Instrument Responses

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IRIS DMC
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What is an Instrument Response?

A response describes how an instrument changes an input signal to produce an output signal.
When are Instrument Responses Important?

\[
\text{TimeSeries}_1(t) = \text{Source}(t) \times \text{Earth}(t) \times \text{Instrument}_1(t)
\]
\[
\text{TimeSeries}_2(t) = \text{Source}(t) \times \text{Earth}(t) \times \text{Instrument}_2(t)
\]
When are Instrument Responses Important?

TimeSeries1(t) = Source(t) * Earth(t) * Instrument1(t)
TimeSeries2(t) = Source(t) * Earth(t) * Instrument2(t)

When you’re:

♫ Studying wave sources
♫ Studying earth structure or propagation effects
♫ Studying ground motion (size and units matter)
♫ Comparing or using records from diverse instrumentation
♫ Archiving data for others’ use
When are Instrument Responses Not Important?

\[
\text{TimeSeries}_1(t) = \text{Source}(t) \times \text{Earth}(t) \times \text{Instrument}_1(t) \\
\text{TimeSeries}_2(t) = \text{Source}(t) \times \text{Earth}(t) \times \text{Instrument}_2(t)
\]

Sometimes when you’re:

- Imaging
- Picking
- Using homogeneous instrumentation
- Unconcerned about size and units
Anatomy of an Instrument Response

- The sequence is the “response cascade”
- Each step within the cascade is a “stage”
- Cascade each stage in the order in which it was applied during recording
What We’ll Do

- Sensors & Amplifiers
  - Where do amplitude and phase response (Bode) plots come from?
  - Where do poles and zeros come from?
  - How are amplitude & phase responses related to poles & zeros?
  - SEED sensor and amplifier responses
  - Other useful things to know about sensor and amplifier responses
What We’ll Do

- Dataloggers and Filters
  - How dataloggers work
  - Analog to Digital Conversion
  - Oversampling, decimation and other filtering
  - Where do FIR coefficients come from?
  - How are amplitude and phase responses related to FIR coefficients?
  - SEED datalogger and filter responses
  - Other useful things to know about datalogger and filter responses
What We’ll Do

- Response Tools and Notes
  - Nominal Response Library
  - Retrieving responses from the DMC
  - Writing responses (dataless SEED)
  - Removing instrument responses
  - Verifying responses
Sensors

- have continuous inputs and outputs (they’re analog!)

- They usually change the units of the property being measured into Volts.

- Solving the sensor’s equation for its output at all frequencies gives us its frequency response function (a polynomial) that describes the sensor’s frequency-dependent amplitude and phase changes.

- The frequency response function is a special case of the more descriptive transfer function – a polynomial that can be defined by its roots (poles and zeros) if factored, or from its coefficients if expanded form.
Sensor Example: Passive Seismometer

Equation of Motion

\[ x'' + 2h\omega_0 x'(t) + \omega_0^2 x(t) = -u''(t) \]

where

- \( x(t) \) = relative mass displacement
- \( u''(t) \) = ground acceleration (input signal)
- \( \omega_0 \) = angular natural frequency
- \( h \) = damping factor (0 <= h <= 1)

From Scherbaum (1996)
Sensor Example:
Passive Seismometer

From differential equations, we know to try a solution that describes harmonic oscillation where

\[ x(t) = A_0 e^{j\omega t} \]

\[ x'(t) = j\omega A_0 e^{j\omega t} \]

\[ x''(t) = -\omega^2 A_0 e^{j\omega t} \]

\[ u''(t) = -\omega^2 A_1 e^{j\omega t} \]

\( \omega \) is a constant angular frequency, for now

and for constant \( \omega \)

\( \text{Real}\{x(t)\} \) is a cosine wave with amplitude \( A_0 \)

\( \text{Imaginary}\{x(t)\} \) is a sine wave with amplitude \( A_0 \)
Linear Time-Invariant Systems

- But we’d like to solve for all frequencies. Fortunately, seismometers are linear time-invariant systems (LTI), meaning that for a function $\phi$ that converts input signal $u(t)$ to output signal $x(t)$

$$x(t) = \phi[u(t)]$$

- Superposition is valid

$$\Phi[u_1(t) + u_2(t)] = \phi[u_1(t)] + \phi[u_2(t)]$$

- And the order in which we scale doesn’t matter

$$\phi[A_1u(t)] = A_1\phi[u(t)]$$

- Regardless of when we perform these operations
So we can use the Fourier Transform (the sum of solutions over all $\omega$) to describe the behavior of a sensor over all $\omega$. Making earlier substitutions and simplifying

$$-\omega^2 A_0 + 2h\omega_0 j\omega A_0 + \omega_0^2 A_0 = \omega^2 A_i$$

Solving for the ratio of output/input gives the **Frequency Response Function**

$$T(j\omega) = \frac{A_o}{A_i} = \frac{\omega^2}{[\omega_0^2 - \omega^2 + j2h\omega_0\omega]}$$
Frequency Response Function

Where the Real part of the Frequency Response Function describes Amplitude as a function of frequency

\[ |T(j\omega)| = \frac{|A_o/A_i|}{|A_o/A_i|} = \frac{|A_o|}{|A_i|} \]

\[ = \omega^2 / \{\sqrt{\omega_0^2 - \omega^2}^2 + 4h^2w_0^2w^2\} \]

And the phase angle is

\[ \phi(\omega) = \arctan(\text{Imaginary}/\text{Real}) \]

\[ = \arctan(-2h\omega_0\omega / \omega_0^2-\omega^2) \]
The plots of amplitude and phase as a function of frequency are often called Bode plots.

- Phase is $\sim 0$ at frequencies in the passband.
- Phase varies rapidly near the natural period.
Non-Linear Systems

- When the output of a system depends strongly on the input amplitude, superposition and scaling do not hold.

- Examples of nonlinear behavior include:
  - Seismometers with off-center masses
  - Analog to digital convertors with a faulty resistor
  - Others?
Transfer Function

Another way to solve the seismometer’s equation of motion is to solve its Laplace transform. Recall that

\[ x'' + 2h\omega_0 x'(t) + \omega_0^2 x(t) = -u''(t) \]

Substituting

\[ x(t) \leftrightarrow X(s) \]
\[ x'(t) \leftrightarrow sX(s) \]
\[ x''(t) \leftrightarrow s^2 X(s) \]
\[ u''(t) \leftrightarrow s^2 U(s) \]
\[ s = \sigma + j\omega \]

Substituting

\[ s^2 X(s) + 2h\omega_0 sX(s) + \omega_0^2 X(s) = -s^2 U(s) \]
Transfer Function

\[ s^2X(s) + 2\omega_0 sX(s) + \omega_0^2 X(s) = -s^2U(s) \]

- Solving for the ratio of output/input gives the Transfer Function
  \[ T(s) = \frac{X(s)}{U(s)} \]
  \[ = \frac{-s^2}{[s^2 + 2\omega_0 s + \omega_0^2]} \]

- Values of \( s \) that make the numerator go to zero are “zeros”. Where are they in this example?

- Values that make the denominator go to zero are “poles”. Factoring the denominator gives the value of its two poles
Transfer Function

\[ T(s) = \frac{-s^2}{s^2 + 2h\omega_0 s + \omega_0^2} \]

\[ = \frac{-s^2}{(s - p_1)(s - p_2)} \]

Factoring the denominator using the quadratic equation, gives two poles

\[ p_1 = -[h - \sqrt{h^2 - 1}] \omega_0 \]

\[ p_2 = -[h + \sqrt{h^2 - 1}] \omega_0 \]

If the sensor is underdamped \((h<1)\), the term under the \(\sqrt{}\) will be imaginary.

You can recreate the transfer function knowing just its poles and zeros.

You can also recreate the transfer function if you store the coefficients of the numerator \((0, 0, -1)\) and denominator \((\omega_0^2, 2h\omega_0, 1)\)
Relationship between the Frequency Response and Transfer Functions

Notice how similar the Transfer and Frequency Response Functions are.

Recall that complex $s = \sigma + j\omega$.

The Frequency Response Function is a special case of the Transfer Function where $\sigma = 0$.

In other words, the Frequency Response Function is the imaginary part of the Transfer Function.

$$T(s) = \frac{-s^2}{[s^2 + 2h\omega_0 s + \omega_0^2]}$$

$$T(j\omega) = \frac{\omega^2}{[-\omega^2 + j2h\omega_0 \omega + \omega_0^2]}$$
Relationship between the Frequency Response and Transfer Functions

- The **corner frequency** of a pole or zero can be found by taking its modulus ($\sqrt{Re^2 + Im^2}$). Remember that you may need to convert from radians into Hz!

- Each **zero** introduces a **positive** slope of the amplitude response on a log-log plot by 6 dB/octave (or 20 dB/decade) at frequencies higher than its corner frequency.

- Each **pole** introduces a **negative** slope of the amplitude response on a log-log plot by 6 dB/octave (or 20 dB/decade) at frequencies higher than its corner frequency.

- A pole and zero at the same corner frequency will cancel each other.
Relationship between the Frequency Response and Transfer Functions

Network: XX, Station: NS305, Channel: SHZ
BeginTime: 2006,1,00:00:00
MinFreq: 0.0001, MaxFreq: 10,000.000000001, NumFreqs: 10001, Spacing: Logarithmic
OutputUnits: Default, SensFreq=5.0Hz, NormA0=1.0
A Note About the Time Domain

- Superposition and Scaling allow us to multiply the Amplitude spectra of successive LTI response stages in the frequency domain. The time-domain equivalent of this is convolution.

- There is also a time-domain representation of the response called the Impulse Response Function. It is the output signal that results from a dirac delta input signal.

- The Fourier Transform of the Impulse Response Function is the Frequency Response Function.

- The Laplace Transform of the Impulse Response Function is the Transfer Function.

- Manufacturers often “fit” poles and zeros to the Fourier Transform of the impulse response rather than deriving them.
SEED Sensor Stage

- Input units reflect what sensor measures (SI units)
- Pole-zero curve is normalized (=1 in passband). $A_0$ must have same units as poles and zeros
- Poles and zeros can be listed in units of Radians (A – most common) or Hz (B). (1 radian = $2\pi$ Hz)

The stage 1 Gain blockette lists the sensor sensitivity.
Normalization

- You normalize the pole/zero curve so that you can multiply by the sensor gain and the resulting curve will equal the sensor gain in the passband.

- $A_0$ is the factor you multiply the pole/zero curve by at the normalization frequency to get a value of 1.

- If your sample rate is low enough that sensor normalization frequency is no longer in the passband, you may need to normalize at a lower frequency.

- If the passband is not exactly flat and you need to move your normalization frequency, you may need to specify a sensor gain that differs a little from that reported by the manufacturer.
Normalization

Suppose the sensor gain is known at 1 Hz, but your 1 sps LHZ channel has no amplitude there?

1. Find a lower frequency in the passband.
2. Find the sensor gain value at that frequency (plot only the sensor stage).
3. Find and enter A0 for the new frequency.
4. Change the sensor gain to the value in step 2.
For SEED, it’s preferred that the sensor’s response have a passband that is flat to the property being measured. A velocity transducer should have a “velocity response” – its passband is flat to velocity with input units of Meters/second.

It’s also possible to create an “acceleration response” for a velocity transducer. Since $T'(s) = sT(s)$, taking the derivative of a velocity response adds a zero at 0.

Creating a “displacement response” from a velocity response is equivalent to removing a zero since integrating $T(s)$ is equivalent to dividing by $s$. 
How Do These Differ?
How Do These Differ?
Many dataloggers have analog preamplifiers that boost signal prior to digitization. Some stations use separate amplifiers.

Amplifiers change only the amplitude of the signal independently (we assume) of frequency.

In SEED, it is recommended that the amplifier have its own stage and include only a Gain description.
More about Sensors

Passive velocity seismometers

- have a simple mass-spring-damping system that requires no electricity for operation.
- have 2 zeros at 0 and 2 poles at the natural period related to the mass-spring system.
- sensitivity, poles, zeros and damping depend on their resistors, mass, period and mechanical damping as described here: http://ds.iris.edu/NRL/sensors/sercel/passive_responses.html
- If the impedance contrast between sensor and amplifier is less than 2 orders of magnitude, the amplifier will change the sensor damping and, therefore, its poles and zeros.
More about Sensors

Active velocity seismometers

- use feedback electronics to modify the natural period of the mass-spring system and to control the damping, therefore they require electricity for operation

- Have 2 zeros at 0, 2 poles at the natural frequency, plus additional poles and/or zeros at higher frequencies that describe the feedback electronics
Dataloggers

- may include an analog preamplifier that changes the gain of the signal
- sample the input voltage, changing its gain and units and creating an initial sample rate
- decimate the sampled voltage using digital Finite Impulse Response (FIR) filters, which changes its sample rate and occasionally changes its gain.
- may include additional filters such as
  - an analog anti-alias filter,
  - Infinite Impulse Response (IIR) filters
Dataloggers

Analog to Digital Conversion

- A simple analog to digital converter (ADC) samples by comparing an input voltage at regular time intervals to reference voltages to determine its size.

- The states for comparators L1, L2 and L3 are initially (0,0,0).
- Each comparator whose voltage is exceeded by Vin gets set to 1.
- A voltage with comparator states (1,1,0) has 2 counts.

From Havskov and Alguacil, 2004
Dataloggers

Analog to Digital Conversion

- The input sample rate is determined by the ADC.
- The ADC scale factor in Counts/Volt depends on the ADC size (the number of comparisons it can make = the number of counts it can recognize) and the voltage range allowed. So a true 24-bit ADC sampling a voltage range of 40 Vpp has scale factor:

\[
\text{ADC scale factor} = 2^{24} \text{ Counts} / 40 \text{ Volts} = 4.194 \times 10^5 \text{ Counts/Volt} = 1 \text{ / Least Significant Bit (LSB)}
\]

Voltage Range Equivalents
- 40 Volts peak-to-peak (Vpp)
- 20 Volts peak (Vp)
- +/-20 Volts Full Scale Voltage
SEED ADC Stage

Analog to Digital Conversion

Digital stage
Units change
One coefficient (unity)
Input sample rate
This is not a FIR stage, so FIR delays are zero
ADC scale factor & normalization frequency
Dataloggers

FIR Filtering - Oversampling and Decimation

Older dataloggers relied on an analog anti-alias low-pass filter to prevent aliasing during sampling.

Modern dataloggers oversample and decimate data using digital Finite Impulse Response (FIR) filters. FIR filtering extends the passband up to 70-90% of the Nyquist frequency.

Oversampling and FIR Decimation also mitigates quantization noise.
Dataloggers

**FIR Filters**

- are digital filters typically represented in the time domain using coefficients.
- are weighted averages – they decimate by averaging the amplitudes of surrounding input samples to obtain output samples (stable).
- must average future samples, so there is a delay caused by waiting for these future samples to arrive. Dataloggers correct time tags for this delay.
- must be normalized (the coefficients must sum to 1) or else they will change the gain of each sample.
Dataloggers

Because FIR Filters average amplitudes over neighboring samples, they mitigate quantization error.

From Scherbaum (1996)
Dataloggers

FIR filters are

- zero phase (they don’t alter phase),
- low-pass filters with
- unity gain (they don’t alter amplitude).

Their decimation factor reflects how frequently they are applied to the input time series.
SEED FIR Stages

- Digital stage, units of Counts
- Normalized coefficients
- Input sample rate & decimation factor
- FIR delay (positive) = (\#coeffs - 1) / (2 \times \text{Input sample rate}) for symmetric (acausal or zero-phase) filters
- Unity gain at the normalization frequency
Dataloggers

Analog Anti-Alias Filters

Some dataloggers have an analog anti-alias filter between the preamp and the ADC. It is described using poles and zeros. The following example is from the Nanometrics Taurus.

Input and Output units are Volts

Gain need not be unity
Dataloggers

Infinite Impulse Response (IIR) filters

❖ Some dataloggers have an optional Infinite Impulse Response (IIR) filter available.

❖ IIR filters are computationally fast compared to FIR filters – they depend on fewer samples.

❖ A value calculated by an IIR filter includes previous output samples to which the IIR filter has already been applied one or more times. Because of this, they can be notoriously unstable.

❖ IIR filters are not linear phase – they alter the phase of the input signal.
Dataloggers

Infinite Impulse Response (IIR) filters

- IIR filters are great for real-time phase picking – they introduce little delay and can produce minimum-phase arrivals for easier picking.

- Data filtered by IIR filters is appropriate for in-house analysis, but should not be archived as the main data stream.

- In SEED, IIR filters should be represented as a digital pole-zero response stage because this introduces less round off error than a coefficient representation.
Sensors may be made with:

- one signal output wire plus ground (single-ended)
- two signal output wires plus ground (double-ended).

Double-ended output is called “Differential output” because the signal on the second output is inverted so that the two signals can be differenced at the datalogger. This cancels noise induced in the cable leading from sensor to datalogger.
Differential Output

- The “output +” is the original sensor signal.
- “output –” is the inverted signal from the second sensor output.
- Trace 3 is the difference of the two output traces.

If the noise (right) were to be induced in the sensor cable, it should be similar on both output wires. Taking the difference of the output traces subtracts out the noise, but adds the signal.

From Havskov and Alguacil, 2004
Dataloggers may be made with either single-ended or differential input.

Sensors with differential output may specify their sensitivities either in the form of “2 * 750 V/m/s” or “1500 V/m/s differential; 750 V/m/s single-ended”.

Connecting a differential output sensor to a single-ended input datalogger decreases the amplitude by a half.

From Havskov and Alguacil, 2004
What is the NRL?

- Library of manufacturers’ recommended nominal instrument responses
- SEED RESP files
- Help matching an instrument’s configuration with the correct response
- Notes describing instrument and response differences
Nominal Response Library (NRL)

How is the NRL constructed?

- Response information retrieved from manufacturer
- Instruction file links instrument configuration with pole/zero or FIR coefficient files
- Generate RESP files from instruction file
- Accuracy checking
When Do I Need a Custom Response?

Update your Nominal Response if:

- you have calibration info
- your accelerometer full scale voltage and/or clip level differs
- you have a passive sensor and
  - your resistors differ
- you need to take sensor-amplifier impedance into account
- You’ve set a software gain on your datalogger
A Few Tools for Retrieving Response Information

- Nominal Response Library
  - http://ds.iris.edu/NRL/
- Manufacturers’ recommended responses
- RESP format
  - (http://ds.iris.edu/ds/nodes/dmc/data/formats/resp/)
A Few Tools for Retrieving Response Information

 Metadata Aggregator

 http://ds.iris.edu/MDA/

 Response information for data archived at IRIS

 Formats

 RESP (http://ds.iris.edu/ds/nodes/dmc/data/formats/resp/)

 SAC PoleZero

 Displacement response in nm
 Poles and zeros in radians
 CONSTANT = total sensitivity * A₀

 FDSN StationXML (http://www.fdsn.org/xml/station/)
A Few Tools for Retrieving Response Information

- **IRIS Web Services**
  - [http://service.iris.edu/](http://service.iris.edu/)
  - Response information for data archived at IRIS
- **Formats**
  - station service (text & FDSN stationXML)
  - resp service (RESP)
  - sacpz service (SAC pole zero format)
A Few Tools for Retrieving Response Information

- **breq_fast**
  - [http://ds.iris.edu/SeismiQuery/breq_fast.phtml](http://ds.iris.edu/SeismiQuery/breq_fast.phtml)
  - Response information for data archived at IRIS

**Formats**

- **RESP**
- **Dataless SEED** ([http://www.fdsn.org/seed_manual/SEEDManual_V2.4.pdf](http://www.fdsn.org/seed_manual/SEEDManual_V2.4.pdf))
- **Full SEED** ([http://www.fdsn.org/seed_manual/SEEDManual_V2.4.pdf](http://www.fdsn.org/seed_manual/SEEDManual_V2.4.pdf))
A Few Tools for Writing SEED Metadata

Antelope
- http://www.brtt.com/software.html
- Native response format: CSS
  (see Antelope man page for “response”)

Portable Data Collection Center (PDCC)
- Native response format: RESP from the NRL

Station Information System (SIS)
- USGS regional network partners
- Native response format: RESP from the NRL, stationXML
**Response Correction**

- An instrument response can be removed from data by:
  - Deconvolution in the time domain
  - Division of amplitude spectra in the frequency domain

\[
\text{Data spectrum} \cdot \frac{1}{\text{Amplitude response}} = \text{ideally…}
\]
Response Correction

- But suppose your data has extra noise at long period
- Limiting the frequency band with a bandpass filter can help
- Spectral prewhitening can sometimes help by evening out the spectrum
A Few Tools for Response Correcting Data

- **IRIS timeseries web service**
  [http://service.iris.edu/irisws/timeseries/1/](http://service.iris.edu/irisws/timeseries/1/)

- **SAC**
  - **Software request**
  - **Examples**
    [http://geophysics.eas.gatech.edu/people/jwalter/sacresponse.html](http://geophysics.eas.gatech.edu/people/jwalter/sacresponse.html)

- **Matlab Example**
  [http://www.mathworks.com/matlabcentral/fileexchange/48966-rawseismicinstrumentcorrection/content/RawSeismicInstrumentCorrection.m](http://www.mathworks.com/matlabcentral/fileexchange/48966-rawseismicinstrumentcorrection/content/RawSeismicInstrumentCorrection.m)
Tools for Verifying Responses

  - Command line C program
  - Reads SEED RESP files
  - Sanity checking for basic sensitivity
  - Summarizes output sample rate & units
  - Creates ASCII files containing amplitude and phase spectra.
To verify responses in a new dataless SEED file

Create RESP files using the rdseed program
(http://ds.iris.edu/ds/nodes/dmc/software/downloads/)

Run evalresp on each RESP file, directing the output to a file

For that output file, egrep -i "(FAIL|ERROR)" output_file
Tools for Verifying Responses

- Also, verify the response curve graphically
- JPlotResp (http://ds.iris.edu/ds/nodes/dmc/software/downloads/)
  - Reads RESP files
  - Runs evalresp
  - Bode plots (stages plotted as composite or separately)
  - Mouse-over discovery of curve values
- Metadata Aggregator
  - Bode plots
Verifying Responses

- Do the high- and low-frequency corners look correct?
- Does this look like a velocity response?
- Is the normalization frequency within the passband?
- Is the plotted Nyquist frequency consistent with sample rates in the dataless and miniSEED?

Metadata Aggregator

STS-2 Sensor
Finding $A_0$ with JPlotResp

1. Create a copy of your RESP file and set $A_0$ and the sensor sensitivity to 1.

2. Use JPlotResp to plot just stage 1 of your edited RESP.

3. Use “mouseover” to find the amplitude of your pole-zero curve at your normalization frequency (SensFreq). $A_0$ is the inverse of this.

4. Restore the sensor sensitivity in your RESP and include your new $A_0$.

5. Replot the sensor stage to make sure the amplitude is now the sensor sensitivity.
Tools for Verifying Responses

- MUSTANG data quality metrics
  - [http://service.iris.edu/mustang/](http://service.iris.edu/mustang/)
  - The following metrics operate on response-corrected data. Unexpected results may indicate incorrect response information
    - noise-psd
    - noise-pdf
    - noise-mode-timeseries
    - measurements
      - dead_channel_exp
      - pct_below_nlnm
      - pct_above_nhnm
      - transfer_function
### Pole Typo

**Pct Below Nlnm Metric**

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**HHE poles:**

**Complex poles:**

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**HHN poles:**

**Complex poles:**

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<td>+2.2211 E+02</td>
</tr>
<tr>
<td>3</td>
<td>-2.2211 E+02</td>
<td>-2.2211 E+02</td>
</tr>
</tbody>
</table>

**Sign error**
The data sample rate was 100 sps, but the FIR cascade was for a 1 sps stream. FIR responses have lobes at $f > \text{Nyquist}$. Since there is no energy in 1 Hz data at those frequencies, you don’t see the lobes when you instrument correct…

…unless you remove this response from higher sample rate data that does have energy there!
Incorrect Sensor Response

This MUSTANG query retrieved values of `pct_above_nhnm` measurements having 20% or more energy above the New High Noise Model for the CM network.

The sensor response archived was a placeholder until the needed instrument can be added to the NRL.
References


Contacting Me

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