Seisan response files for MVO broadband stations

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1 Summary

Seismometers modify their input signals, and therefore removal of the instrument response is essential in order to recover the true ground motion. The Seisan software used for seismic analysis at MVO uses response (or calibration) files to deal with this effect, and these files should therefore be kept up to date, yet a coherent method for creating and maintaining up to date response files has not been applied consistently at MVO before. To fulfil this need, this document describes a consistent method for creating response files for the broadband seismic stations at MVO, which follows closely the examples set out in the seisan manual(s).

The effects of the new response files were tested on a variety of recent seismic data. The changes compared to the use of existing calibration files were small in most cases, so recalculation of old response files and also local magnitudes was not deemed necessary.

The process of creating new response files has been semi-automated via two shell scripts, and instructions on how to use these, so as to keep calibration files up to date, are provided.

2 Background

2.1 Instrument response and poles and zeroes

Seismic signals recorded by a seismometer differ from the true ground motion, as the seismometer modifies the input signal. Proper and careful removal of the effects of the instrument response is therefore critical, if the true ground motion (be it physically displacement, velocity or acceleration) is to be analysed.

The way in which a seismometer modifies the input signal to produce an output signal is called its *transfer function*. For passive sensors this is well known and depends only on the natural period of the seismometer and its damping constant. Modern broadband instruments however may have a more complicated response, and their transfer functions are often expressed in terms of *poles* and *zeroes*, which arise as the roots (zeroes) of the numerator and denominator if the transfer function, $T(\omega)$ is written as a division of rational, factorised polynomial functions of $i\omega$:

$$T(\omega) = c\frac{(i\omega - z_1)(i\omega - z_2)\dots(i\omega - z_{nz})}{(i\omega - p_1)(i\omega - p_2)\dots(i\omega - p_{np})} \tag{1}$$

where c is a normalisation constant, with p_n and z_n and the poles and zeroes respectively. This is often called the poles and zeroes representation, and describes the complete, frequency dependent, response of the sensor output to input ground motion. This is, in general, a complex function which contains both the amplitude and phase response. An example of the amplitude response for an idealised 1 Hz seismometer is shown in Figure 1, which plots the displacement, velocity and acceleration response. Note that the velocity response is flat within the “passband” of the seismometer, in this case above 1 Hz.

Additionally, frequency independent factors are needed to scale the amplitude, including the gain of seismometer (sometimes called sensitivity or generator constant) and the recording media gain, in our case the calibration factor of the digitiser used to digitise the analogue signal from the instrument.

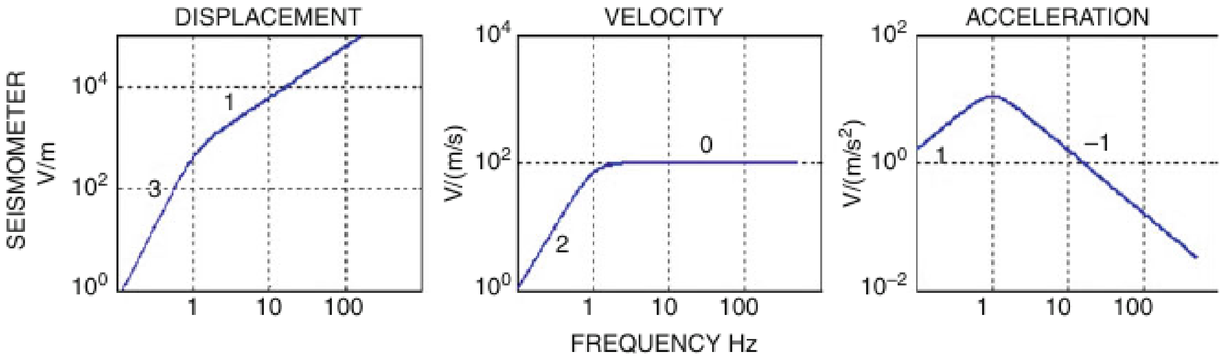

Figure 1: Example transfer function showing the amplitude response for the displacement, velocity and acceleration of an idealised seismometer with a natural period of 1s. The numbers represent the asymptotic slope, and it can be seen that the velocity response is flat within the passband of the instrument, here at frequencies above 1 Hz. The phase response is not shown. Taken from Havskov & Alguacil (2014).

2.2 Method: resp using Güralp poles and zeroes

Seisan deals with the instrument response through response or calibration files, and this document follows the method laid out in the example in the seisan manual (Ottemöller et al., 2011) to create appropriate response files for a Güralp broadband instrument. A similar example is described in more detail in the "Basic SEISAN for volcano monitoring" document (*seisan_volcano.pdf*, Lockhart (2009)), and in fact it is this case that was used as the basis of the method described here, applicable for MVO.

The seisan program which creates response files is called **resp**. This can be run in several ways, for example by specifying the sensor and recording media characteristics interactively (i.e. gain, period, calibration constant etc.) or by use of external files containing the poles and zeroes which describe the instrument's transfer function (Equation 1), and, if the gain and calibration constants are included, the complete response. In our case we use the second of these two approaches. To achieve this, several pieces of information are needed from the Güralp documentation: the digitiser calibration factor, the gain of the seismometer and the poles and zeroes of the seismometer which describe its transfer function.

1. **Digitiser.** The calibration factor for use in seisan is supplied by Güralp in units of $\mu V/count$, so must first be converted to units of $counts/V$. For example, for the vertical, Z2, component of digitiser C499 is given as: 3.208 $\mu V/count$. This is equivalent to $10^6/3.208 = 311720.70$ $counts/V$.

2. **Seismometer gain.** The sensitivity or gain of the velocity output of the seismometer is already specified by Güralp in the correct units of $V/m/s$. For example, seismometer T4F33 has a gain for the vertical component of 3206 $V/m/s$ (2×1603 since differential output is used).

3. **Seismometer poles and zeroes.** The poles and zeroes specified in the Güralp documentation are given in units of Hz, however seisan uses units of rad/s, so these must be converted. This is achieved by multiplying the values of each pole or zero (given by Güralp) by a factor of 2π.

   Since the normalisation factor for the transfer function is specified at 1 Hz this also needs to be converted to radians. To do this, the supplied constant is multiplied by a factor of $2\pi^{(np-nz)}$. Where np and nz are the number of poles and zeroes respectively. This factor arises to ensure the amplitude remains the same after conversion, i.e. by cancelling out the 2π factors introduced for each individual pole and zero.

   In addition to conversion from Hz to radians, the transfer function must also be converted to displacement, since seisan uses *displacement* and the Güralp documentation gives the *velocity* response. Fortunately this is very easy to achieve, by simply introducing an additional zero (with a value of 0) to the transfer function. Note that this is exactly equivalent to multiplying the transfer function by $i\omega$, or $(i\omega - 0)$ factorised (since the transfer function is a polynomial of $i\omega$) which is in turn equivalent to an integration of the signal, and hence a conversion from velocity to displacement.

Items 2 and 3 above can be used to create a text file, e.g. `T4F33Z.txt`, containing the converted poles and zeroes for the displacement response of a given component of a given seismometer. Note that the total normalisation constant is given by multiplying together the normalisation constant of the transfer function (newly calculated in radians) by the gain of instrument (in $V/m/s$). The format of the file is simply a header line containing: the number of poles, the number of zeroes and the normalisation constant; followed by the poles and zeroes, with one per line with the real and imaginary parts specified. For example, file `T4F33Z.txt` would look like:

```
3 4 -1006.7
-0.14803 -0.14803
-0.14803 0.14803
-314.16 0
0 0
0 0
999.03 0
0.0 0.0
```

i.e. with 3 poles and 4 zeroes (note the additional zero at 0 which was added on the last line)

Note that the digitiser calibration constant could be included in the total normalisation factor at this stage, but to allow for different seismometer and digitiser combinations this is supplied to **resp** separately, as the "recording media gain". Hence, after running the program the input given to **resp** to produce an output calibration file is (input in bold):

CHOSE OUTPUT FORMAT: **4** - GSE2 format using poles and zeroes. This format was chosen to: follow the example in *seisan_volcano.pdf*, for wider compatibility and to differentiate from older response files.

TYPE OF SENSOR: **1** - =None. This is because the complete response of the sensor is included in the poles and zeroes files.

RECORDING MEDIA GAIN (COUNT/V, M/V OR TIMES), enter for 1.0 ? **e.g. 311720.70** - here the digitiser calibration factor is inputted, e.g. using the example of C499 from earlier, this would be: 311720.70 $counts/V$.

DIGITIZER SAMPLE RATE (BEFORE POSSIBLE FIR FILTER): **100** - sampling rate is assumed to be 100 Hz for all channels.

DIGITIZER MODEL: **CMG-DM24 + e.g. C499 + e.g. T4F33** - here the digitiser and seismometer serial numbers are additionally supplied, such that they appear in the final output response file (GSE2 format appears to have no separate comment line).

AMPLIFIER GAIN (DB), ENTER FOR 0 DB (GAIN 1.0) ? **0** - all gain is already included in the poles and zeroes file and the digitiser constant.

NUMBER OF FILTERS (0-10), RETURN FOR NONE ? <**return**> - no additional filters used (the effect of digitiser anti-aliasing filter is assumed to be negligible)

FILE NAME FOR FILE WITH POLES AND ZEROS FOR SEISMOMETER, RETURN FOR NO FILE **e.g. T4F33Z.txt**

NUMBER OF FIR FILTER STAGES **0**

FILE NAME FOR MEASURED VALUES, RETURN FOR NO FILE <**return**>
The amplitude response (of the displacement) is then displayed in the console, and should look something like:

```
            AMPLITUDE RESPONSE   NO SENSOR         DISPLACEMENT
 AMPL      ----------------------------------------------------------------
  52.8     I.         .         .         .         .         .     +++++I
  25.6     I                                                  ++++++     I
  12.4     I.         .         .         .         .    ++++.         .I
  5.99     I                                          ++++               I
  2.90     I. . . . . . . . . . . . . . . . . . .+++++. . . . . . . . . .I
  1.40     I                                 ++++                        I
 0.680     I.         .         .       ++.++       .         .         .I
 0.329     I                       +++++                                 I
 0.159     I.         .        ++++       .         .         .         .I
 0.771E-01 I. . . . . . . .++++ . . . . . . . . . . . . . . . . . . . . .I
 0.373E-01 I.         . +++     .         .         .         .         .I
 0.181E-01 I          ++                                                 I
 0.875E-02 I.        +.         .         .         .         .         .I
 0.424E-02 I       ++                                                    I
 0.205E-02 I. . .++ . . . . . . . . . . . . . . . . . . . . . . . . . . .I
 0.993E-03 I    +                                                        I
 0.480E-03 I.  +      .         .         .         .         .         .I
 0.233E-03 I ++                                                          I
 0.113E-03 I+         .         .         .         .         .         .I
           ----------------------------------------------------------------
 FREQ      0.01      0.03      0.14      0.71      3.68      19.19    100.00
GAIN FACTOR AT 1 HZ: 0.627E+10     RETURN FOR PHASE RESPONSE
```

Note the change in slope at approximately the period of the seismometer (i.e. 30s or 0.0333Hz in this example), and that the amplitude is normalised to 1 at 1 Hz. Pressing <return> again gives the phase response. Then:

GSE RESPONSE FILE (Y/N=default)? **y**
Enter station code. e.g. BERGE, max 5 chars **e.g. MBLG**
Enter component (4 chars) **e.g. BH Z**
Enter date as YYYYMMDDHHMMSS, at least up to the day (e.g. 19880123): **e.g. 20150121** A pop-up window then appears displaying the amplitude and phase response again. Press "q" to close the window. The GSE2 format response file, e.g. `MBLG_BH_Z.2015-01-21-0000_GSE`, should now have been created in the current directory. The resulting file looks like:

```
CAL2 MBLG  BHZ                0.16E+00      1.  100.00000 2015/01/21 00:00
PAZ2  1 V -0.10067000E-05                   3   4 Laplace transform
 -0.14803000E+00 -0.14803000E+00
 -0.14803000E+00  0.14803000E+00
 -0.31416000E+03  0.00000000E+00
  0.00000000E+00  0.00000000E+00
  0.00000000E+00  0.00000000E+00
  0.99903003E+03  0.00000000E+00
  0.00000000E+00  0.00000000E+00
DIG2  2  0.31172000E+06   100.00000 CMG-DM24 C499 T4F33
```

The first line contains: the station code, component, sample rate and start date. The PAZ2 line shows a gain factor (1) and the output units (V for Volts) followed by the normalisation constant, consisting of the normalising factor at 2π rads $\times$ the instrument gain, but with an additional factor of 10^{-9} since this value is in V/nm. The number of poles and zeroes are also shown, with the next set of lines giving the values of these (in radians). The DIG2 line contains the digitiser calibration factor and sampling rate, as well as the digitiser and seismometer serial numbers for reference. More detailed information on the GSE format for response files is given in Appendix C.2 of the Seisan manual.

3 Testing of new response files

Using the method outlined in the previous section, GSE format response files for the *current* configuration of stations/seismometers/digitisers (as shown in Table 1) were created. These were then tested by converting a range of data. Three recent examples were chosen: a teleseismic earthquake arrival (14-Oct-2014), a large regional earthquake (19-Dec-2014), and a large M_L3.0 VT earthquake from SHV on 12-Nov-2014. For each example the raw, uncorrected waveform in counts was corrected to: 1) true ground velocity, 2) true ground displacement (using a 200s high-pass filter) and 3) the approximate displacement response from a Wood-Anderson seismometer (8-pole 1.25-20Hz filter) as this is used by seisan to measure amplitudes for local magnitude calculations. This conversion was done with the seisan program **wavetool**, using both the existing seisan response files, and the newly created ones via the method above. Figure 2 shows an example of this comparison, for the Wood-Anderson displacement signals for a M_L3.0 VT earthquake on 12-Nov-2014.

Station Code	Seismometer serial	Seismometer period [s]	Digitiser serial	Start date [UTC]
MBBY	T36253	60	D912	11-Dec-2013 17:40
MBFR	T4G40	30	DD12	22-Mar-2013 16:20
MBGB	T4343	30	DD47	09-Jul-2014 20:20
MBGH	T4F33	30	DD44	01-Jun-2010 00:00
MBLG	T4G41	30	C499	08-Jun-2012 20:00
MBLY	T4344	30	DD38	05-Jul-2012 17:10
MBRY	T4D68	30	DD39	14-Oct-2013 00:00
MBWH	T36255	60	A2241	05-Oct-2011 00:00
MBWW	T333	120	A2826	26-Mar-2012 00:00

Table 1: Current configuration of broadband stations in the MVO seismic network, showing the periods and serial numbers of the seismometers and digitisers in use and the date of deployment.

The old/existing response files (for these recent examples at least) were created with **resp** using a different approach to that outlined in this document, with information specified interactively to the program: such as the instrument type (seismometer), the instrument gain, period and damping, and the digitiser calibration factor (recording media gain). In most cases, files containing the (unconverted velocity response) Güralp poles and zeroes were also used, and there is a concern that this meant the some information, such as the normalisation factor for the transfer function, was corrected for twice or not utilised correctly or at all. In addition it is highly likely that this process was not applied consistently in the past, and in particular, it is certain that calibration and response files were not kept up to date with changes of instrument or digitiser.

However, the results in Figures 2 and 3 show, in general, a favourable comparison between the two sets of converted data; with the amplitudes (maximum peak-to-peak values are given in *nm*) matching quite closely. There are exceptions; notably station MBWH, which shows a factor of 3 reduction in amplitude using the new response files. However, this is due to confusion over the value of the gain of the instrument, which although specified as $2\times\sim3000\ V/m/s$ in the documentation, has a value of $2\times1000\ V/m/s$ physically printed on the instrument. The former appears to be correct, with the value on the label assumed to be the standard values for the CMG-3ESPCD model, rather than the specific configuration. Note also that the problems with conversion of data from MBLG are due to data gaps, and the effect of the filtering on this data producing incorrect results.

For the longer timeseries (20 minutes of data) for the teleseismic earthquake in Figure 3, it can be seen that despite the 200s high-pass filter, there are still significant problems with very-long period noise being blown up during the integration process. This effect may be more noticeable for the 30s instruments compared to the more broadband 60 or 120s sensors. However, in two cases (MBGB and MBGH) the new response files fair better at suppressing this, indicating correct deconvolution of the instrument response. This example reinforces the need for the correct instrument response files to be used when analysing longer timeseries or longer waveforms such as the VLP (very-long period) signals seen at SHV in March 2012 and March 2014.

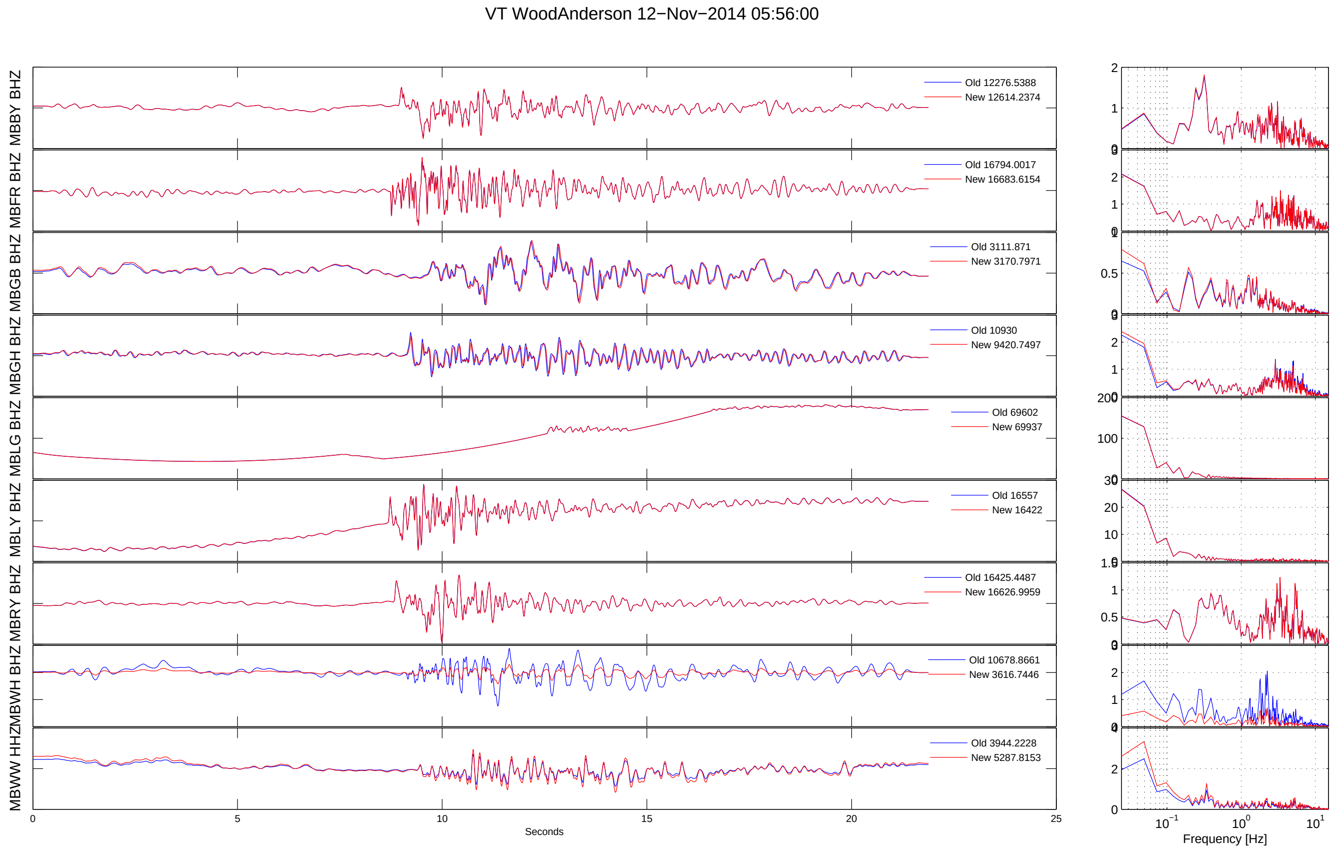

Figure 2: Displacement waveforms and spectra (filtered to approximate a Wood-Anderson seismometer response in order to calculate local magnitudes) using the old (blue) and new (red) seisan response files. Maximum peak-to-peak amplitudes (in *nm*) are displayed. Data are from a M_L3.0 VT earthquake on 12-Nov-2014. Note the problems with data from station MBLG due to gaps.

4 Implementation

Following successful testing, the newly created response files for the *current* configuration have now been copied to the ~/CAL directory on both **seisan** and **piton**. Note that in some cases these replaced existing files in seisan format (i.e. file names ending in SEI) and in some cases were new additions; such as when only a digitiser had been changed and creation of new response files had not been a priority.

Because of the minimal differences observed in the amplitudes during the testing and comparison, it was not deemed necessary to go back and change or update old response files. Hence also, local magnitudes have *not* been re-calculated. Testing and comparison showed the effect of the new response files might change the magnitudes by around 0.1 or 0.2 units (mainly due to MBWH amplitude changes), which was decided to be not significant enough to warrant the considerable amount of time and effort it would take to re-pick amplitudes and re-calculate the magnitudes for all VT events.

5 Instructions for creating new response files

5.1 create_resp

In order to automate the process and make it easy(ier) to keep the seisan response files up to date, a series of new scripts has been written to produce GSE2 format response files for a given station/instrument/digitiser.

The main bash script is called **create_resp** and is located in the ~/bin directory on the **seisan** machine. It requires five input arguments, which can either be supplied as command line arguments or specified interactively.

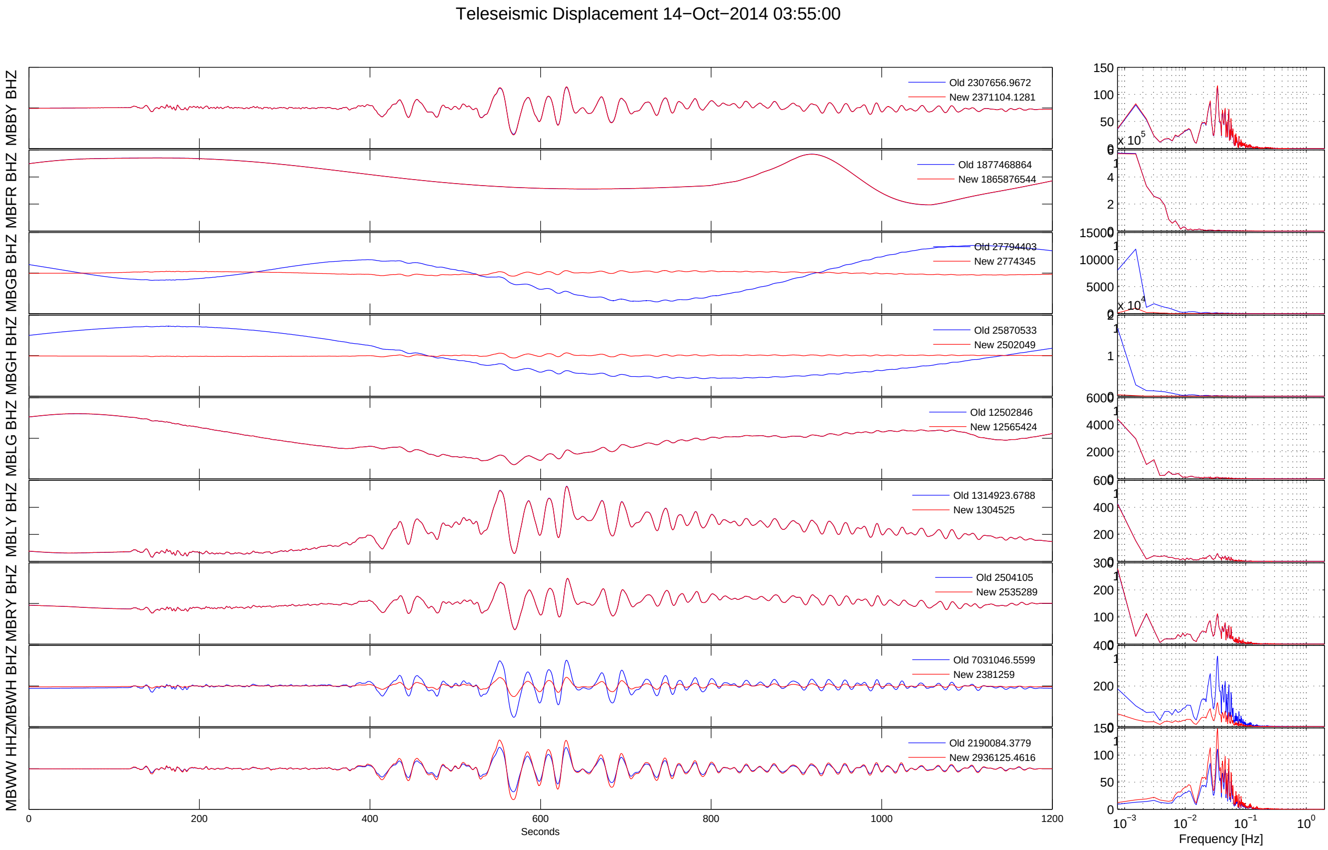

Figure 3: Displacement waveforms and spectra using the old (blue) and new (red) seisan response files. Data were high-pass filtered with a 200s (0.005Hz) high-pass filter during deconvolution of the instrument response. Maximum peak-to-peak amplitudes (in *nm*) are displayed. Data are from a teleseismic earthquake arrival on 14-Oct-2014.

These required arguments are:

1. The four letter station code (e.g. MBLG)
2. The 3 letter channel code (e.g. BHZ)
3. The date/time from which in the calibration file should apply. Format: yyyymmdd(HHMMSS)
4. Seismometer serial number (e.g. T4F33)
5. Digitiser serial number (e.g. C499)

The script uses the supplied information to retrieve appropriate values for the digitiser and seismometer calibration and calls **resp** to produce a GSE2 format response file. Digitiser calibration constants are stored in text files, in directory: `~/etc/create_resp/dig_cals`. Each line of these files contains a value in $counts/V$, with a letter to indicate the component (Z, N, or E). This directory should already contain files for most of the digitisers commonly used for MVO seismic data acquisition. However, to create a response file for a station with a new or previously unused digitiser, a text file containing the calibration values *MUST* first be created in this directory before **create_resp** is run.

5.2 paz_new

The poles and zeroes files (already converted to rad/s, and with the calibration constant re-normalised and multiplied by the instrument gain) are also stored in plain text files, in directory: `~/etc/create_resp/paz` on **seisan**. These were created by another bash script **paz_new** (which is also located in `~/bin` directory on **seisan**) which uses values from the Güralp documentation to produce new poles and zeroes files in the correct format. The seismometer gains are stored in text files in `~/etc/create_resp/gains`, and the poles and zeroes as specified by Güralp are stored in `~/etc/create_resp/paz_gur`. As with the digitisers, files for most of the seismometers commonly used at MVO should already have been created. However, for a station with a new or previously unused seismometer the steps are:

1. Create a file with the seismometer gains in the `gains` directory. Filename is `gains_[serial].txt`. e.g. `gains_T4F33.txt`. The file format is one line per component, with the component letter, a "2" (for differential mode, assumed for most) and the gain in $V/m/s$. e.g.

   ```
   Z 2 1603
   N 2 1595
   E 2 1575
   ```

   for seismometer T4F33.

2. Add the seismometer serial number to the list of serial numbers in **paz_new**, before running this script to re-create files for all seismometers. Then **create_resp** can be run to produce the response file(s).

5.3 Caveats

Note that the procedure described above applies to **Güralp broadband stations ONLY**, and any short period stations need to be treated separately, with files created directly using **resp**. Please also note that any files created for the `~/CAL` directory on **seisan** should, for the moment, also be *manually copied* to the same directory on **piton**.

References

Havskov, J. & Alguacil, G., 2014. Seismic Instrument Response, Correction for, in *Encyclopedia of Earthquake Engineering*, pp. 1–14, eds Beer, M., Kougioumtzoglou, I. A., Patelli, E., & Au, I. S.-K., Springer Berlin Heidelberg.

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