Step-response signals recorded at seismic stations in Alaska
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Contents

Table C1: Table of observations (by row) and hypotheses (by column). The larger the number, the stronger the support a particular observation has for a particular hypothesis. A question mark (?) or two (??) indicates an extra level of uncertainty for a rating.

	clipping	regional (real) signal	installation settling (e.g., sand compaction)	local effects outside of the installation	saturation of the feedback loop in the instrument
pervasive at some sites over many years	1	2	2 ?	3	3
rarer at bedrock sites	2	2	3	3	2 ?
can appear on 1, 2, or 3 components	2	2	2 ?	2	3
can exhibit up or down polarities in all three components	3	3	2	2	3
appears to be seasonal, with more in the summer	1	?	3 ?	3 ?	?
more common on some stations directly after installation	2	2	4	2	2 ?
correlated with the max count on raw seismograms	3	3	3	3	3
sometimes appears in the absence of any shaking	1	?	3	?	??
at some sites, E and Z signals are directly proportional	2	1	1	1	3??
at some sites the signal is larger on horizontals than verticals	2	?	3	4	?
often the E and N components are directly proportional	?	2	2	1	??
CONCLUSION	1	1	2 ?	2 ?	3 ?

C1 Key points [Table C1]

1. Summary

   (a) Using a $T \geq 10$ s filter on the raw seismograms, we identified a long-period spurious signal for small earthquakes recorded at distances <100 km. We'll refer to this peculiar long-period signal as a "step-response signal". We don't know what is causing this unwanted signal.

   (b) The step-response signal is widespread on the stations we examined. Using a matched filter approach (Section C4), we identified the step-response signal on earthquakes in the AEC catalog, earthquakes not in the AEC catalog, and also non-earthquake signals.

   (c) Based on the points below, we believe that this is a signal related to the signals discussed in *Zahradnik and Plešinger* (2005, 2010); *Vackar et al.* (2015) and *Delorey et al.* (2008). (They imply that the step-response signal can be removed, which is good news.) We cannot completely explain our observations (notably the linear correlation between E and N amplitudes; see below) in terms of local tilting, and we therefore invoke some problem with the instrument response, such as saturation of the feedback loop.

      i. We add several new observations to the above references. It is as of yet unclear if the geology/climate of Alaska leads to these points below.

         A. The step-response signal is seasonal.
         The polarity of the step-response signal can also be seasonal. For example, at MDM.AK in 2015, most signals were in the summer months. However, positive amplitude signals were only in the early summer, and negative amplitude signals were only in the late summer.

         B. The step-response signal is extremely pervasive at some sites, with up to many thousands of events per year. Note: some of these sites (M27K, about 1000 signals per month) were identified as defective and replaced (M27K replaced in August. 2015).

         C. The step-response signal can occur independently of ground shaking.

         D. The step-response signal can occur during teleseismic events.

   (d) The effect is most significant on MDM.AK, FPAP.XV, M27K.TA, and O22K.TA, all of which may have problems.

2. Observations

   (a) The step-response signal is pervasive at some sites (e.g., MDM, BPAW, FPAP, F4TN, FAPT, M27K, O22K).

   (b) The step-response signal is significantly affecting science quality at many TA stations.

   (c) The step-response signal is rare at bedrock sites NEA2 and F8KN. NEA2 is a TA-style deep borehole, whereas F8KN is shallowly buried (about 1 m) and sitting directly on bedrock.

   (d) The step-response signal does not appear on all three components all the time; sometimes it is 1, 2, or 3 (Figure C5).

   (e) The step-response signal appears to be seasonal, with more occurring in the summer (e.g., BPAW Figure C15).

   (f) The step-response signal is more common directly after station installation (e.g., F7TV Figure C21 and FNN2 Figure C22).

(g) The step-response signal is correlated with the max-count on the raw seismograms. This strongly implies that it is related to high-amplitude ground motion at the site.

  i. The signal sometimes appears in the absence of any shaking, so ground motion is not necessary to produce this signal.

(h) At some stations (MDM Figure C8, FPAP Figure C18), the step-response signal on the E and Z components are nearly directly proportional, with no relation on the N component.

At other stations (F4TN Figure C24, F3TN Figure C20, FAPT Figure C25, FNN2 Figure C28, FTGH Figure C26), the step-response signal is larger on the horizontals than the verticals by 1-2 orders of magnitude. However, when this is the case, the E and N components **are** proportional (directly or inversely). **This is not consistent with a tilt signal. If the signal is caused by localized tilting, then you would expect a "disc" of dots in the lower figure (like Figure C26); instead we see a strong correlation among E and N amplitudes.**

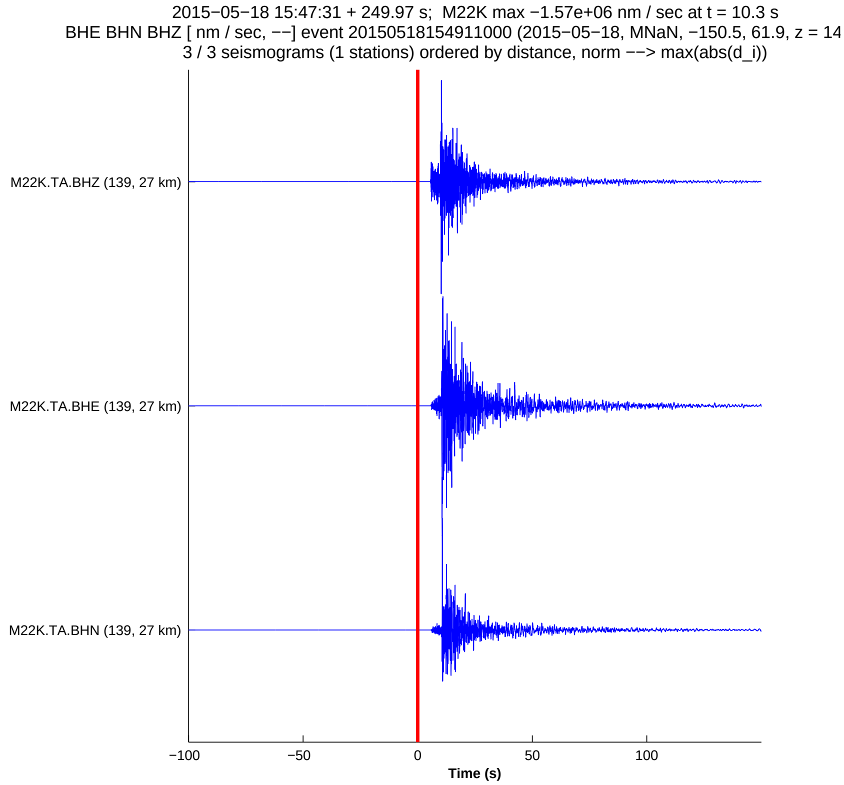
(i) MDM exhibits the step-response signal before and after it was a posthole trillium (July 2014). However, before MDM was a posthole, it was on a frost-jacked pad. We don't want to interpret the older MDM results too closely.

(j) In none of our cases is the max-count reading exceeding the threshold of $\pm 2^{23}$ counts $= \pm 8388608$ or roughly $\pm 8 \times 10^6$ counts. Furthermore we see no square waves. So we have no basis for calling this "clipping."

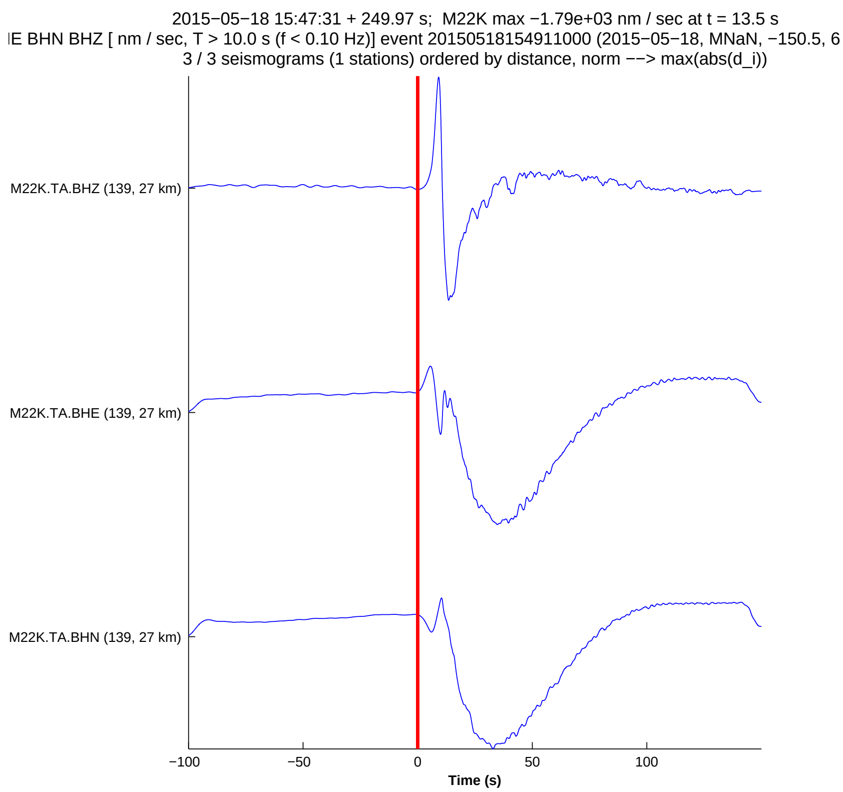
C2 Examples of the step-response signal in Earthscope TA data.

The highest quality seismic stations and installations in Alaska are likely those of the Transportable Array. To show that these stations are not immune to the step-response signal documented in this report, we provide some examples:

- Figure C1 shows nonlinear response to a local earthquake
- Figure C2 shows nonlinear response to a regional earthquake
- Figure C3 shows nonlinear response to a teleseismic earthquake



(a)



(b)

Figure C1: Nonlinear response to a local earthquake. M4.1 EQ recorded at M22K at 27 km distace. (top) Raw data (bottom) Low-pass filtered at 10 seconds. The max amplitude of the raw data is about 10% of the clip level.

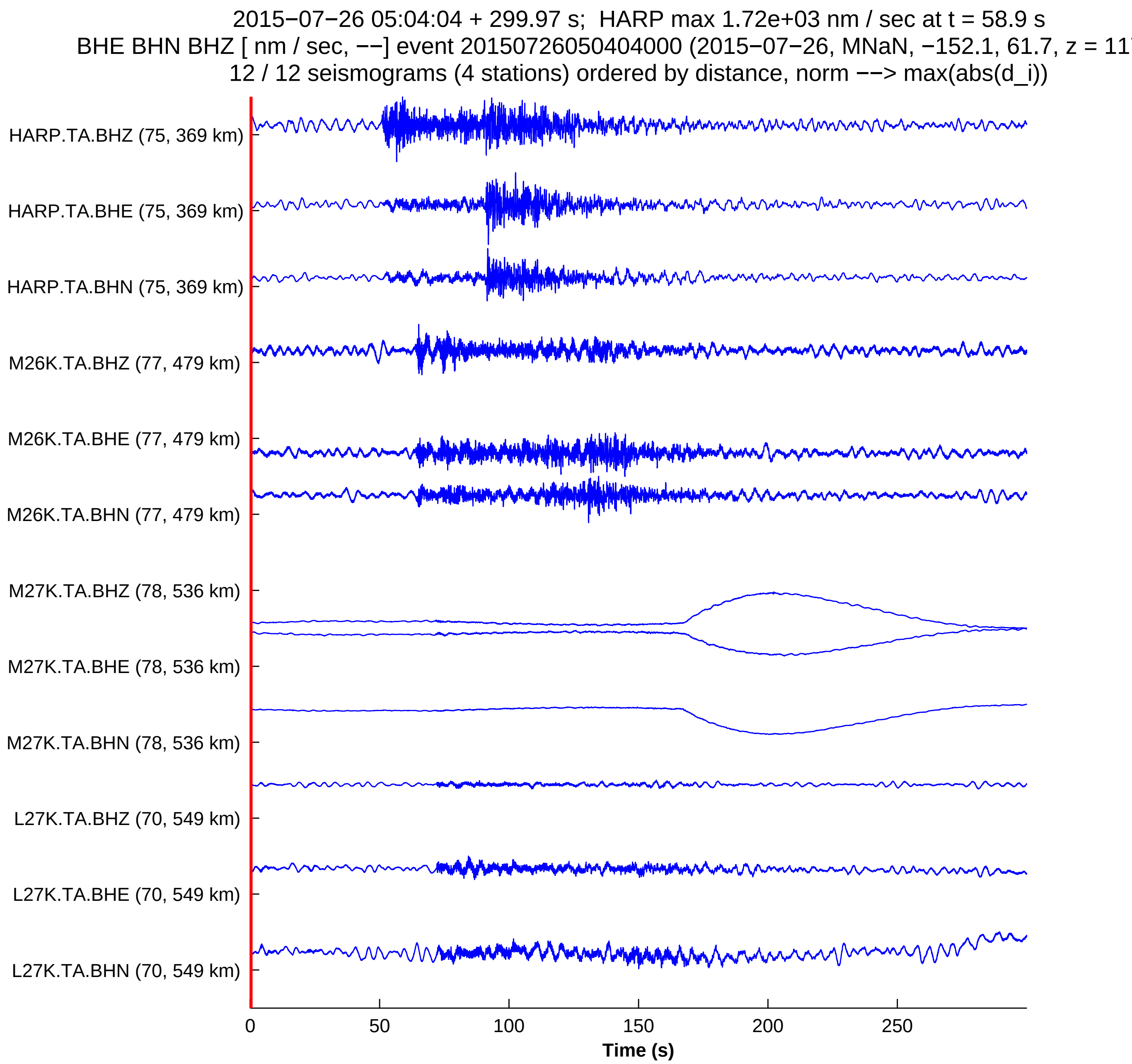


Figure C2: Nonlinear response to a regional earthquake. M3.1 EQ recorded at M27K at 536 km distace. Raw data is plotted. Several nearby recordings are shown for comparison. NOTE: M27K was deemed defective at this time. With about 1000 events per month, this signal may just be coincident with this earthquake.

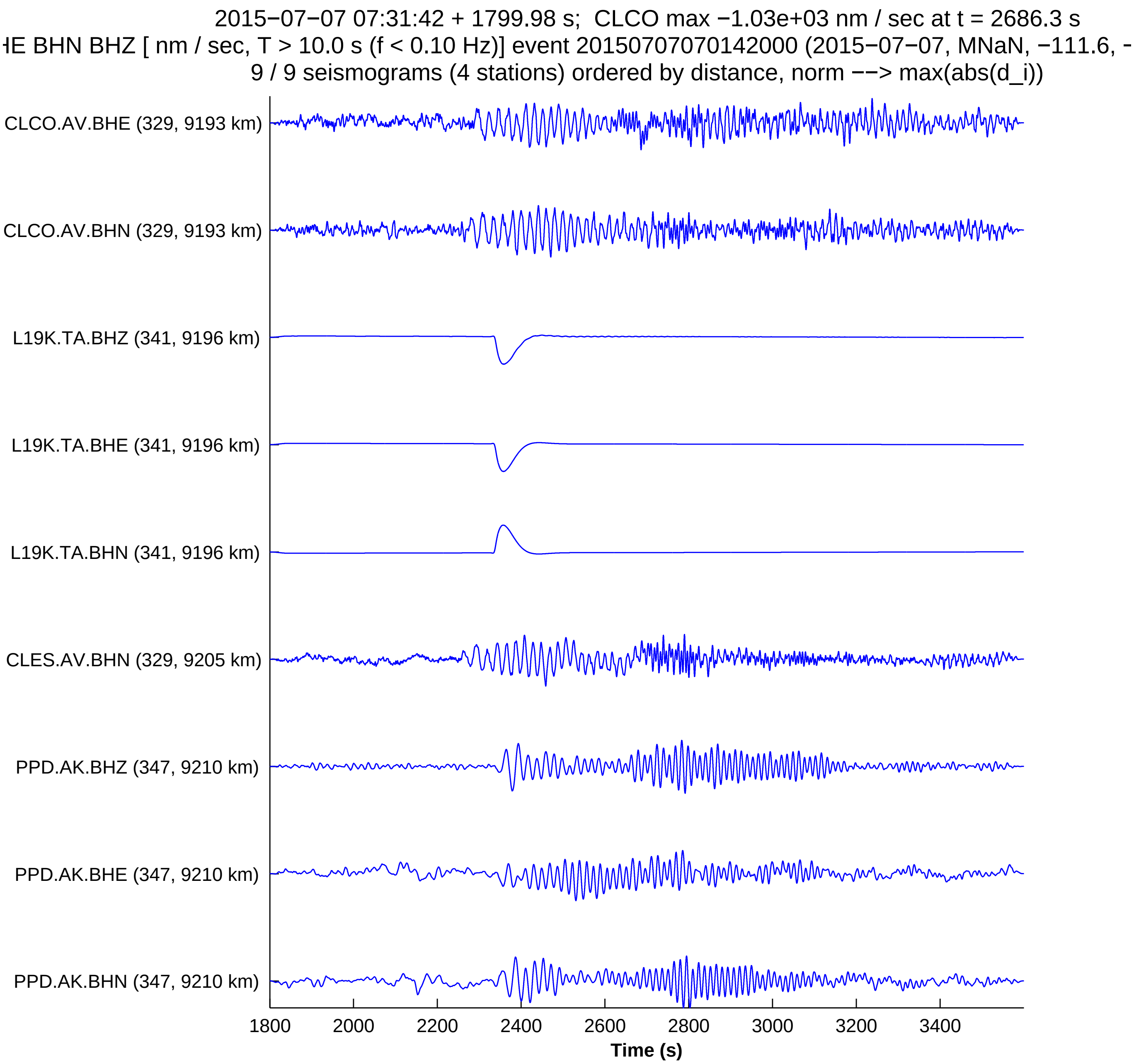


Figure C3: Nonlinear response to a teleseismic earthquake. M5.9 EQ recorded at L19K at 9000 km distace. Low pass filtered data at 10 seconds is plotted. Several nearby recordings are shown for comparison.

C3 Figures for the 2015-10-31 earthquake

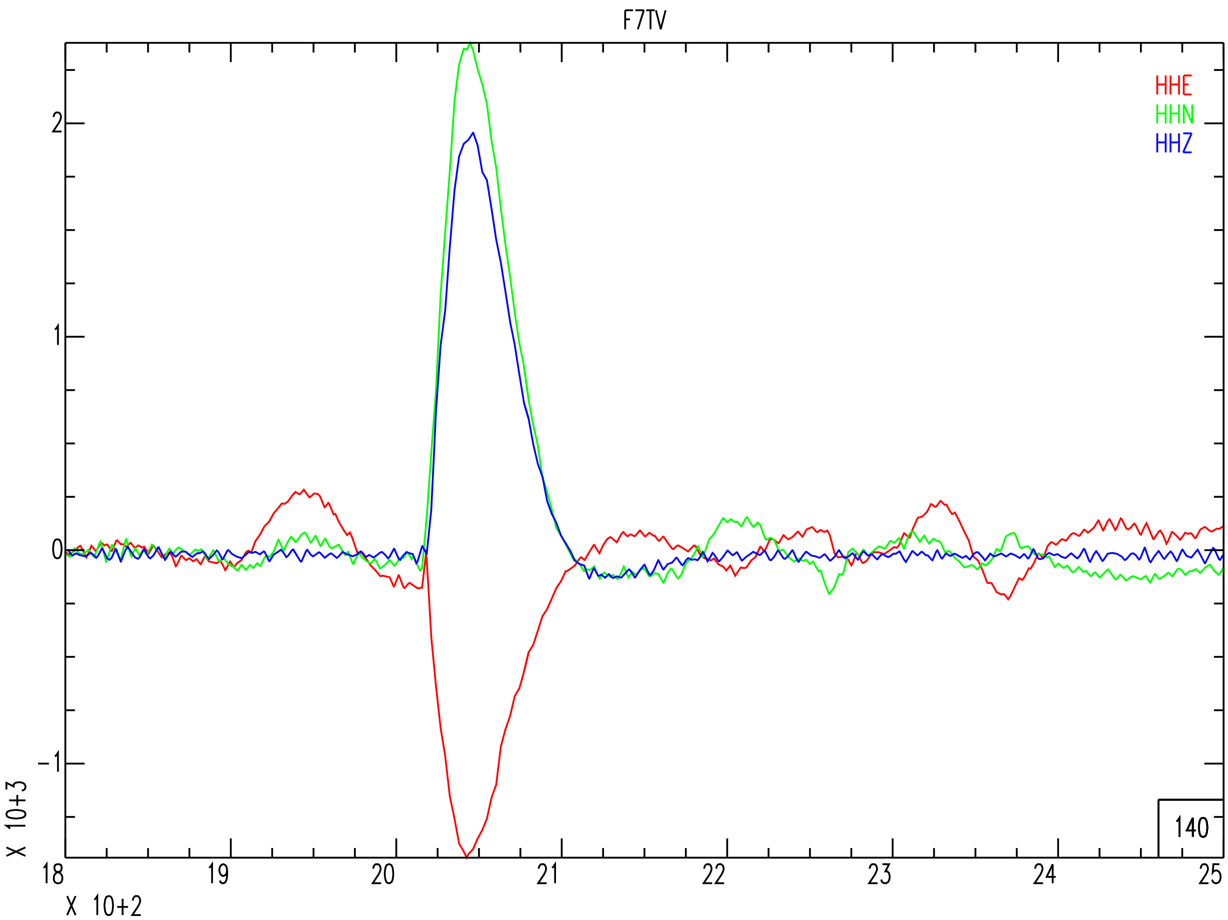
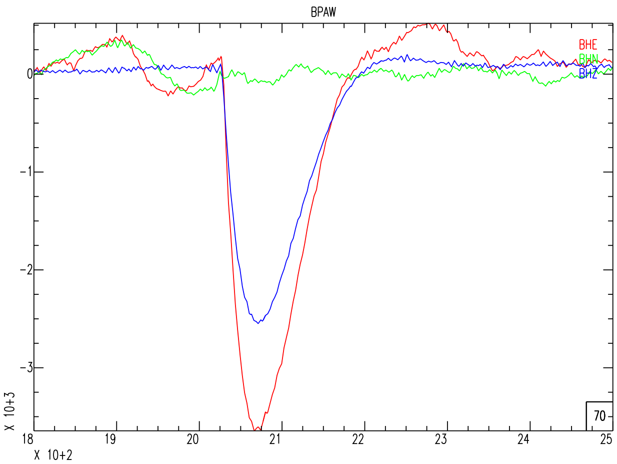
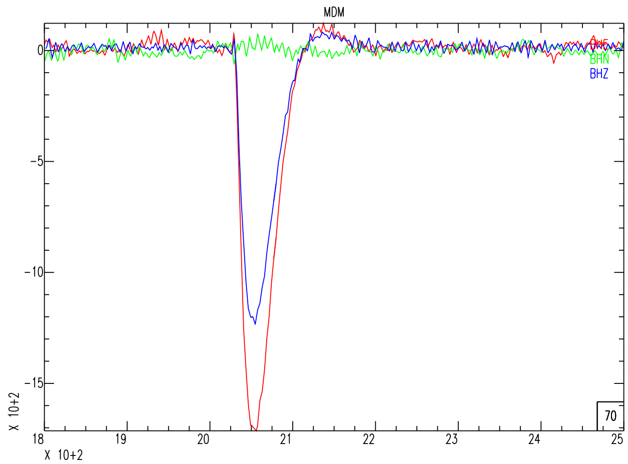


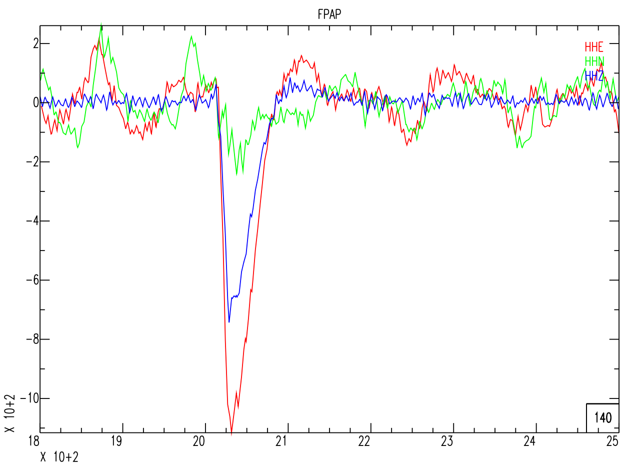
Figure C4: Examples of step-response signal for 2015-10-31 earthquake for F7TV. For this station, the signal appears on all three components. For other stations, it only appears on 1 or 2 components (Figure C5).



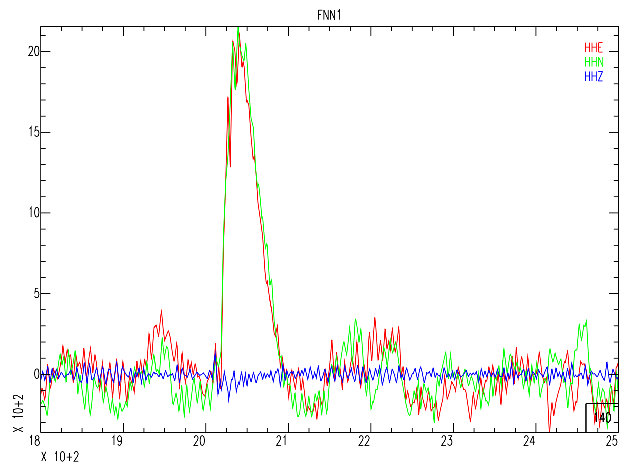
BPAW: vertical and east



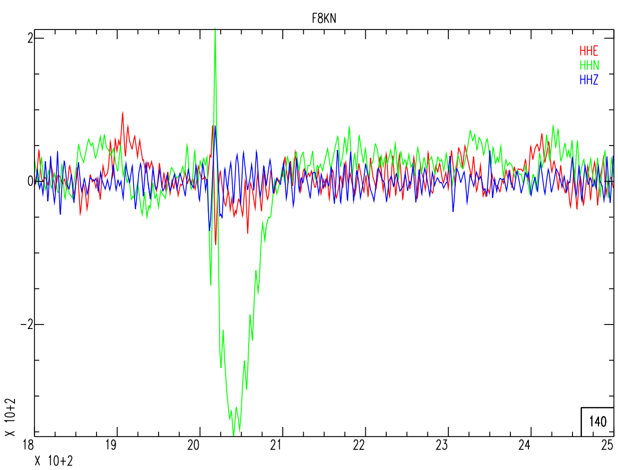
MDM: vertical and east



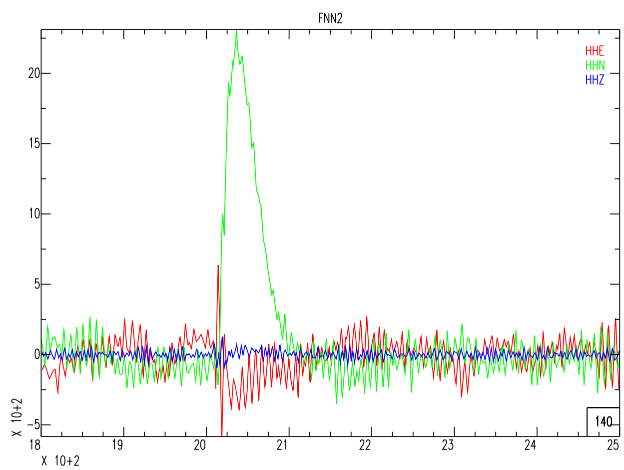
FPAP: vertical and east



FNN1: east and north



F8KN: north



FNN2: north

Figure C5: Examples of step-response signalfor 2015-10-31 earthquake. Blue = vertical, red = east, green = north.

C4 Matched Filter Detections of the step-response signal

Here is how the figures in this section were made.

1. We create a template out of the step-response signal generated by the 2015-10-31 and 2016-01-14 earthquakes for FLATS stations, and by visual scanning of TA stations.
2. We correlate this template against the continuous time series
   - We search for both positive and negative step-response signal.
3. Three types of figures are shown here
   - Clipping History: (top) log10 of the amplitude of the step-response signal; (middle) Cumulative number of positive, negative, and total number of step-response signal; (bottom) histogram by month.
   - Waveform Examples: Some low passed filtered examples of matches.
   - Amplitudes of the step-response signal on all three components (E vs. Z, N vs. Z, and N vs E).
4. We search through continuous waveform archives of TA stations, low pass filtered at 10 seconds.
   - We make templates out of the step-response signal for stations M27K, N19K, I23K, O22K, and A21K.
   - We have observed the step-response signal on every TA station in Alaska, though with widely varying occurrence rates (from a few per year to several thousand per year).
   - The step-response signal is strongly seasonal on many TA stations.
   - The step-response signal is readily apparent on Mustang plots, as higher-power lines sloping upwards towards longer periods (see Figure C11)

References

Delorey, A. A., J. Vidale, J. Steim, and P. Bodin (2008), Broadband sensor nonlinearity during moderate shaking, *Bull. Seismol. Soc. Am.*, *98*(3), 1595–1601, doi:10.1785/0120070225.

Vackar, J., J. Burjanek, and J. Zahradnik (2015), Automated detection of long-period disturbances in seismic records; MouseTrap code, *Seismol. Res. Lett.*, *86*(24), 442–450, doi: 10.1785/0220140168.

Zahradnik, J., and A. Plešinger (2005), Long-period pulses in broadband records of near earthquakes, *Bull. Seismol. Soc. Am.*, *95*(5), 1928–1939, doi:10.1785/0120040210.

Zahradnik, J., and A. Plešinger (2010), Toward understanding subtle instrumentation effects associated with weak seismic events in the near field, *Bull. Seismol. Soc. Am.*, *100*(1), 59–73, doi:10.1785/0120090087.

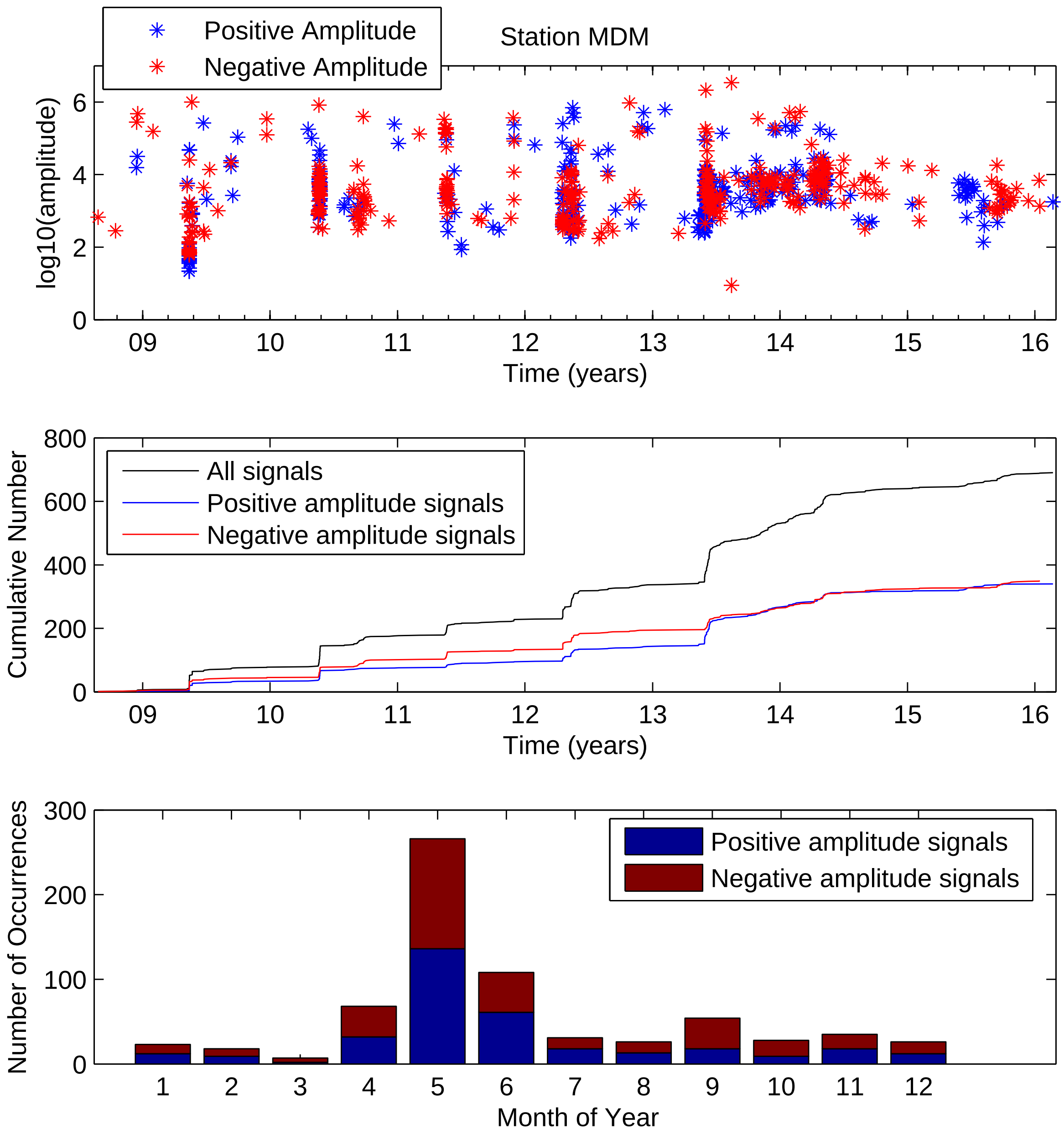


Figure C6: Clipping History at MDM, BHZ component. Both positive and negative step-response signal are plotted. Three different insturments occupied MDM over this time period. It was a Trillium 120 until 2013/08/14, a Guralp CMG3ESP until 2014/07/28, and a Trillium 120PH up to the present. During the first two epochs, the sensor was on a frost-jacked pad and was unreliable. Note how, during the 120PH epoch (in 2015), the step-response signalhas positive polarities in early summer and negative polarities in the late summer.

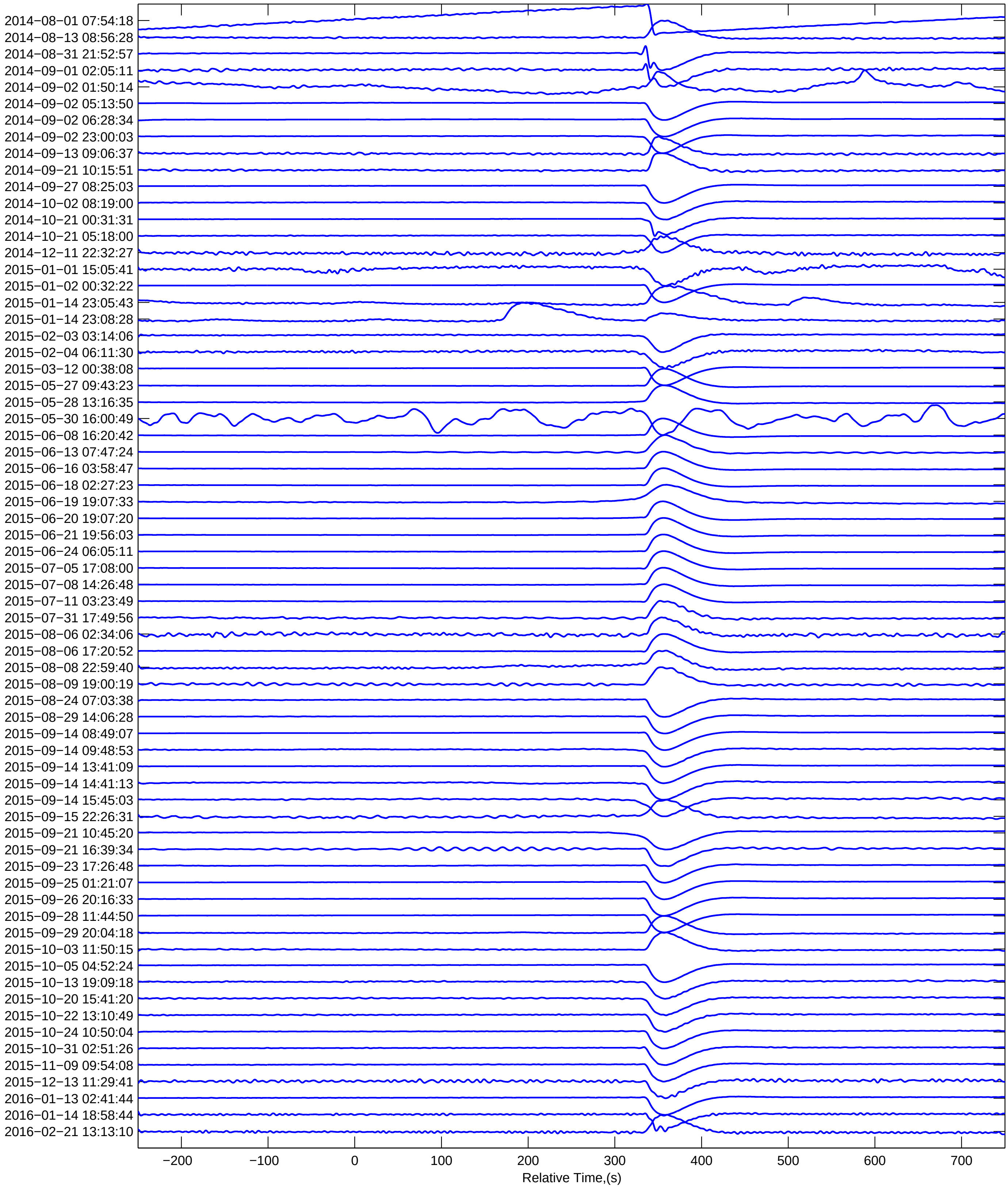


Figure C7: Low pass filter at 10 seconds of the step-response signal at MDM BHZ from matched filtering are plotted.

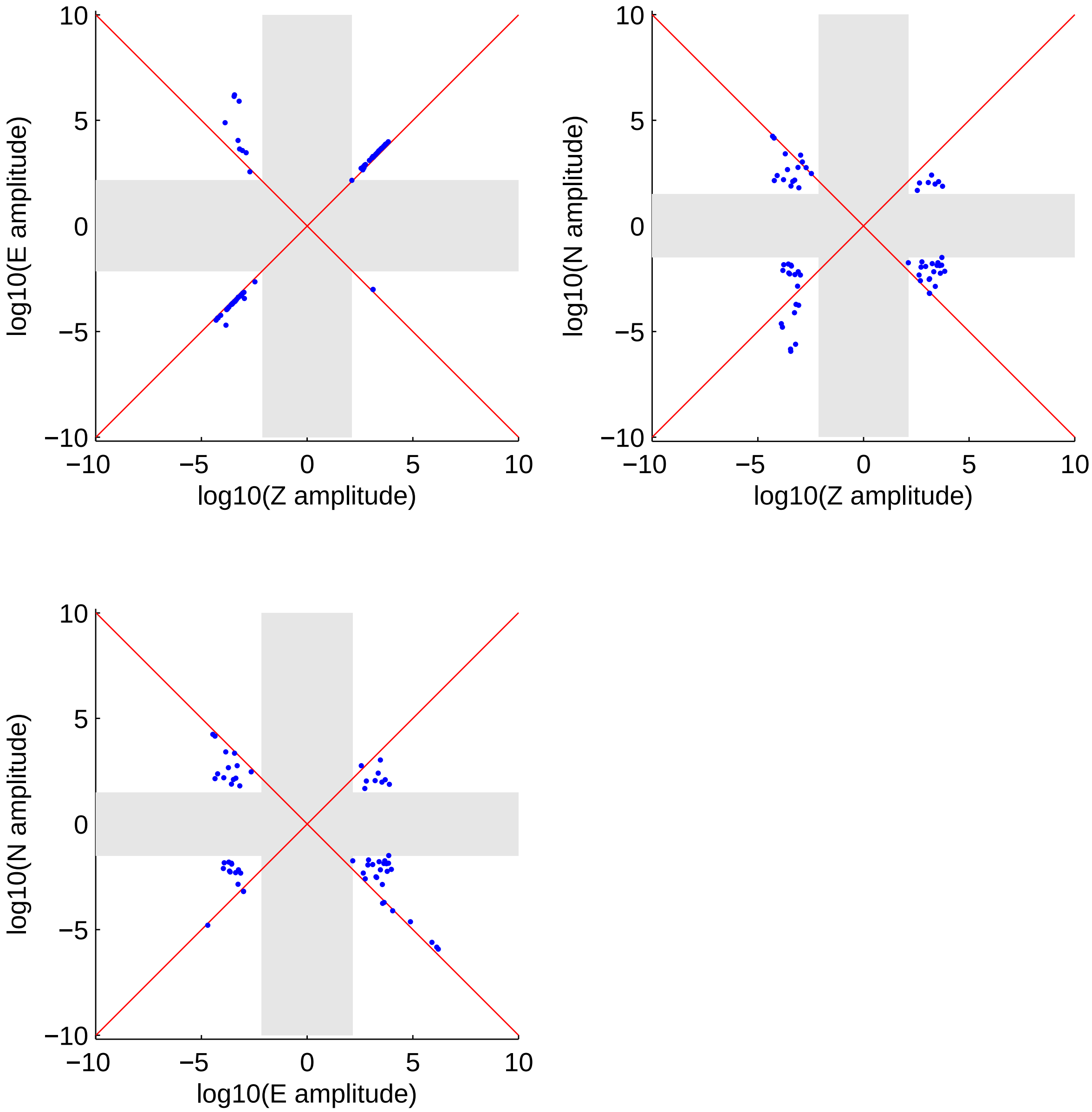


Figure C8: Relative amplitudes of the step-response signal at MDM on all three components, only for the recent epoch with the Trillium120PH. Note the strong correlation between the E and Z components.

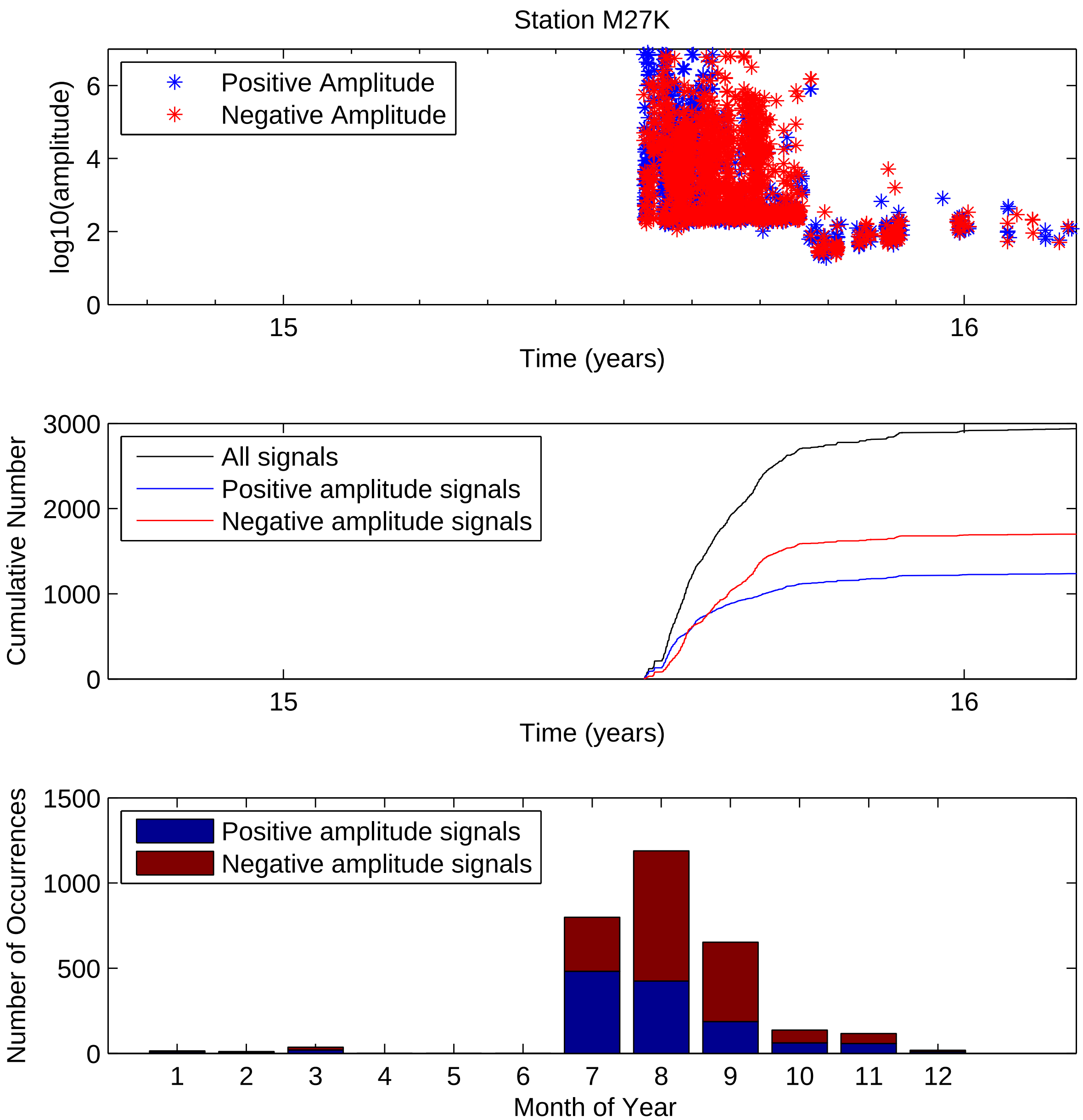


Figure C9: History of the step-response signal at station M27K, BHZ component. This station was installed July 2015.

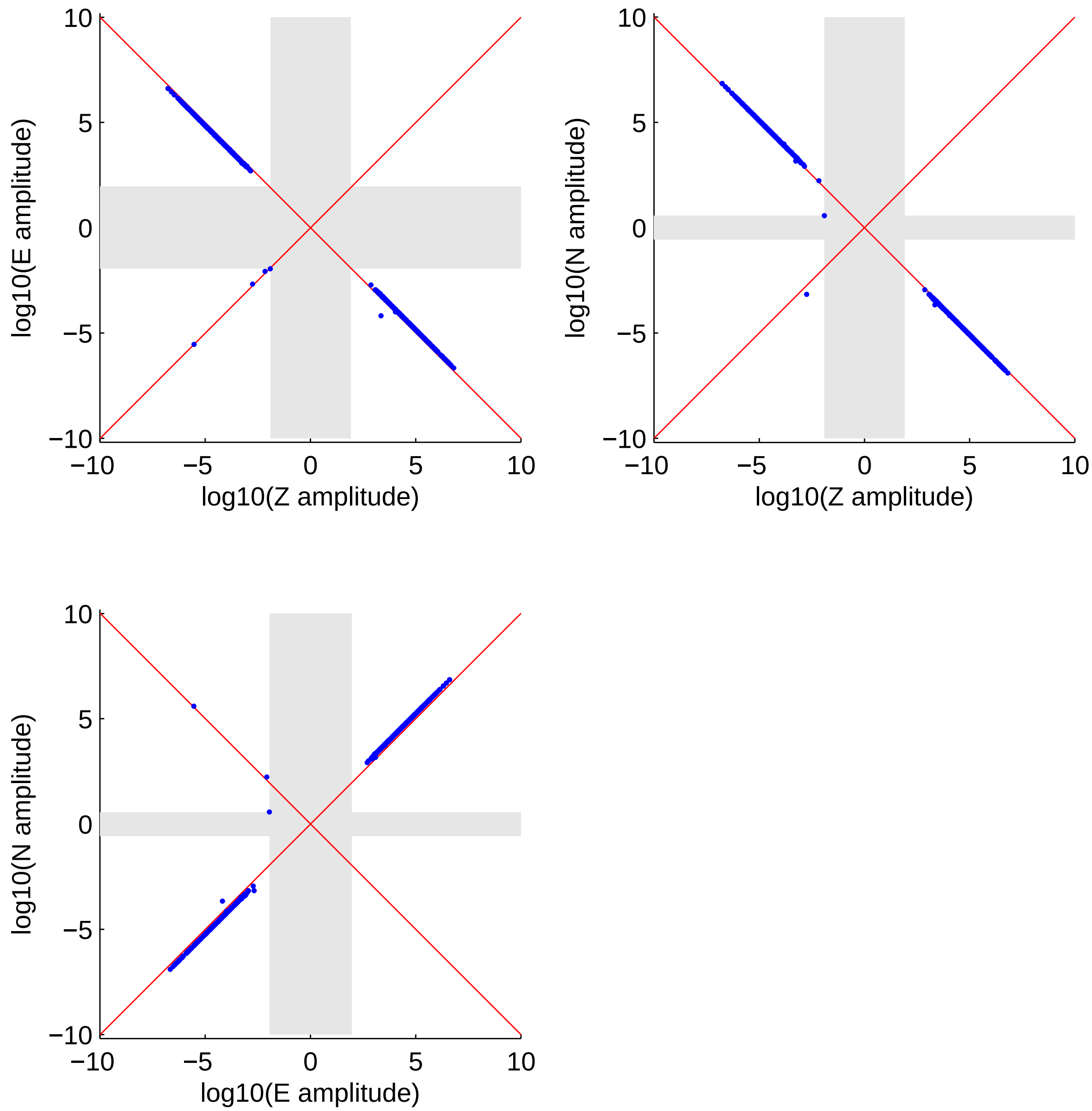


Figure C10: Relative amplitudes of the step-response signal at M27K on all three components

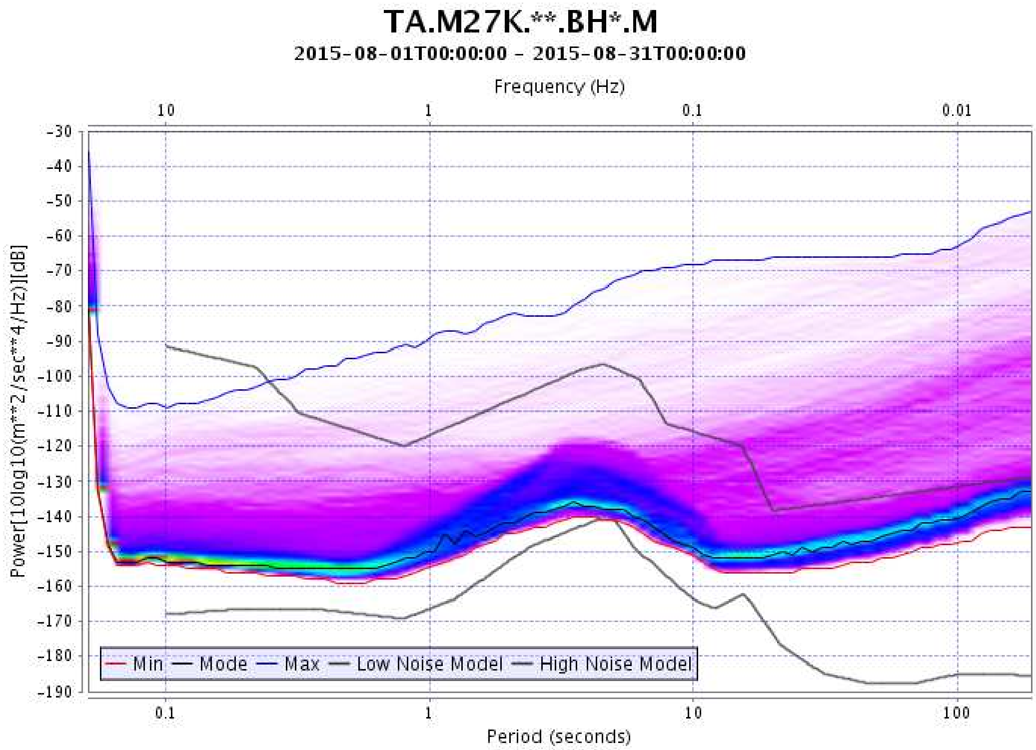


Figure C11: Mustang Plot for M27K during October, where most of the step-response signal were identified.

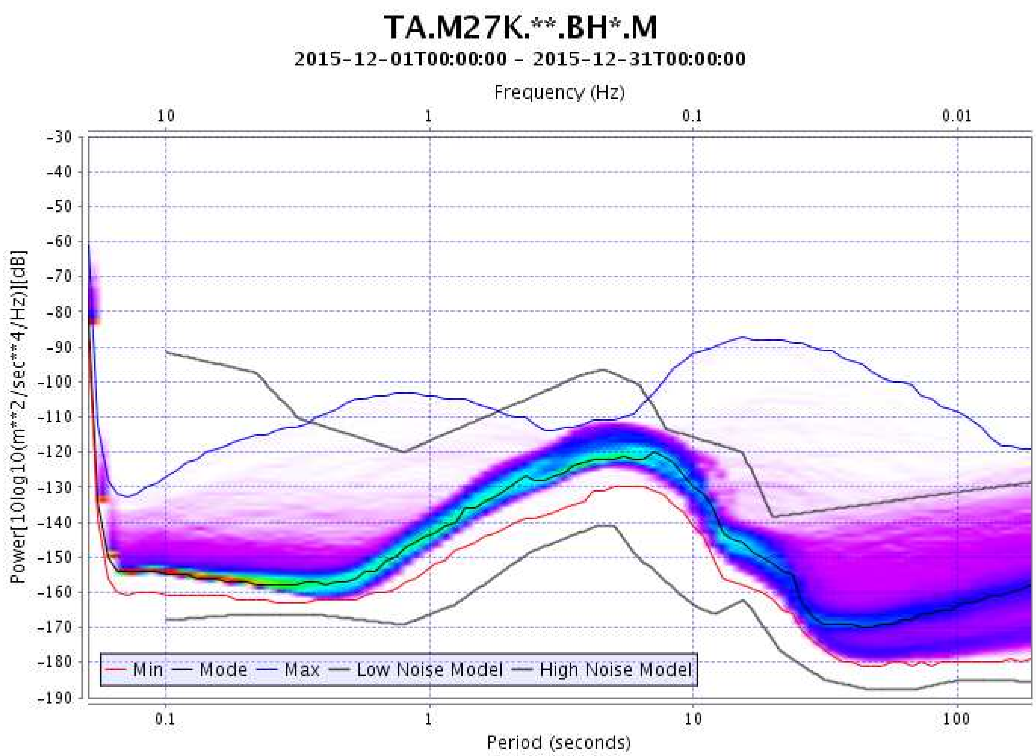


Figure C12: Mustang Plot for M27K during December, where the fewest of the step-response signal were identified.

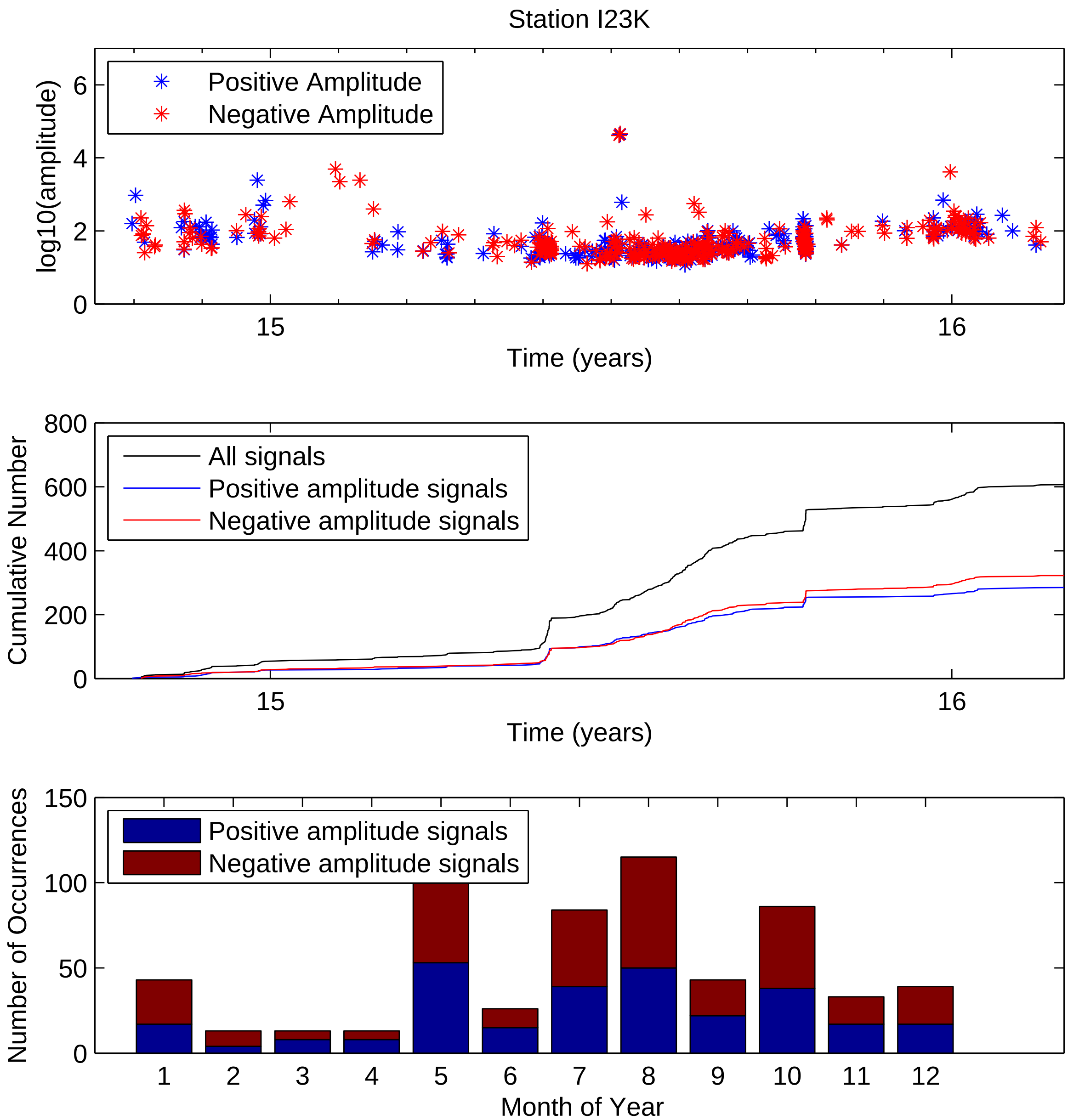


Figure C13: History of the step-response signal at station I23K, BHZ component.

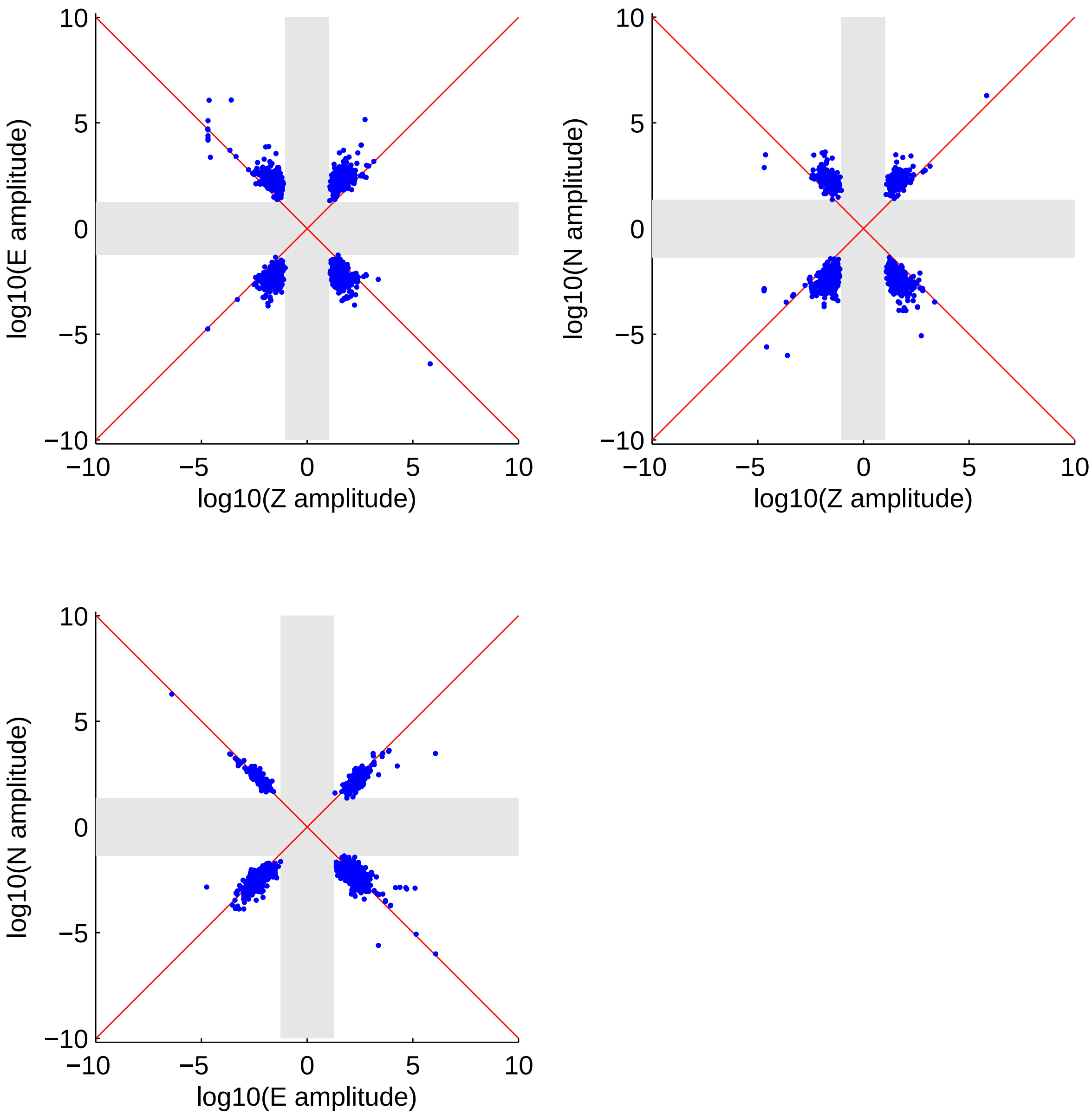


Figure C14: Relative amplitudes of the step-response signal at I23K on all three components

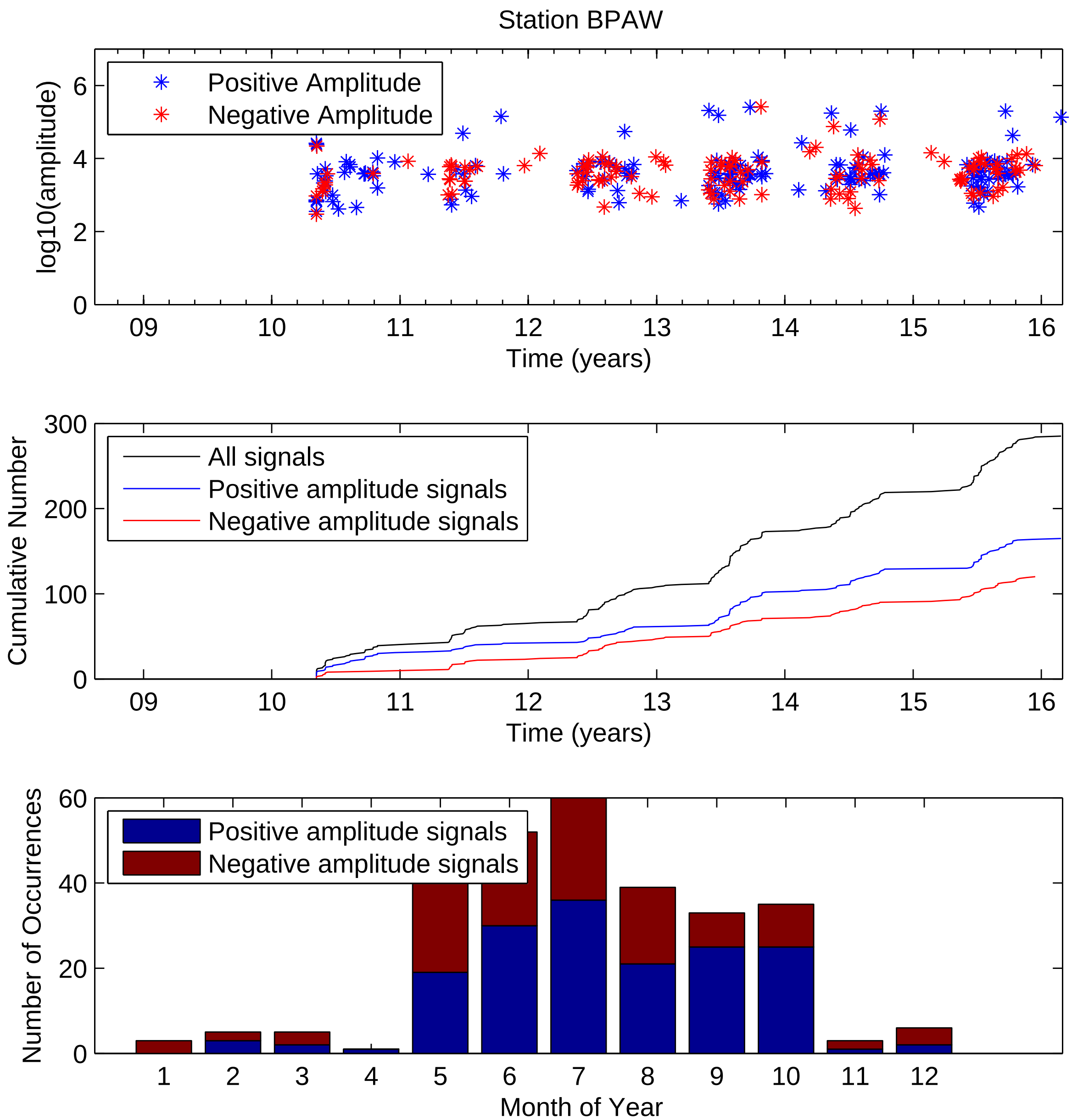


Figure C15: Clipping History at BPAW, BHZ component. Both positive and negative step-response signal are plotted.

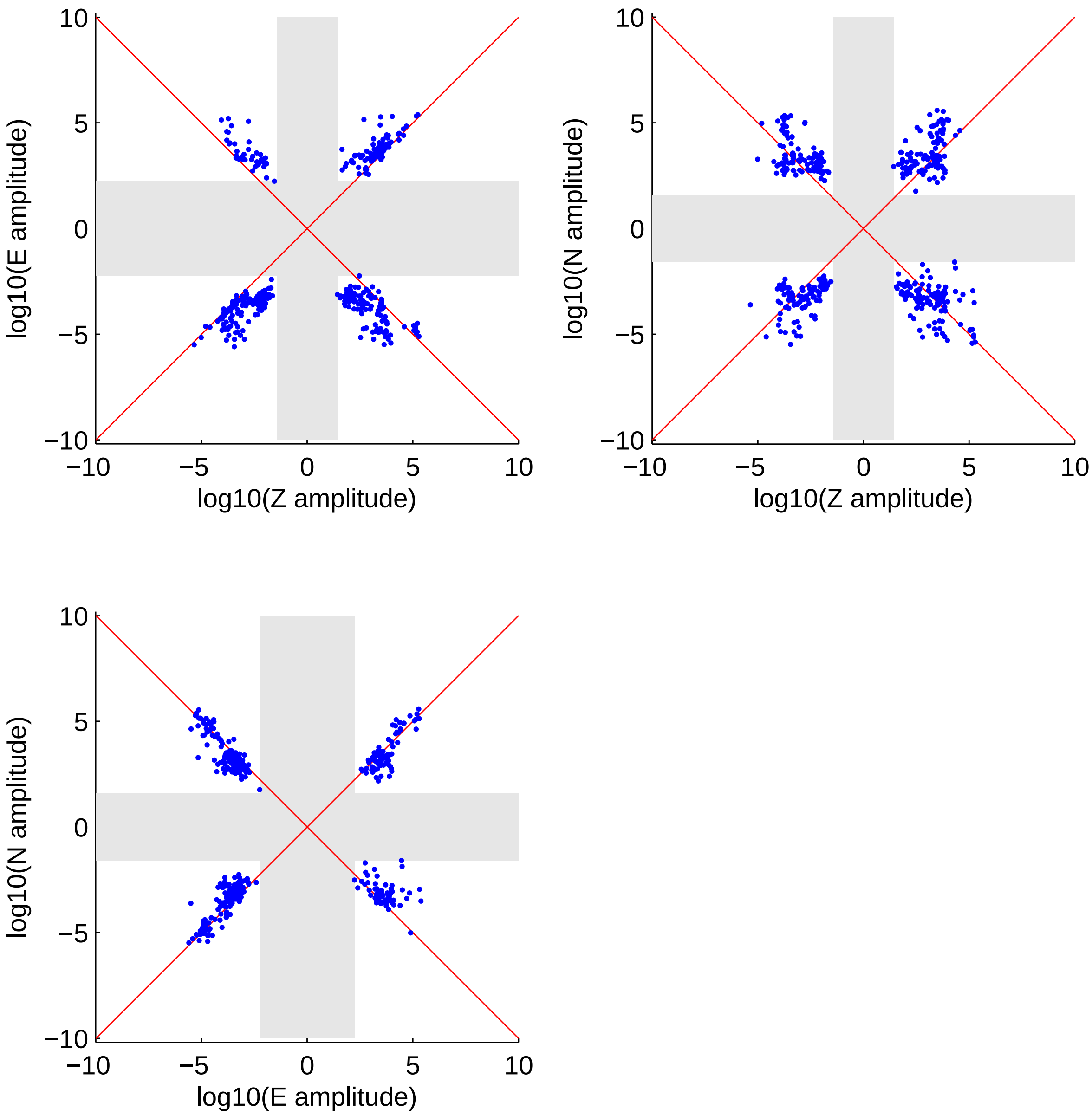


Figure C16: Relative amplitudes of the step-response signal at BPAW on all three components.

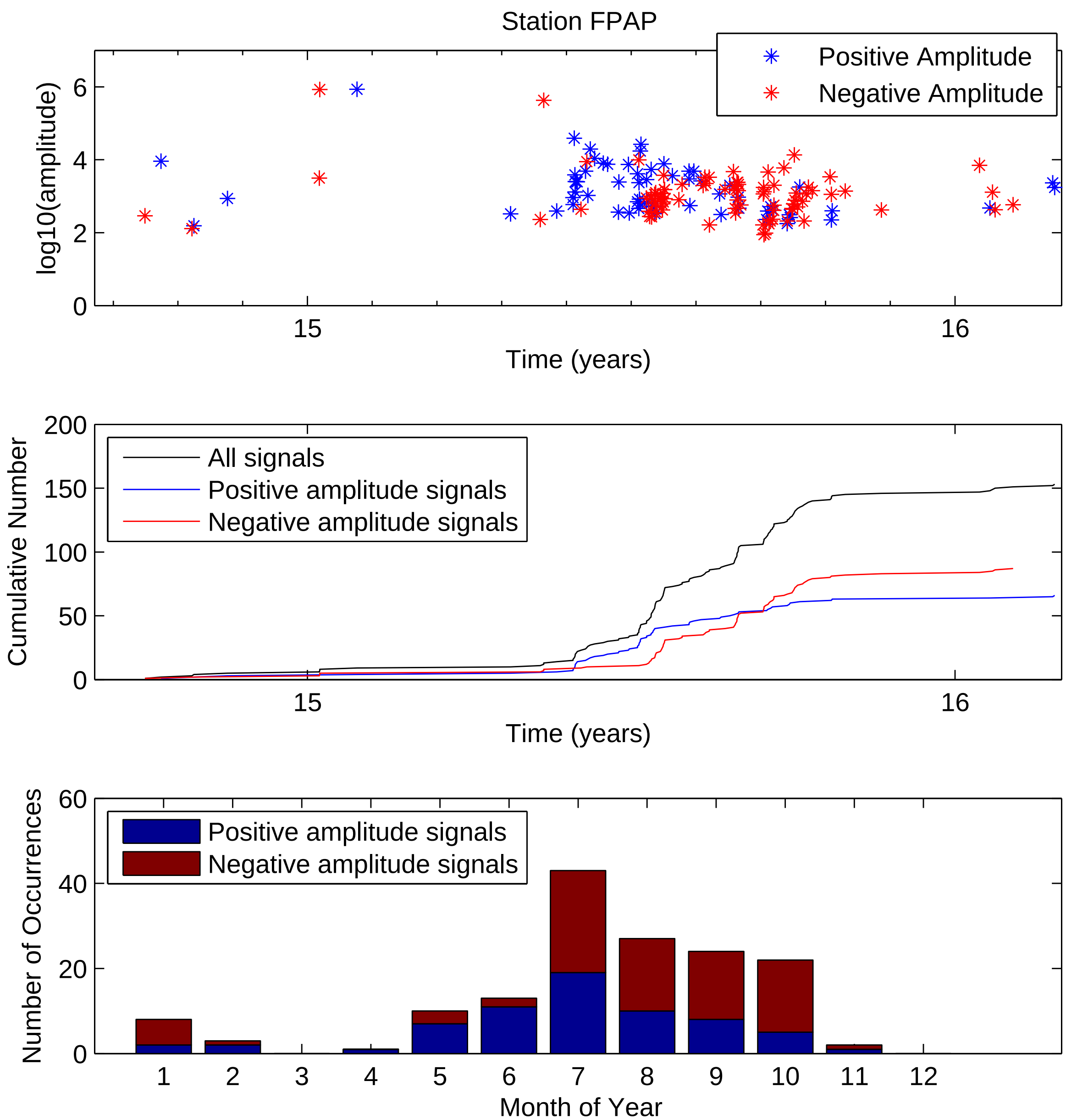


Figure C17: Clipping History at FPAP, HHZ component. Both positive and negative step-response signal are plotted. Note how, like MDM, the step-response signalhas positive polarities in early summer and negative polarities in the late summer.

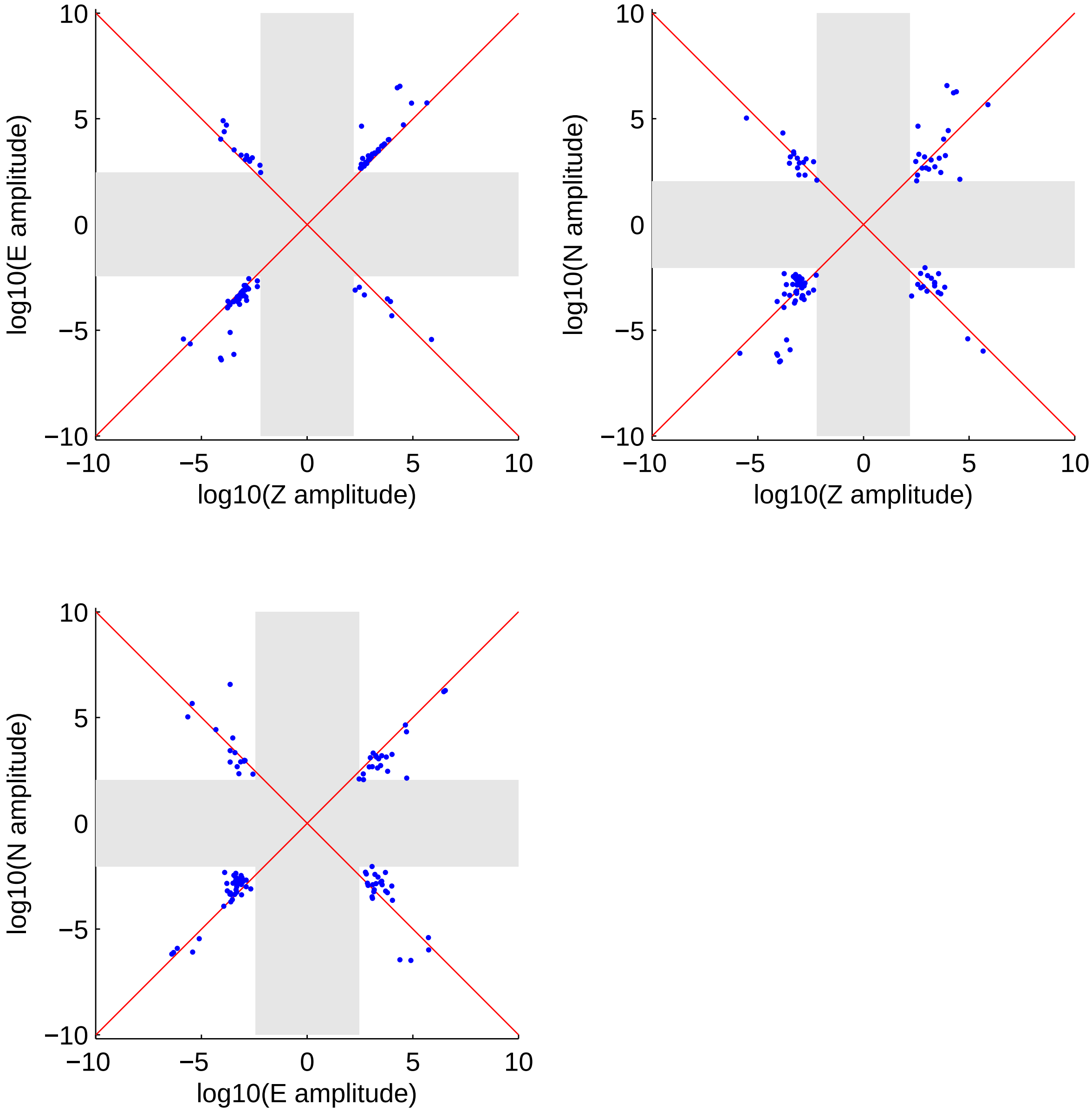


Figure C18: Relative amplitudes of the step-response signal at FPAP on all three components.

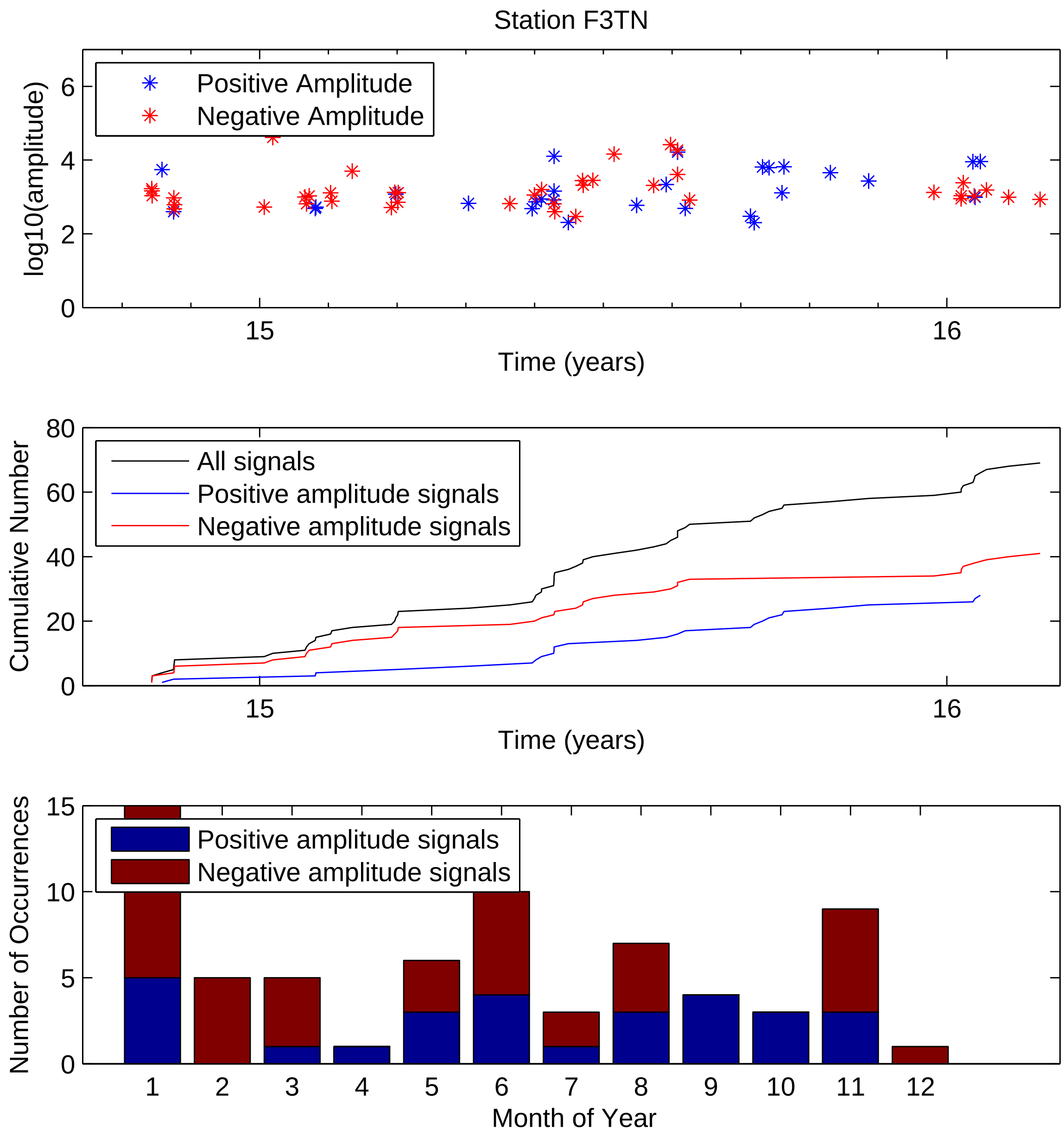


Figure C19: Clipping History at F3TN, HHZ component. Both positive and negative step-response signal are plotted.

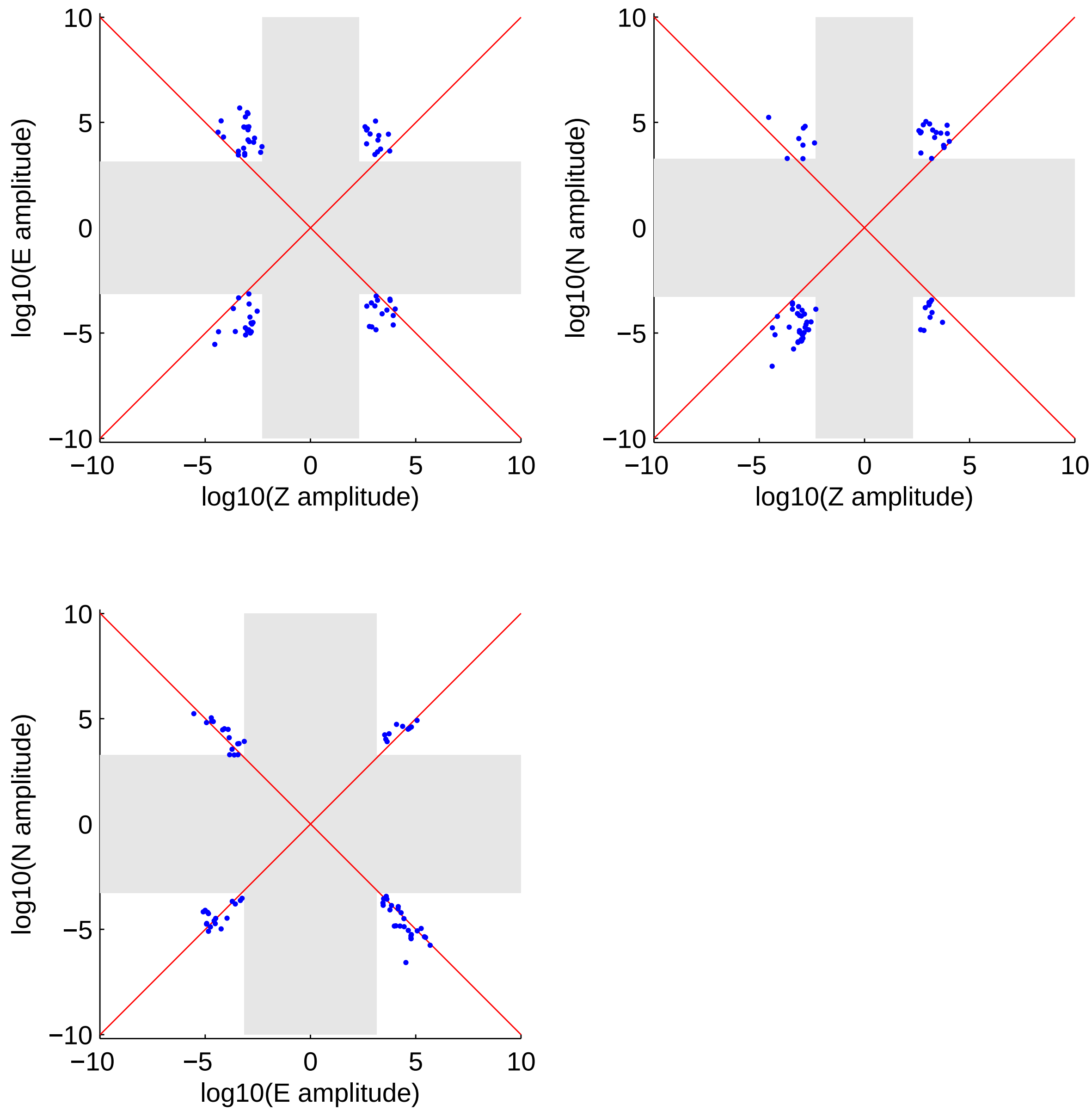


Figure C20: Relative amplitudes of the step-response signal at F3TN on all three components.

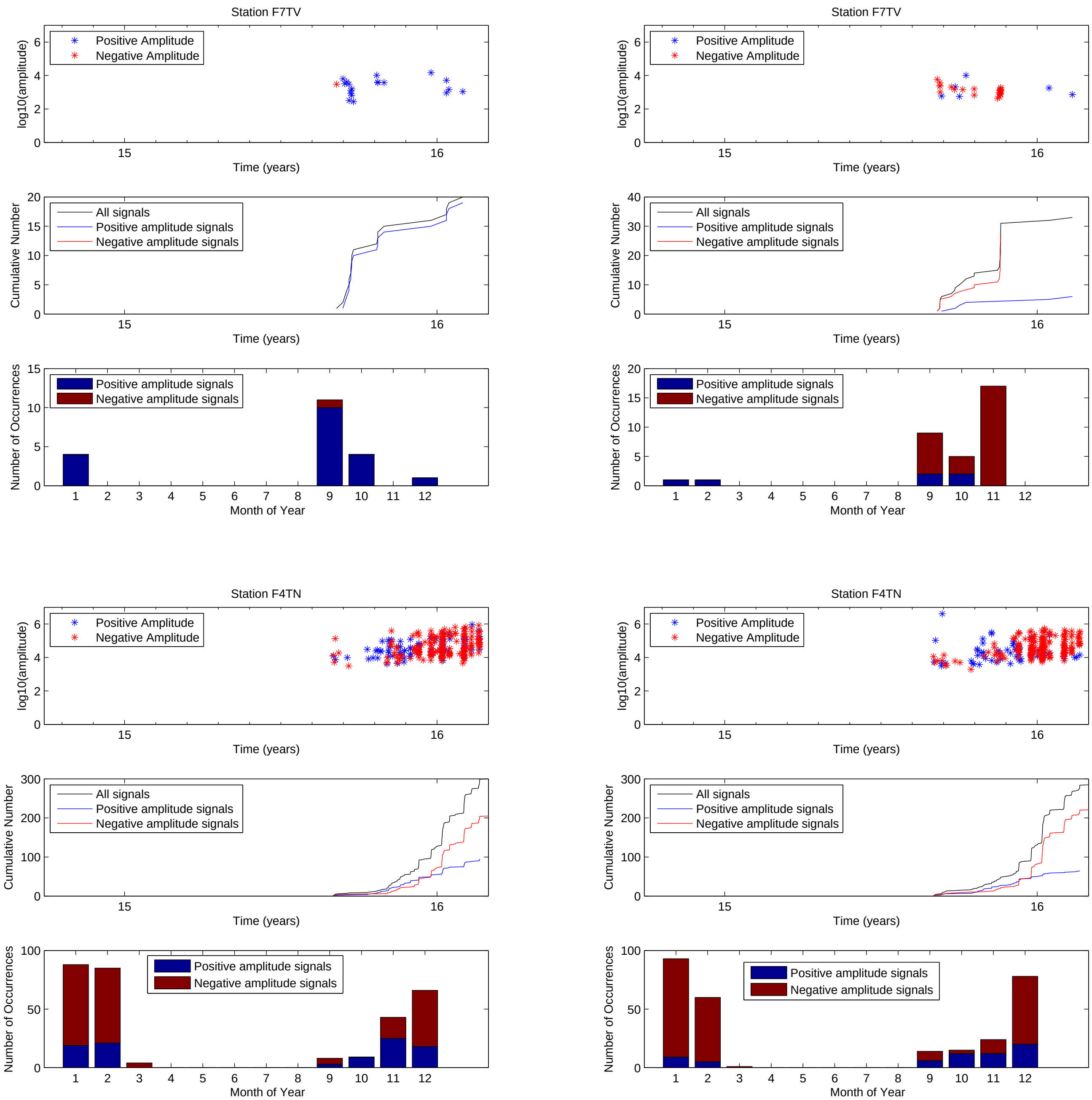


Figure C21: Shorter time series here (F7TV HHZ; F7TV HHN; F4TN HHE; F4TN HHN)

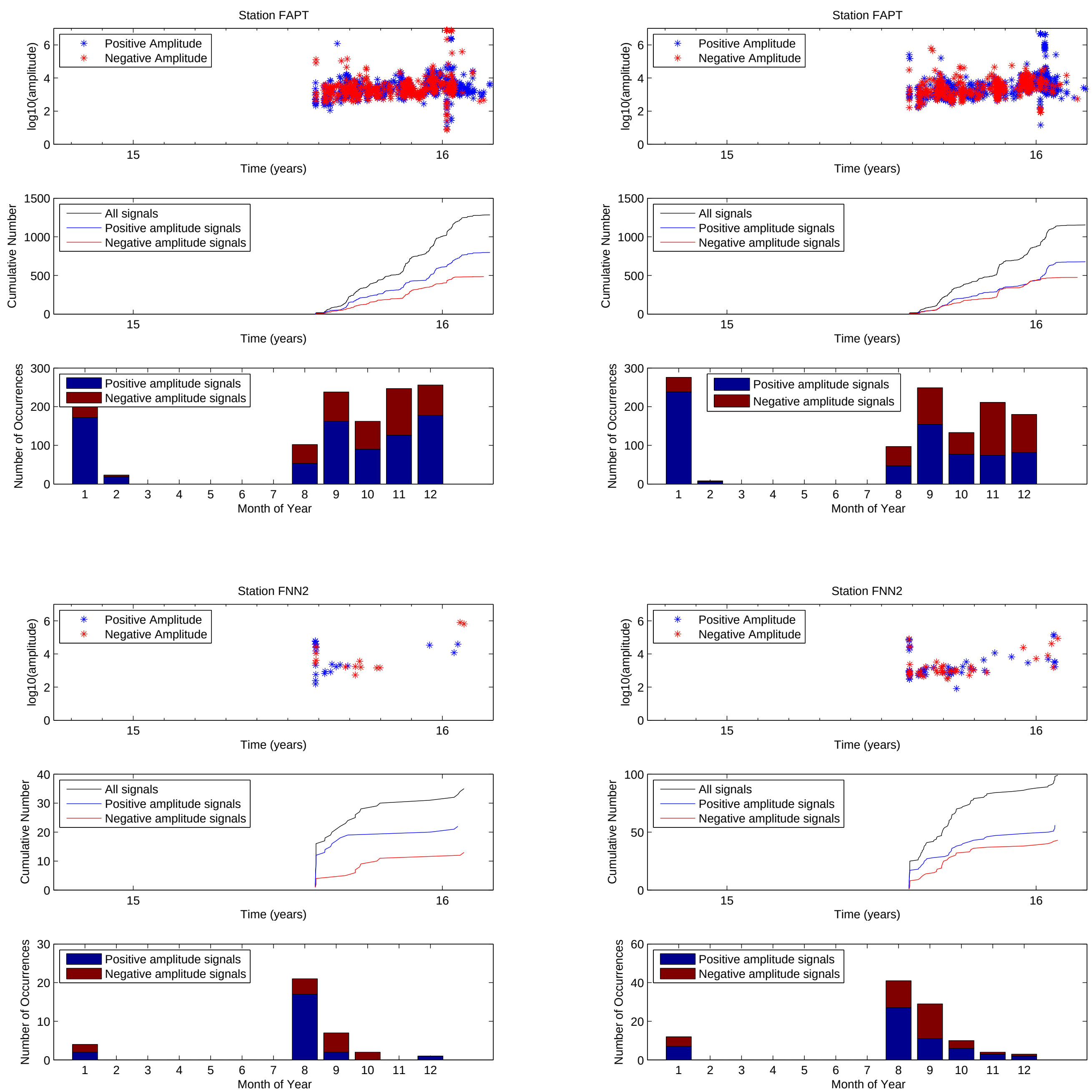


Figure C22: Shorter time series here (FAPT HHE; FAPT HHN; FNN2 HHE; FNN2 HHN)

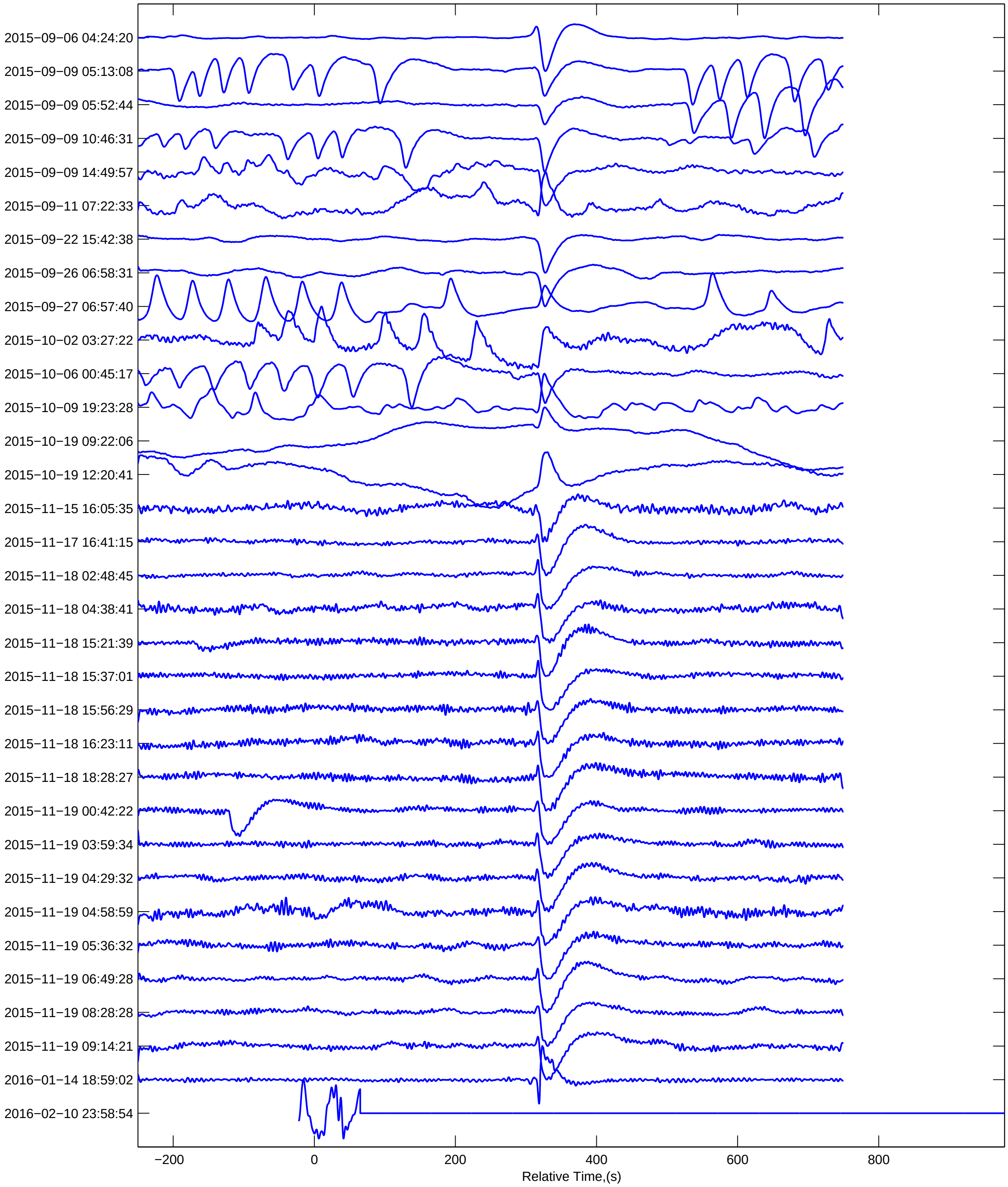


Figure C23: Low pass filter at 10 seconds of the step-response signal at F7TV HHN from matched filtering are plotted.

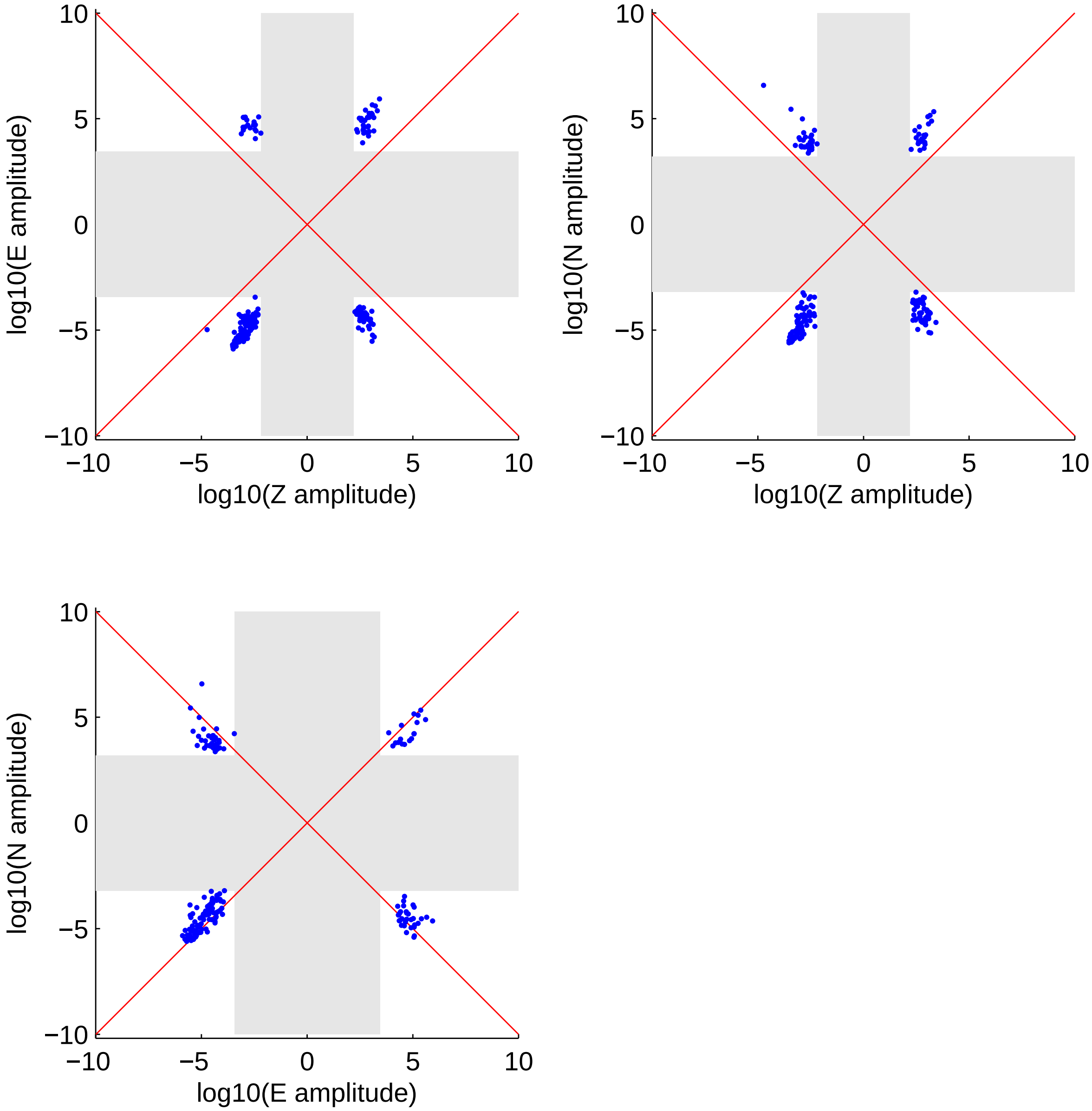


Figure C24: Relative amplitudes of the step-response signal at F4TN on all three components.

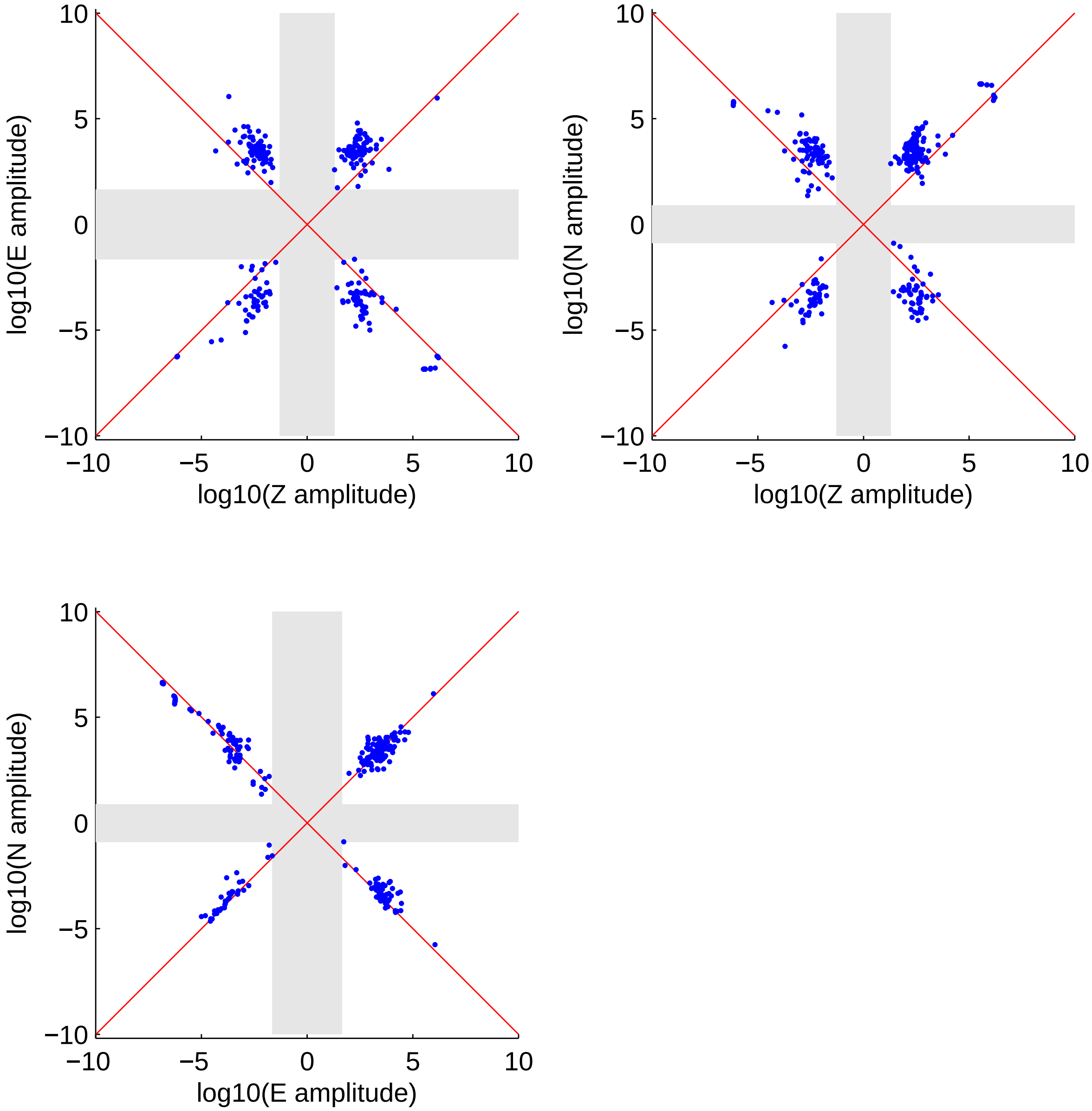


Figure C25: Relative amplitudes of the step-response signal at FAPT on all three components.

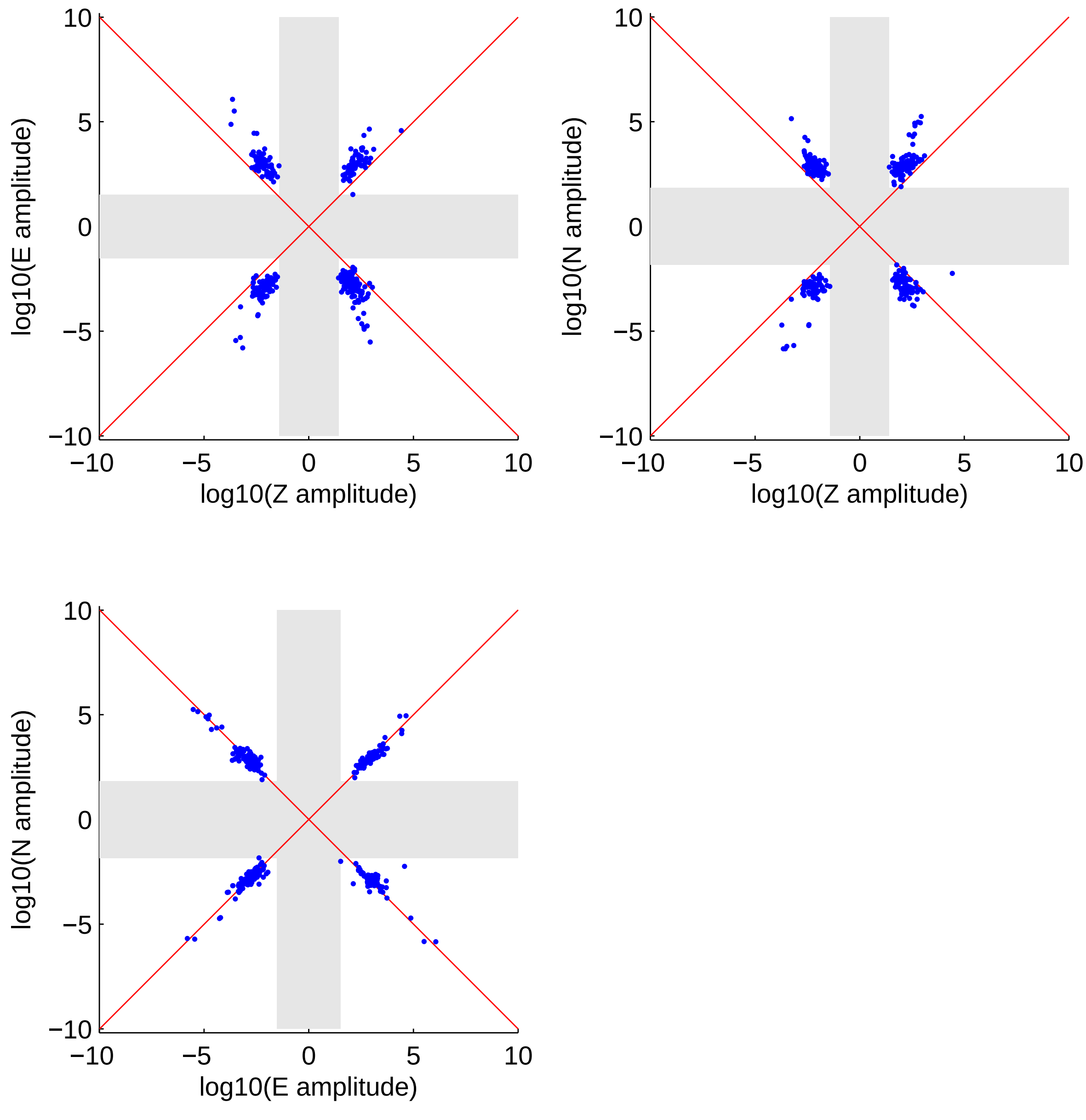


Figure C26: Relative amplitudes of the step-response signal at FTGH on all three components.

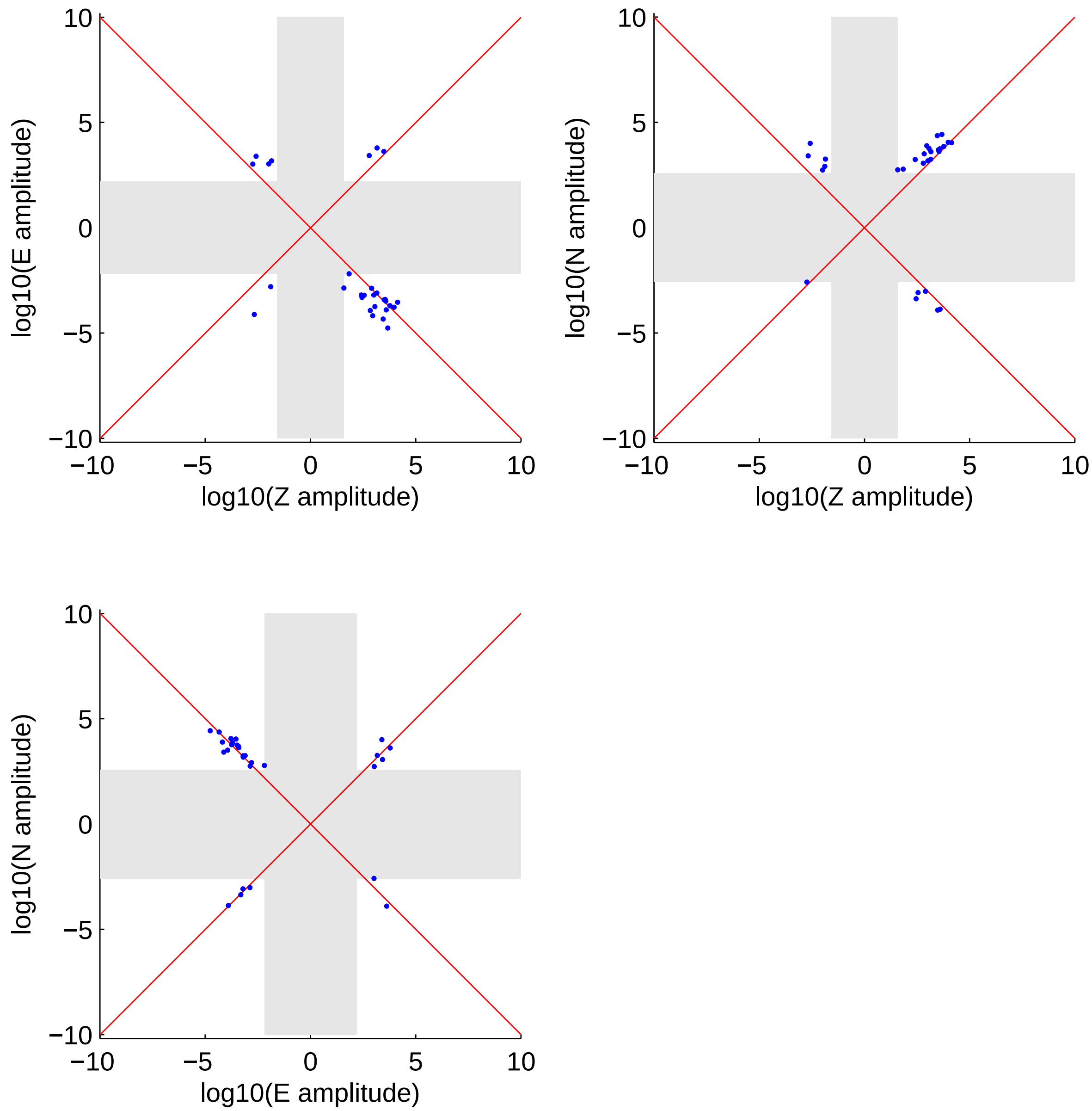


Figure C27: Relative amplitudes of the step-response signal at F7TV on all three components.

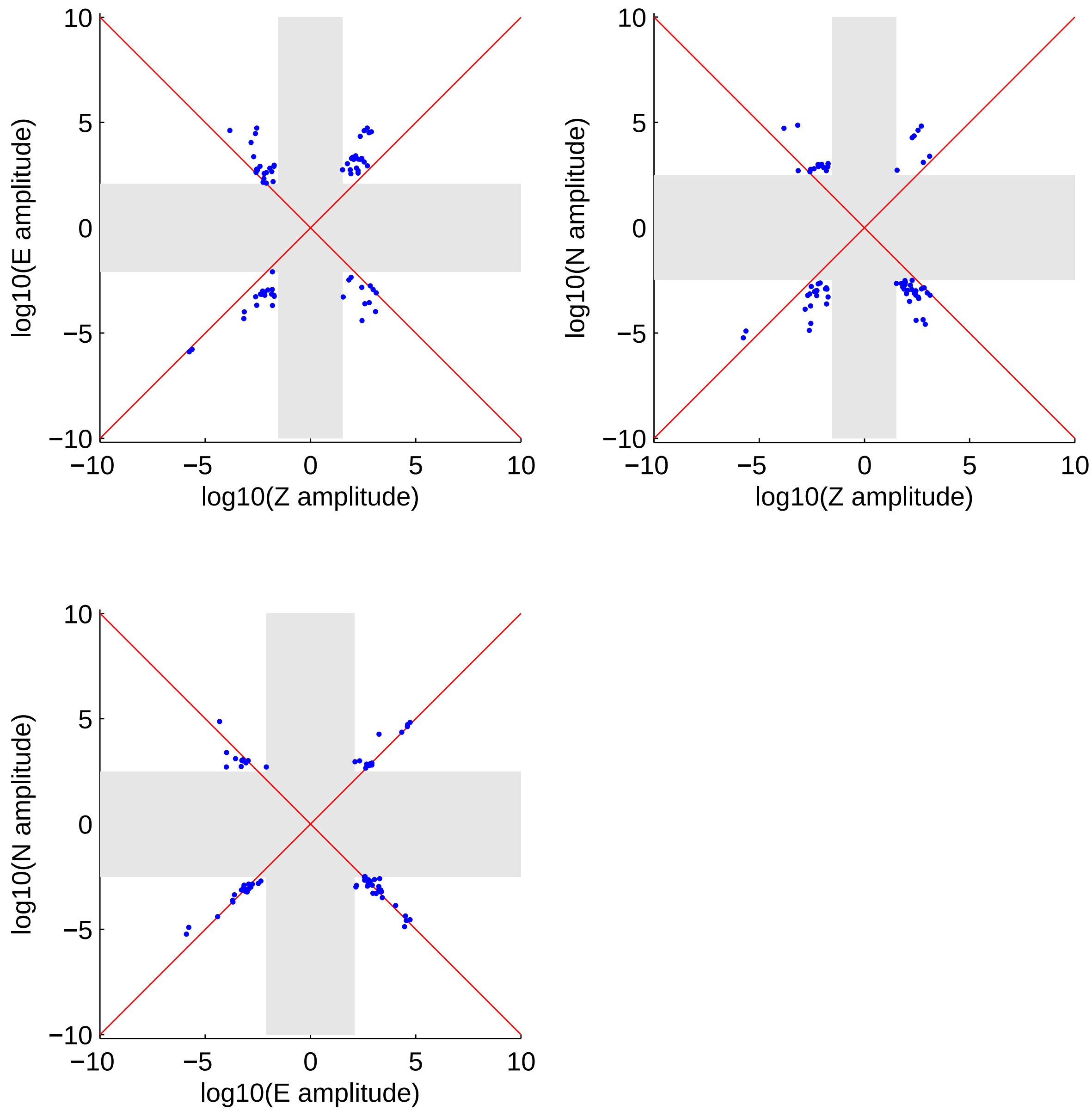


Figure C28: Relative amplitudes of the step-response signal at FNN2 on all three components.