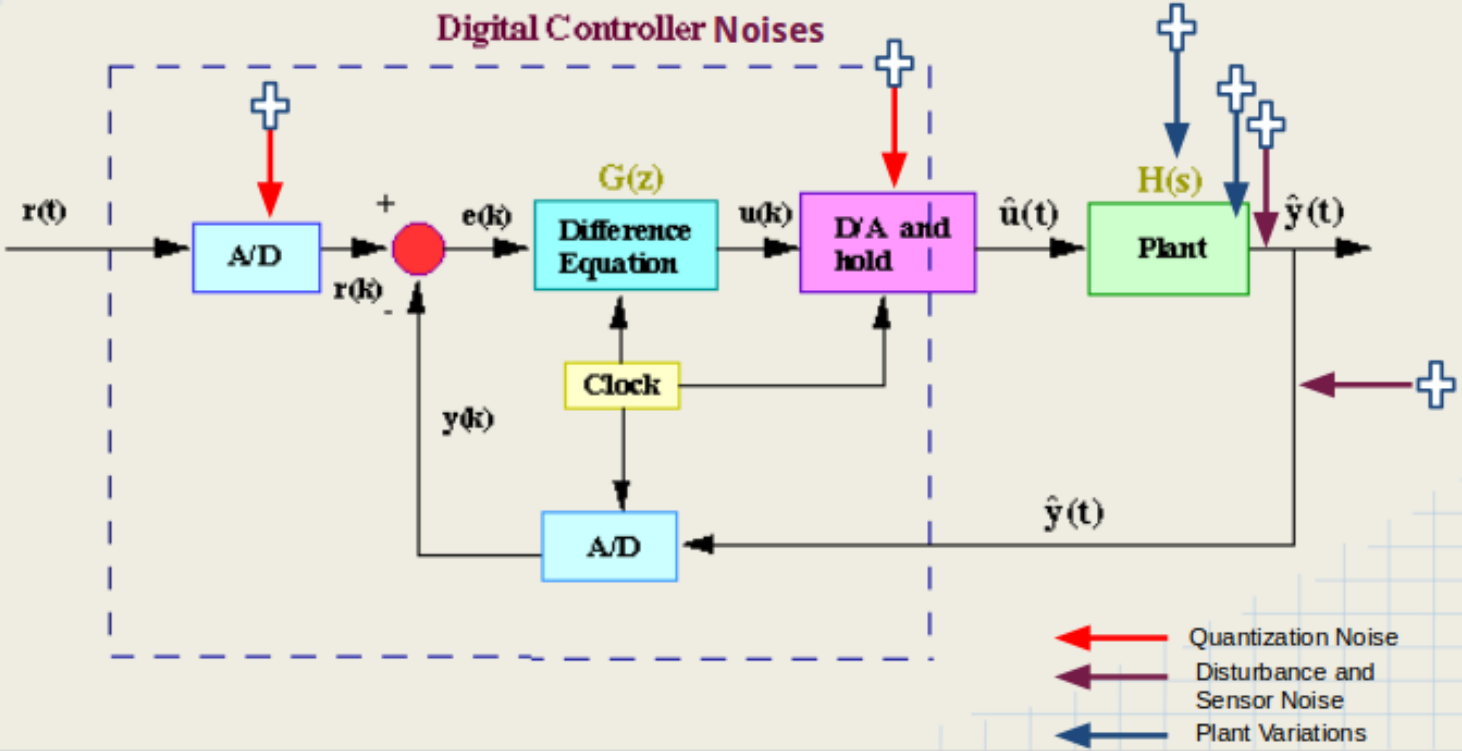
Quantization Noise Sources



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ADC and DAC

- Sampling and Quantization : ADC
  - Finite Precision

- Truncation and Interpolation : DAC

Digital Filter / Compensator

- Noise during Addition
- Noise on Multiplication
- Order of mathematical operations, filter structures

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Things Done

- ADC Quantization Noise Analysis
  - Dither
  - Noise Shaping
- Digital Filter Structures
  - Parallel Form
  - Cascade Form
  - DF1, DF2, State Space Representations, LNF etc.
- Precision Analysis
  - Fixed Point Noise Analysis
  - Floating Point Noise Analysis
- Noise Modeling
  - Quantizers, types and models
  - Statistical Theory of Quantization Noise…

….. and a lot more

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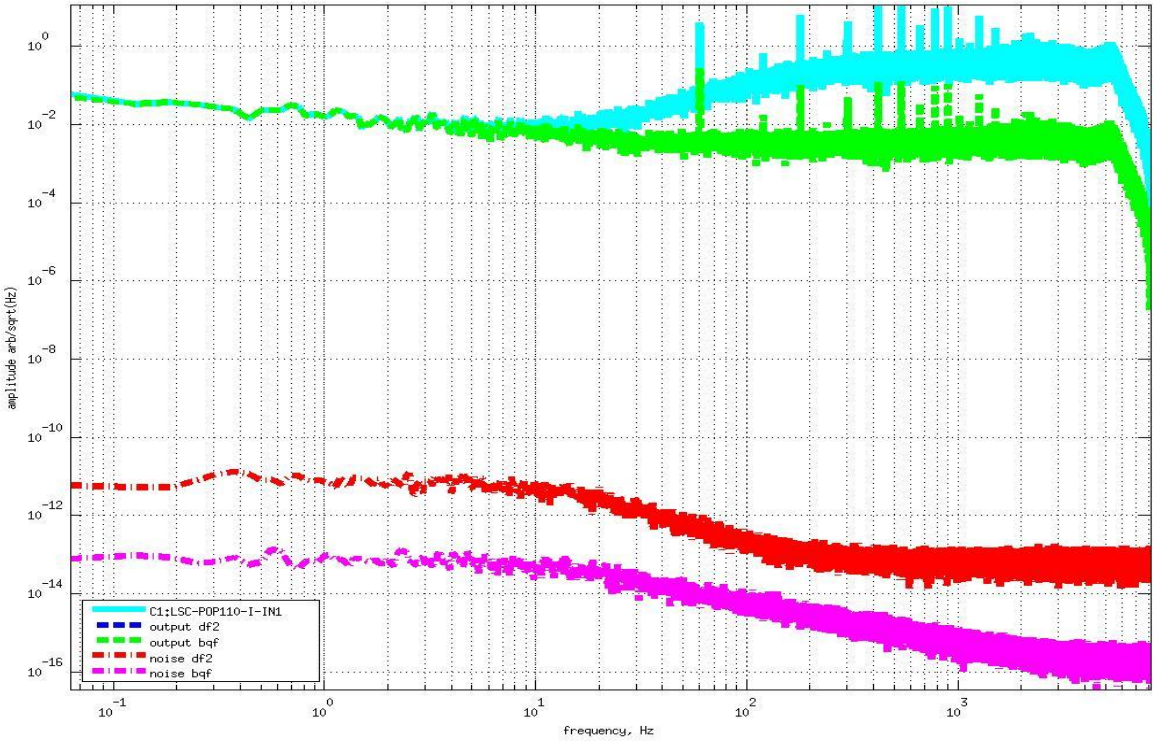
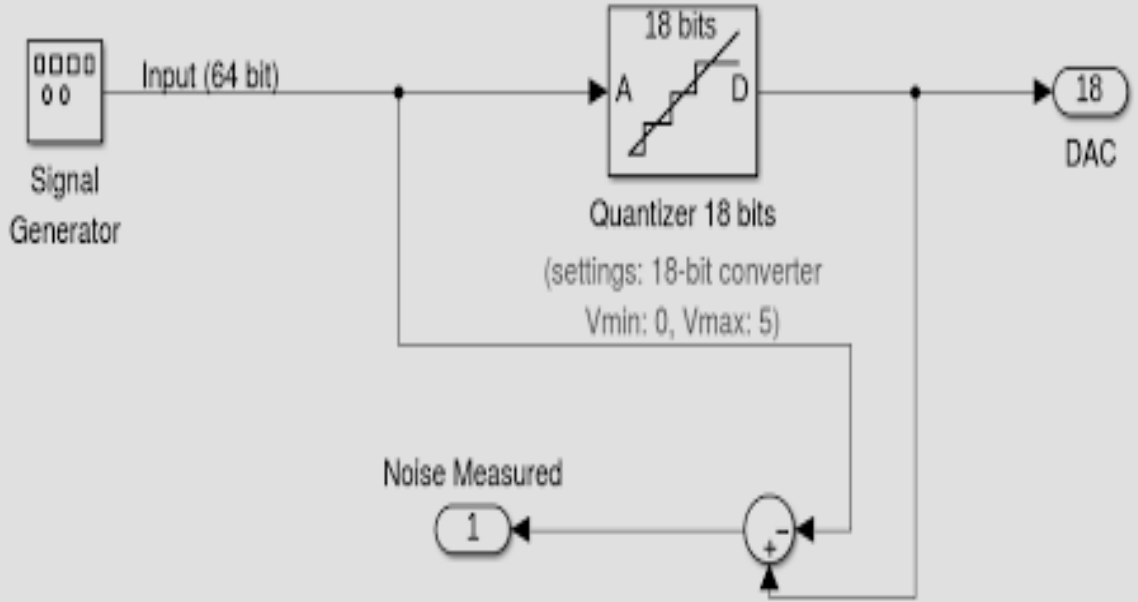
Digital Filter Noise Analysis



DAC Noise Analysis



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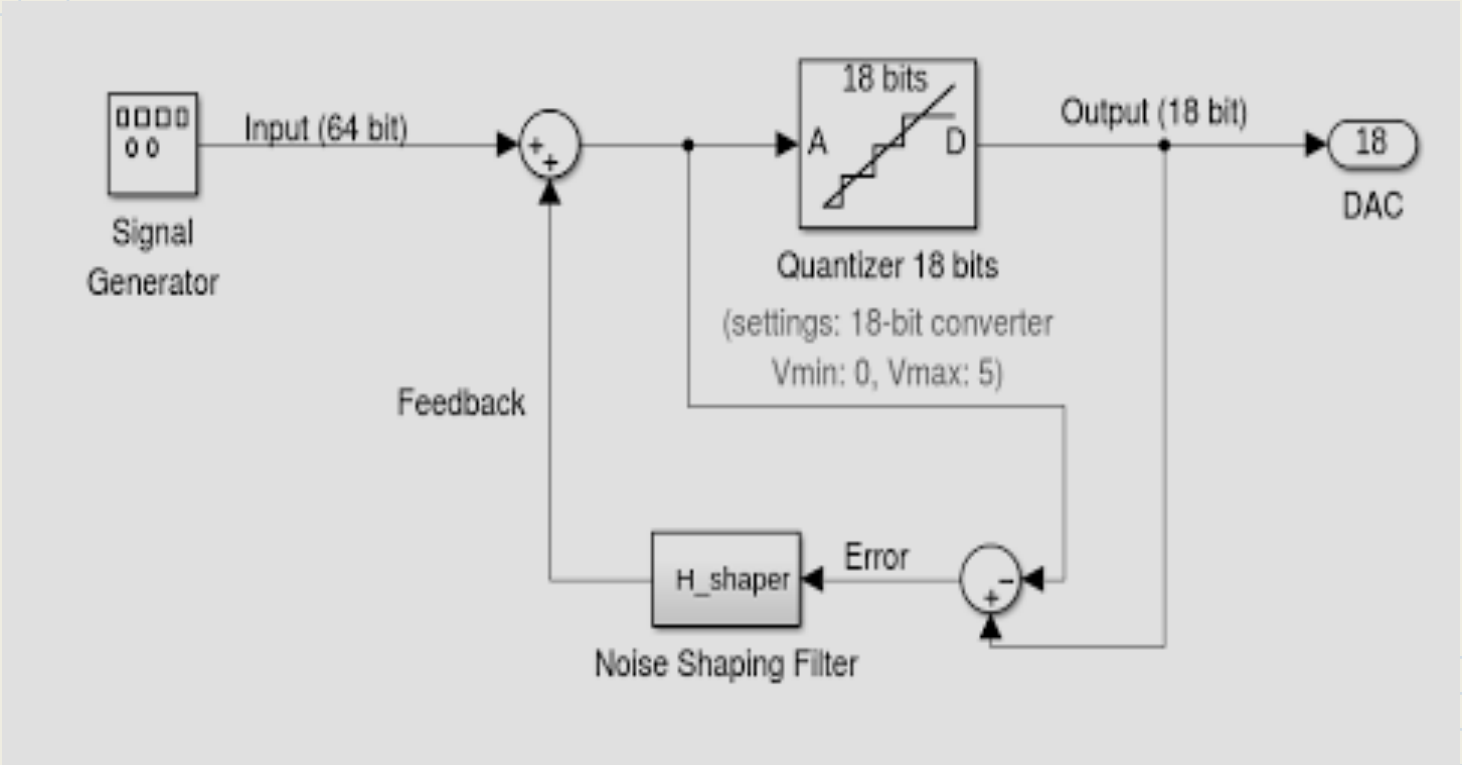
DAC Noise Shaping



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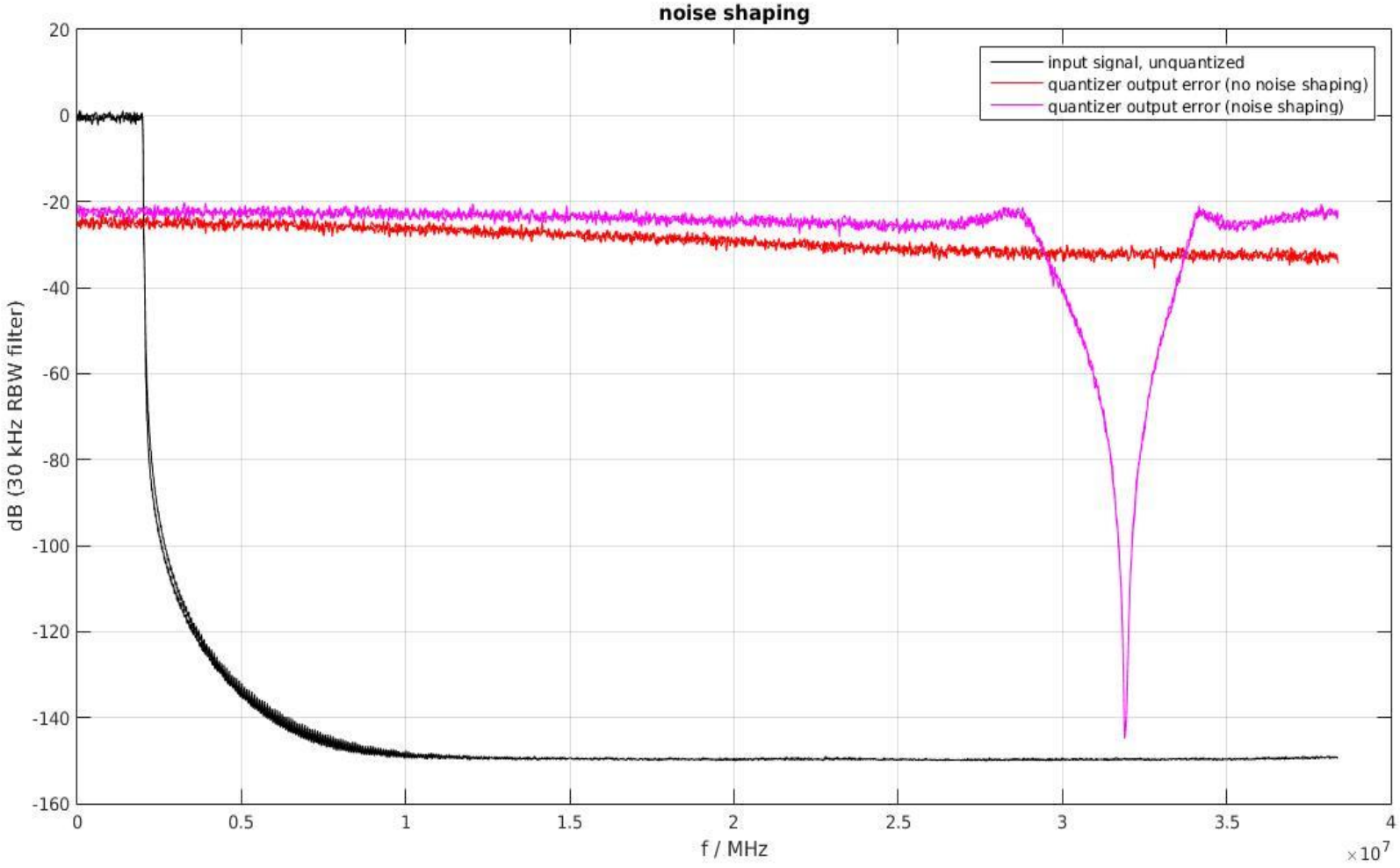
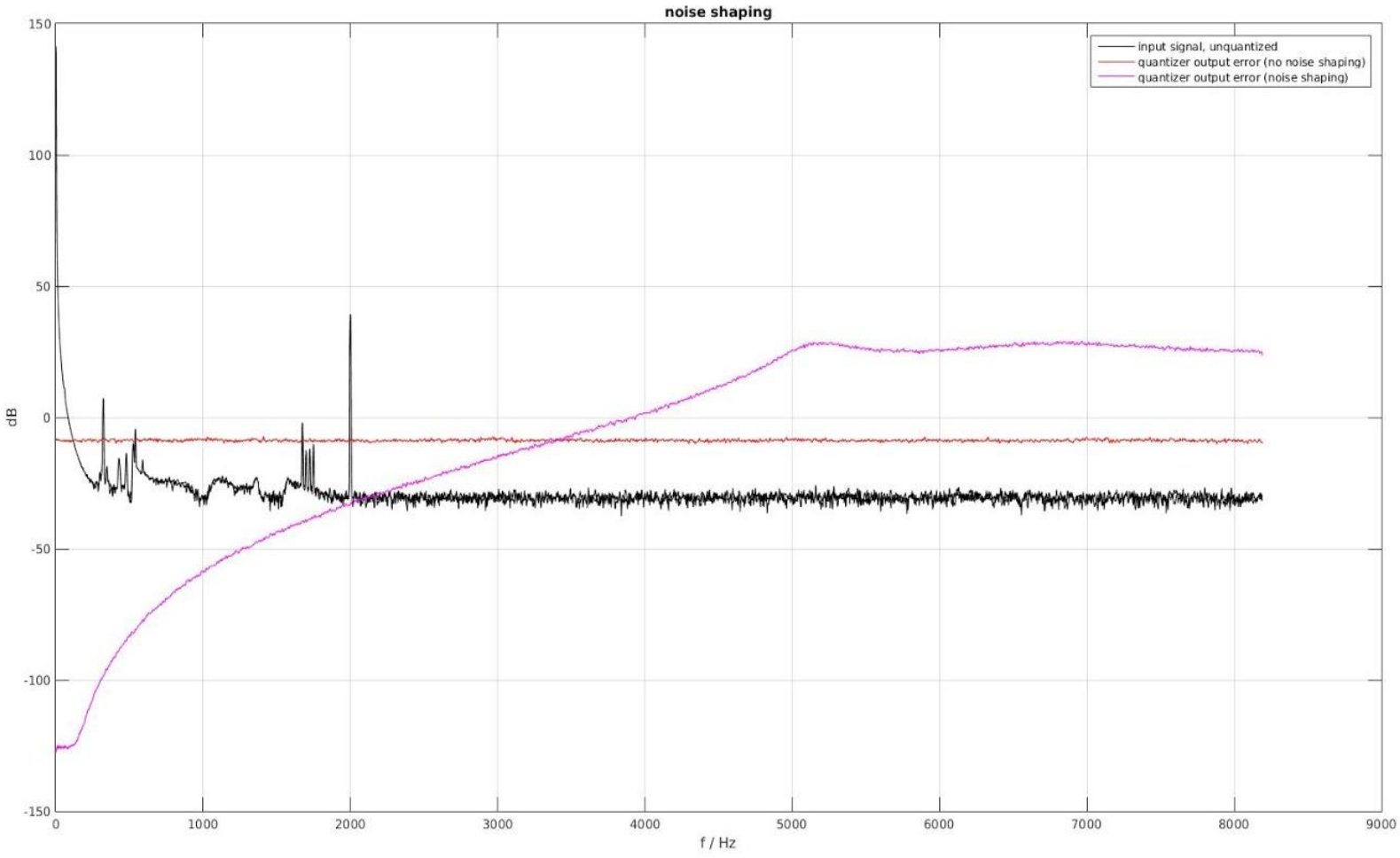

noise shaping
input signal, unquantized
quantizer output error (no noise shaping)
quantizer output error (noise shaping)
dB (30 kHz RBW filter)
f / MHz
×10^7
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0
0.5
1
1.5
2
2.5
3
3.5
4


noise shaping
input signal, unquantized
quantizer output error (no noise shaping)
quantizer output error (noise shaping)
dB
f / Hz
150
100
50
0
-50
-100
-150
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

Results and Conclusions

Two Major Conclusions:

- Digital Filter Quantization Noise : Low Noise Form
  - A good filter structure over DF2
  - More than 90% filters: Safe!

- DAC Quantization Noise
  - Noise Shaping is Effective and Useful

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Why LIGO?

Radio:EM Waves :: LIGO : Gravitational Waves

- Astrophysics (dependence on EM Waves)
- Telescope / Microscope
- Reflection/Absorption of EM Waves. GW?

More Importantly,

- History of the Universe: The Big Bang?

New…. Unknown …. Revolutionary ….

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Multiple Detectors

Other than the two US detectors at Hanford, Washington and Livingston, Louisiana:

- VIRGO : Pisa, Italy
- GEO 600: Germany
- KAGRA : Japan

and what about LIGO & India?

Why Multiple Detectors?

Mentors

- Christopher Wipf
  Postdoc, LIGO, Caltech

- Rana Adhikari
  Professor, Caltech

- Jameson Graef Rollins
  Postdoc, LIGO Caltech

Bibliography

LIGO Observatory Images : www.ligo.org
GW Image: www.space.com
Charges at Rest: www.amasci.com
Interferometer Schematic: www.williamsonlabs.com
Tidal Waves: www.lifeingroup5.com
Mirage: www.whyy.org
Digital Control System Block Diagram: ctms.engin.umich.edu
All other graphs and simulations are from MATLAB & SimuLink 2015
Registered : Academic Version

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Thank You

Q & A

Ayush Pandey