Lecture 3

Digital Control

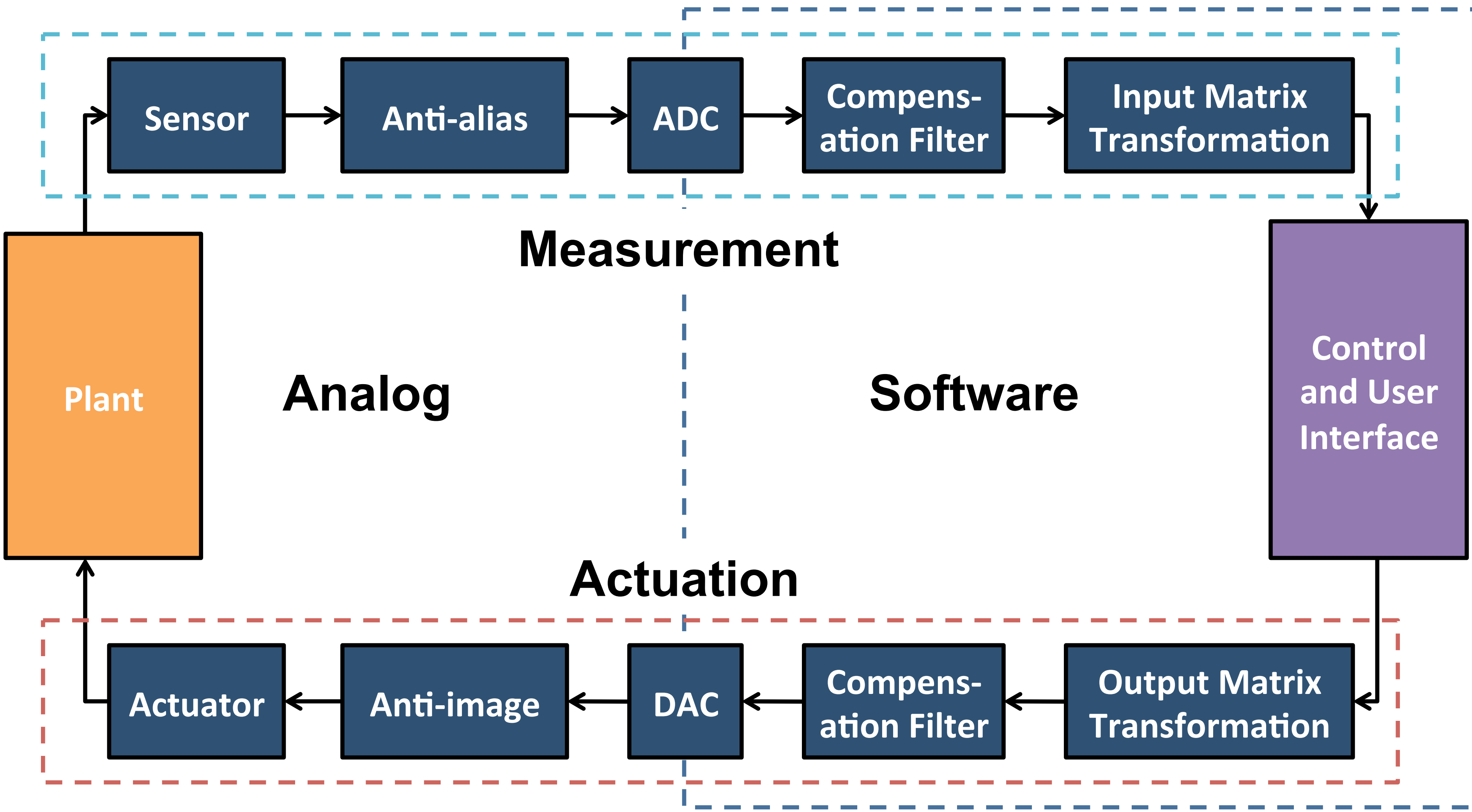
- Part 1: Sampling
- Part 2: User interface
- Part 3: Digital time & frequency domain

Lecture 3

Digital Control

- Part 1: Sampling

Digital Feedback Signal Flow



Sampling Hardware

- ADC – **A**nalog to **D**igital **C**onverter. Samples the data and brings it into the computer.
- Anti-Alias filter – filters noise close to and above the sampling frequency.
- DAC – **D**igital to **A**nalog **C**onverter. Outputs the computer signals.
- Anti-Image filter – filters harmonics close to and above the sampling frequency.

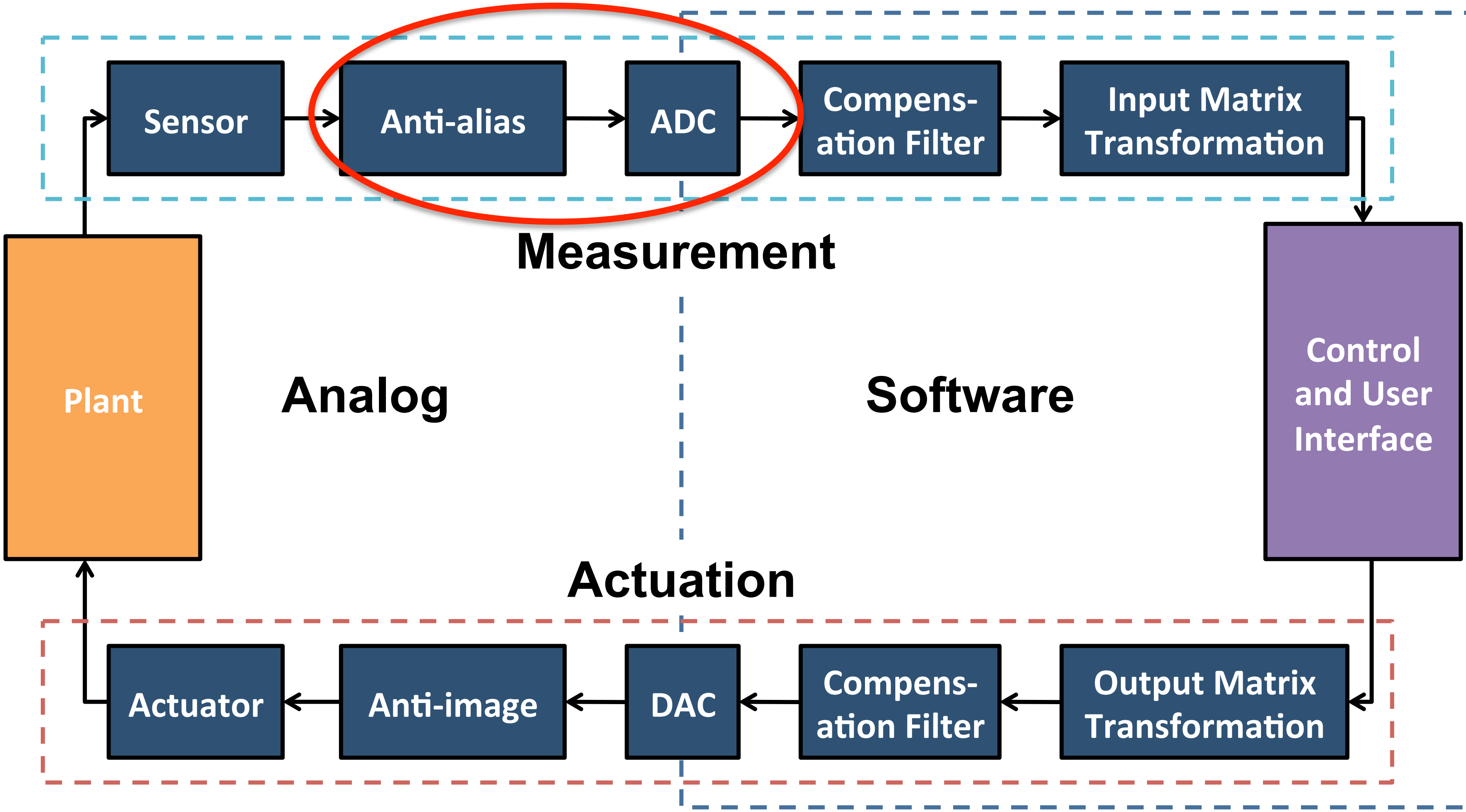
Optional Software Blocks

- **Compensation blocks** – Can also be called 'calibration' blocks. These are optional, and are used to cancel out the analog frequency response of sensors and actuators and/or put them into meaningful units.
- **Matrix transformations** – Also optional. Are used to put sensor and actuator signals into useful coordinate systems. For example, 2 vertical sensors next to each other can be combined to give you a vertical (Z) and a rotation (roll) signal.

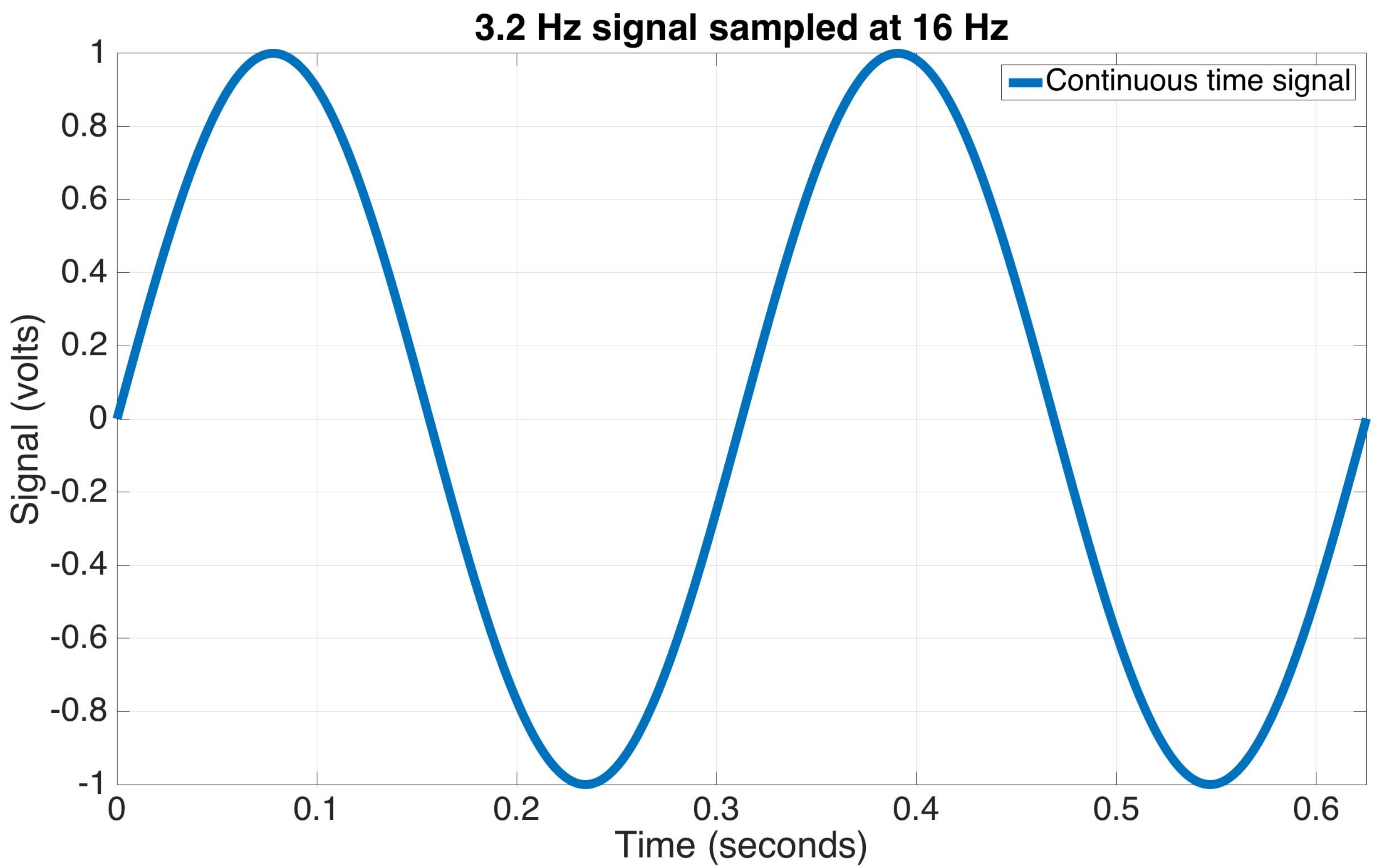
Software Blocks

- **Control and user interface** – Where the control filters and control logic goes. Also, the software that allows the user to interact with the control lives here.

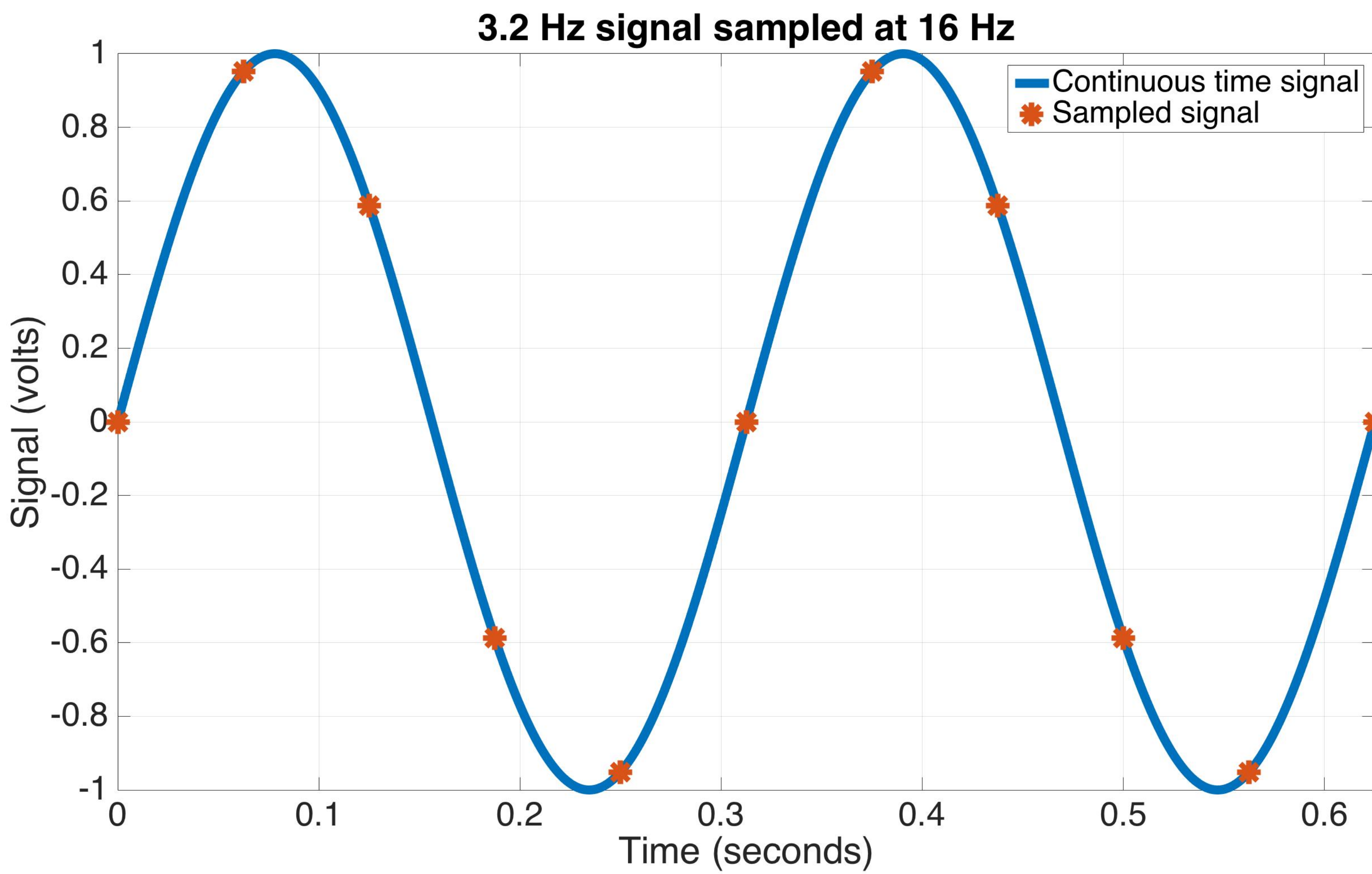
Digital Feedback Signal Flow



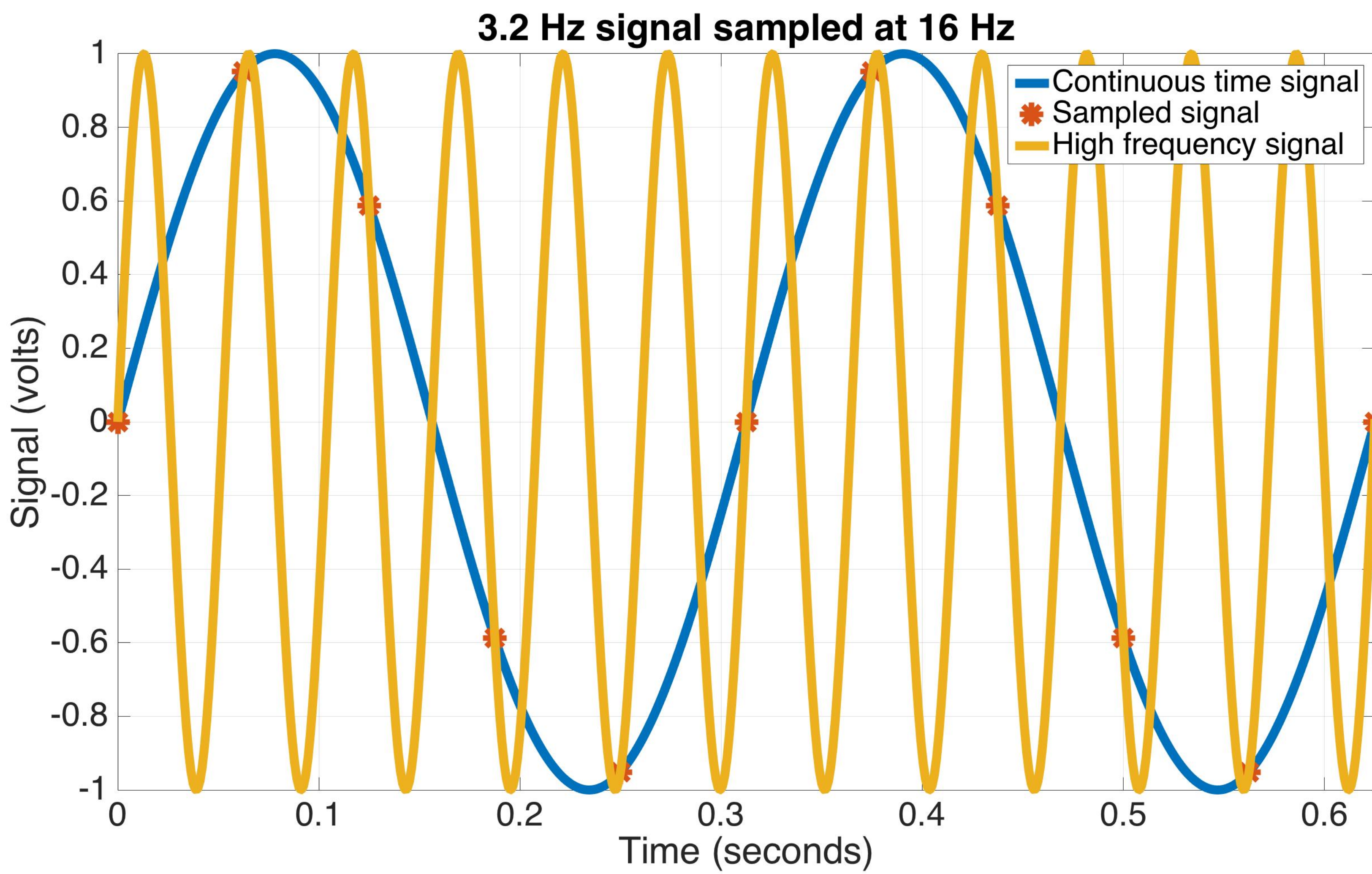
Aliasing – time domain



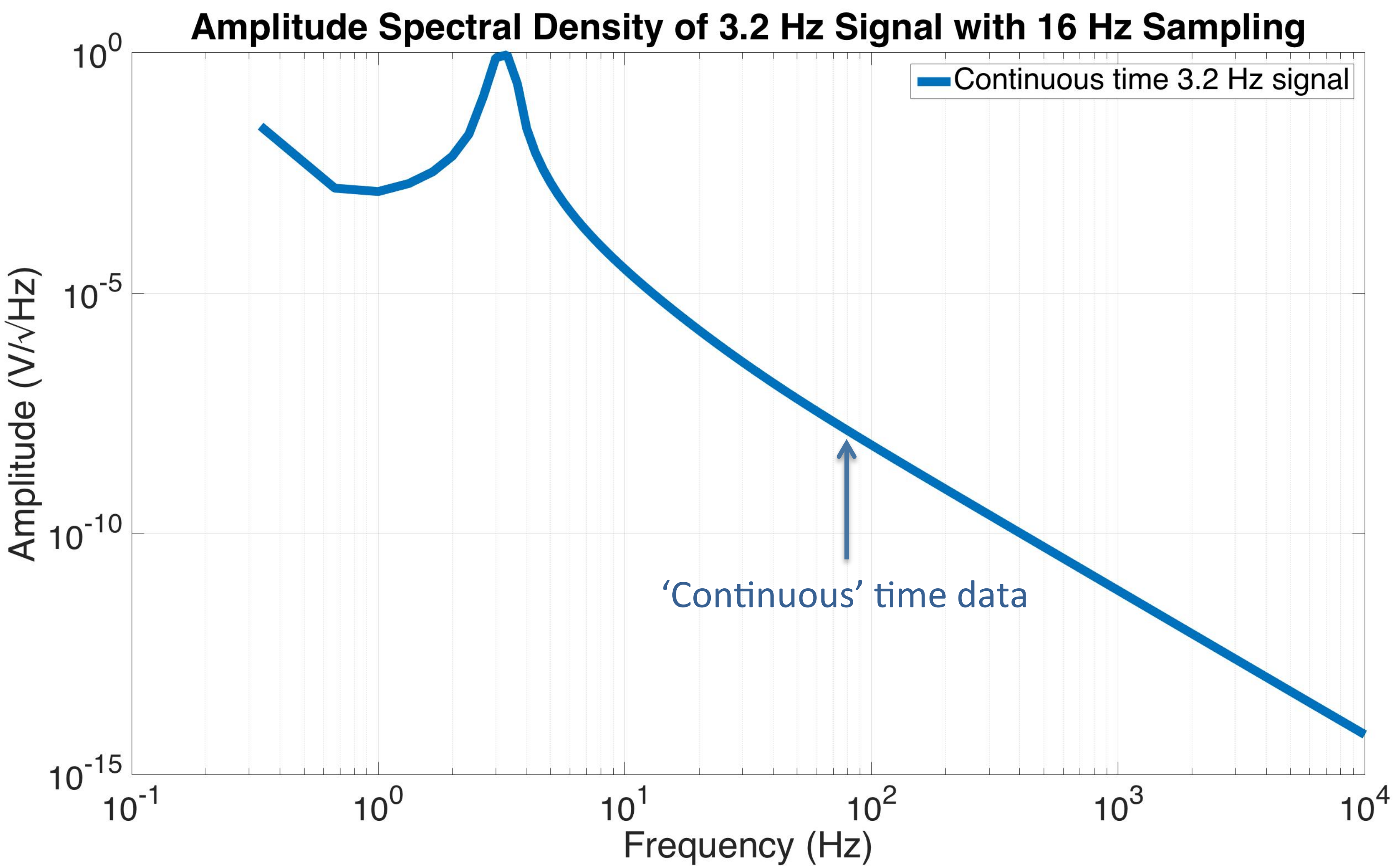
Aliasing – time domain



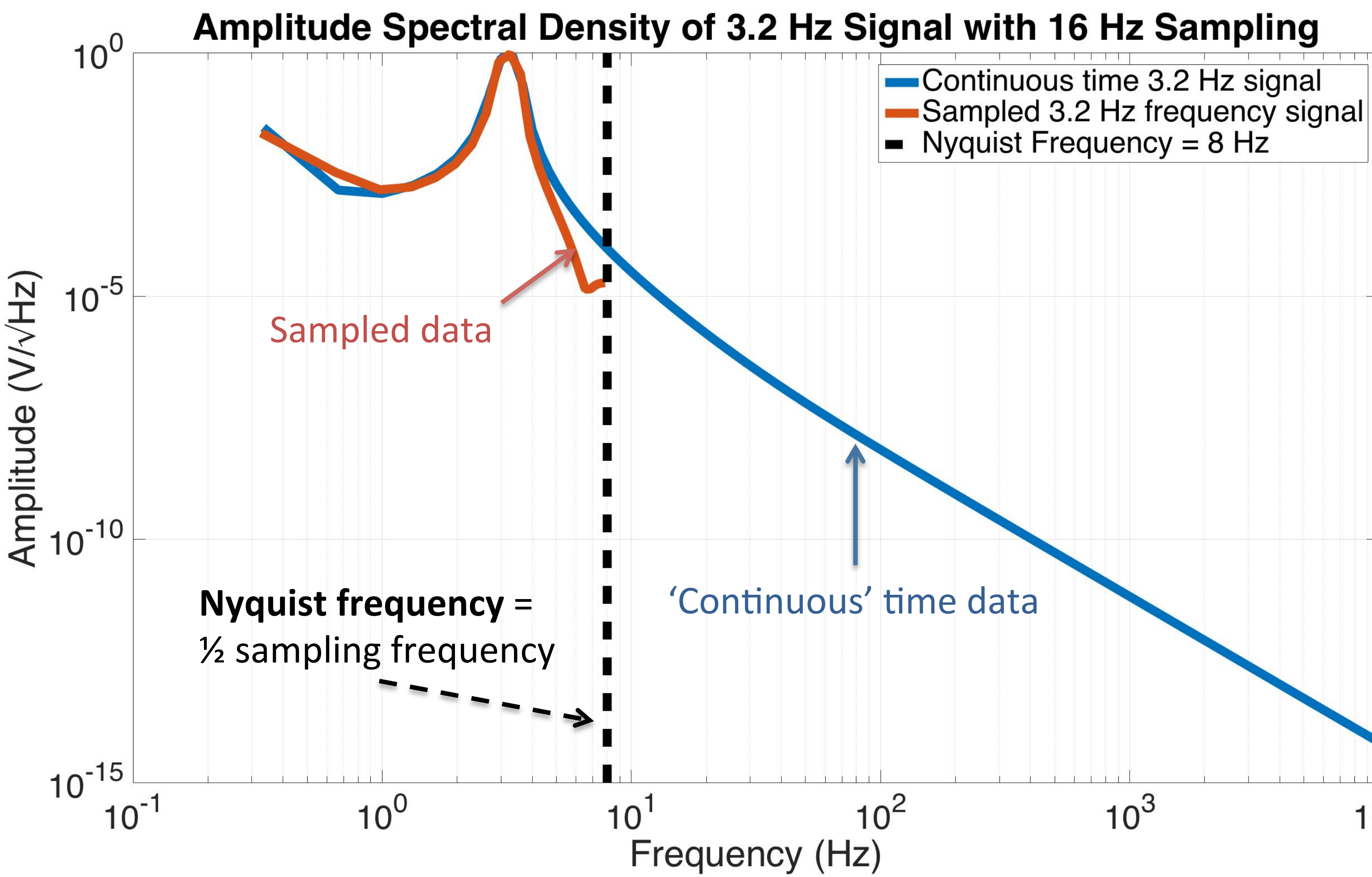
Aliasing – time domain



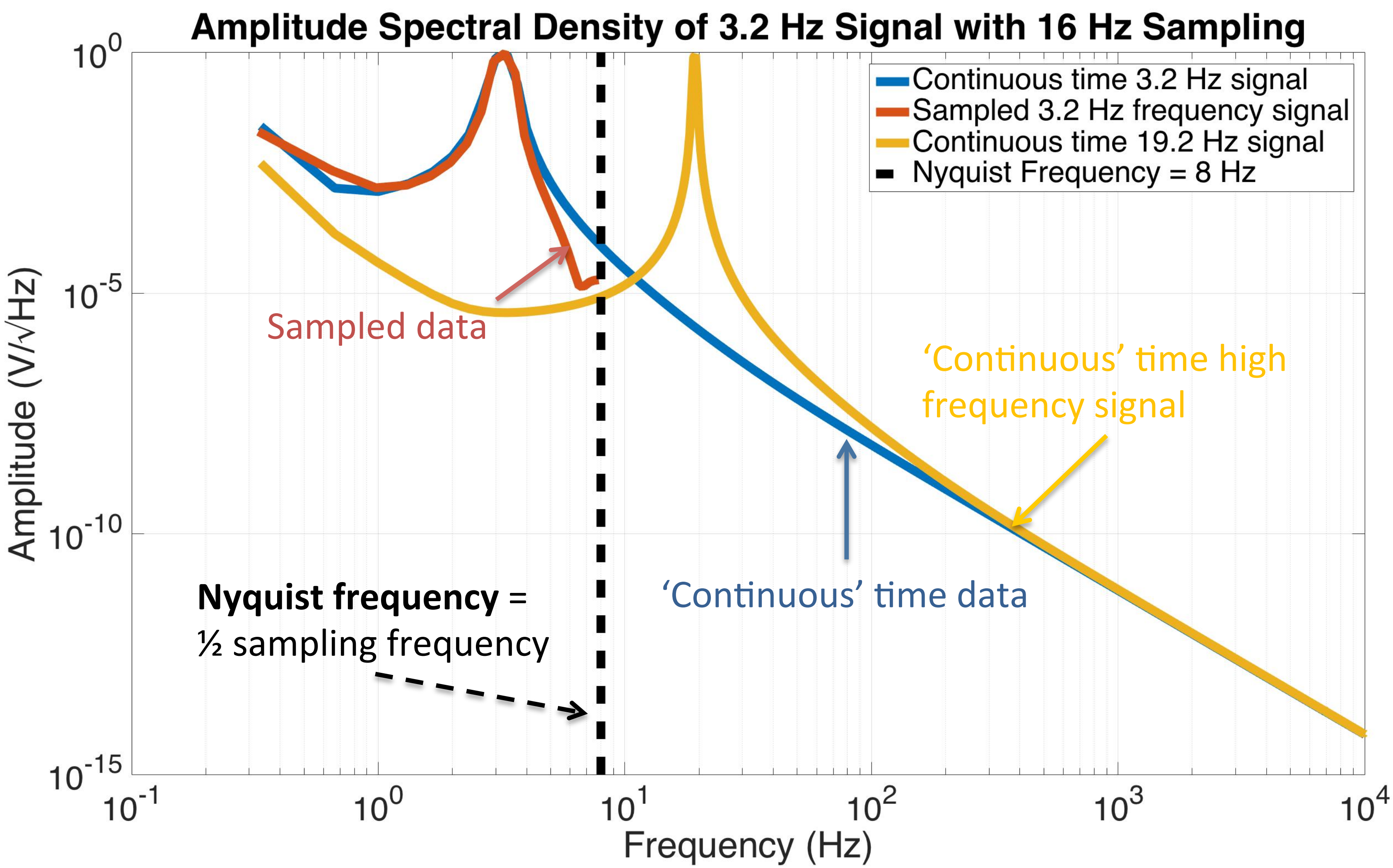
Aliasing – frequency domain



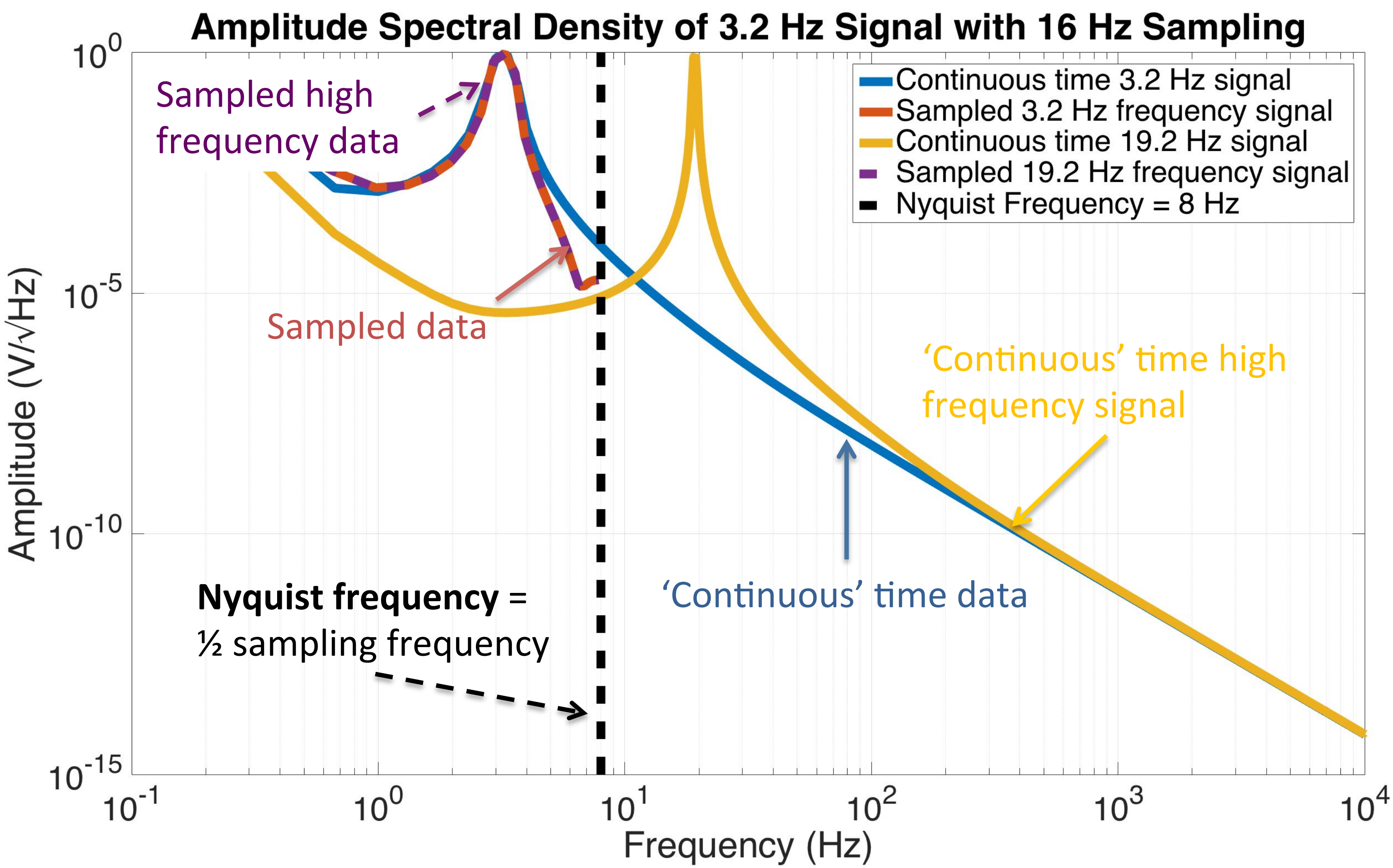
Aliasing – frequency domain



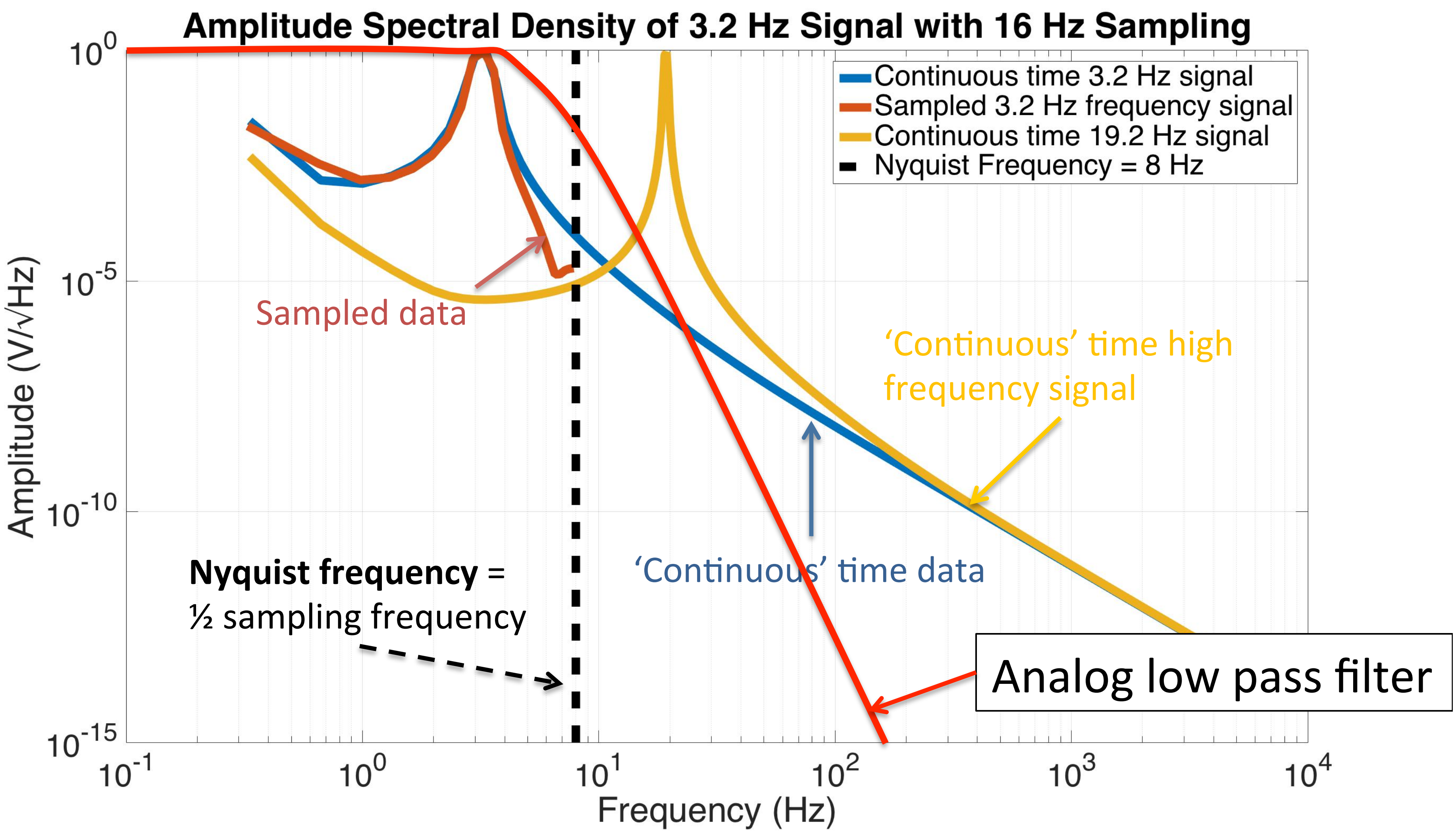
Aliasing – frequency domain



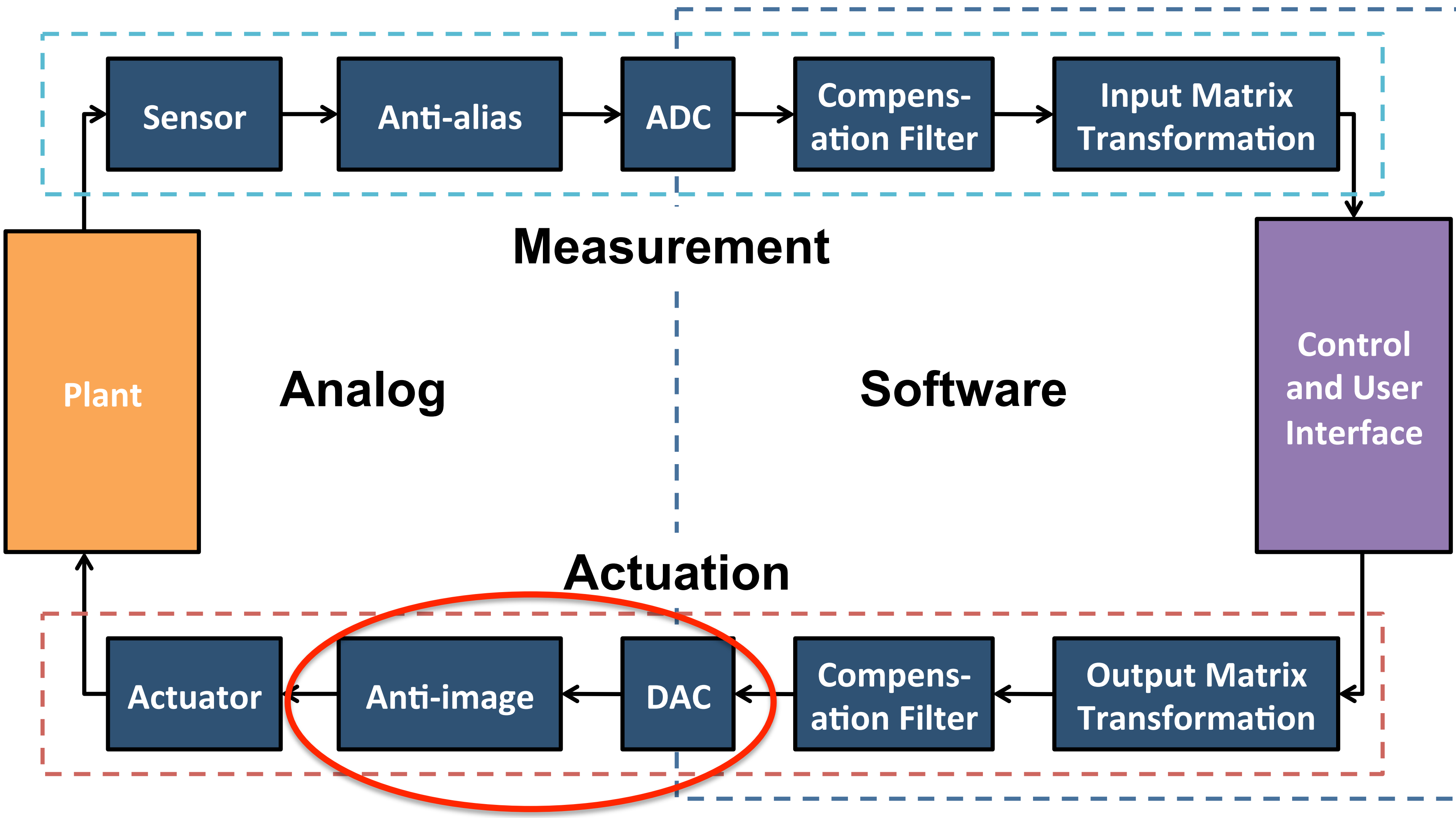
Aliasing – frequency domain



Aliasing – frequency domain

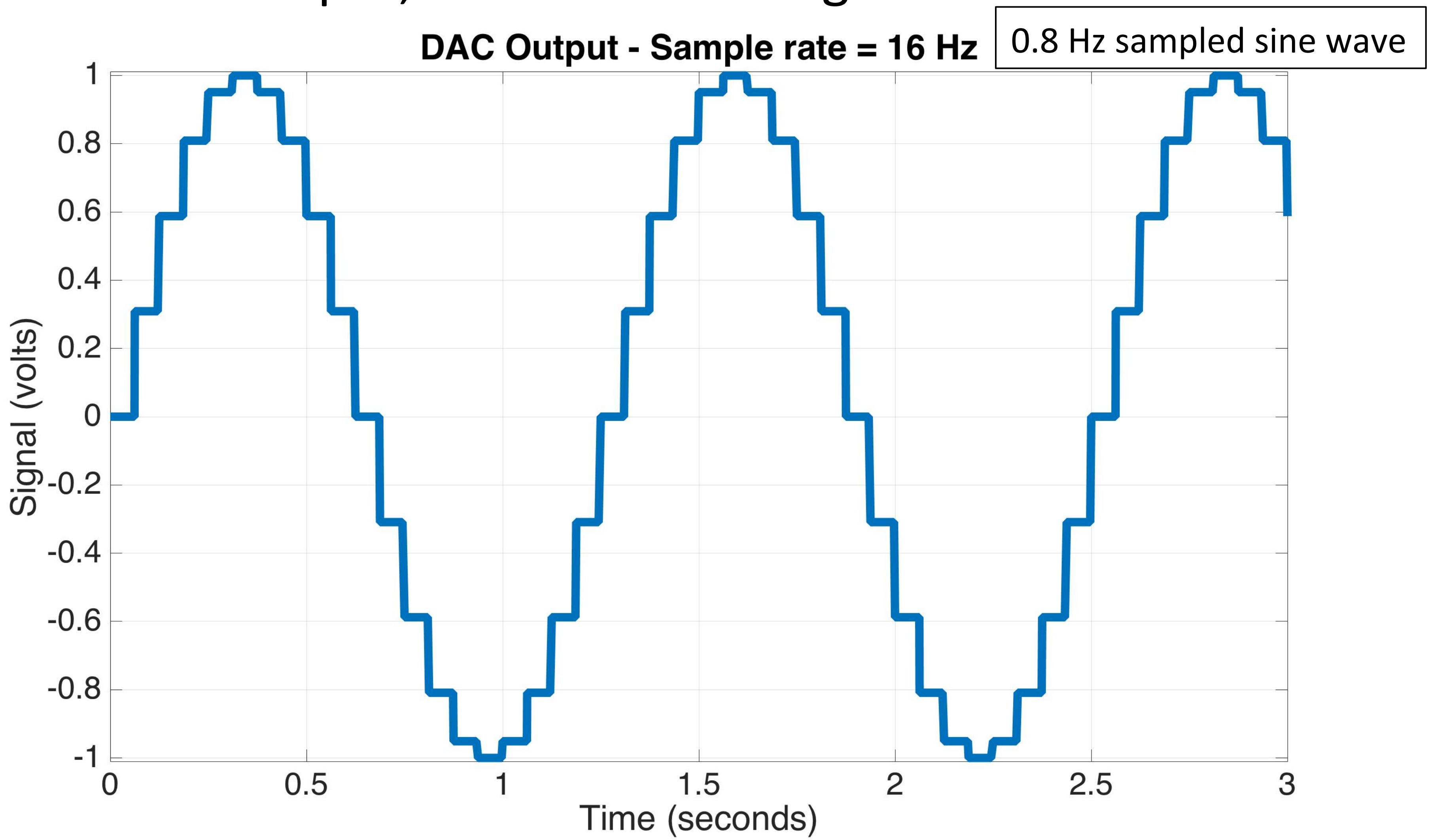


Digital Feedback Signal Flow



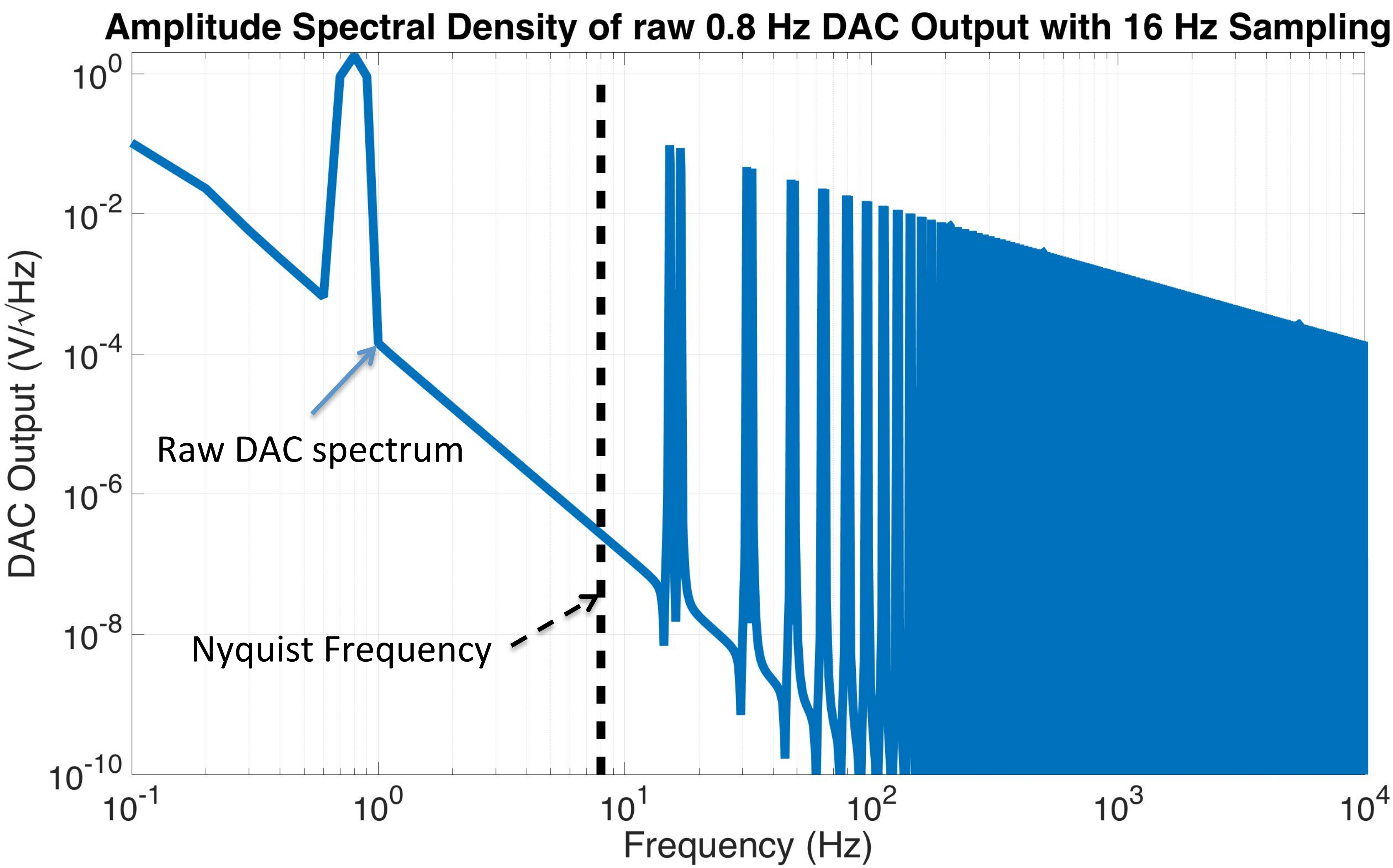
Anti-Image filtering

Raw DAC output, before AI filtering



Anti-Image filtering

Raw DAC output, before AI filtering



Anti-Image filtering

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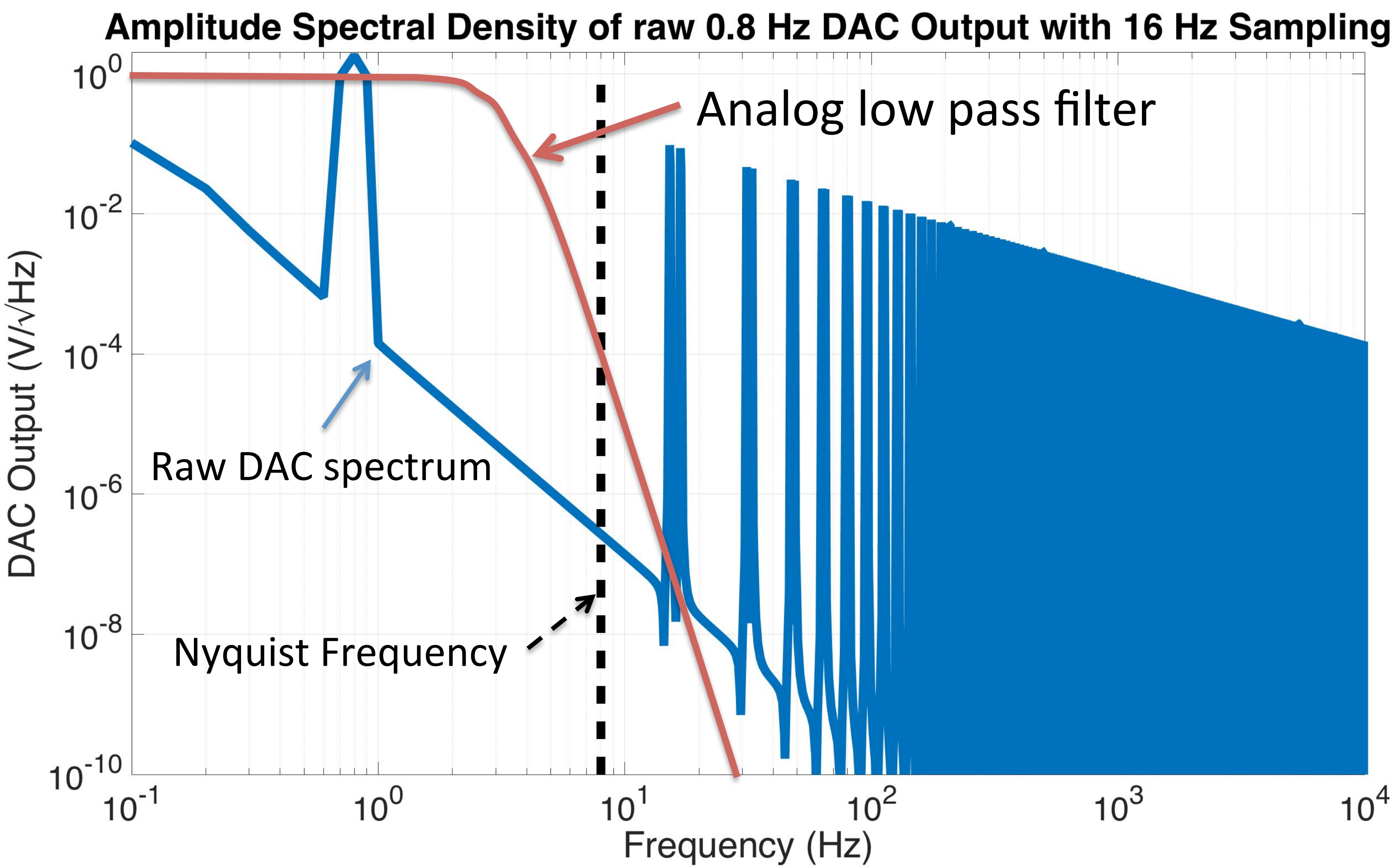
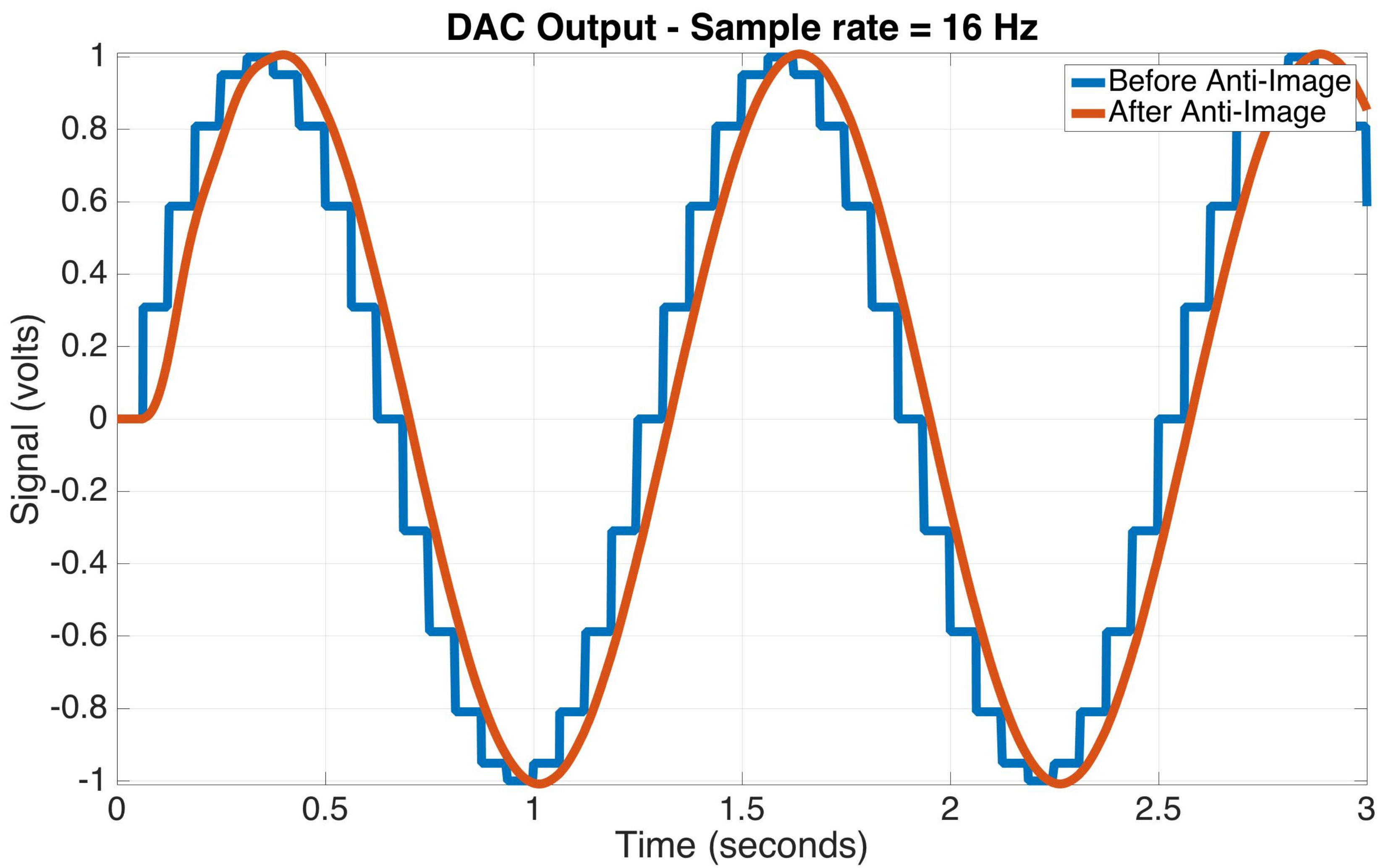
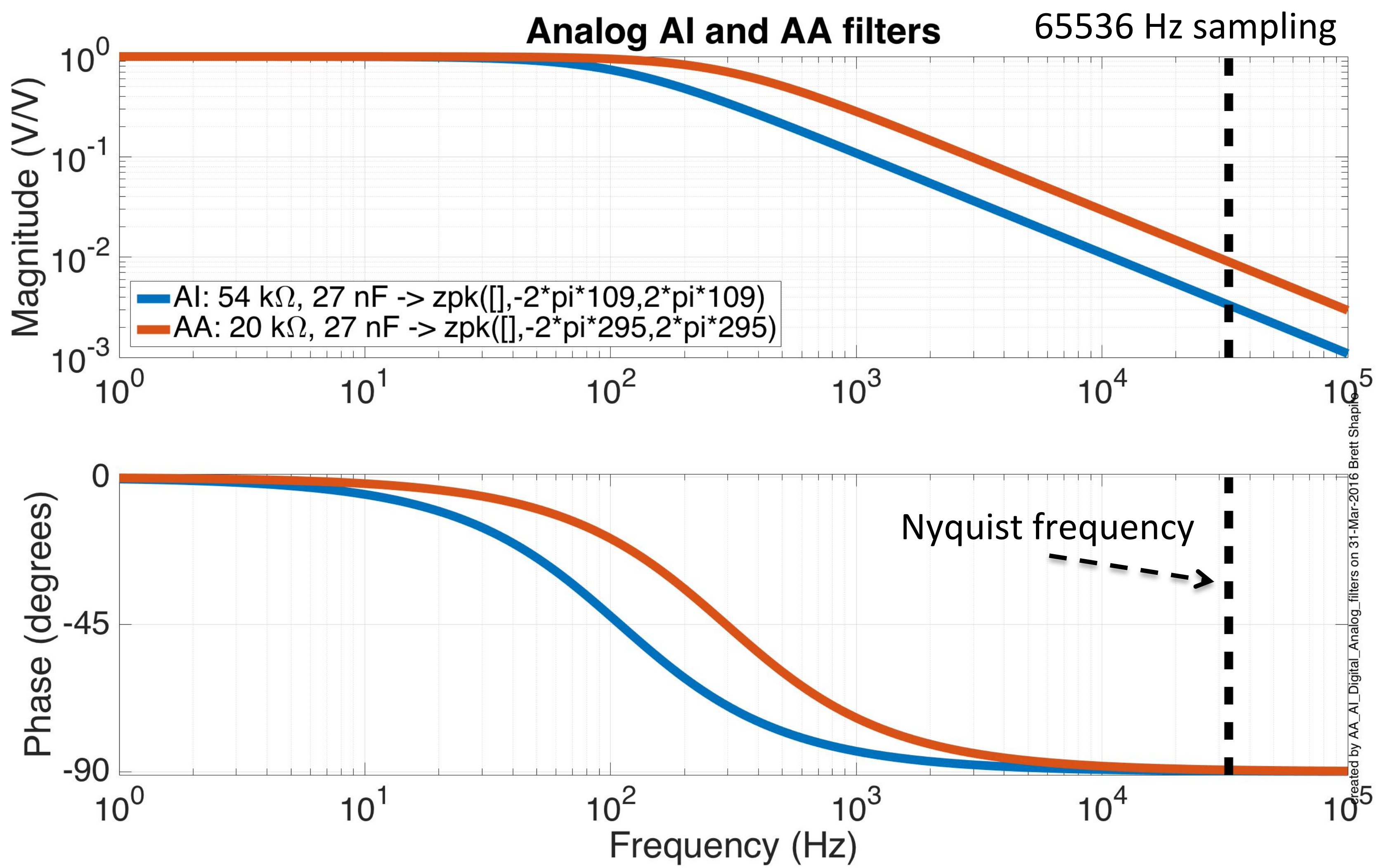


Anti-Image filtering

DAC output, after AI filtering



AA & AI filters from Stanford



Electronics Hardware

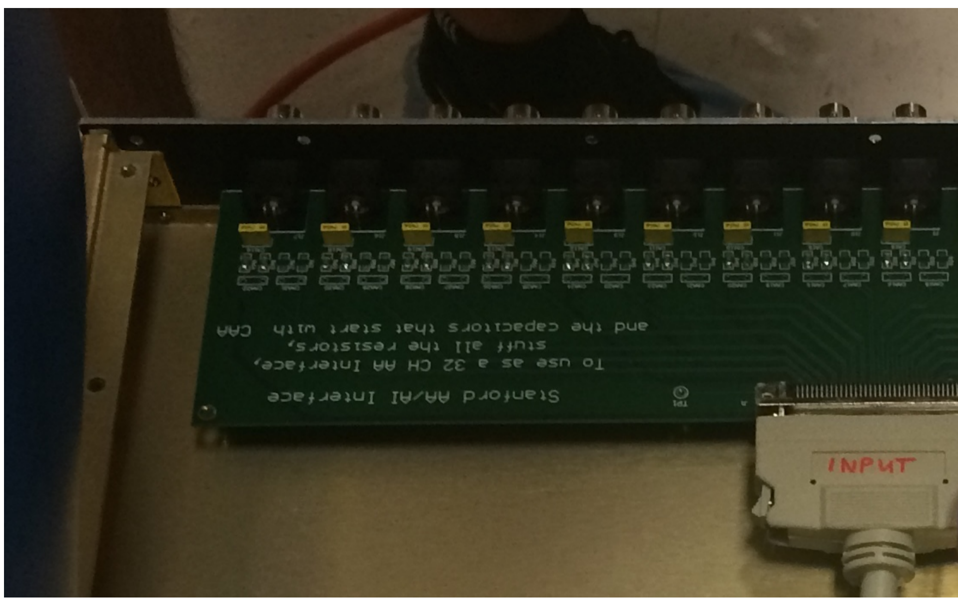
AA and AI boards

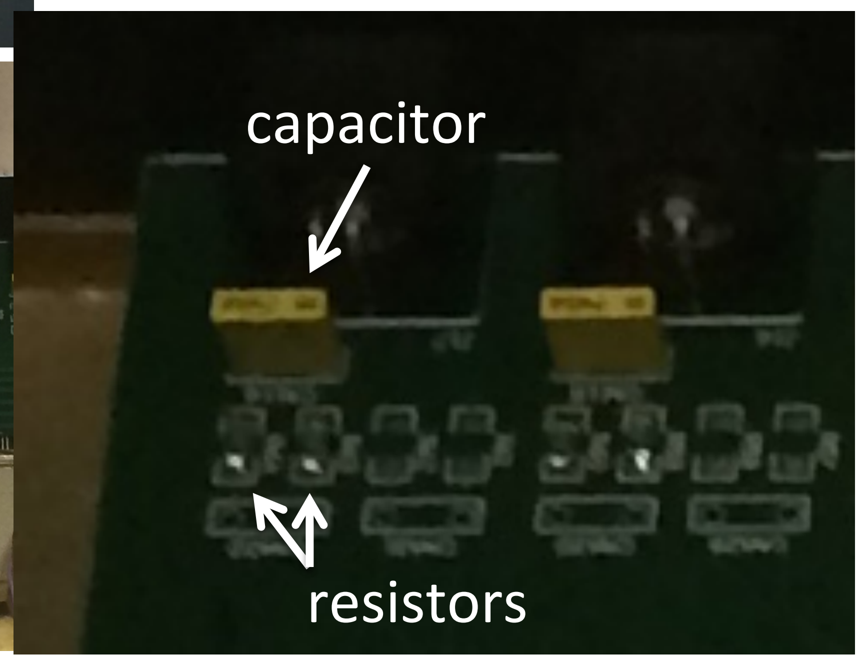
Input/Output (I/O) Chassis

- Has the DACs and ADCs

AA/AI boards

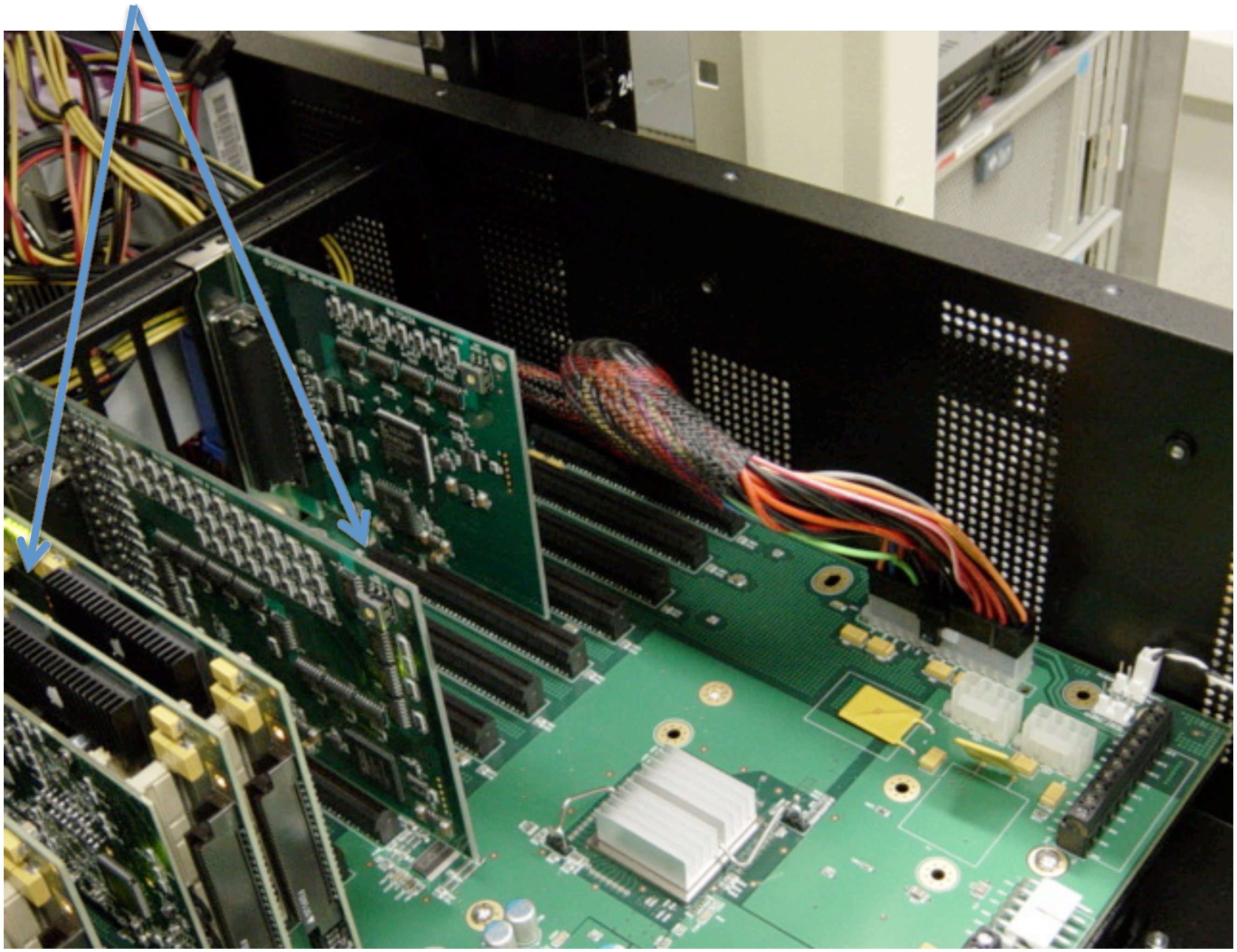
RC circuit:
pole frequency $= \dfrac{1}{2\pi RC}$





I/O Chassis

DAC and ADC cards



From T1000422

Computers

Front-end computer
Runs the real-time control system
Receives signals from ADC
Sends signals to DAC

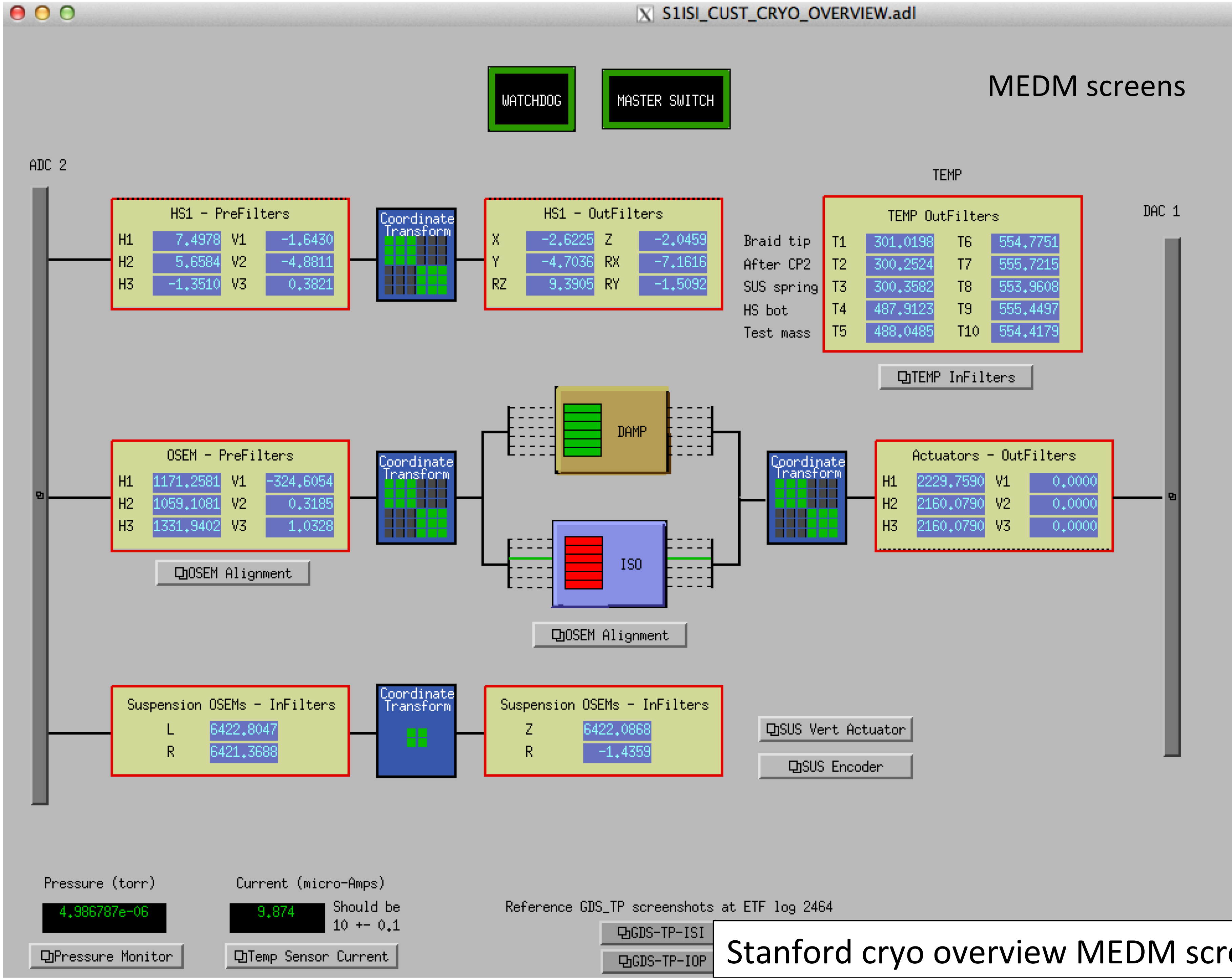
Workstation
Runs the user interface

Lecture 3

Digital Control

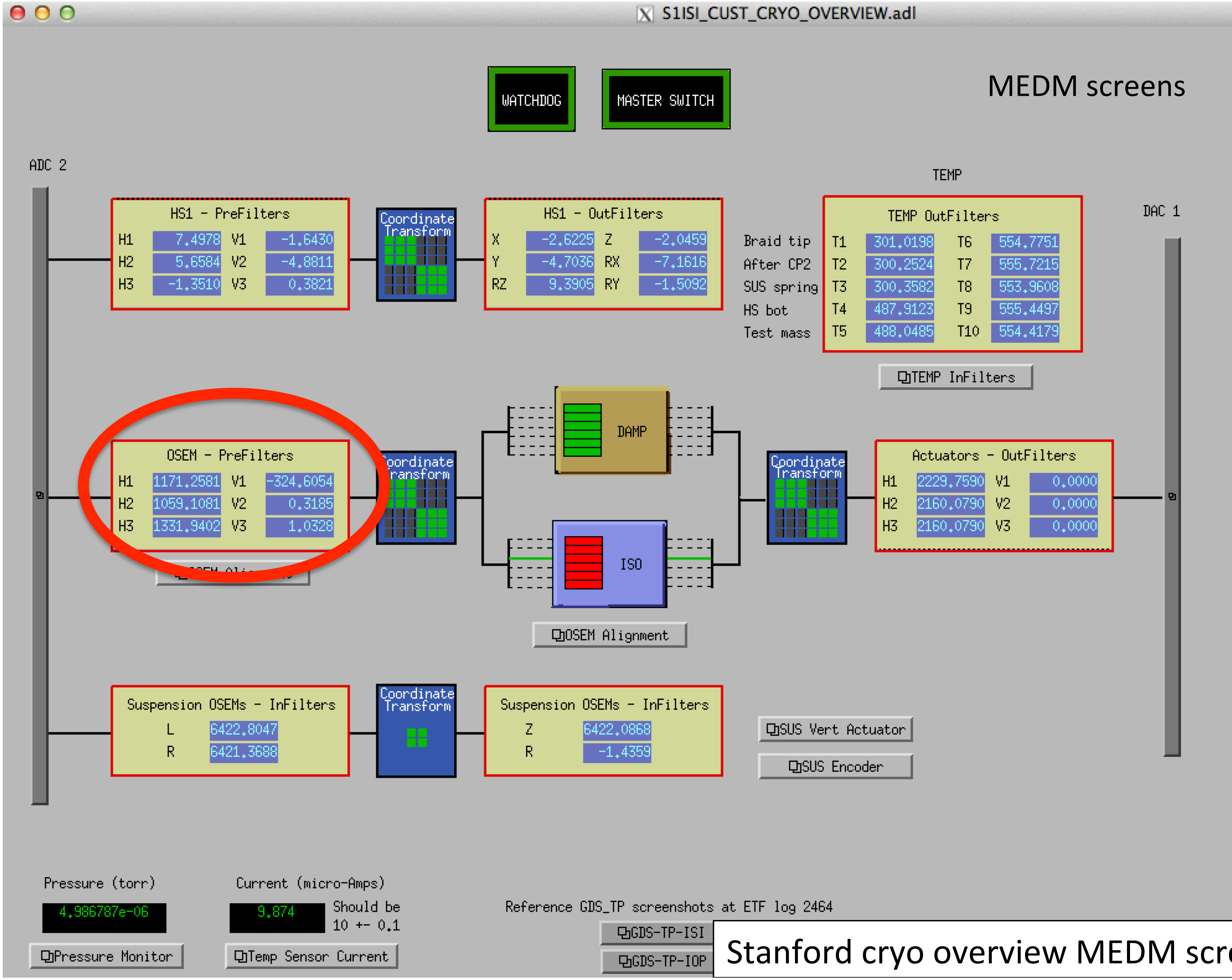
- Part 2: User interface

MEDM screens

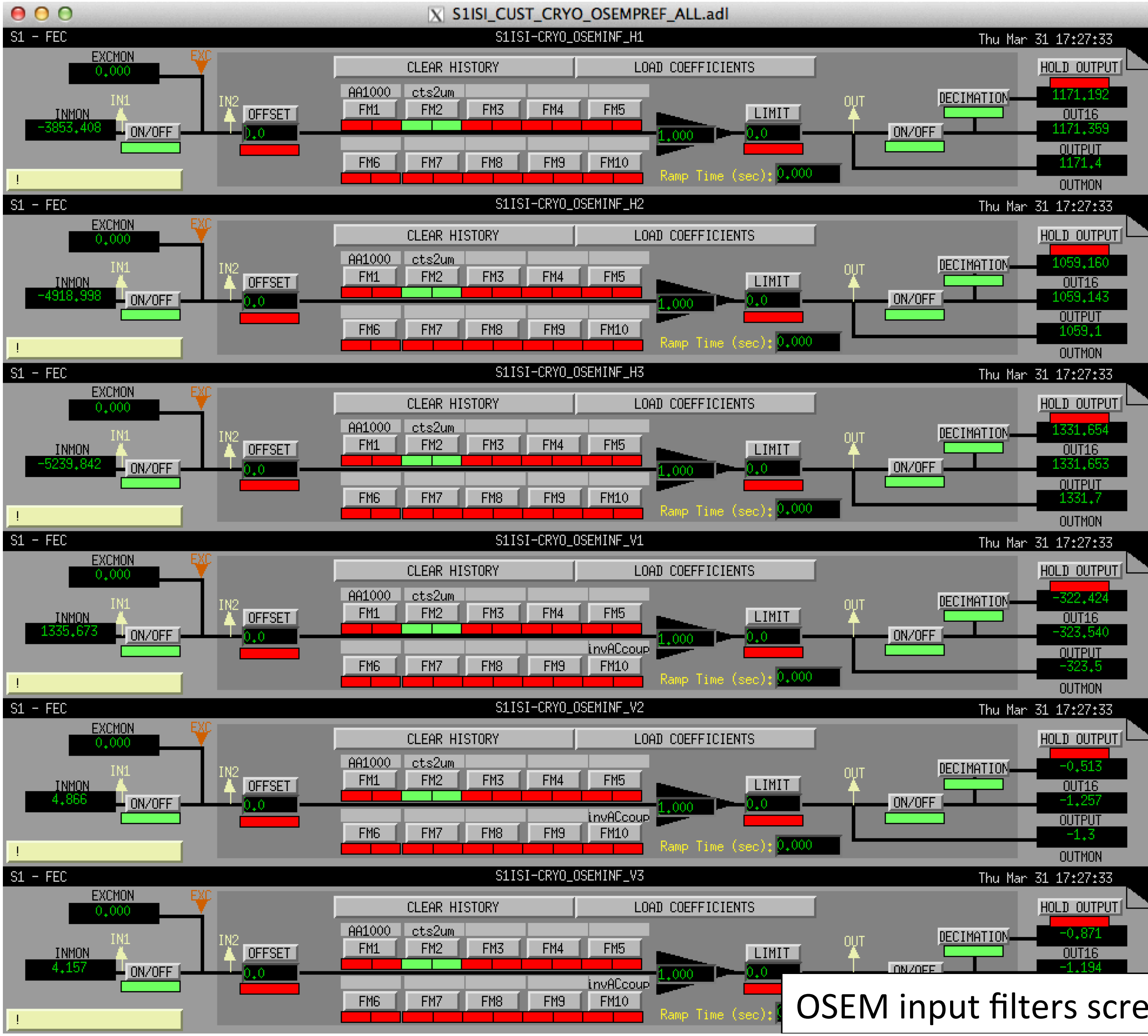


Stanford cryo overview MEDM screen

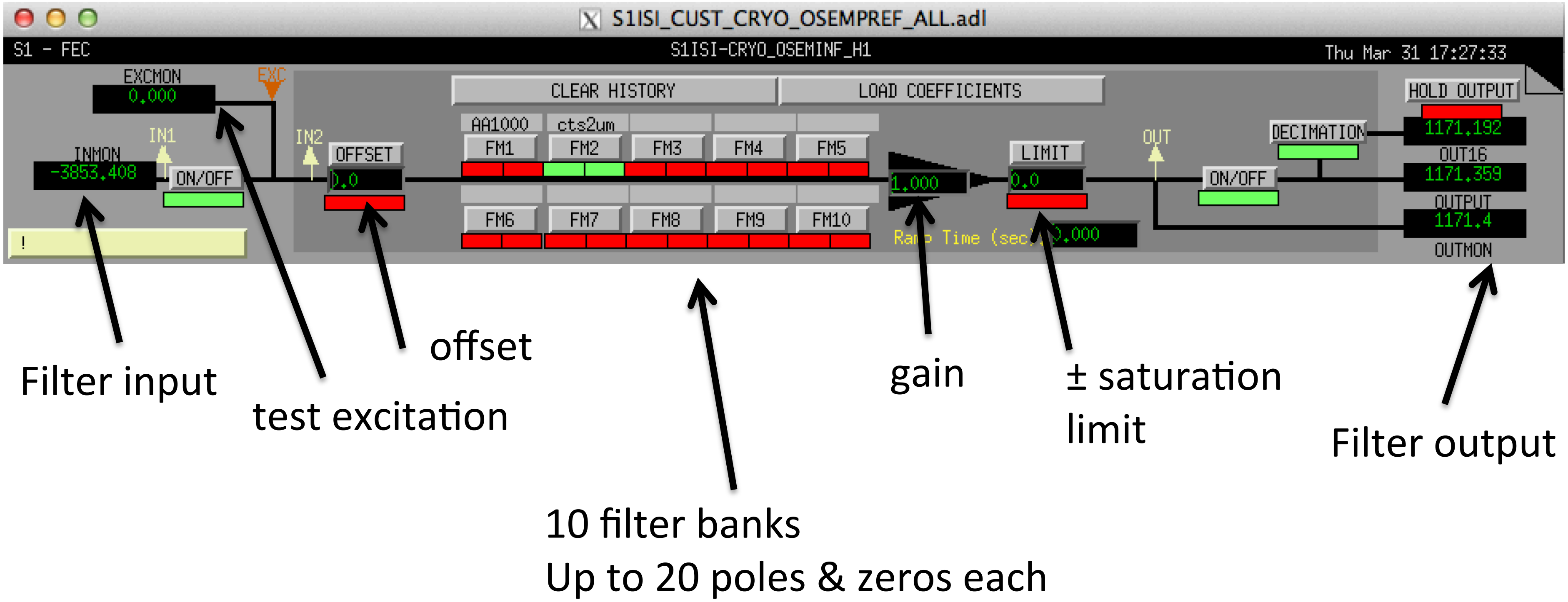
MEDM screens



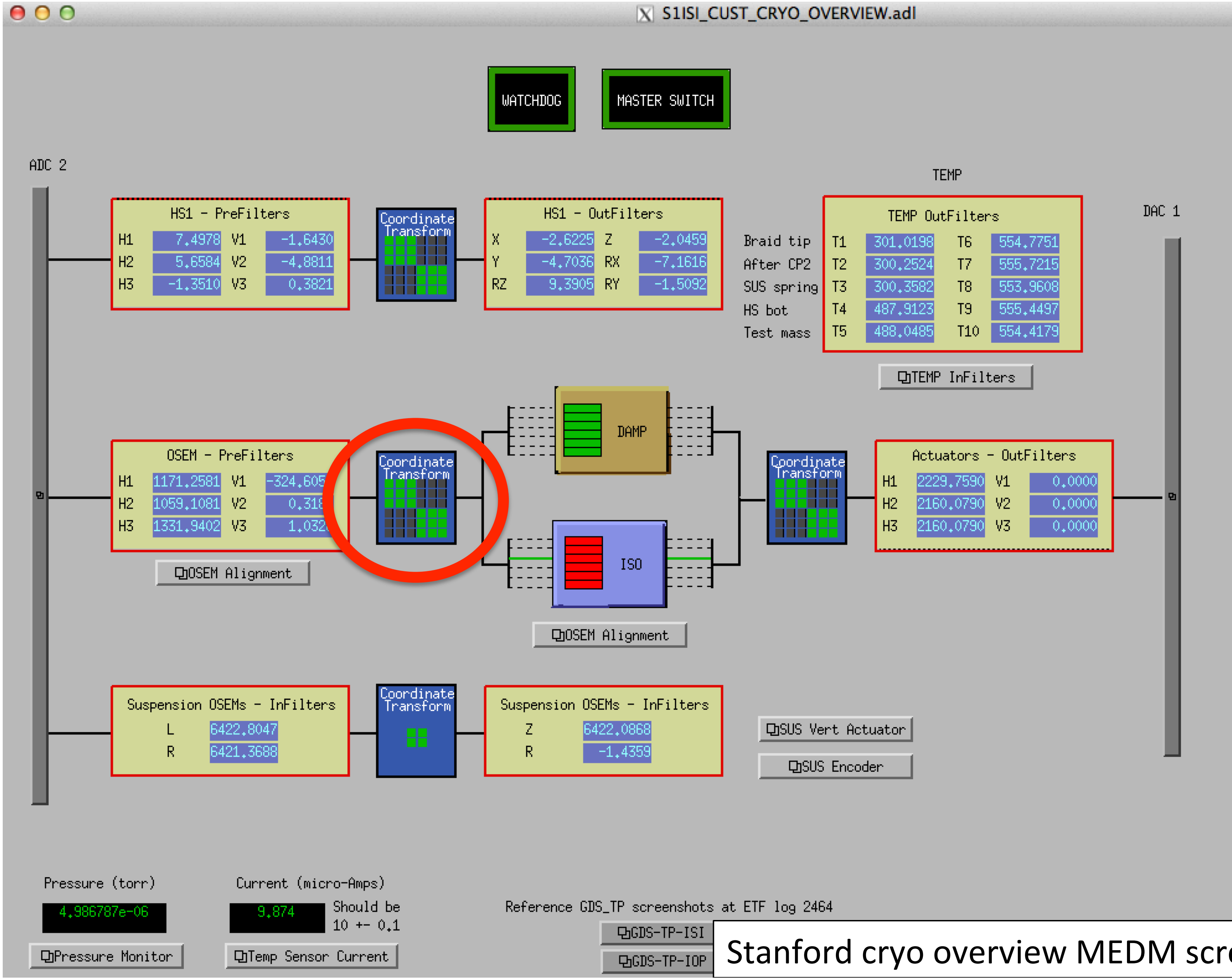
Stanford cryo overview MEDM screen



OSEM input filters screen



Standard filter module



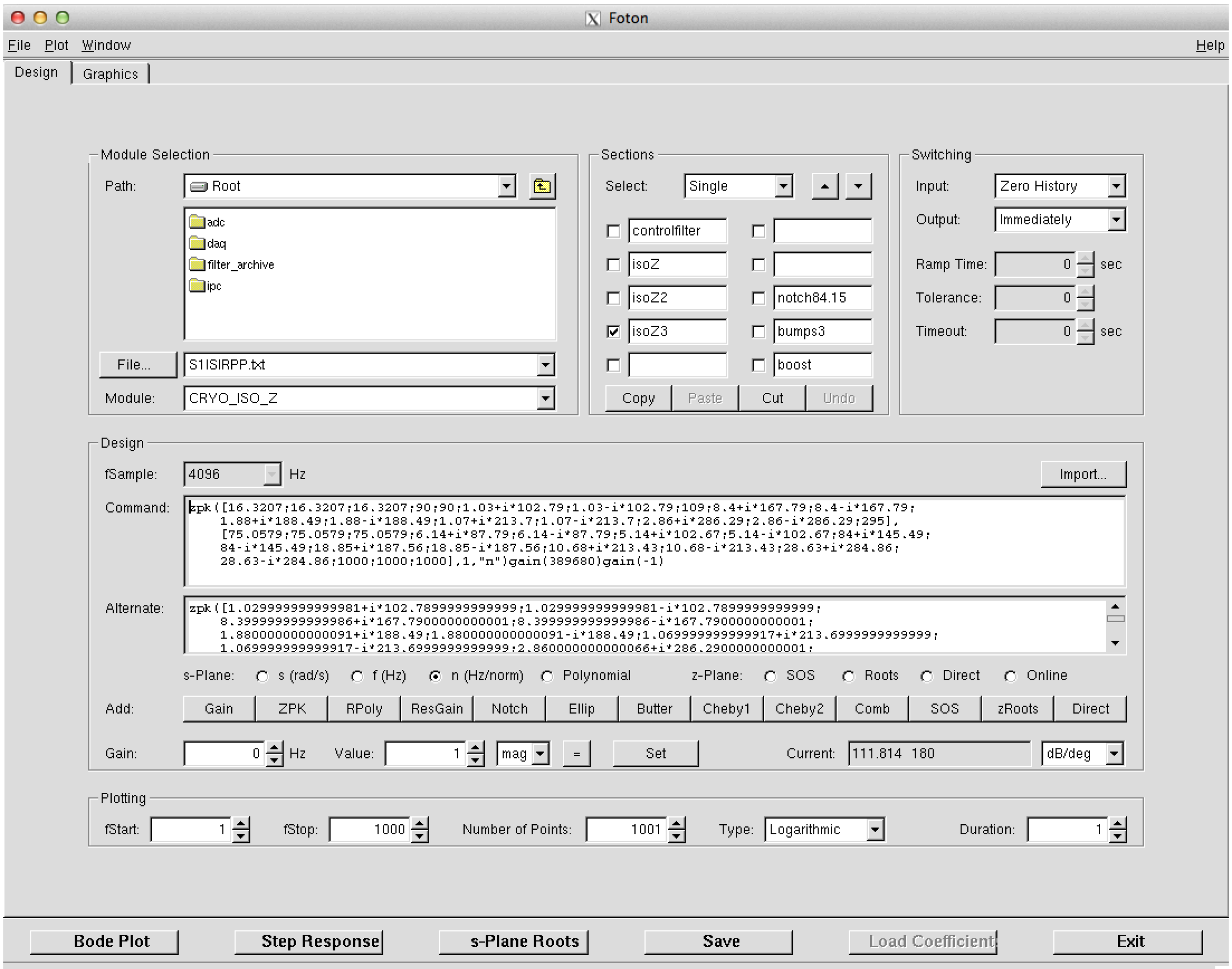
Stanford cryo overview MEDM screen

OSEM Sensor Input Matrix

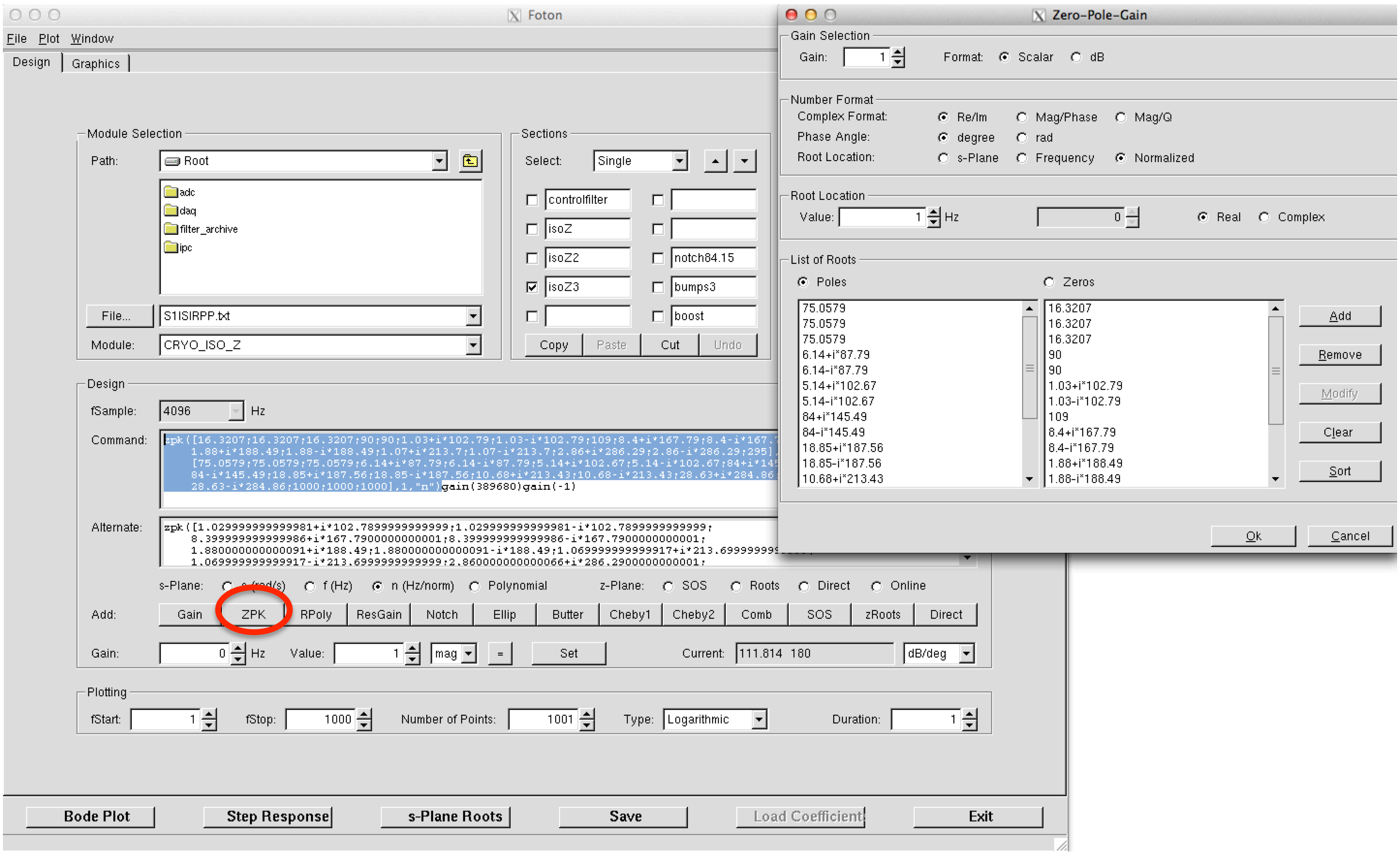

S1ISI_CUST_CRYO_OSEM2CART.adl

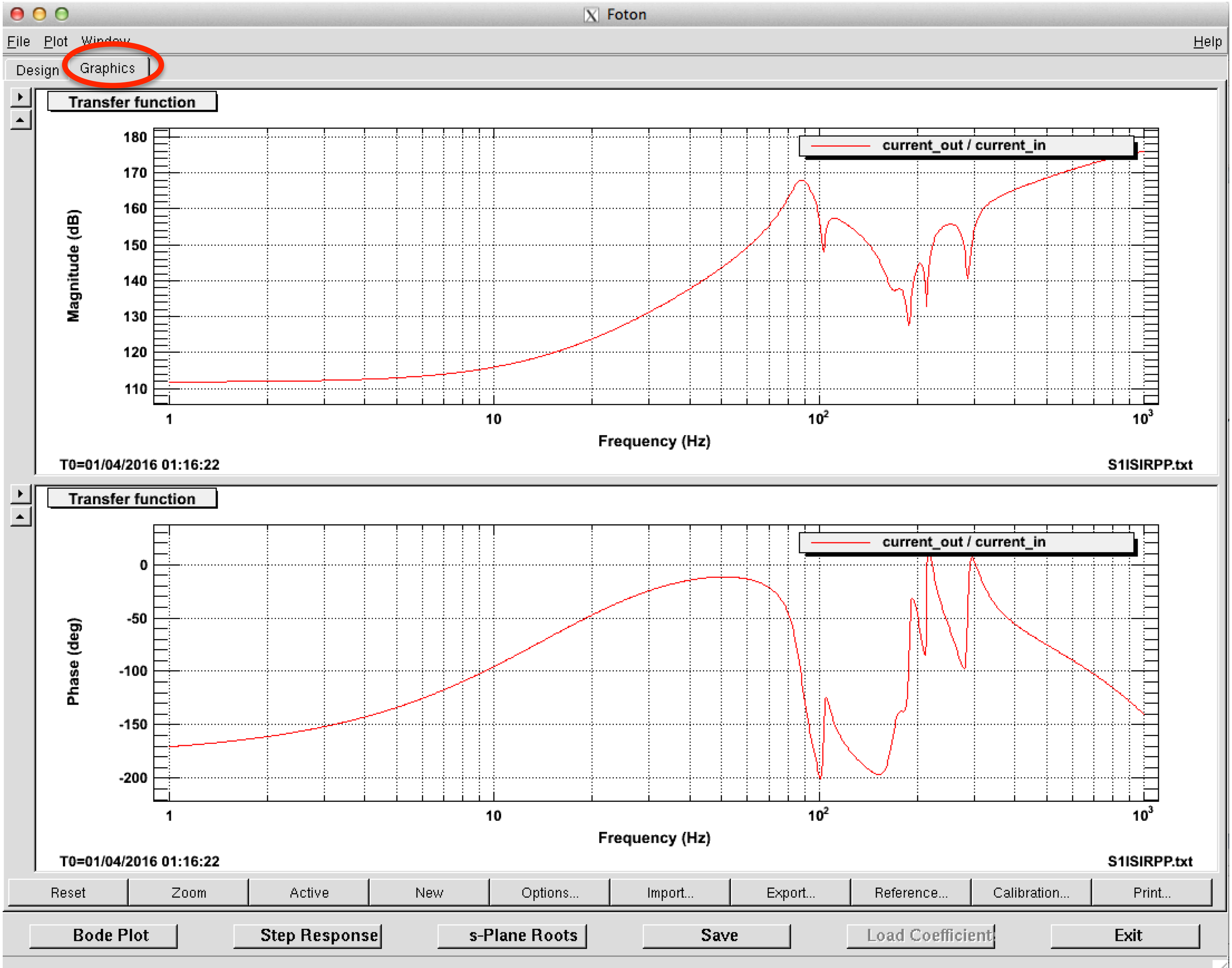
	H1	H2	H3	V1	V2	V3
X	0.22230	-0.6555	0.43320	0.00000	0.00000	0.00000
Y	-0.6285	0.12170	0.50680	0.00000	0.00000	0.00000
RZ	0.64430	0.64430	0.64430	0.00000	0.00000	0.00000
Z	0.00000	0.00000	0.00000	0.33333	0.33333	0.33333
RX	0.00000	0.00000	0.00000	-0.4315	1.27110	-0.8396
RY	0.00000	0.00000	0.00000	1.21860	-0.2356	-0.9830

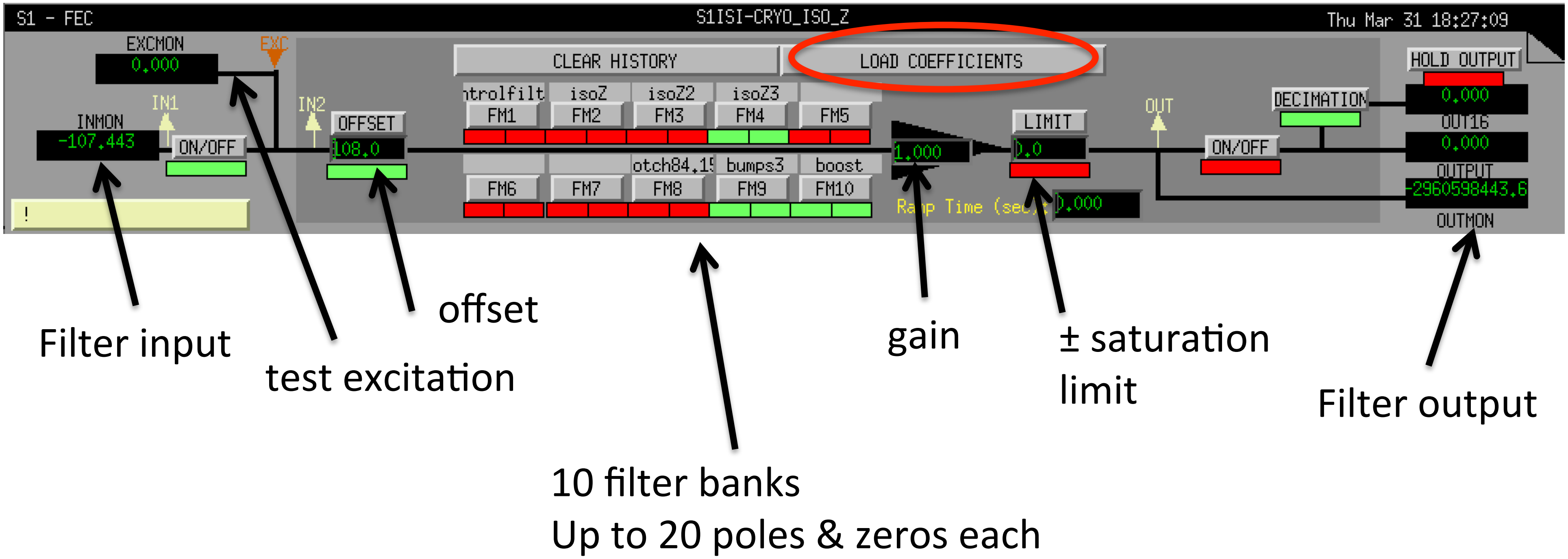
foton – install filters



foton – install filters

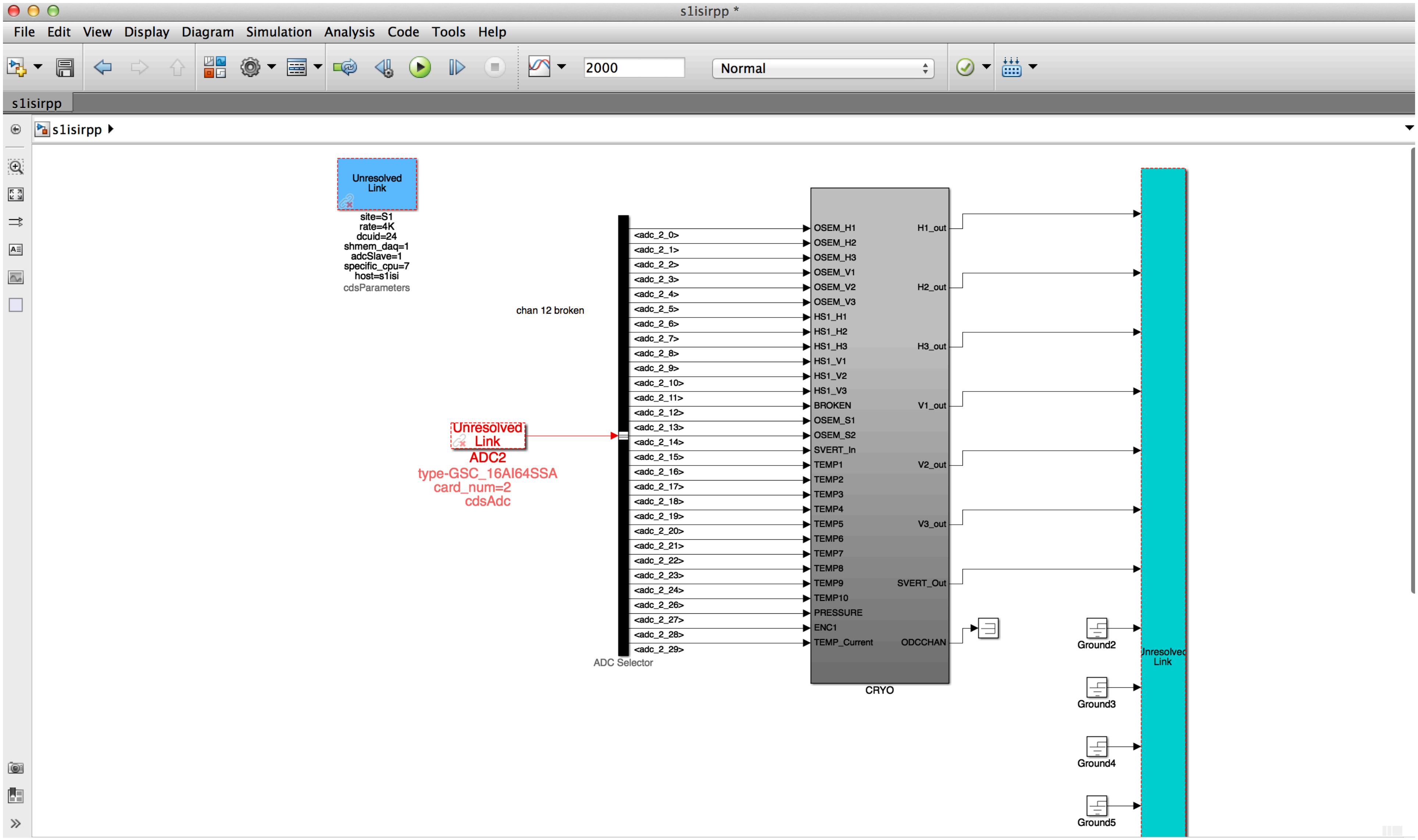



Foton
File
Plot
Window
Help
Design
Graphics
Transfer function
current_out / current_in
Magnitude (dB)
180
170
160
150
140
130
120
110
1
10
10^2
10^3
Frequency (Hz)
T0=01/04/2016 01:16:22
S1ISIRPP.txt
Transfer function
current_out / current_in
Phase (deg)
0
-50
-100
-150
-200
1
10
10^2
10^3
Frequency (Hz)
T0=01/04/2016 01:16:22
S1ISIRPP.txt
Reset
Zoom
Active
New
Options...
Import...
Export...
Reference...
Calibration...
Print...
Bode Plot
Step Response
s-Plane Roots
Save
Load Coefficient
Exit

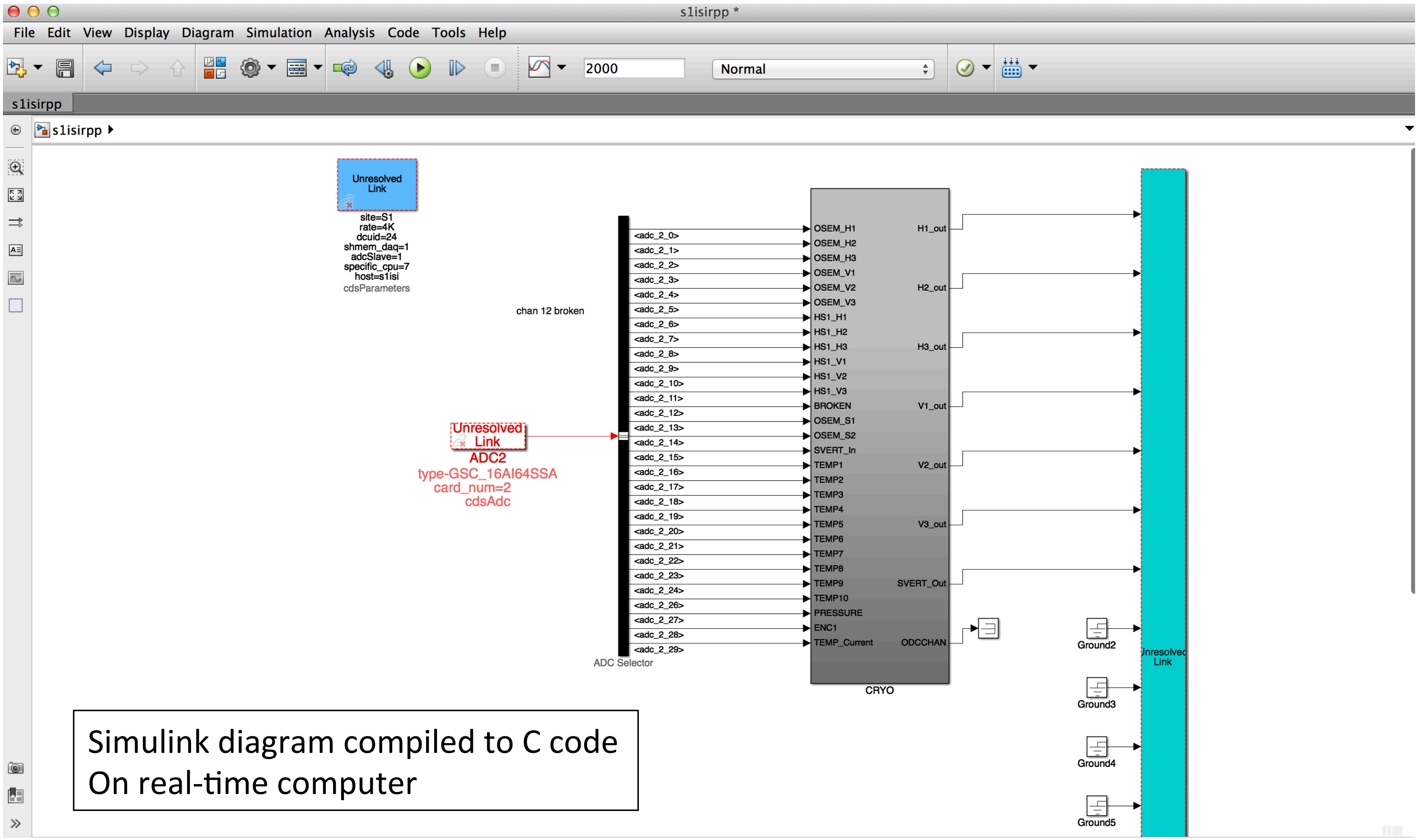


Loading filter banks

Realtime code designed in Matlab Simulink



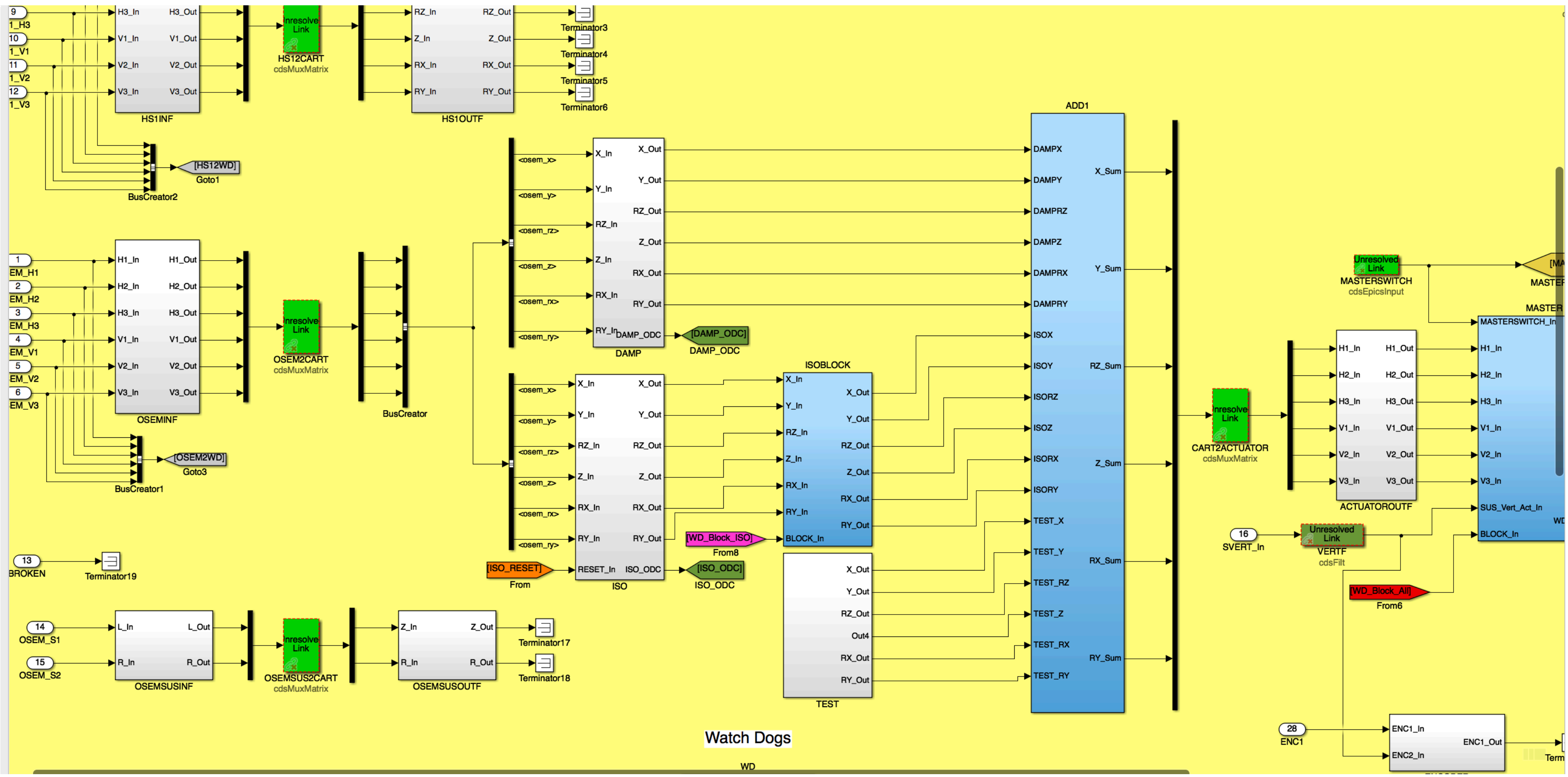
Realtime code designed in Matlab Simulink



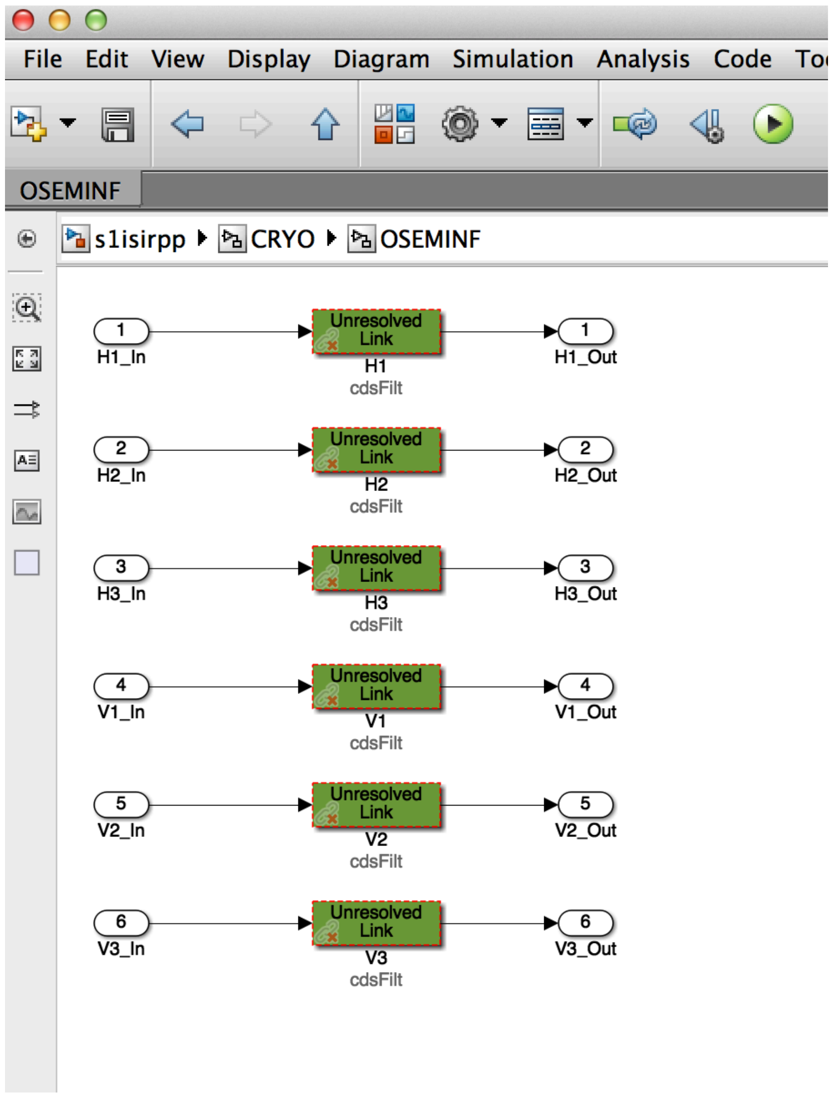
Simulink diagram compiled to C code
On real-time computer

Realtime code designed in Matlab Simulink

CRYO block



Realtime code designed in Matlab Simulink



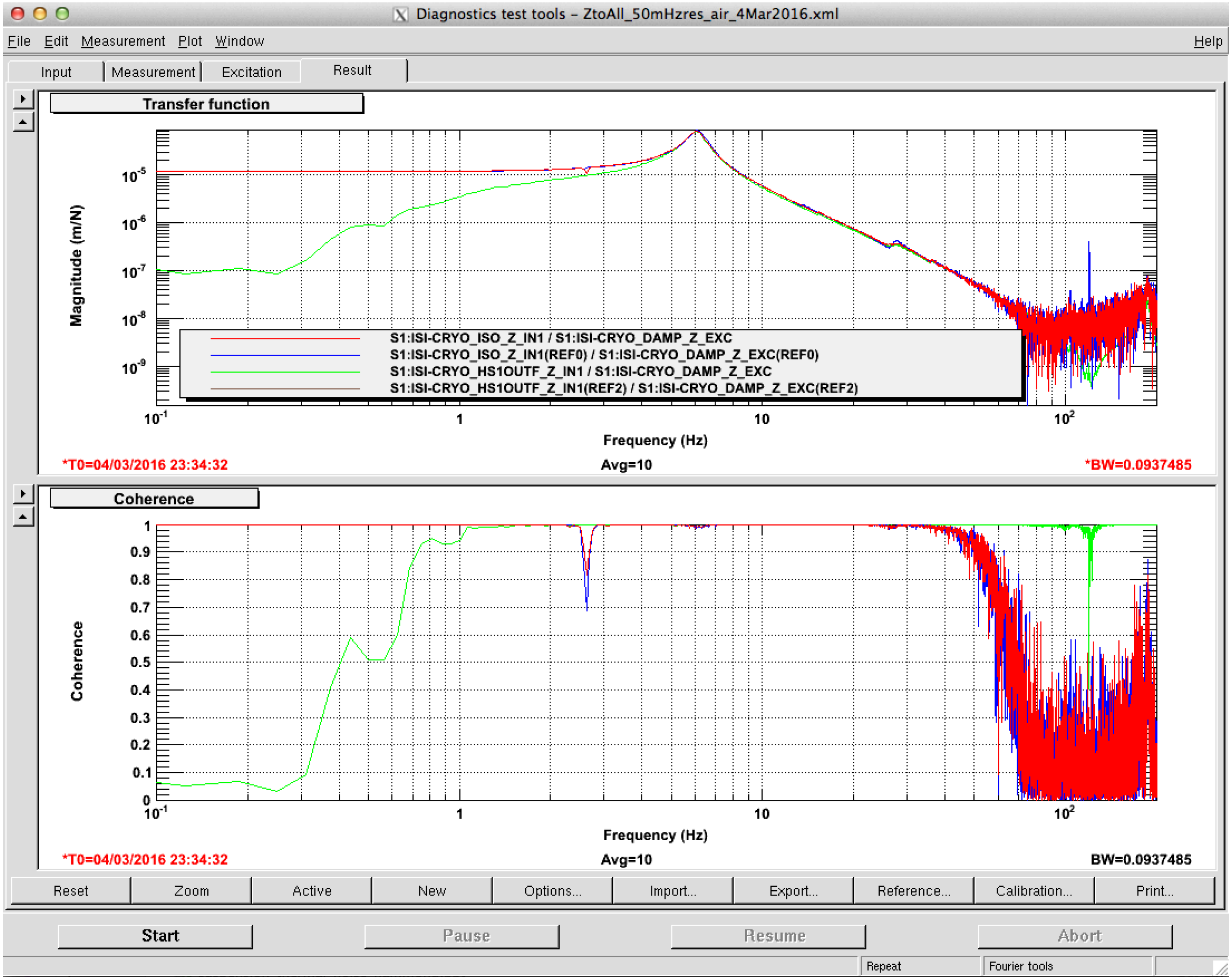
CRYO/OSEMINF block

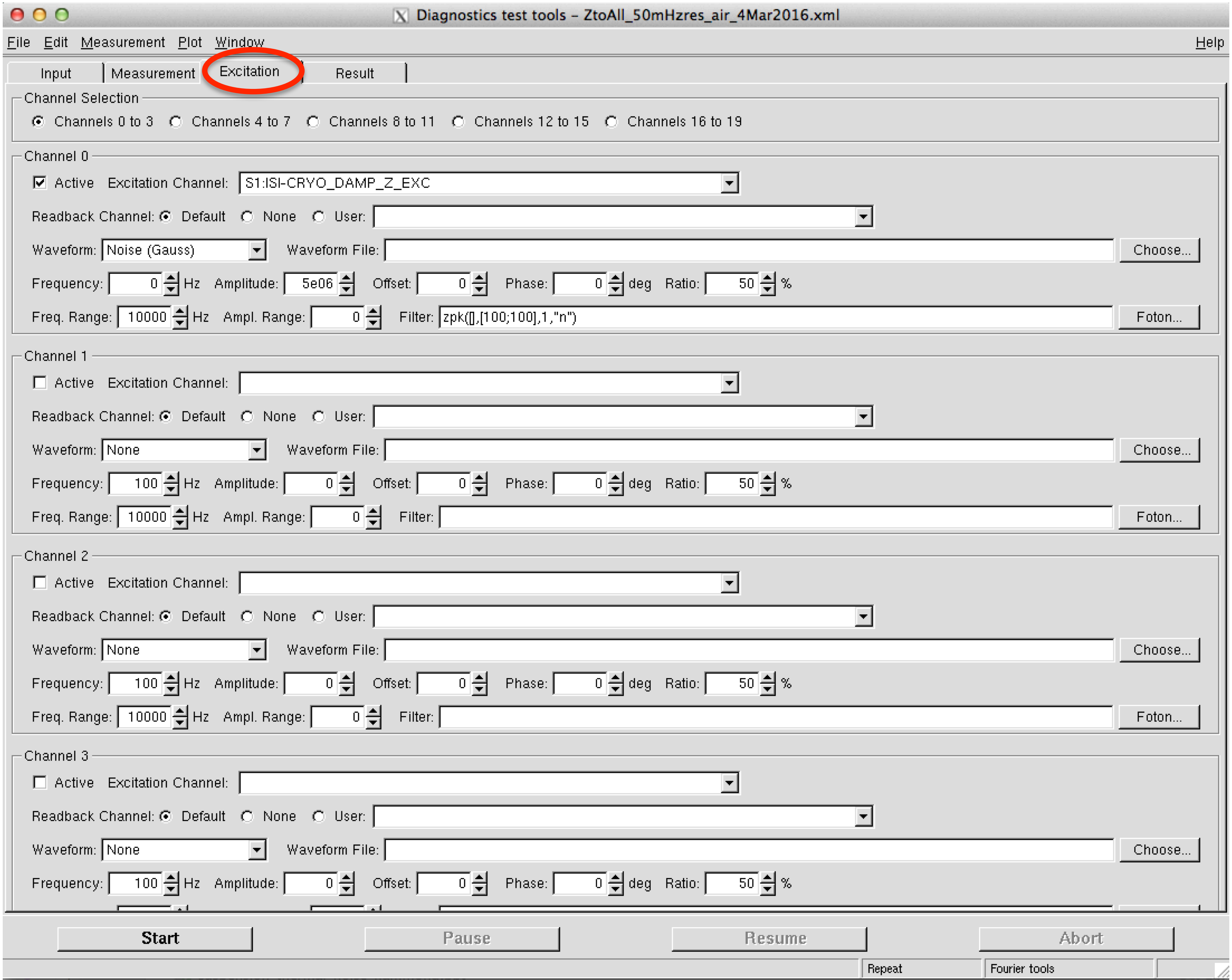
Making Measurements

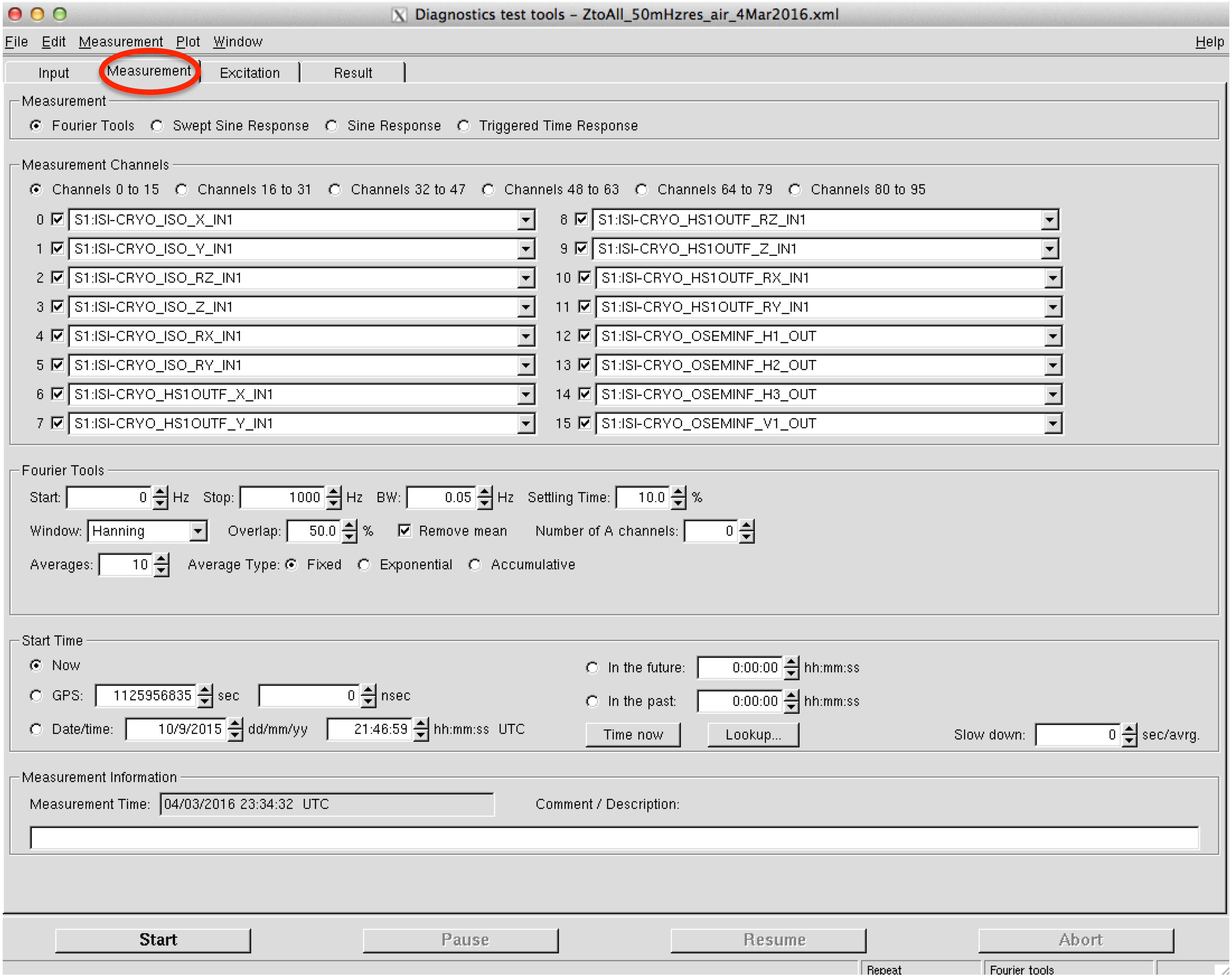
Diagnostic Test Tools (DTT) - Measure TFs and ASDs, etc

Dataviewer – time data plots in real time

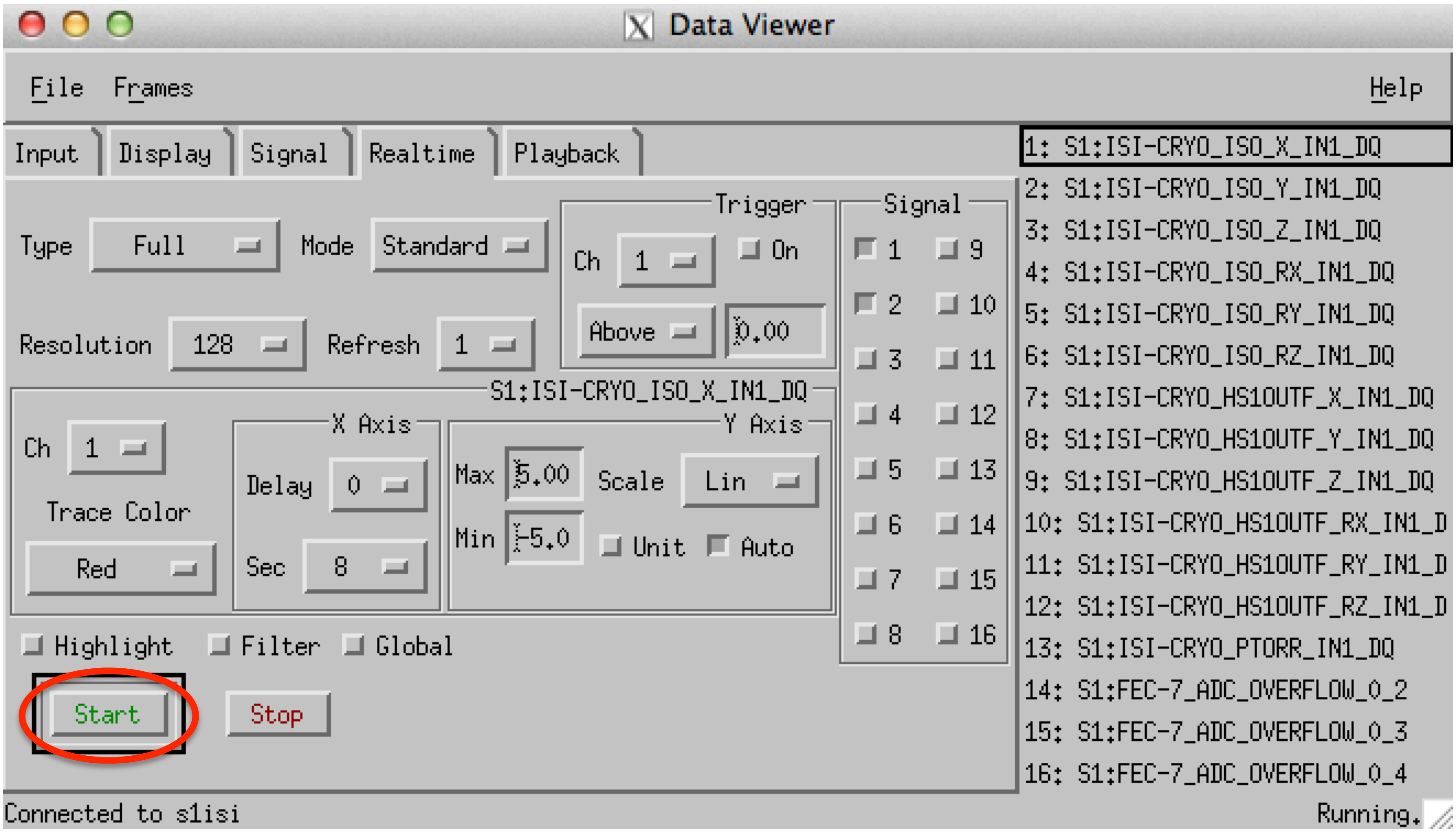
DTT – make measurements



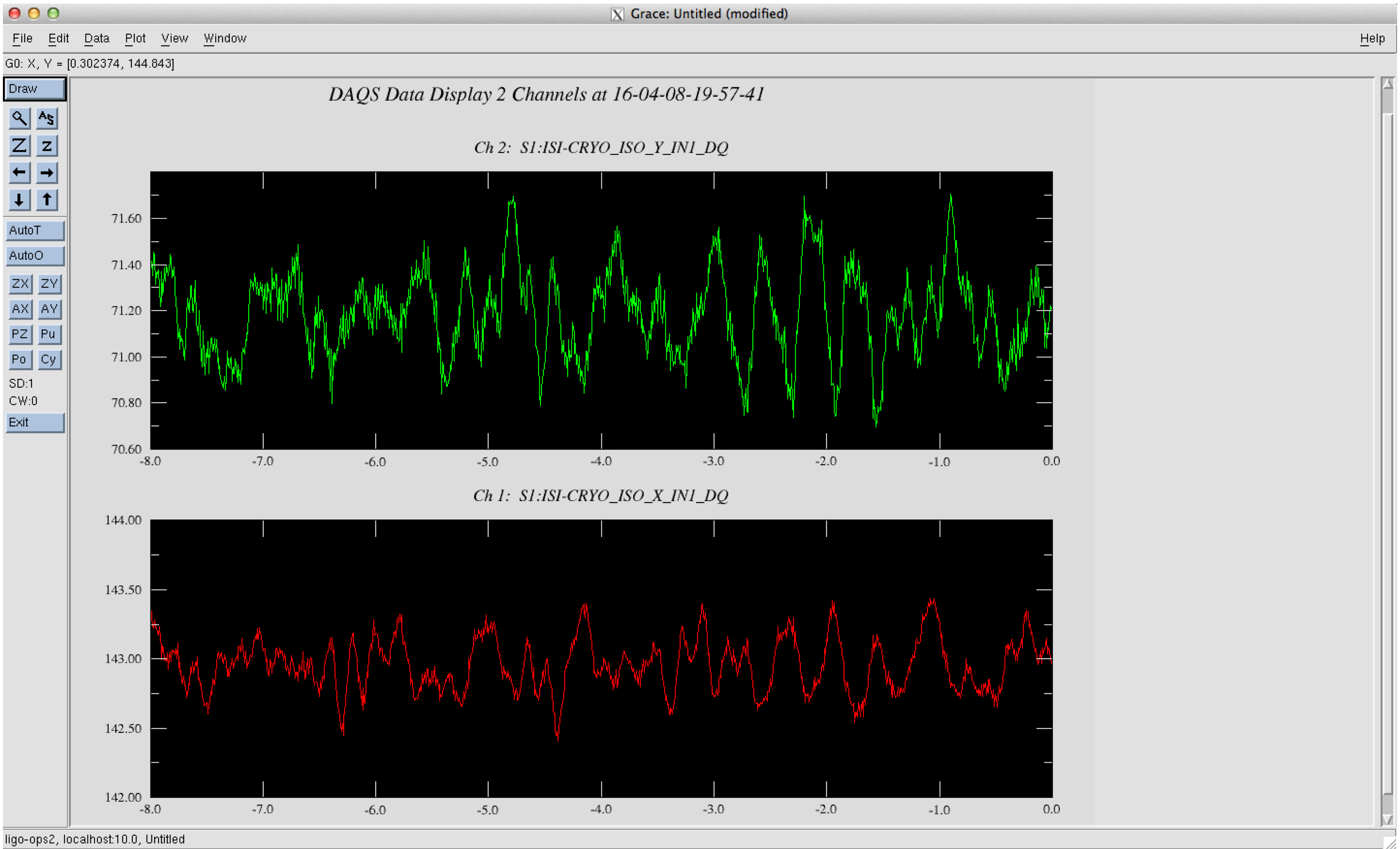

Diagnostics test tools – ZtoAll_50mHzres_air_4Mar2016.xml
File
Edit
Measurement
Plot
Window
Help
Input
Measurement
Excitation
Result
Channel Selection
Channels 0 to 3
Channels 4 to 7
Channels 8 to 11
Channels 12 to 15
Channels 16 to 19
Channel 0
Active
Excitation Channel:
S1:ISI-CRYO_DAMP_Z_EXC
Readback Channel:
Default
None
User:
Waveform:
Noise (Gauss)
Waveform File:
Choose...
Frequency:
0
Hz
Amplitude:
5e06
Offset:
0
Phase:
0
deg
Ratio:
50
%
Freq. Range:
10000
Hz
Ampl. Range:
0
Filter:
zpk([],[100;100],1,"n")
Foton...
Channel 1
Active
Excitation Channel:
Readback Channel:
Default
None
User:
Waveform:
None
Waveform File:
Choose...
Frequency:
100
Hz
Amplitude:
0
Offset:
0
Phase:
0
deg
Ratio:
50
%
Freq. Range:
10000
Hz
Ampl. Range:
0
Filter:
Foton...
Channel 2
Active
Excitation Channel:
Readback Channel:
Default
None
User:
Waveform:
None
Waveform File:
Choose...
Frequency:
100
Hz
Amplitude:
0
Offset:
0
Phase:
0
deg
Ratio:
50
%
Freq. Range:
10000
Hz
Ampl. Range:
0
Filter:
Foton...
Channel 3
Active
Excitation Channel:
Readback Channel:
Default
None
User:
Waveform:
None
Waveform File:
Choose...
Frequency:
100
Hz
Amplitude:
0
Offset:
0
Phase:
0
deg
Ratio:
50
%
Start
Pause
Resume
Abort
Repeat
Fourier tools


Diagnostics test tools – ZtoAll_50mHzres_air_4Mar2016.xml
File Edit Measurement Plot Window
Help
Input
Measurement
Excitation
Result
Measurement
Fourier Tools
Swept Sine Response
Sine Response
Triggered Time Response
Measurement Channels
Channels 0 to 15
Channels 16 to 31
Channels 32 to 47
Channels 48 to 63
Channels 64 to 79
Channels 80 to 95
0 S1:ISI-CRYO_ISO_X_IN1
1 S1:ISI-CRYO_ISO_Y_IN1
2 S1:ISI-CRYO_ISO_RZ_IN1
3 S1:ISI-CRYO_ISO_Z_IN1
4 S1:ISI-CRYO_ISO_RX_IN1
5 S1:ISI-CRYO_ISO_RY_IN1
6 S1:ISI-CRYO_HS1OUTF_X_IN1
7 S1:ISI-CRYO_HS1OUTF_Y_IN1
8 S1:ISI-CRYO_HS1OUTF_RZ_IN1
9 S1:ISI-CRYO_HS1OUTF_Z_IN1
10 S1:ISI-CRYO_HS1OUTF_RX_IN1
11 S1:ISI-CRYO_HS1OUTF_RY_IN1
12 S1:ISI-CRYO_OSEMINF_H1_OUT
13 S1:ISI-CRYO_OSEMINF_H2_OUT
14 S1:ISI-CRYO_OSEMINF_H3_OUT
15 S1:ISI-CRYO_OSEMINF_V1_OUT
Fourier Tools
Start: 0 Hz
Stop: 1000 Hz
BW: 0.05 Hz
Settling Time: 10.0 %
Window: Hanning
Overlap: 50.0 %
Remove mean
Number of A channels: 0
Averages: 10
Average Type: Fixed
Exponential
Accumulative
Start Time
Now
GPS: 1125956835 sec
0 nsec
Date/time: 10/9/2015 dd/mm/yy
21:46:59 hh:mm:ss UTC
In the future: 0:00:00 hh:mm:ss
In the past: 0:00:00 hh:mm:ss
Time now
Lookup...
Slow down: 0 sec/avrg.
Measurement Information
Measurement Time: 04/03/2016 23:34:32 UTC
Comment / Description:
Start
Pause
Resume
Abort
Repeat
Fourier tools

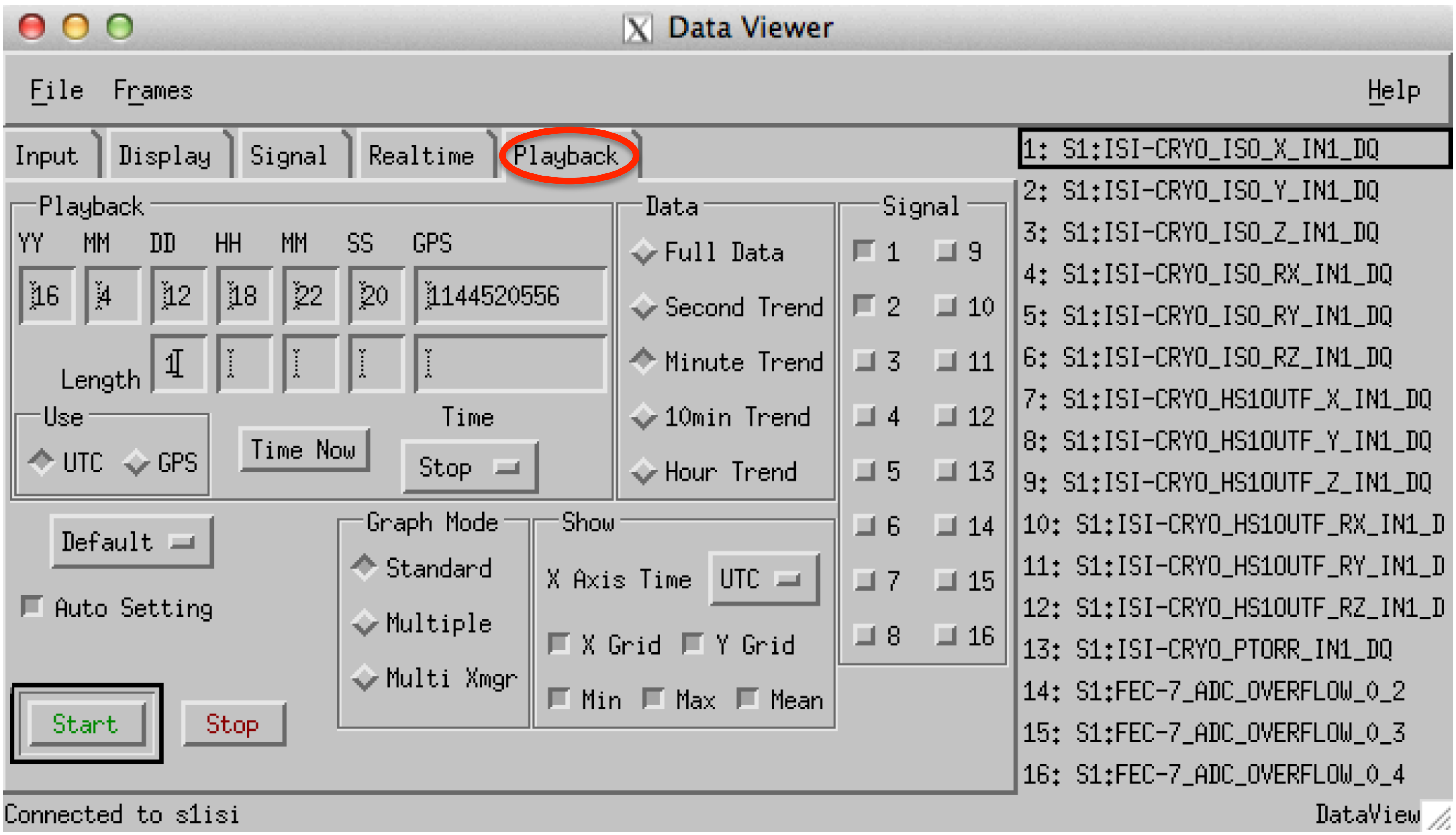
Dataviewer – realtime data



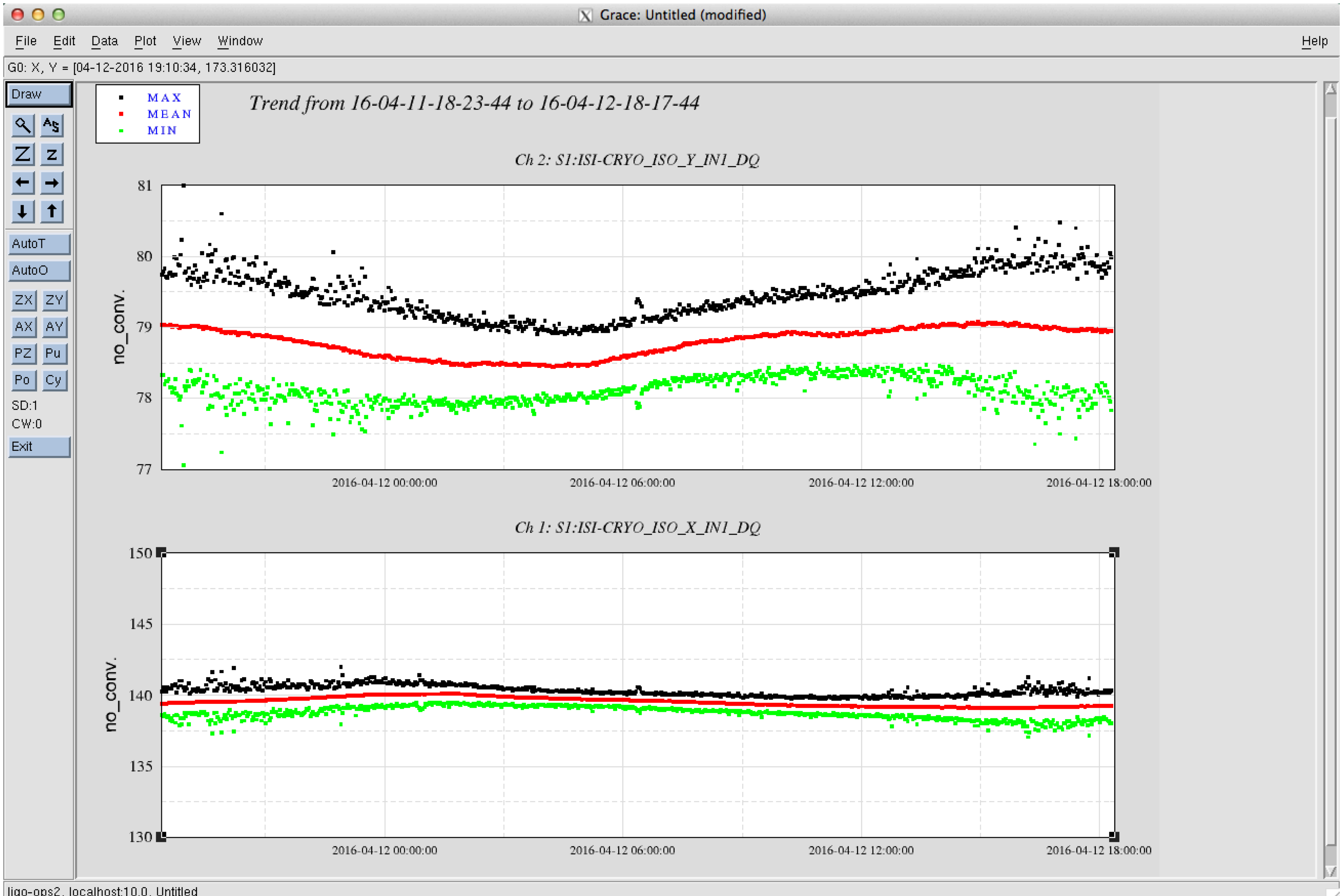
Dataviewer – realtime data



Dataviewer – past data



Dataviewer – past data



Lecture 3

Digital Control
- Part 3: Digital time & frequency domain

Filters: Continuous to Digital Conversion

$$\dot{y} + ay = x$$

Differential equation: continuous time

$$\dot{y} \approx \frac{y(k+1) - y(k)}{dt}$$

Approximation of derivative, where *k* is the current sample

$$\frac{y(k+1) - y(k)}{dt} + ay(k) = x(k)$$

Approximation of EOM

$$\boxed{y(k+1) = dt\left[x(k) - ay(k)\right] + y(k)}$$

Difference equation: digital

Z-Transform

Analogous to the Laplace s-transform for continuous systems

d/dt -> s for continuous systems
k+1 -> z for digital systems

Z-Transform

Analogous to the Laplace s-transform for continuous systems

d/dt -> s for continuous systems
k+1 -> z for digital systems

Digital	**Continuous**
Difference equation $y(k+1) = dt\left[x(k) - ay(k)\right] + y(k)$	Differential equation $\dot{y} + ay = x$

Z-Transform

Analogous to the Laplace s-transform for continuous systems

d/dt -> s for continuous systems
k+1 -> z for digital systems

Digital	**Continuous**
Difference equation $y(k+1) = dt\left[x(k) - ay(k)\right] + y(k)$	Differential equation $\dot{y} + ay = x$
z-transform $yz = dt\left(x - ay\right) + y$	s transform $ys + ay = x$

Z-Transform

Analogous to the Laplace s-transform for continuous systems

d/dt -> s for continuous systems
k+1 -> z for digital systems

Digital	**Continuous**
Difference equation $y(k+1) = dt\left[x(k) - ay(k)\right] + y(k)$	Differential equation $\dot{y} + ay = x$
z-transform $yz = dt\left(x - ay\right) + y$	s transform $ys + ay = x$
Transfer function $y = \dfrac{dt}{z + dt * a - 1} x$	Transfer function $y = \dfrac{1}{s+a} x$

Z-Transform

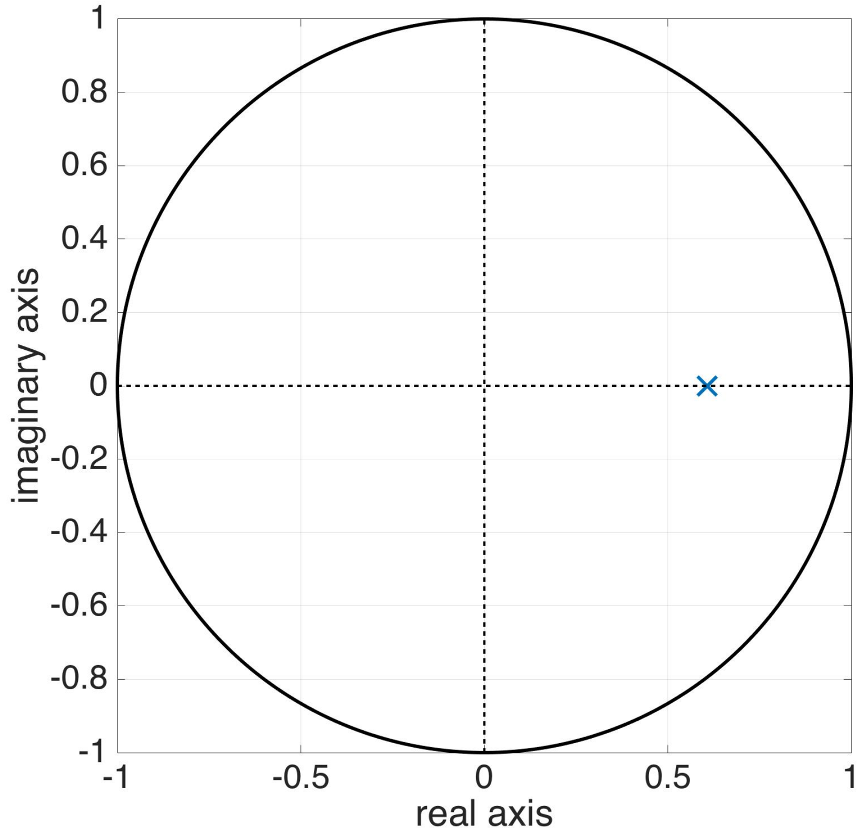
Digital	**Continuous**
Difference equation $y(k+1) = dt\left[x(k) - ay(k)\right] + y(k)$	Differential equation $\dot{y} + ay = x$
z-transform $yz = dt\left(x - ay\right) + y$	s transform $ys + ay = x$
Transfer function $y = \frac{dt}{z + dt * a - 1}x$	Transfer function $y = \frac{1}{s+a}x$
Frequency domain interpretation $z = e^{i\frac{2\pi}{f_s}f}$	Frequency domain interpretation $s = i2\pi f$

Z-Transform

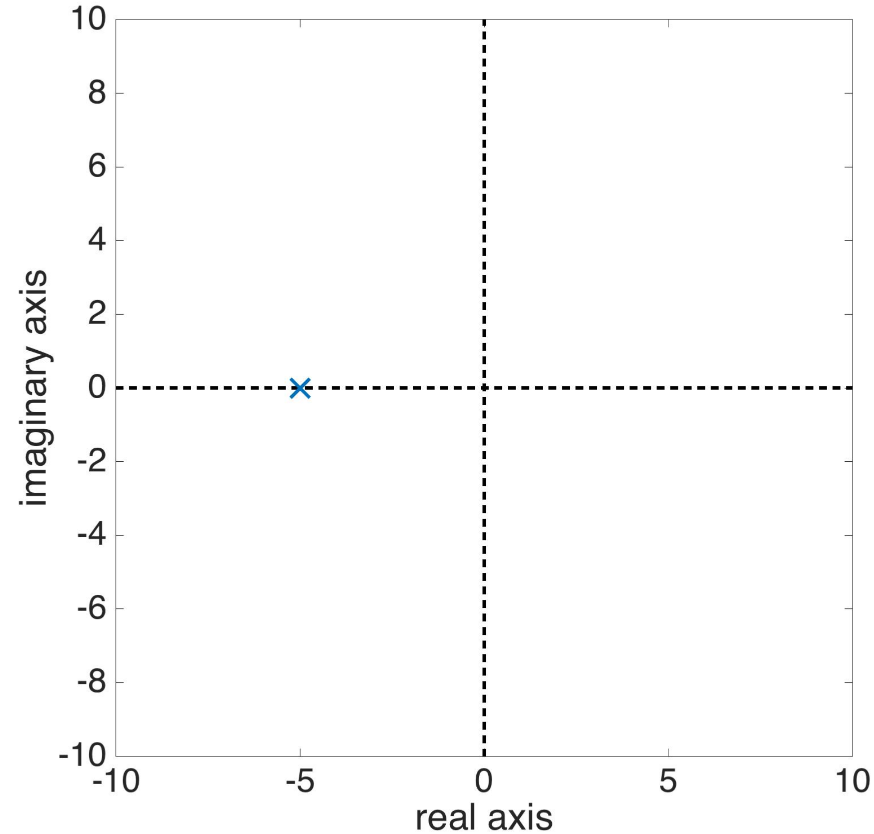
Digital	**Continuous**
Difference equation $y(k+1) = dt\left[x(k) - ay(k)\right] + y(k)$	Differential equation $\dot{y} + ay = x$
z-transform $yz = dt\left(x - ay\right) + y$	s transform $ys + ay = x$
Transfer function $y = \dfrac{dt}{z + dt * a - 1}x$	Transfer function $y = \dfrac{1}{s+a}x$
Frequency domain interpretation $z = e^{i\frac{2\pi}{f_s}f} \approx \dfrac{1}{f_s}s$ where $f_s >> f$	Frequency domain interpretation $s = i2\pi f$

Complex plane pole-zero map

Digital



Continuous

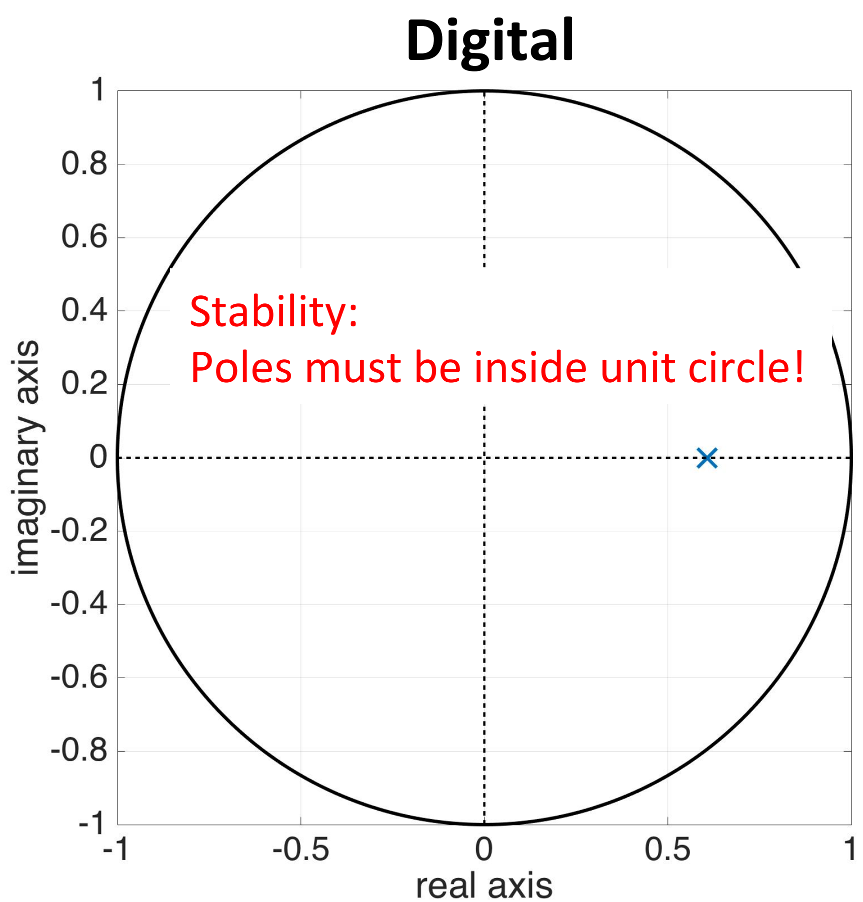


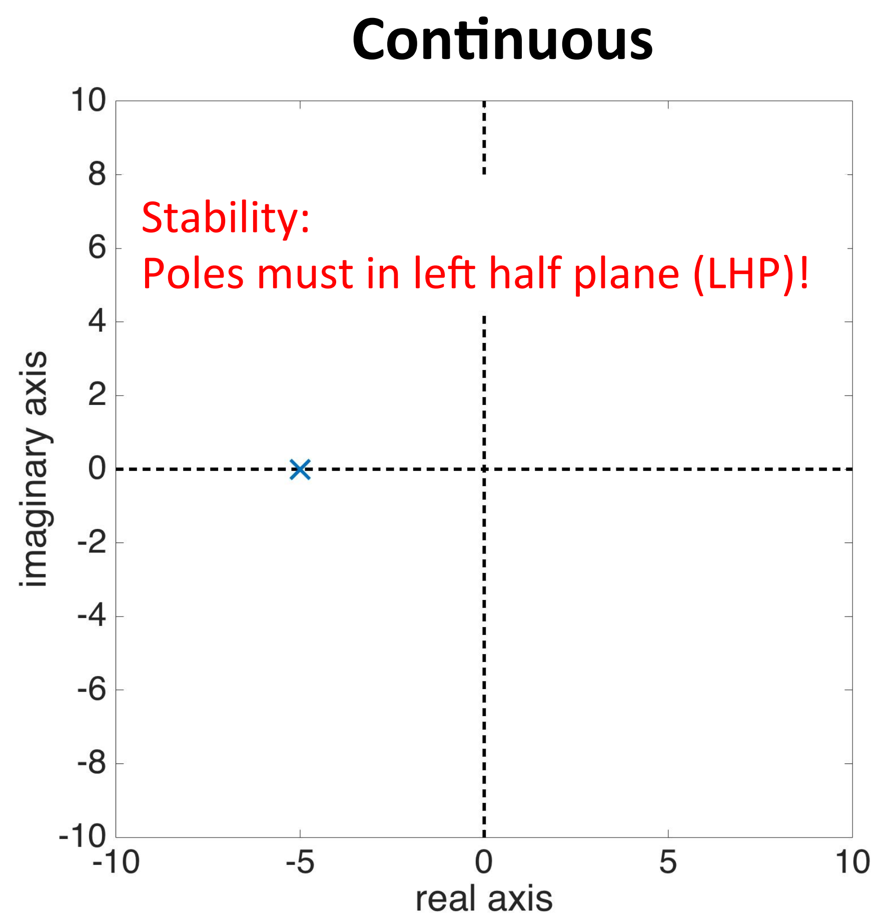
$$y = \frac{dt}{z + dt * a - 1} x$$

a = 0.5 rad/s
dt = 0.1 s

$$y = \frac{1}{s + a} x$$

Complex plane pole-zero map





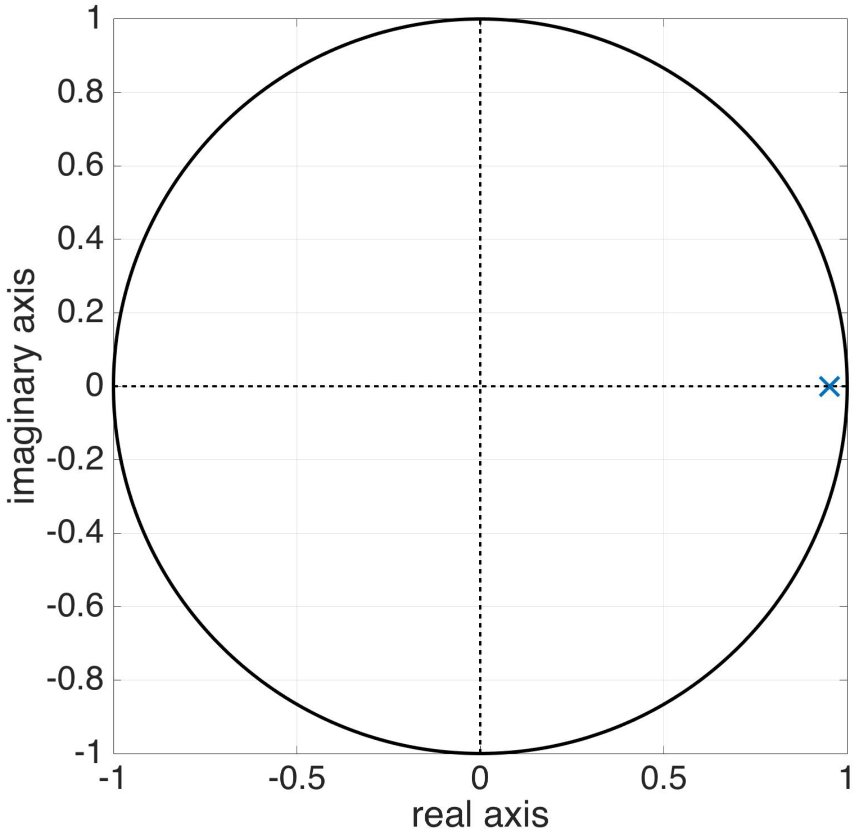
$$y = \frac{dt}{z + dt * a - 1} x$$

a = 0.5 rad/s
dt = 0.1 s

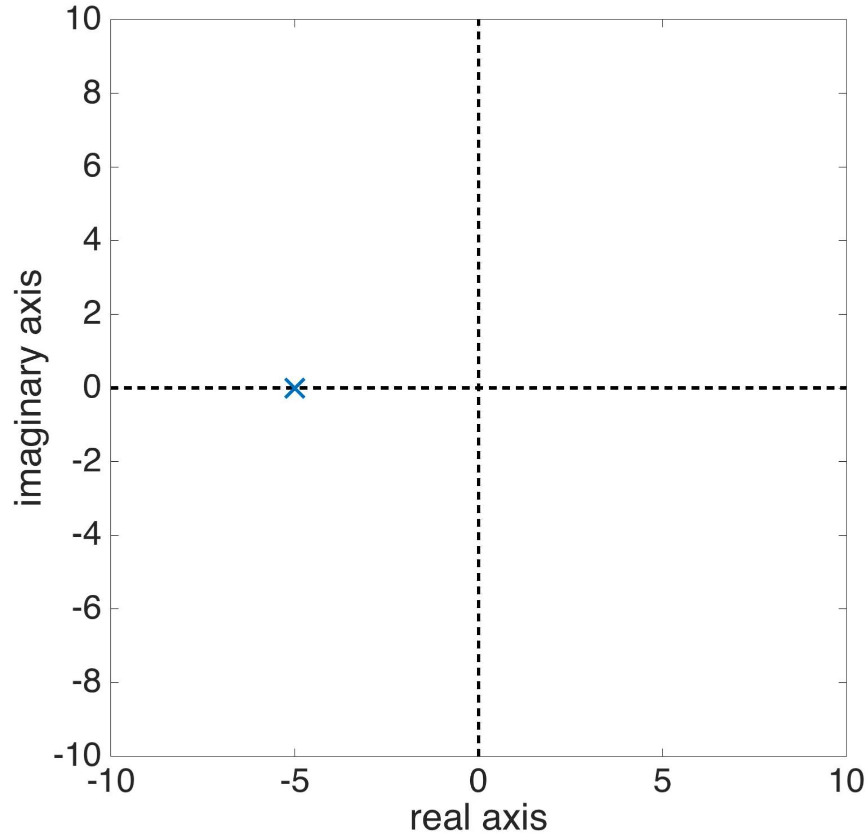
$$y = \frac{1}{s + a} x$$

Complex plane pole-zero map

Digital



Continuous



$$y = \frac{dt}{z + dt * a - 1} x$$

a = 0.5 rad/s
dt = 0.01 s

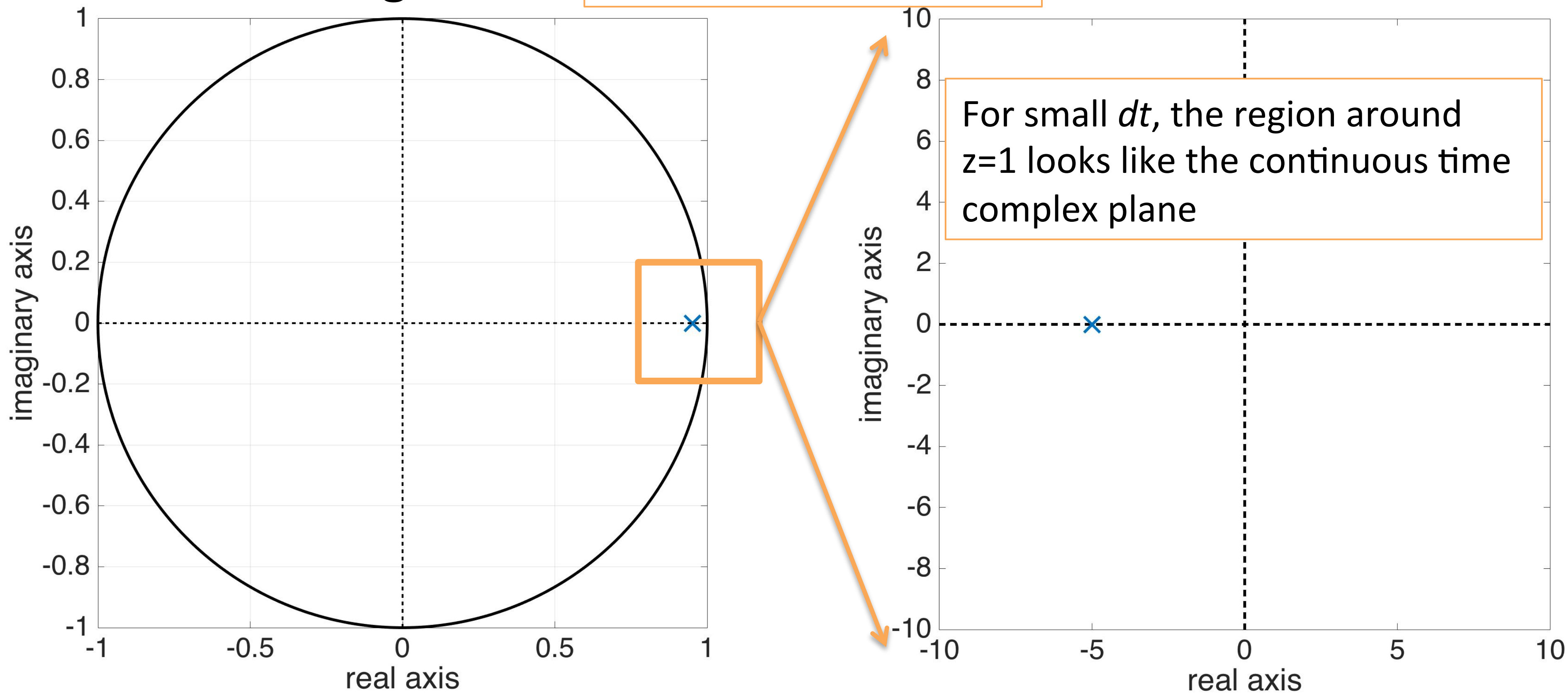
$$y = \frac{1}{s + a} x$$

Complex plane pole-zero map

Digital

$$z_{pole} \approx 1 + dt * s_{pole}$$

Continuous



$$y = \frac{dt}{z + dt * a - 1} x$$

a = 0.5 rad/s
dt = 0.01 s

$$y = \frac{1}{s + a} x$$

Matlab has various conversions from Laplace to Z

Continuous time TF **HAM_ISI =**

$$\frac{1}{1900 s^2 + 3092 s + 1.258e05}$$

```
Digital_filter = c2d(HAM_ISI,0.001,'ZOH')
```

First order hold

0.001 = sample time (s)

$$\frac{2.63e\text{-}10\, z + 2.629e\text{-}10}{z^2 - 1.998 z + 0.9984}$$

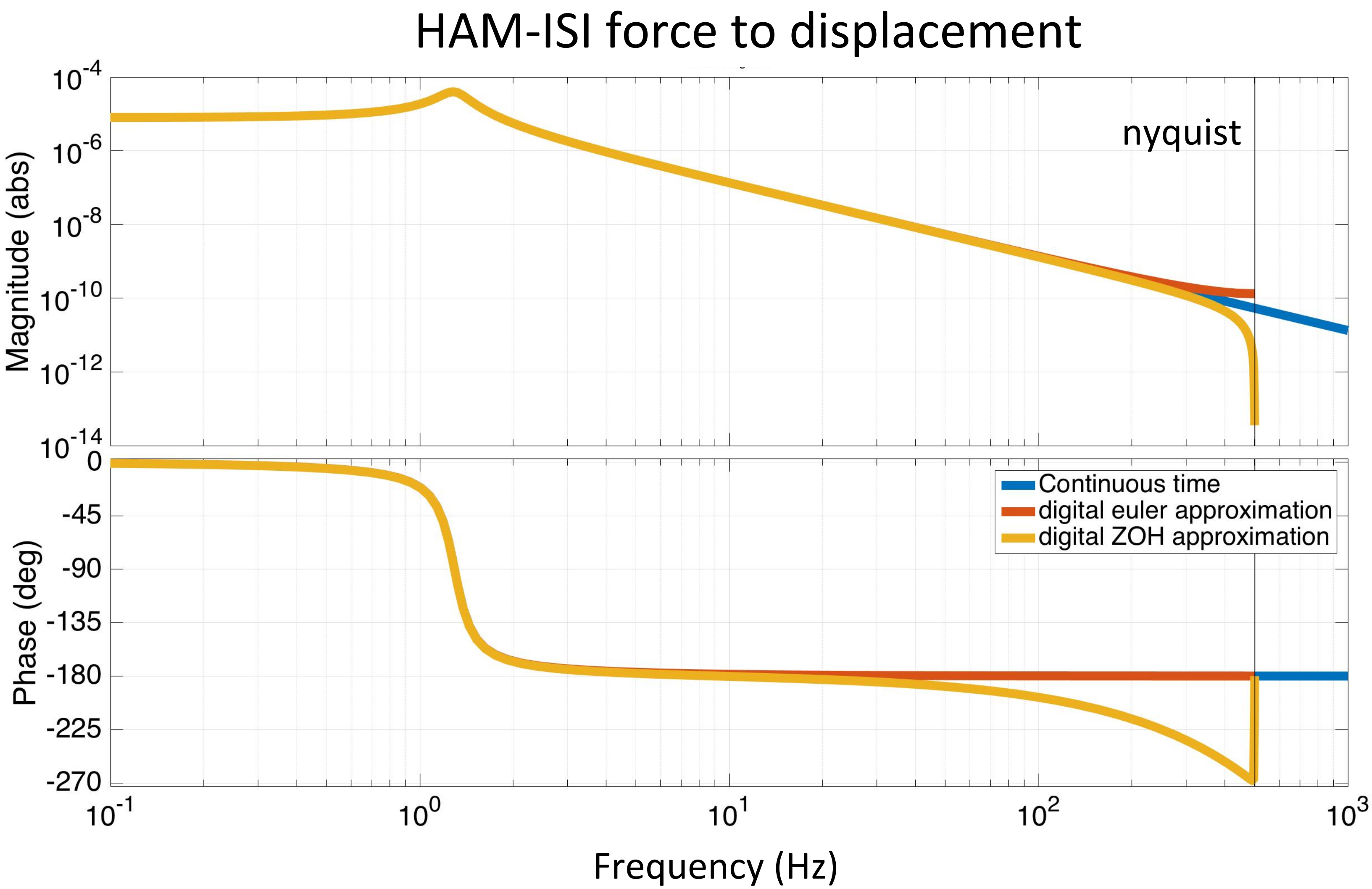
```
Digital_filter = c2d(HAM_ISI,0.001,'tustin')
```

$$\frac{1.315e\text{-}10\, z^2 + 2.629e\text{-}10\, z + 1.315e\text{-}10}{z^2 - 1.998 z + 0.9984}$$

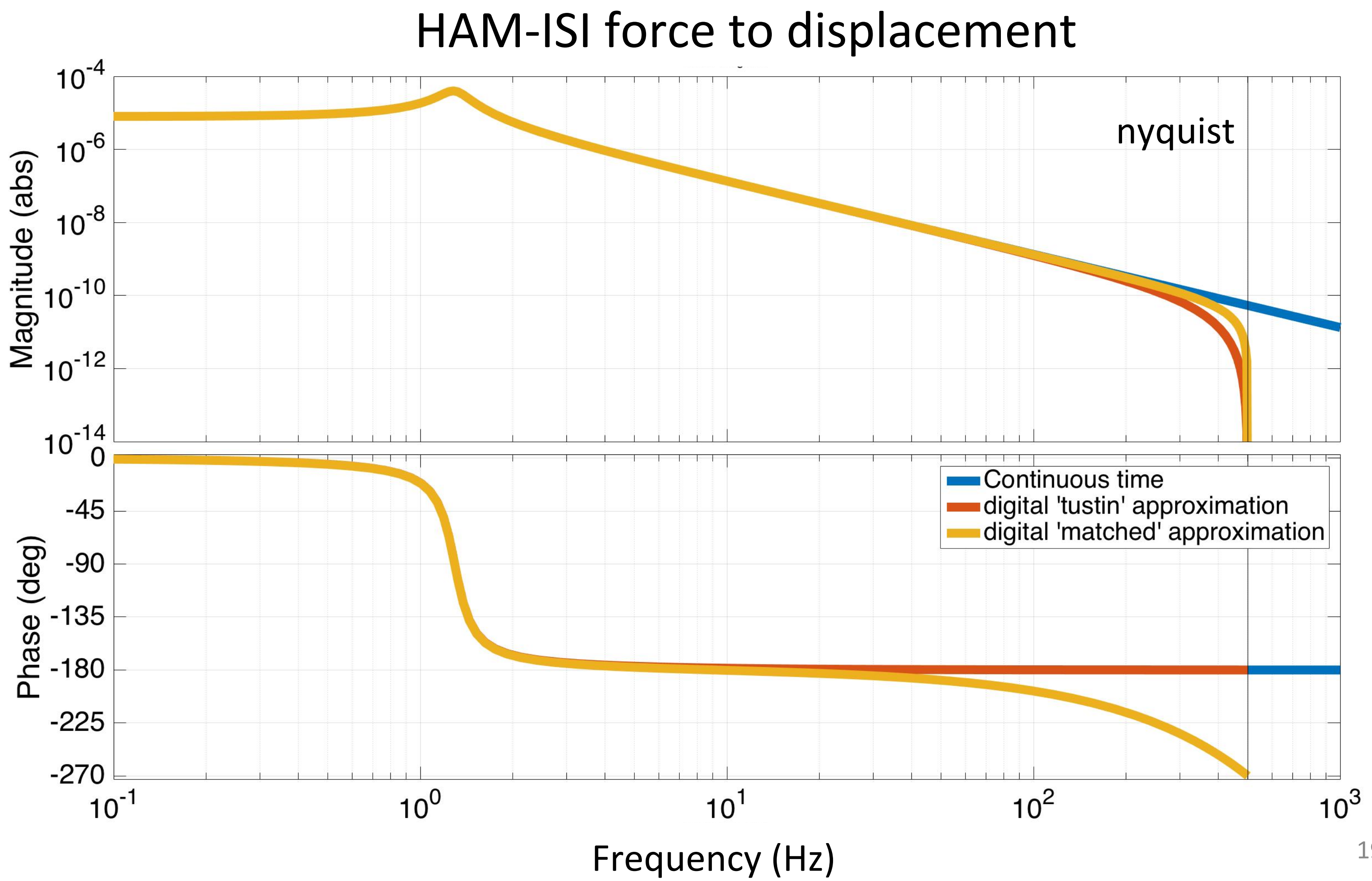
```
Digital_filter = c2d(HAM_ISI,0.001,'matched')
```

$$\frac{2.629e\text{-}10\, z + 2.629e\text{-}10}{z^2 - 1.998 z + 0.9984}$$

Digital TF Bode Plots



Digital TF Bode Plots

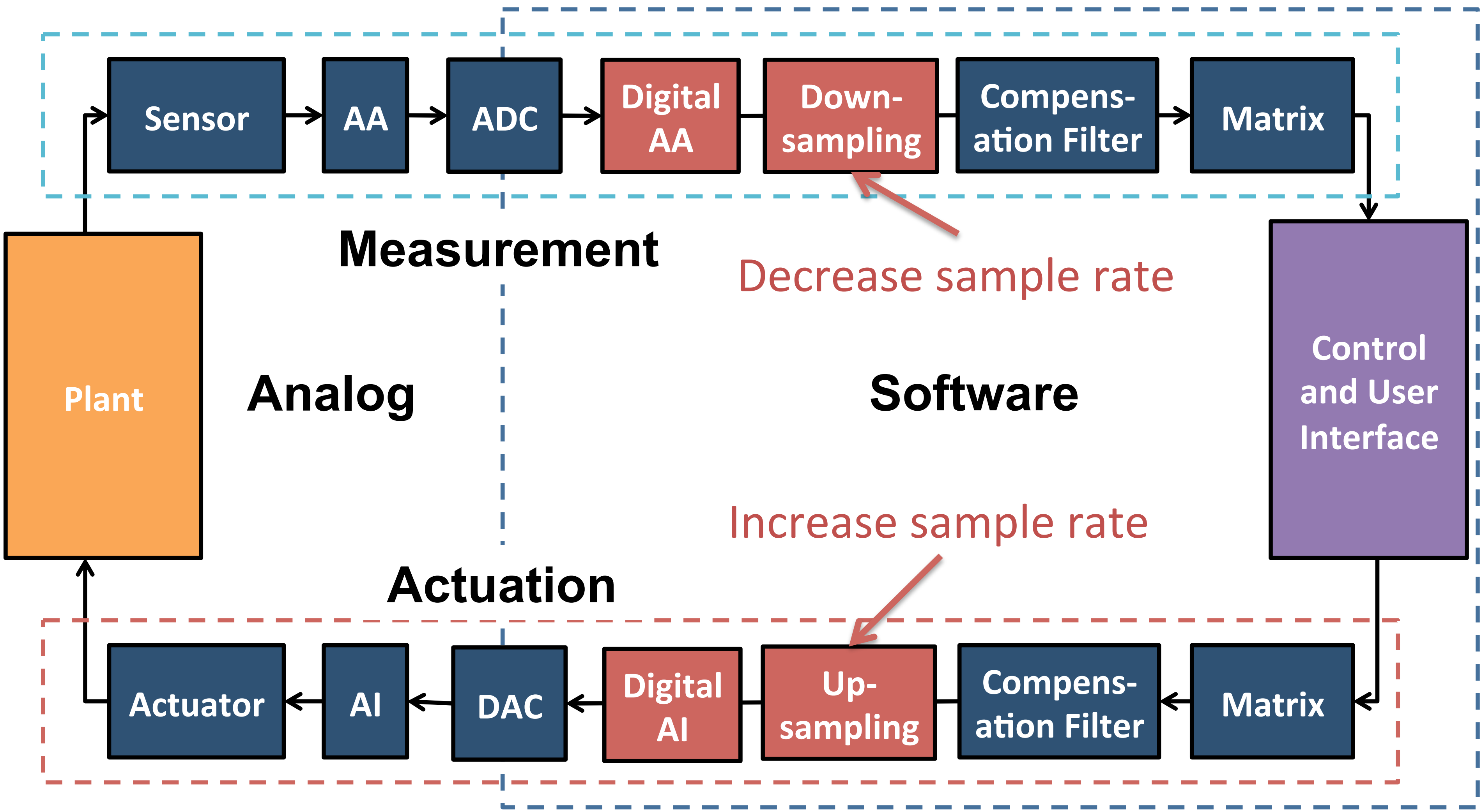


Lecture 3 Summary

- ADCs and DACs are used to sample signals and move them into and out of the computer.
- Anti-alias and Anti-image filters smooth over the transitions through the ADC and DAC to remove unwanted high frequency content.
- LIGO has various software tools for controlling and interfacing with realtime systems.
- The z-transform is the digital equivalent to the Laplace *s*-transform (needed since sampling is nonlinear).

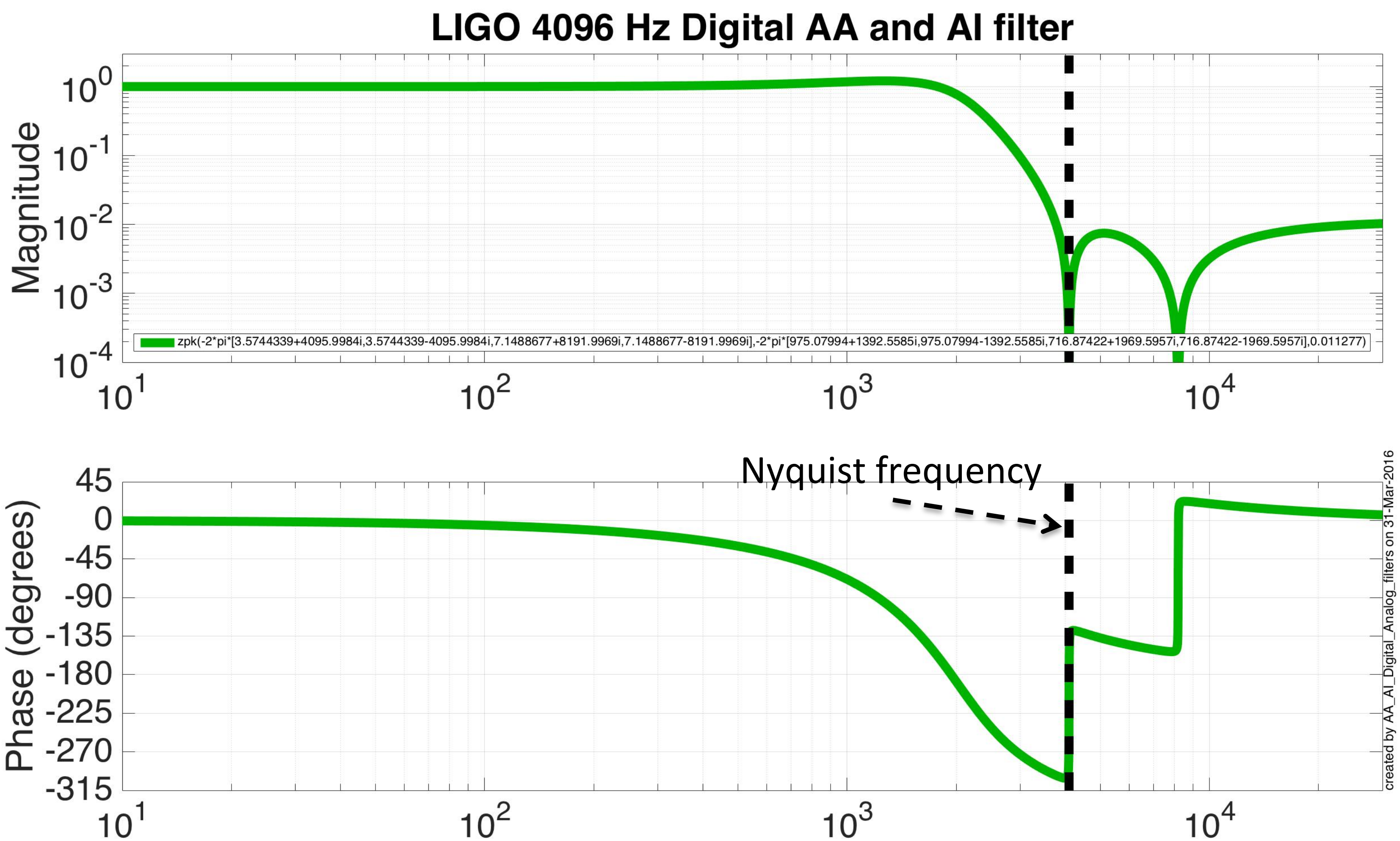
Lecture 3 – Backups

Oversampled Signal Flow

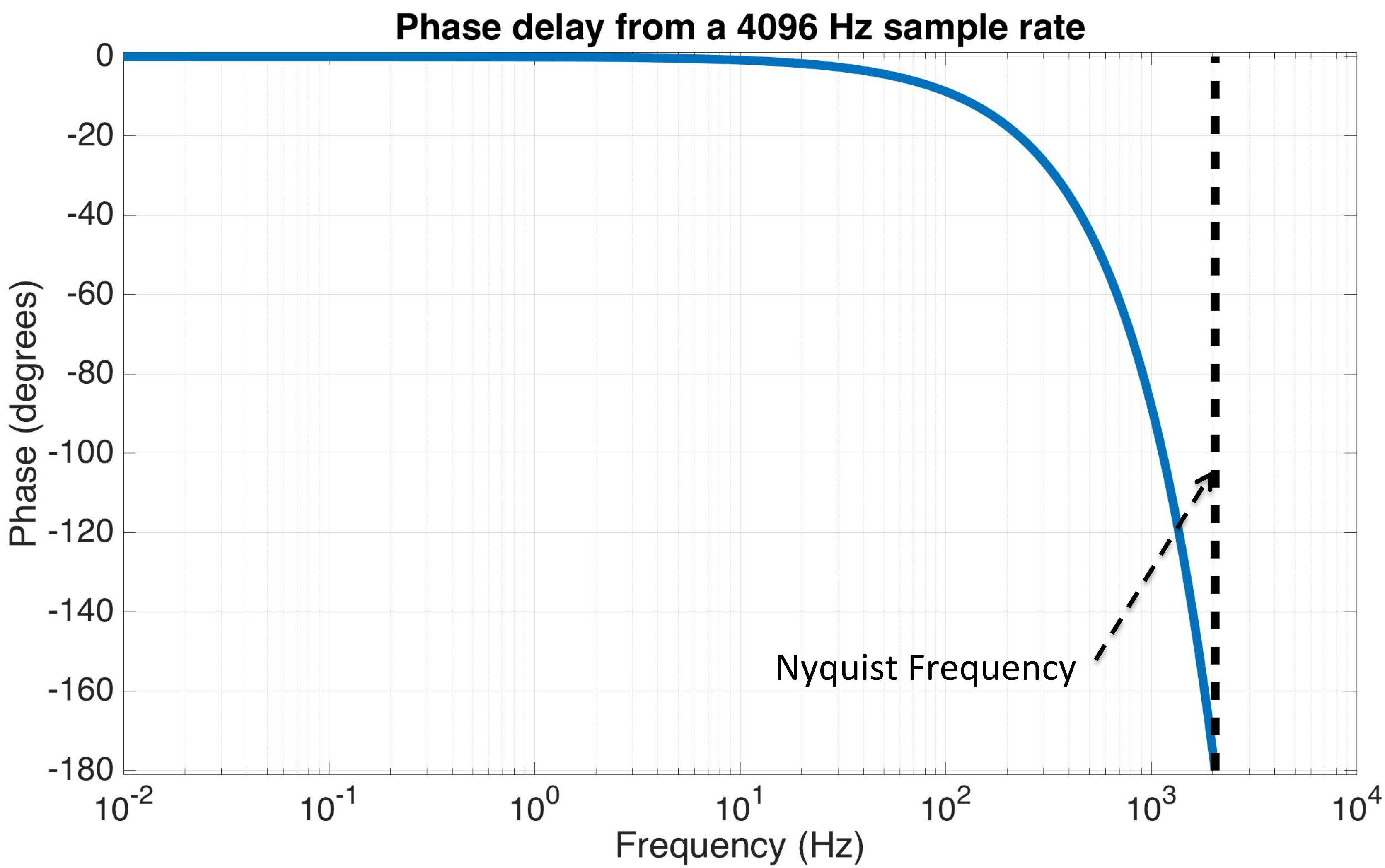


Oversampled Signal Flow

The ADC and DAC sample at 65536 Hz, the controller samples at 4096 Hz



Sampling Phase Loss

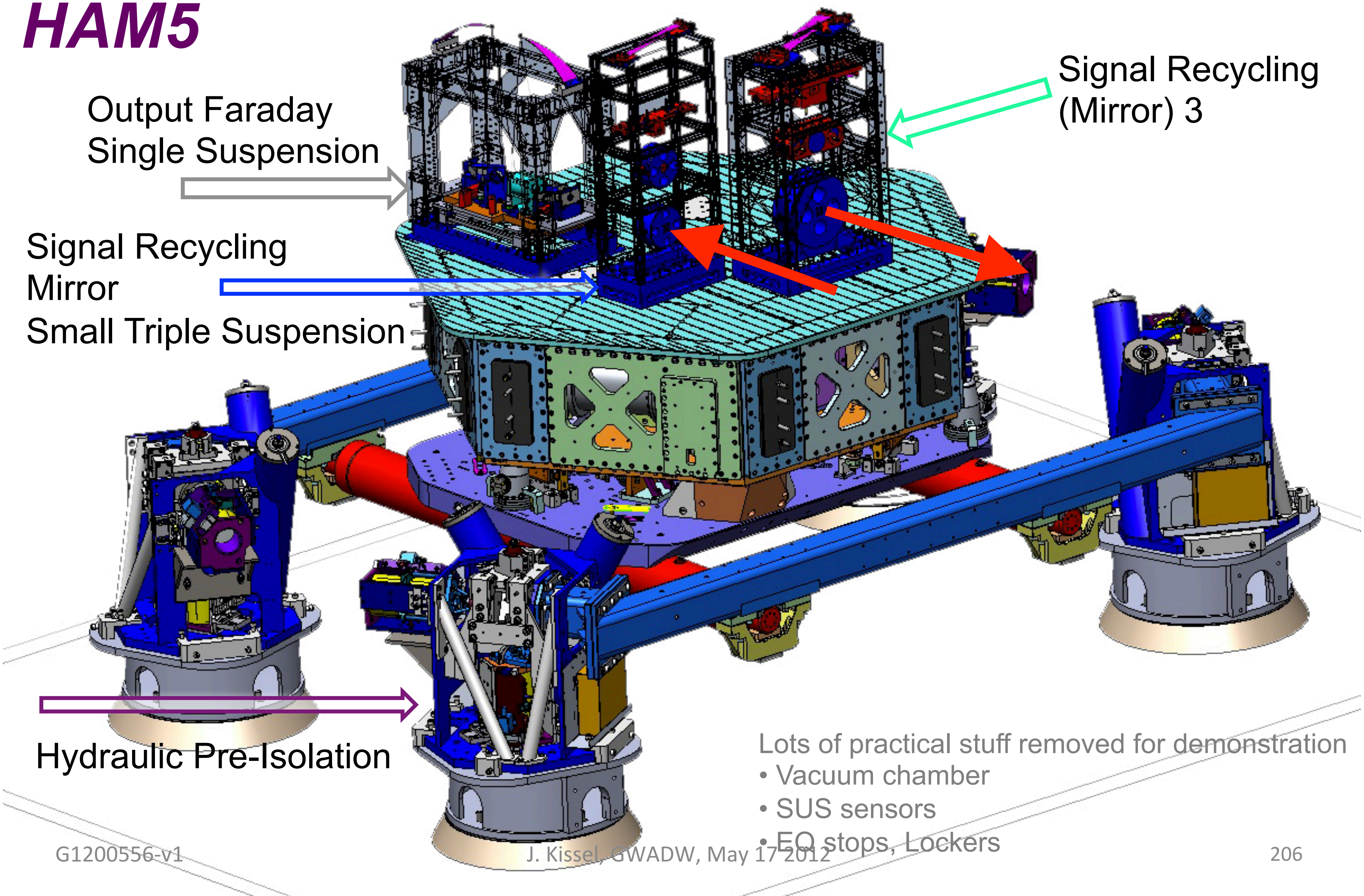


ISO Block

S1ISI_CUST_CRYO_ISO_ALL.adl
S1 - FEC
S1ISI-CRYO_ISO_X
S1ISI-CRYO_ISO_Y
S1ISI-CRYO_ISO_RZ
S1ISI-CRYO_ISO_Z
S1ISI-CRYO_ISO_RX
S1ISI-CRYO_ISO_RY
Thu Mar 31 17:22:30
EXCMON
INMON
ON/OFF
OFFSET
CLEAR HISTORY
LOAD COEFFICIENTS
FM1 FM2 FM3 FM4 FM5
FM6 FM7 FM8 FM9 FM10
LIMIT
Ramp Time (sec):
DECIMATION
HOLD OUTPUT
OUT16
OUTPUT
OUTMON
Current State
Correct State
State BAD
Gain BAD
Gain OK

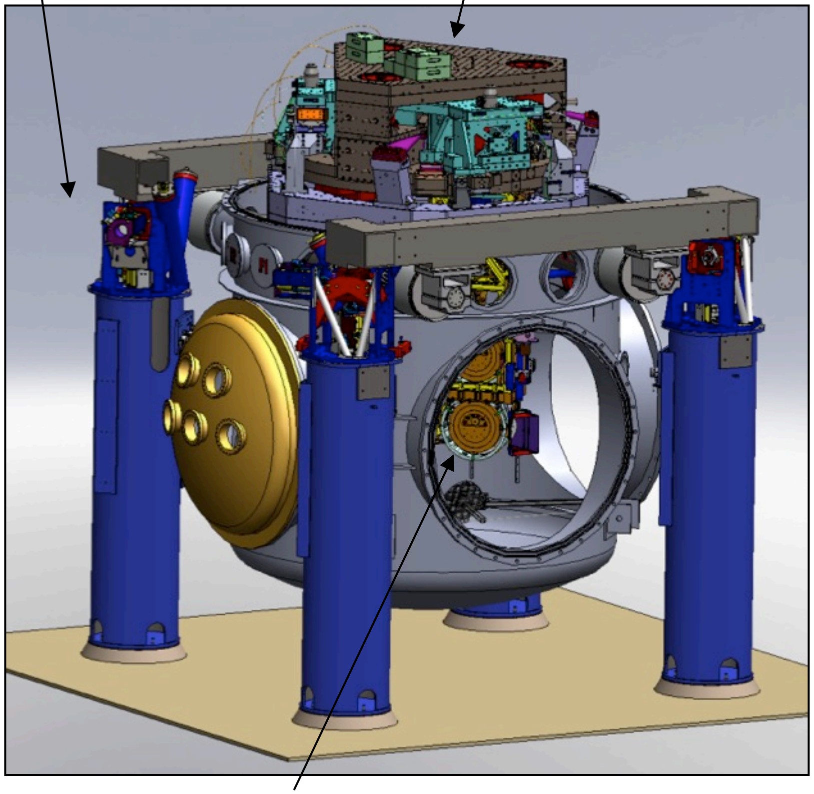
General BackUps

Advanced LIGO
A single output chamber is complicated!



Lots of practical stuff removed for demonstration
- Vacuum chamber
- SUS sensors
- EQ stops, Lockers

BSCs – core optics



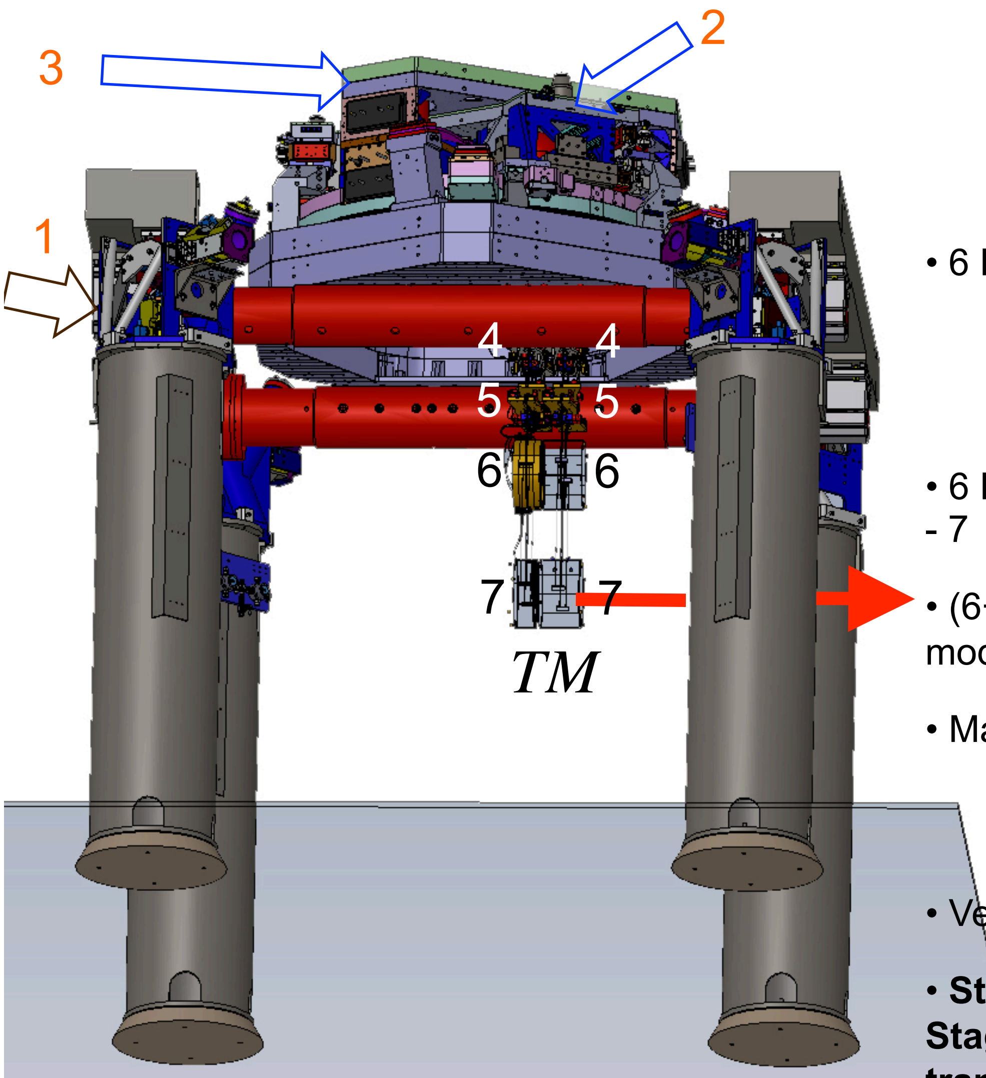
hydraulic external pre-isolator (HEPI) (one stage of isolation)

active isolation platform (2 stages of isolation)

quadruple pendulum (four stages of isolation) with monolithic silica final stage

Hybrid Systems

Advanced LIGO - The Design



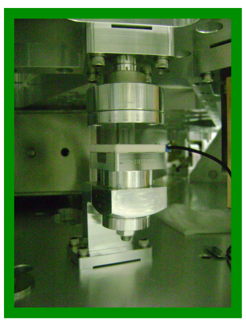
- 7 Stages of Isolation
  - Hydraulic Preisolation
  - Blade spring and wire flexures
  - Monolithic Final Stage
- 6 DOF sensing on stages 1 – 4, 3 DOF on 5 – 6
  - Inertial and displacement on stages 1-3
  - Displacement only on stages 4 - 6
- 6 DOF DC - 1kHz actuation on Stages 1 – 4, 3 DOF on 5 - 7
- (6+6+6+[3*6+4]) = 40 out of 42 Trans./Rot. resonant modes sensed and controlled
- Many-control-loop system
  - Sensor blending, Feed back, Feed forward, Sensor Correction, Heirarchical control
- Versatile 800 kg payload
- **Stage 1 – 3 "Performance limited by sensor noise," Stage 4 – 7 "Performance limited by direct transmission of platform motion"**

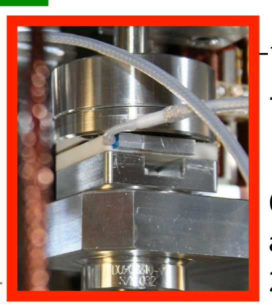
Sensor Noise

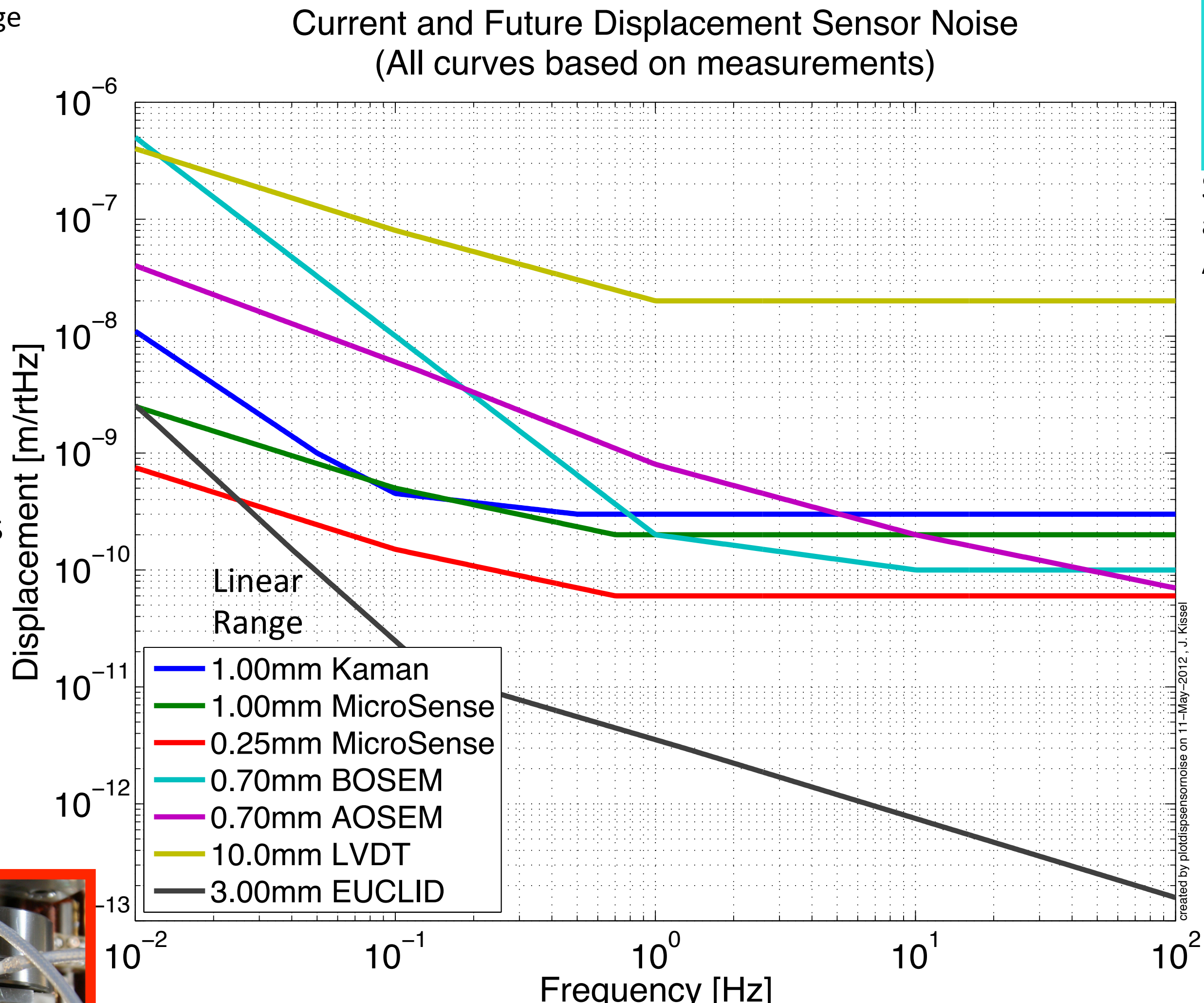
Displacement Sensors

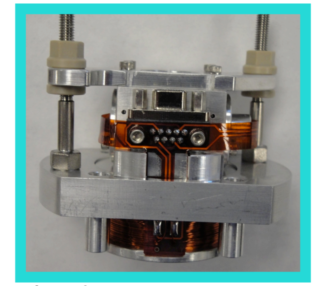

Inductive
aLIGO Pre-isolator
Stage


Inductive
VIRGO / GEO / KAGRA SAS

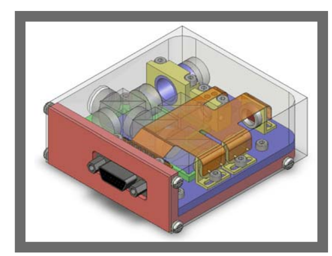

Capacitive
aLIGO Stage 1
ISIs


Capacitive
aLIGO Stage
2 ISIs




Shadow Sensor
aLIGO SUS Top Stages
AEI 10m SUS Top Stages


Shadow Sensor
aLIGO SUS Lower
Stages

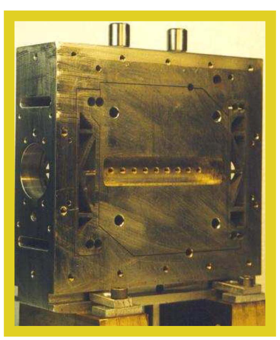

Interferometeric,
U of Birmingham
Prototype (As yet
Non-UHV Comp.)

Sensor Noise

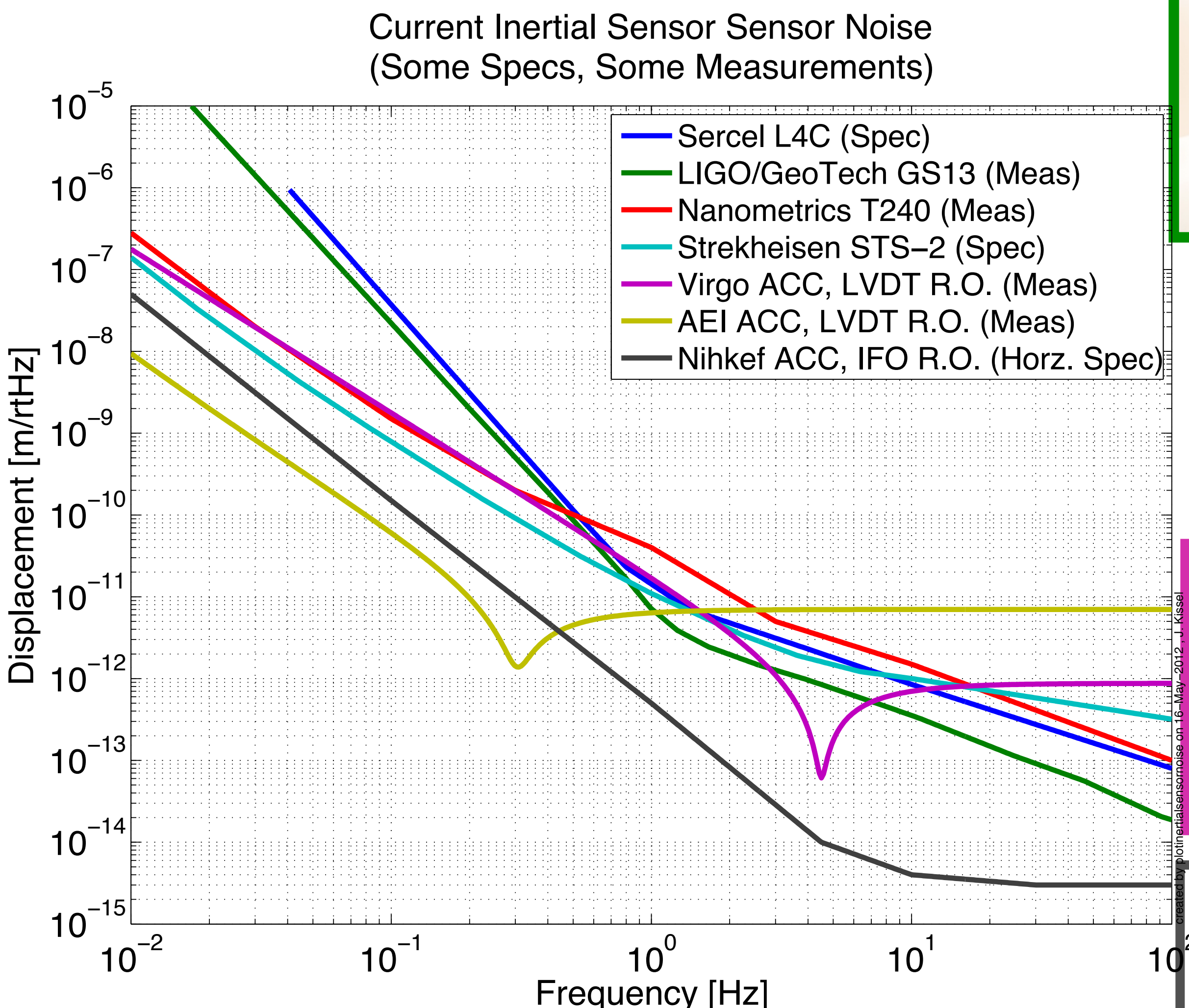
Inertial Sensors

aLIGO Pre-isolator Stage
aLIGO Stage 0 & 1 ISIs
AEI-SAS Vert. Witness

aLIGO Pre-isolator Stage

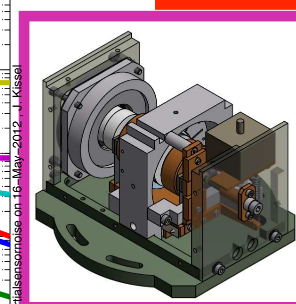


AEI-SAS Horz. Witness
(Watt Linkage)

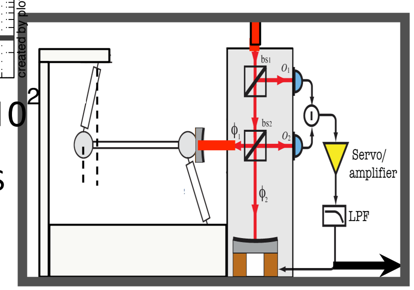


aLIGO
Stage 1
& 2 ISIs

aLIGO
Stage 1
ISIs



iVIRGO
F0, F7



aVIRGO MultiSAS
Horz. Witness
(Watt Linkage)

SEI Sensors and Their Noise

"Low" Frequency

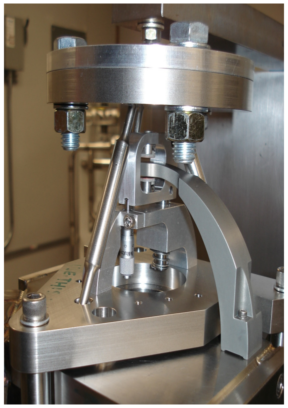
DC

10 mHz

1 Hz

800 Hz

"High" Frequency



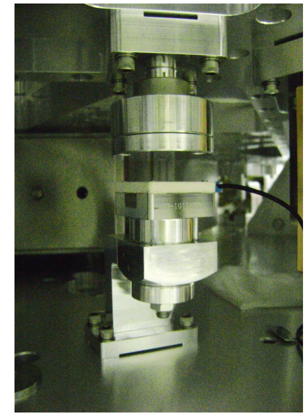
IPS

Kaman's Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Reasonable Noise, Long Range



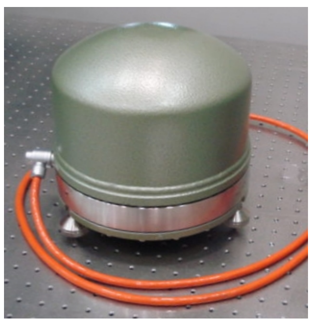
CPS

MicroSense's Capacitive Displacement Sensors

Used On: HAM-ISIs and BSC-ISIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Good Noise, UHV compatible



STS2

Strekheisen's STS-2

Used On: HEPIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Best in the 'Biz below 1 Hz, Triaxial

T240

Nanometric's Trillium 240

Used On: BSC-ISIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Like STS-2s, Triaxial, no locking mechasim -> podded

GS13

GeoTech's GS-13

Used On: HAM-ISIs and BSC-ISIs

Used For: ≥ 0.5 Hz Control

Used 'cause: awesome noise above 1Hz, no locking mechanism -> podded

L4C

Sercel's L4-C

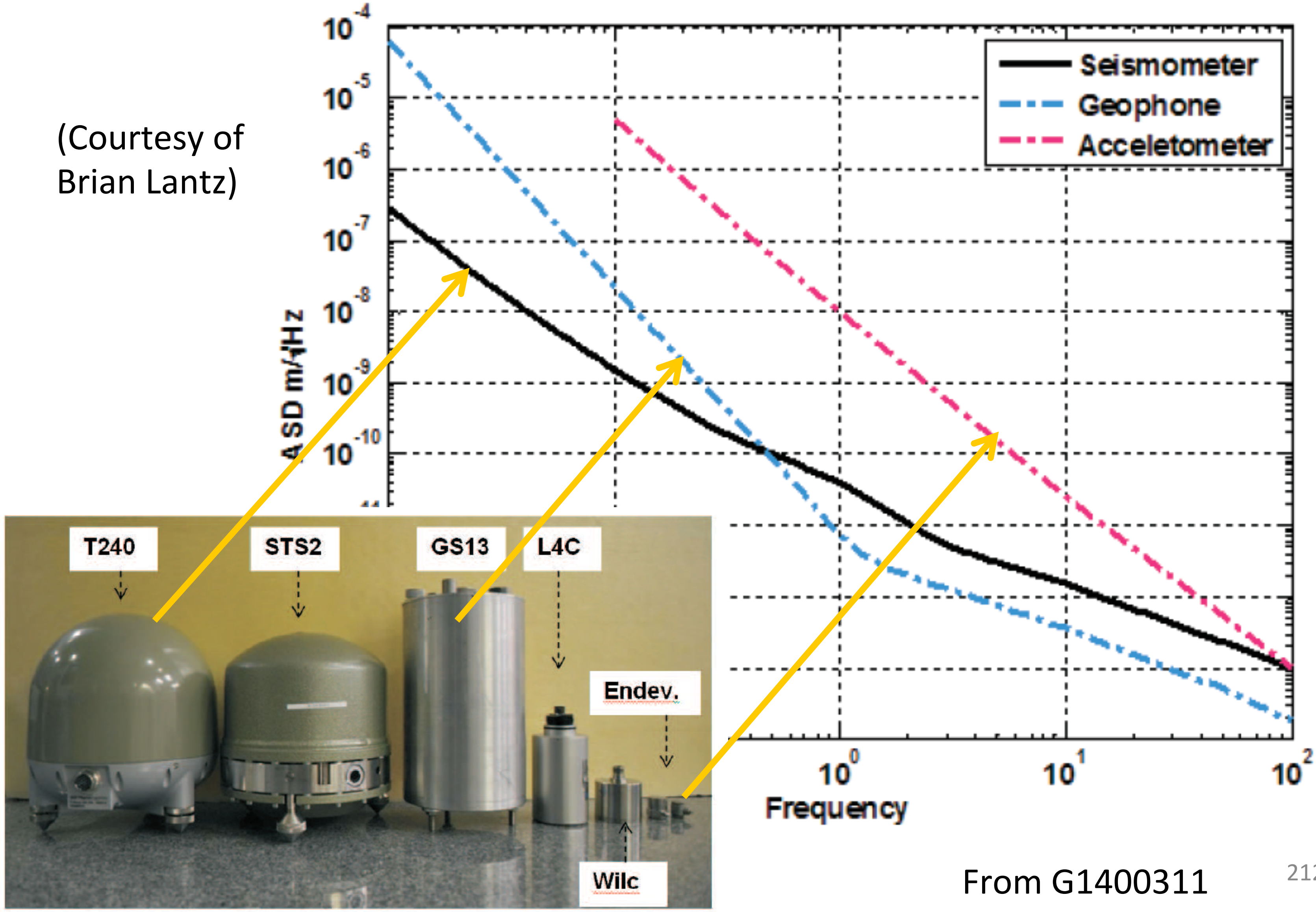
Used On: All Systems

Used For: ≥ 0.5 Hz Control

Used 'cause: Good Noise, Cheap, no locking mechanism -> podded

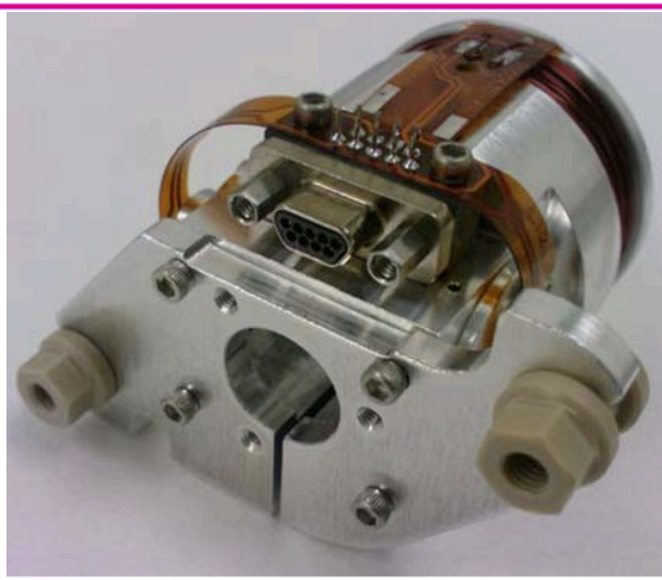
Sensor size and noise

(Courtesy of Brian Lantz)

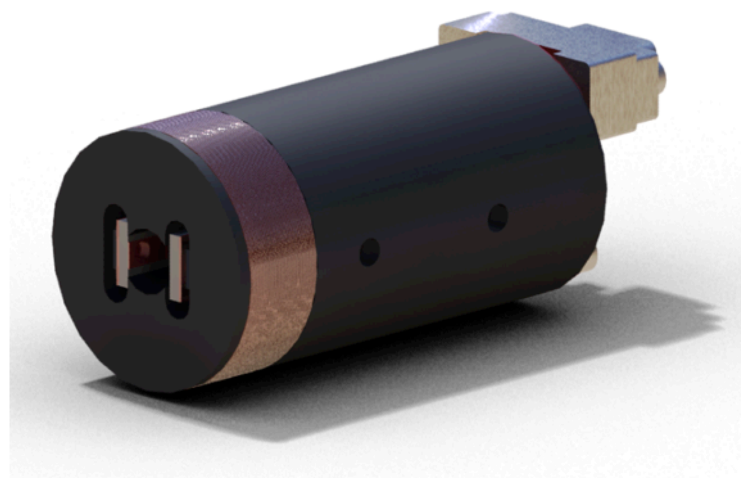


From G1400311

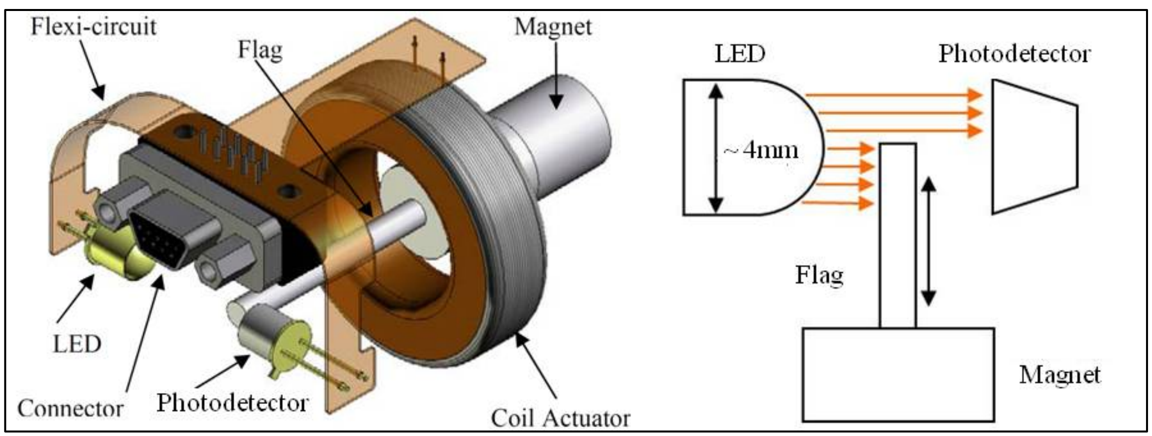
Optical Sensor ElectroMagnet (OSEM)



Birmingham OSEM (BOSEM)



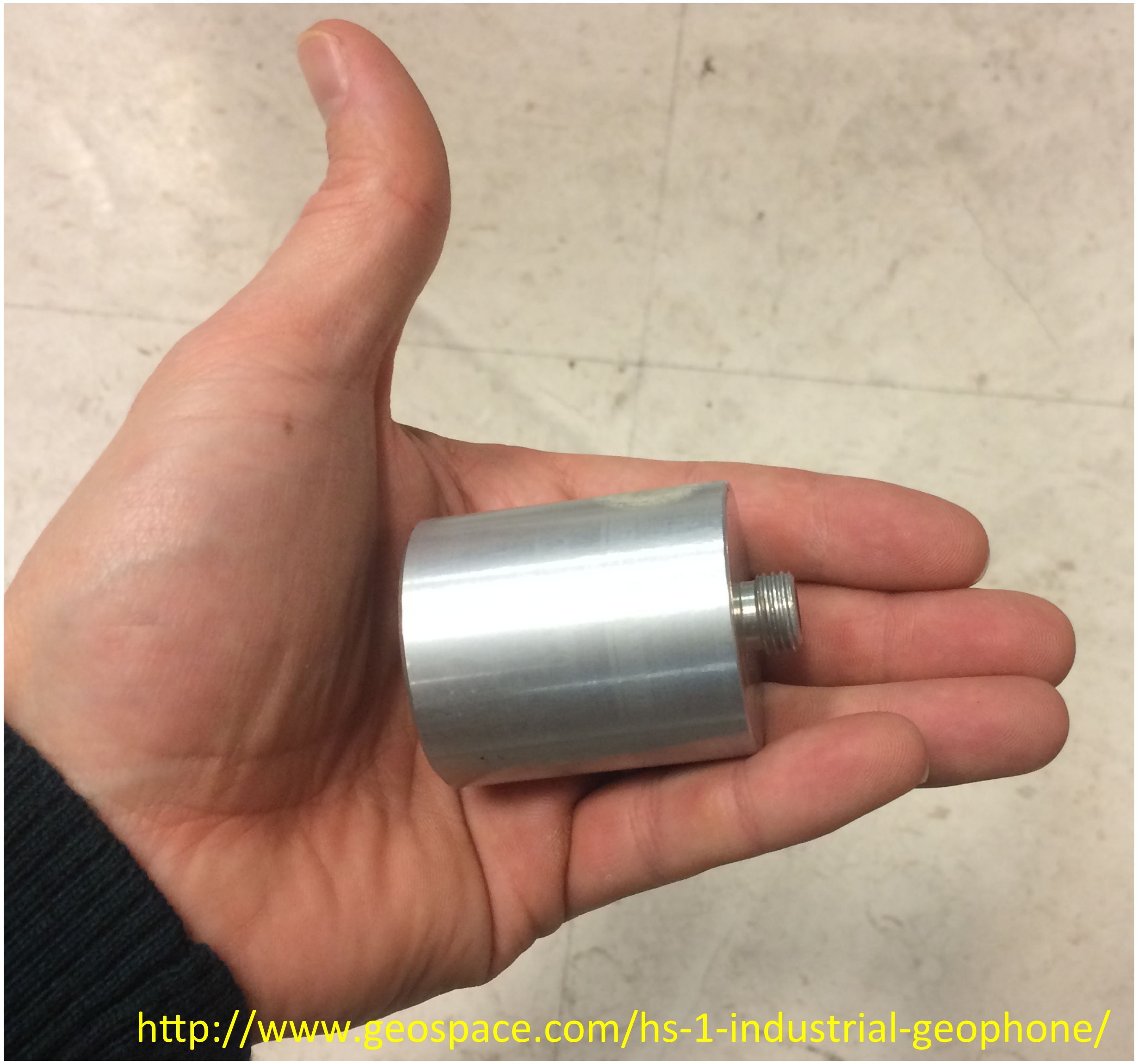
Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM



BOSEM Schematic

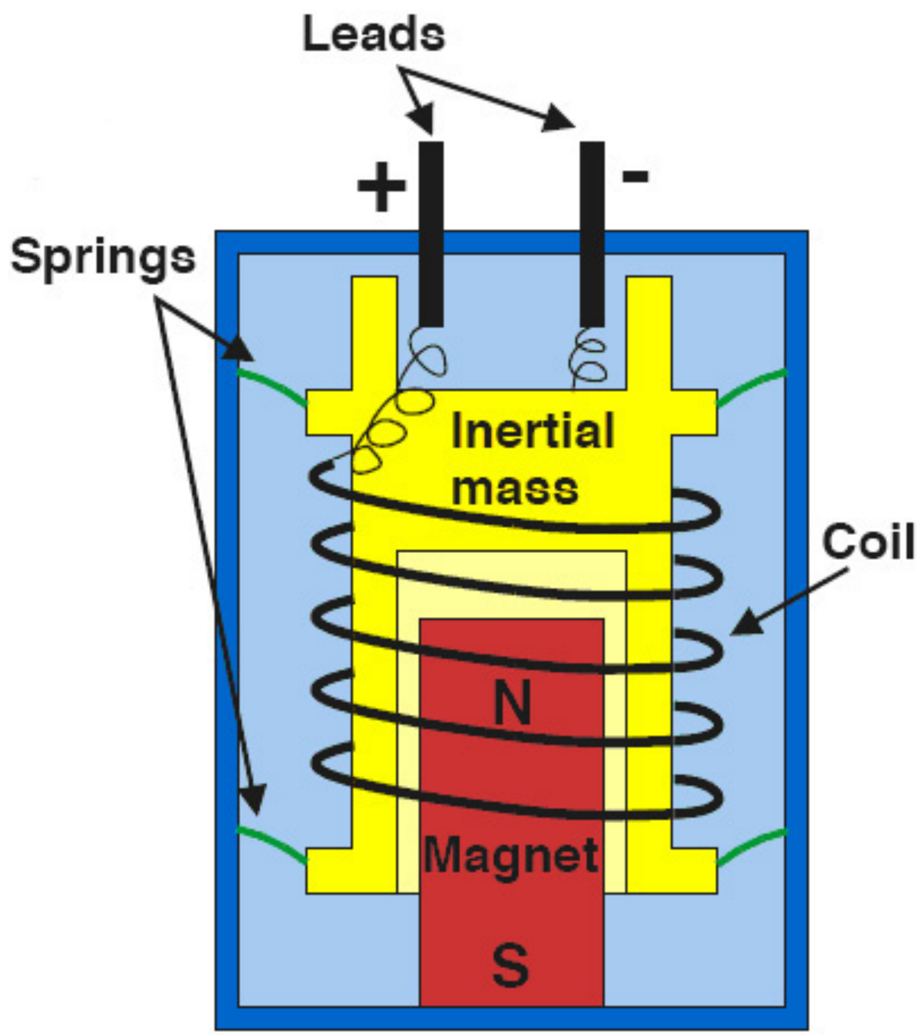
Magnet Types (M0900034)
- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

HS1 Geophones



http://www.geospace.com/hs-1-industrial-geophone/

Geophone Schematic



Source: http://newsline.linearcollider.org/readmore_20070809_ftr1.html