# Studies of DECam's focal plate dynamics

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## ABSTRACT

Herman please write an abstract with a summary of the set up and the intension of the measurements. One we have them I will add a short summary of the results (like the bubbles are/are not a problem. Herman please write an abstract with a summary of the set up and the intension of the measurements. One we have them I will add a short summary of the results (like the bubbles are/are not a problem. Herman please write an abstract with a summary of the set up and the intension of the measurements. One we have them I will add a short summary of the results (like the bubbles are/are not a problem.

## 1. INTRODUCTION

We need to describe here in detail why we are doing this measurement so the reader knows what to expect and what to pay attention to. We also need to describe why we chose the setup and speculate about how final this measurements are, for example we are not using the final focal plate, is this a problem? We also need to give the reader a summary of what we will write in each section. This is useful in case the reader is not interested in seen all the details of the measurement and wants to jump to specific part.

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## 2. SETUP

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## 3. GEOPHONE SPECIFICATIONS AND INSTALLATION

To perform the focal plate vibration measurements we used geophones manufactured by Geo Space Geophysical Instrumentation. We used the type GS-11D, 4.5 Hz, 4000 $\Omega$ like the one shown in Figure 1. Figure 2 shows the response curve for these geophones, we used then in the open configuration given by curve A. These geophones are suited for low temperature applications.

The geophones were attached to the focal plate as shown in Figure .... Here we need to describe, how they were attached, the polarities, position with respect to the center (etc ..) and how we define the coordinate system. A clean hand sketch with the focal plate and the coordinate system can be inserted here.

Figure 1. Picture of a geophone GS-11D like the ones used to perform the measurement in this write-up.

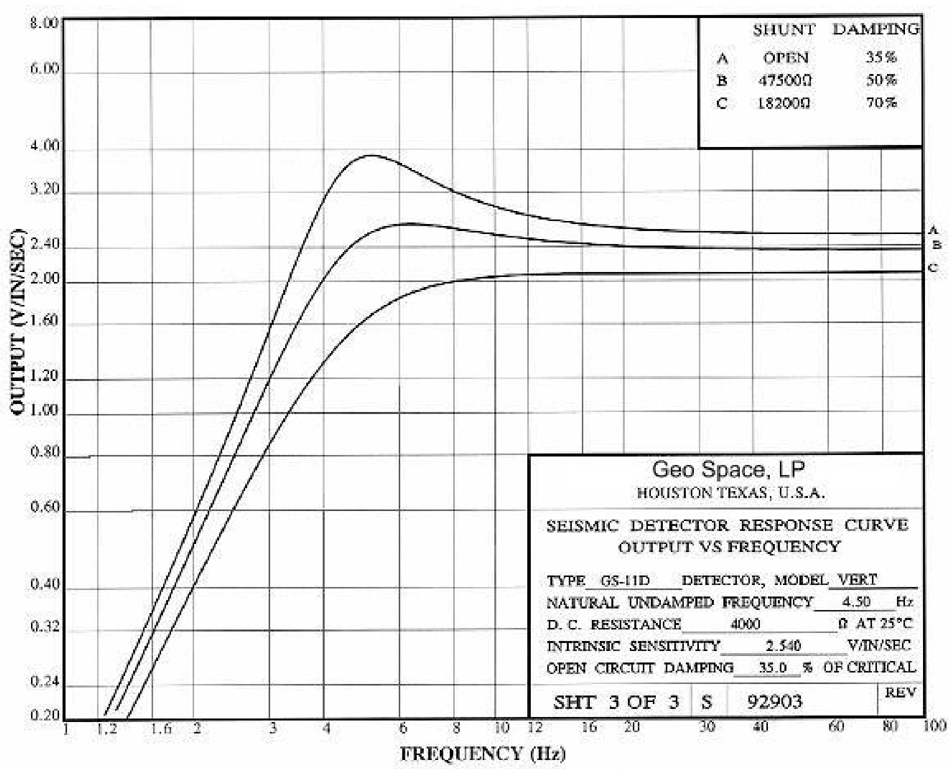


Figure 2. Calibration curve for geophone GS-11D, 4000 Ω. The open configuration (curve A) was used to perform the measurements in this write up.

## 4. DATA COLLECTION

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## 5. GEOPHONE DATA ANALYSIS

For small displacements we can assume that to a very good approximation all restoring forces are proportional to displacements and all dissipative forces are proportional to velocities. In this approximation the general motion in any given direction can be written as a superpositions of damped harmonic oscillations like the one given in Eq. 10. So the general motion in an arbitrary direction $x$ can be written as

$$\begin{aligned} x(t) &= \sum_{k=1}^{N} x_{0k}\, e^{-b_k(t-t_0)/2}\, \cos\left[w_{0k}(t-t_0)+\phi_{0k}\right] && (1) \\ &= \sum_{k=1}^{N} A_k\, e^{-b_k t/2}\, \cos(w_{0k}t+\phi_k) && (2) \\ &= \sum_{k=1}^{N} A_k\, e^{-\pi\Gamma_k t}\, \cos(2\pi f_{0k}\, t+\phi_k) && (3) \end{aligned}$$

where we have written

$$A_k = x_{0k}\, e^{\pi\Gamma_k t_0} \quad , \quad \phi_k = \phi_{0k} - 2\pi f_{0k} t_0 \quad , \quad w_{0k} = 2\pi f_{0k} \quad , \text{and} \quad b_k = 2\pi\Gamma_k \tag{4}$$

The velocity in the same direction is given by

$$v(t) = \sum_{k=1}^{N} A_k\, v(t|f_{0k}, \Gamma_k, \phi_k) \tag{5}$$

where

$$v(t|f_0, \Gamma, \phi) = -\, e^{-\pi\Gamma t}\, \left[\pi\Gamma\cos(2\pi f_0 t+\phi) + 2\pi f_0\, \sin(2\pi f_0 t+\phi)\right] \tag{6}$$

The geophones are essentially a coil with a moving magnetized core. The output voltage produced by the coil depends on how the magnetic flux through the coil changes with time. The magnetic flux in the coil is a function of the position of the core, therefore the output voltage of the geophone will be a function of the velocity of the core. The geophones of course respond to acceleration because for constant velocity the coil and the core don't move with respect to each other, but the geophone's output depends on the core's velocity relative to the coil. Therefore we can write the geophone's output as

$$V(t) = G\, v(t) \tag{7}$$

where $G$ is a geophones calibration that translates velocity to voltage. For the geophones we used in our measurements (GS-11D, 4000 Ω) $G = 0.1$ Volts/(mm/sec). If V(f) is the Fourier Transform of the geophone's output voltage we have that

$$V(f) = G \sum_{k=1}^{N} A_k \, v(f|f_{0k}, \Gamma_k, \phi_k) \tag{8}$$

where $G$ could be a function of frequency and $v(f|f_0, \Gamma, \phi)$ is the Fourier Transform of the velocity given in Eq. 6 and was calculated in Appendix A Eq. 29

$$v(f|f_0, \Gamma, \phi) = \frac{-(\Gamma^2/4 + f_0^2)\,\cos\phi - if(\Gamma/2\,\cos\phi + f_0\,\sin\phi)}{f_0^2 + \Gamma^2/4 - f^2 + i\Gamma f} \tag{9}$$

## APPENDIX A. FOURIER TRANSFORM OF A DAMPED OSCILLATION

In this appendix we will calculate the Fourier Transform (FT) of a displacement $x(t)$ and its velocity $v(t)$. For $t < 0$ the displacement is $x(t) = 0$, and for $t > 0$ it is

$$x(t) = x_0 \, e^{-bt/2} \, \cos(w_0 t + \phi) \tag{10}$$

which is a solution of the harmonic oscillator equation

$$\frac{d^2x}{dt^2} + b\frac{dx}{dt} + w'^2 \, x = 0 \tag{11}$$

with $w_0 = \sqrt{w'^2 - (b/2)^2}$.

Following the Fast Fourier Transform (FFT) we will use to transform the voltage measurements, we define the FT of x(t) as

$$x(w) = \int_{-\infty}^{\infty} x(t) \, e^{-iwt} \, dt \tag{12}$$

In order to calculate $x(w)$ it is convenient to write Eq. 10 as

$$\begin{aligned} x(t) &= \frac{x_0}{2} \, e^{-bt/2} \left[ e^{i(w_0 t + \phi)} + e^{-i(w_0 t+\phi)} \right] && (13) \\ &= \frac{x_0}{2} \left[ e^{i\phi} \, e^{\lambda t} + e^{-i\phi} \, e^{\lambda^* t} \right] && (14) \end{aligned}$$

with $\lambda = -b/2 + iw_0$. Then the FT is

$$\begin{aligned} x(w) &= \frac{x_0}{2} \left[ e^{i\phi} \int_0^\infty e^{(\lambda - iw)t} \, dt + e^{-i\phi} \int_0^\infty e^{(\lambda^* - iw)t} \, dt \right] && (15) \\ &= \frac{x_0}{2} \left[ \frac{-e^{i\phi}}{\lambda - iw} + \frac{-e^{-i\phi}}{\lambda^* - iw} \right] && (16) \\ &= \frac{x_0}{2} \left[ \frac{e^{i\phi}}{b/2 - iw_0 + iw} + \frac{e^{-i\phi}}{b/2 + iw_0 + iw)} \right] && (17) \\ &= x_0 \left[ \frac{(b/2 + iw) \cos\phi - w_0 \sin\phi}{(b/2 + iw)^2 - (iw_0)^2} \right] && (18) \\ &= x_0 \left[ \frac{(b/2 \cos\phi - w_0 \sin\phi) + iw \cos\phi}{w_0^2 - w^2 + b^2/4 + ibw} \right] && (19) \end{aligned}$$

Now we transform the last equation to frequency using $w_0 = 2\pi f_0$, $w = 2\pi f$ and $\Gamma = b/2\pi$

$$x(f) = \frac{x_0}{2\pi} \left[ \frac{(\Gamma/2 \cos\phi - f_0 \sin\phi) + if \cos\phi}{f_0^2 + \Gamma^2/4 - f^2 + i\Gamma f} \right] \tag{20}$$

Now we calculate the FT of the velocity

$$\begin{aligned} v(t) = \frac{d}{dt}x(t) &= -x_0 \, e^{-bt/2} \, [(b/2)\cos(wt + \phi) + w \sin(wt + \phi)] && (21) \\ &= \frac{x_0}{2} \left[ \lambda \, e^{i\phi} \, e^{\lambda t} + \lambda^* \, e^{-i\phi} \, e^{\lambda^* t} \right] && (22) \end{aligned}$$

In the second step we used Eq. 14. Then the FT of the velocity is

$$v(w) = \frac{x_0}{2}\left[\lambda\, e^{i\phi}\int_0^\infty e^{(\lambda-iw)t}\,dt + \lambda^*\, e^{-i\phi}\int_0^\infty e^{(\lambda^*-iw)t}\,dt\right] \tag{23}$$

$$= -\frac{x_0}{2}\left[\frac{\lambda\, e^{i\phi}}{\lambda - iw} + \frac{\lambda^*\, e^{-i\phi}}{\lambda^* - iw}\right] \tag{24}$$

using

$$\lambda(\lambda^* - iw) = \lambda\lambda^* - i\lambda w = b^2/4 + w_0^2 + ibw/2 + w_0 w \tag{25}$$

$$\lambda^*(\lambda - iw) = \lambda^*\lambda - i\lambda^* w = b^2/4 + w_0^2 + ibw/2 - w_0 w \tag{26}$$

we get

$$v(w) = -x_0\left[\frac{(b^2/4 + w_0^2 + ibw/2)\,\cos\phi + iw_0 w\,\sin\phi}{w_0^2 - w^2 + b^2/4 + ibw}\right] \tag{27}$$

$$= -x_0\left[\frac{(b^2/4 + w_0^2)\,\cos\phi + iw(b/2\,\cos\phi + w_0\,\sin\phi)}{w_0^2 - w^2 + b^2/4 + ibw}\right] \tag{28}$$

Again we transform the last equation to frequency using $w_0 = 2\pi f_0$, $w = 2\pi f$ and $\Gamma = b/2\pi$

$$v(f) = -x_0\left[\frac{(\Gamma^2/4 + f_0^2)\,\cos\phi + if(\Gamma/2\,\cos\phi + f_0\,\sin\phi)}{f_0^2 + \Gamma^2/4 - f^2 + i\Gamma f}\right] \tag{29}$$

## APPENDIX B. CHECKING THE ANALYSIS PROGRAMS

To check our programs and the consistency of our Fourier Transforms with the FFT used in the analysis we generated a "voltage" file like the ones produced by the geophones. The voltages in this file were calculated using Eqs 5 to 7. Seven resonances similar to the ones extracted from the measured data were used in the generation. The frequencies $f_0$ and widths $\Gamma$ of these resonaces are listed in Table 1. The $t = 0$ generated amplitudes $A^g_{0.00}$ and phases $\phi^g_{0.00}$ for each resonance and the corresponding chanel are listed in Table 2. The generated voltages $V(t)$ are shown in Figure 3. Like in the case of the real data the analysis of the generated voltages was started at $t$ =0.02 sec. The extrapolated to $t = 0.02$ sec amplitudes $A^g_{0.02}$ and phases $\phi^g_{0.02}$ are shown in Table 2. Figure 4 shows the Fourier Transform of the generated data, and Figures 5 and 6 show the results of the fits to the generated data. The fits were performed using Eqs 8 and 9. "Measured" from the fits were the frequencies $f_0$ and widths $\Gamma$ shown in Table 1, and the amplitudes $A^m_{0.02}$ and phases $\phi^m_{0.02}$ shown in Table 2. The excellent agreement between the "generated" and "measured" values confirms that all the programs are working properly.

Table 1. Table of "generated" and "measured" frequencies $f_0$ and widths $\Gamma$. A total of seven resonances were included in the generation and the analysis.

| Resonance | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Generated $f_0$ | 77.00 | 81.00 | 91.00 | 159.00 | 176.00 | 184.00 | 190.00 |
| Generated $\Gamma$ | 9.00 | 1.80 | 5.00 | 4.00 | 6.20 | 5.50 | 3.60 |
| Measured $f_0$ | 77.06 | 81.01 | 91.00 | 159.00 | 176.02 | 184.00 | 190.00 |
| Measured $\Gamma$ | 9.11 | 1.79 | 5.00 | 3.97 | 6.12 | 5.54 | 3.65 |

Table 2. Table of "generated" and "measured" amplitudes $A$ and phases $\phi$. $A^g_{0.00}$ and $\phi^g_{0.00}$ are the generated amplitudes and phases; $A^g_{0.02}$ and $\phi^g_{0.02}$ are the generated amplitudes and phases extrapolated to $t$=0.02 sec using Eq. 4; $A^m_{0.02}$ and $\phi^m_{0.02}$ are the measured amplitudes and phases at $t$=0.02 sec.

| | Resonance number | $A^g_{0.00}$ $\mu$m | $\phi^g_{0.00}$ degrees | $A^g_{0.02}$ $\mu$m | $\phi^g_{0.02}$ degrees | $A^m_{0.02}$ $\mu$m | $\phi^m_{0.02}$ degrees |
|---|---|---|---|---|---|---|---|
| Channel 1 (x) | 1 | 10.0 | 110. | 5.68 | 304.4 | 5.77 | 306.0 |
| | 2 | 2.5 | 0. | 2.23 | 223.2 | 2.22 | 225.3 |
| | 3 | 5.6 | 215. | 4.09 | 150.2 | 4.07 | 152.7 |
| | 4 | 1.9 | 310. | 1.58 | 14.8 | 1.46 | 19.3 |
| | 5 | 0.2 | 60. | 0.14 | 247.2 | 0.14 | 246.5 |
| | 6 | 4.1 | 0. | 2.93 | 244.8 | 2.93 | 250.1 |
| | 7 | 0.9 | 35. | 0.72 | 323.0 | 0.74 | 328.7 |
| Channel 2 (y) | 1 | 9.0 | 100. | 5.11 | 294.4 | 5.19 | 296.2 |
| | 2 | 2.3 | 355. | 2.05 | 218.2 | 2.05 | 220.2 |
| | 3 | 6.7 | 35. | 4.89 | 330.2 | 4.90 | 332.9 |
| | 4 | 0.4 | 100. | 0.31 | 164.8 | 0.31 | 169.9 |
| | 5 | 1.6 | 170. | 1.08 | 357.2 | 1.06 | 1.6 |
| | 6 | 2.4 | 170. | 1.70 | 54.8 | 1.70 | 60.0 |
| | 7 | 1.4 | 5. | 1.12 | 293.0 | 1.13 | 298.5 |
| Channel 3 (z) | 1 | 1.6 | 55. | 0.91 | 249.4 | 0.93 | 251.3 |
| | 2 | 0.1 | 260. | 0.09 | 123.2 | 0.09 | 123.6 |
| | 3 | 0.7 | 45. | 0.51 | 340.2 | 0.52 | 342.8 |
| | 4 | 0.2 | 70. | 0.16 | 134.8 | 0.16 | 139.8 |
| | 5 | 1.1 | 170. | 0.75 | 357.2 | 0.73 | 1.9 |
| | 6 | 0.5 | 350. | 0.35 | 234.8 | 0.36 | 240.4 |
| | 7 | 0.7 | 15. | 0.56 | 303.0 | 0.57 | 308.7 |

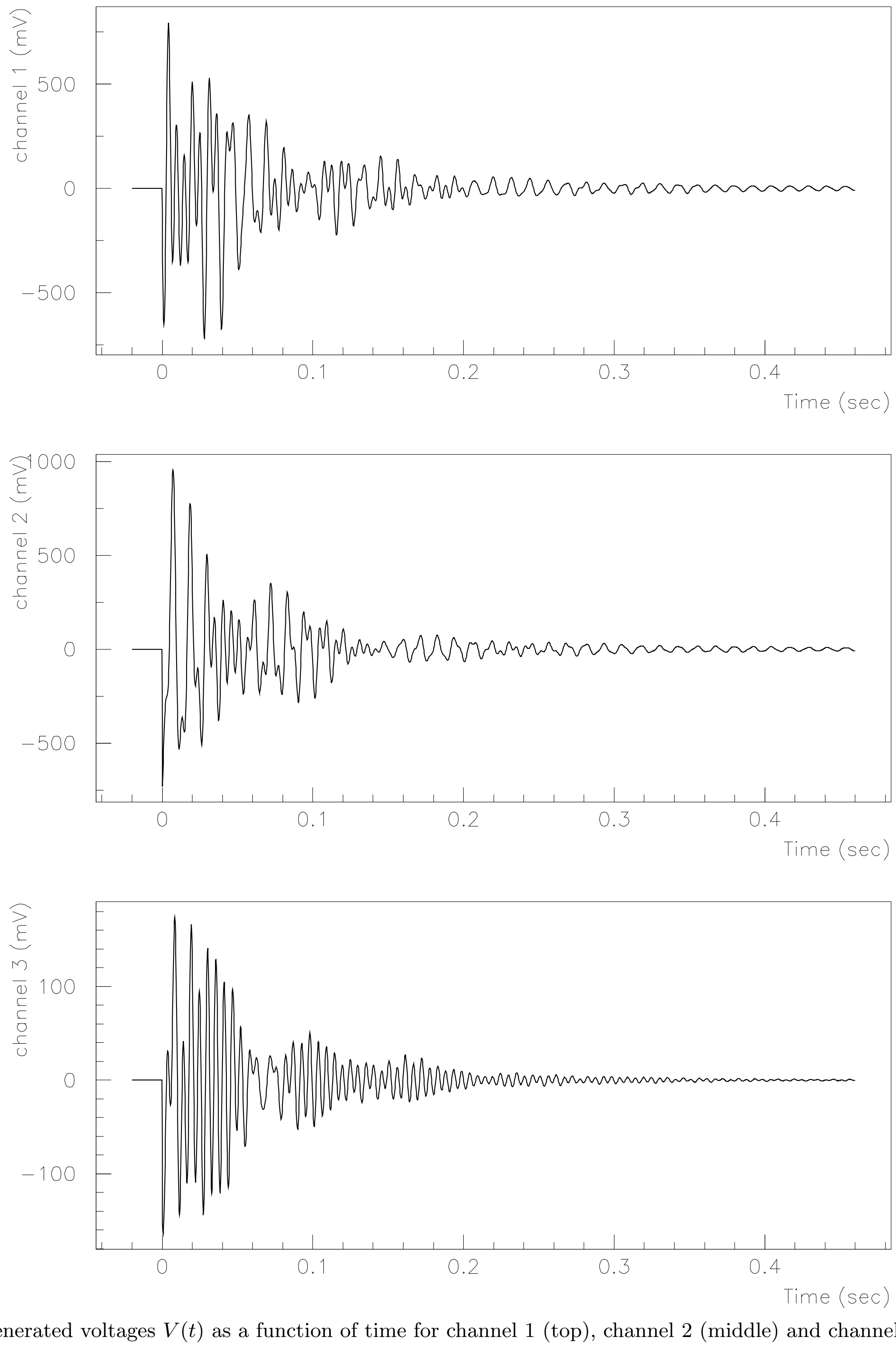


Figure 3. Generated voltages $V(t)$ as a function of time for channel 1 (top), channel 2 (middle) and channel 3 (bottom).

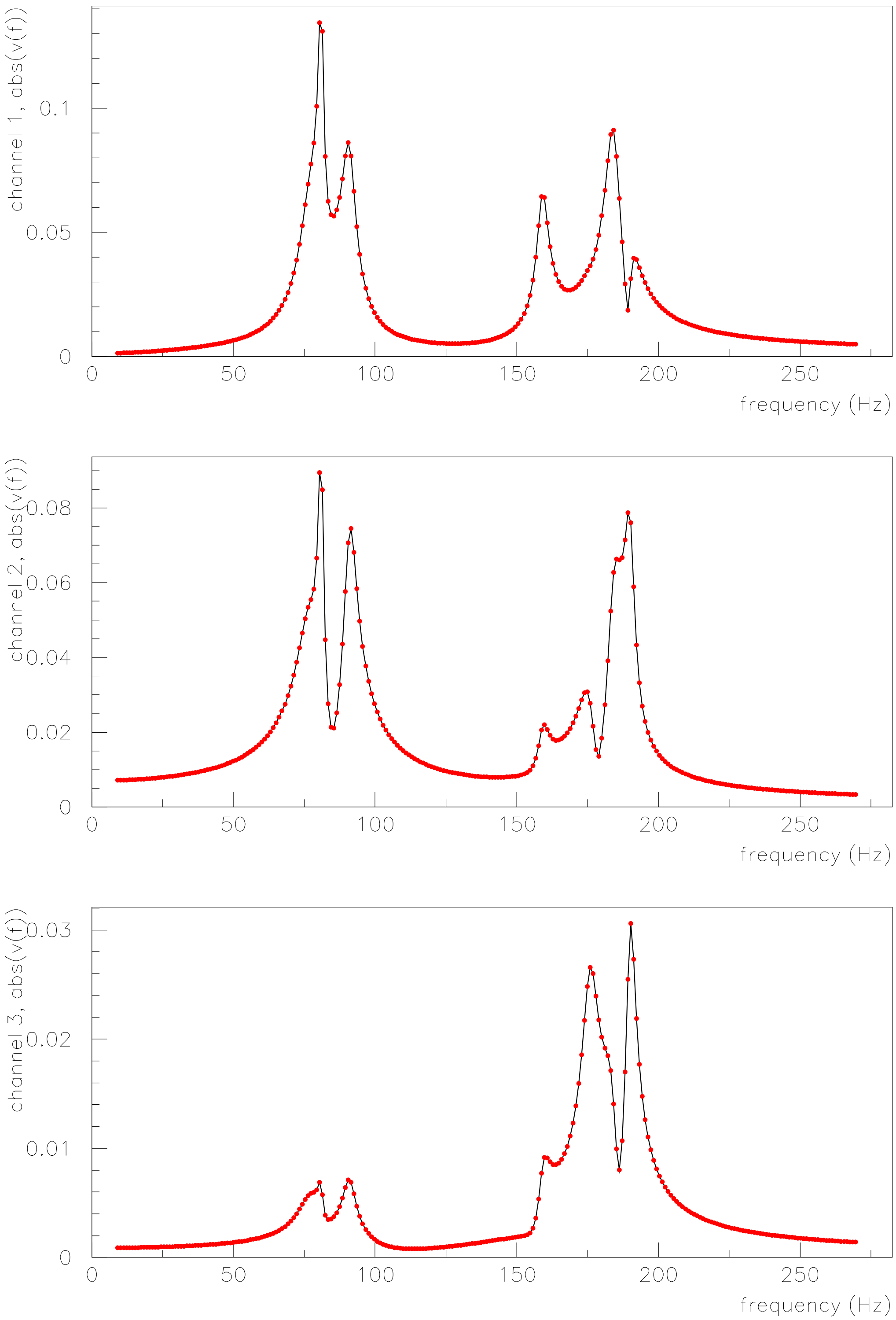


Figure 4. Plots showing $|v(f)|$ for chanels 1 to 3 (top to bottom) for the generated data. $v(f) = V(f)/G$ is the Fourier Transform of the generated velocity $v(t) = V(t)/G$, where $V(t)$ is the generated voltage, $V(f)$ its Fourier Transform and $G = 0.1$ V/(mm/sec) is the geophone's calibration constant.

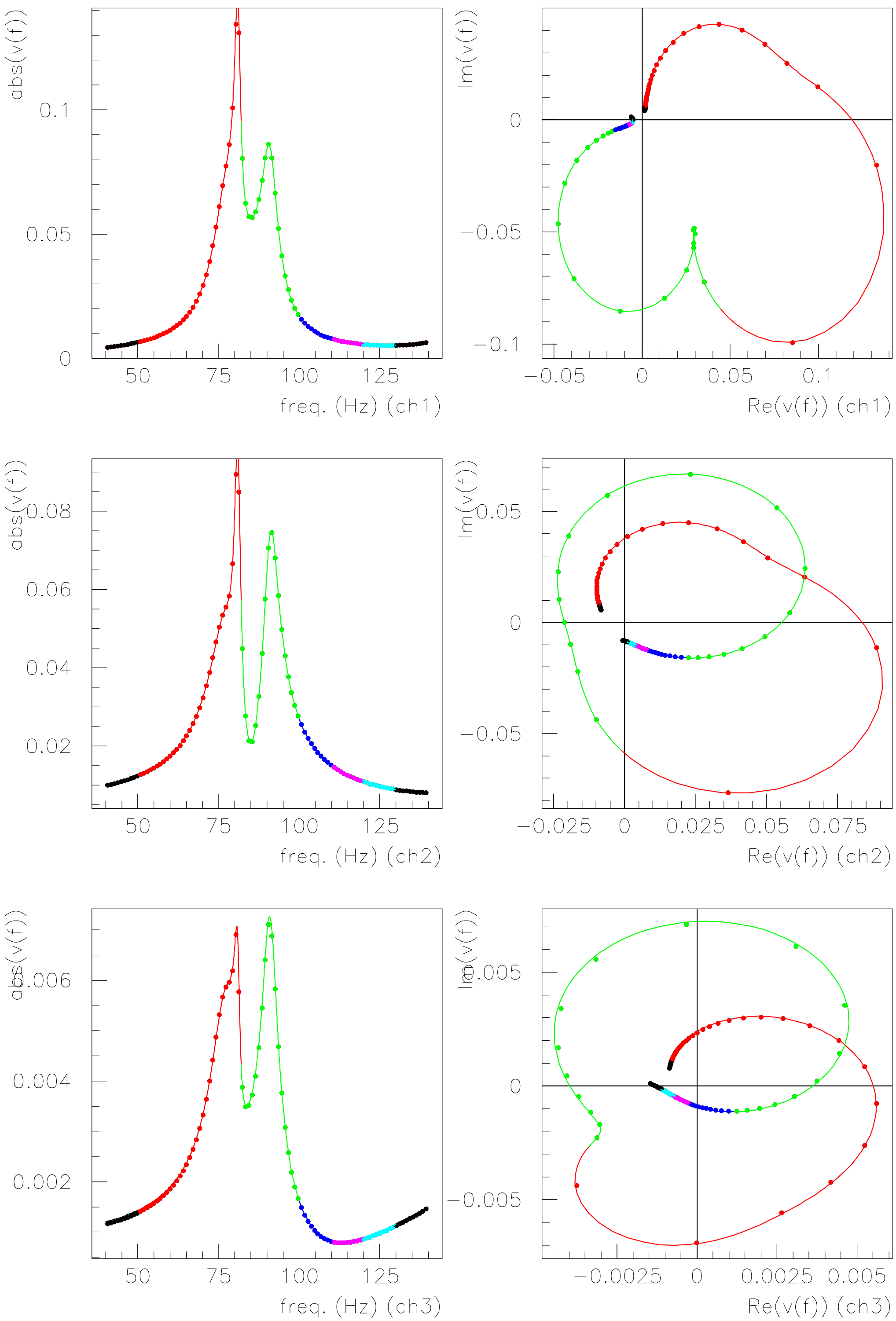


Figure 5. The plots on the left show the module $|v(f)|$ in the 60 to 140 Hz frequency range. The plots on the right show the Argand diagrams Imag$\{v(f)\}$ vs Real$\{v(f)\}$ for the same frequency range. Chanels 1, 2 and 3 are displayed from top to bottom. The points correspond to the FT of the generated data and the lines are the results of the fits using Eqs 8 and 9.

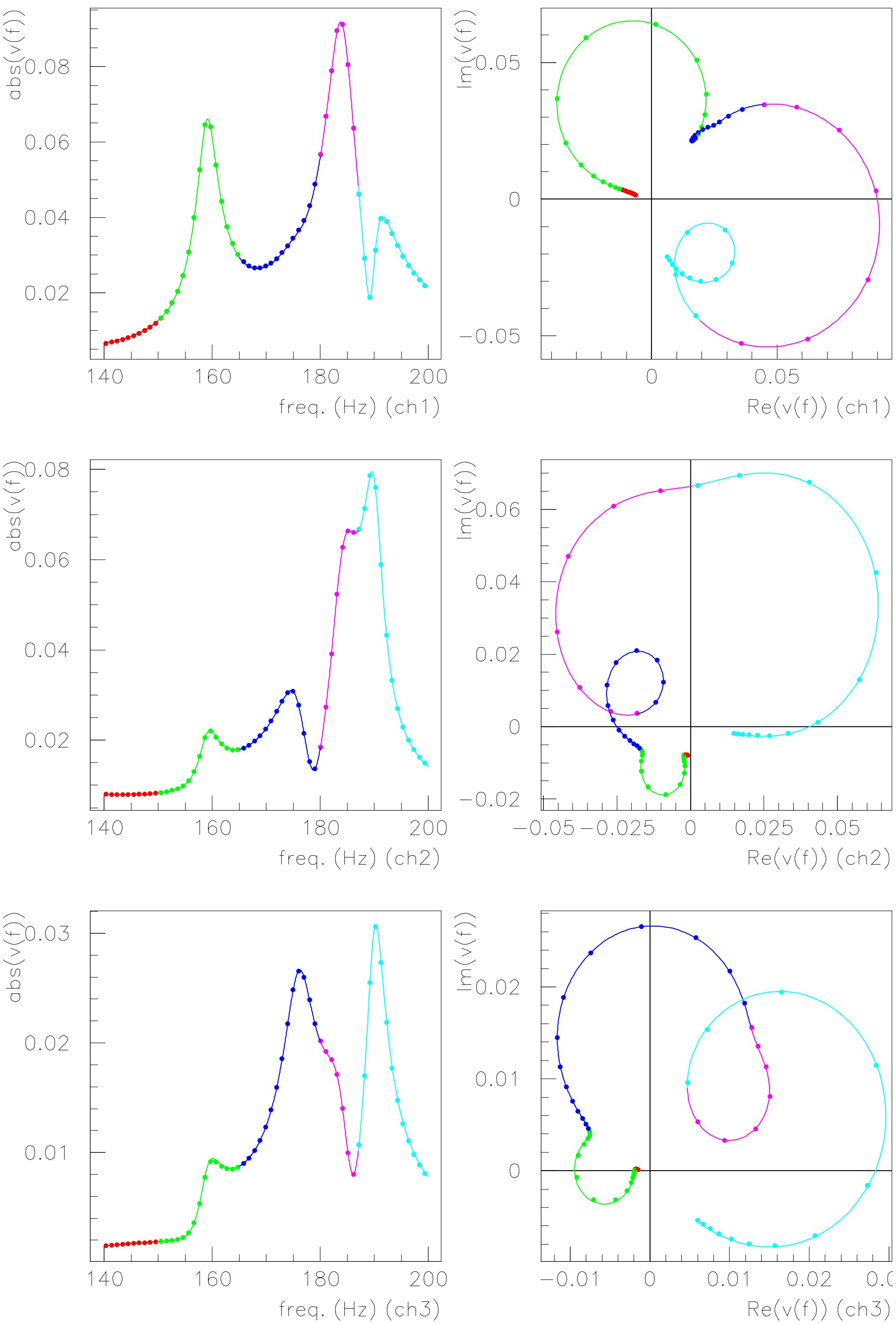


Figure 6. The plots on the left show the module $|v(f)|$ in the 140 to 200 Hz frequency range. The plots on the right show the Argand diagrams Imag$\{v(f)\}$ vs Real$\{v(f)\}$ for the same frequency range. Chanels 1, 2 and 3 are displayed from top to bottom. The points correspond to the FT of the generated data and the lines are the results of the fits using Eqs 8 and 9.