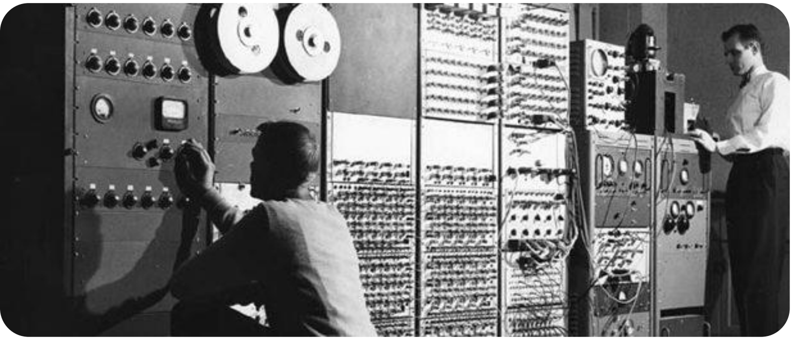
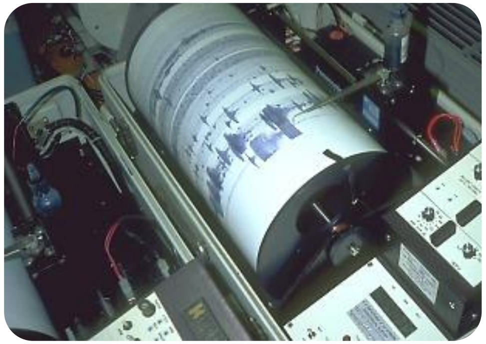
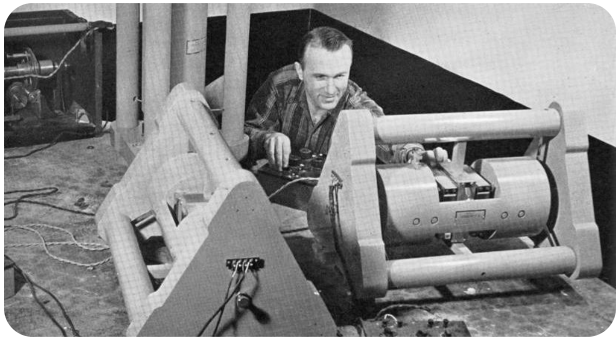
SAND2018-2665PE

Exceptional service in the national interest

Sandia National Laboratories

Calibrating Data from the Leo Brady Seismic Network

Brian YOUNG, Robert E. ABBOTT

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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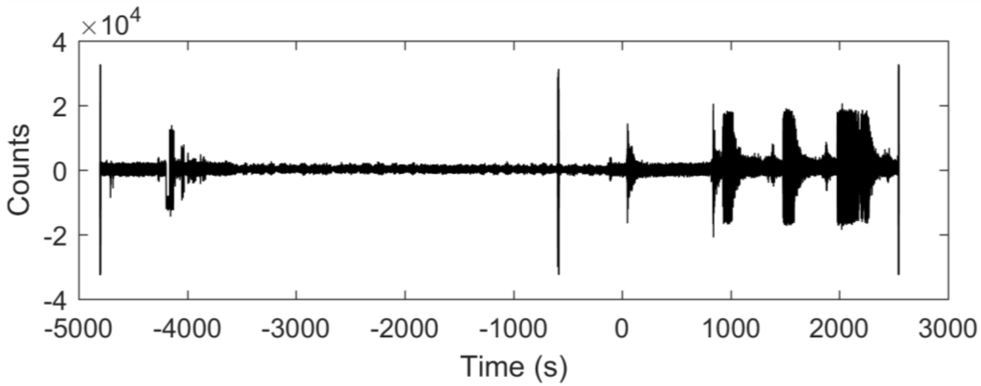
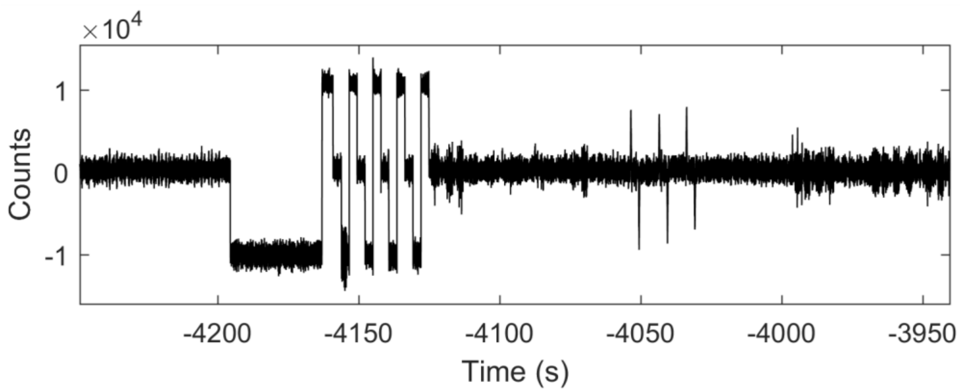
Instrument Sensitivity

Leo Brady—Data we've got





Boxcar – Leeds – VSP÷5

REVISED 10/17/67

SEISMIC FIELD SHEET...Page 5

TAPE CHANNEL 5 DATA

6819-1

VCO FREQUENCY in CPS	INSTRUMENT	CAL db PTA 0 PAD	RUN db PTA 0 PAD	BAND EDGE SENS.*	ELECTR. GAIN	CAL BATT. VOLTS
1120	TSP÷5	48	96	.5v		.45v
1300	TSP×1					
1480	RSP÷25		84			
1660	RSP÷5					
1840	RSP×1					
2030	VSP÷25		84			
2230	VSP÷5					
2450	VSP×1					

* Band Edge = 100% of bandwidth

SHORT PERIOD WEIGHT LIFTS

			DAMPING
VERTICAL	10.8 DIV. @	48 db	13:1
RADIAL	14.9 DIV. @	48 db	11:1
TANGENTIAL	12 DIV. @	48 db	12:1

SHORT PERIOD WEIGHT/MICRONS

VERTICAL	.255 gms. =	.319 u
RADIAL	2.000 gms. =	.250 u
TANGENTIAL	2.000 gms. =	.250 u

NGC-23 CALIBRATION

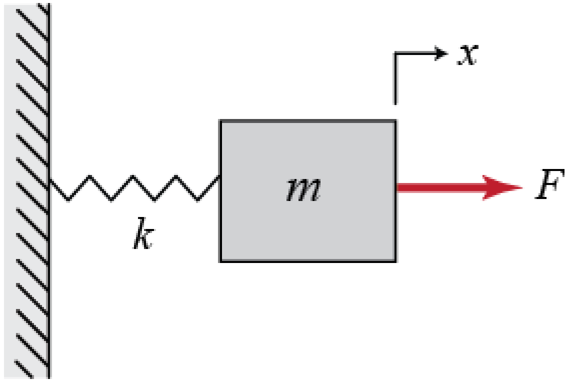
VERTICAL	DIV. @	db
RADIAL/STS	DIV. @	db
RADIAL/NTS	DIV. @	db

Seismic Arrival Time* ______

* Ely and Battle Mt. only. Other stations are noted on Field Data Sheet

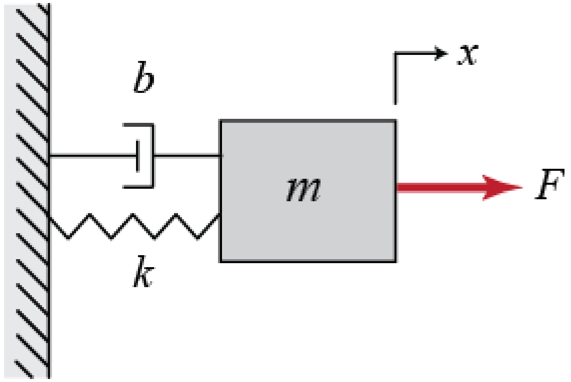
Seismometer theory in 2 slides

$$\sum F = 0 \qquad F = ma \qquad F = kx$$



$$m\ddot{x} + kx = 0$$

Cartoons: University of Michigan



$$m\ddot{x} + b\dot{x} + kx = 0$$

Seismometer:

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = 0$$

Seismometer theory in 2 slides

Seismometer:

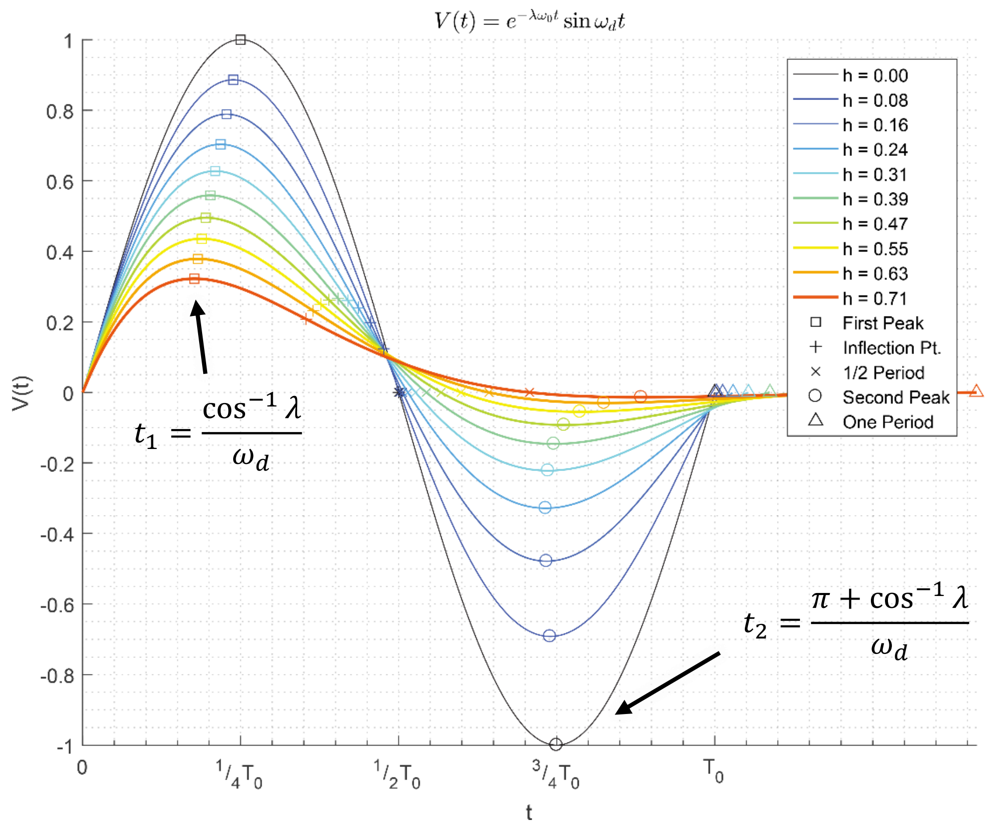
$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = 0$$

Initial conditions for weight lift:

$$x(0) = x_0; \quad \dot{x}(0) = 0$$

Deflection (from Hooke's Law):

$$F = kx \quad \Rightarrow \quad x_0 = \frac{m_w g}{m_s \omega_0^2}$$



Electromagnetic seismometer:

$$V(t) = G\dot{x}(t) \;=\; -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t}\sin\omega_d t \qquad \omega_d = \omega_0\sqrt{1-\lambda^2}$$

Seismometer theory in 2 slides

Seismometer:

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = 0$$

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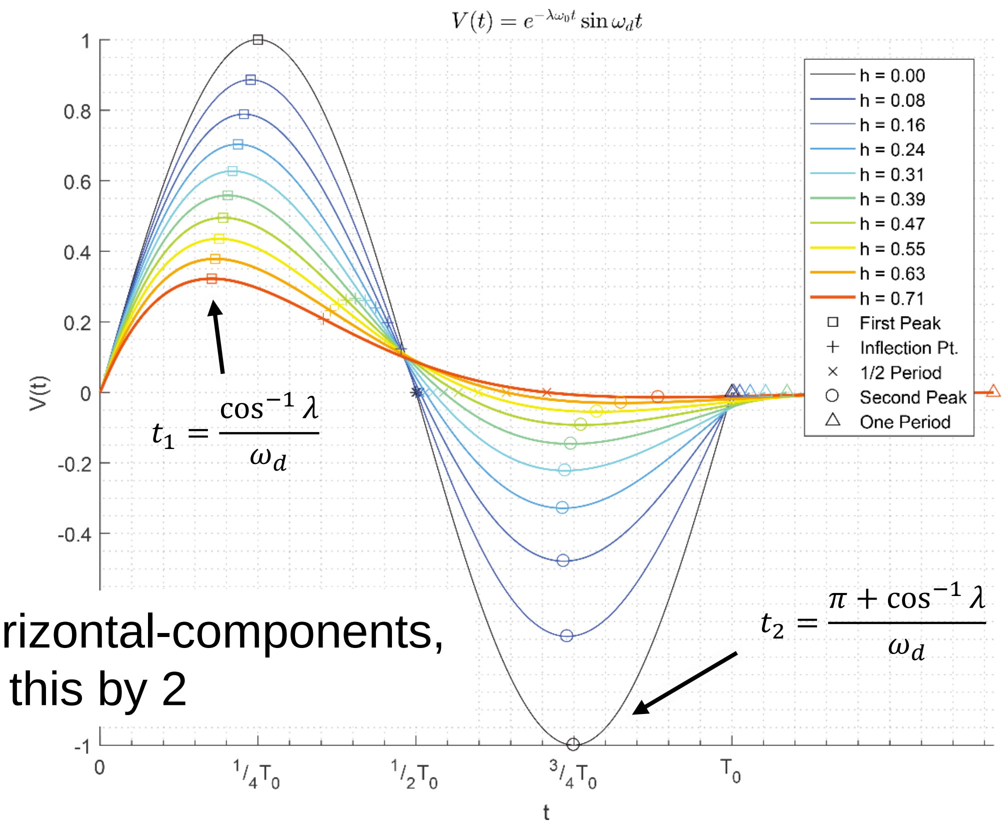
For horizontal-components,
Divide this by 2



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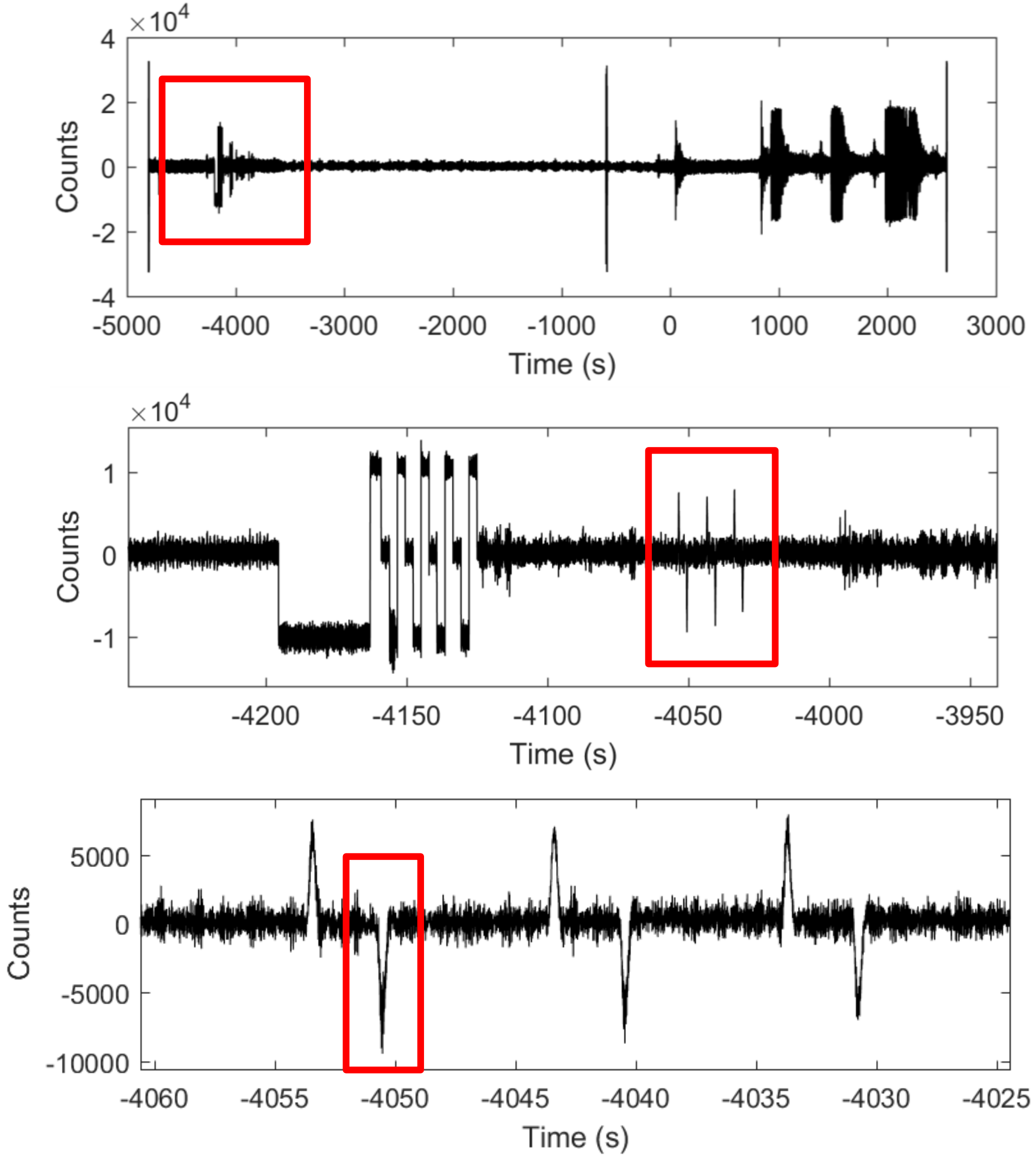
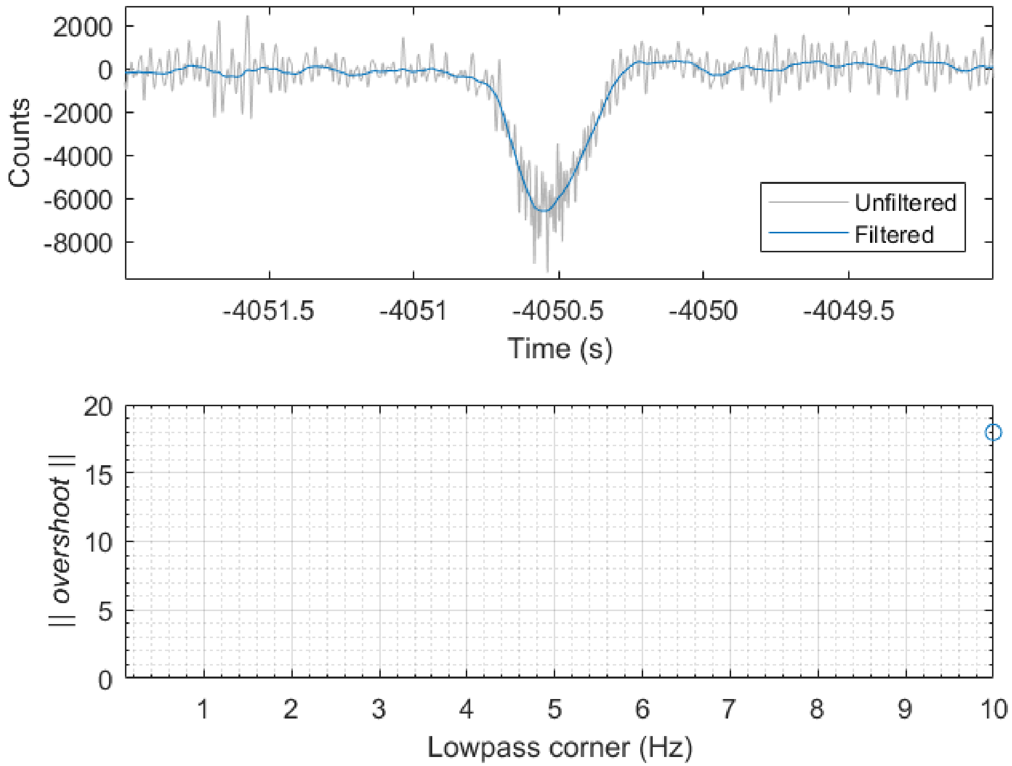
1. Locate the first weight lift



2. Recover the weight lift



1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

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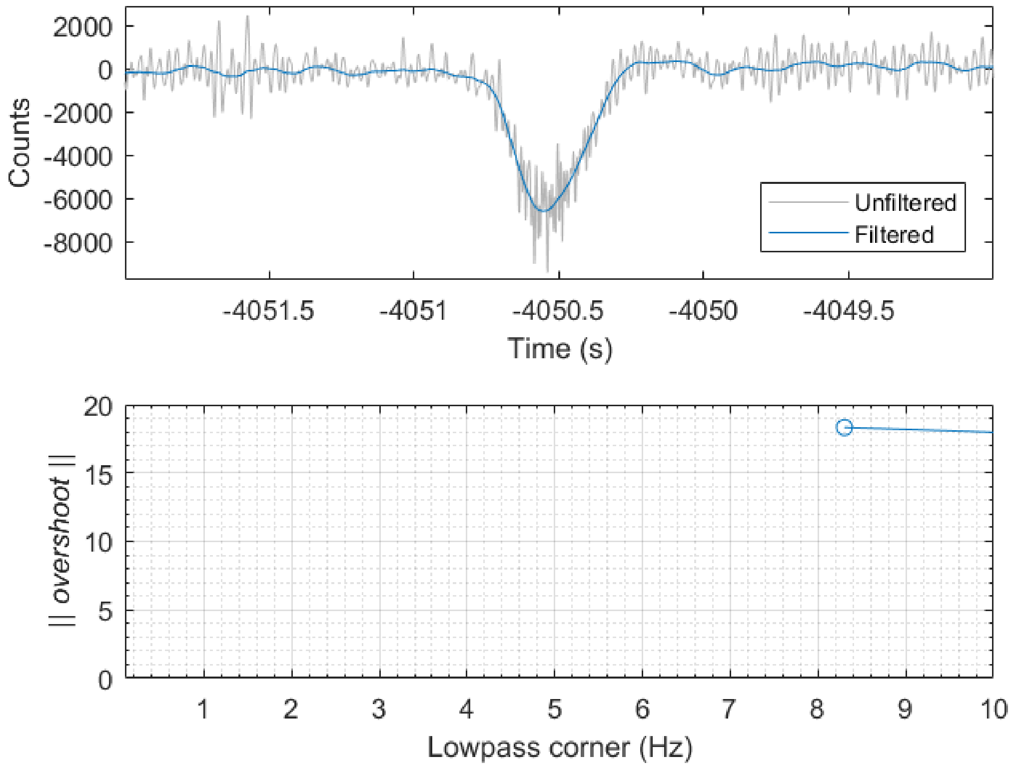

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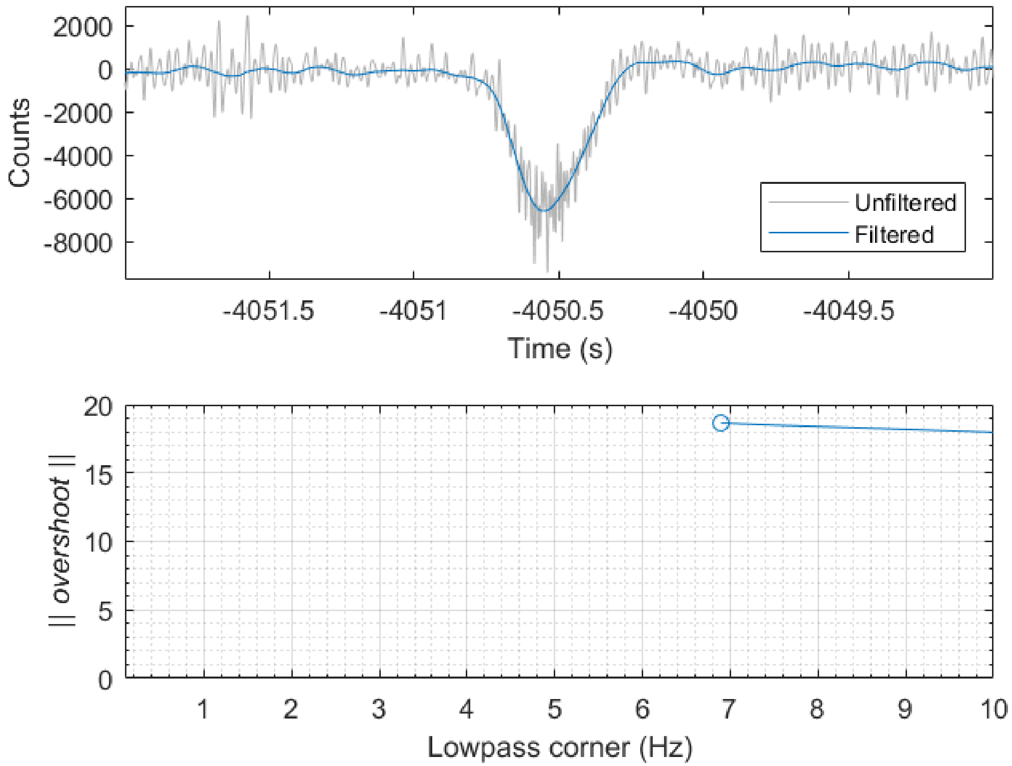

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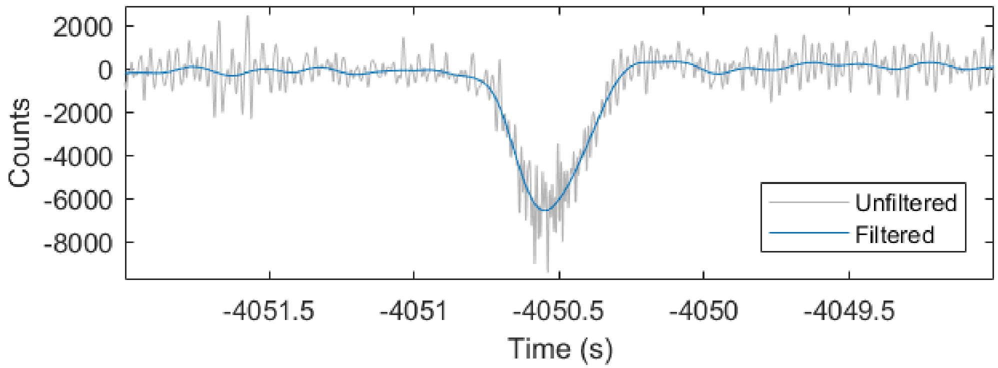

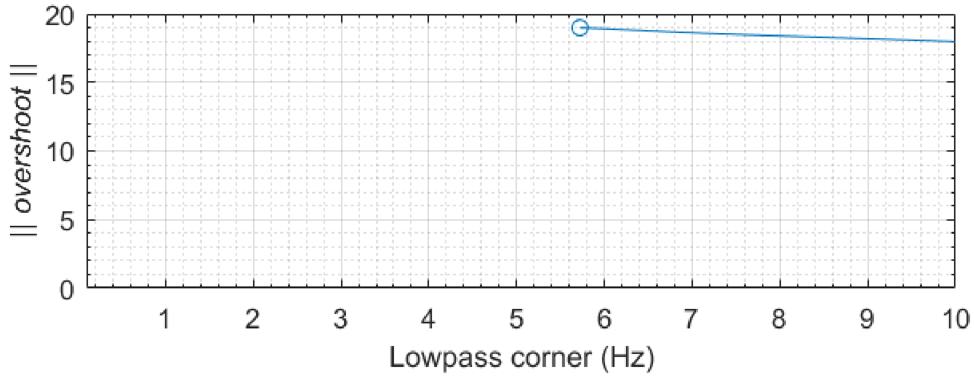

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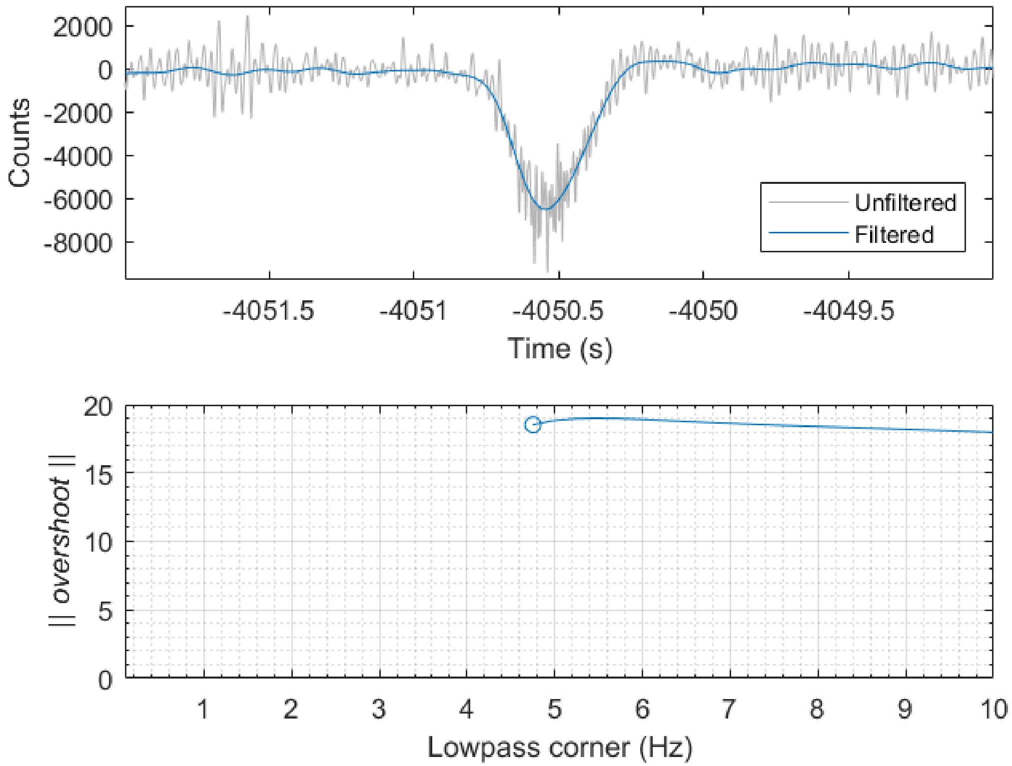

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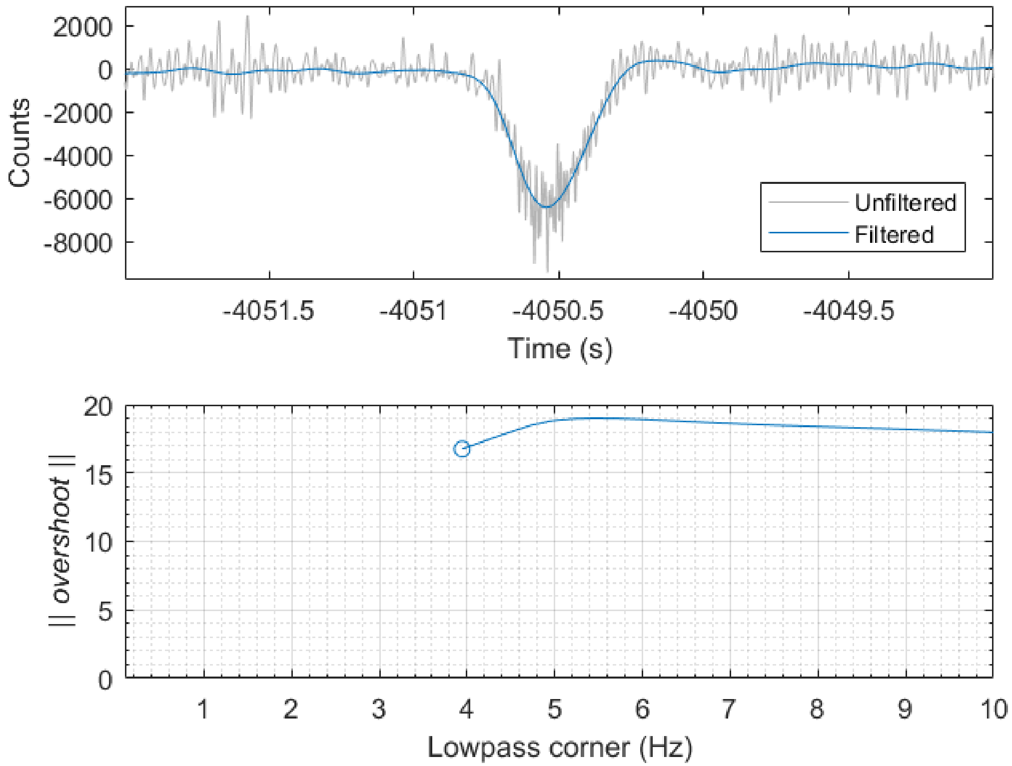

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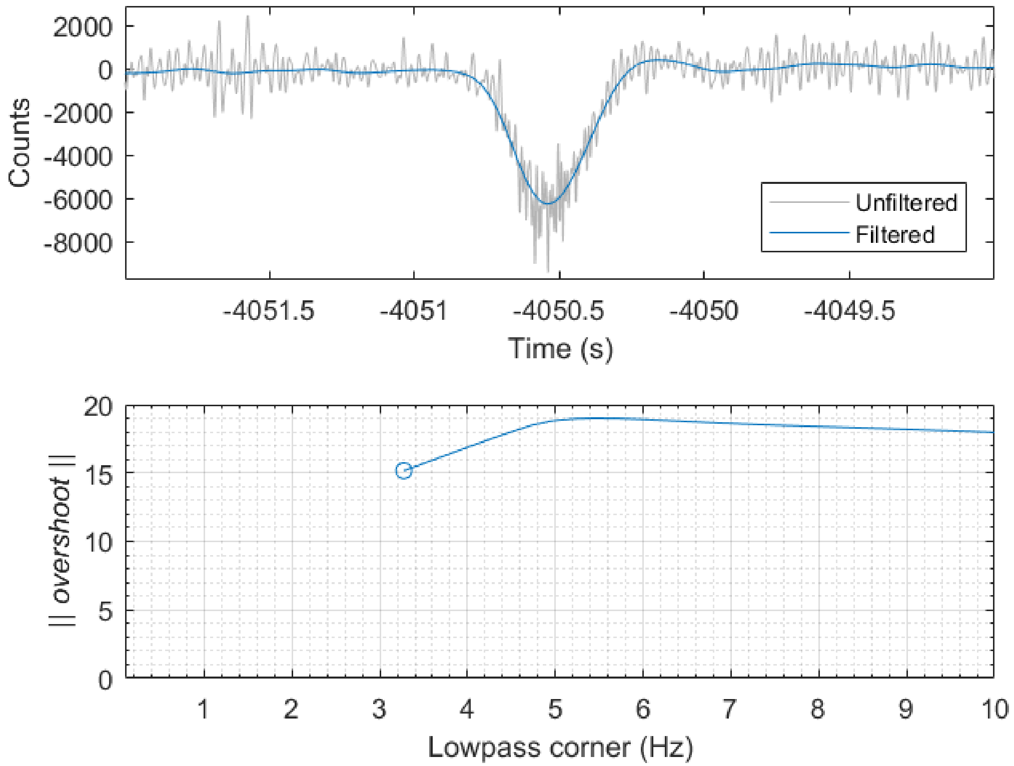

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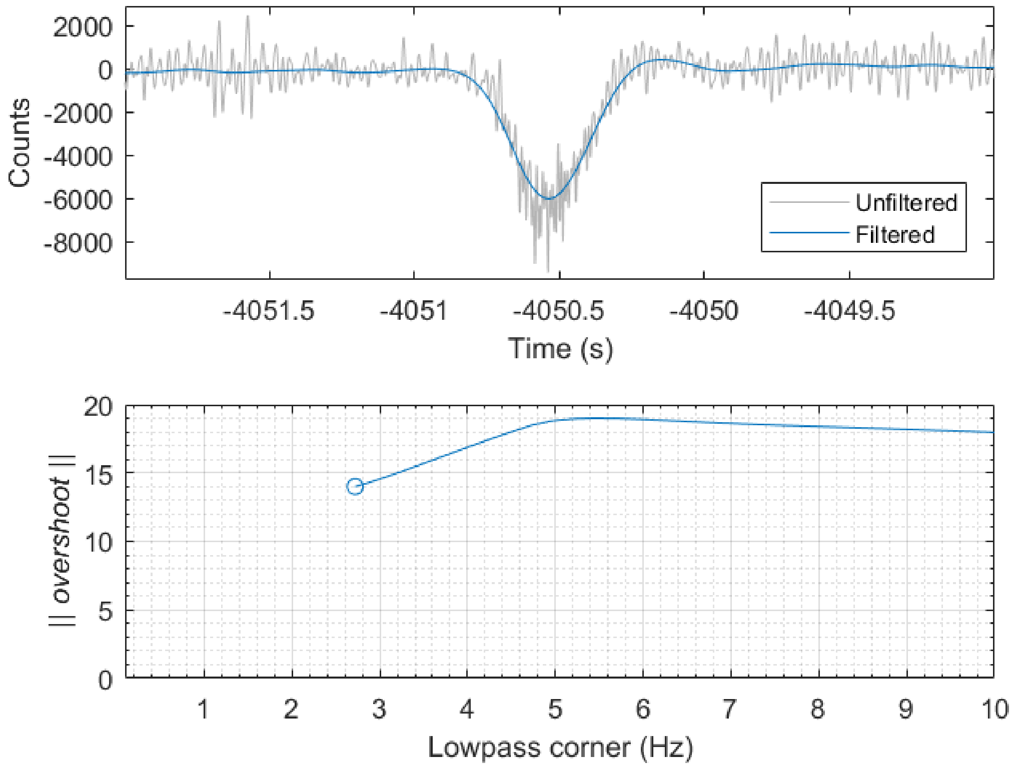

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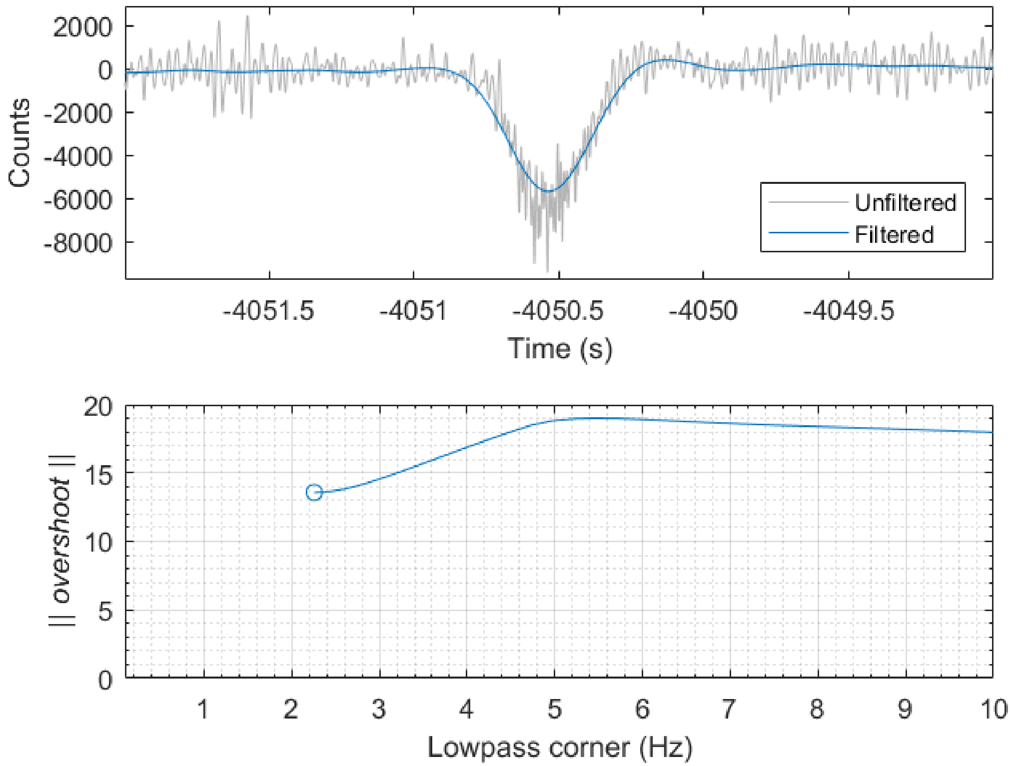

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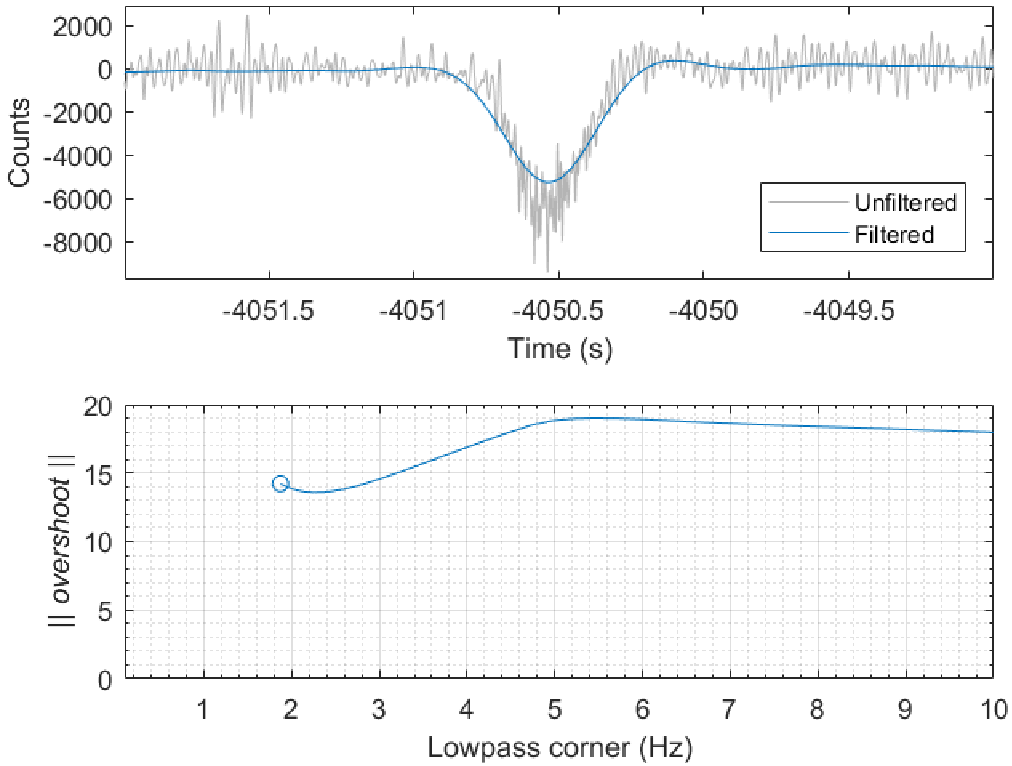

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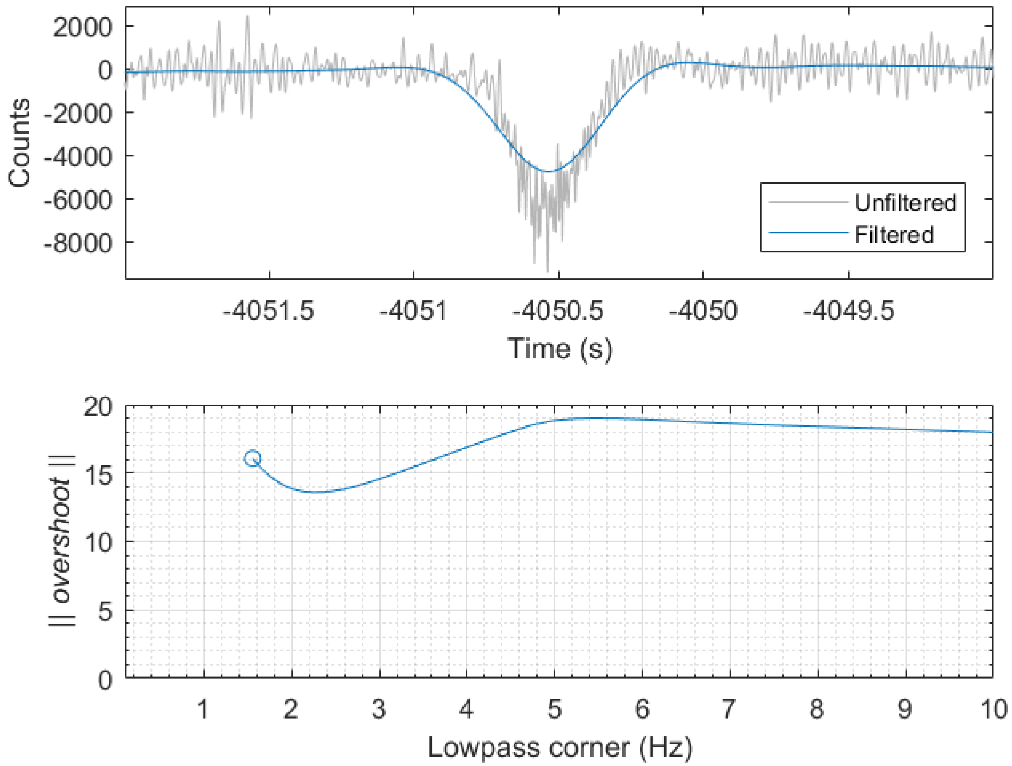

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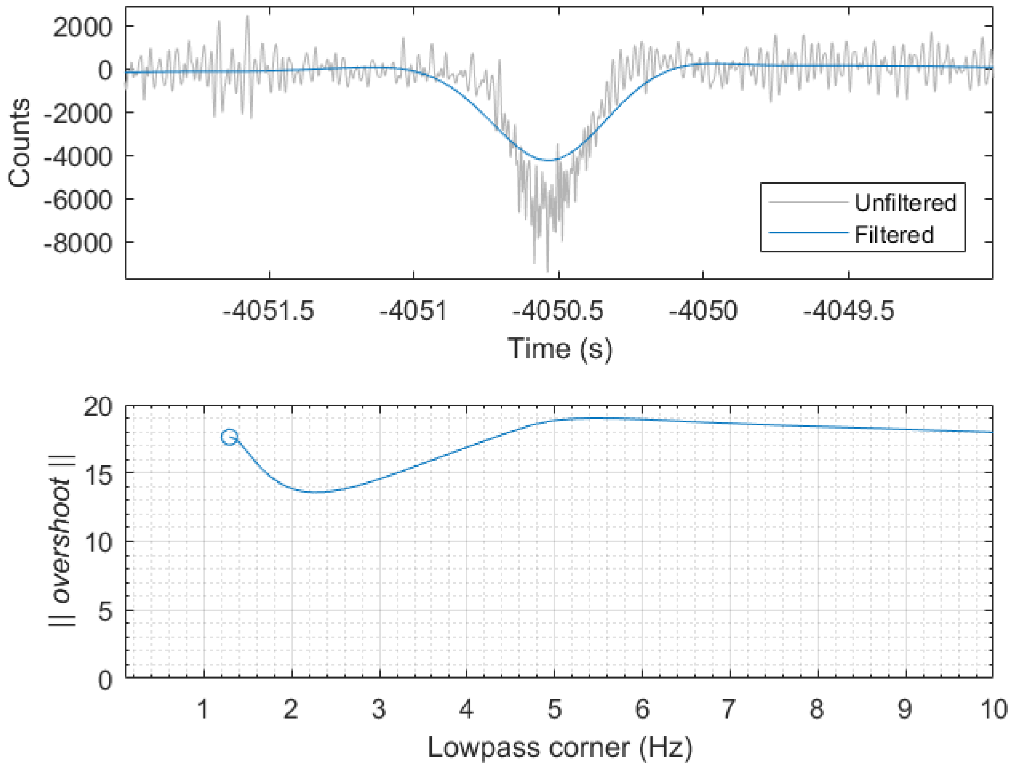

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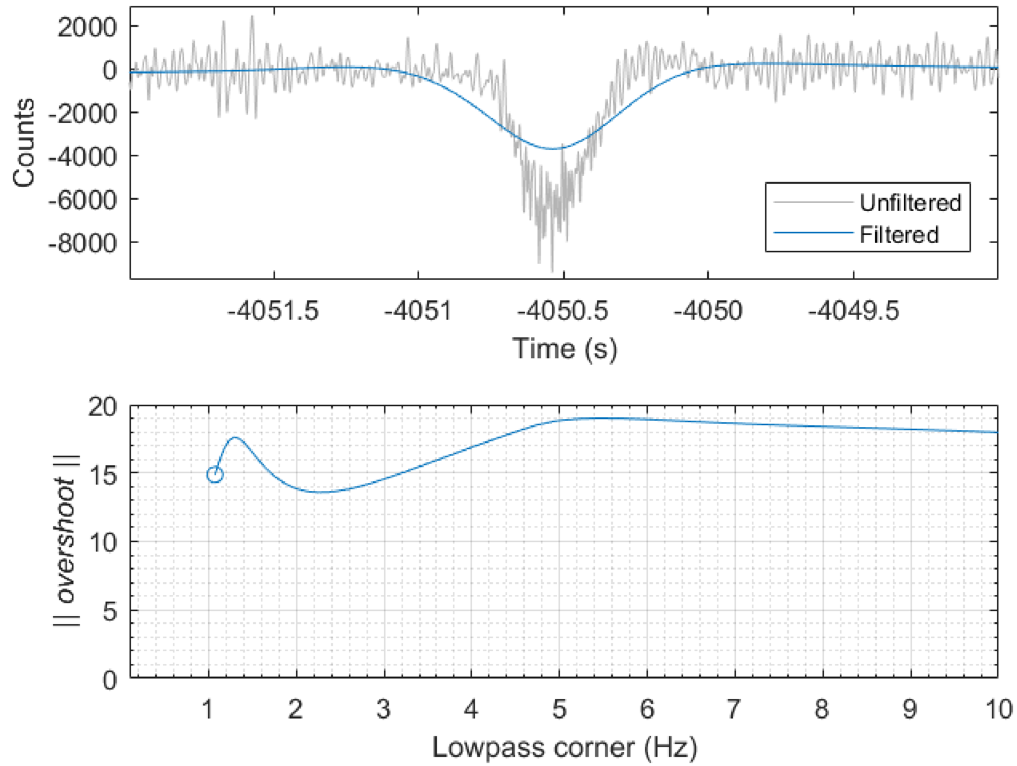

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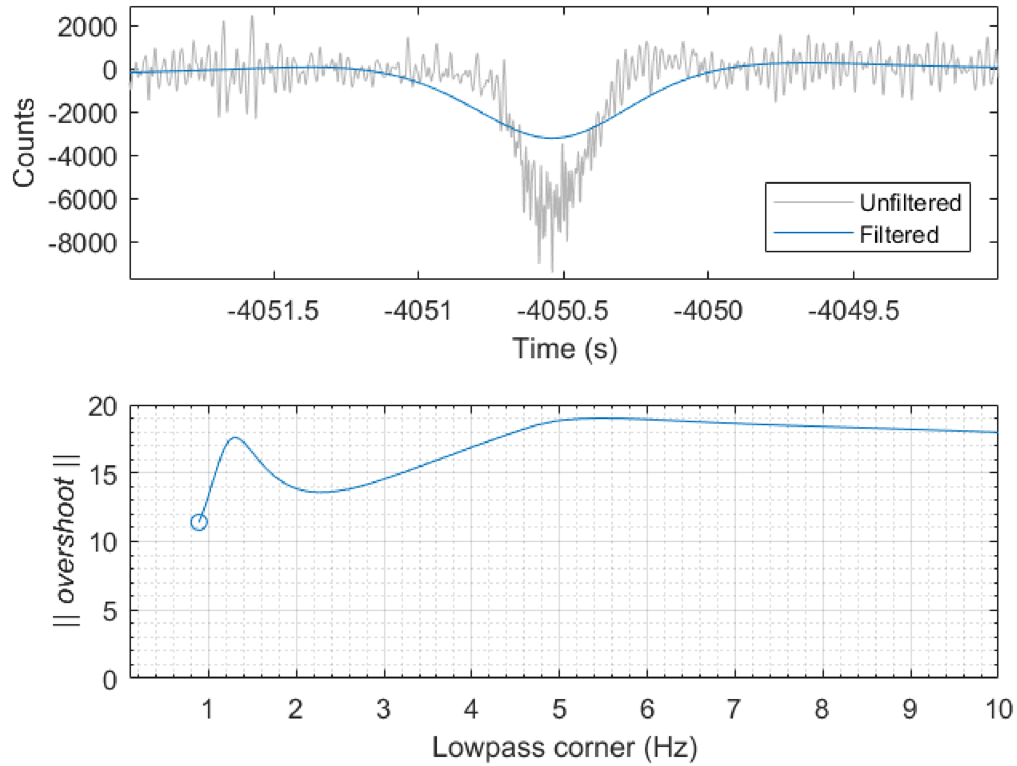

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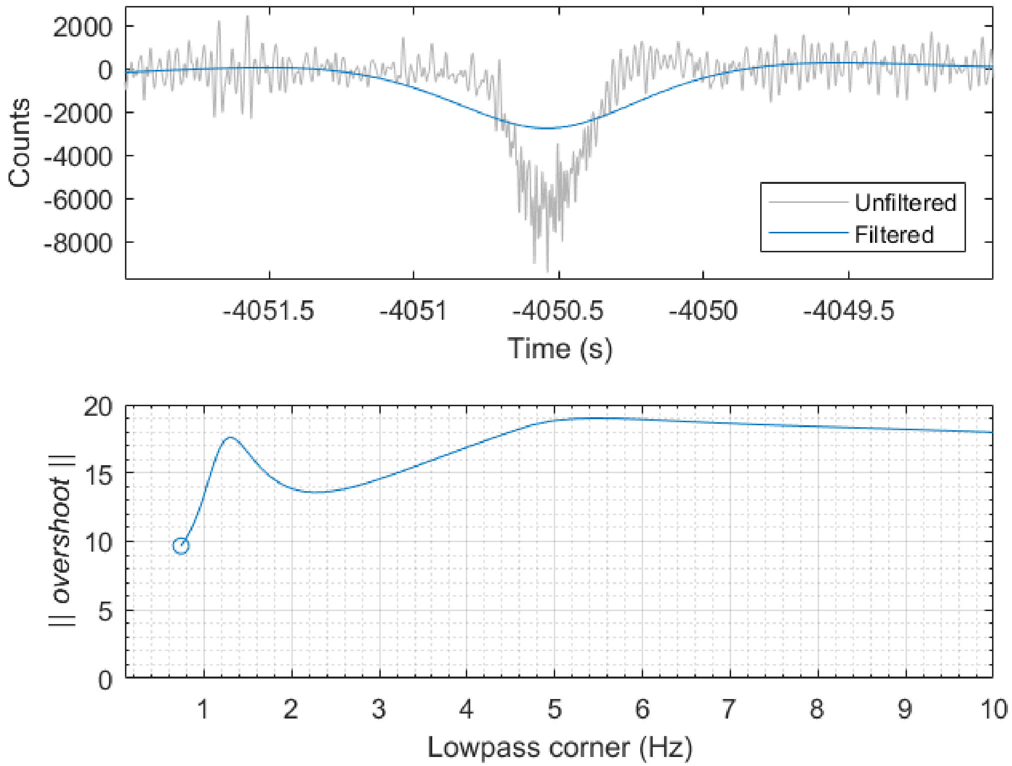

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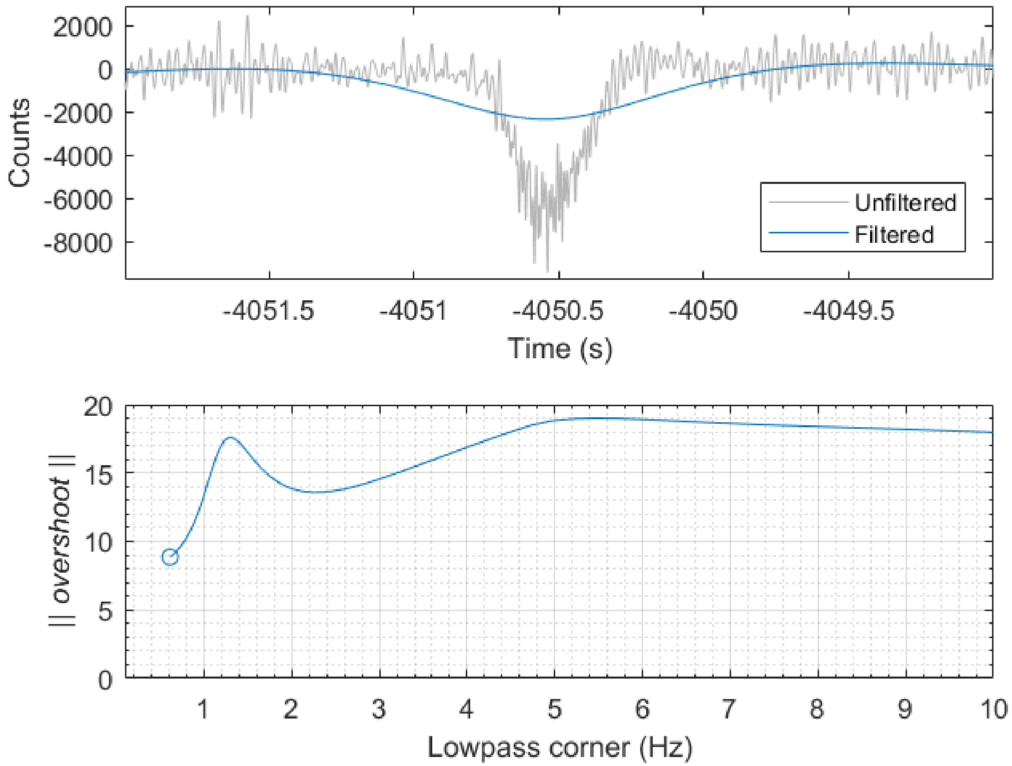

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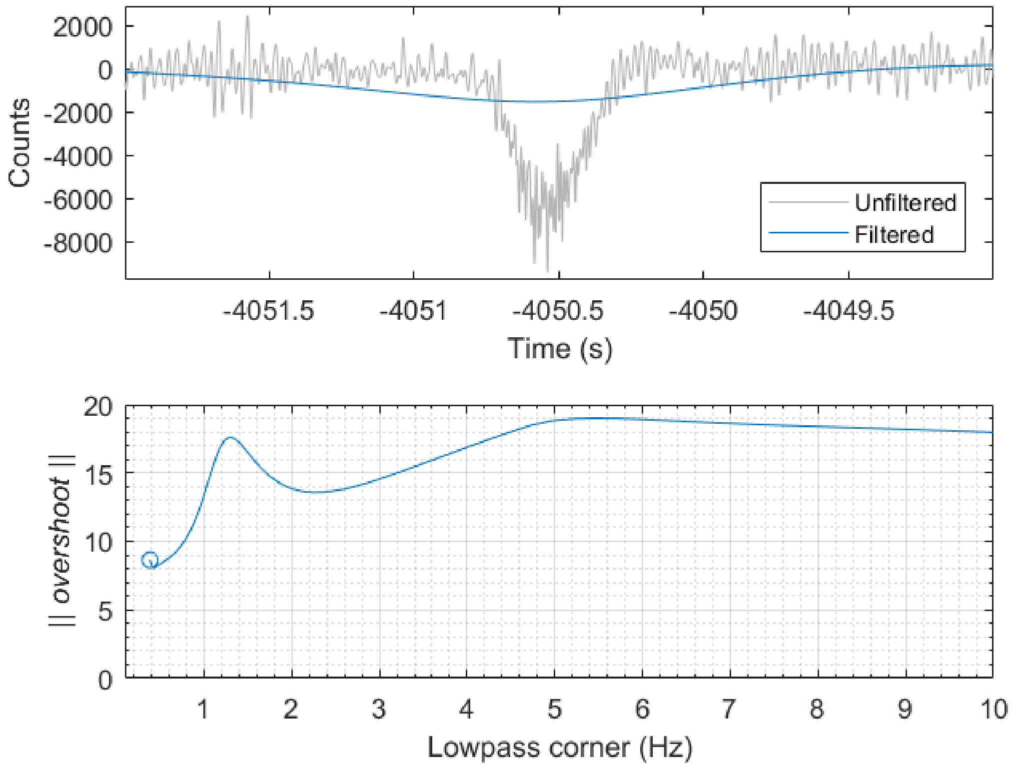

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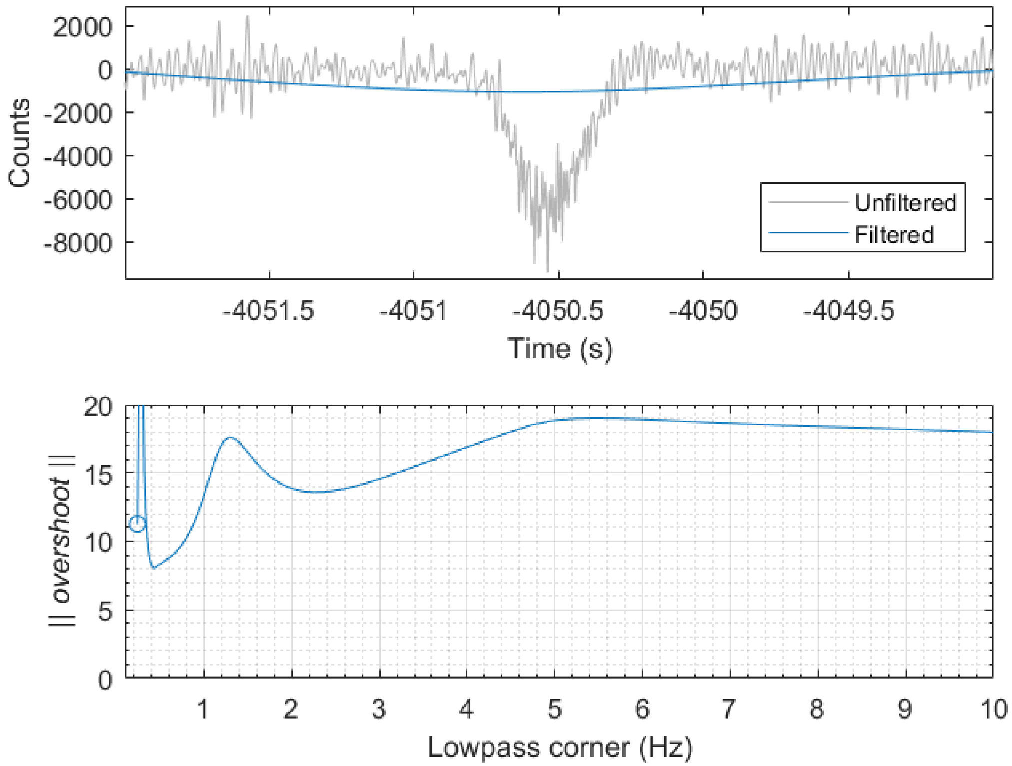

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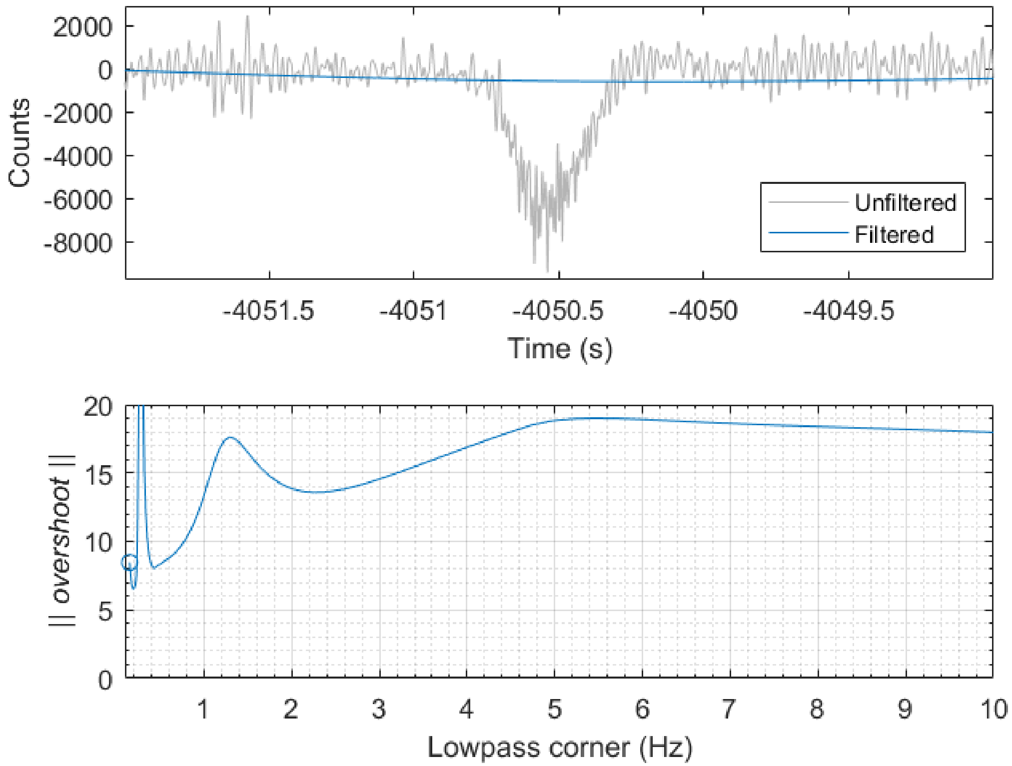

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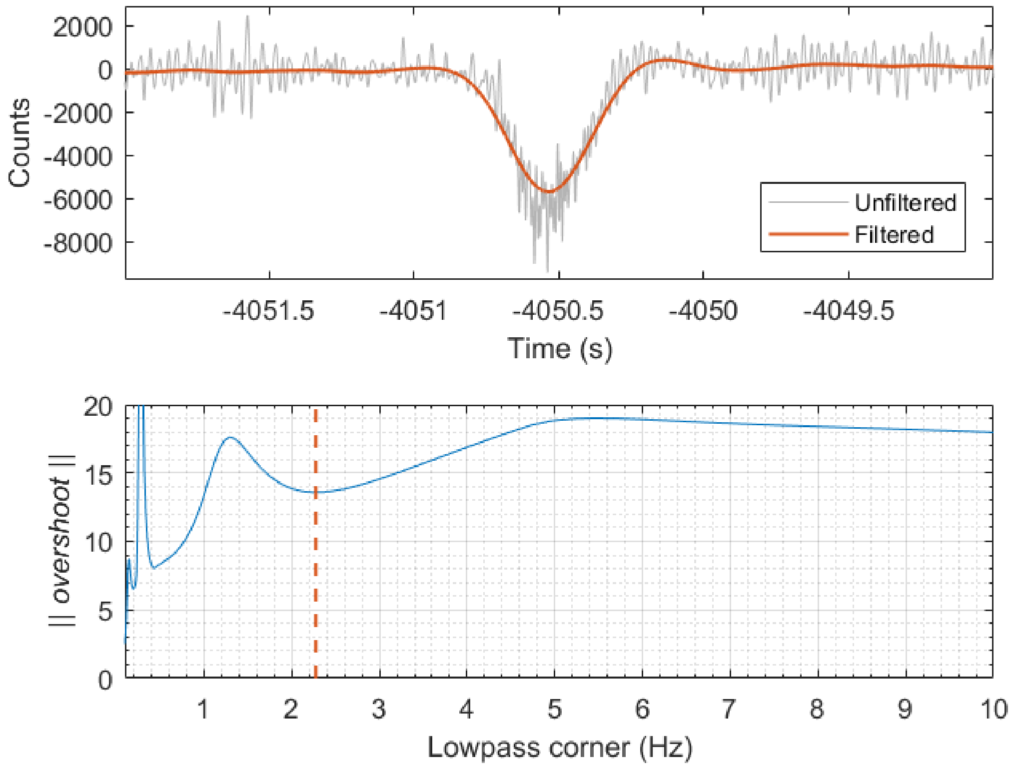
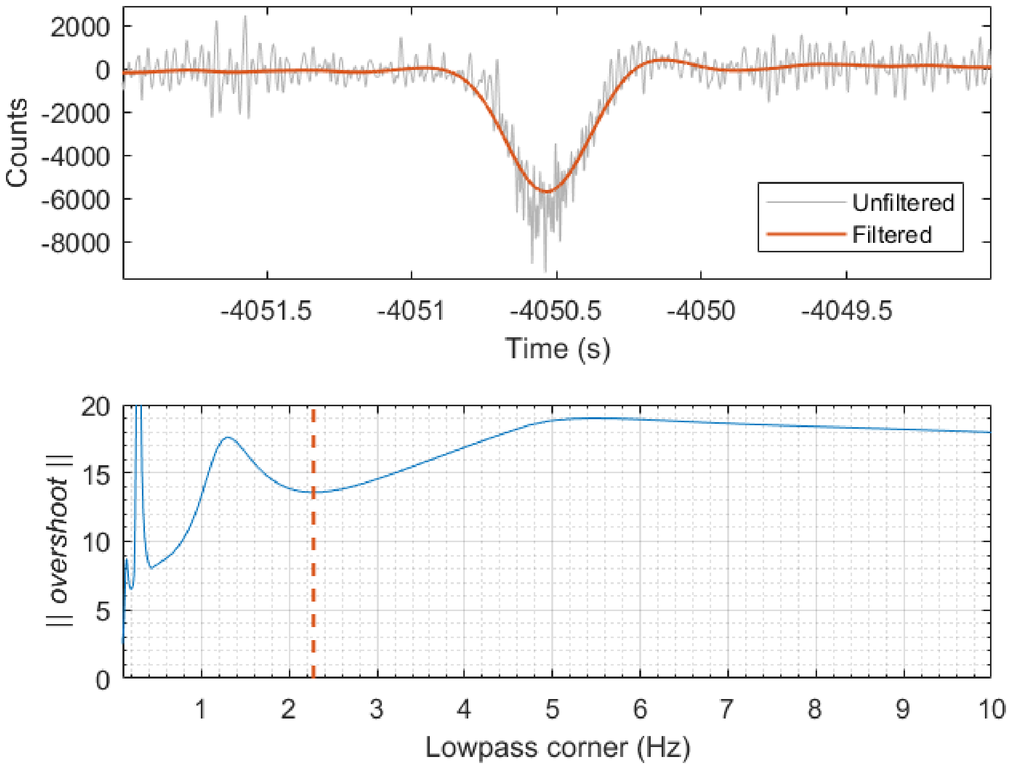


1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

3. Measure instrument constants



1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

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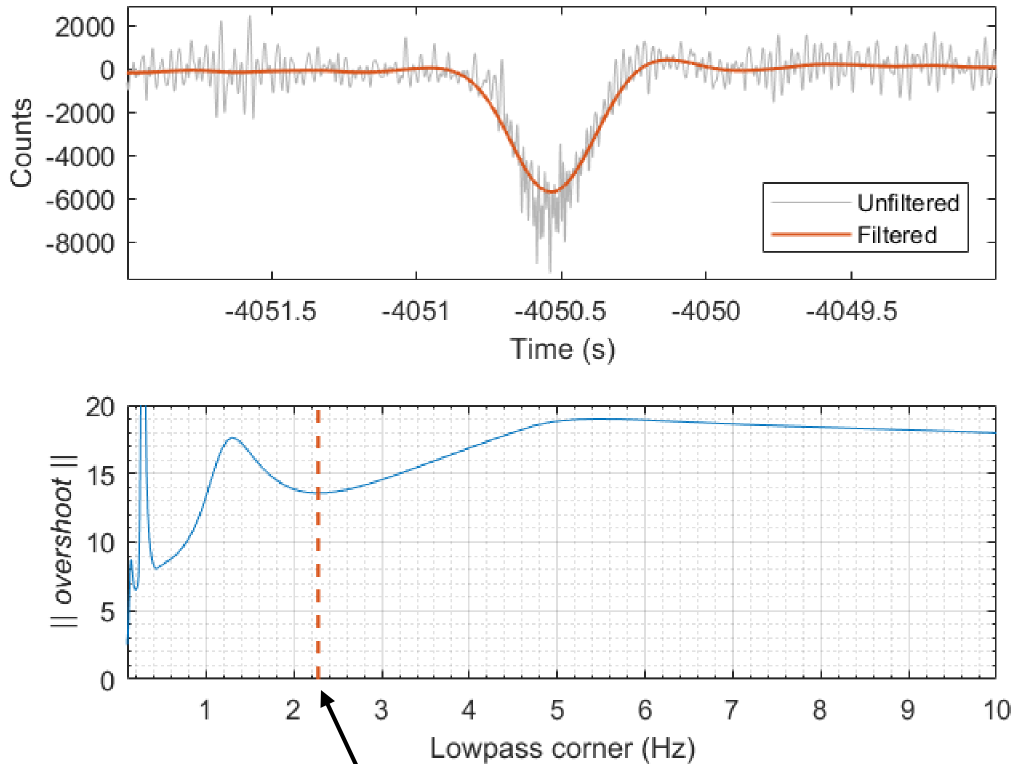

$f_c \approx 2.3\ Hz$

3. Measure instrument constants

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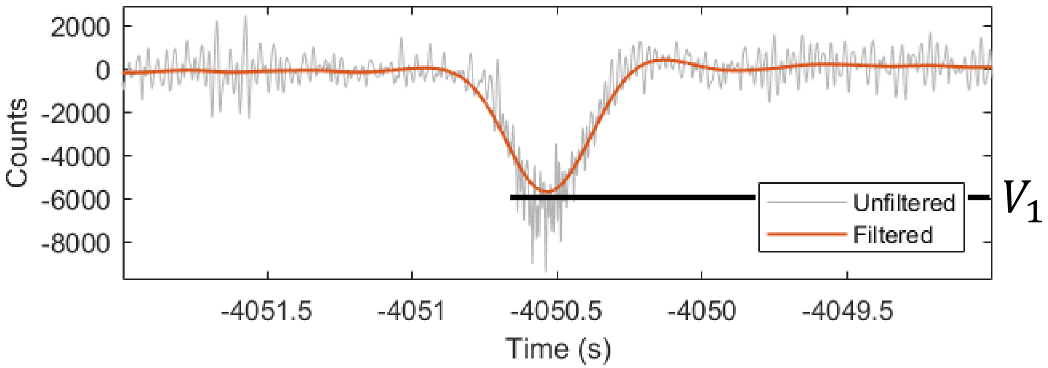
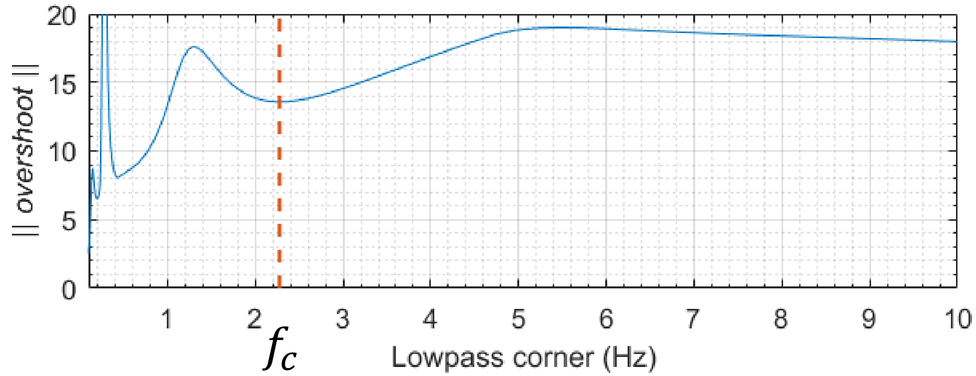


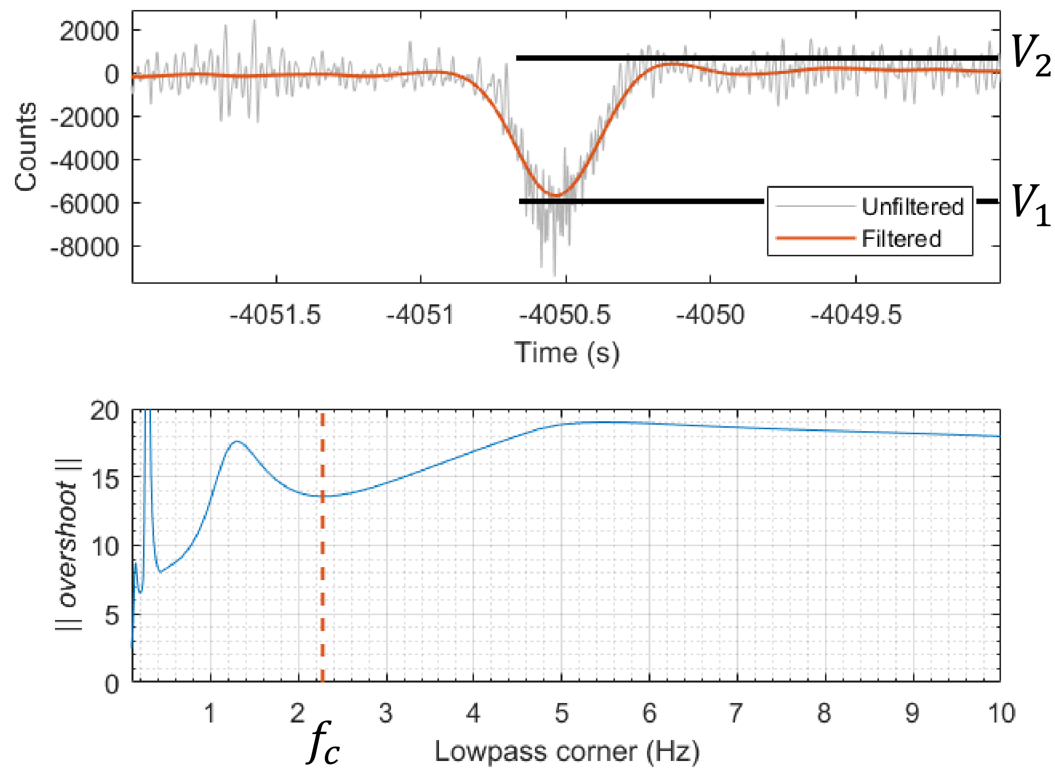


3. Measure instrument constants

Sandia National Laboratories

$f_c \approx 2.3\ Hz$

$V_1 = -5692$ cts

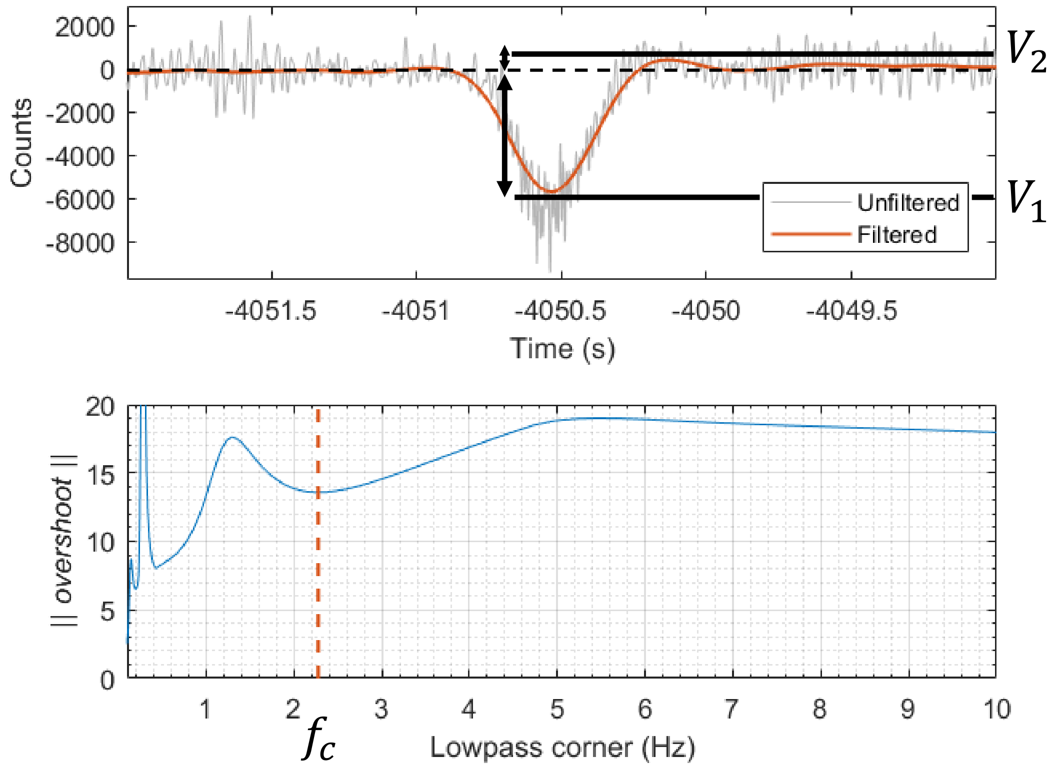


3. Measure instrument constants

$f_c \approx 2.3\ Hz$

$V_1 = -5692$ cts

$V_2 = 419$ cts



3. Measure instrument constants

$f_c \approx 2.3\ Hz$

$V_1 = -5692$ cts

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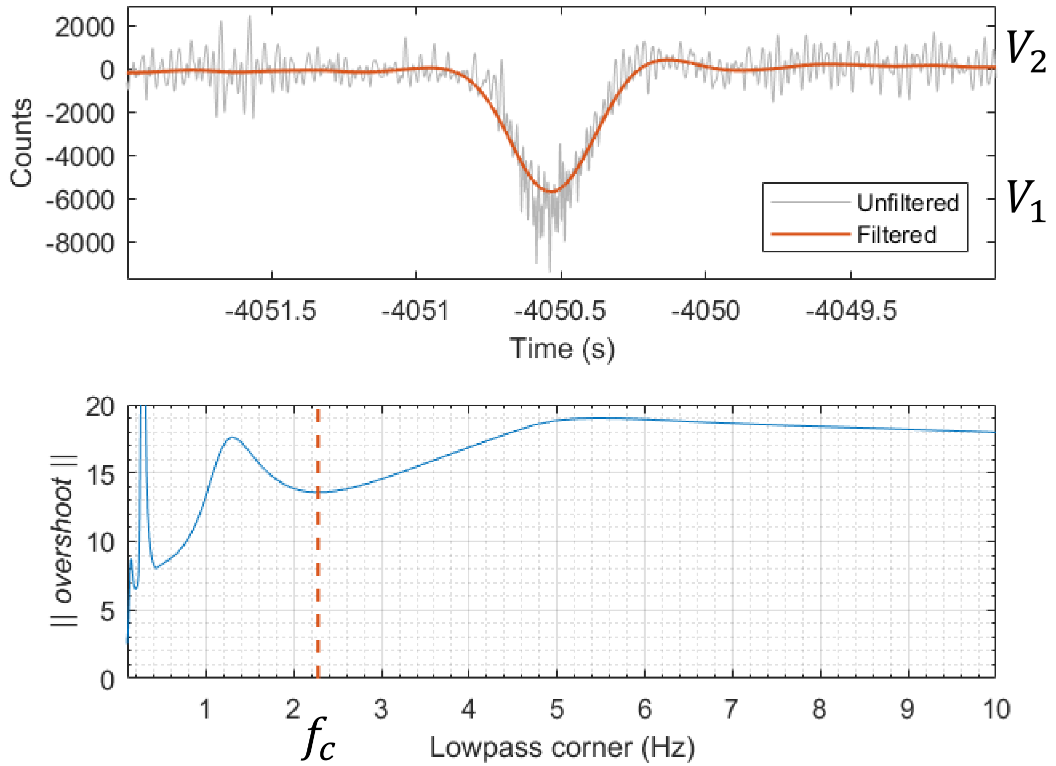
$\left|\frac{V_1}{V_2}\right| = 13.58$



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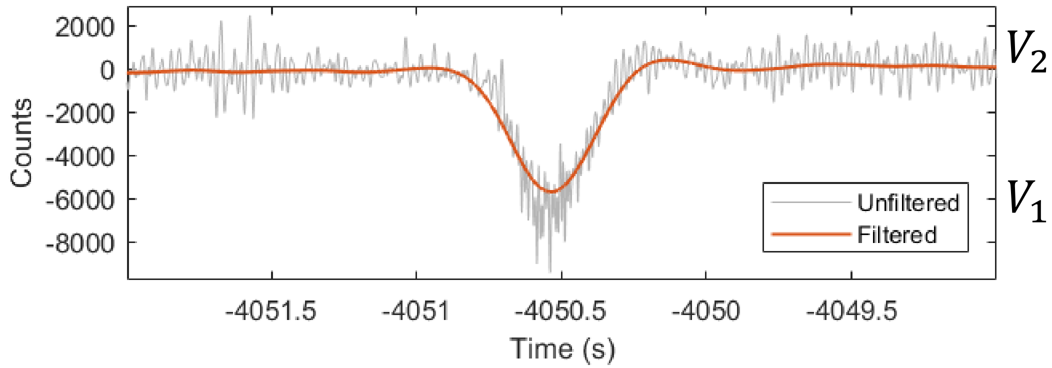
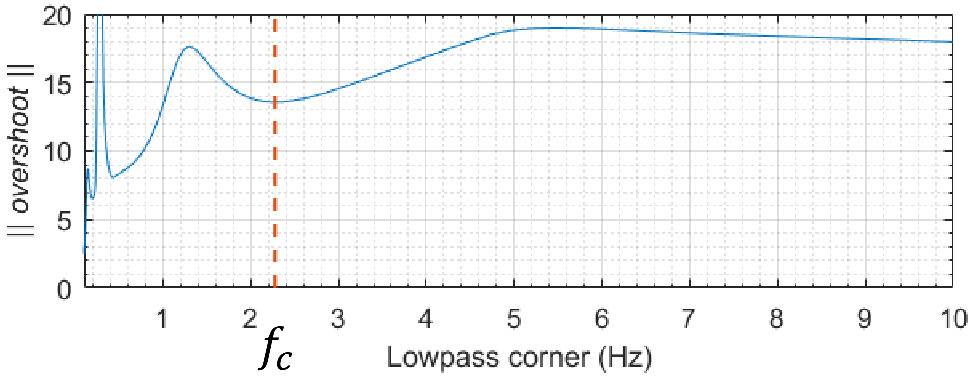
$$\left|\frac{V_1}{V_2}\right| = 13.58$$

$$\delta = \ln\left|\frac{V_1}{V_2}\right| = 2.61$$





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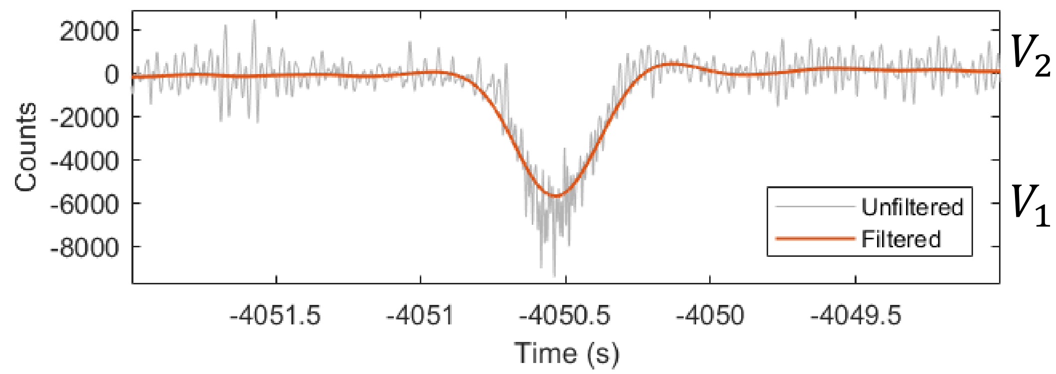
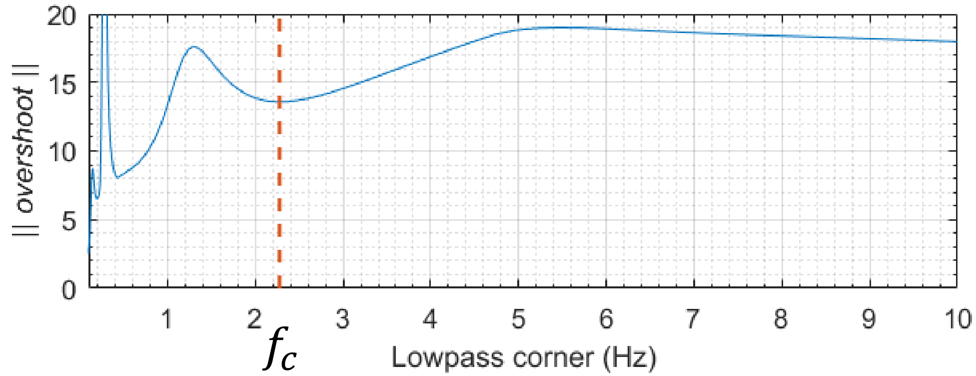
$$\delta = \ln\left|\frac{V_1}{V_2}\right| = 2.61$$

$$\lambda = \frac{\delta}{\sqrt{\pi^2 + \delta^2}} = 0.6389$$





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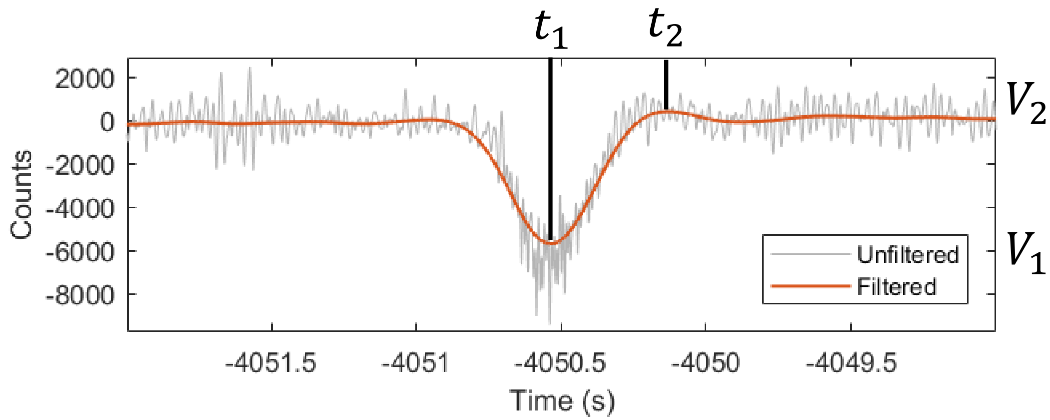

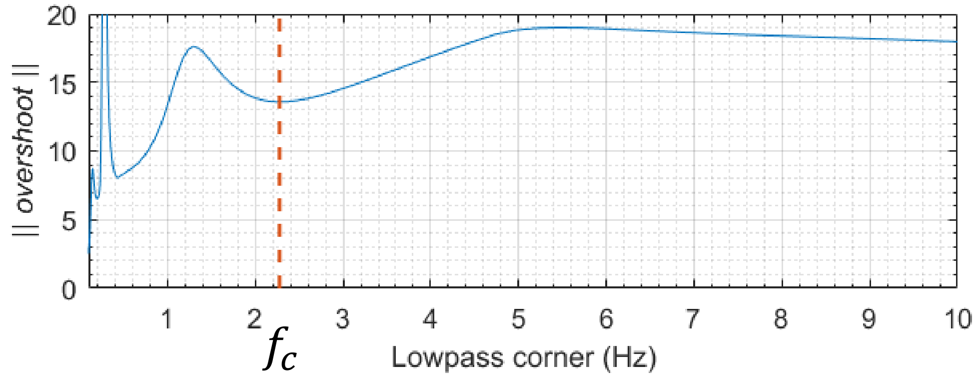

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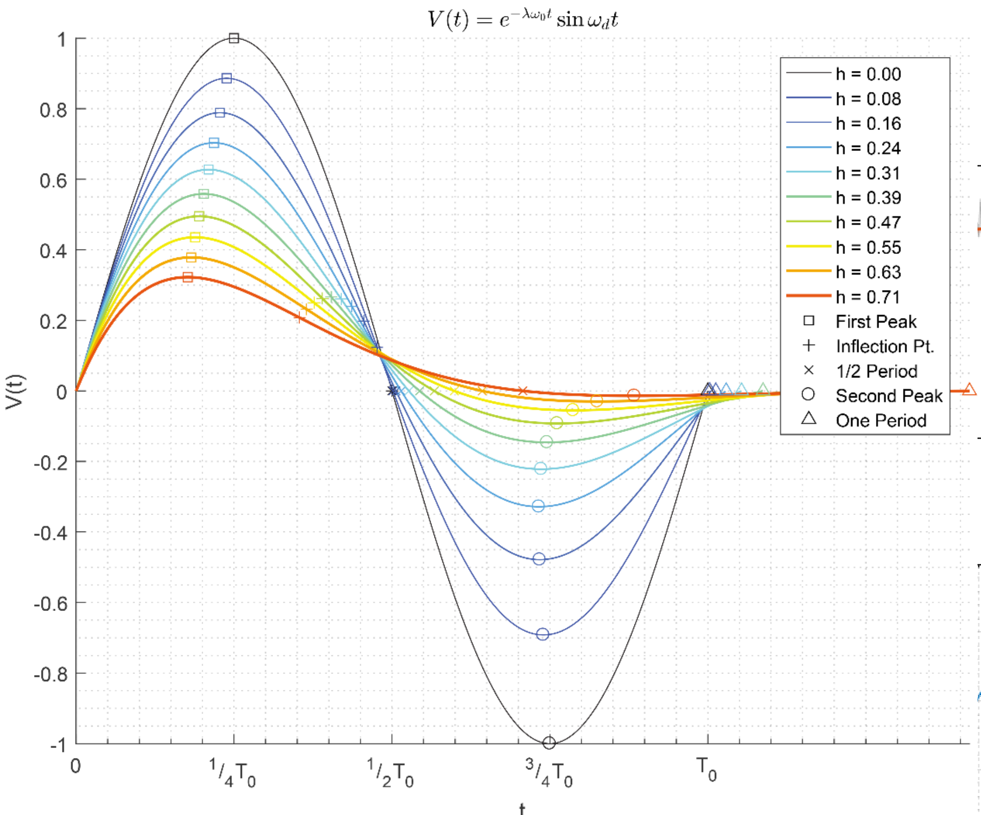
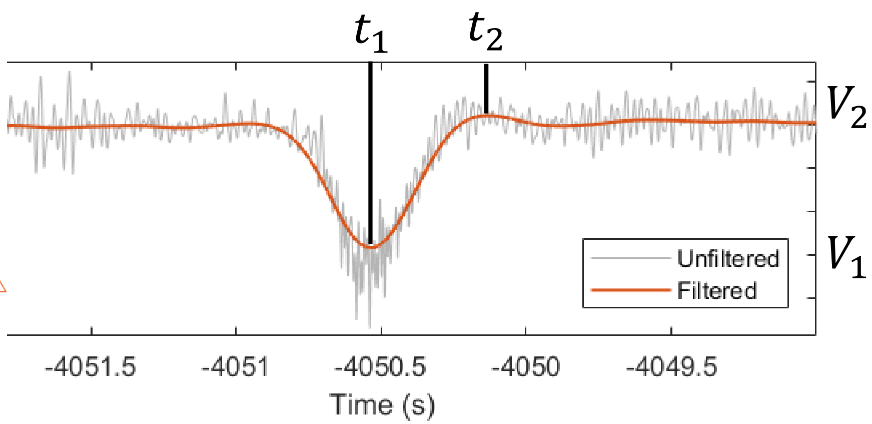
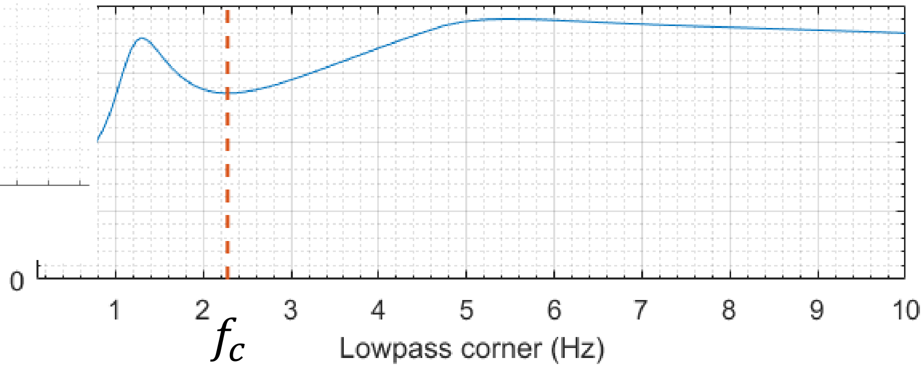


$$\frac{1}{2}T_d = t_2 - t_1$$





1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

3. Measure instrument constants

$f_c \approx 2.3\ Hz$

$V_1 = -5692$ cts

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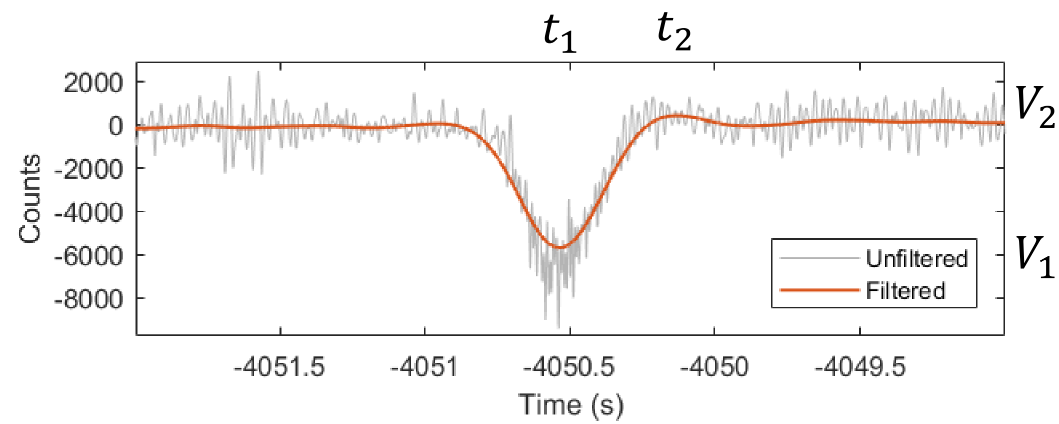
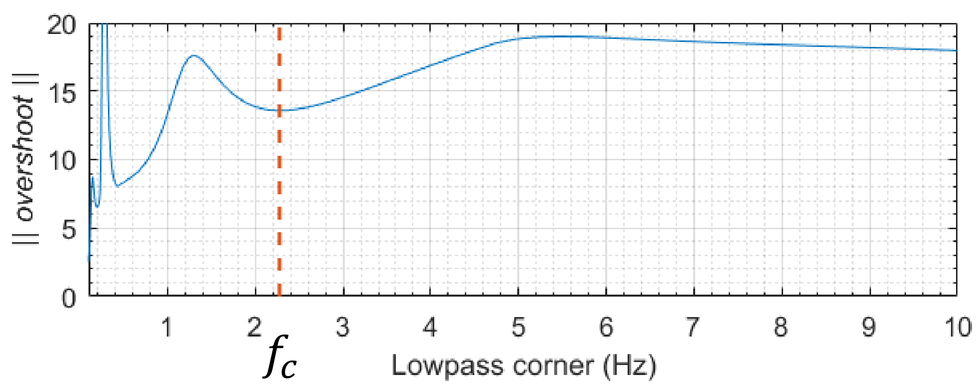
$$\frac{1}{2}T_d = t_2 - t_1 = 0.42\ \text{s}$$

$$\omega_d = 2\pi f_d = \frac{2\pi}{T_d} = 7.48$$





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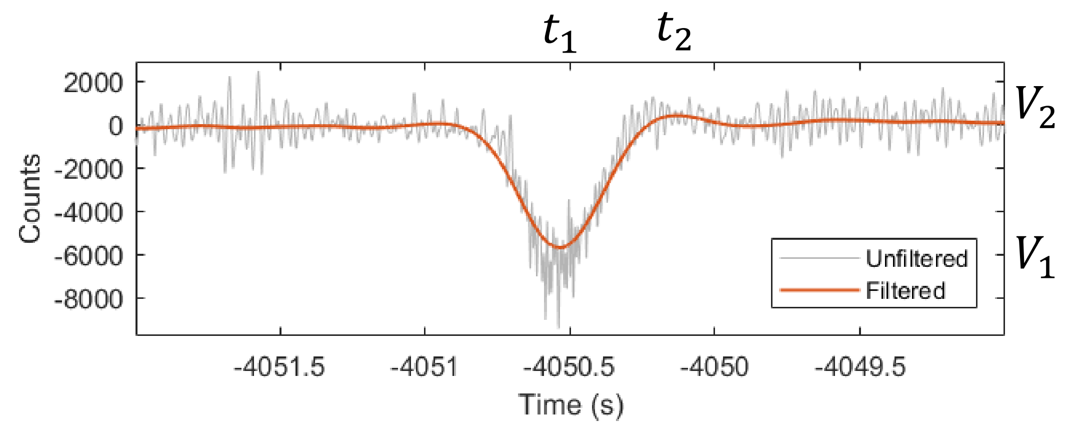
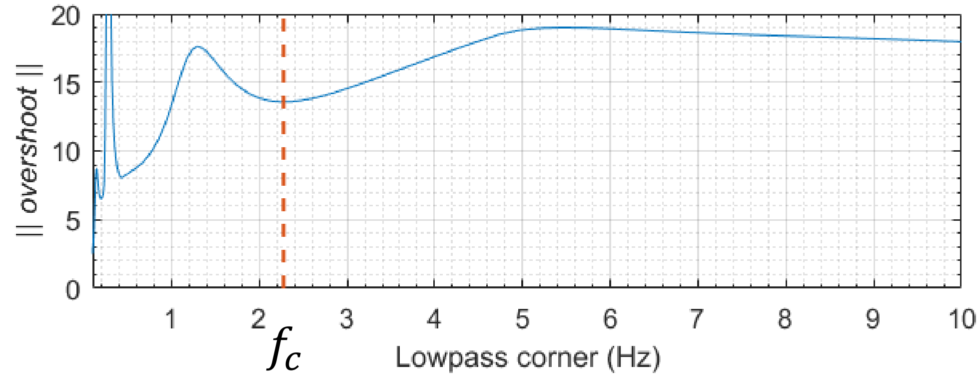
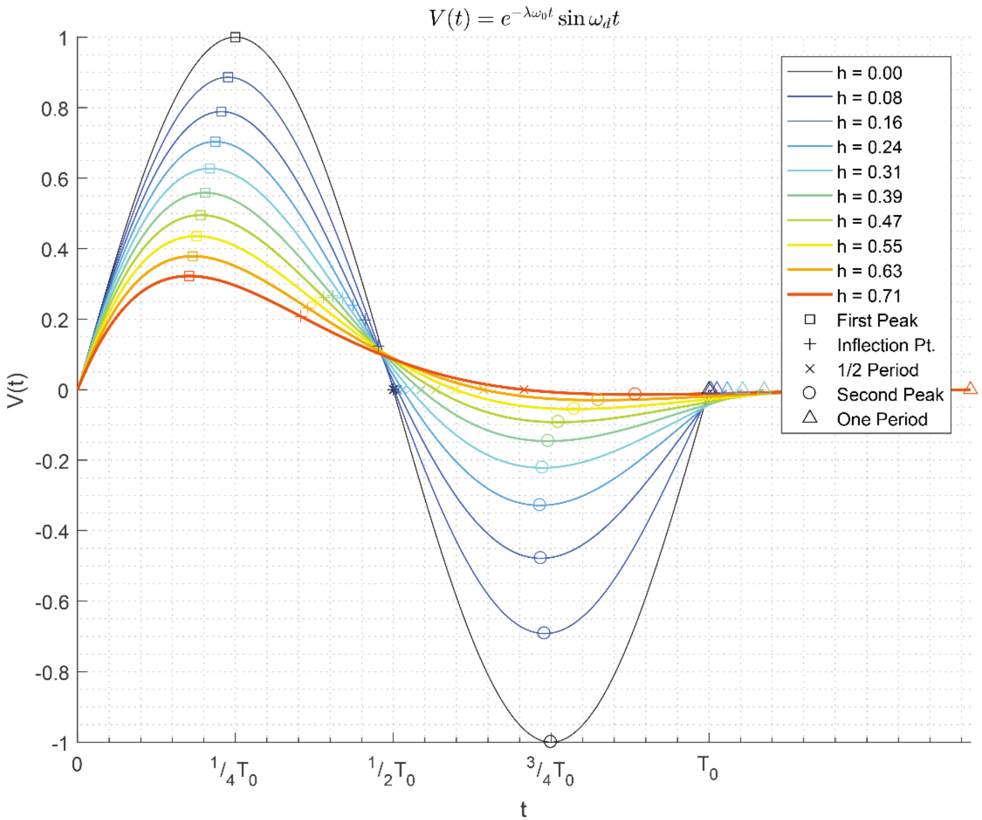




$\omega_d = 2\pi f_d = \frac{2\pi}{T_d} = 7.48$ $\quad \omega_d = \omega_0\sqrt{1-\lambda^2}$ $\quad \omega_0 = 9.72$ $\quad f_0 = 1.54$ Hz

4. Solve for generator constant

$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t} \sin\omega_d t$$

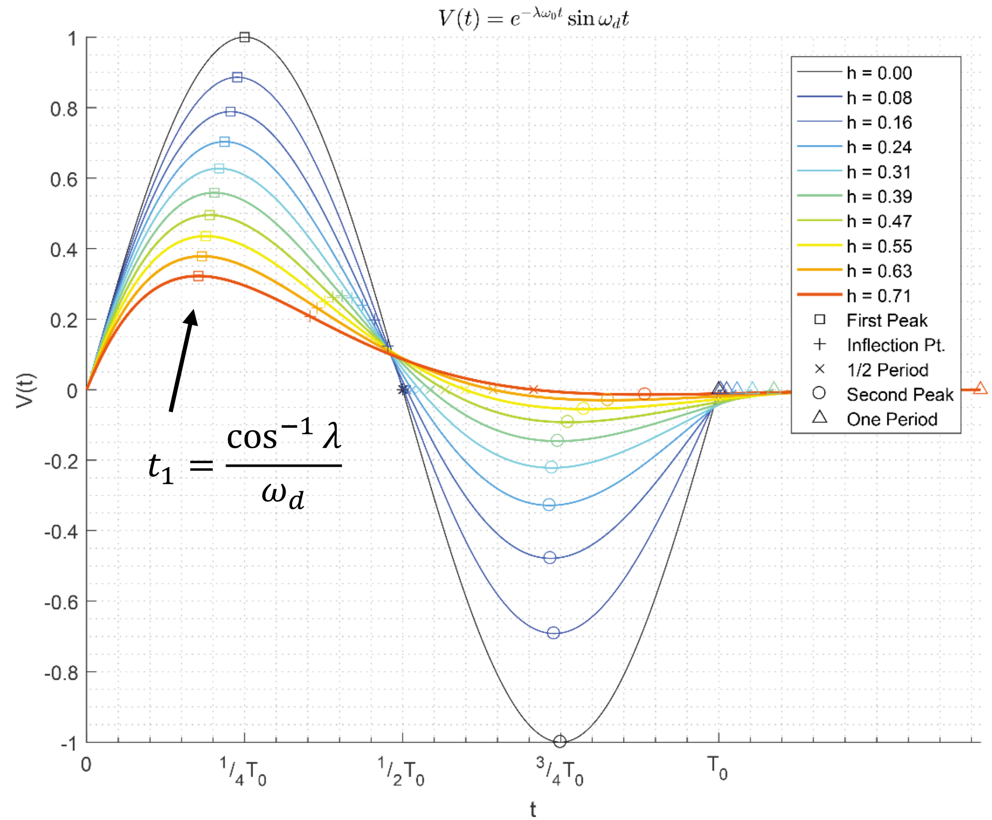


4. Solve for generator constant

Sandia National Laboratories

$$V(t) = -G\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t}\sin\omega_d t$$

$$V(t_1) = -G_1\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t_1}\sin\omega_d t_1$$



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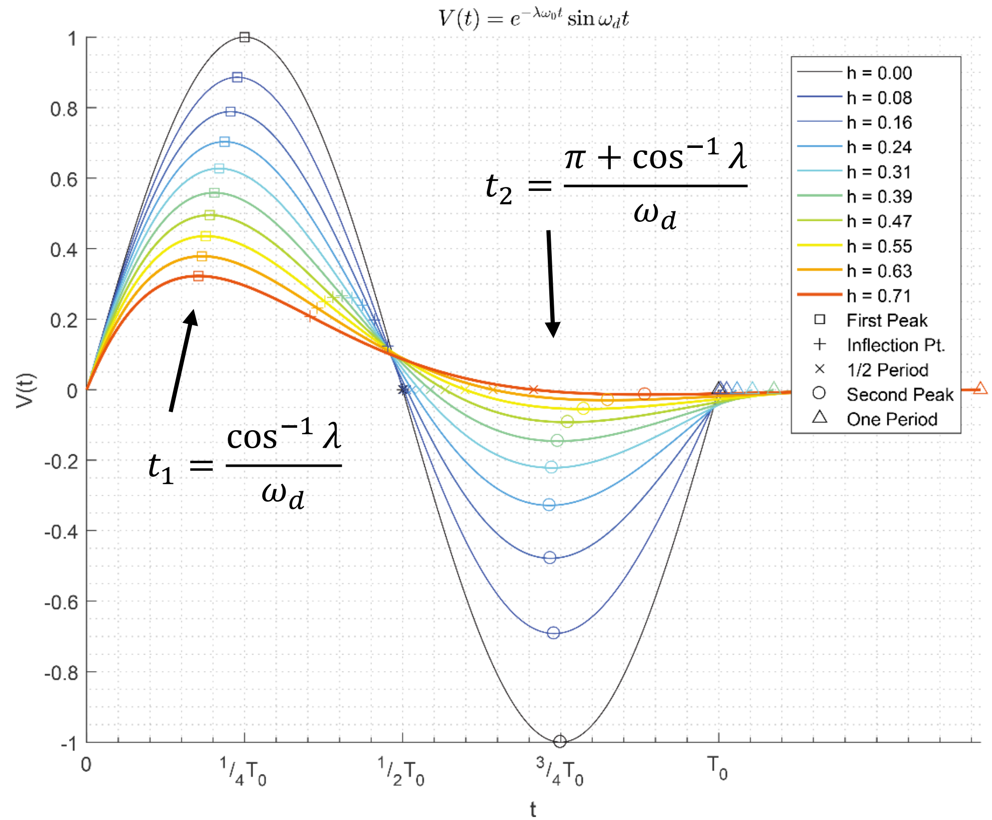

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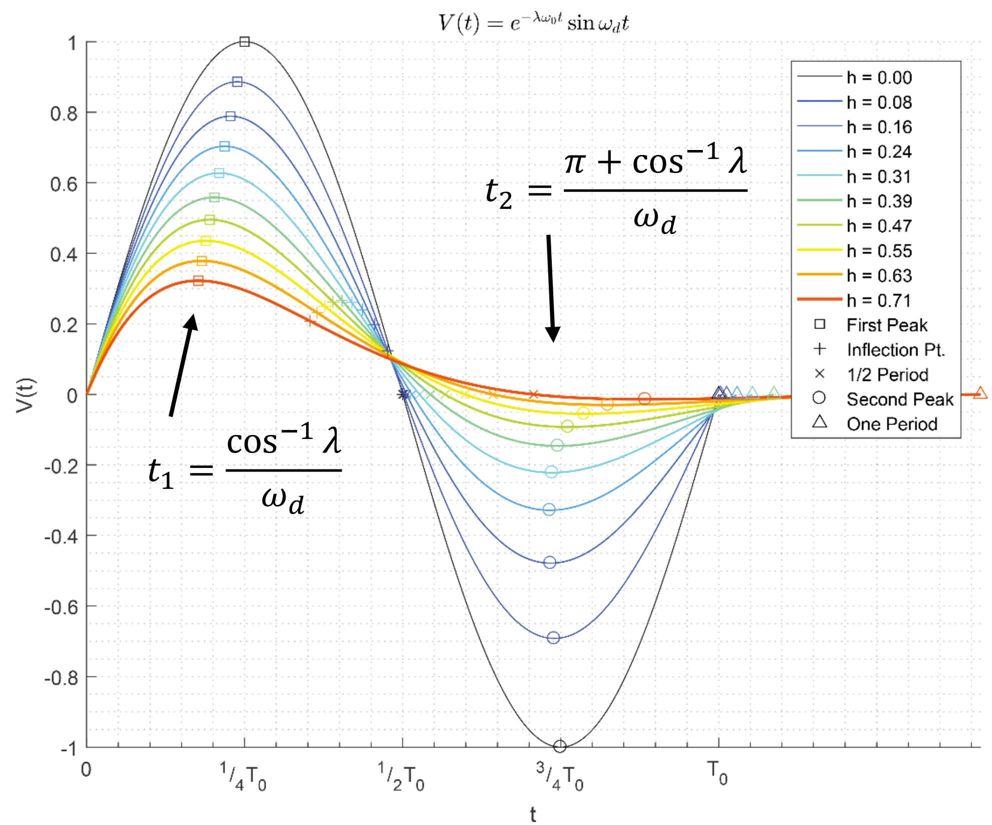
$$V(t_2) = -G_2\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t_1}\sin\omega_d t_2$$

$$G = \frac{G_1 + G_2}{2}\left[\frac{\text{cts}}{\text{m/s}}\right]$$



4. Solve for generator constant

$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t} \sin \omega_d t$$

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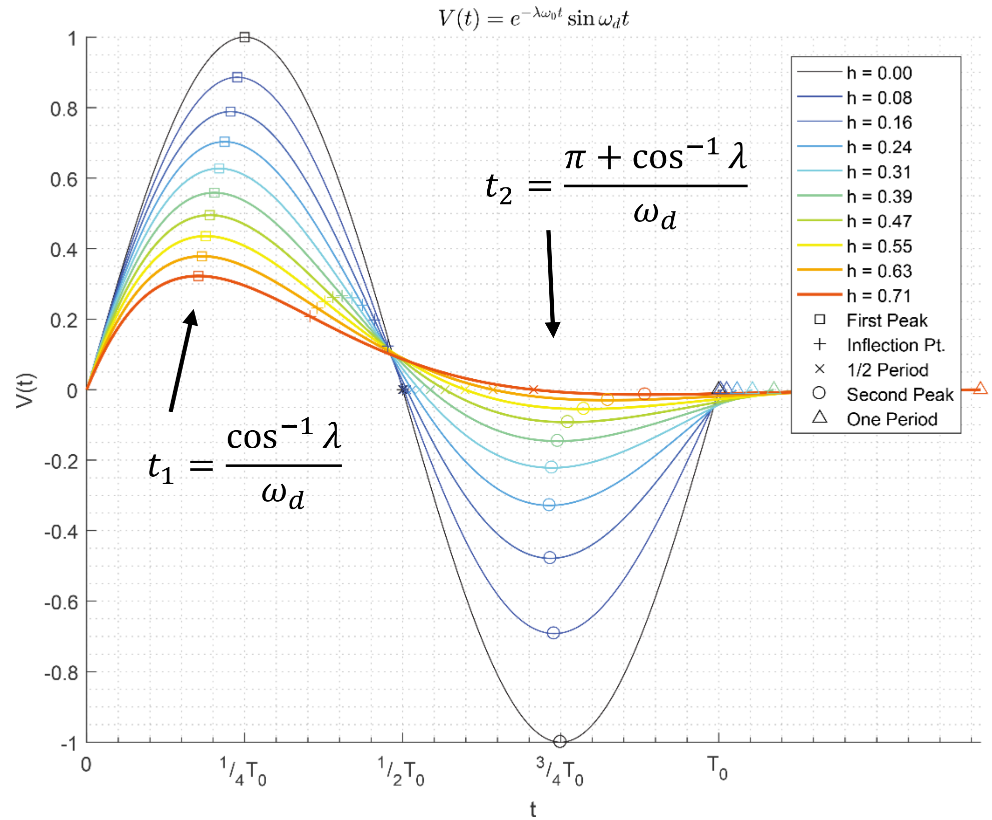
$$V(t_2) = -G_2\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t_1} \sin \omega_d t_2$$

$$G = \frac{G_1 + G_2}{2} \left[\frac{\text{cts}}{\text{m/s}}\right]$$



$m_w = 0.255$ [g] $m_s = 107.5$ [kg] $g = 9.80665$ [m/s^2]

5. Dynamic magnification

- G is units of *digital counts* per *velocity*
  - per velocity of <u>*seismic mass*</u> motion
- Seismic mass doesn't move 1:1 with ground motion
  - It moves less

Undriven seismometer:

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = 0$$

Driven seismometer:

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = -\ddot{u}$$

Arbitrary acceleration
(Earth ground motion)

5. Dynamic magnification

Arbitrary acceleration
(Earth ground motion)

Driven seismometer:

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = -\ddot{u}$$

Fourier Transform:

$$\mathcal{F}[\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x] = \mathcal{F}[-\ddot{u}]$$

$$\Rightarrow (-\omega^2 + i2\lambda\omega_0\omega + \omega_0^2)\hat{x} = \omega^2\hat{u}$$

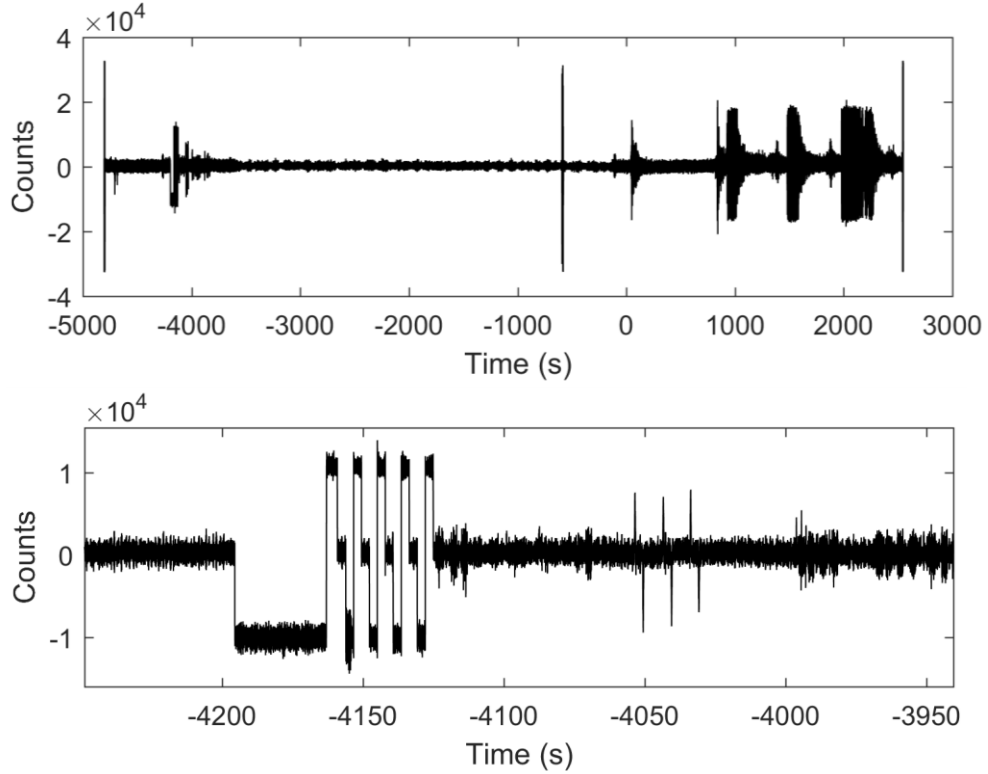
Solve for *Earth movt* per *mass movt*

$$\underbrace{\left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega^2} - 1\right)^2 + 4\lambda^2\frac{\omega_0^2}{\omega^2}}$$

Magnitude as a
function of *frequency*

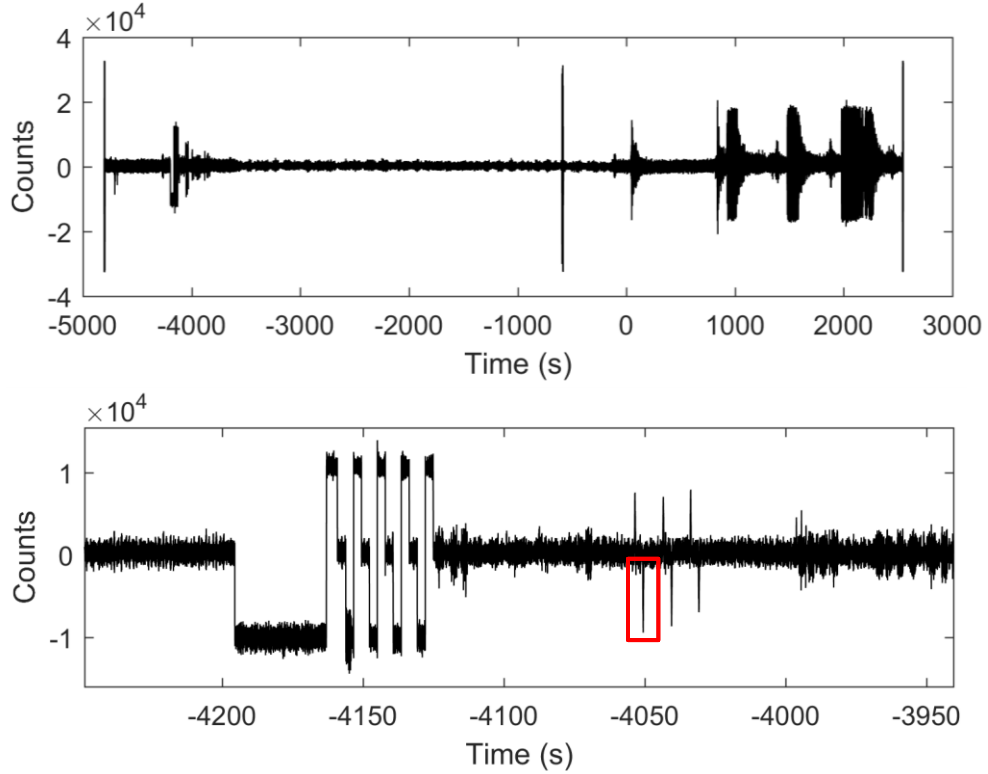
…in units of $\left[\frac{\text{earth movt}}{\text{mass movt}}\right]$

Let’s calibrate some data



Boxcar – Leeds – VSP÷5

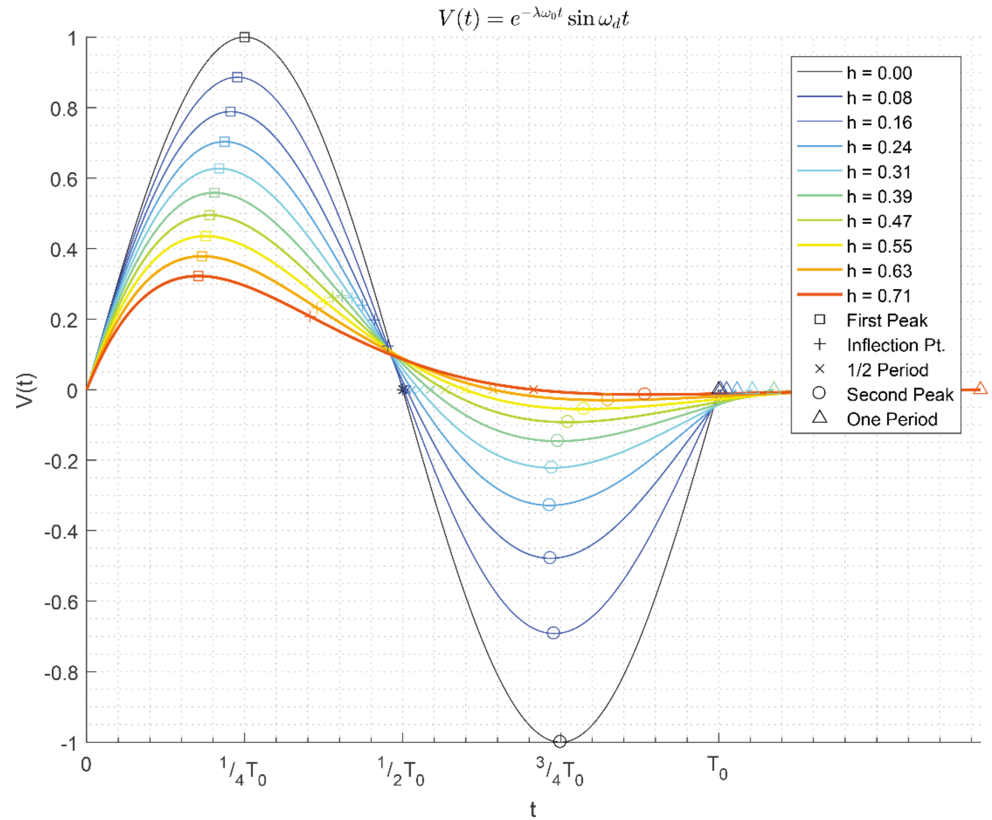
Let’s calibrate some data



Boxcar – Leeds – VSP÷5

Let's calibrate some data

$$V(t) = -G\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t}\sin\omega_d t$$

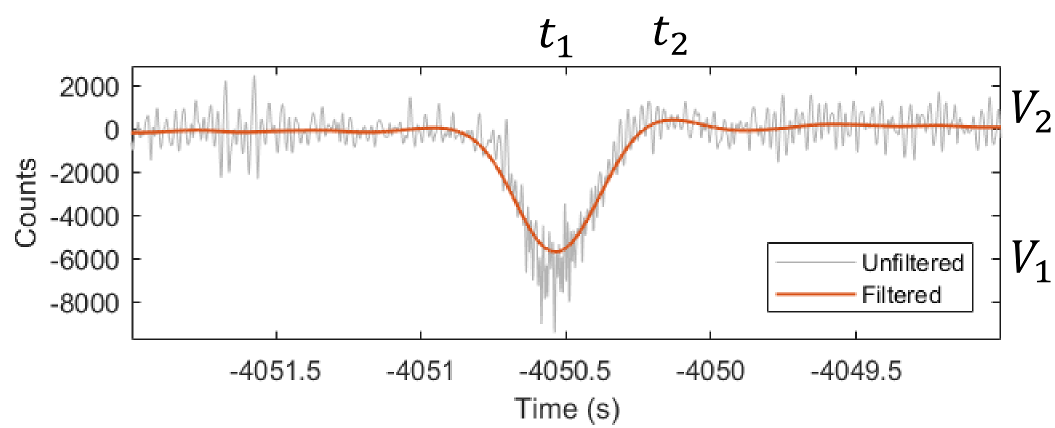


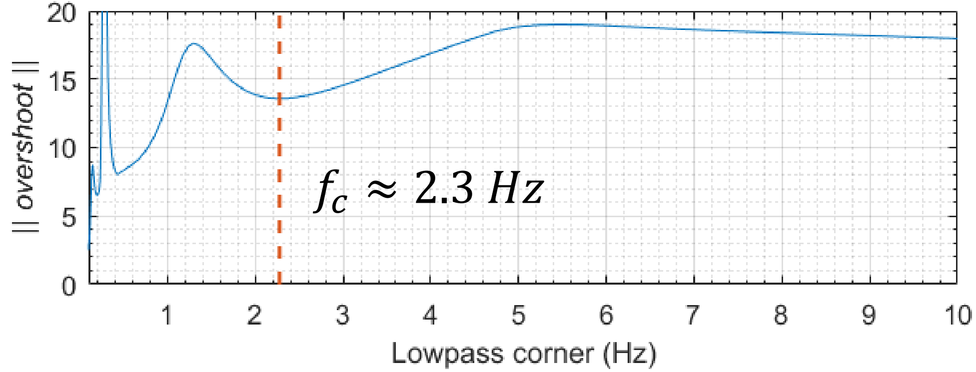
$m_w = 0.255$ [g] $\quad$ $m_s = 107.5\ [kg]$ $\quad$ $g = 9.80665\ [m/s^2]$

Let's calibrate some data

$$V(t) = -G\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t}\sin\omega_d t$$

$V_1 = -5692$ cts $\quad V_2 = 419$ cts





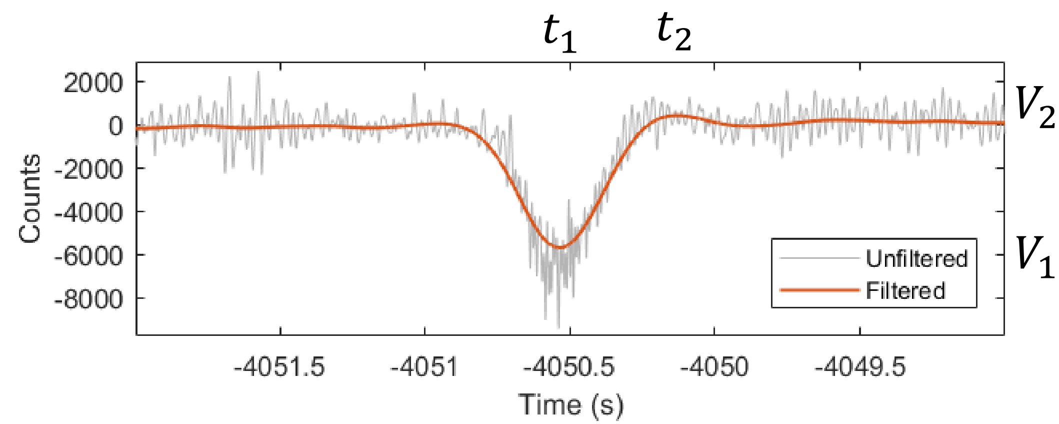
Let’s calibrate some data

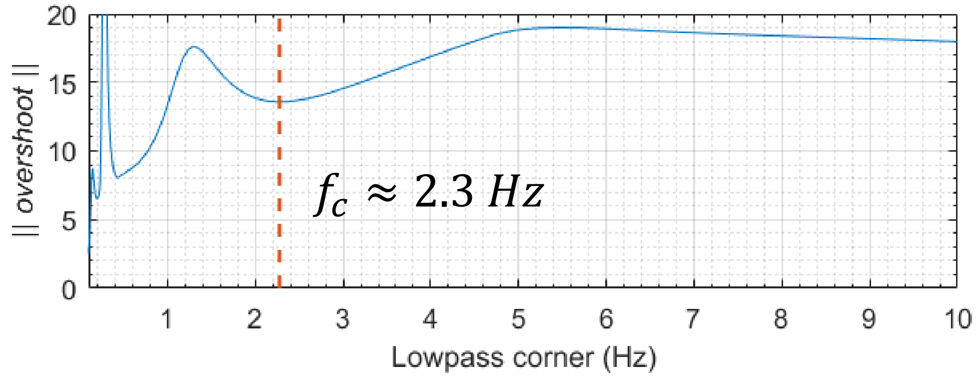
$$V(t) = -G\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t}\sin\omega_d t$$

$$V_1 = -5692\ \text{cts} \qquad V_2 = 419\ \text{cts}$$

$$\left|\frac{V_1}{V_2}\right| = 13.58 \qquad \delta = \ln\left|\frac{V_1}{V_2}\right| = 2.61$$

$$\lambda = \frac{\delta}{\sqrt{\pi^2+\delta^2}} = 0.6389$$





Let's calibrate some data

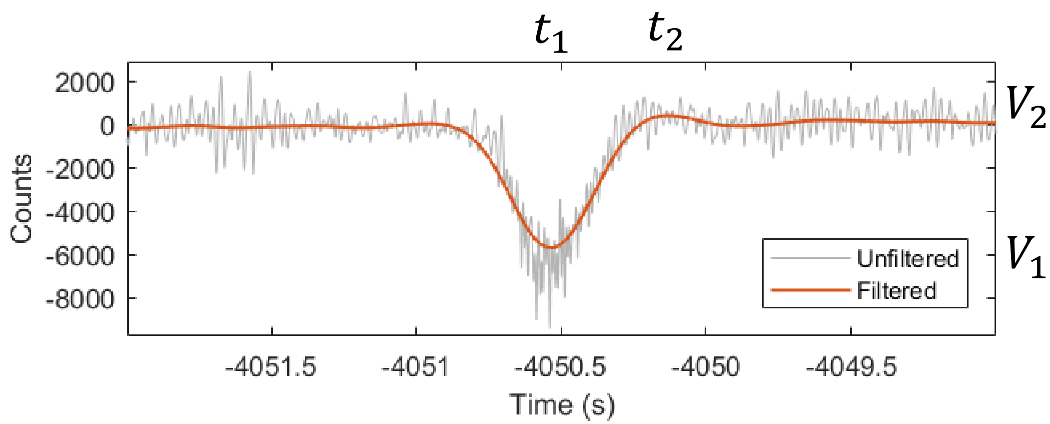
$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t} \sin\omega_d t$$

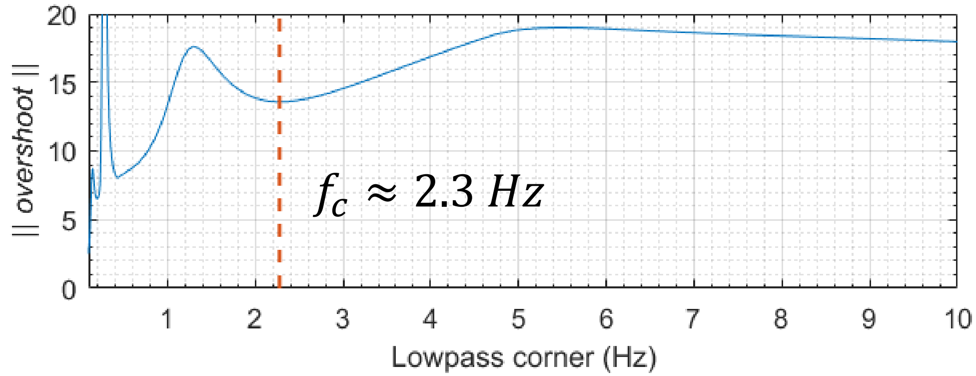
$V_1 = -5692 \text{ cts} \qquad V_2 = 419 \text{ cts}$

$\left|\frac{V_1}{V_2}\right| = 13.58 \qquad \delta = \ln\left|\frac{V_1}{V_2}\right| = 2.61$

$$\lambda = \frac{\delta}{\sqrt{\pi^2 + \delta^2}} = 0.6389$$

$\frac{1}{2}T_d = 0.42 \text{ s} \qquad T_d = 0.84 \text{ s}$





Let's calibrate some data

$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t} \sin \omega_d t$$

$V_1 = -5692$ cts $\qquad V_2 = 419$ cts

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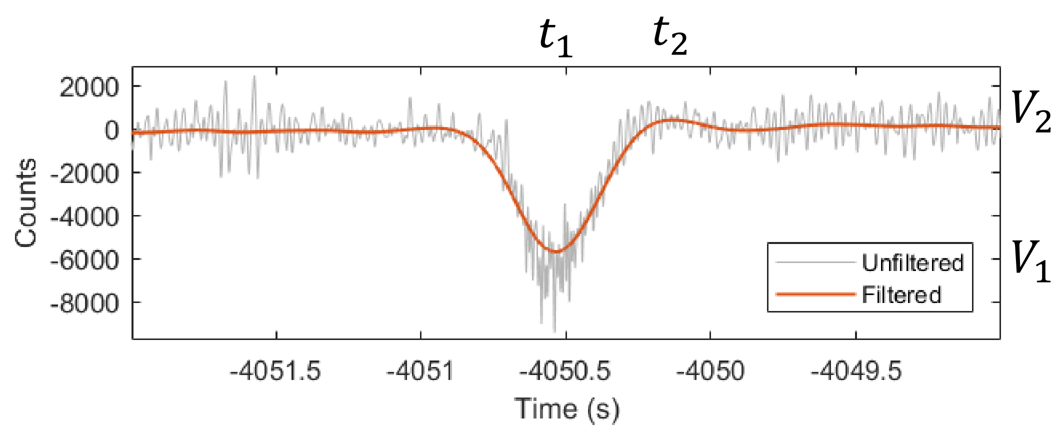
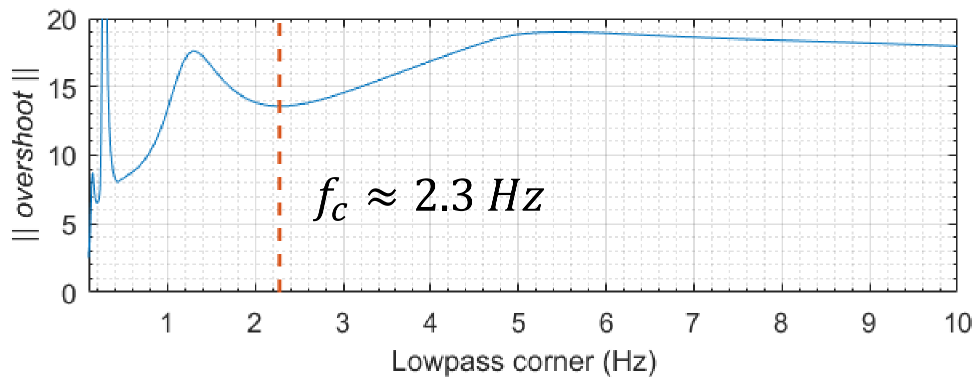
$$\frac{1}{2}T_d = 0.42 \text{ s} \qquad T_d = 0.84 \text{ s}$$

$$\omega_d = 7.48$$

$$\omega_d = \omega_0\sqrt{1-\lambda^2} \;\Rightarrow\; \omega_0 = 9.72$$





Let's calibrate some data

$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t}\sin\omega_d t$$

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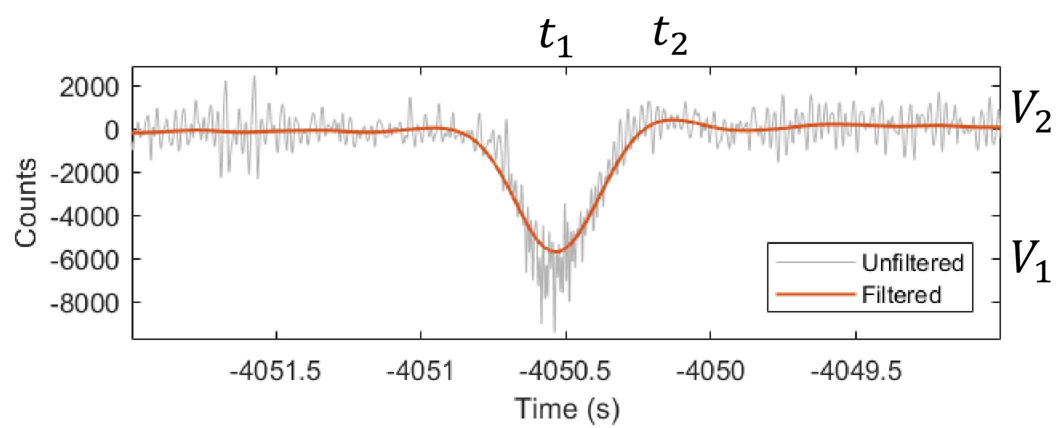
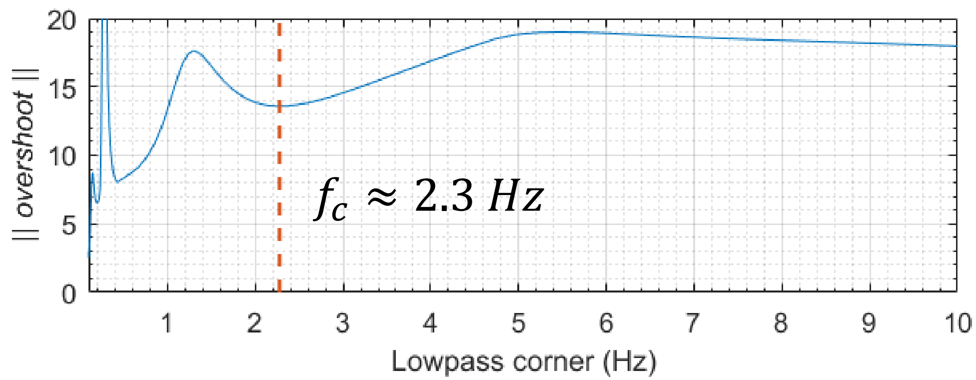




$$\omega_d = \omega_0\sqrt{1-\lambda^2} \;\Rightarrow\; \omega_0 = 9.72 \qquad t_1 = \frac{\cos^{-1}\lambda}{\omega_d} = 0.12\ [\mathrm{s}] \qquad t_2 = \frac{\pi + \cos^{-1}\lambda}{\omega_d} = 0.54\ [\mathrm{s}]$$

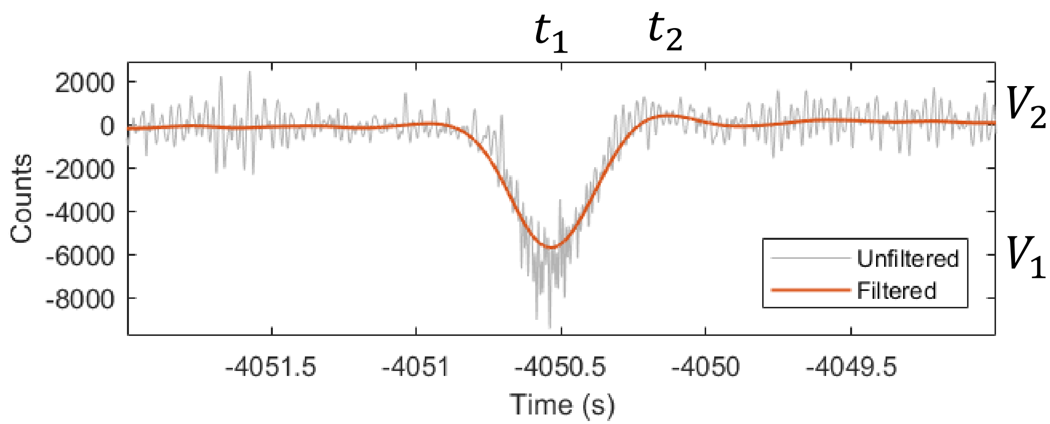
$m_w = 0.255$ [g] $\qquad m_s = 107.5\ [kg]$ $\qquad g = 9.80665\ [m/s^2]$

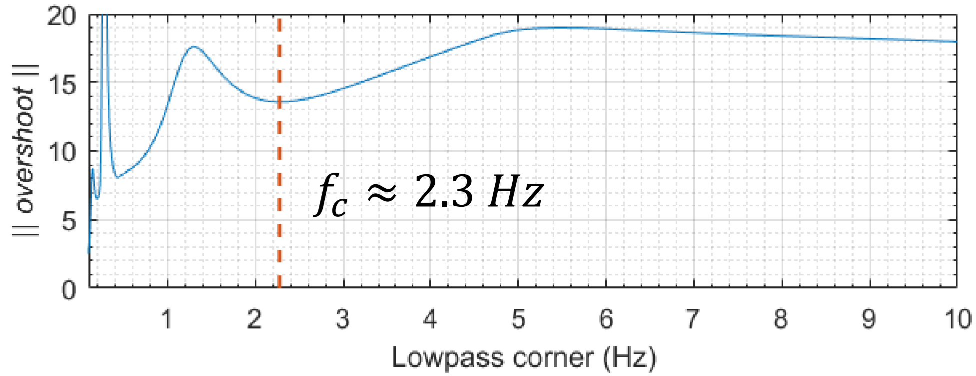
Let's calibrate some data

$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t} \sin \omega_d t$$

$$V(t_1) = -G_1\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t_1} \sin \omega_d t_1$$

$$G_1 = 4.9327 \times 10^9$$





1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

Let’s calibrate some data

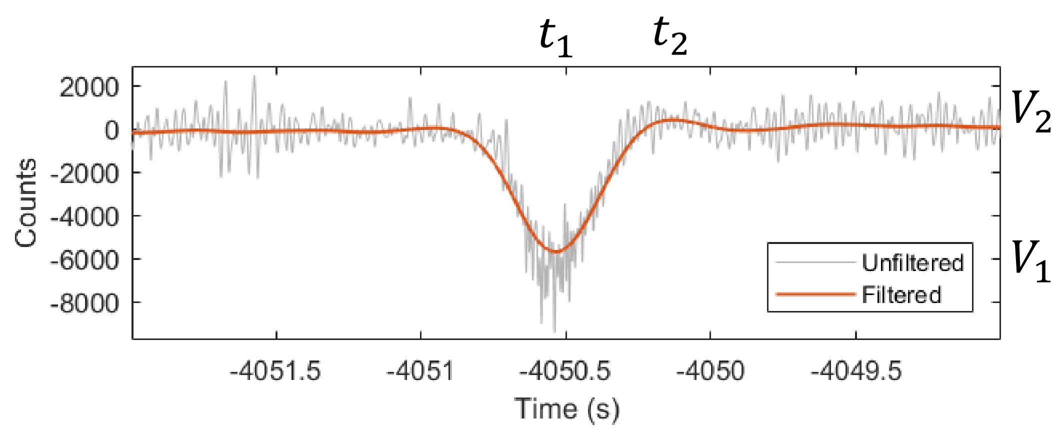
$$V(t) = -G\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t}\sin\omega_d t$$

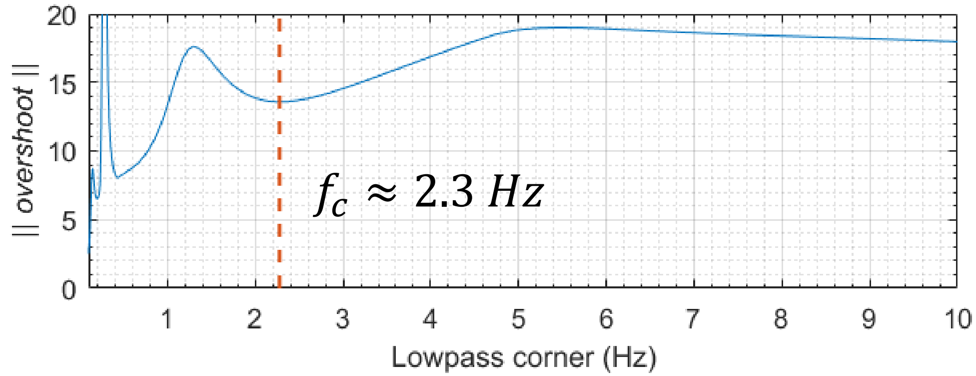
$$V(t_1) = -G_1\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t_1}\sin\omega_d t_1$$

$$G_1 = 4.9327 \times 10^9$$

$$V(t_2) = -G_2\,\frac{m_w g}{m_s \omega_d}\,e^{-\lambda\omega_0 t_1}\sin\omega_d t_1$$

$$G_2 = 4.9327 \times 10^9$$





Let's calibrate some data

$$V(t) = -G\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t} \sin \omega_d t$$

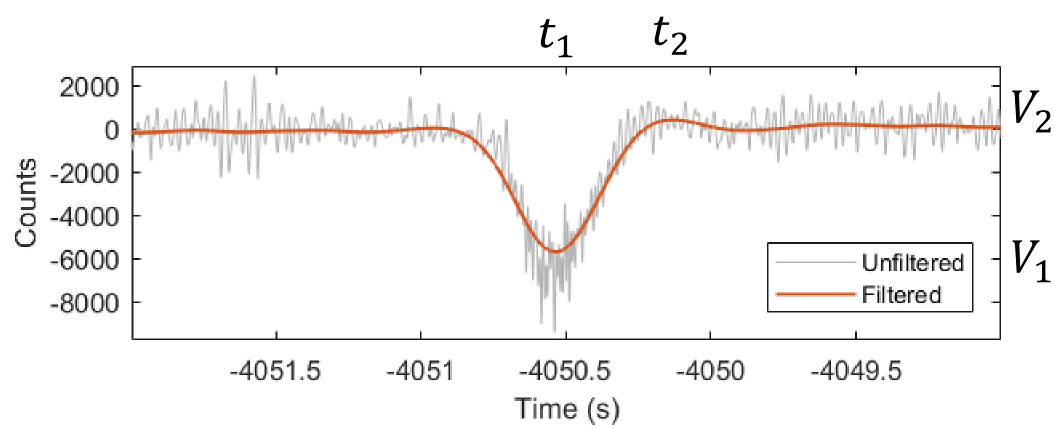
$$V(t_1) = -G_1\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t_1} \sin \omega_d t_1$$

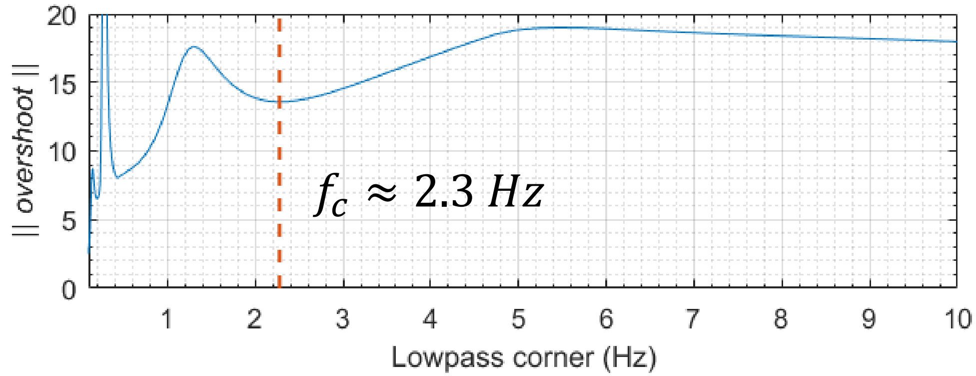
$$G_1 = 4.9327 \times 10^9$$

$$V(t_2) = -G_2\frac{m_w g}{m_s \omega_d} e^{-\lambda\omega_0 t_1} \sin \omega_d t_1$$

$$G_2 = 4.9327 \times 10^9$$

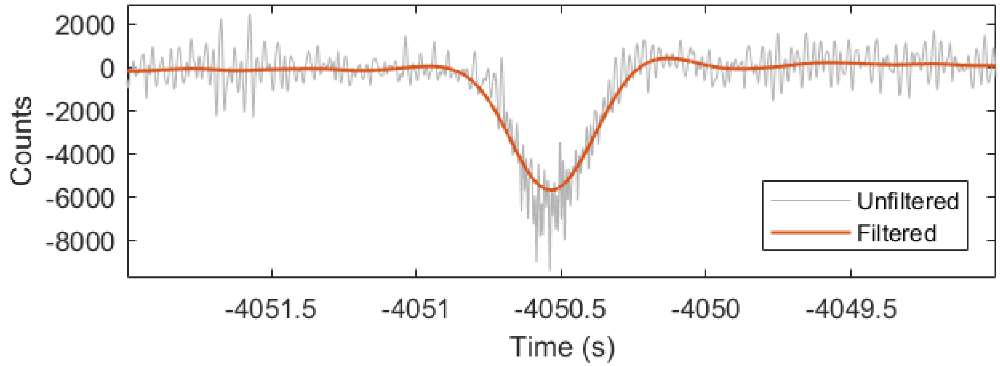
$$G = \frac{G_1 + G_2}{2} = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$





Let’s calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

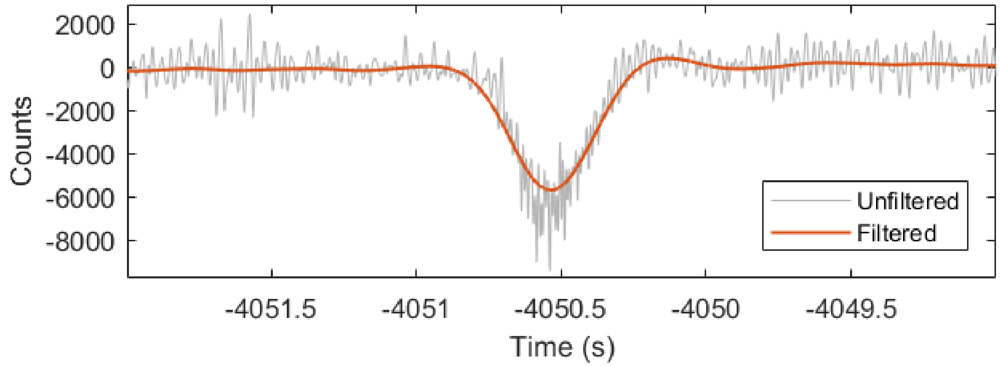


$$M^2(\omega) = \left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega^2} - 1\right)^2 + 4\lambda^2 \frac{\omega_0^2}{\omega^2} \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

Let’s calibrate some data

$$G = 4.9327 \times 10^{9} \left[\frac{\text{cts}}{\text{m/s}}\right]$$

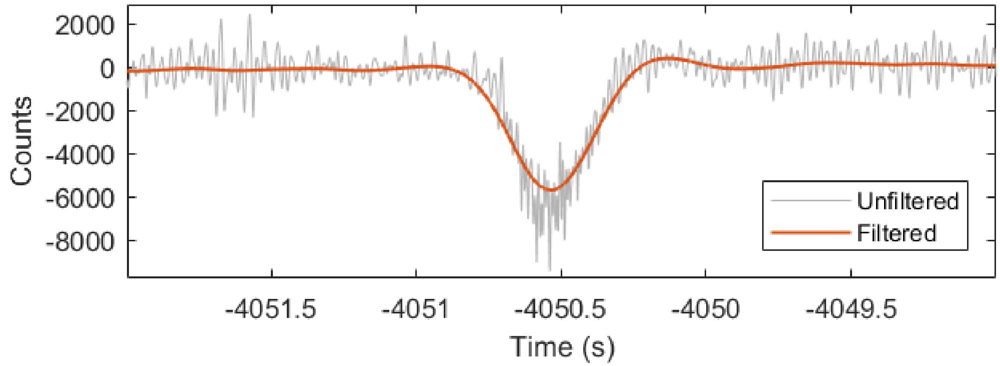


$$M^2(\omega) = \left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega^2} - 1\right)^2 + 4\lambda^2 \frac{\omega_0^2}{\omega^2} \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

$$M^2(\omega_d) = \left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega_d^2} - 1\right)^2 + 4\lambda^2 \frac{\omega_0^2}{\omega_d^2}$$

Let's calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$



$$M^2(\omega) = \left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega^2} - 1\right)^2 + 4\lambda^2\frac{\omega_0^2}{\omega^2}\left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

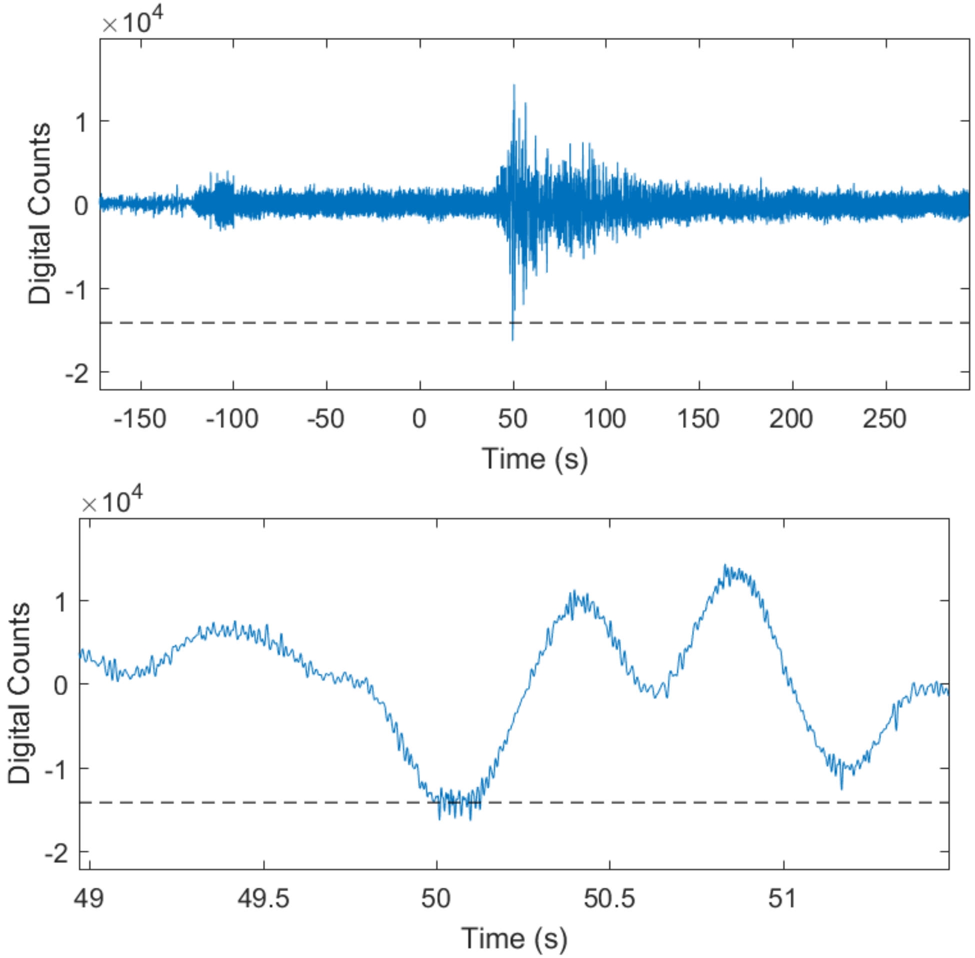
$$M^2(\omega_d) = \left|\frac{\hat{u}}{\hat{x}}\right|^2 = \left(\frac{\omega_0^2}{\omega_d^2} - 1\right)^2 + 4\lambda^2\frac{\omega_0^2}{\omega_d^2}$$

$$M(\omega_d) = 1.7985\left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

Let's calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$



Peak ground velocity (PGV)

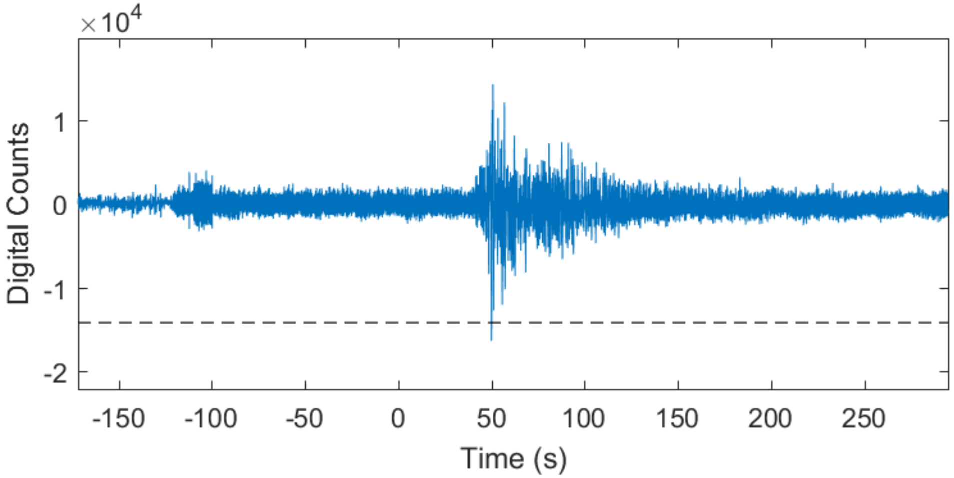
1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

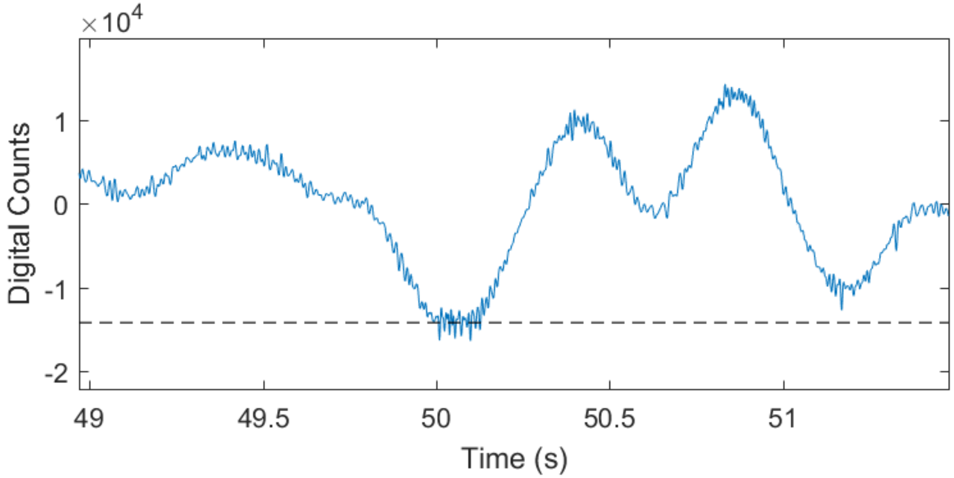
Let's calibrate some data

$$G = 4.9327 \times 10^{9} \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

$$PGV = 14233\ [\text{cts}]$$





Peak ground velocity (PGV)

Let's calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

$$PGV = 14233\ [\text{cts}]$$

REVISED 10/17/67

SEISMIC FIELD SHEET...Page 5

TAPE CHANNEL 5 DATA

6819-1

VCO FREQUENCY in CPS	INSTRUMENT	CAL db PTA 0 PAD	RUN db PTA 0 PAD	BAND EDGE SENS.*	ELECTR. GAIN	CAL BATT. VOLTS
1120	TSP÷5	48	96	.5 v		.45 v
1300	TSP×1	↓	↓	↓		↓
1480	RSP÷25		84			
1660	RSP÷5		↓			
1840	RSP×1		↓			
2030	VSP÷25		84			
2230	VSP÷5		↓			
2450	VSP×1	↓	↓	↓		↓

* Band Edge = 100% of bandwidth

SHORT PERIOD WEIGHT LIFTS

				DAMPING
VERTICAL	10.8	DIV. @	48 db	13:1
RADIAL	14.9	DIV. @	48 db	11:1
TANGENTIAL	12	DIV. @	48 db	12:1

SHORT PERIOD WEIGHT/MICRONS

VERTICAL	.255	gms. =	.319 u
RADIAL	2.000	gms. =	.250 u
TANGENTIAL	2.000	gms. =	.250 u

NGC-23 CALIBRATION

VERTICAL	~	DIV. @	~ db
RADIAL/STS	~	DIV. @	~ db
RADIAL/NTS	~	DIV. @	~ db

Seismic Arrival Time* ______

* Ely and Battle Mt. only. Other stations are noted on Field Data Sheet

$$PGV = \frac{14233 \times 5\ [\text{cts}]}{\boxed{10^{-\frac{84\ [\text{dB}]}{20}}}} \times \frac{\frac{1\ [\text{m/s}]}{4.9327 \times 10^9\ [\text{cts}]}}{\boxed{10^{-\frac{48\ [\text{dB}]}{20}}}} \times \frac{1.7985\ [\text{earth movt}]}{1\ [\text{mass movt}]} = 0.1637\ [\text{cm/s}]$$

1986 APR 26 Boxcar (1.3 Mt // NV-209) @ Leeds, UT: VSP÷5

Let’s calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

$$PGV = 14233\ [\text{cts}] = \boxed{0.1637\ [\text{cm/s}]}$$

Murphy & Lahoud (1969)

$$PGV = 31.1W^{.505}R^{-1.58}$$

Analysis of seismic peak amplitudes from underground nuclear explosions. *Bull. Seismo. Soc. Am.*, 59(**6**).

Let’s calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

$$PGV = 14233\ [\text{cts}] = \boxed{0.1637\ [\text{cm/s}]}$$

Murphy & Lahoud (1969)

$$PGV = 31.1 W^{.505} R^{-1.58} = \boxed{0.1620\ [\text{cm/s}]}$$

BOXCAR

$W = 1300\ [\text{kt}]$

Leeds, UT

$R = 276\ [\text{km}]$

Let’s calibrate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

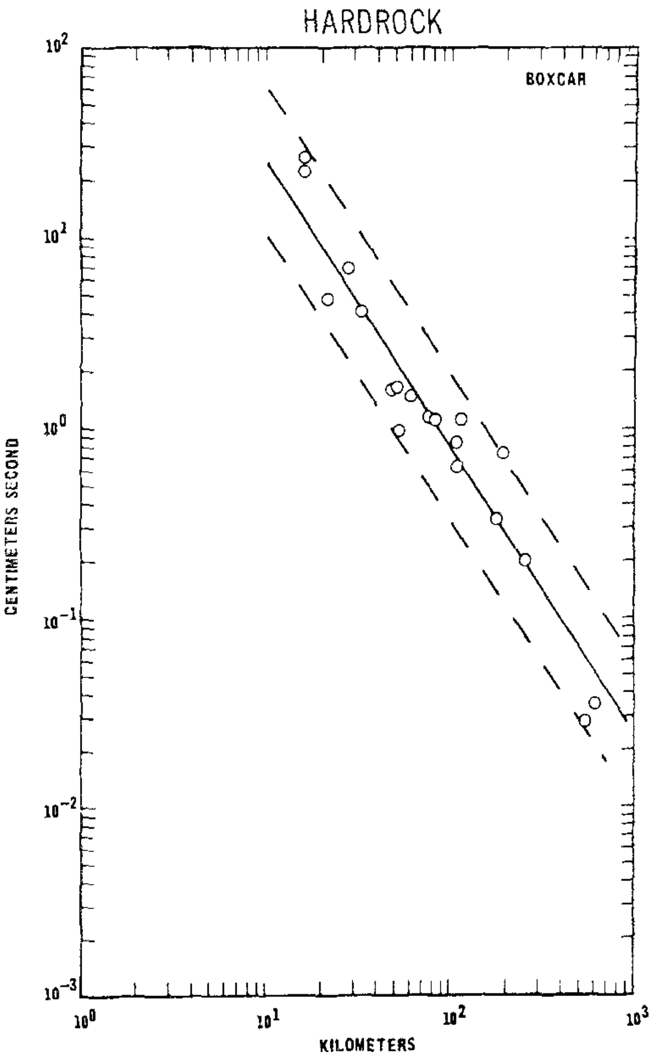
$$PGV = 14233\ [\text{cts}] = \boxed{0.1637\ [\text{cm/s}]}$$

Murphy & Lahoud (1969)

$$PGV = 31.1 W^{.505} R^{-1.58} = \boxed{0.1620\ [\text{cm/s}]}$$

BOXCAR $\quad$ Leeds, UT

$W = 1300$ [kt] $\quad R = 276$ [km]



Let's calculate some data

$$G = 4.9327 \times 10^9 \left[\frac{\text{cts}}{\text{m/s}}\right]$$

$$M(\omega_d) = 1.7985 \left[\frac{\text{earth movt}}{\text{mass movt}}\right]$$

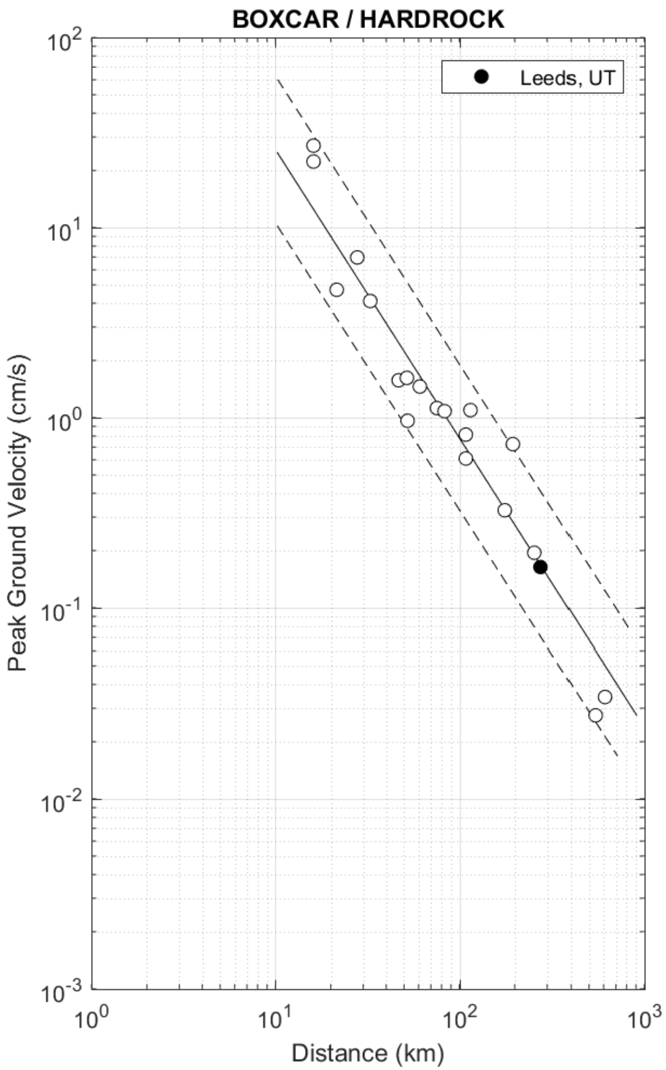
$$PGV = 14233\ [\text{cts}] = \boxed{0.1637\ [\text{cm/s}]}$$

Murphy & Lahoud (1969)

$$PGV = 31.1 W^{.505} R^{-1.58} = \boxed{0.1620\ [\text{cm/s}]}$$

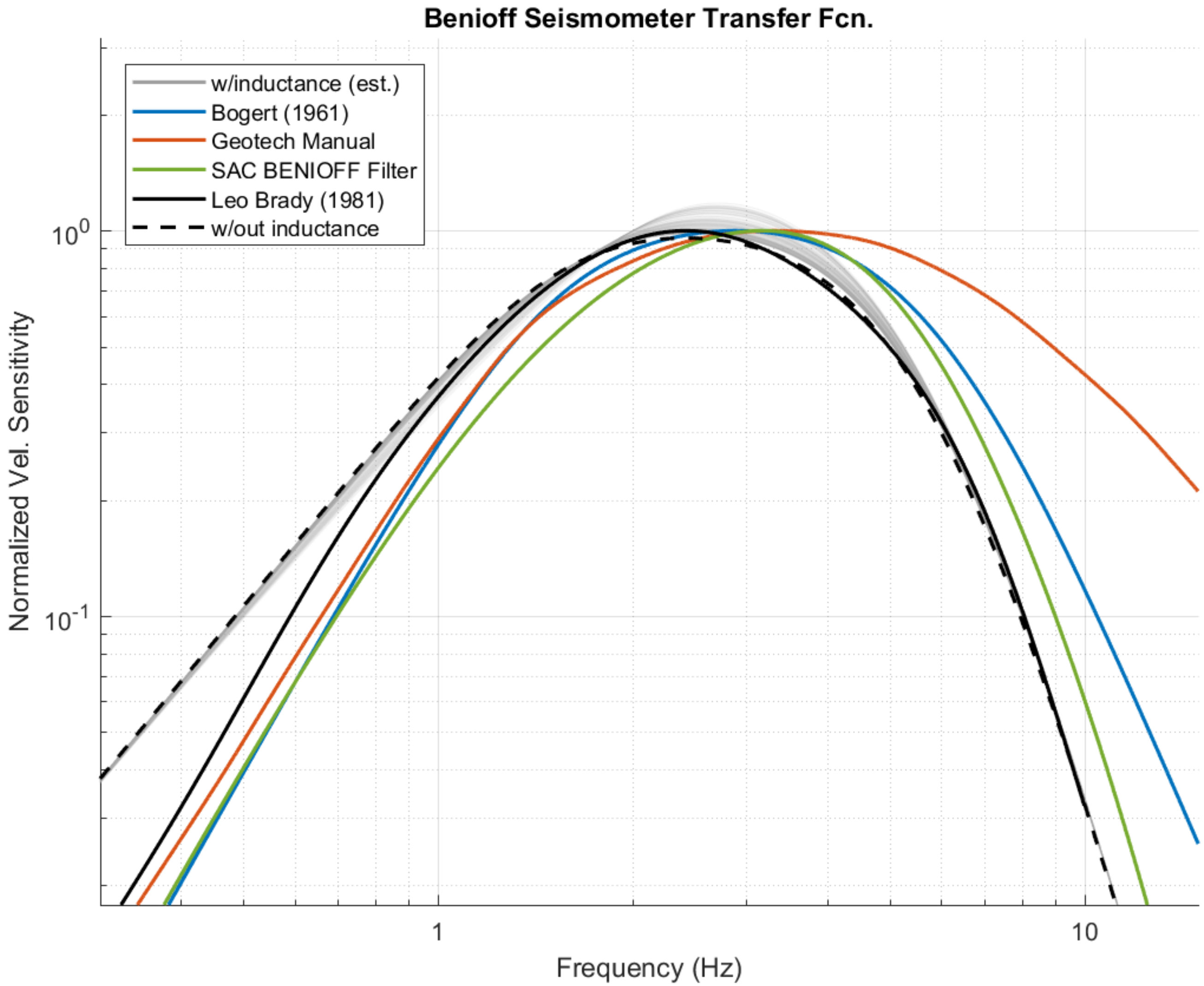
BOXCAR $W = 1300$ [kt]

Leeds, UT $R = 276$ [km]

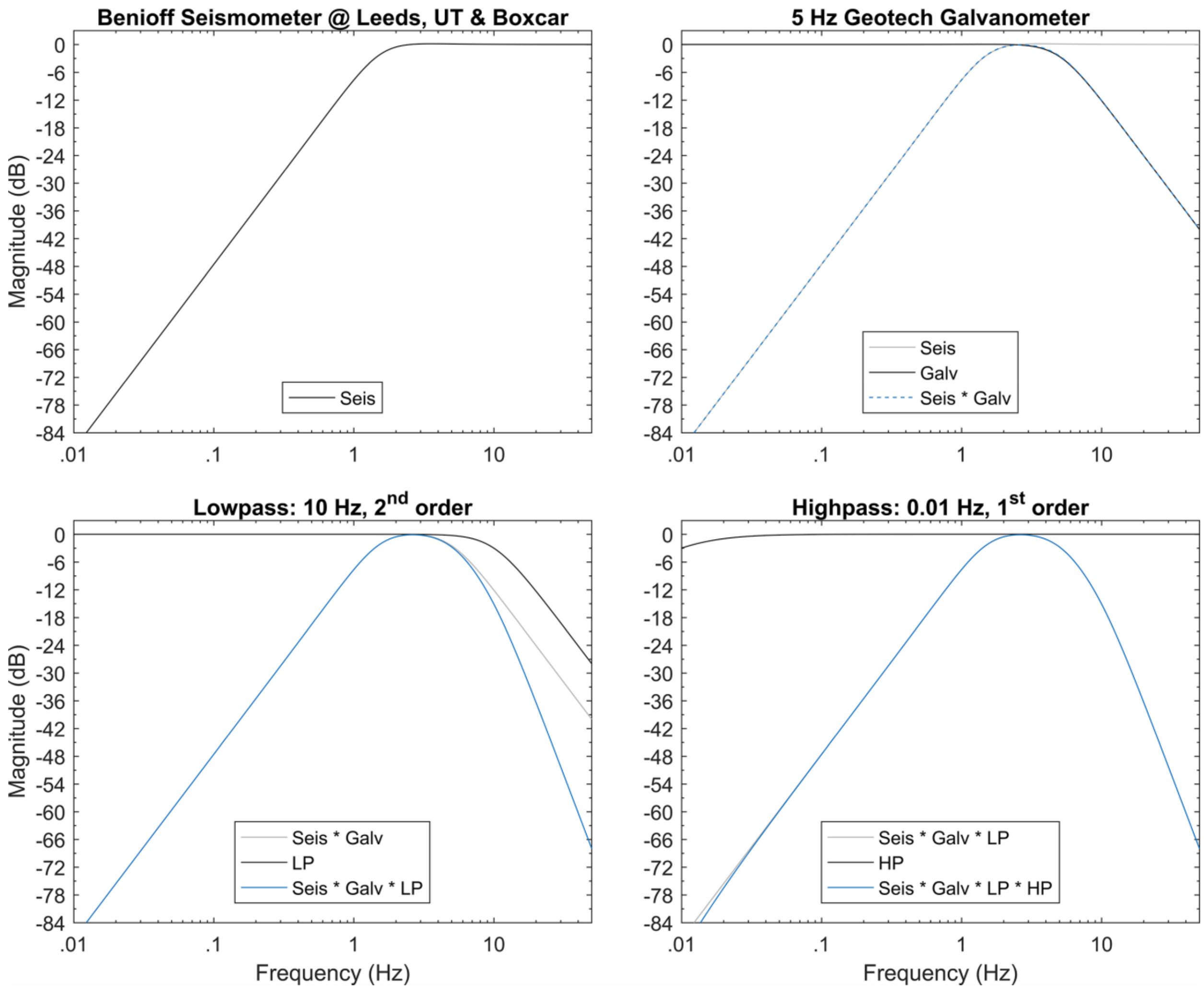


Instrument Response

Comparison of freq. resposnes



Building an instrument response



Building an instrument response

Velocity transfer function

$$\hat{T}_V(\omega) = \frac{\omega^2}{\omega_s^2 - \omega^2 + i2\lambda_s\omega_s\omega} \cdot \frac{1}{\omega_g^2 - \omega^2 + i2\lambda_g\omega_g\omega}$$

Seismometer	Galvanometer
(Benioff 1051/1101)	*(Geotech Model 4100-13)*
$\omega_s = 2\pi \cdot 1.54\ [\mathrm{Hz}]$	$\omega_g = 2\pi \cdot 5\ [\mathrm{Hz}]$
$\lambda_s = 0.6389$	$\lambda_g = 0.675$

Building an instrument response

Velocity
transfer function

$$\hat{T}_V(\omega) = \frac{\omega^2}{\omega_s^2 - \omega^2 + i2\lambda_s\omega_s\omega} \cdot \frac{1}{\omega_g^2 - \omega^2 + i2\lambda_g\omega_g\omega}$$

Seismometer
(Benioff 1051/1101)

Galvanometer
(Geotech Model 4100-13)

$$\cdot \frac{i\omega Q\sqrt{2}}{\omega_{c,hp} + i\omega} \cdot \frac{\omega_{c,lp}^2}{w_{c,lp}^2 - \omega^2 + i\omega\omega_{c,lp}Q^{-1}}$$

Filter FL201
(Geotech PTA Model 4300 Manual, Fig. 4)

1st order
highpass

$Q = -3$ [dB]

$\omega_c = 0.01$ [Hz]

2nd order
lowpass

$Q = -3$ [dB]

$\omega_c = 8$ [Hz]

Building an instrument response

Velocity transfer function

$$\hat{T}_V(\omega) = \frac{\omega^2}{\omega_s^2 - \omega^2 + i2\lambda_s\omega_s\omega} \cdot \frac{1}{\omega_g^2 - \omega^2 + i2\lambda_g\omega_g\omega}$$

Seismometer *(Benioff 1051/1101)*

Galvanometer *(Geotech Model 4100-13)*

$$\cdot \frac{i\omega Q\sqrt{2}}{\omega_{c,hp} + i\omega} \cdot \frac{\omega_{c,lp}^2}{w_{c,lp}^2 - \omega^2 + i\omega\omega_{c,lp}Q^{-1}}$$

1st order highpass

2nd order lowpass

Filter FL201 *(Geotech PTA Model 4300 Manual, Fig. 4)*

$$\cdot \frac{i\omega Q\sqrt{2}}{\omega_{c,hp} + i\omega} \cdot \frac{\omega_{c,lp}^2}{w_{c,lp}^2 - \omega^2 + i\omega\omega_{c,lp}Q^{-1}}$$

Phototube Amp *(Geotech PTA Model 4300 Manual, Fig. 11)*

$Q = -3$ [dB] $\qquad Q = -3$ [dB]

$\omega_c = 0.01$ [Hz] $\qquad \omega_c = 5$ [Hz]

Building an instrument response

Velocity transfer function

$$\hat{T}_V(\omega) = \frac{\omega^2}{\omega_s^2 - \omega^2 + i2\lambda_s\omega_s\omega} \cdot \frac{1}{\omega_g^2 - \omega^2 + i2\lambda_g\omega_g\omega}$$

Seismometer *(Benioff 1051/1101)*

Galvanometer *(Geotech Model 4100-13)*

$$\cdot \frac{i\omega Q\sqrt{2}}{\omega_{c,hp} + i\omega} \cdot \frac{\omega_{c,lp}^2}{w_{c,lp}^2 - \omega^2 + i\omega\omega_{c,lp}Q^{-1}}$$

1st order highpass

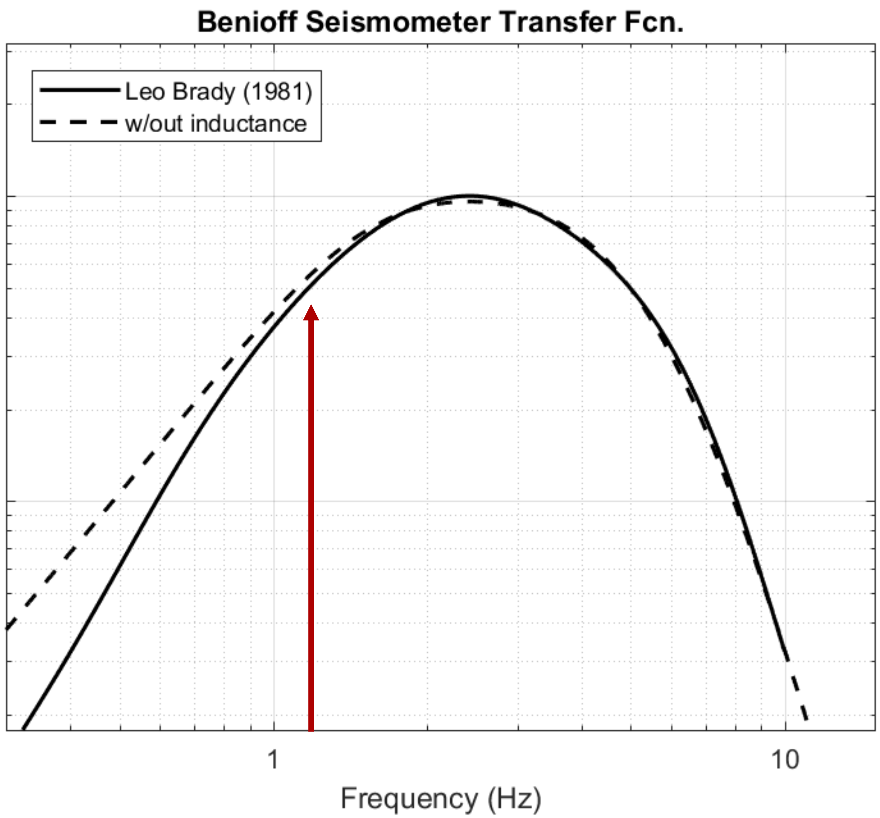
2nd order lowpass

Filter FL201 *(Geotech PTA Model 4300 Manual, Fig. 4)*

$$\cdot \frac{i\omega Q\sqrt{2}}{\omega_{c,hp} + i\omega} \cdot \frac{\omega_{c,lp}^2}{w_{c,lp}^2 - \omega^2 + i\omega\omega_{c,lp}Q^{-1}}$$

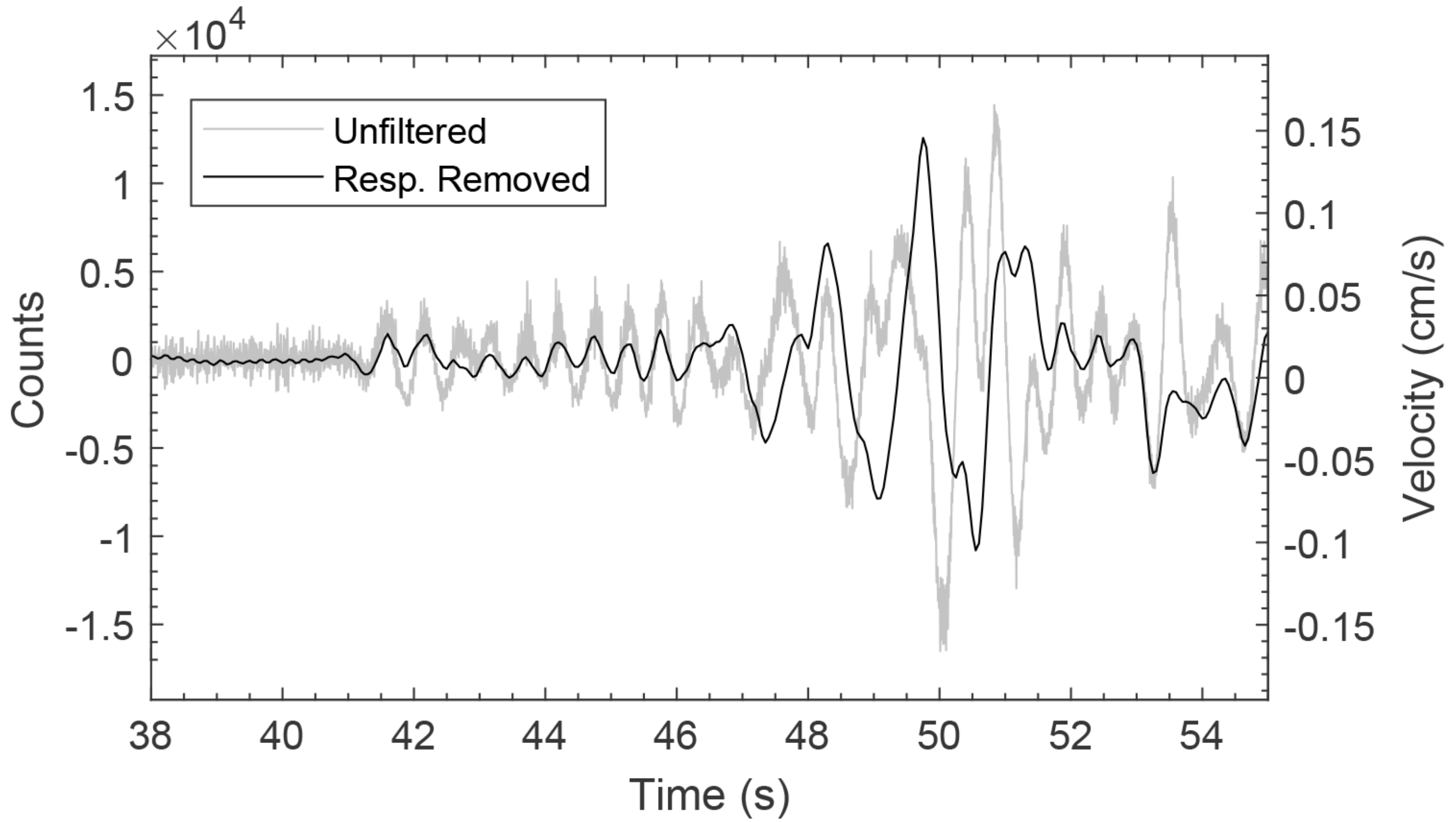
Phototube Amp *(Geotech PTA Model 4300 Manual, Fig. 11)*

Final calibration



$$f_d = 1.1905 \text{ [Hz]}$$

Final calibration



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Legacy Data project: An SNL multi-department effort!

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