Instrument Response Functions

aka 'The Dark Arts'

Slides first authored and presented by Bob Woodward
Exercises first authored and presented by Suzan van der Lee
Merged and Modified by Suzan van der Lee, with and additional slide form Chuck Ammon.

EarthScope USArray Data Processing Short Course

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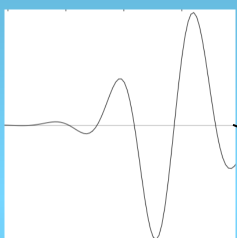
Northwestern University

Outline

- The basics - ground motion to counts
- What each stage does
- Reading RESP files
- When to use ‘em, when to lose ‘em
- Remove the instrument response from a record of choice.

From Earth to Your Desktop

- Key system components
  - Seismometer, digitizer, telemetry, Array Network Facility, DMC
  - Metadata are added by ANF



seismometer

volts

Q330

miniSeed

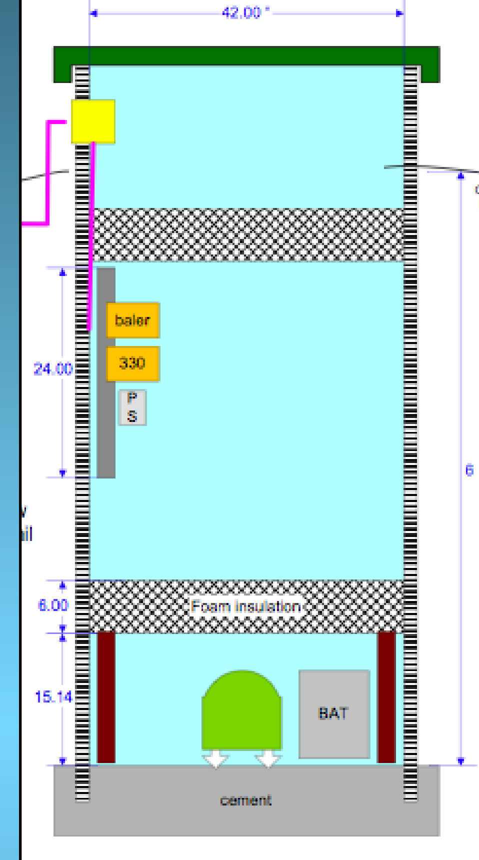
ANF

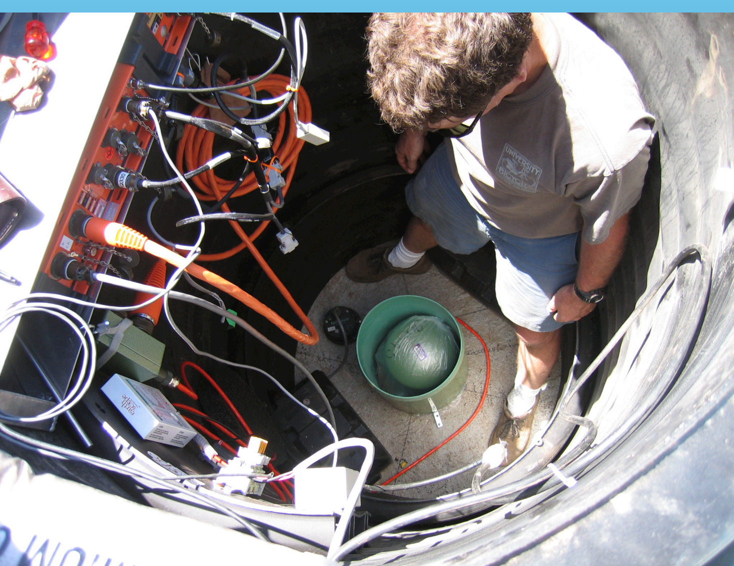
miniSeed & metadata

DMC

miniSeed

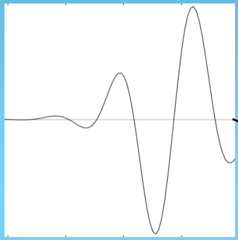
Seed





From Earth to Your Desktop

mechanical response
(poles and zeroes)



electrical response
(“gain factor”)*

seismometer

volts

AD response
(FIR filters)

Q330

counts

miniSeed

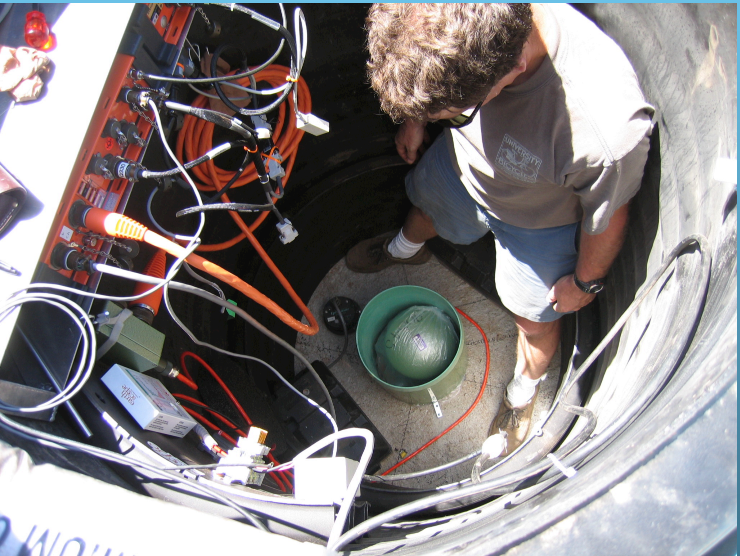
ANF

miniSeed &
metadata

DMC

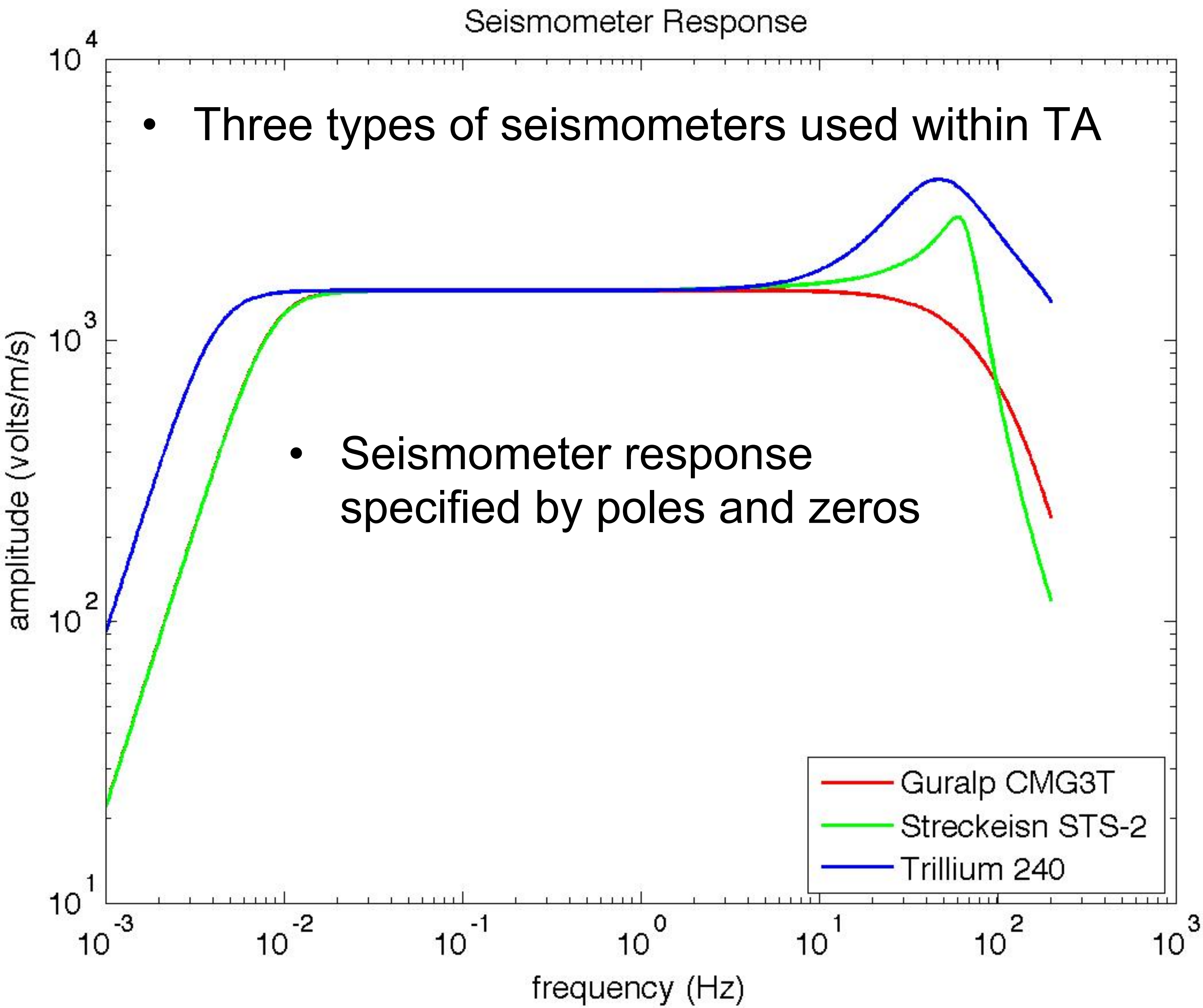
miniSeed

Seed

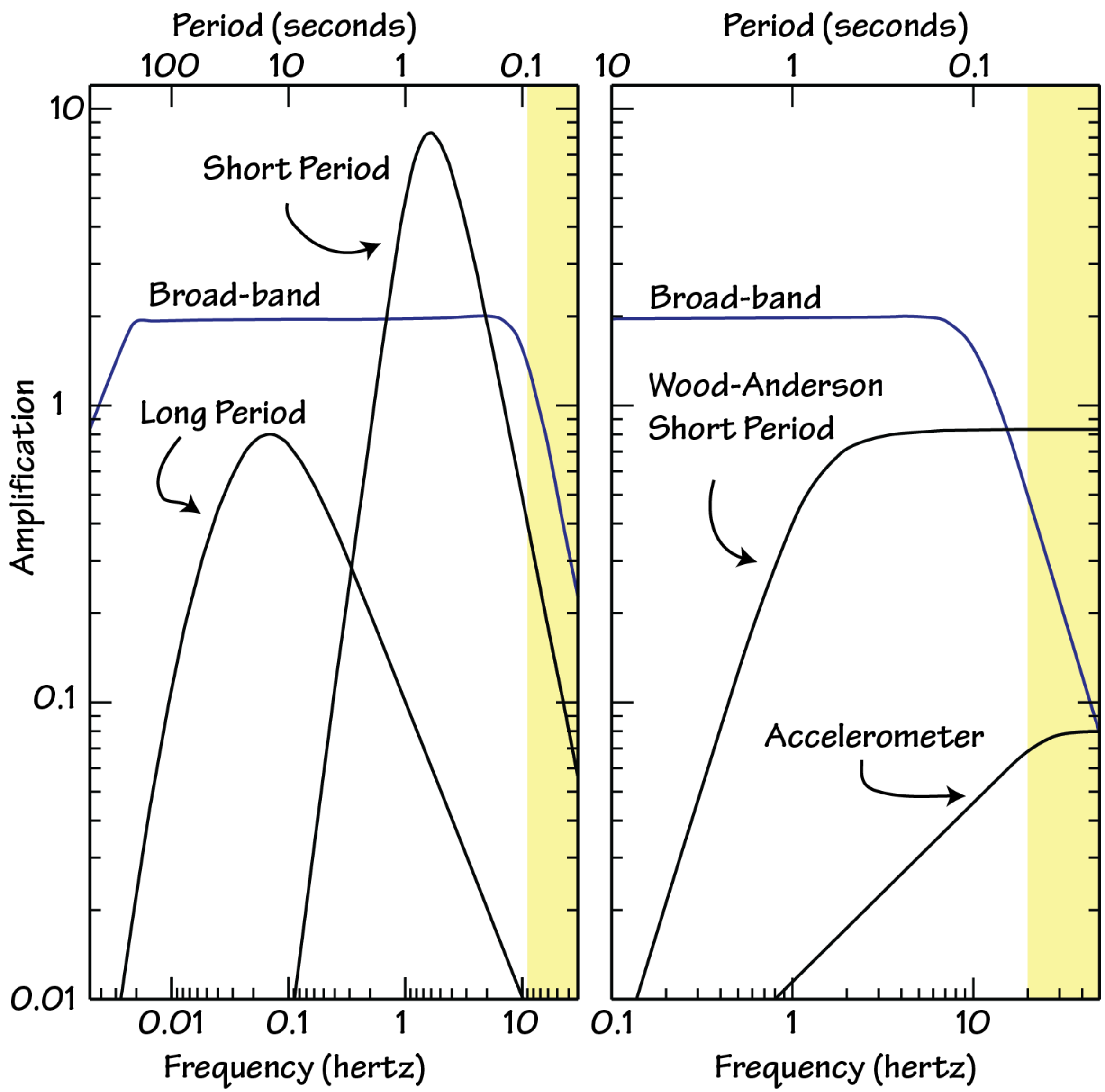


- Three types of seismometers used within TA

- Seismometer response specified by poles and zeros

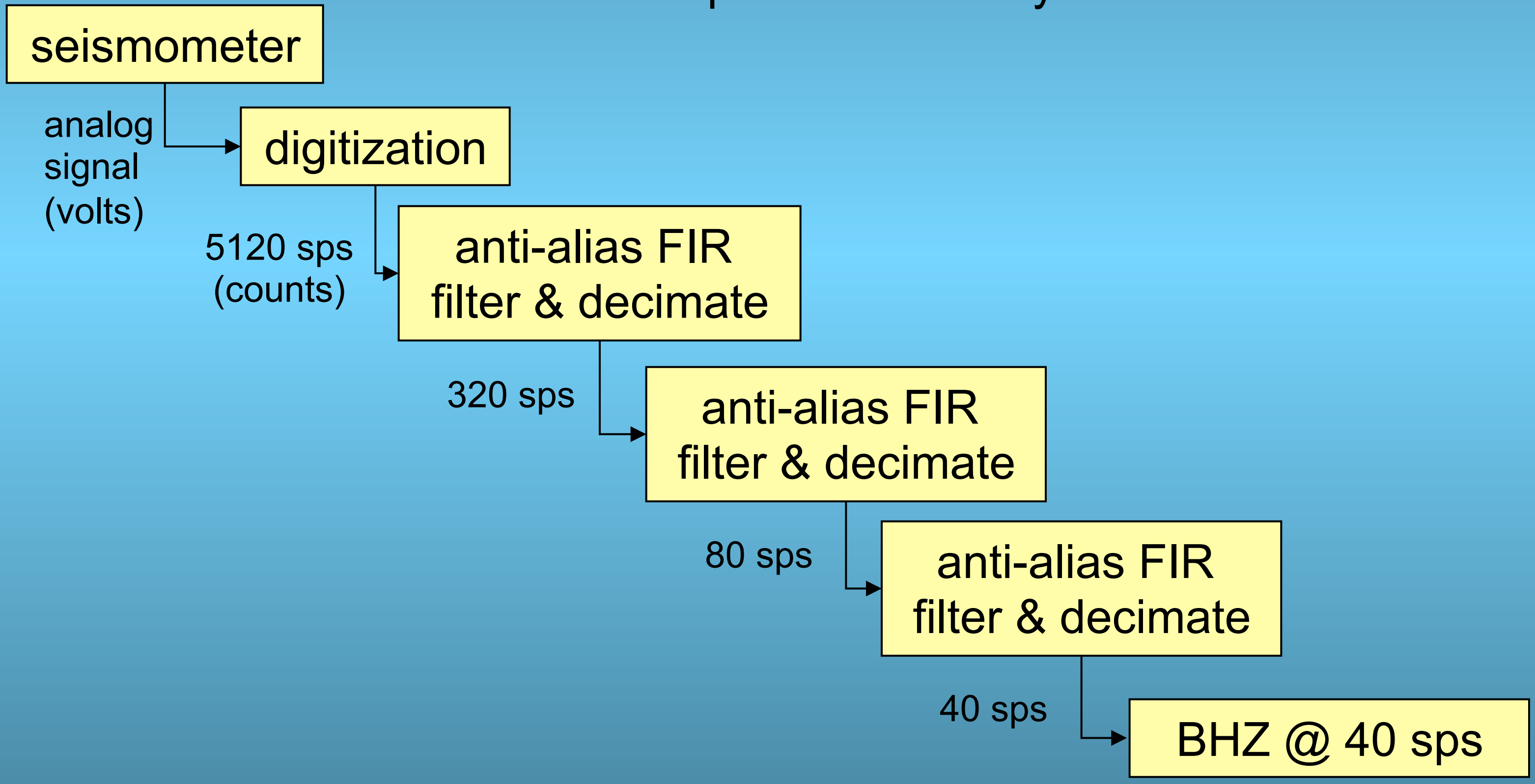


Seismometer Types



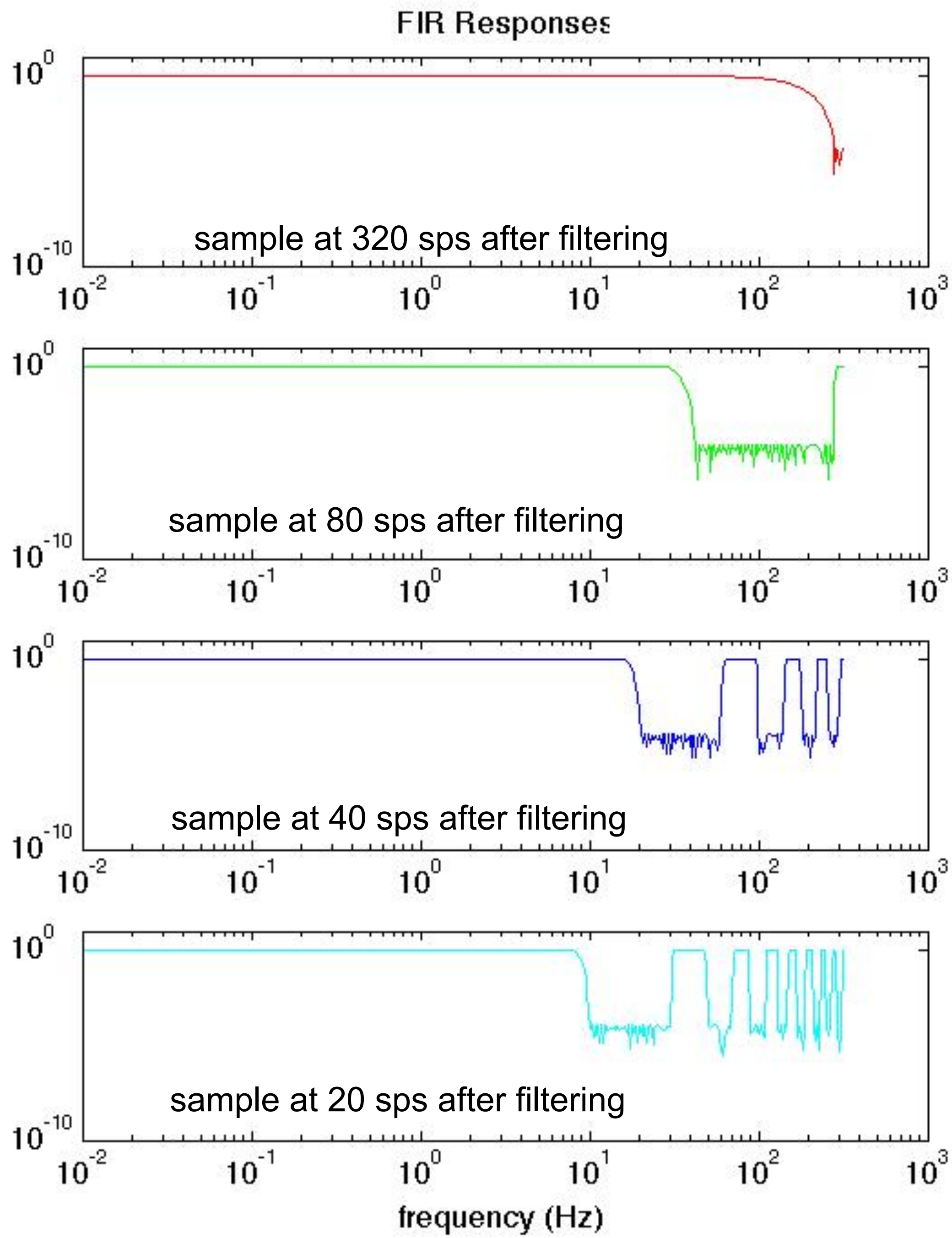
The signal processing chain

- High initial sample rate - no anti-alias filtering
- Cascade of Finite Impulse Response (FIR) filters
  - Provide anti-alias low-pass filters
- Each low-pass followed by decimation



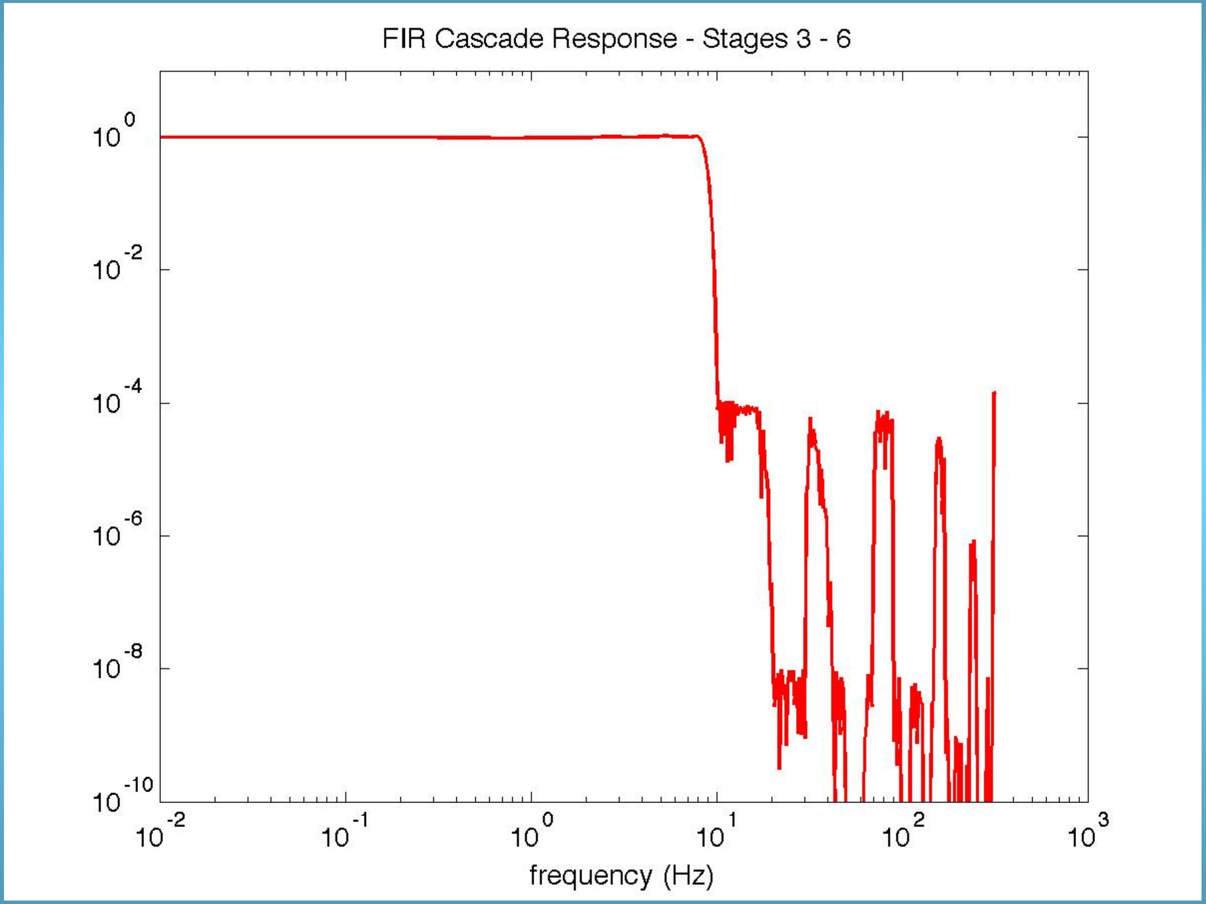
FIR Cascade

- Combined effect of FIR cascade prevents aliasing



FIR Cascade - Cumulative Response

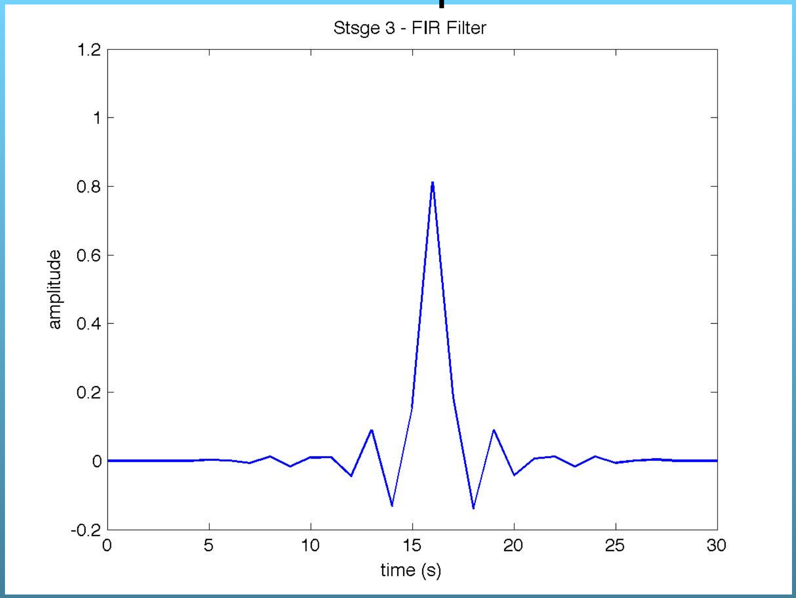
- Response shown for final BH channel sampled at 20 sps



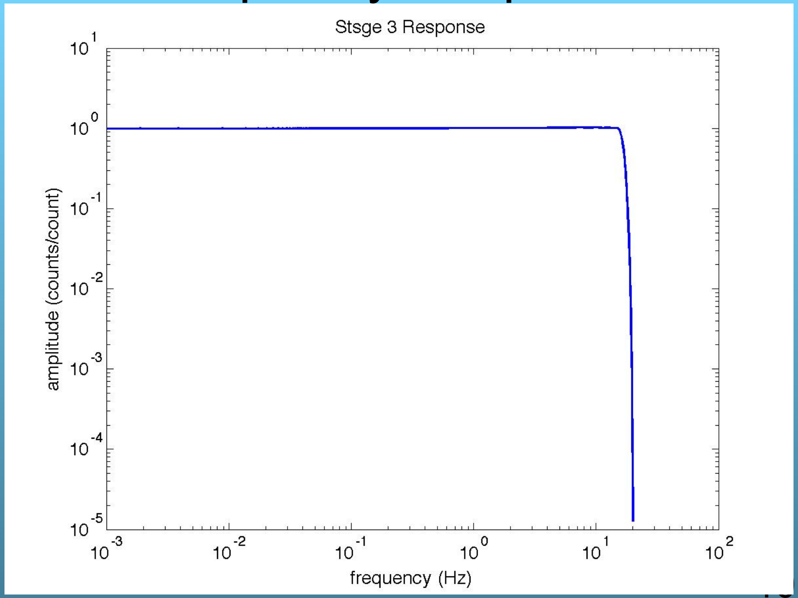
The TA: Composite FIR Filter

- Represent the entire FIR filter cascade with a single filter
- Seed provides time domain representation

Time Domain Representation

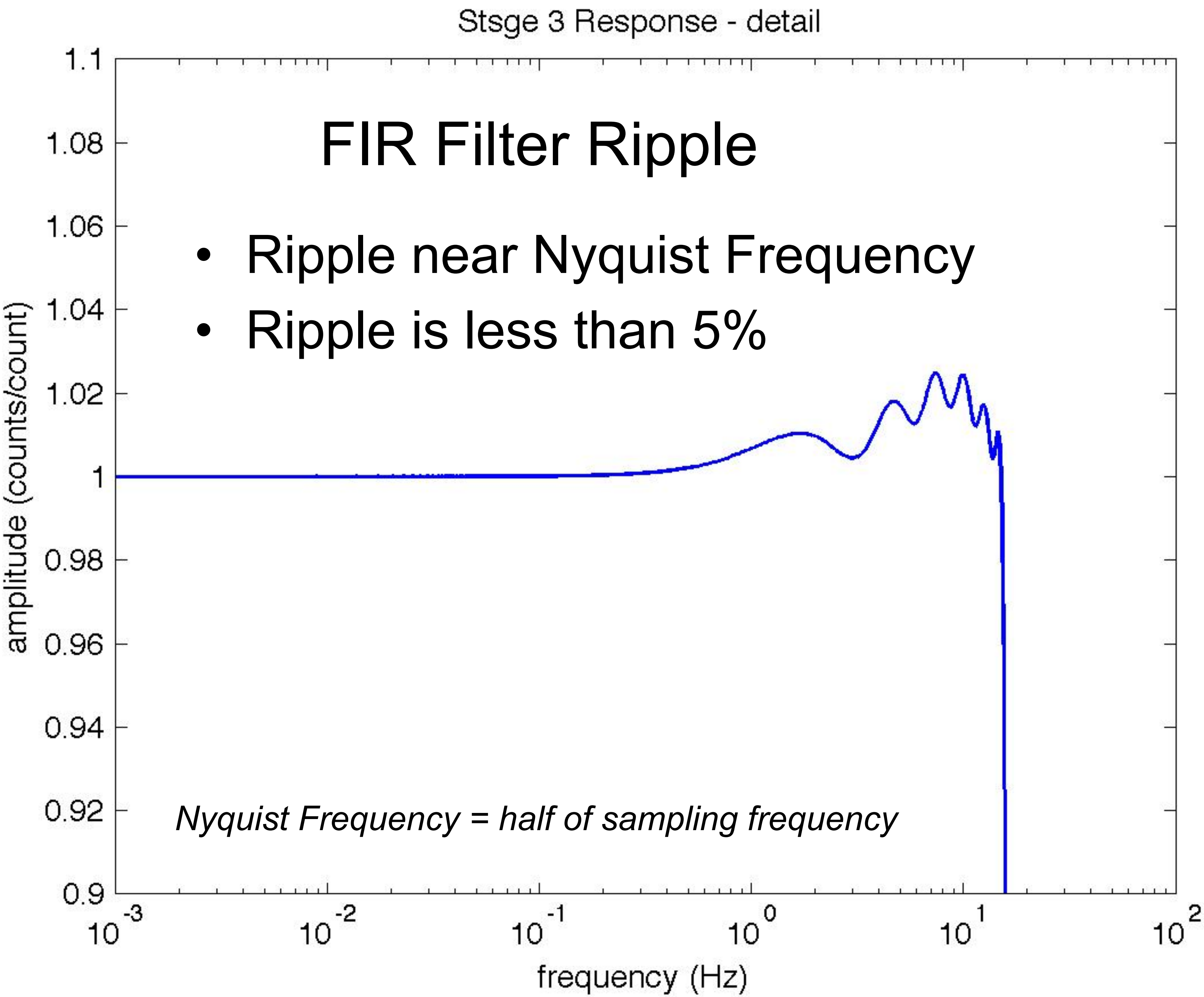


Frequency Response



FIR Filter Ripple

- Ripple near Nyquist Frequency
- Ripple is less than 5%



Nyquist Frequency = half of sampling frequency

Some Comments on Phase

- TA uses Quanterra Q330 data acquisition systems
  - All Q330s in "linear phase" FIR filter configuration

- Linear phase FIR filters
  - Constant phase delay as a function of frequency
    - Phase delay correction is applied
    - Applied correction specified in metadata
  - Acausal

- Q330 can be programmed to use minimum phase filters
    - Causal
    - Non-constant phase
- Want more info?
  - *Of Poles and Zeros* by Frank Scherbaum

Recap on FIR Filters

- What are they used for?
  – Low-pass anti-alias filtering
- When can you ignore them?
  – When working at frequencies reasonably* below the Nyquist frequency
- What are their side-effects?
  – Slight rippling (in amplitude) near Nyquist frequency
  – Acausal ringing for sharp onsets (ringing is at frequencies near Nyquist)
- What can be done about the side-effects?
  – Knowledge is power - steer clear of side-effects

Obtaining the Instrument Response

- SEED volume provides all information (metadata) necessary to compute the *complete** instrument response

- *rdseed* will extract the metadata into ASCII files
  - Use the "-R" option on *rdseed*
  - Creates "RESP" files*

- Key reference on how to interpret the instrument response-related metadata
  - SEED Manual, Appendix C

- What follows are some notes on how to read RESP files

Reading a *RESP* file

- The metadata in SEED volumes are structured into “blockettes”
- Blockettes are structured into fields
- RESP files identify blockette & field
  - Everything to the right of the colon is the field value
  - Comments indicated by “#”

```
#         << IRIS SEED Reader, Release 4.7.5 >>
#
#         ======== CHANNEL RESPONSE DATA ========
B050F03     Station:     X22A
B050F16     Network:     TA
B052F03     Location:    ??
B052F04     Channel:     BHZ
B052F22     Start date:  2008,010,00:00:00
B052F23     End date:    No Ending Time
#         =======================================
```

Stage 1 - Seismometer

```
#          +             +---------------------------------------------+          +
#          +             |   Response (Poles & Zeros),  X22A ch BHZ   |          +
#          +             +---------------------------------------------+          +
#
B053F03     Transfer function type:                A [Laplace Transform (Rad/sec)]
B053F04     Stage sequence number:                 1
B053F05     Response in units lookup:              M/S - velocity in meters per second
B053F06     Response out units lookup:             V - emf in volts
B053F07     A0 normalization factor:               5.714E+08
B053F08     Normalization frequency:               0.2
B053F09     Number of zeroes:                      2
B053F14     Number of poles:                       5
#           Complex zeroes:
#             i  real          imag          real_error    imag_error
B053F10-13    0  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
B053F10-13    1  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
#           Complex poles:
#             i  real          imag          real_error    imag_error
B053F15-18    0 -3.701000E-02  3.701000E-02  0.000000E+00  0.000000E+00
B053F15-18    1 -3.701000E-02 -3.701000E-02  0.000000E+00  0.000000E+00
B053F15-18    2 -1.131000E+03  0.000000E+00  0.000000E+00  0.000000E+00
B053F15-18    3 -1.005000E+03  0.000000E+00  0.000000E+00  0.000000E+00
B053F15-18    4 -5.027000E+02  0.000000E+00  0.000000E+00  0.000000E+00
#
#          +                +--------------------------------------+          +
#          +                |       Channel Gain,  X22A ch BHZ     |          +
#          +                +--------------------------------------+          +
#
B058F03     Stage sequence number:                 1
B058F04     Gain:                                  1.504200E+03
B058F05     Frequency of gain:                     2.000000E-01 HZ
B058F06     Number of calibrations:                0
```

$$G(f) = S_d A_0 \frac{\prod_{n=1}^{N} (s - r_n)}{\prod_{m=1}^{M} (s - p_m)} = S_d A_0 H_p(s)$$

$$s = i 2 \pi f$$

Stage 2 - “Mechanical → electrical”

```
#          +             +----------------------------------------+            +
#          +             |   Response (Coefficients),  X22A ch BHZ   |            +
#          +             +----------------------------------------+            +
#
B054F03    Transfer function type:                D
B054F04    Stage sequence number:                 2
B054F05    Response in units lookup:              V - emf in volts
B054F06    Response out units lookup:             COUNTS - digital counts
B054F07    Number of numerators:                  0
B054F10    Number of denominators:                0
#
#          +                   +------------------------------+                    +
#          +                   |   Decimation,  X22A ch BHZ   |                    +
#          +                   +------------------------------+                    +
#
B057F03    Stage sequence number:                 2
B057F04    Input sample rate:                     4.000000E+01
B057F05    Decimation factor:                     1
B057F06    Decimation offset:                     0
B057F07    Estimated delay (seconds):             0.000000E+00
B057F08    Correction applied (seconds):          0.000000E+00
#
#          +               +---------------------------------------+               +
#          +               |       Channel Gain,  X22A ch BHZ       |               +
#          +               +---------------------------------------+               +
#
B058F03    Stage sequence number:                 2
B058F04    Gain:                                  4.194300E+05
B058F05    Frequency of gain:                     2.000000E-01 HZ
B058F06    Number of calibrations:                0
```

Unit conversion

Digitizer gain

```
#          +              +---------------------------------------+            +
#          +              |   Response (Coefficients),  X22A ch BHZ   |            +
#          +              +---------------------------------------+            +
#
B054F03     Transfer function type:                  D
B054F04     Stage sequence number:                   3
B054F05     Response in units lookup:                COUNTS - digital counts
B054F06     Response out units lookup:               COUNTS - digital counts
B054F07     Number of numerators:                    39
B054F10     Number of denominators:                  0
#           Numerator coefficients:
#             i, coefficient,  error
B054F08-09    0  1.671680E-13  0.000000E+00
B054F08-09    1  5.201300E-07  0.000000E+00
.
.
.
B054F08-09   37  8.027790E-06  0.000000E+00
B054F08-09   38 -4.512370E-06  0.000000E+00
#
#          +                    +-------------------------------+
#          +                    |   Decimation,  X22A ch BHZ    |
#          +                    +-------------------------------+
#
B057F03     Stage sequence number:                   3
B057F04     Input sample rate:                       4.000000E+01
B057F05     Decimation factor:                       1
B057F06     Decimation offset:                       0
B057F07     Estimated delay (seconds):               5.000000E-01
B057F08     Correction applied (seconds):            5.000000E-01
#
#          +                +---------------------------------------+          +
#          +                |       Channel Gain,  X22A ch BHZ      |          +
#          +                +---------------------------------------+          +
#
B058F03     Stage sequence number:                   3
B058F04     Gain:                                    1.000000E+00
B058F05     Frequency of gain:                       2.000000E-01 HZ
B058F06     Number of calibrations:                  0
```

(NB: coefficients deleted to save space)

Stage 3 - Cumulative FIR filter

$$y_k = \sum_{n=0}^{L} b_n x_{k-n}$$

$$G(f) = S_d \sum_{n=0}^{L} b_n z^{-n}$$

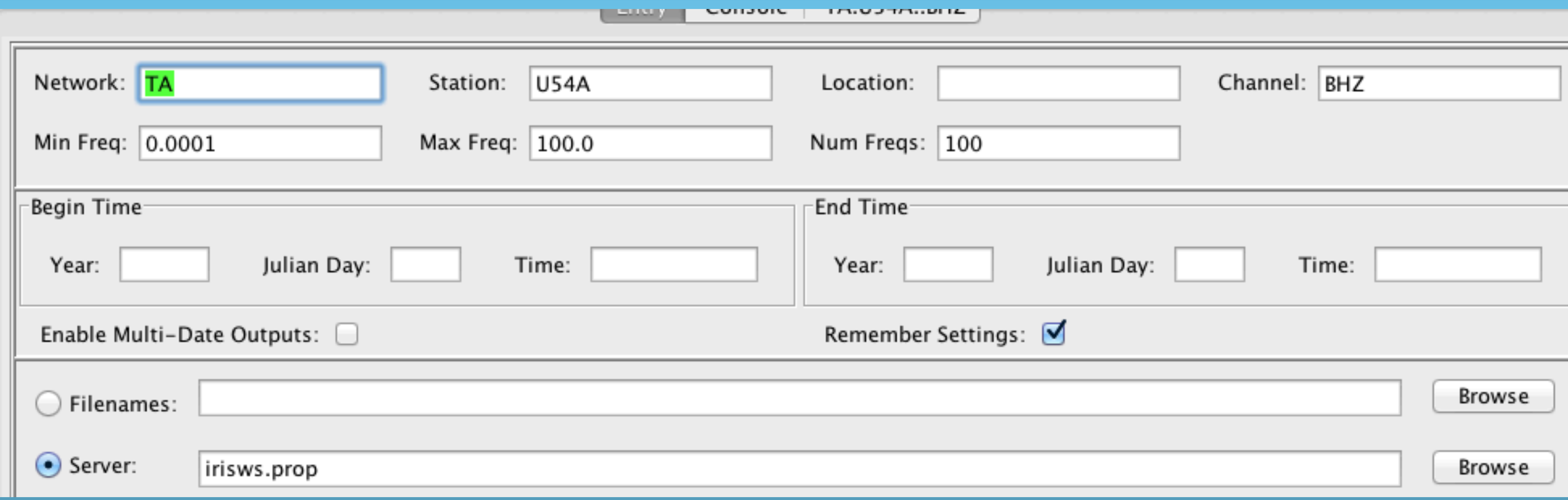
$$z = e^{i2\pi f \delta t}$$

Stage "0" - Overall Sensitivity

```
#        +                +----------------------------------------+                 +
#        +                |   Channel Sensitivity,  X22A ch BHZ   |                 +
#        +                +----------------------------------------+                 +
#
B058F03     Stage sequence number:                  0
B058F04     Sensitivity:                            6.309070E+08
B058F05     Frequency of sensitivity:               2.000000E-01 HZ
B058F06     Number of calibrations:                 0
```

Exploring Instrument Response

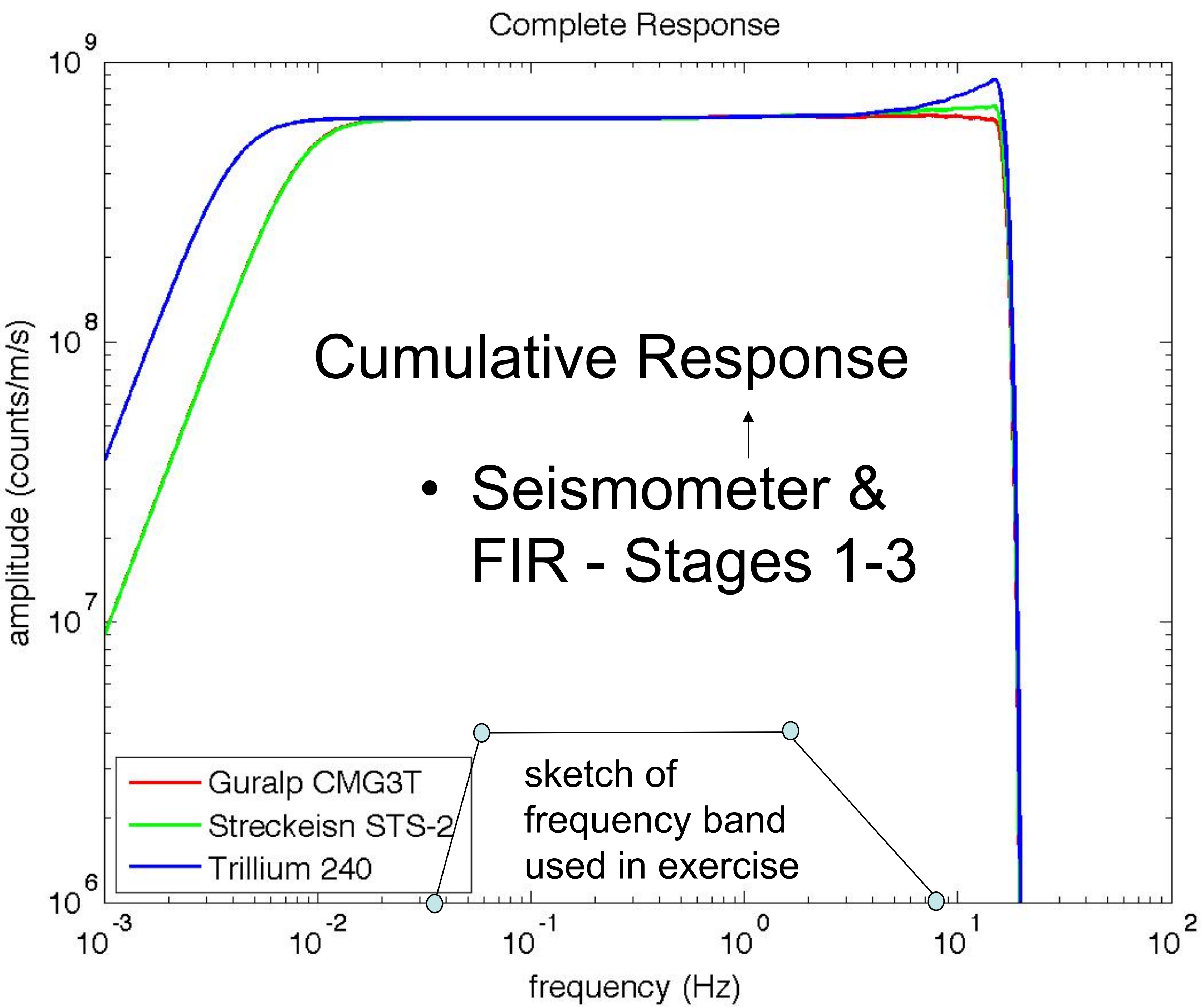
1. Install JPlotResp
2. Start JPlotResp (which you installed on Monday)
3. Enter network “TA” and your favorite station name, e.g. U54A at Nelson’s Funny Farm, TN.



5. Select the Server:irisws radio button (web services)
6. Click “Plot” at the bottom

Exploring Instrument Response

1. Now look at each of the three stages separately using the "Start Stage" and "End Stage" fields.
2. Now use "0" for both Stage fields.
3. Describe differences between the four plots and discuss with your neighbors.
4. Try to explain differences between the four plots and share with the class.


Complete Response
Cumulative Response
• Seismometer &
FIR - Stages 1-3
sketch of
frequency band
used in exercise
Guralp CMG3T
Streckeisn STS-2
Trillium 240
amplitude (counts/m/s)
frequency (Hz)
10^9
10^8
10^7
10^6
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2

Summary - Instrument Responses

- Working in the "pass band"?
  - Simply using overall sensitivity may be sufficient
  - Amplitude response virtually constant
- For most applications simply using the poles and zeros is sufficient
  - Can safely neglect the FIR filters most of the time
- Be careful of working up against the Nyquist
  - Acausal ringing
  - Some ripple - but less than 5%
- Tools such as *evalresp* and *SAC* make it easy to work with responses
- Bigger worry
  - Structuring your instrument response calculations (e.g., deconvolution) for numerical stability

Exercise

1. Open SAC
2. Type “help transfer”
3. Look over the entire *document* that is SAC’s response to your request for help.
4. Read the section “EVALRESP OPTION”

Removing an Instrument Response

1. Find files extracted from a full seed volume in the shared Wednesday folder.
2. Extracted files are SAC “data” (waveforms), PZ files, and RESP.* files:
   - rdseed -d -p -R -f 2011-08-23_MW5.7_Virginia.93351.seed
   - Choose your favorite TA (or other station), let;s say it’s “ISCO”
3. then run SAC
   - SAC> qdp off
   - SAC> r *.ISCO.*BHZ*SAC
   - SAC> p
   - SAC> rtrend
   - SAC> taper
   - SAC> p
   - SAC> w over
   - SAC> setbb pziscoz SAC_PZs_US_ISCO_BHZ_00_2011.094.21.39.00.0000_2013.220.16.43.60.99999
   - SAC> transfer from polezero subtype %pziscoz to none FREQ 0.004 0.006 2 3

Removing an Instrument Response

1. Save the result of the transfer command and compare the original waveform. What happened?
2. What happens if you do not remove the mean and linear trend (rtrend)?
3. What happens if you do not taper the ends of the waveform to 0 start and ending values (taper)?
4. What response stage is taken into account by this transfer command?

Removing an Instrument Response

1. Find the sensitivity for stage 0 in the RESP file for your chosen station and channel.
2. Go back to SAC
   - SAC> r <the result of your prior transfer command>
   - SAC> mul <what value you found for stage-0 sensitivity>
   - SAC> dif
   - SAC> p
3. Save this result and compare it to the original waveform. What happened?

Removing an Instrument Response

1. Back to SAC
   - SAC> r *ISCO.*BHZ* (The version already detrended and tapered)
   - SAC> transfer from evalresp fname RESP.US.ISCO.00.BHZ to none FREQ 0.004 0.006 2 3
2. How does this result compare to the previous using the PZ file?
3. How does the result below compare to the uncorrected seismogram?
   - SAC> r *ISCO.*BHZ* (The version already detrended and tapered)
   - SAC> transfer from evalresp fname RESP.US.ISCO.00.BHZ to vel FREQ 0.004 0.006 2 3
4. Can you **discuss** these differences with your neighbors?
5. What are/should be the units on the vertical axis?

Exercise

1. Find the IRIS web service (http://services.iris.edu) for time series.
2. Find out how to convert “counts” (the ground motion value plotted on the y axis) to m/s (SI units) via a simple scaling factor.
3. Choose “output=plot” and plot your favorite seismogram in SI units[1].

1. This is very useful for outreach and teaching!

Removing an Instrument Response

1. Find the value of the Sensitivity for the various non-zero stages in the RESP file and multiply them. Compare the result with the stage-zero sensitivity and **share** and discuss with others.
2. Find the value of the A0 normalization constant and the stage 0 sensitivity and multiply them. Compare this number to the CONSTANT in the PZ file and **share** and discuss with others.
3. Do the PZ and RESP files have the same poles and zeroes? **Discuss** and **explain** any differences

Removing an Instrument Response

Think about your own research.

Do you need to correct your waveforms for the instrument response?

Share with neighbors and/or the class.