# Correspondence with Erhard Wielandt regarding the use of some of his seismic data analysis programs.

To: Prof. Erhard Wielandt
From: Brett Nordgren
Subject: Instrument performance results
Date: 4 Jan, 2010

Dear Professor Wielandt,

I am hoping that you have time to take a look at the results we are getting with the Force-Balance Vertical that Angel Rodriguez had with him at the November, 2008 Costa Rica meeting.
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**Subject: Re: Instrument performance results**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 04 Jan 2010 22:26 GMT**
**.....**

**If you like, I would be interested in analyzing your data for myself. I would need a time series from a quiet interval of several hours (preferably 12 or more) in ASCII, and of course the instrument parameters. I will be glad to help you in any way you consider as useful (although I would fully understand if you prefer to continue on your own, as I would probably have done). In any case, you are welcome to ask me if you have any questions.**

To: Erhard Wielandt
From: Brett Nordgren
Subject: The acid test
Date: 5 Jan, 2010

......
Thank you very much for your thoughtful reply and for your offer to help analyze our noise.
What would be an appropriate sample rate for such a data set?
My goal is to get 24 hours for both ours and the Trillium which I hope to have ready within a week.
.....

**Subject: FBV data**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 07 Jan 2010 19:15 GMT**

**thank you again. It appears, in fact, that your instrument compares favourably with the compact Trillium, which is a respectable result.**

**......**
**If you prepare an ASCII data set for me (I hope it is not too much of a burden on you), then one sample per second would be perfect provided that you can apply an anti-alias filter before the decimation. If you cannot, it would be better to have the original data even if this is a large data set. In the latter case, I would prefer not to receive it by e-mail but to download it from your server by ftp.**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Re: FBV data
Date: 8 Jan, 2010

I have assembled a 24 hour, 1 SPS text-formatted record of several of our data channels

http://bnordgren.org/seismo/091227.24hr.zip ~580KB

All files are of digitizer counts and are unfiltered, with a sample rate of 1 SPS.
I attempted to put them in SEIFE format, except that I was not confident of my ability to properly enter the FORTRAN format codes, so I didn't attempt to enter it in any of the files. I retained the PSN event-file header lines but commented them out.

1) 091227.000042.bhz-FBV.txt
FBV mid band sensitivity is 4.802 nm/sec / count (note that the PSN event-file headers display cm/sec / count)
1 zero at 0
1 zero somewhere beyond 50,000 sec time varying, due to the integrator capacitor leakage time-constant and dielectric soak.
2 poles at 50 seconds, damping 0.7

.........
Regarding aliasing: These were all sampled at 200 SPS and decimated inside the WinSDR data acquisition program to 1 SPS using a 200 point moving average. As I understand it, that should pretty well avoid aliasing problems.

**Subject: Re: FBV data**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 11 Jan 2010 18:46 GMT**

**thank you for the data. I had a quick look at them; they are OK and I am sure I can analyze them. You will hear from me then.**
**........**

**I have so far only analyzed the FBV and Trillium traces. The FBV signal was deconvolved so that the response should be the same as for the Trillium. The coherency**

**is above 0.8 in the four 1/6-decade bands centered at 121, 83, 56, and 38 mHz (six bands per decade). So we see the seismic noise in a rather limited bandwidth, but unfortunately I cannot determine its absolute level because I don't know the response of the anti-alias filter.**

**At periods between 25 and 120 seconds, both traces show nearly the same incoherent noise, about 16 dB above the LNM. This is somewhat strange. One might suspect that it is 1/f digitizer noise. But if both digitizer channels have the same internal noise, then it should appear with a larger amplitude in the FBV trace after the deconvolution beyond 50 seconds. I don't quite understand this. The agreement of the rms amplitudes must be coincidental.**

**At still longer periods, the FBV trace is clearly noisier than the deconvolved Trillium trace, so this may now be digitizer noise amplified by the deconvolution.**

**In order to measure the sensor noise properly, it may be necessary to use a preamp between the seismometer and the digitizer, or use a 24-bit digitizer. Obviously, the FBV is now so good that the digitizer is no longer adequate. That's of course good news, but means more work waiting to be done.**

**And, please check what kind of anti-alias filter was used.**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Re: noise analysis
Date: 12 Jan, 2010

......
I tried these files with 'bandnois' and this time I obtained results that appear to make much more sense.

The anti-alias filtering was done in the data acquisition program, by taking a 200-point moving average of data originally sampled at 200 SPS, although after that, the averaged data values are apparently being rounded to integers, wasting much valuable information.

When Dave gets back home toward the end of the month I may be able to get the original 200 SPS data from him (17million points per day) and do my own decimation, rather than depending on the WinSDR program. That will also help the resolution as I won't round the results. We can mail memory sticks back and forth to share these large files.

I spoke with Dave today about adding some additional amplification in order to get our bit-sensitivity higher for testing purposes if that is needed. It may be that eliminating the data rounding will accomplish a similar result.

**Subject: Re: noise analysis**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 13 Jan 2010 10:03 GMT**

**Dear Brett:**
**thank you for the new data set. In fact it gives more reasonable results (see attachments). However, the mystery remains that the two systems show nearly the same but incoherent noise up to about 100 seconds. The two sensors may in fact happen to produce nearly the same internal noise, why not? At longer periods the FBV is a bit noisier, but this may be due to the rounding error elevated by the inverse filtration. In any case: even if all this turns out to be instrumental noise, the FBV is still a very useful seismometer!**

**There is still one step in the processing chain which I don't like: calculating each 1 Hz sample as the average of 200 200-Hz samples isn't a correct anti-alias filtration. One must apply a sharp digital filter that suppresses signals above the new Nyquist frequency. Simple averaging cannot do this. So it is possible that the decimated series contains aliased high-frequency noise. It may therefore be worthwhile to analyze the original 200 Hz data. If you want me to do this, you could mail them on a CD-ROM. It would also be useful to have a broadband record of an eartquake well above the noise level, in order to determine the relative response more precisely (especially for the Guralp, which could then be included in the analysis).**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Re: noise analysis
14 Jan, 2010

Thank you so much for processing our data. This is good information.

My goal has been to duplicate those measurements so that we can better understand the effects of design changes as we try out new ideas in the future. I am interested in what software you use to do the deconvolution and filtering of the data. When doing our own decimating, I understand why low-pass filtering at something below the downsampled Nyquist frequency is desirable, but what filter shape and number of poles would be appropriate? So far I hadn't found anything in your software collection that appeared to apply to the deconvolution and filtering tasks, though I may have missed it.

I am hoping eventually to be able to use any of your tools which can be applied to our problems.

So far I managed to run BANDNOIS on the original data. The results are interesting, but difficult to explain. I uploaded a file which shows the output data for both instruments, both before modification, and also your data after deconvolution and filtering. There is also a plot of the four data sets along with the NLNM. Before processing, the Trillium looks much worse in the mid-frequency range and appears to have virtually constant noise density over that range. That seems very strange, though I certainly could have created the problem myself.

In studying these data, I am wondering how much significance should be given to noise performance more than a decade below the instrument's eigenfrequency? It would seem that any such noise would be outside its expected useful range.

http://bnordgren.org/seismo/bandnois091227.pdf

I will work to get some quake data from the three instruments to permit some calibration. I believe that the recent Haiti quake did not saturate the high-gain channels of any of the three, so it may provide a good set to work on.

When Dave gets home I will see if we can get some 200SPS, 24 hour records put on a CD. If we can make one, where should we send it? Our current data acquisition software uses a proprietary, compressed format, which must be exported and converted to text by the related analysis program, and it has problems exporting 200SPS data in pieces larger than 240 minutes, which then have to be reassembled into the final text file. So it may take some time to do it right.

That reminds me of an issue I was wondering about. Can the alias-filtering process be used to increase the precision of the data by adding a couple of decimal places to the samples? I would think that the effective digitizer precision could be improved to significantly less than one count, though possibly not its noise.

**Subject: Re: noise analysis**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 16 Jan 2010 21:36 GMT**

**I'll try to answer your questions in order - it may take more than one mail.**

**Filtering and deconvolution software: I'm always using my program SEIFE. It does (among many other things) recursive (IIR) filtering. One can select type of filter (high-pass, low-pass, or inverse thereof), corner period and damping of second-order filters, or higher-order filters which are then assumed to be of Butterworth type. Specifically for deconvolving a seismometer response, one can either select total removal of the response (which is however an unstable process, so the trace runs offscale after some time), or select a new combination of corner period and damping.**

**Decimation in data acquisition systems (like Quanterra)**

**is normally done with transverse (FIR) filters, which I have not implemented generally. (I have never built a data acquisition system of my own; I don't know how to write real-time software.)**
**For decimation with SEIFE I use a transverse filter with a cosine-square impulse response whose width is two new sampling intervals. That's not perfect, but in most cases sufficient; it completely suppresses signals at the new Nyquist frequency, so it does not create aliasing at very low frequencies. If this should be insufficient (which I have never observed) I can still use additional higher-order Butterworth filters forward and (to eliminate the phase response) also backward. SEIFE does all this.**

**The most recent versions of my programs, including detailed descriptions (.doc) of their use, are on my website**

http://www.software-for-seismometry.de

**SEIFE was never meant to be a complete seismological program package; it is just a collection of small programs**

**You question the significance of sensor performance far below the instrument's eigenfrequency. Of course you are right, at least formally; users should not expect an instrument to be good far beyond its specified passband. Still this is where you can most easily see what the potential of a sensor is. We might get some hints from the FBV how to build less expensive seismometers which nevertheless perform reasonably at long periods. I think this is worthwhile.**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Re: noise analysis
Date 16 Jan, 2010

I have been looking through your Web site at some length. Now I'll focus on SEIFE and see what I can figure out.

Dave and Angel will be pleased to hear your opinion that long period noise testing will be worthwhile. In the design we have demonstrated a few new possibilities. For one, we are using amplifiers in all the feedback branches. Today's best parts seem to be quiet enough to allow acceptable performance. The capacitors are polyester in order to keep the electronics board small (vs polypropylene). To my surprise, their measured leakage resistance was high enough to have a leakage time-constant in the hundreds of thousands of seconds, which should be more than adequate.

Regarding DSP, I have found an excellent on line e-book "The Scientist and Engineer's Guide to Digital Signal Processing", available free http://www.analog.com/en/embedded-processing-dsp/learning-and-development/content/scientist_engineers_guide/fca.html (8MB) I think it has everything I need. It clearly shows the advantages of using a more nearly optimal filter design vs performing a moving average.

In another message, I am sending a link to some other test data which I have been assembling. Now I hope to figure out how to also deconvolve and otherwise manipulate the data myself.

**Subject: more decimal places, etc.**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 19 Jan 2010 20:50 GMT**

**Thank you also for the reference to the DSP book, which I have downloaded. I find it is well written, interesting, and quite complete.**

**I also got your new data but didn't analyze them yet.**

**There is one question left from your previous mail: Can the alias-filtering process be used to increase the precision of the data by adding a couple of decimal places to the samples? Yes, it can, and this is systematically done in many digitizers. The secret is to sample at a higher frequency than is finally needed, then anti-alias filter and decimate. The method depends on the assumption that the quantization (rounding) error is random; of course if the digitizer is, for small input signals, stuck at a certain digital output, then averaging doesn't improve the resolution. Often a little trick helps. Lennartz (a local company building seismological equipment) were able to improve the resolution of one of their (now outdated) acquisition systems from 12 to 16 bits without changing the 12-bit digitizer. They added a little high-frequency noise to the signal, ran the digitizer at a higher rate, and then decimated down; the added noise was suppressed by the anti-alias filter. And, of course, all 24-bit Delta-Sigma type digitizers make heavy use of the same principle. They originally generate a data stream with one bit resolution and decimate it to create 24 bits. In this case, an elaborate feedback mechanism ensures that the quantization error is random and constitutes a high-frequency signal that is suppressed by the anti-alias filter. The method does, of course, not eliminate electronic noise, so it is only useful if the 1-bit conversion unit is extremely precise. There is ample literature on this in the internet.**

**I'll come back when I have looked at the new data.**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Re: more decimal places, etc.
Date 21 Jan, 2010

I have been experimenting, using the SEIFE programs with increasing success. However I find that the 2-hour data file for the FBV instrument which I prepared for the analysis is not being accepted by the programs. So far I have looked at the header which appears to be correct, and I now hope to investigate more to see if I can locate the problem.

**Subject: Re: more decimal places, etc.**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 21 Jan 2010 17:47 GMT**

**Dear Brett:**
**I think I know what may be the problem with SEIFE and your files. It is probably the missing decimal point in those samples that happen to be integer numbers. When you specify an "F" format such as F12.3, FORTRAN expects to find either a number with a decimal point in it (no matter where), or a sequence of up 15 digits into which a point can be inserted after position 12.**

**I read your files in the ASCII mode where all headers are ignored and the data are read in free format. This works well without any editing of the data file, but you must tell SEIFE what the sampling interval is, and how many header lines to skip. The following is the parameter file I used to read the 1 Hz Trillium data (the file was previously renamed bhz-trill.txt):**

```
asc bhz-trill.txt trill.vlp 1. 30
hpb 1200. 2
 lpb 30. 6
 he2 50. 0.7 120. 0.7
fac 6.1
 fac 4.8
skp 2300
rem Signal now in nm/s up to 120 s, additional HP 1200 s
npl
end
```

**The lines beginning with a blank are deactivated. The "he2" line specifies the deconvolution filter for the FBV when activated.**

**I hope this will work for you as well. If the problem continues just send me one of the data sets in question.**

**Subject: Re: Calibration data**
**From: Erhard Wielandt**
**To: Brett Nordgren**

**Date: 22 Jan 2010 19:22 GMT**

**Dear Brett:**
**I started looking at the "calibration" data. The record of the big earthquake is beautiful, if it is allowed to say so after such a terrible event. Strangely, I could read two of the files with SEIFE using the "fil" command but one, the bhz-ph file, only with "asc". I didn't find out why - it's a bit difficult to look at 720000 samples with the editor. In any case, I could read it, and the signal looks OK.**
**...................**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Re: Calibration data
Date: 22 Jan, 2010

You identified the problem with the files. Thank you. Once I knew to look for the tabs, it was obvious, and the corrected files have been uploaded in a zip file. I had been importing the text files into Excel to do a bit of formatting and DC removal, and when I saved them, in some cases Excel chose to add the tabs. In the future I can be watching for the problem.

http://bnordgren.org/seismo/CalibrationFiles2.zip

They didn't work with my seife, either, the way I was having it read them.

**Subject: first results**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 25 Jan 2010 10:57 GMT**

**Dear Brett:**
**thank you for the new data files. I could read these without problems.**
**I assembled from previously existing programs a program called 'inverseif' that determines parameters of a deconvolution filter that transforms the record of one seismometer into that of another seismometer. You could also say it moves the poles of the transfer function of one seismometer to match those of the second, based on records of the same event. I tried this only for the low-frequency poles so far, using the Haiti event. (The program will soon appear in my website but I must first test it a bit more and write a description.)**

**According to the P&Z table from the data sheet, the Trillium has a corner period of 120.0 s and damping 0.705.**

**Using this as a reference, I find for the FBV:
relative gain 1.26, corner period 51.7 s, damping 0.671.**

**The results depend slightly on the time window in which I fit the seismograms. I have chosen a time window from 400 to 1100 s because it contains the largest amplitudes at periods around 50 s. If I fit the whole seismogram, I get: gain 1.26, period 51.6 s, damping 0.680.**

**The residual is interesting (see attached plots). The FBV has some very-long-period noise, at periods around 600 s. The Trillium has an ugly nonlinearity, causing a long-period transient around 1300 seconds where the large Rayleigh-wave amplitudes arrive.
I will analyze the other seismograms as well but this may take a little more time.**

screen003.png

screen002.png

screen001.png

**Subject: explanations
From: Erhard Wielandt
To: Brett Nordgren
Date: 25 Jan 2010 12:11 GMT**

**my last mail was a bit too short because lunch was imminent. I should have explained the figures.**

**Figures 2 and 3: signals from INVERSEIF. Traces from top to bottom: the target trace (here Trillium), the input trace to the deconvolution (here FBV). Synthetic output traces with the start parameters (which were 50 s and 0.7 for the FBV) and the end parameters. Trace 5: residual between traces 1 and 4. Fit from 400 to 1100 seconds in fig. 2 and from beginning to end in fig.3. Note the indicated "Max" (maximum) amplitude and "F.S." (full scale) in counts.**

**To decide whether the long-period transient in the bottom trace of fig. 3 comes from the FBV or the Trillium, I low-pass filtered both traces with a second-order, 300 s low-pass filter. Fig. 1 shows that the Trillium is the culprit.**

To: Erhard Wielandt
From: Brett Nordgren
Subject: Temperature
Date: 25 Jan, 2010

Thank you for the analysis data, and particularly for the explanations. My goal is to be able to do this myself and observing how you go about it is a great help.

On another subject:
I have long been interested in the effects of temperature variations on the velocity output, but I have seen relatively little written about the effect and wonder if it is simply too obvious to merit general discussion. When we asked Nanometrics what we should expect with the Trillium Compact, they simply referred us to the User's Manual, which contains nothing on the subject.

What we have observed is that for diurnal temperature variations, the velocity output closely tracks the rate of temperature change. After working through the numbers I believe I can provide a simple computation of that effect.

For an instrument having a velocity response with two zeros at zero and two poles at period $T_L$ seconds, and having a spring with temperature coefficient (of elasticity) of K ppm/degC, for slow changes, and neglecting other temperature effects, the output response to the rate of temperature change is given by,

dVel / dTemp/dt = -6.90E-5 * K * $T_L$^2 um/sec per DegC/hour
For the record, 6.90E-5 = g / (4 Pi^2 * 3600)

For our instrument with $T_L$ = 50 sec and K = -240ppm/degC we would expect to see approximately 41.4 um/s / degC/hour

We can see that effect quite clearly with the FBV by viewing its integrator voltage and temperature channel vs time, which are shown at http://bnordgren.org/seismo/FBVtemp.gif

The three traces display approximately 24 hours from the FBV. The top trace is the internal temperature as measured on the circuit board and is about 0.0305 degC per count (10mV/degC) or about 0.66 degC max to min during the day. The second trace is the integrator voltage and the bottom trace is the integral of the velocity output, as computed by seife.

There appears to possibly be a slight time delay from the temperature sensor to the instrument response of somewhat less than an hour, which doesn't seem unreasonable.

For an instrument having $T_L$ = 360 sec and K = 5ppm/degC one might expect 44.7 um/s / degC/hour. These effects may be quite large when compared with other diurnal variations and clearly suggest the need for extreme temperature stability if one is hoping to observe them.

**Subject: Re: Temperature**
**From: Erhard Wielandt**
**To: Brett Nordgren**
**Date: 26 Jan 2010 11:04 GMT**

**the effect of temperature on seismometers and spring gravimeters is in principle quite predictable as long as you don't use a thermally self-compensated design. Roughly speaking, you expect the spring force to have a certain coefficient of temperature, something like -250 ppm per Kelvin for uncompensated materials. Equivalently, you may assume that a force corresponding to 250 ppm of the pendulum's weight acts on the sensor when the temperature changes by 1 K. Or, that gravity changes by 250 ppm per K. This assumption leads to your formula.**

**The reason why you don't find much discussion of temperature effects in the literature is probably that they are easily eliminated by thermal shielding at those frequencies in which most seismologists are interested. Older seismologists know about this. Some of the younger generation are not aware of the problem, and install their broadband seismometers without any shielding, with disastrous results. The time constants of well-designed thermal shields are in the order of an hour or so. This causes a delay as you have observed. Spring gravimeters always have a thermostat because at tidal periods, shielding is ineffective and the predominant periods of tidal and environmental signals are the same.**

**The matter becomes complex if you try to design a sensor so that it is internally compensated. One must then not only take into account the TC of elasticity but also thermal expansion coefficients. Different thermal time constants will then be involved and hysteresis becomes noticeable. A statically compensated pendulum will not be well compensated at seismic frequencies. So careful shielding and a stable environment remain essential even for self-compensated sensors. -**

**My program "inverseif" says that your Guralp sensor has a free period of 89.3 seconds, damping 0.690, and a relative gain of 1.064 against the Trillium-Compact. The rms misfit is below three parts in 1000 as for the FBV. As judged from the attached lowpass-filtered traces (inverse-filtered to a corner of 120 s, low-pass filtered at 300 s, original gain) the Guralp appears to be the best of the three instruments at very long periods, closely followed by the FBV.**

**I would like to include your data (decimated to 1 Hz sampling) as test data for inverseif in my website. Is this all right?**

screen004.png