ENVELOPE 5.3

Signal-envelope estimation from unevenly spaced paleoclimatic time series

Manual (September 2004)

This program has been placed in the public domain. You should feel free to pass the program to your colleagues as long as you do not charge for it and you include each of the original files in unaltered form. The latest version of the program can be found at the following web site: `http://www.palmod.uni-bremen.de/~mschulz/`

The program has been tested, though not rigorously, and is correct to the best of my knowledge. If you find any errors or have any suggestions, I would appreciate if you would let me know:

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ENVELOPE was used in the following paper; please consider to cite this paper if you use the program to analyze your data for publications:

Schulz, M., Berger, W. H., Sarnthein, M. and Grootes, P. M. 1999: Amplitude variations of 1470-year climate oscillations during the last 100,000 years linked to fluctuations of continental ice mass. *Geophys. Res. Lett.*, **26**, 3385-3388.

DISCLAIMER OF WARRANTY

1. Program Description

ENVELOPE estimates temporal changes in amplitude (= signal envelope) and phase of a signal component of given period `filtper` using a modified version of the harmonic-filtering algorithm of Ferraz-Mello (1981), which fits a sinusoidal wave $s(t)$ with amplitude a, signal frequency $f_s = 1/$`filtper` and phase Φ, i.e.,

$$s(t) = a \sin(2\pi f_s t + \Phi)$$

to a time series by means of least-squares (t denotes time). This method can process unevenly spaced time series directly, without the requirement of interpolation. The time-series model (1) is extended to allow for temporal variations in amplitude and phase:

$$s(t) = a(t) \sin(2\pi f_s t + \Phi(t)).$$

To obtain time-dependent estimates $a(t)$, $\Phi(t)$, and signal $s(t)$ the time series is analyzed within a moving window of width `Tseg`:

$$\texttt{Tseg} = \texttt{wfac} \times \texttt{filtper},$$

where `wfac` is a width-factor and `filtper` denotes the signal periodicity of interest.

The window is shifted consecutively by one data point along the time axis of the input time series. Each “window segment” is linearly detrended and can be tapered prior to the estimation, i.e., fitting of the sinusoid to the data within the window. The resulting amplitude and phase of the best-fit sinusoid are saved *vs.* the average of the observation times within the current segment. Note that in case of unevenly spaced time series, segments are of equal duration (`Tseg`) but do not necessarily contain the same number of data points.

The selection of `wfac` will be a compromise between minimizing the statistical error (large wfac required) and maximizing the temporal resolution (small `wfac` required). Depending on the signal-to-noise ratio, typical values for `wfac` are in the range 3 to 5. Note that due to the finite window width, a step-like increase in signal amplitude appears `wfac` × `filtper` wide (cf. Mudelsee and Schulz, 1997 and example below).

Another effect of the final window width is that signal components with periodicities below and above `filtper` will affect the estimation. A measure of this bias is the half-amplitude bandwidth (*BW*), which is approximately given by:

$$BW = \beta / (\texttt{wfac} \times \texttt{filtper})$$

where the factor β depends on the applied taper:

Taper	β
Rectangular	1.14
Welch	1.54
Hanning	2.09
Triangular	1.70
Blackmann Harris	2.38

2. Installation/Contents of the ZIP Archive

Copy the ZIP-archive to an empty directory and unpack it, e.g. by entering the following command at the DOS prompt:

```
pkunzip envelope53.zip
```

This should result in the following files in the ENVELOPE directory:

`envelope53.exe`	Executable file
`envelope5.cfg`	Configuration file
`usage53.pdf`	Manual (this file)
`example.cfg`	Configuration file for example
`100k_jmp.dat`	Example data file
`100k_jmp.res`	Example results

3. Running ENVELOPE

ENVELOPE requires Win9x, NT, 2000 or above and a Pentium III or better CPU (versions for older CPUs are available upon request). All program options and parameters are set in a configuration file that is passed to ENVELOPE via the command line. An example configuration file (`envelope5.cfg`) is included. To run the program, open a DOS-Box, change to the ENVELOPE directory and enter a command line of the following structure:

```
envelope53 myfile.cfg
```

3.1 Configuration File Format

The configuration file is in ASCII format and can be edited with any text editor. It is recommended that you copy the original `envelope5.cfg` file to a working file in order to have a backup. The configuration file contains a Fortran 90 namelist, e.g.:

```
&cfg
    fnin = 'c:/data/foo.dat',
   fnout = 'c:/data/foo.plt',
 filtper = 100.0,
    wfac = 4.0,
  unwrap = .true.,
    iwin = 2
/
```

(If you are unfamiliar with namelists, please note the following:

- a string `&cfg` in the first line and a single slash in the last line
- each data line, except the last, ends with a comma
- filenames must be enclosed in '...' or " ..."
- directories are marked by a normal slash and NOT by the usual DOS backslash
- namelist entries can be in lower or upper case
- comment lines are marked by a leading "!")

The parameters in the namelist have the following meaning:

`fnin` Input filename (full path!) with time series data.
`fnout` Results are written to this file (ASCII-formatted GNUPLOT script file).
`filtper` Period of interest (same time unit as input data).

`wfac` Window-width factor (typical values 3-5; fractional values, e.g. 3.5, are allowed).

`unwrap` Toggle phase unwrapping:

if set to `T`: try to remove 360° phase jumps (default),

if set to `F`: save raw phase estimates.

`iwin` Taper-type identifier:

0: Rectangular (= no taper)

1: Welch

2: Hanning

3: Triangular

4: Blackman-Harris.

<u>Except unwrap all parameters must be specified.</u>

3.2 Input Data Format

Time series data are read from space- or tab-delimited ASCII files of the following format:

```
# comment lines
    # .
    # .
    t(1)   x(1)
    t(2)   x(2)
     .       .
     .       .
    t(N)   x(N)
```

where `t(1)` < `t(2)` < ... < `t(N)` denote sampling times, which can be geological ages or physical times. The sampling times can be evenly or unevenly spaced. The maximum number of data points N is limited to 25,000. Program versions for larger values of N are available upon request.

ENVELOPE checks if the ages are in increasing order. If the program encounters decreasing ages, that is, $t(i+1) < t(i)$, it will stop. Identical age entries and the corresponding data values are automatically averaged. The averaged time series is written to the file `TimeSeries.avg`.

The input file must not contain more than two data columns. Make sure that the file contains <u>no blank lines</u> at the end of the file and within the data section. Comment lines are indicated by a leading # and are only allowed at the beginning of the file. The number of comment lines is unlimited.

4. Output

- Estimated parameters are written to the file defined by `FNOUT`.
- Warning messages are written to `NYQ_ERR.DAT`..
- Automatically averaged time series, generated from input files with duplicate age entries, are saved to `TimeSeries.avg`.

The output file is an ASCII-formatted script file for the GNUPLOT graphic package. Alternatively, it can be imported into most spreadsheets for plotting. The contents of the file should be largely self explanatory:

1. The header section lists the main settings from the configuration file.

2. The line Occurrences of `filtfrq` > local `f_Nyq` indicates how often the spacing of the input time was insufficient to resolve the periodicity of interest. That is, whether 1/`filtper` exceeds the Nyquist frequency between any two sampling times a window segment. Times at which the Nyquist criterion is violated are listed in the file `NYQ_ERR.DAT`.

3. GNUPLOT section: The lines from `set title` to `plot '-' u 1:4` are for controlling GNUPLOT and can be deleted if another plot package is used.

4. The data section consists of the following four columns:

`Time` Average of the sampling times within moving window for which instantaneous amplitude and phase are estimated.

`Amplitude` Estimated instantaneous amplitude (= envelope); $a(t)$ in Eq. (2). Values have the same physical unit as the input data.

`Phase` Estimated instantaneous phase; $\Phi(t)$ in Eq. (2). Since the time-series model (Eq. 2) assumes a physical time axis, the instantaneous phase will change by 180° if geological ages are input. (This is only relevant if the phase angles of *two* time series are compared to obtain a lead/lag relationship.)

`Signal` Estimated signal; $s(t)$ in Eq. (2).
The signal can also be considered as bandpass-filtered version of the input time

series for a filter with period `filtper` and bandwidth *BW* (see above).

Usually one plots amplitude or signal *vs.* time. The instantaneous phase can be used to assess the frequency stability of the signal component under consideration because the time-derivative of the instantaneous phase is a measure of the instantaneous frequency (cf. Hinnov et al., 2002).

5. Example Computation

The test data set (`100k_jmp.dat`) consists of a 100-ky sinusoidal wave embedded in white noise (see top panel of the attached figure). The amplitude of the 100-ky signal jumps from zero to one at 1 My. To estimate this evolution of the amplitude for `wfac = 4`, open a DOS-Box, change to the ENVELOPE directory and enter the following command:

```
envelope53 example.cfg
```

The results of the computation will be written to the file `example.plt`, which should be identical to the file `100k_jmp.res`. The attached figure shows the estimated envelope and signal for `wfac = 1, 2, 3` and 4.

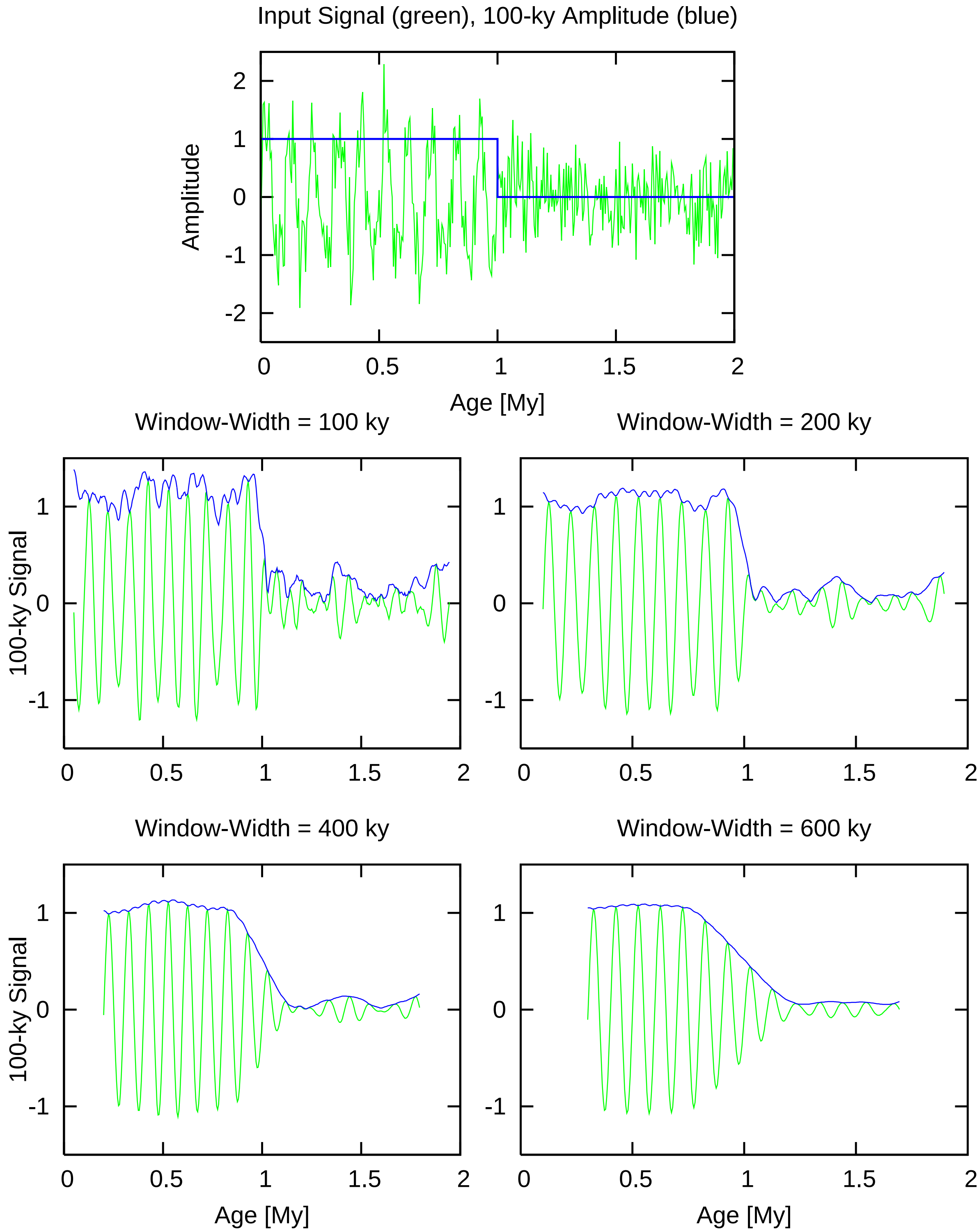
6. References

Ferraz-Mello, S. 1981: Estimation of periods from unequally spaced observations. Astron. J., **86**, 619-624.

Hinnov, L. A., Schulz, M. and Yiou, P. 2002: Interhemispheric space-time attributes of the Dansgaard-Oeschger oscillations between 100 and 0 ka. *Quat. Sci. Rev.*, **21**, 1213-1228.

Mudelsee, M. and Schulz, M. 1997: The Mid-Pleistocene climate transition: onset of 100 ka cycle lags ice volume build-up by 280 ka. Earth Planet. Sci. Lett., **151**, 117-123.

Time-Dependent 100-ky Signal + White Noise



(Envelope 5; Welch Window, A_{noise} = 0.5)