Earth Surf. Dynam., 6, 669–686, 2018
https://doi.org/10.5194/esurf-6-669-2018

Earth Surface Dynamics
Open Access

The R package "eseis" – a software toolbox for environmental seismology

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Received: 22 December 2017 – Discussion started: 8 January 2018
Revised: 19 June 2018 – Accepted: 4 July 2018 – Published: 17 August 2018

Abstract. Environmental seismology is the study of the seismic signals emitted by Earth surface processes. This emerging research field is at the intersection of seismology, geomorphology, hydrology, meteorology, and further Earth science disciplines. It amalgamates a wide variety of methods from across these disciplines and ultimately fuses them in a common analysis environment. This overarching scope of environmental seismology requires a coherent yet integrative software which is accepted by many of the involved scientific disciplines. The statistic software R has gained paramount importance in the majority of data science research fields. R has well-justified advances over other mostly commercial software, which makes it the ideal language to base a comprehensive analysis toolbox on. The article introduces the avenues and needs of environmental seismology, and how these are met by the R package "eseis". The conceptual structure, example data sets, and available functions are demonstrated. Worked examples illustrate possible applications of the package and in-depth descriptions of the flexible use of the functions. The package has a registered DOI, is available under the GPL licence on the Comprehensive R Archive Network (CRAN), and is maintained on GitHub.

1 Introduction

Environmental seismology exploits the seismic signals emitted by Earth surface processes, the processes that shape our planet (Larose et al., 2015; Burtin et al., 2016). This new research field emerged as more sensitive, mobile, and flexible sensors and data loggers became available. The field was pioneered by studies of mass wasting and fluvial process in high mountain landscapes, explicitly bridging seismological expertise with key geomorphic interests (e.g. Helmstetter and Garambois, 2010; Burtin et al., 2010; Dammeier et al., 2011; Hibert et al., 2011). In parallel, the foundations were laid for physical models relating measured seismic signals to underlying physical processes (e.g. Tsai et al., 2012; Gimbert et al., 2014; Farin et al., 2015). This increasingly allows applications of the technique for early warning and rapid response aspects (Mainsant et al., 2012; Hibert et al., 2014; Zeckra et al., 2015), for investigating event trigger processes (Dietze et al., 2017b), for monitoring extremely active landscapes (Bartholomaus et al., 2012; Burtin et al., 2013; Schöpa et al., 2018), and also for exploring the precision and limitations of the seismic method (Dietze et al., 2017a).

Seismic data processing tools have reached an advanced and diversified level. There is a wealth of encapsulated programmes, software libraries, and script language routines available (for examples see e.g. IRIS, 2017a; ETH, 2017, and links therein). Due to their structure, compiled software solutions can usually only provide very limited interaction capabilities with other generic data analysis tools, such as Python or MATLAB, that can be utilised for exploratory, explanatory, and inverse data manipulation beyond the designed work focus of the initial software. Ideally, software used for processing data with a broad context of application should be open, transparent, user driven (see Sect. 2), flexible, and extendible, and it should have a wide acceptance in different fields of science. It should be easy to learn and support efficient and fast computation of large and diverse data sets. The free statistic software R (RCoreTeam, 2015) is one example of software that fulfils these requirements. Across scientific disciplines and on the commercial market, R has gained worldwide acceptance as a robust, easy to learn, innovative, and flexible software and language (Tippmann, 2014). This is reflected by a rich number of online tutorials, text books, webinars, the utilisation of R in academic teaching courses, the predominant role R plays in medical and life sciences, and the more than 10000 packages hosted on the Comprehensive R Archive Network (CRAN).

Besides these software structural points, there are further arguments for providing new functionalities for the wider environmental seismology purpose rather than working with existing tools. Software tailored to signals emitted by Earth surface processes require other numerical approaches to problems like seismic event picking and classification or seismic source location than are expected in a classic seismology scope. These other approaches need to be provided without compromising the existing functionalities. Additionally, the environmental seismology community produced a series of innovative models to relate Earth surface dynamics to the seismic signals they generate (e.g. Tsai et al., 2012; Gimbert et al., 2014) or to changes in the medium in which the seismic waves travel (Sens-Schoenfelder and Larose, 2008; Larose et al., 2015). These models and approaches should be fused into a coherent software environment rather than staying published as isolated programmes or pseudo-code definitions to allow their seamless inclusion in interdisciplinary studies.

2 Environmental seismology and open science

The reproducibility of scientific research is a key goal identified across disciplines (e.g. Lane, 2014; David et al., 2016; Munafó et al., 2017). The foundations of reproducible research are complete access to both the data and software used to generate the results. The former is increasingly demanded by research funding agencies and journals, usually in the form of data repositories including allowance of access embargo periods of some months. This data policy is especially relevant for seismic data usable for investigating environmental dynamics because the data can be used for many different purposes beyond the initial research scope. However, the other requirement, open software, is less often provided. Proprietary software with licence costs may be a minor issue within universities in western societies but becomes a major obstacle for less developed countries.

Another aspect of reproducibility with respect to software concerns the lifetime, computer platform support, and version of the analysis software (Kreutzer et al., 2017). Ideally, the calculations should be possible and yield the same results across all major computer platforms (Windows, Linux, Mac OS) and across different versions of the software. Since the latter requirement is difficult to maintain and may be in conflict with the actual purpose of software updates, there should at least be some information on the version with which the results were obtained and the possibility to use exactly this software version for reproducing previous work. R with its package policy (RCoreTeam, 2015) is a pillar of stability in this respect; all versions of a package are kept in online accessible archives and community-driven projects such as "docker"' (Karambelkar, 2017) and "packrat"' (Ushey et al., 2016) allow version-specific processing environments. While it is hard to estimate the future lifetime and acceptance of any software, R has been actively used for decades, is still continuously growing in terms of users and provided packages, and is based on a foundation that clearly states its code of conduct and long-term strategy of software development (The R Foundation for Statistical Computing, 2018).

Processing seismic data involves a long work flow with many processing steps, each requiring individual parameter adjustments. Thus, not only data availability and open source software are key requirements for reproducible science, but also full documentation of the processing chain. To secure reproducibility and transparency the software should contain a processing documentation scheme. There are ways to combine continuous explanatory text with code snippets and the results of its evaluation (e.g. Jupyter or R notebooks and markdown files), which can be provided as a Supplement to publications. However, a more robust way would be an implicit one that does not require the scientist to take care of migrating the analysis steps into full documentation manually.

Documentations of functions should be coherent and systematic. While scripts that circulate among working groups may be adequately documented in some cases, it is a rather common phenomenon that updates or changes in the code diffuse into different script versions and branches if not coordinated centrally. Likewise, the practice of commenting and documenting is far from being a standard. To avoid such pitfalls, R and its package strategy have rigorous standards that no package can circumvent (RCoreTeam, 2015). A package must always contain a concise and detailed description document, plain text function definitions and optional additional low-level code, reference documentation, example data sets, and tested examples for each function. A package undergoes extensive automatic and manual tests before it is accepted by the CRAN and packages like "roxygen2" (Wickham and Chang, 2017) allow automated builds or updates of the documentation from within the function source code. In a similar manner, incrementally maintaining and updating a package needs to follow the same systematic and rigorous criteria as a submission to the CRAN. Git and GitHub provide all the essential functionalities to pursue this goal (Chacon and Straub, 2013). The above-mentioned mechanisms of appropriate documentation and integrity control can be found in different software, although they are fundamental to R.

3 The package contents

The R package “eseis” version 0.4.0 is available on the CRAN. It has been assigned a DOI for reference (Dietze, 2018). Development is handled via Git and the respective latest developer version is hosted on GitHub. Information about updates, content, applications, and bugs is hosted on a package website (http://micha-dietze.de/pages/eseis.html, last access: 13 August 2018). The package contains 51 functions, two example data sets, and a reference manual. It makes use of a series of dependency packages, namely “caTools” (Tuszynski, 2014), “fftw”’ (Mersmann, 2017), “IRISSeismic”’ (Callahan et al., 2017), “matrixStats”’ (Bengtsson, 2017), “methods”’ (RCoreTeam, 2017), “multitaper”’ (Rahim et al., 2014), “raster”’ (Hijmans, 2017), “Rcpp”’ (Eddelbuettel et al., 2017), “rgdal”’ (Bivand et al., 2017), “signal”’ (Ligges et al., 2015), “sp”’ (Pebesma and Bivand, 2017), and “XML”’ (Temple Lang and CRANTeam, 2017).

Installing the package from CRAN is perhaps the most convenient way (`install.packages(”eseis”)`). However, to get the latest developer version and other branches, the GitHub repositories need to be used. With the package “devtools” (Wickham and Chang, 2017) it is easy to do this in R by running one line of code:

```
devtools::install_github(
 repo= "coffeemuggler/eseis",
 ref = "0.4.0").
```

Some computer platforms require prior installation of R-independent software such as Java runtime environment, openGL, fftw, or gdal. Once all these dependencies are installed, “eseis” can be installed.

The package allows all typical base functionalities for a seismic data analysis work flow: data import and export, signal processing and preparation, event picking, seismic source location, spectrum and spectrogram computation, and plot generation (Fig 1). Further functions allow seismic data download from available databases and conversion of raw measurement files to a coherent file structure picked up by other functions. Thus, “eseis” is clearly distinct from other available R packages that mainly focus on data import and quality control (“IRISSeismic”; Callahan et al., 2017) or earthquake analysis (“RSEIS”; Lees, 2017, and its interlinked packages). It provides a consistent approach to importing different data types to an adequate object structure, handling their processing with homogenised arguments and work flows throughout and implicitly tracing this processing history for report generation. Thus, it contributes to transparent and comprehensible data analysis beyond the seismic background.

3.1 General package philosophy

The eseis object paradigm. In the “eseis” package seismic data are handled as an S3 object of class `eseis` (e.g. `x`), which is basically a list objects with four elements: the signal vector (`x$signal`), a list with meta-information (`x$meta`), another list with the raw header information of the imported file (`x$header`), and a list containing the processing history the `eseis` object has been subject to (`x$history`, see below). Thus, whatever the file format of the imported data (see Sect. 3.2.1), it is always represented in the same way within the “eseis” environment. Although it would be possible from a computational point of view to handle only the signal vector of an imported seismic file, it is much more fail safe, coherent, and convenient to work with the `eseis` object. In many processing steps it is necessary to access or even modify object attributes such as the start time (`x$meta$starttime`) and number of samples (`x$meta$n`) or the sampling interval (`x$meta$dt`). The functions of the package automatically query or update these attributes if needed so that changes in any of the parameters do not need to be considered.

The processing history to which an imported seismic data set has been subject is recorded in the `eseis` object itself (`x$history`). This allows full access to the work flow that leads to the values the object contains at a given time. Upon creation of an `eseis` object, due to importing a seismic file, two base list elements are created. The first one documents the computer system configuration under which the object has been created (`x$history[[1]]`). It includes among others the R version, the computer platform and operating system, local settings such as UTF encoding and time zone, and the other attached R packages in their current version. The second list element (`x$history[[2]]`) documents the actual file import step. Like for any other subsequent processing function the documentation includes the time stamp of the function call, the function call itself, all function arguments with the respective values, and the duration of the function operation. With each subsequent processing step a new history list element is appended. This feature provides the information to reproduce all results. The function `write_report` can be used to generate html-based report documents of `eseis` objects, which can be stored for traceability purposes, shared with colleagues, or published along with the raw data in articles.

The function naming scheme follows a higher-level convention. There are currently eight groups to which all functions belong and that appear in the function name: read and write seismic files (`read_` and `write_`), plot data and data derivatives (`plot_`), signal processing (`signal_`), spatial data handling and source location (`spatial_`), lookup tables and parameter lists (`list_`), model definitions (`model_`), and auxiliary functions for convenient data management (`aux_`). This naming scheme is partly due to the R package and function documentation convention, which is basically reference documentation in which a manual is compiled by sorting all functions of a package in alphabetic instead of semantic order. The naming scheme is also designed to minimise so-called masking effects and multiply assigned function names masking each other when several packages are loaded. Although it is in principle easy to point at the right function by adding the package name and two colons in front of the function name (e.g. `eseis::read_sac`), this is not intuitive and would be in conflict with several of the premises defined in Sects. 1 and 2.

Full support of and access to native R functionalities is a further key objective of the `eseis` package. This means that `eseis` objects can be passed to all efficient data manipulation approaches in R such as piping with the “magrittr” package (Bache and Wickham, 2014), vectorised manipulation of lists of `eseis` objects with `lapply`, and multicore data manipulation with `parLapply` on computers with more than one CPU. In many cases function source code was written in vectorised form to optimise performance. Likewise, full access is also present to the “eseis” object itself. Thus, tasks like accounting for missing data and NA values or even redating procedures of time series from different loggers can always be imposed on the data sets by using base R functions. Numerical output and derivatives of the input data can be handled as ordinary R objects.

3.2 Available functions

The “eseis” package is designed for full processing routines of seismic data from the import of raw files to data preparation, analysis, presentation and/or visualisation, and export or passing to further R and external functionalities. It is not the main goal of the “eseis” package to provide import filters for the broad range of seismic data formats, for example as Obspy (Beyreuther et al., 2010) does. However, if future user feedback indicates that support of additional formats is a vital goal, this could be implemented coherently, e.g. by utilising existing solutions via Python integration to R (Allaire et al., 2018). In addition to data import, more complex, predefined work flows are implemented, such as converting nonstandard seismic file formats to mseed or SAC files and organising them in a coherent file structure, preparing overview spectrogram panel plots for a seismic network throughout the station deployment time period, or importing all seismic traces of a given event based on time, channel (i.e. an orthogonal spatial signal component), and stations to include. Documentation of all functions and example data sets as a mandatory part of the package compilation process is available as a PDF document on the CRAN. However, “eseis” is not designed as a substitute for classic seismic data analysis tools such as SAC or Obspy, which may be much more appropriate when the main tasks include having full support of all relevant seismic data file formats, full access to XML-SEED, and classic seismology research fields.

3.2.1 Data import

Supported seismic file types are SAC (IRIS, 2017b) and miniseed (IRIS, 2012), implemented by the functions `read_sac` and `read_mseed` (Fig. 1). These two formats are widely used and/or easy to import–export. By default, the import will yield an `eseis` object unless the user wishes to work with a separate signal and time vector (`eseis = FALSE`). Thus, regardless of the input file format, the resulting object is a homogeneous representation of the signal and its metadata. It is always possible to specify several seismic files in consecutive order to obtain a continuous trace in R (`append = TRUE`; otherwise, each file will be imported separately to yield a list of the individual traces). It is possible to select the individual object elements to be imported or omitted (e.g. `signal = FALSE`), which is useful to just screen the header or meta-information of seismic files instead of reading the entire signal vector. The function `read_mseed` wraps functions of the package “IRISSeismic” (Callahan et al., 2017) to prevent redundant coding efforts. Since SAC and mseed carry different information in their header parts it is possible to manually edit the `$header` or `$meta` elements of the resulting `eseis` objects, e.g. to add or extract event-based information for further analysis.

A more convenient and robust way to import seismic data from local files is provided by the function `aux_getevent`. It requires specifying a time period, the channel(s), and one or more station IDs and reads all data into a coherent list object, which can be directly used for further signal processing steps. However, the function requires the data to be stored in a predefined directory structure (Fig. 2). The files must be stored in directories organised by year and Julian day. In each Julian day directory, an hourly seismic file must be named with station ID, Julian day, hour, minute, and second of the start time of the seismic signal, seismic channel name, and file extension (Fig. 2). This structure and naming convention is the basis for `aux_getevent` and many other functions of the `aux_` family. If future avenues of research suggest further structure and naming schemes, these can be implemented as well. The easiest way to bring files into the described structure is to use the functions `aux_organisecentaurfiles` and `aux_organisecubefiles`. The former is originally written for seamless conversion of files recorded by a Nanometrics Centaur data logger but can also be used with other loggers if these store the data in an appropriate format and structure (see function documentation for details). The latter function is designed for files recorded by Digos DataCube loggers and handles the complete work flow of converting daily cube files to mseed files, cutting them to hourly segments, optionally further to SAC files, and establishing the directory structure as described above. The two data loggers are the most widely used ones during projects of the author, but if users of the package express the need for support of additional loggers this can be incorporated in future versions of the package.

Apart from local seismic files it is possible to work with seismic data from web-based services, such as IRIS

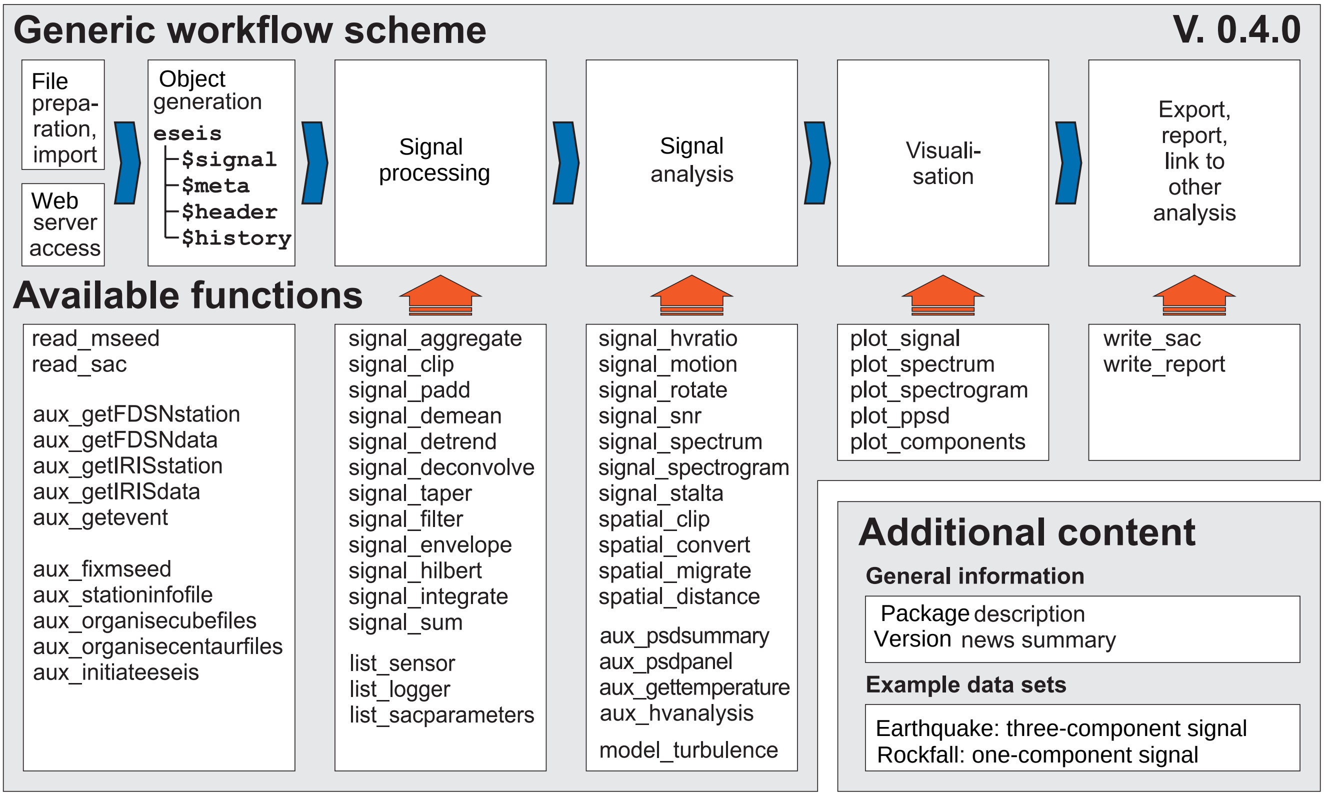


Figure 1. General work flow and available functions of the "eseis" package.

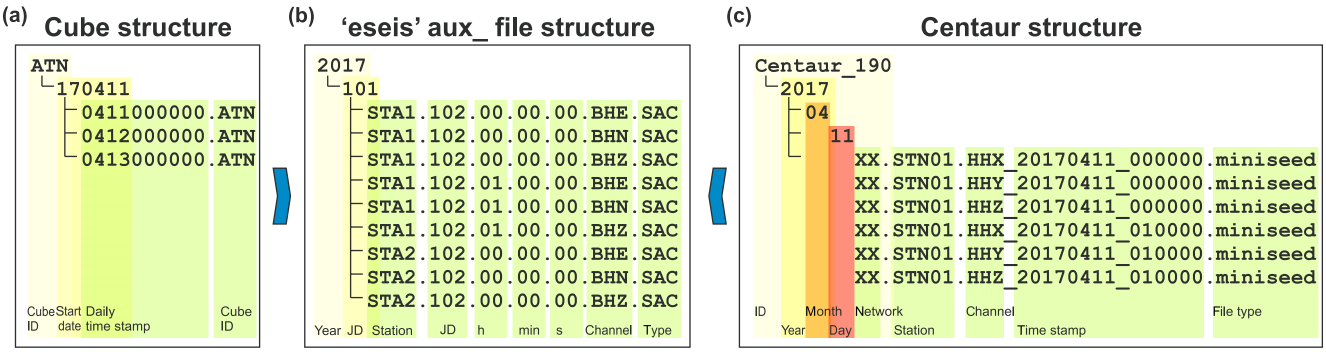


Figure 2. File organisation from the commonly used data loggers Digos DataCube **(a)** and Nanometrics Centaur **(b)** and how they are converted to the standard structure used by most of the auxiliary functions of the "eseis" package. After conversion, seismic files are organised into year and Julian day directories and within these as file names denoting station ID, Julian day, hour, minute, second, channel, and file name extension.

or FDSN dataselect. These options are implemented by `aux_getIRISstation`, `aux_getIRISdata`, `aux_getFDSNstation`, and `aux_getFDSNdata` (Fig. 1). The basic principle behind both the IRIS-based and the FDSN-based functions is that first one needs to identify seismic stations that are present within a given radius around a location defined by latitude and longitude. With the station data (the sncl code for `aux_getIRISdata` and network ID and station code for `aux_getFDSNdata`) at hand, the mseed data sets can be temporarily downloaded and imported as an `eseis` object.

The "eseis" package does currently not support the import and export of established metadata formats, such as dataless seed or stationXML. Thus, this extended meta-information is currently not available within the package ecosystem, and the typical information needed to process the data, such as representation of poles and zeros to deconvolve a signal, must be provided manually (see, for example, Sect. 4.1.2).

3.2.2 Data processing

The next steps after the import of seismic data typically include signal processing in order to prepare the data for the actual analysis part. In most cases it is necessary to correct the signal for the instrument response, i.e. signal deconvolution, performed by the function `signal_deconvolve`. The main arguments needed for deconvolution are the characteristics of the sensor (poles, zeros, generator constant, or sensitivity and the normalisation factor) and logger (AD conversion factor). Additional arguments can be set if appropriate (`gain` correction, `p` signal taper proportion, `waterlevel` value to avoid division by zero). The deconvolution step differs from the approach implemented in, for example, Obspy (Beyreuther et al., 2010), in which dataless seed files are the primary carrier of parameter information. In the case that more sophisticated logger set-up parameterisations (e.g. filter coefficients) are required, the data must be preprocessed with an appropriate software before being imported to R.

The deconvolved signal can be subject to manipulations like removing the mean (`signal_demean`) or linear trend (`signal_detrend`), tapering by proportions of the signal length or numbers of samples (`signal_taper`) to remove edge effects, aggregating or decimating (`signal_aggregate`) to decrease the sampling density, padding the data with zeros to reach a length equal to the positive integer n^2 (`signal_padd`) for more robust and efficient Fourier transform operations, integrating (`signal_integrate`) to calculate displacement from velocity, calculating the vector sum of signal components (`signal_sum`), calculating the Hilbert transform (`signal_hilbert`) and the signal envelope (`signal_envelope`), and filtering the signal in the time domain (`signal_filter`). It is also possible to clip an imported signal to a given time interval (`signal_clip`).

With an appropriately prepared (`eseis`) object signal analysis can be performed. Available functionalities allow events to be picked based on the classic STA/LTA algorithm (Allen (1982), `signal_stalta`), which is implemented as C++ code, calculating spectra (`signal_spectrum`), spectrograms (`signal_spectrogram`), and the signal-to-noise ratio (`signal_snr`), rotating the signal components (`signal_rotate`), inferring particle motion analysis (`signal_motion`), and calculating the horizontal to vertical spectral ratio (`signal_hvratio`). Special emphasis is on spatial analysis to locate environmental signals, one of the main application fields of environmental seismology (`spatial_migrate`, cf. Burtin et al., 2016; Dietze et al., 2017b, along with helper functions to prepare spatial data (`spatial_clip`, `spatial_convert`, `spatial_distance`). For more complex but routine analysis tasks, there is a growing suite of auxiliary functions. These include the possibility to generate overview panels of spectrograms, either for constant time intervals across all stations in a seismic network (`aux_psdpanel`) or for different time aggregation levels but a single seismic station (`aux_psdsummary`). The function `aux_hvanalysis` performs a comprehensive horizontal to vertical spectral ratio analysis for given time slices and generates graphical output of the results.

Visualisation of the data is key for the final presentation of the results. R offers powerful methods for high-quality plot output, though the scripting effort for user-adopted plots can be fairly high (e.g. Dietze et al., 2016) and the learning curve is steep. Thus, all plot functions in the “eseis” package are set up with meaningful default arguments to minimise the amount of overhead code to generate a fairly pretty plot. Likewise, the massive amount of data to handle (more than 17 million samples per day for a single component recorded at 200 Hz) can easily bring the default plot functions of R to a limit. Thus, the plot functions in the “eseis” package were optimised for speed and aggregation of data beyond visible effects. The package allows for the plotting of the signal waveforms (`plot_signal`), their spectra (`plot_spectrum`), calculated spectrograms (`plot_spectrogram`) and probabilistic spectra (`plot_ppsd`), and the three signal components as a 2-D plot, 3-D plot, and interactive rotatable 3-D scene (`plot_components`; see Fig. 3).

The export of seismic data is not one of the key features of the “eseis” package. Currently, writing functionality is only implemented for the SAC file format (`write_sac`), which can be easily converted to different formats by other software (e.g. Beyreuther et al., 2010). To enable full reproducibility of any analysis step in the package (see Sect. 3.1), the function `write_report` generates a summarising html-based report of the manipulation history of the `eseis` object (see Fig. 4). The metadata section of the displayed example report shows that there is no information given in the imported SAC file about items such as network code, sensor and logger, or station location. Thus, such reports can be used to document shortcomings, but also when they have been fixed during the processing chain.

In order to use the numerical data for further analysis in R or to generate used-adopted plots, every function (except for some plot functions and the report function) returns standard R objects, either as lists of class `eseis` or numerical matrices, vectors, and spatial data objects.

3.3 Example data sets

The “eseis” package contains two example data sets of minimum size that are used to illustrate the functionalities of the package. One data set contains the seismic signal of a rockfall preceded by a small earthquake recorded by the vertical signal component. The other data set contains a typical earthquake recorded by three spatial components. Both data sets were recorded by a temporary network in the Lauterbrunnen Valley dedicated to analysing rockfall activity and its trigger conditions (i.e. event ID 30 in Dietze et al., 2017b). The network consisted of Nanometrics Trillium Compact TC120s

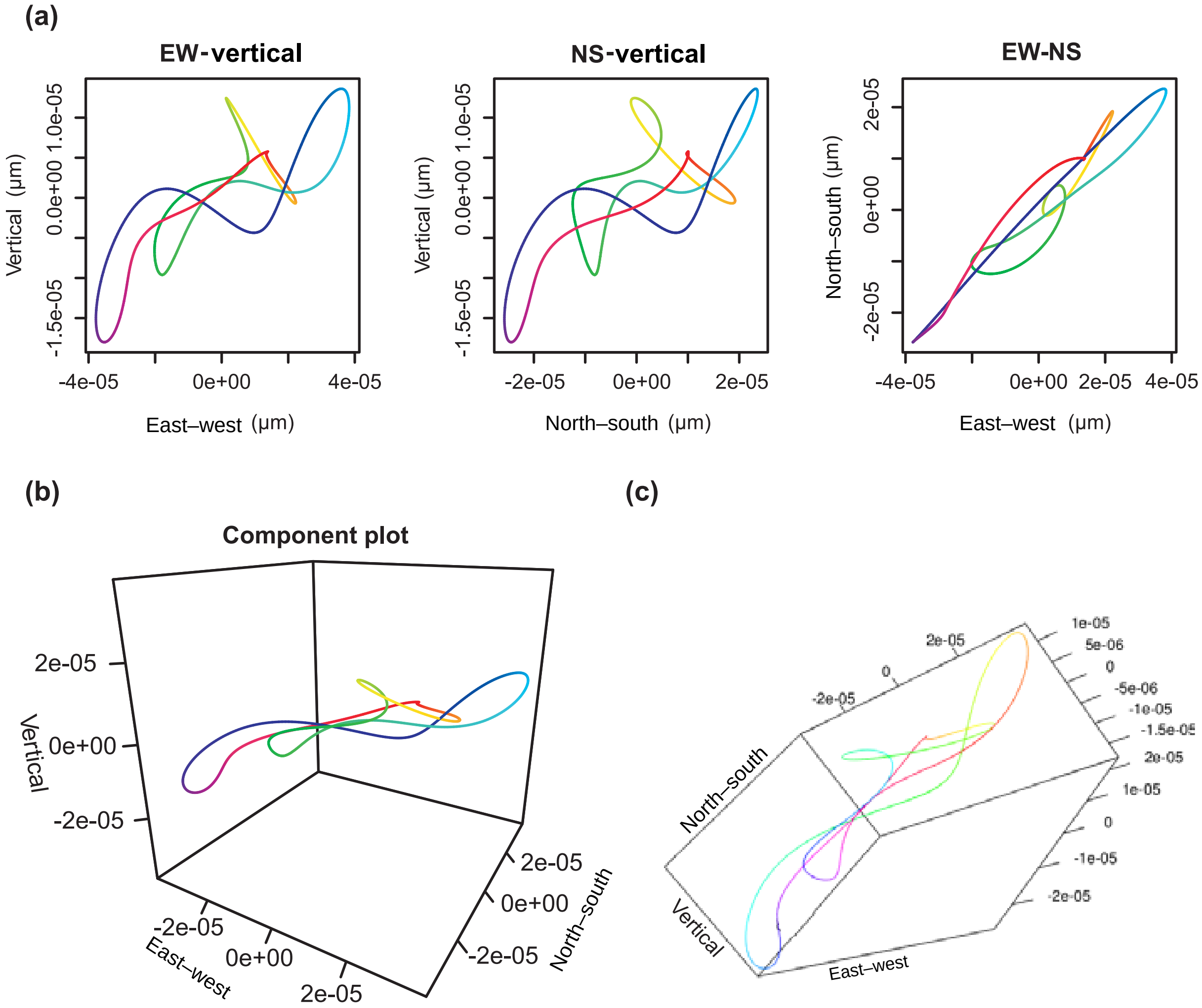


Figure 3. Plot types to visualise particle motion. **(a)** 2-D plots of the components, **(b)** 3-D perspective plot, and **(c)** a screen shot of an interactive scene that can be rotated and zoomed.

sensors being sampled by Digos DataCube^{3}ext loggers at 200 Hz with a gain of 1.

4 Worked examples

Two worked examples are discussed to illustrate the capabilities and typical work flows of the “eseis” package. With the focus on package utilisation, study site description and environmental interpretation of the results are kept minimal. Both worked examples are provided as R markdown documents in the Supplement.

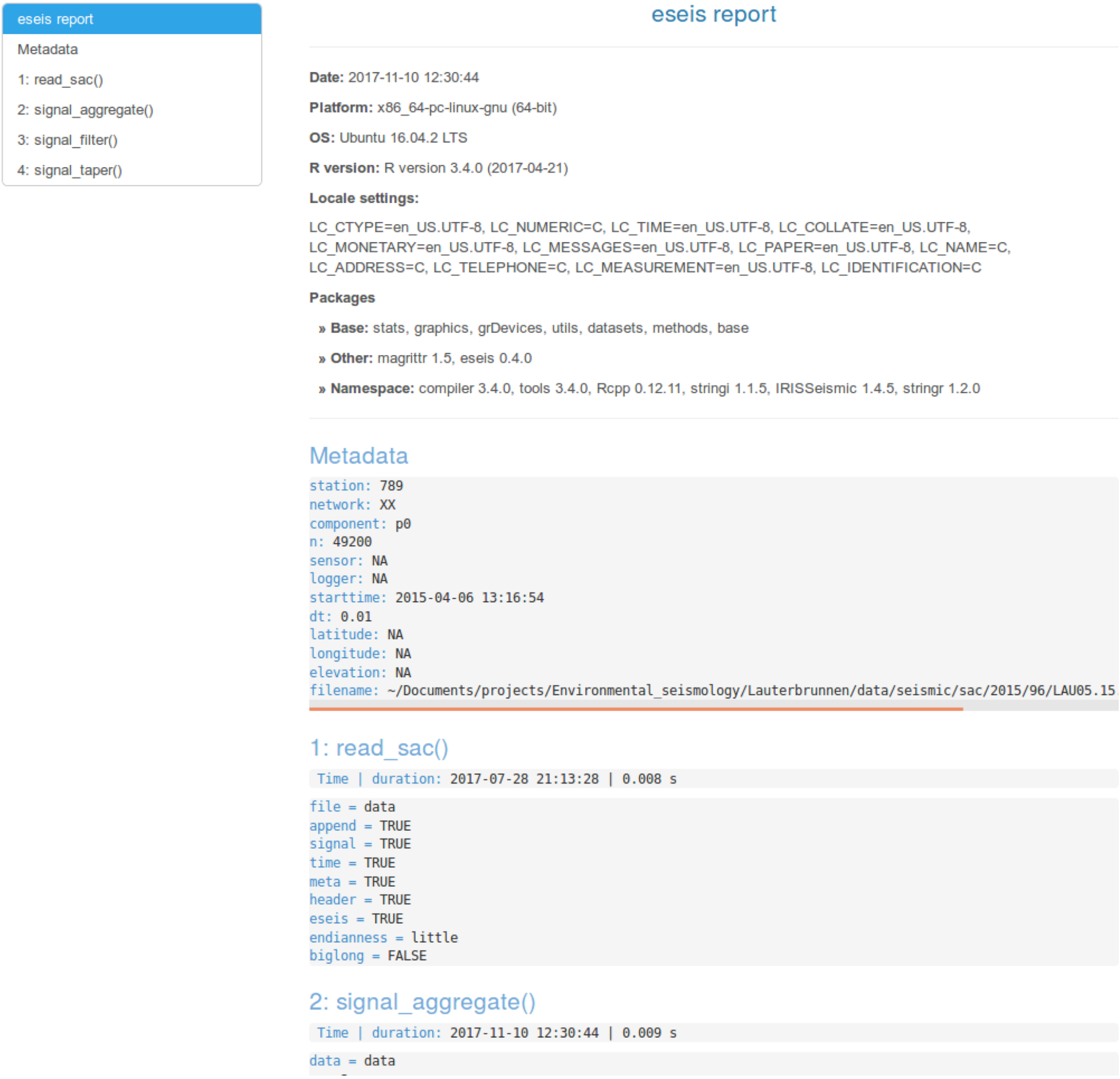
A typical session or script initiation contains loading the package, setting the workspace (the directory in which all data will be searched and stored by default), and reading the station info table, i.e. a table that contains essential information about the seismic stations (see Table 1).

```
## load package
library("eseis")

## set working directory
setwd(dir = "~/data/seismic/")

## load station info table
stations <- read.table(
  file = "stations.txt",
  header = TRUE,
  stringsAsFactors = TRUE)
```

While many subsequent processing and analysis steps are similar to classic seismological work flows, there are also approaches rather unique to signals encountered in seismic studies of environmental dynamics. These include the location of seismic sources (e.g. Sect. 4.1.6) or modelling the seismic signatures of flowing water (Sect. 4.2).



eseis report

Date: 2017-11-10 12:30:44

Platform: x86_64-pc-linux-gnu (64-bit)

OS: Ubuntu 16.04.2 LTS

R version: R version 3.4.0 (2017-04-21)

Locale settings:

LC_CTYPE=en_US.UTF-8, LC_NUMERIC=C, LC_TIME=en_US.UTF-8, LC_COLLATE=en_US.UTF-8, LC_MONETARY=en_US.UTF-8, LC_MESSAGES=en_US.UTF-8, LC_PAPER=en_US.UTF-8, LC_NAME=C, LC_ADDRESS=C, LC_TELEPHONE=C, LC_MEASUREMENT=en_US.UTF-8, LC_IDENTIFICATION=C

Packages

» **Base:** stats, graphics, grDevices, utils, datasets, methods, base

» **Other:** magrittr 1.5, eseis 0.4.0

» **Namespace:** compiler 3.4.0, tools 3.4.0, Rcpp 0.12.11, stringi 1.1.5, IRISSeismic 1.4.5, stringr 1.2.0

Metadata

```
station: 789
network: XX
component: p0
n: 49200
sensor: NA
logger: NA
starttime: 2015-04-06 13:16:54
dt: 0.01
latitude: NA
longitude: NA
elevation: NA
filename: ~/Documents/projects/Environmental_seismology/Lauterbrunnen/data/seismic/sac/2015/96/LAU05.15
```

1: read_sac()

```
 Time | duration: 2017-07-28 21:13:28 | 0.008 s
```

```
file = data
append = TRUE
signal = TRUE
time = TRUE
meta = TRUE
header = TRUE
eseis = TRUE
endianness = little
biglong = FALSE
```

2: signal_aggregate()

```
 Time | duration: 2017-11-10 12:30:44 | 0.009 s
```

```
data = data
```

Figure 4. Section of the html-based report output. The interactive document lists the computer and software environment under which the processing took place, as well as all manipulation steps the data set was subjected to, including function calls and argument values.

4.1 Cliff coast collapses

During a pilot study, the cliff coast section of Germany’s largest island, Rügen, was instrumented by four Nanometrics Trillium Compact 120s broadband seismometers and Digos Cube^{3}ext data loggers recording at 200 Hz and powered by 70 Ah batteries. The stations were deployed between April and May 2017 on top of the approximately 100 m high chalk cliffs, spaced by about 1 km in hand-dug pits about 50 cm deep. The primary purpose of this monitoring campaign was to detect and locate cliff collapses that occur as rockfalls, rock avalanches, rotational slides, and debris flows (LUNG, 2003).

4.1.1 Raw data handling

Data processing starts with copying the raw files from the data loggers to a local directory in a way depicted in Fig. 2a and creating the station info file (see Table 1). Specifically, it is a file denoting station ID, full station name, longitude (easting), latitude (northing), elevation, sensor installation

Table 1. Station information table containing all relevant metadata for the deployed seismic stations. Coordinates x and y are given in UTM coordinates (zone 33N), and station z and station d denote station elevation (m a.s.l.) and sensor deployment depth (m).

ID	Name	x	y	Station z	Station d	Sensor type	Logger type	Sensor ID	Logger ID
RUEG1	Open Backyard	413107.2	6048242.7	NA	0.5	TC120s	Cube3ext	NA	ARV
RUEG2	Beloved Peregrine	414441.7	6046841.3	NA	0.5	TC120s	Cube3ext	2796	ART
RUEG3	Shrapnel City	414189.2	6045155.2	NA	0.5	TC120s	Cube3ext	2763	ARS
RUEG4	Running Fishermen	413969.6	6043145.7	NA	0.5	TC120s	Cube3ext	2797	ARU

depth, sensor type, logger type, sensor ID, and logger ID. This information can either be collated manually or by using the function `aux_stationinfofile`, which extracts most of the relevant data from the cube files. The function can be run on a given fraction of CPUs (e.g. `cpu = 0.5`) and the number of cube files to be analysed for extracting the station coordinates can be set as well (e.g. `n = 11`). The function creates the station info ASCII table and, if enabled by the user, files with the GPS data.

```
aux_stationinfofile(
  name = "station_info_RUEG17_network_dd",
  input_dir = "../cube/",
  output_dir = "../sac/",
  station_ID = c("RUEG1", "RUEG2",
                 "RUEG3", "RUEG4"),
  station_name = c("Open Backyard",
                   "Beloved Peregrine",
                   "Shrapnel City",
                   "Running Fishermen"),
  station_d = rep(x = 0.5,
                  times = 4),
  sensor_type = rep(x = "TC120s",
                    times = 4),
  logger_type = rep(x = "Cube3ext",
                    times = 4),
  sensor_ID = c(NA, 2796, 2763, 2797),
  logger_ID = c("ANT", "ANN",
                "ALF", "ANV"),
  unit = "dd",
  gipptools =
    "~/software/gipptools-2017.013/")
```

Based on the station info file the data can be transformed from the initial structure to the one shown in Fig. 2b. This step is done by the function `aux_organisecubefiles`. In order to use the function the GIPPtools software (Lendl, 2017) has to be installed.

```
aux_organisecubefiles(stationfile =
  "station_info_RUEG17_network_dd.txt",
  input_dir = "../cube/",
  output_dir = "../sac/",
  format = "sac",
  gipptools =
    "~/software/gipptools-2017.013/",
  verbose = TRUE)
```

The user can decide if the output files shall be mseed or SAC files (e.g. format = ``sac″), which naming convention shall be used (e.g. channel_name = ``p″), and how many CPUs shall be used. GIPPtools offers further options to control how to handle samples outside of GPS time stamps (`fringe`) and the degree of command line processing information (`verbose`). In more recent Java runtime environment versions, on which GIPPtools is based, there has been a problem with the heap space, which led to crashes of GIPPtools during cube file conversion. This shortcoming can be accounted for by increasing the value of `heapspace`. Likewise, the function accepts manually converted mseed files to be organised in the output structure (`mseed_manual = TRUE`). Otherwise, the function converts all cube files to daily mseed files, clips these to hourly files, imports them to R, appends the metadata, creates the output directory structure, and saves the files in that structure in the desired file format.

4.1.2 Event data import

Seismic data of events can be imported either by providing the relevant seismic file names, importing them and clipping them to the relevant time window (e.g. 10 s), which can be done manually in a loop (not advised and not shown), or as a list approach.

```
## define files to import
files <- c(
"2017/080/RUEG1.17.80.04.00.00.BHZ.SAC",
"2017/080/RUEG2.17.80.04.00.00.BHZ.SAC",
"2017/080/RUEG3.17.80.04.00.00.BHZ.SAC",
"2017/080/RUEG4.17.80.04.00.00.BHZ.SAC")

## manual import
x <- list(RUEG1 = read_sac(
  file = files[1]),
          RUEG2 = read_sac(
  file = files[2]),
          RUEG3 = read_sac(
  file = files[3]),
          RUEG4 = read_sac(
  file = files[4]))

## list-based import and clipping
x <- lapply(X = files,
```

```
            FUN = read_sac)
names(x) <- stations$ID

## clip signal to event
x <- signal_clip(
  data = x,
  limits = as.POSIXct(
    x = c("2017-03-21 04:38:50",
          "2017-03-21 04:39:00"),
    tz = "UTC"))
```

Another way, `aux_getevent`, would combine the `read_sac` and `signal_clip` calls from above but also account for problems such as time limits out of the data range or events covering more than a full hourly seismic file. The event data can be imported by using the following code, in which `station$ID` denotes the seismic station IDs of the station info table (Table 1).

```
## load event data
x <- aux_getevent(
  start = as.POSIXct(
    x = "2017-03-21 04:38:50",
    tz = "UTC"),
  duration = 10,
  station = stations$ID,
  component = "BHZ",
  dir = "sac/")

## simplify structure
x <- lapply(X = x,
            FUN = function(x) {x[[1]]})
```

Either way, the result is a list containing the vertical components (‘‘BHZ”) of all four seismic stations for the given time interval. For further signal inspection, analysis, and interpretation, one usually corrects for the instrument response. The respective function `signal_deconvolve` needs additional information about characteristics of the seismic sensor and data logger (see Sect. 3.2.2), the logger gain, the fraction of the signal that will be tapered during the deconvolution process (by default 10^{-6}), and a water level value (by default 10^{-6}).

```
## deconvolve signals
x <- signal_deconvolve(
  data = x,
  sensor = "TC120s",
  logger = "Cube3extBOB")
```

In the case that a sensor or data logger is not contained in the list provided with the package, the example part of the function documentation shows how to use user-defined deconvolution parameters.

4.1.3 Data processing

The vertical component signals of the four stations can now be detrended, filtered, tapered, and, for example, plotted (Fig. 5a).

```
## detrend signals
x <- signal_detrend(
  data = x)

## filter signals
x <- signal_filter(
  data = x,
  f = c(5, 10))

## taper signal based on n samples
x <- signal_taper(
  data = x,
  n = 300)

## plot signal waveforms
lapply(X = x, FUN = plot_signal)
```

4.1.4 Data analysis

Likewise, one can calculate spectra and spectrograms (time evolution of spectra calculated within time windows) from the signals. Any spectrum is calculated using functionalities from the package “stats” (RCoreTeam, 2017), namely `spec.pgram` (spectral density is estimated based on a smoothed periodogram) and `spec.ar` (spectral density is estimated from an autoregressive fit). Both functions have further arguments, for example to pad the time series with zeros and remove the mean, which can be passed through `signal_spectrum` using the `...` argument if appropriate. The default option of `signal_spectrum` is the periodogram option, whereas the autoregressive variant results in a generally smoother spectrum (Fig. 6). Additionally, for very short signals, it is possible to utilise the multi-taper option (`multitaper = TRUE`; Thomson, 1982). However, this increases computation time significantly. As a bridge between time domain (signal waveform) and frequency domain (signal spectrum), there are spectrograms. There, a signal is cut into optionally overlapping windows and spectra are calculated for each of these windows. Thus, spectrograms represent the spectral evolution of a signal with time. Welch (1967) introduced the idea to calculate spectra for each window based on sub-windows, which again may or may not overlap within a window. Thereby, the spectra are averaged and result in a more robust and smoothed representation. This option is implemented by the option `Welch = TRUE`. Likewise, multi-tapers can be utilised for spectrograms (`multitaper = TRUE`), again keeping in mind that this results in significant additional computation time.

```
## spectrum autoregressive option
s_2 <- signal_spectrum(
  data = x$RUEG2,
  method = "autoregressive")

## spectrogram, Welch option
s_3 <- signal_spectrogram(
  data = x,
  Welch = TRUE,
```

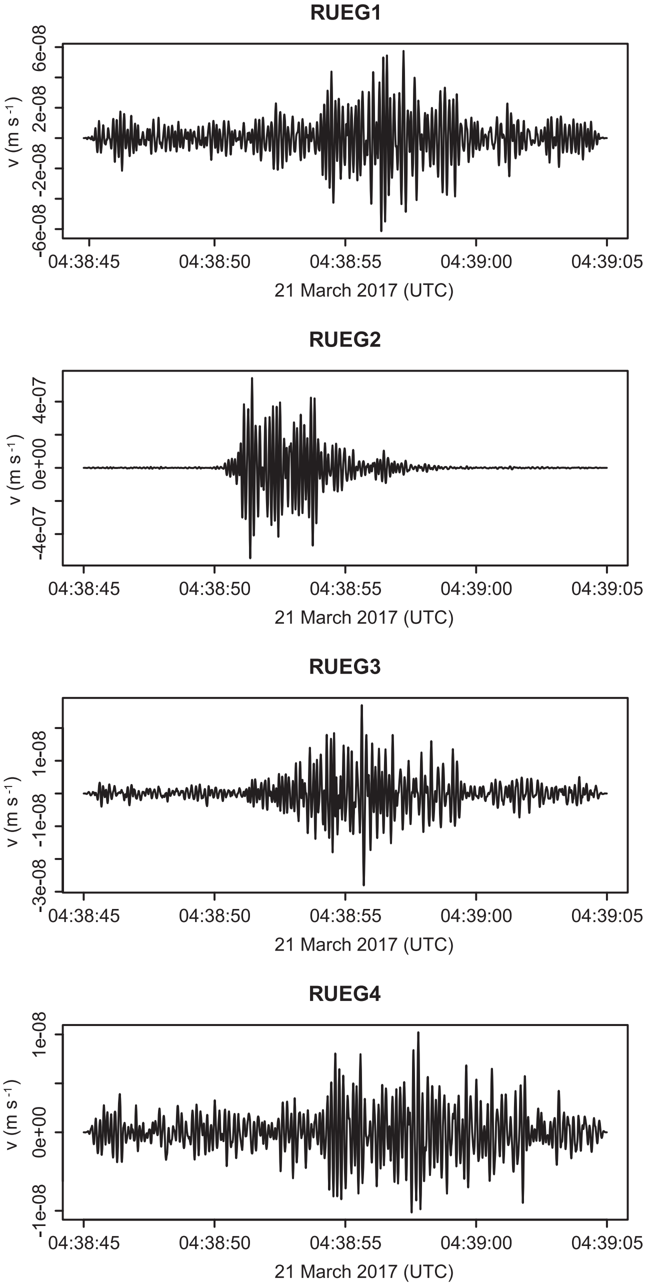


Figure 5. Seismic waveforms of a cliff coast collapse as recorded by four stations in the Jasmund National Park. Signals have been deconvolved, detrended, filtered between 5 and 8 Hz, and tapered by 300 samples. Note that time offset and amplitude decrease as the event is recorded further away from its origin about 80 m east of station RUEG2.

```
  window = 1.0,
  window_sub = 0.7,
  overlap = 0.95,
  overlap_sub = 0.95)
```

4.1.5 Plotting

Plotting spectral data sets is possible by designated functions; `plot_spectrum` is used for spectra. Note how the periodogram-based spectrum (Fig. 6a) creates a much rougher graph than the autoregressive option (Fig. 6b). The spectrogram (`plot_spectrogram`, Fig. 6c) shows the onset of the cliff collapse and how it is dominated by frequencies below 20 Hz that give way to prolonged activity across the full recorded frequency spectrum after about 5 s. The probabilistic spectrogram (`plot_ppsd`, Fig. 6d) depicts how the collapse event shifts the entire frequency spectrum by about 30 dB towards higher power, especially in the 5 to 15 Hz range.

4.1.6 Source location

Locating the source of a seismic signal is one of the most relevant goals in environmental seismology. However, classic seismological approaches fail or at least need modification to be appropriately applied to the seismic signals emitted by Earth surface processes (e.g. Lacroix and Helmstetter, 2011; Burtin et al., 2013; Dietze et al., 2017b). Currently, the "eseis" package contains a full waveform or signal envelope migration approach (i.e. surface wave migration) that performs a grid search to find the location in space that best explains the overall time offsets between event signals as recorded at pairs of stations. The algorithm is based on methods described by Burtin et al. (2013, and references therein). The location of a seismic source with this approach requires a digital elevation model (DEM) depicting the topography of the area within which the source shall be searched. The DEM is used to generate distance maps, i.e. lookup tables of topography-corrected surface distances between a seismic station and any pixel. These distances are later converted to travel times using average apparent surface wave velocities, and the pixel with the best overall travel time value explaining the time offsets between station pairs is deemed to be the most likely source location. The distance maps are created with the function `spatial_distance`, which requires the DEM data set and the seismic station coordinates usually delivered with the station info file, and returns the distance data sets and the inter-station distances as a list object for later use. The calculation of the lookup tables is computationally extensive and can take hours for a grid with some 10 000 pixels. It is thus useful to save the output of the function for efficient later use.

```
## load DEM
dem <- raster::raster(
  x = "dem_alos_crop.img")

## create distance maps
D <- spatial_distance(
  stations = stations[,3:4],
  dem = dem)

## save distance maps
save(D, file = "distance_data.rda")
```

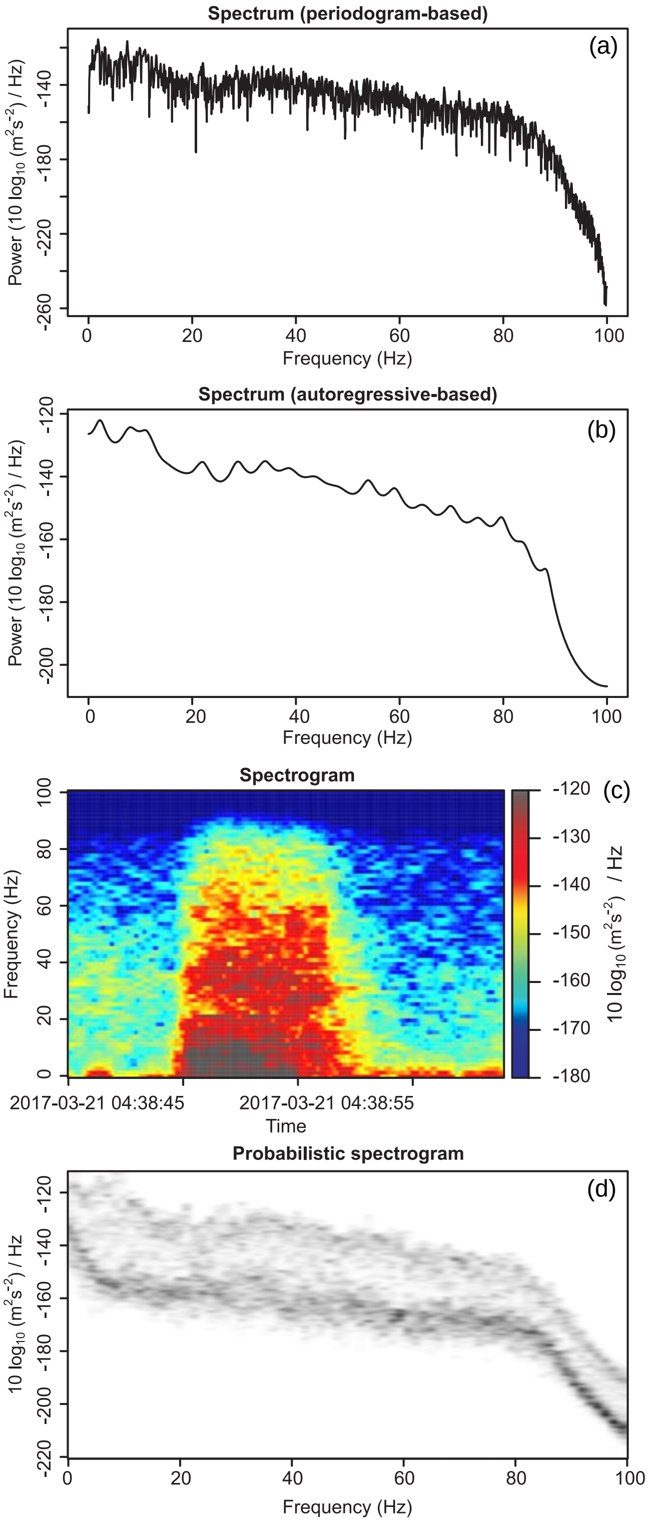


Figure 6. Spectra (**a** and **b**), spectrogram **(c)**, and probabilistic spectrogram **(d)** of the cliff collapse event depicted in Fig. 5 at station RUEG2.

The second step in locating a seismic source is to pass the envelopes of the seismic signals of an event to the function `spatial_migrate`, which further requires the distance data, the apparent seismic wave velocity, and the sampling frequency (e.g. as denoted in the metadata part of the ‘`eseis` objects). The apparent wave velocity is the average velocity with which the seismic signals propagate along the surface. Finding a meaningful estimate of this value is crucial and can significantly influence the resulting seismic source location estimate (e.g. Burtin et al., 2013; Dietze et al., 2017a). The function output is a raster object with the average distance-corrected cross-correlation coefficient for each pixel.

```
## calculate envelopes
e <- signal_envelope(data = s)

## locate event source
xy <- spatial_migrate(
  data = e,
  d_stations = D$stations,
  d_map = D$maps,
  v = 900)

## clip location estimates
xy_clip <- spatial_clip(
  data = xy,
  quantile = 0.99)
```

Usually, one wants to clip the location estimate map to values higher than a given threshold quantile, which can be done using the function `spatial_clip`. The output can be plotted onto a hill shade (`hs`) map of the terrain.

```
## plot hillshade
plot(hs,
     col = grey.colors(200),
     legend = FALSE)

## plot location map
plot(xy_clip,
     add = TRUE,
     col = adjustcolor(
       col = rainbow(100),
       alpha.f = 0.7),
     legend = FALSE)

## add station locations to map
points(x = stations$x,
       y = stations$y,
       pch = as.character(1:4))
```

This exemplary work flow shows the basic demands for environmental seismology research questions and how they can be approached with the “eseis” package. Most of the described functions have further arguments to customise data processing and manipulate numerical and graphical output. For further details about the functions see the package doc-

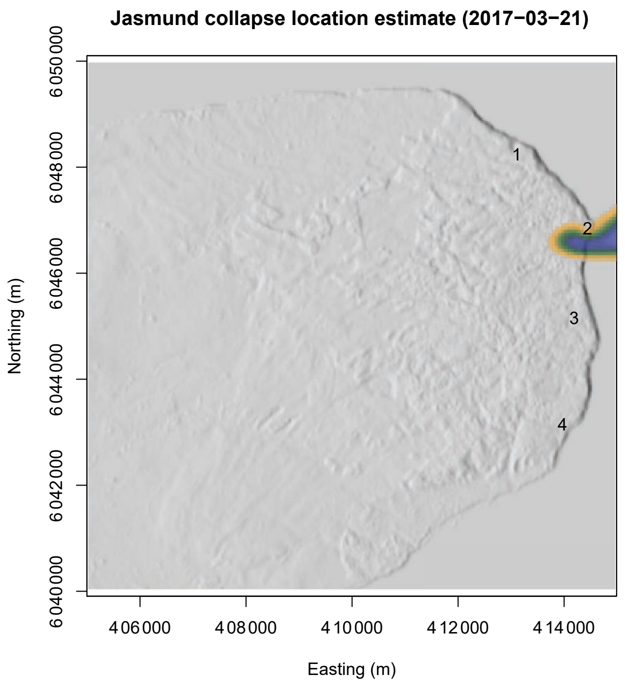


Figure 7. Seismic location estimate of the cliff collapse event depicted in Fig. 5 as a semi-transparent hill shade map overlay with seismic station locations indicated by numbers.

umentation. For general R-related details about handling objects, passing arguments, and optimising plot output see the generous amount of available tutorials and text books (e.g. Adler, 2012; Albert and Rizzo, 2012).

4.2 Modelling fluvial dynamics

Rivers cause seismic signals due to transported particles impacting the bed, waves at the water surface, cavitation, and turbulent flow (Gimbert et al., 2014). For the latter, dominant source, Gimbert et al. (2014) have developed a physical model. This model has been translated to R by Sophie Lagarde and became a part of the “eseis” package. It calculates a seismic power spectral density estimate based on parameters describing the fluid, topography, and bedrock–sediment properties, as well as a series of seismic boundary conditions, in total a set of 23 function arguments.

Here I show how the model can be applied and illustrate the flexibility of the package when combining “eseis” functionalities with generic R capabilities. The model is used to predict the water level of the Wernersbach, a small river in the Tharandter Wald near Dresden, Germany, through a period of about 3 days during which a small flood occurred. The Wernersbach is a typical upland river with a catchment size of 4.6 km^2 and average slopes of 3 %. The bed is composed of sand and pebbles, and the adjacent terrace contains loamy to sandy Quaternary deposits. The stage has been monitored independently by optical sensing (Eltner et al., 2017). Hourly precipitation data from a meteorological station in Wilsdruff, about 6 km to the north, were exploited using the package “rdwd” (Boessenkool, 2017) to check for contamination of the seismic signal by raindrop impacts. A Nanometrics Trillium Compact 120s broadband seismometer and Nanometrics Centaur data logger, recording at 400 Hz with a 40 V input range, provide the empirical seismic data set.

The empirical data were imported as hourly signal traces of the vertical component with a two-sided buffer of 300, deconvolved, detrended, filtered between 5 and 190 Hz, and clipped to the full hour to account for edge effects. The spectra were calculated with method = ``autoregressive” to receive smoothed estimates, and the spectral power values for frequencies between 10 and 100 Hz were stored for further analysis. This frequency window was decisively used to avoid low-frequency contamination of the record by dynamics other than fluvial.

The turbulence model is a deterministic one. However, when run through R it is easy to include uncertainty in the model parameters with a Markov chain Monte Carlo approach. For this, all relevant model parameters were randomly resampled 10^4 times according to the boundaries given in Table 2. This approach was applied to a series of potential water levels (from 0.01 to 2.00 m in steps of 0.05 m), yielding a set of 60 000 potential spectra that served as a lookup table for the empirical data (Fig. 8a). The hourly empirical spectra were compared with the Monte-Carlo-based potential model spectra to extract only model solutions with average differences below the 0.05 quantile, i.e. the $> 95\,\%$ best fits to the data. From these solutions the means and standard deviations of the respective water levels were computed and interpreted as possible river stages (Fig. 8b).

The respective R code is provided in the Supplement with less illustrative additional text compared to the first example to show a minimum amount of information needed to document code. However, an inspection of the code reveals how most of the criteria defined in Sect. 2 can be met. The magrittr-based piping operator (`%>%`) is used to efficiently pass the `eseis` object from one preparation function to another. Whenever the functions of the “eseis” package are not sufficient to realise the envisioned analysis step, generic R is used. In this case, the spectra are clipped to the frequency range of interest (10–100 Hz) and stored as a data frame for further use. Likewise, the Monte-Carlo-based model spectra are isolated from the `eseis` objects and converted to a numerical matrix for efficient further calculations.

When inspecting the model output together with the other data (Fig. 8) it is evident that the turbulence model by Gimbert et al. (2014) provides a fair estimate of the independently constrained water level of the instrumented river even though the deployment conditions (distance to source, dense tree cover that effectively transmits wind energy into the ground; Dietze et al., 2015) and river boundary conditions (river size and total water run-off, river course far from straight, relative water level change during the flood) are far from favourable

Table 2. Input parameters and value ranges for the turbulence model of Gimbert et al. (2014) as implemented in the “eseis” package.

Parameter	Function argument name	Range	Unit
Average sediment size	d_s	0.001–0.01	m
Sediment size log standard deviation	s_s	1.0–1.5	log(m)
Sediment specific density	r_s	2600–2700	$\mathrm{g\,cm^{-3}}$
River width	w_w	1.0–1.5	m
River height	w_h	0.01–2.00	m
River gradient	w_a	0.03–0.05	rad
Frequency range to model	f	10–100	Hz
Station distance to source	r_0	1.5	m
Reference frequency	f_0	1	Hz
Quality factor at f_0	q_0	5–10	dimensionless
Group velocity	f_0	800–1000	$\mathrm{m\,s^{-1}}$
Quality factor increase exponent	p_0	0.40–0.60	dimensionless
Displacement amplitude factors	n_0	0.5–0.7, 0.7–0.9	dimensionless

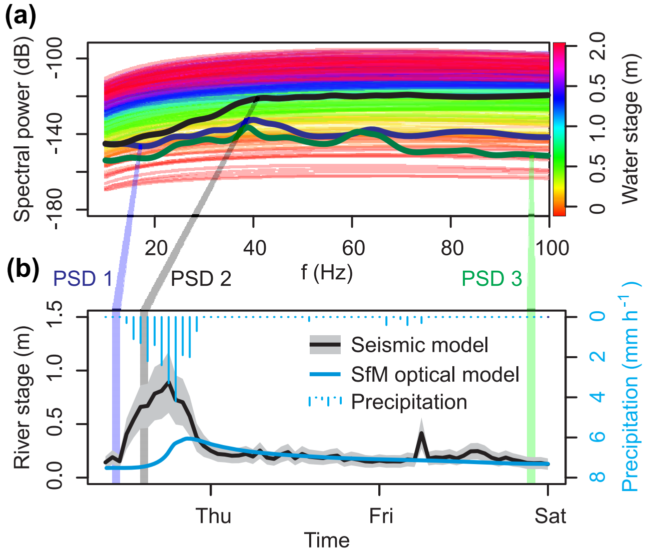


Figure 8. Results of the turbulence modelling exercise. **(a)** Monte-Carlo-based estimates of spectral power for different water stages at the Wernersbach site together with representative empirical spectra (see panel **(b)** for timing of the representative spectra). **(b)** Seismically estimated water levels including parameter-inherent uncertainty ranges (grey polygon and line) together with independent structure-from-motion-based water levels and precipitation data from a meteorological station about 6 km away. Note contamination of the seismic signal of fluvial turbulence by precipitation on Thursday and peak in seismic power due to station maintenance on Friday morning.

from a seismic and modelling perspective. For most of the modelled time period the independent water level estimate overlaps the uncertainty range of the seismic model, except for the late hours of Wednesday, 26 July 2017, when the rainstorm that triggered the small flood contaminates the seismic signal with drop impacts (see Turowski et al. (2016) for an example of the seismic signature of rain) and the maintenance visit of a nearby stream gauge early Friday.

5 Avenues of package development

The “eseis” package as described in this article is merely a snapshot of the current state of development. Projecting recent activity due to adding new functions, implementing optimised routines, feature enhancements, and bug fixes due to feedback from package users, it is hard to define a level which may be interpreted as a development plateau. However, there is a series of obvious features that should be included to expand the applicability of the package. Including these features would be significantly facilitated by expanding the number of scientists that contribute functions and interact with the package maintainer.

5.1 Anticipated future functionalities

The current functionality of the package is devoted to the analysis of signals actively emitted by Earth surface processes. An entirely different field of application is monitoring the changes in the properties of the material through which the seismic waves travel. Bedrock and sediment cover are not static parts of the system; they change by, for example, different groundwater levels, freeze–thaw transitions, propagation and closure of cracks, and reversible–irreversible compaction. Coda wave interferometry and seismic noise cross-correlation (e.g. Sens-Schoenfelder and Larose, 2008; Larose et al., 2015) are powerful methods to tackle this field. Thus, integrating the basic calculations into the “eseis” package is a relevant future task.

The location of environmental seismic sources can be determined by several approaches, of which the signal migration technique is just one. Other approaches rely on cross-correlating signals of station pairs and identifying the wave train azimuth that best explains the correlation offsets, i.e. beam forming (e.g. Lacroix and Helmstetter, 2011). For strong signals with clearly separated wave types, polarisation analysis allows for finding the azimuth from which a signal approaches a seismic station (Jurkevics, 1988; Vilajosana et al., 2008). Apart from signal correlation approaches, the amplitude of signals as recorded across a seismic network can also be used to find a location that best explains the exponentially decreasing amplitudes with distance from source to station (Aki and Ferrazzini, 2000; Burtin et al., 2016). Most of these location approaches were formulated in a script language and can thus in principle be translated to R to become valuable in increasing the applicability and flexibility of the package.

Physically based or empirical scaling models for turbulence other than fluid are becoming increasingly available (e.g. Tsai et al., 2012; Farin et al., 2015) and will allow for the tackling of innovative research questions, especially when combined with R-provided methods to account for the inherent uncertainty of the model parameters, way beyond the simple example from Sect. 4.2. Integrating such models into the “eseis” package is a step that has already started and will continue.

A key functionality for a wider acceptance of the “eseis” package will be its role in importing and exporting a wider range of data formats. Although with the SAC and mseed format the two most commonly used formats are supported – at least for import – there are other file formats in use that should be included. One potential way of reaching this goal without duplicating existing work would be to use the Obspy capacities for reading and writing data by integrating the respective modules into the compilation part while installing the package or by simply wrapping the Python code in R functions, which would make a local Obspy installation a requirement.

5.2 Getting involved

The “eseis” package will and can only evolve according to the emerging needs of researchers. Thus, from a user perspective, the most important avenue to contribute is to report bugs, provide feedback about missing features, and raise ideas on how to improve functionalities and applications. The appropriate place to do this is the GitHub page of the project: https://github.com/coffeemuggler/eseis.

In R, the transition from user to developer is soft and does not include a steep learning curve. This is one of the reasons why R has become so widely accepted and used (Tippmann, 2014). Thus, contributing ideas in the form of R code, whether models or data analysis functions, is highly welcome and would further improve the package development. R has a refined approach to assign roles to package development collaboration teams, which guarantees acknowledgement and transparency for the persons contributing to individual items of a package (RCoreTeam, 2016).

6 Conclusions

The “eseis” package provides functions to import, prepare, manipulate, analyse, visualise, and export seismic data. Thus, it contains all functionalities to engage with seismic data in general and environmental seismology topics specifically. It is not intended to replace existing open software such as Obspy that is in several fields more powerful and efficient. Rather, it is tailored to bridge different environmental scientific fields at a low level of complexity utilising an easy to learn yet broadly accepted scripting language. It contributes to this bridging effect by guaranteeing support and passing data to other differently specialised R packages.

The package will thrive from interaction between users, developers, and users eventually becoming developers – a common effect among the R community. Thus, the package maintainer openly welcomes feedback and suggestions to improve and broaden the functionality and to fix bugs and drawbacks.

One key but hitherto not fully agreed precondition to transparent and reproducible science also requires citing software and documenting the actual software environment. Citing, for example, R packages appropriately (a job that can be easily done with the R function `citation(‘‘package_name”, auto = TRUE)`) does not only acknowledge the effort scientists put into providing such tools for a broad audience. More importantly, it ensures the reproducibility of scientific results. This citing culture includes at best information about the computer platform and key system parameters, the version of the software and packages used, and the analysis chain (including parameter values). The “eseis” package provides straightforward support for this with the `write_report` function. Combined with a version control software, such as Git, the full timeline for data processing and analysis script evolution can be documented easily.

Code and data availability. The R package “eseis” (Dietze, 2018) is available both on the Comprehensive R Archive Network (CRAN) and on GitHub.

The Supplement related to this article is available online at https://doi.org/10.5194/esurf-6-669-2018-supplement.

Author contributions. MD wrote the R package “eseis”, evaluated the worked examples, and wrote the paper.

Competing interests. The author declares that there is no conflict of interest.

Special issue statement. This article is part of the special issue “From process to signal – advancing environmental seismology”. It is a result of the EGU Galileo conference, Ohlstadt, Germany, 6–9 June 2017.

Acknowledgements. The author of this article wishes to thank Kirsten Elger for DOI and landing page coordination, Anette Eltner for providing the optical water level data, Stefanie Puffpaff, Ingolf Stodian, and the Jasmund/Rügen National Park team for the seamless collaboration and data assistance, Arnaud Burtin for essential discussion at early stages of the project and insight to his scripts, Sophie Lagarde for her efforts in writing up the turbulence model, Anne Schöpa and Kristen Cook for helpful feedback on the package performance and discovering painful bugs, Trond Ryberg and Christoph Lendl for the patience with my demands, Karl-Heinz Jäckel for enlightening discussions about sensors and data handling, Omnirecs for providing tailored instruments, and the R community for the marvellous range of just perfect packages.

The article processing charges for this open-access
publication were covered by a Research
Centre of the Helmholtz Association.

Edited by: Florent Gimbert
Reviewed by: two anonymous referees

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