RSEIS: Seismic Time Series Analysis in R

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Abstract

I present several new packages for analyzing seismic data for time series analysis and earthquake focal mechanisms. The packages consists of modules that 1) read in seismic waveform data in various common exchange formats, 2) display data as either event or continuous recordings and 3) performs numerous standard analyses applied to earthquake and volcano monitoring. RSEIS is designed as a research tool aimed at investigators who need to quickly assess large amounts of time-series as they are related to the spatial distribution of geologic structure and wave propagation. In addition to time series analysis, a spatial mapping program is included that ties waveforms and radiation patterns to geographical data-base and mapping programs.

1 Waveform Analysis

The waveform module of RSEIS reads in seismic data in SEGY, SAC, AH, UW and various ASCII formats. The core of these modules are a set of C programs that pass waveforms back to R and wrappers that create lists of seismograms. RSEIS was written primarily for use with continuous data, so the R code is able to sort a large database consisting of continuous data from several stations and numerous components. Each component of the waveform database may have a different sample rate and may require very different handling in terms of instrument de-convolution. Time-windows provided by the user are used to select off parts of the continuous data and rectify timing so that all traces represent identical time slots. Seismic data (binary or ASCII format) are read into R and stored in structures that provide a platform for object oriented manipulation of complex information regarding earth dynamics. In my case,

I use this package to investigate exploding volcanoes in Ecuador, Guatemala, Kamchatka and Italy.

An initial, interactive display of the seismic records is presented to the user and a large array of useful options are available for further processing by buttons that surround the main display but are on the same graphics device. Some of the routines employed in the RSEIS package are drawn from packages already available on the R distribution, for example wavelet transforms - although these have been modified to some extent to accommodate specific concerns of seismologists. Other modules, like those dealing with focal mechanisms and radiation patterns are original and will prove useful for investigators searching for patterns of stress distribution in fault regions.

2 Getting started

Start by downloading packages and installing locally in the machine being used. The packages required by RSEIS include RPMG, and Rwave, and RFOC if focal mechanisms are going to be inspected.

```
> library(RSEIS)
> library(RPMG)
> library(Rwave)
> options(continue = " ")
```

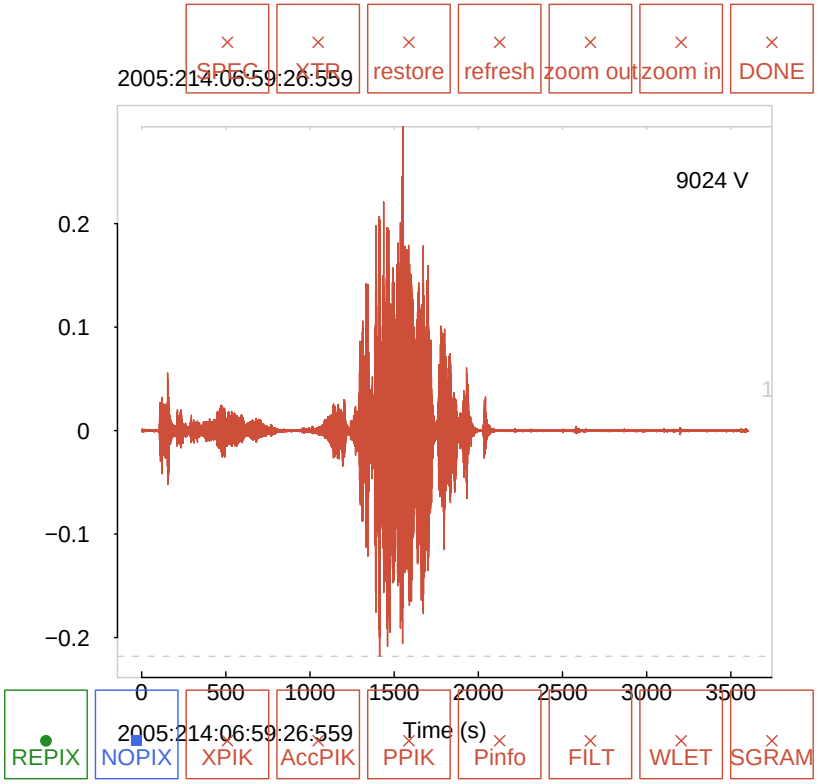
2.1 Example: Reventador Volcano Explosion

There several data set that accompany RSEIS, and these can be loaded with simple calls to data(). For example,

```
> data(KH)
> names(KH)
```

loads a structure that includes wave forms and other important meta-data about the earthquake. To see a view of this data we call the main program and display the earthquake records as they are stored in memory,

```
> STDLAB = c("DONE", "zoom in", "zoom out", "refresh", "restore",
     "XTR", "SPEC", "SGRAM", "WLET", "FILT", "Pinfo")
> PICK.GEN(KH, SHOWONLY = FALSE, STDLAB = STDLAB)
```



In this example we are showing the vertical component of an explosion of Reventador Volcano. The buttons at the top are defaults chosen from a large selection of buttons designed to be useful for analyzing seismic data. To zoom in on the trace, click twice on the trace with the left mouse button, and then terminate by clicking the middle mouse. (Clicking with the middle mouse with now left mouse clicks terminates the interactive session). When your are finished with RSEIS windows click the "Done" button to close the window. Avoid using the small "x" in the corner of the window to terminate because R does not know you have finished yet.

You can view spectra of the signal (SPEC) , spectrograms (SGRAM) and wavelet transforms (WLET). To illustrate, left click on this trace around t=1200 and t=2000, which windows the harmonic tremor part of this explosion. Click middle mouse to zoom in, or select one of the buttons at the top to analyze the time series in the (selected) sub-window. Choose *WLET* to show the wavelet transform of the harmonic tremor and important time variations of the volcano during eruption.

The PICK.GEN program is normally run in interactive mode. In that case, once it is started R is waiting for the user to select traces and buttons for activating a variety of programs and analysis routines. Selection of traces is

accomplished by clicking on the traces, one or more times depending on what is desired. The program needs to know what to do with the selections once that process is over, usually by clicking on a button around the perimeter of the screen. In the next example we will restrict the analysis to just the vertical motion seismic data, at least for now. If you expand the screen, you can re-arrange the buttons by clicking on the refresh button.

PICK.GEN is a general analysis program designed for earthquake studies. It uses the *R*eally Poor Man's GUI to navigate between seismic traces and various analysis procedures. Once the program is started it waits for the user to select on the screen a variety of operations, determined by the user via the button selection, STDLAB. In the main event loop, the user may click on the screen with the left mouse button to hi-light specific traces or windows in the panel. The right mouse click terminates the clicking sequence and a decision is made on what to do, unless a button has been clicked. Generally, one click selects a specific trace, two clicks specify a trace and window in that trace. If the clicking is terminated immediately, before a left mouse is clicked, the program stops and returns NULL. If it terminates after 1 click, a refresh screen command is produced. If there are two or more clicks, and no button is pressed, the last two clicks are used to zoom in the window.

If a button is clicked, however, the program uses the number of clicks to determine which traces to process and what to do. For example, if the "PickWin" button is selected, a new PICK.GEN is spawned where the program gathers all the components for that station, Usually Vertical, North and East, although in the presence of acoustic channels they will also be displayed. The new window is called with a new set of Buttons set up specifically for picking the P, S and Acoustic arrivals. Once that window is finished, focus reverts to the main window and the new picks are registered. Selecting the "SavePF" button will save the new picks to a file for later use.

As another example, if the user clicks twice in a trace panel, and then selects the WLet Button, a wavelet transform of the selected time window is calculated and a special new screen is exposed where the user is now focused until that session is finished by clicking "Done".

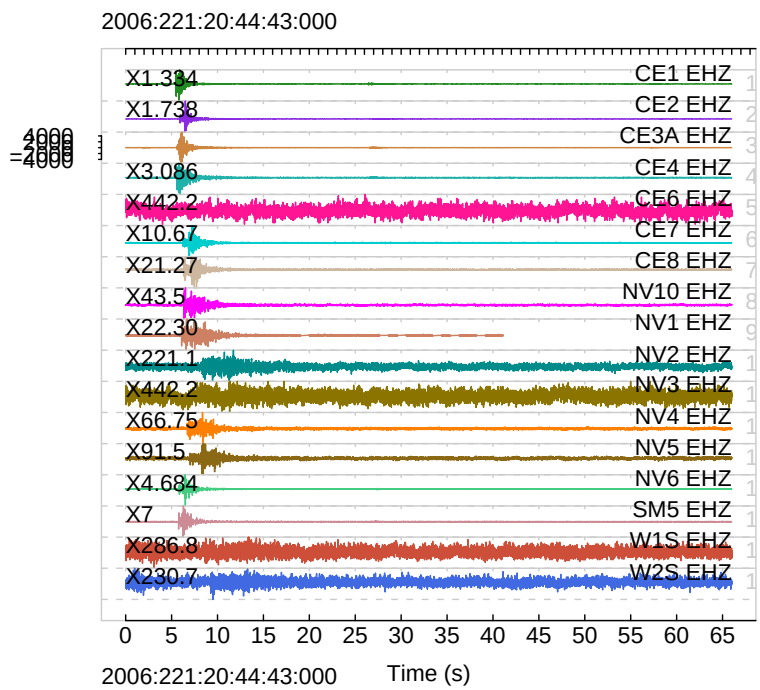
Each Button has different properties based on the requirements for that process. Some buttons expect more than one click to operate properly, others are simple buttons that control the look and feel of the panel. For example, the "restore" button reverts the panel to its original time window. It can be pressed any time and the window will redraw and resize. Each button includes a small set of instructions designed to accomplish a specific task. There are many buttons currently defined, some described below, and there is mechanism for users to make their own on the fly.

2.2 Example: Coso Geothermal Event

```
> data(GH)
> numstas = length(GH$STNS)
```

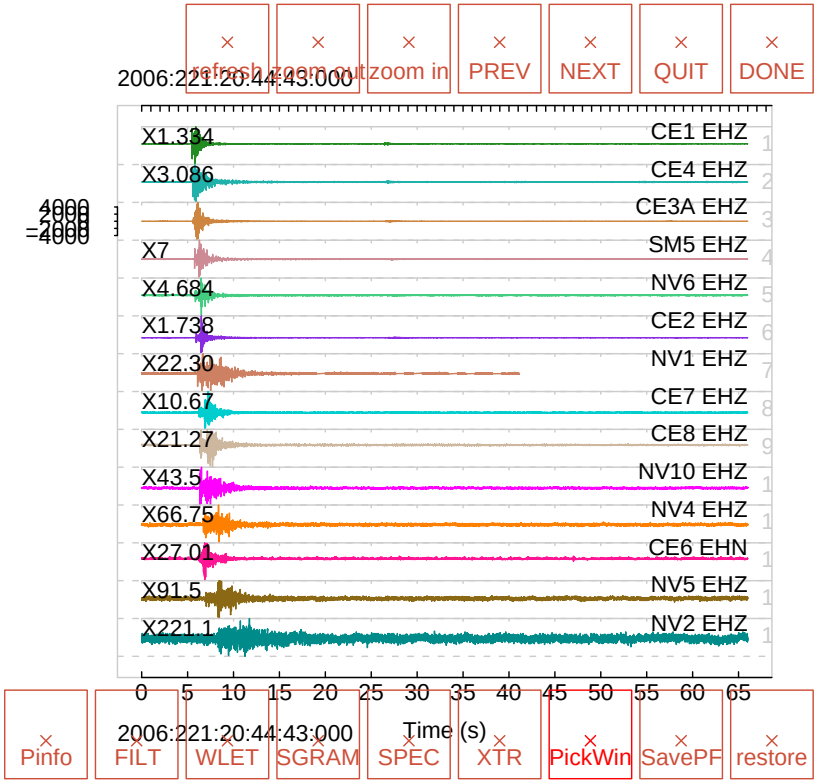
In this example, taken from the geothermal field at Coso, California, there are 49 stations, most of which have three components (Vertical, North and East), although there are a couple of stations that are missing some of the components. This situation is not atypical of earthquake seismic data recorded in the field. If we show only the vertical component traces, The plot is more manageable and easier to view:

```
> verts = which(GH$COMPS == "V")
> STDLAB = c("DONE", "QUIT", "NEXT", "PREV", "zoom in", "zoom out",
     "refresh", "restore", "SavePF", "PickWin", "XTR", "SPEC",
     "SGRAM", "WLET", "FILT", "Pinfo", "WINFO", "PTS", "YPIX",
     "WPIX")
> PICK.GEN(GH, sel = verts, STDLAB = STDLAB, SHOWONLY = TRUE)
```



We see that the stations here are 'mixed up', i.e. arriving at different times.

```
> vertord = getvertsorder(GH$pickfile, GH)
> PICK.GEN(GH, sel = vertord$sel, STDLAB = STDLAB, SHOWONLY = FALSE)
```



A seismic event is usually stored as a combination of waveform information and meta-date associated with the phase arrivals. Phase arrivals are commonly called "picks" since and analyst had to pick the arrival times from a representation of the seismic signals, either on a computer or on a paper record. The picks are stored in RSEIS in a list structure called pickfile which is an optional component of the name waveform structure. The pickfile structure is a list comprising several sub-lists with important information associated with stations and the event (earthquake) source.

```
> names(GH$pickfile)

 [1] "PF"       "AC"       "LOC"      "MC"       "STAS"     "LIP"
 [7] "E"        "F"        "filename" "UWFILEID" "comments" "OSTAS"
[13] "H"        "N"
```

For now we consider the most relevant meta-data,

```
> names(GH$pickfile$STAS)

 [1] "tag"   "name"  "comp"  "c3"    "phase" "sec"   "err"   "pol"   "flg"
[10] "res"   "lat"   "lon"   "z"
```

which is a list of vectors, one for each meta-datum and one element each for each station that has meta-data. We see in this example there are a couple of picks per station, some picks are on the vertical components and some are on the North component or East, there are P and S-wave phase picks.

```
> data.frame(cbind(name = GH$pickfile$STAS$name, comp = GH$pickfile$STAS$comp,
     phase = GH$pickfile$STAS$phase, time = GH$pickfile$STAS$sec,
     lat = GH$pickfile$STAS$lat, lon = GH$pickfile$STAS$lon))
```

```
   name comp phase   time       lat         lon
1   CE1    V     P 48.476   36.0131   -117.8025
2   CE4    V     P 48.532   35.9998   -117.8023
3  CE3A    V     P   48.6   36.0145   -117.8198
4   SM5    V     P  48.74  35.99965 -117.830261
5   NV6    V     P 48.812   35.9823   -117.8076
6   CE2    V     P 48.876   36.0337   -117.7883
7   NV1    V     P 49.072   35.9827   -117.7649
8   CE7    V     P 49.176    36.053   -117.8046
9  NV10    V     P 49.312 35.999056 -117.745194
10  CE8    V     P 49.292   36.0512   -117.8387
11  NV4    V     P 49.688   36.0477   -117.7403
12  NV5    V     P 49.996   36.0839   -117.7536
13  NV2    V     P 51.292   36.0255   -117.6213
14  CE1    N     S 48.752   36.0131   -117.8025
15  CE4    N     S 48.872   35.9998   -117.8023
16 CE3A    N     S 48.908   36.0145   -117.8198
17  SM5    N     S 49.216  35.99965 -117.830261
18  NV6    N     S 49.372   35.9823   -117.8076
19  CE2    N     S 49.444   36.0337   -117.7883
20  CE6    N     S 49.704 36.033665 -117.772726
21  CE7    N     S 49.876    36.053   -117.8046
22  CE8    E     S 50.316   36.0512   -117.8387
23  NV4    N     S 50.984   36.0477   -117.7403
24  NV5    N     S  51.28   36.0839   -117.7536
```

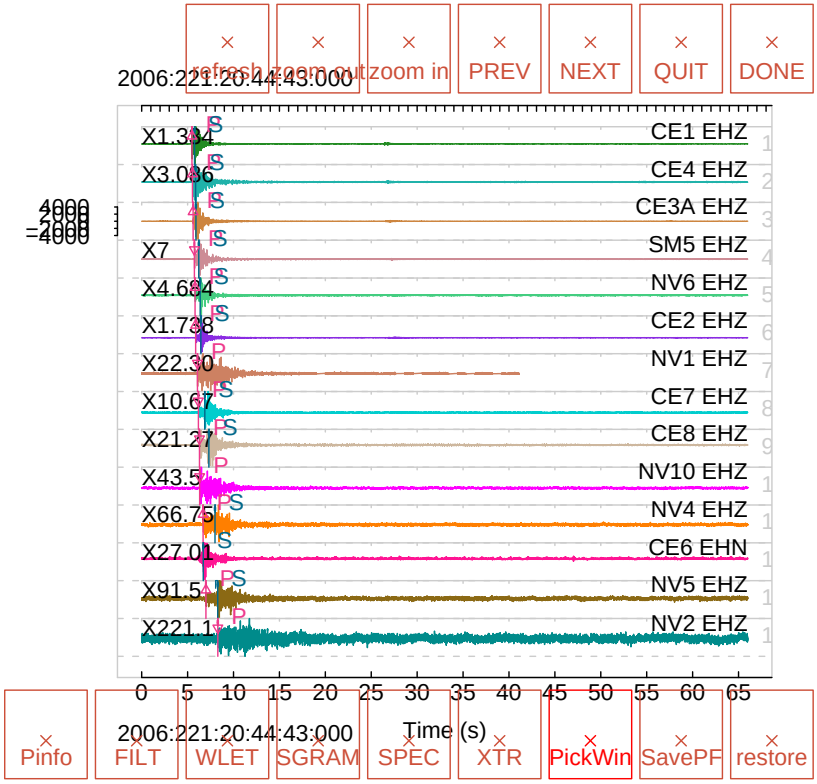
We also store event information:

```
> names(GH$pickfile$LOC)
```

```
 [1] "yr"     "mo"     "dom"    "hr"     "mi"     "sec"    "jd"     "lat"
 [9] "lon"    "z"      "mag"    "gap"    "delta"  "rms"    "hozerr"
```

Using this information we can associate the p-pick with the waveforms, match the timing information and plot together. finally we add the picks to the section:

```
> apx = uwpfile2ypx(GH$pickfile)
> PICK.GEN(GH, sel = vertord$sel, APIX = apx, STDLAB = STDLAB,
     SHOWONLY = FALSE, velfile = VELMOD1D, )
```



Brief documentation for buttons in the PICK.GEN program can be seen by calling the documentation function, either for a specific button

```
> PICK.DOC("WLET")

[1] "WLET: wavelet analysis"
```

or for all possible buttons.

```
> PICK.DOC()

$DONE
[1] "DONE: Close Window and Finish"

$MARK
[1] "MARK Mark a Specific Trace"

$restore
[1] "restore: restore the window traces to full screen"

$`zoom out`
```

```
[1] "zoom out: Zoom out by a percent"

$`zoom in`
[1] "zoom in: Zoom in  by a percent"

$Left
[1] "Left: Shift Left by a percent"

$Right
[1] "Right: Shift Right by a percent"

$SCALE
[1] "SCALE: Toggle: SCALE by trace or scale by Window"

$Postscript
[1] "Postscript: create a Postscript file"

$AUTOP
[1] "AUTOP: Automatic picking on one trace"

$AUTOPALL
[1] "AUTOPALL: Automatic picking on all traces in window"

$DETECT
[1] "DETECT: signal detection using automated picking"

$XTR
[1] "XTR: extract a single trace and return at end of session"

$SIG
[1] "SIG: pulse analysis (chugging)"

$SPEC.old
[1] "SPEC.old: "

$SPEC
[1] "SPEC: MTM spectrum in separate window with options"

$SGRAM
[1] "SGRAM: spectrogram window"

$WLET
[1] "WLET: wavelet analysis"

$FILT
[1] "FILT: filter a trace with a set of choices"
```

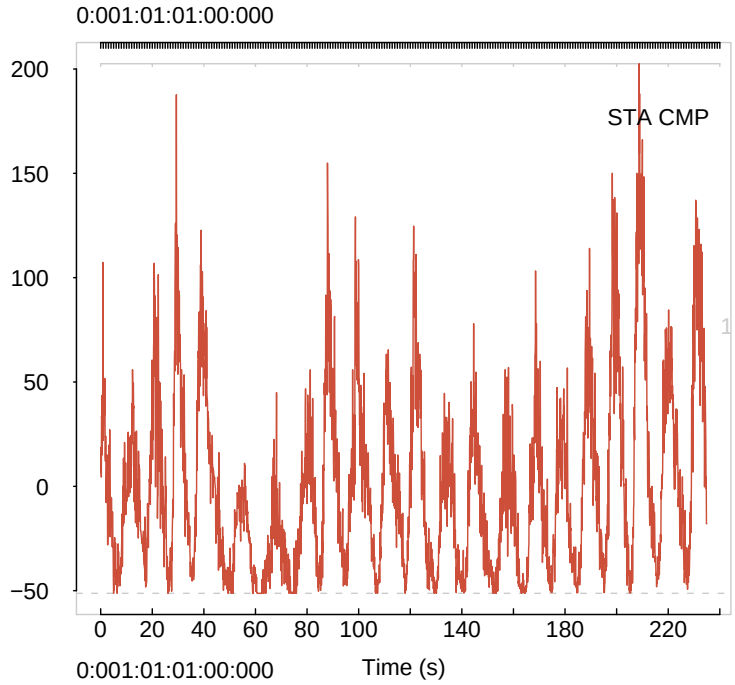
```
$BRUNE
[1] "BRUNE: do brune model analysis for short period data, save meta-data"

$DETAIL
[1] "DETAIL: pick details of first arrivals and save meta data"

$PTS
[1] "PTS: toggle points option, plot each point in time series"

$MMARKS
[1] "MMARKS: Unused"

$PMOT
[1] "PMOT: particle motion hodogram, must have three components in the window"

$STERNET
[1] "STERNET: plot an equal area steronet with the points of the 3-comp seismogram"

$GTAZI
[1] "GTAZI: SVD particle motion in windows (needs 3Comp seis)"

$ENVLP
[1] "ENVLP: get envelope of a windowed time series"

$Pinfo
[1] "Pinfo: pick information"

$XCOR
[1] "XCOR: cross correlation of traces"

$PHLAG
[1] "PHLAG: calculate the phase lag between traces based on cross spectrum"

$YPIX
[1] "YPIX: Y picking"

$WPIX
[1] "WPIX: Window picks"

$EDIX
[1] "EDIX: edit window picks"

$NOPIX
[1] "NOPIX: erase all previous picks"
```

```
$REPIX
[1] "REPIX: restore previously erased picks"

$FLIP
[1] "FLIP: Flip polarity of traces"

$`3COMP`
[1] "3COMP: find all componenets of this station and plot in separate window"

$DOC
[1] "DOC: print Documentation"
```

2.3 Example: SunSpots

One standard data set included in the R Distribution is the sunspot data. As an example of RSEIS we can read this time series in and plot it using the same code introduced above.

```
> data(sunspots)
> ES = prep1wig(wig = sunspots, dt = 1/12, sta = "STA", comp = "CMP",
     units = "UNITS")
> EH = prepSEIS(ES)
> STDLAB = c("DONE", "zoom in", "zoom out", "refresh", "restore",
     "XTR", "SPEC", "SGRAM", "WLET", "FILT", "Pinfo")
> xx = PICK.GEN(EH, STDLAB = STDLAB, SHOWONLY = TRUE)
```



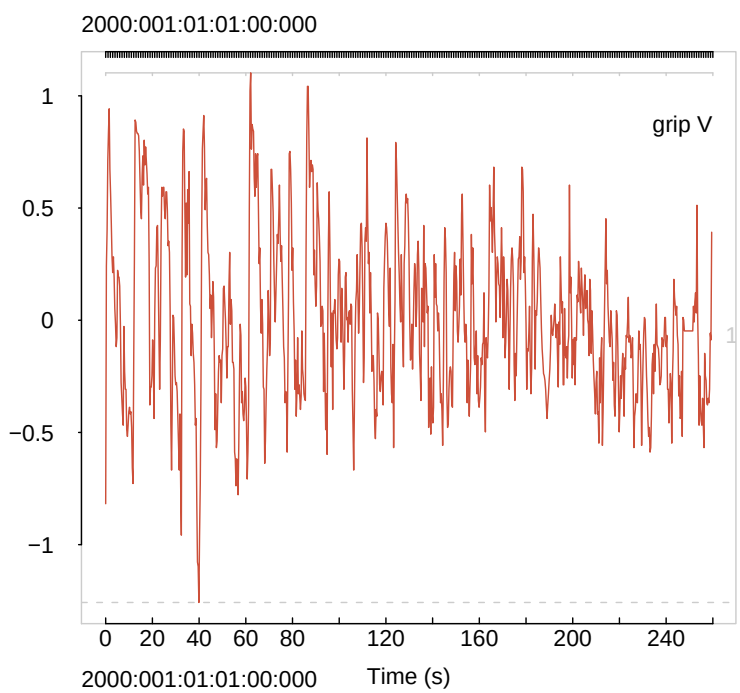

```
> a = list(y = EH$JSTR[[1]], dt = EH$dt[1])
> Mspec = mtapspec(a$y, a$dt, klen = 1024, MTP = list(kind = 1,
    nwin = 5, npi = 3, inorm = 0))
> f = Mspec$freq
> amp = Mspec$spec[1:length(f)]
> ma = amp
> displ = ma
> f1 = 0.01
> f2 = 1/(2 * EH$dt[1])
> flag = f >= f1 & f <= f2
> plxy = "xy"
> plot(range(f[flag]), range(displ[flag]), type = "n", log = plxy,
    axes = FALSE, xlab = "Hz", ylab = "Spec")
> lines(f[flag], displ[flag], col = 1, lty = 1)
> axis(2, las = 2)
> axis(1)
> box()
> L = list()
> L$x = c(0.0939105803154482, 0.183351679178275, 0.350333785192083)
```

```
> L$y = c(31166.8951116052, 7536.36156151748, 2370.29538151056)
> abline(v = L$x, lty = 2, col = grey(0.8))
> text(L$x, rep(max(range(displ[flag])), length(L$x)), labels = round((1/L$x)),
    xpd = TRUE, srt = 45, adj = c(0, 0))
```

2.4 Example: Climate Change

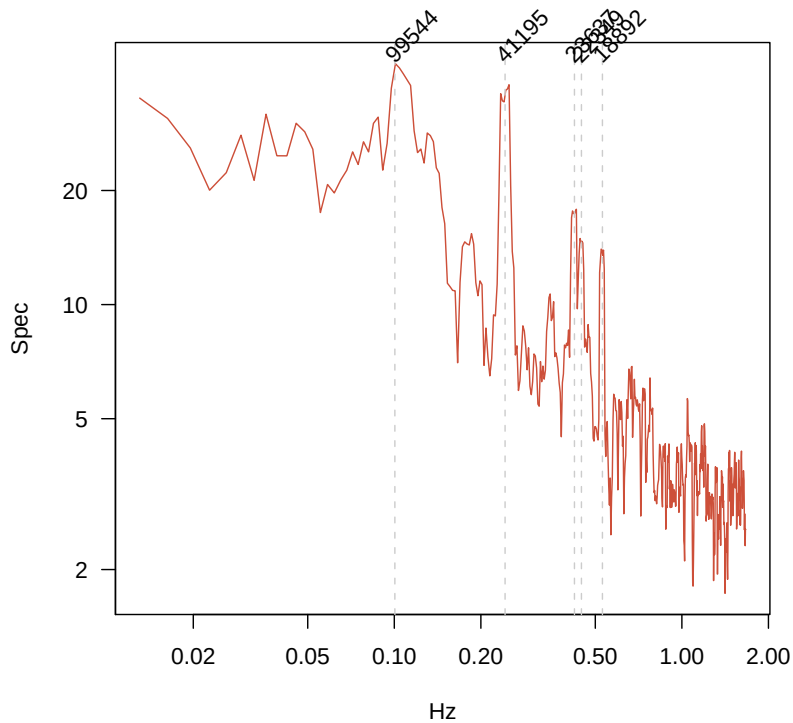
As a final example showing how RSEIS might be used for arbitrary time series, unrelated to seismic data, consider the famous Delta-O18 time series. By windowing the time sereis and looking at the spectrum one can immediately see the Milankovitch cycles at (approximately) 100K, 41K and 20K periods.

```
> data(OH)
> xx = PICK.GEN(OH, sel = which(OH$COMPS == "V"), STDLAB = STDLAB,
    SHOWONLY = TRUE)
```



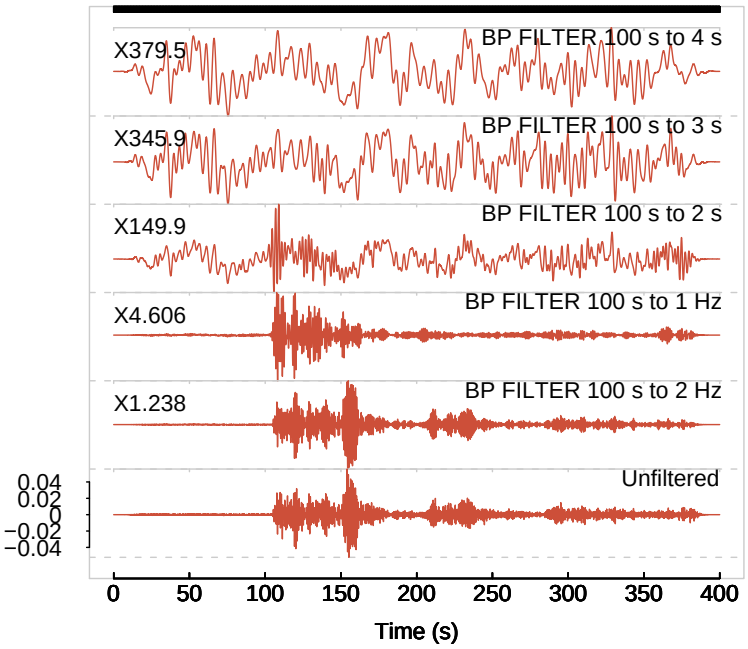

```
> a = list(y = OH$JSTR[[1]], dt = OH$dt[1])
> Mspec = mtapspec(a$y, a$dt, klen = 1024, MTP = list(kind = 1,
    nwin = 5, npi = 3, inorm = 0))
> f = Mspec$freq
```

```
> amp = Mspec$spec[1:length(f)]
> ma = amp
> displ = ma
> f1 = 0.01
> f2 = 1/(2 * EH$dt[1])
> flag = f >= f1 & f <= f2
> plxy = "xy"
> plot(range(f[flag]), range(displ[flag]), type = "n", log = plxy,
    axes = FALSE, xlab = "Hz", ylab = "Spec")
> lines(f[flag], displ[flag], col = 1, lty = 1)
> axis(2, las = 2)
> axis(1)
> box()
> u = par("usr")
> L = list()
> L$x = c(0.242745864538716, 0.423063797271721, 0.447439169221329,
    0.529320129815409, 0.100457805181183)
> L$y = c(37.4392793655756, 19.0231348719557, 15.6564640841027,
    15.0862607475168, 40.6986171075992)
> abline(v = L$x, lty = 2, col = grey(0.8))
> text(L$x, rep(max(range(displ[flag])), length(L$x)), labels = round(10000 *
    (1/L$x)), xpd = TRUE, srt = 45, adj = c(0, 0))
```



To illustrate the effects of comparing numerous filters to a specific volcanic explosions event,

```
> data(KH)
> dt = KH$dt[1]
> y = KH$JSTR[[1]]
> y = y[1:50000]
> y = y - mean(y)
> x = seq(from = 0, by = dt, length = length(y))
> fl = rep(1/100, 5)
> fh = 1/c(4, 3, 2, 1, 0.5)
> FILT.spread(x, y, dt, fl = fl, fh = fh, sfact = 1, WIN = NULL,
    PLOT = TRUE, TIT = NULL, TAPER = 0.05, POSTTAPER = 0.1)
```


X379.5
BP FILTER 100 s to 4 s
X345.9
BP FILTER 100 s to 3 s
X149.9
BP FILTER 100 s to 2 s
X4.606
BP FILTER 100 s to 1 Hz
X1.238
BP FILTER 100 s to 2 Hz
Unfiltered
0.04
0.02
0
−0.02
−0.04
0
50
100
150
200
250
300
350
400
Time (s)