Visualisation for bioacoustics and ecoacoustics in R

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About

Bioacoustics and ecoacoustics are rapidly advancing multi-disciplinary fields of study that focus on how organisms communicate using sound and the overall sound of a landscape (the soundscape). Despite focusing on sound, much of the sharing of ideas between researchers uses graphical representations of some audio features.

The use of visual aids should not come as a surprise; the printing press came centuries before the radio as a means of long-distance communication. Ink on paper has a permanence that sounds would not achieve for a long time after the invention of writing. The current flourishing of acoustic disciplines is driven as much by the low cost and ease of use of products such as AudioMoth and the decreasing cost of digital storage and processing as by novel ideas.

Visualisations of acoustic data, however, are not going away. We are a predominantly visual species, and as ways of summarising acoustic data - or making the ultrasound tangible, they are powerful tools in the hands of the acoustician.

Author

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Chapter 1

Introduction

> "…while we take it for granted that sounds may be described visually, the convention is recent, is by no means universal and, as I will show, is in many ways dangerous and inappropriate."
>
> — Schafer [1977]

While Murray Schafer's *Tuning of the World* [Schafer, 1977] inspired many soundscape scientists, this view is of an earlier time when the concept of multiple simultaneous streams of acoustic data processed in real time by a single entity was still an idea beyond the horizon. Individual sounds could be isolated and studied (as today they still are by bioacousticians interested in the behaviour of individual species). The scale of many contemporary ecoacoustics projects precludes an individual from listening to every minute recorded; the task is no longer delegated to students but to networks of machines.

Additionally, it is now helpful to distinguish between two concepts that Schafer bought together under the concept of *notation*. That is to separate notation (phonetics and musical notation) from visual representations of the physical properties of acoustic waves (e.g. amplitude, frequency).

Historically, researchers used musical notation and phonemes to describe the songs of various animals. However, these methods do not scale to the entirety of the natural soundscape. Parts of the soundscape are beyond the limits of human hearing; the infrasound, the ultrasound, and the quiet. All manner of information is gathered and shared by other species beyond the limits of our perception. Visualisation is the primary tool by which we can interpret the entire soundscape for all species that share it.

1.1 Predominance of the visual

1.2 Basic acoustic concepts

A sound wave is a disturbance in the air that propagates as a series of compressions (the regions between are known as regions of rarefaction), see Figure 1.1. The frequency of a sound wave is the number of compressions and rarefactions that pass a point in a second. The amplitude of a sound wave is the difference between the maximum and minimum pressure of the wave.

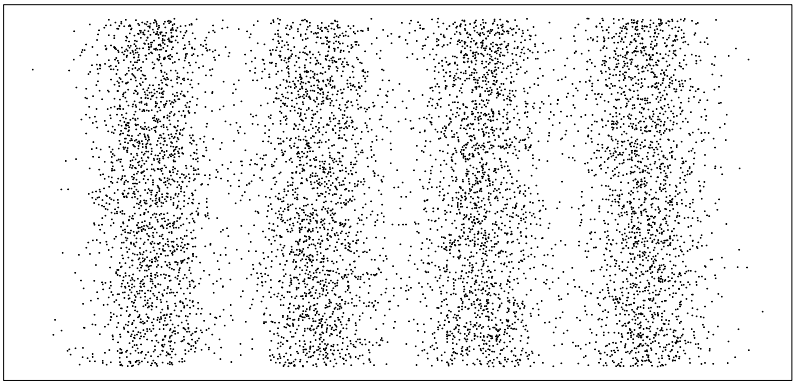

Figure 1.1: A wave in air.

1.3 Types of files

Even though the costs of digital storage have fallen significantly (Figure 1.2), the cost of file transfer and storage are still significant factors in many acoustics projects. For this reason, it is sometimes necessary to compress the audio file in some way: discarding some data in exchange for cost reductions.

This process of compression may affect the visualisation of the audio files or even the possible types of visualisation for a given file.

1.3.1 Uncompressed waveform files

Waveform files are created by sampling the wave amplitude at a sensor at a constant rate, typically tens of thousands of times per second (Figure 1.3).

An analogue-to-digital converter (ADC) converts the continuous variations in amplitude into one of the numerous discrete levels that the ADC can represent

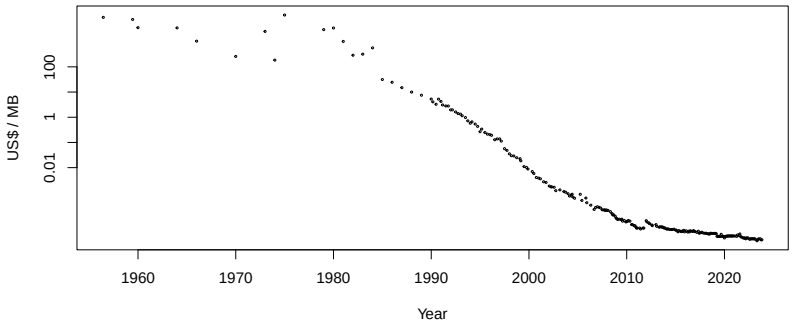

Figure 1.2: Storage costs per megabyte over time. Data from https://jcmit.net/diskprice.htm.

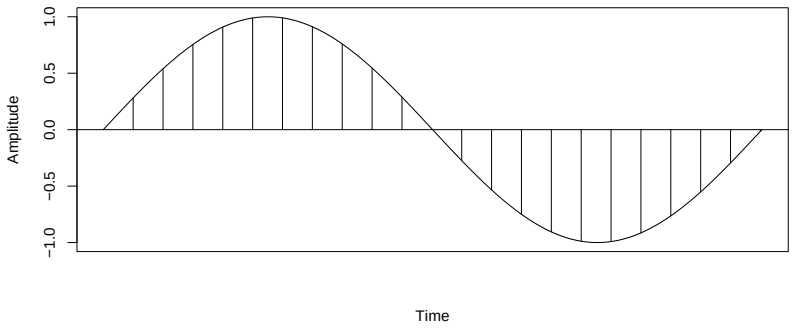

Figure 1.3: Sampling a waveform.

(Figure 1.3. The number of discrete levels is dependent on the analogue-to-digital converter (ADC); a typical 16-bit depth has $2^{16} = 65536$ possible values.

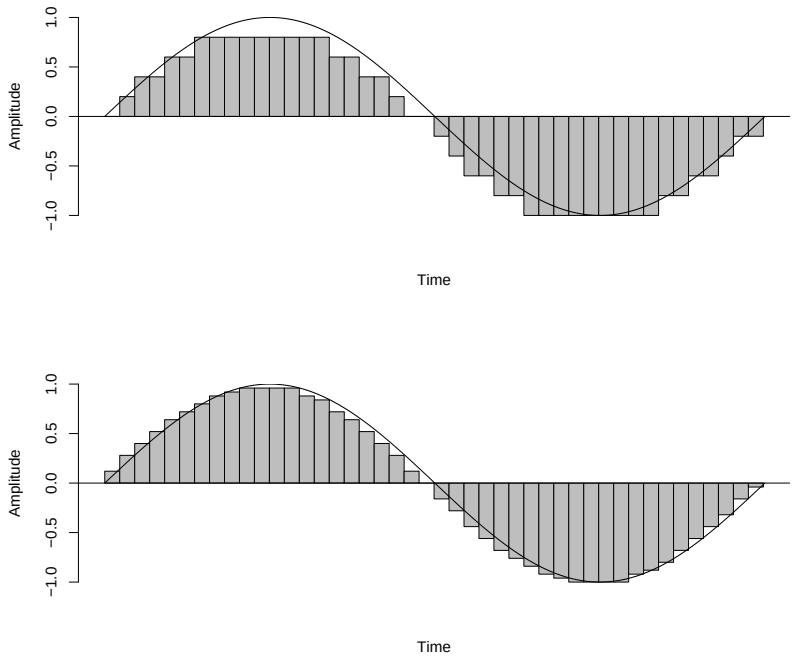

Figure 1.4: A sampled waveform with low bit depth (top) and higher bit depth(bottom).

1.3.2 Lossy compression

1.3.3 zero-crossing

Chapter 2

History

2.1 Goals of visualisation

Many tasks require the visualisation of acoustic information. Purely descriptive graphical representations may aim to invoke in the mind the sound represented. These visualisations allow passing knowledge of how something sounds from one mind to another.

> "I have frequently experimented with graphic notations, and in the course of these experiments it has occurred to me that a new type of artistic experience may be opening up to us, in which musical clements could have revitalized graphic correspondences in such a way that one sensation could be triggered by another to produce synaesthesia - that is, a fusion of two art forms into a unitary experience."
>
> — [Schafer, 1975]

The decreasing costs of electronic data storage and transmission reduce the need for converting audio into graphical form for financial reasons. However, these trends contribute to an increased abundance and availability of acoustic data. It is usually quicker and easier to scan this large quantity of acoustic information when it is represented visually than by listening to it (Figure 2.1).

Notably, many current machine learning techniques used in acoustics work upon data previously converted into graphical form. Is this an optimum method, or just a consequence of the Predominance of the Visual?

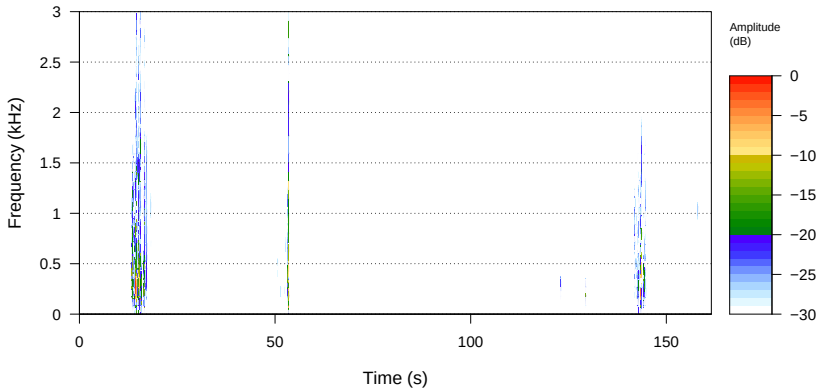

Figure 2.1: Even for a short file of three minutes duration it is quicker to identify regions of interest visually than by listening.

2.2 Descriptive acoustics

2.2.1 Phonemes and onomatopoeia

2.2.2 Musical notation

The standard musical notations show broad similarities with a typical audio visualisation familiar to all bioacousticians and ecoacousticians - the frequency against time plot. Time proceeds in a strictly linear fashion from left to right, and frequency increases from bottom to top.

2.3 Analytic acoustics

2.3.1 The 'big-three'

2.3.1.1 Amplitude vs Time

2.3.1.2 Ampltiude vs Frequency

2.3.1.3 Frequency vs Time

2.3.2 The Fourier Transform

2.3.2.1 Fast Fourier Transform

Chapter 3

Early visualisations - the analogue years

3.1 CRTs

3.2 Print outs

Chapter 4

Static digital images

The three fundamental quantities of sound waves are time, frequency, and amplitude. The most commonly used visualisations of sounds are consequently combinations of these properties.

The `seewave` package [Sueur et al., 2008] is the easiest way to produce these plots. We will use the `sheep` audio sample provided by `seewave` for the first plots.

```
library(seewave)
data(sheep, package="seewave")
```

4.1 The time domain

Time domain techniques analyse the recorded waveform directly. Conversion of a waveform to a spectrum of frequencies is a relatively costly computation. Before digital computers, frequency analysis was hard to achieve with the precision and resolution we are accustomed to today.

4.1.1 Oscillograms

Digitally sampled audio is a series of amplitude measurements sampled at a regular time interval. The most basic plot we could recreate from a sampled file would be plotting amplitude values against time, a plot known as an oscillogram.

Figure 4.1 shows 50 samples from the sheep audio file plotted using the standard R barplot()function. This representation has the advantage that the individual bars are a visual reminder that we are handling a sampled representation instead of a continuously varying waveform. It is common, however, to create a visual

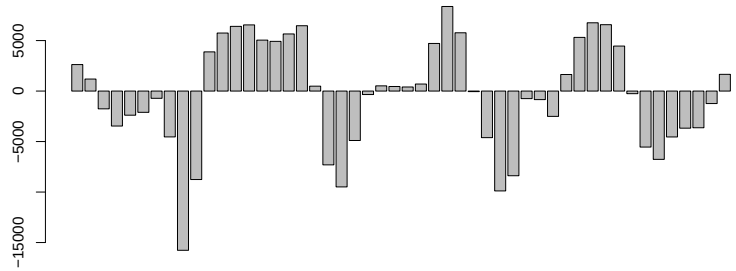

Figure 4.1: Plotting a waveform

representation closer to that of an actual wave (Figure 4.2 shows how this is achieved using base R functions).

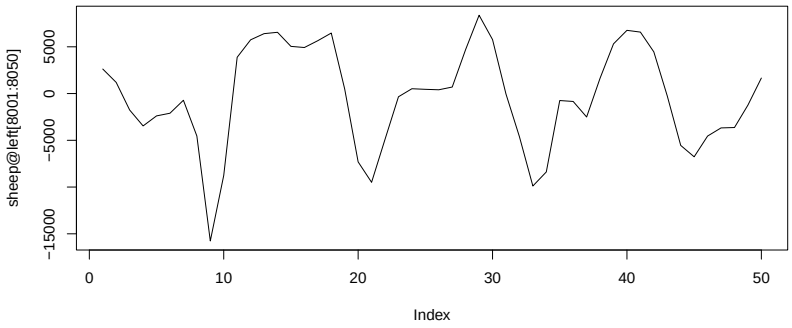

Figure 4.2: Plotting a waveform

The `oscillo()` function from `seewave` handles the labelling of axes for us and is a very convenient solution. Figure 4.3 shows the resulting plot, an oscillogram, for the entire `sheep` file.

4.1.1.1 Relation to time series

The time series plot of a variable against time is often used in statistical analysis of time series. The oscillogram is in fact a time series plot, in this case a plot of a series of amplitude (air pressure) measurements against time.

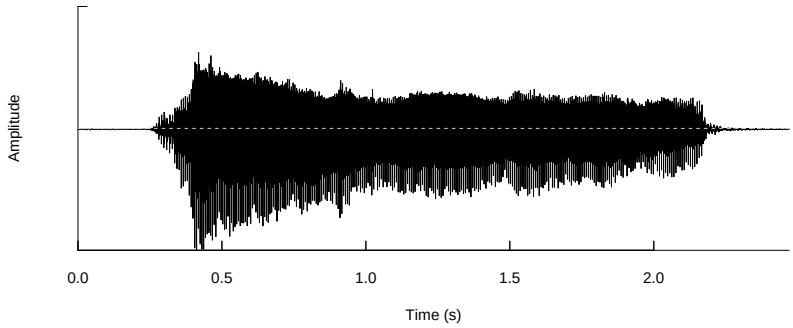

Figure 4.3: Oscillogram

4.2 The frequency domain

The *frequency domain* covers analyses in which frequency data are extracted from the sampled waveform, typically using the *Fast Fourier Transform* algorithm.

4.2.1 Plotting a spectrum

A spectrum is a plot of amplitude against frequency.

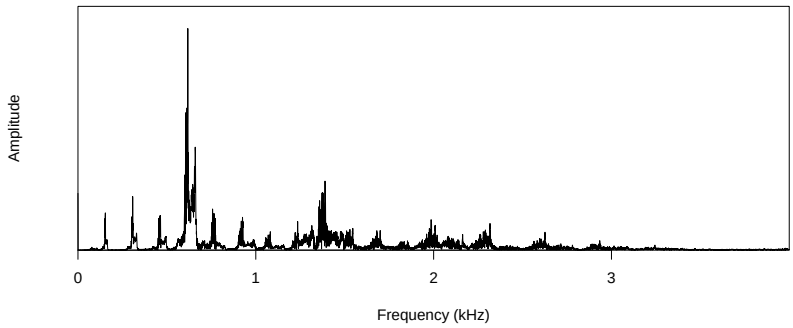

Figure 4.4: Spectrum

4.2.2 Plotting a spectrogram

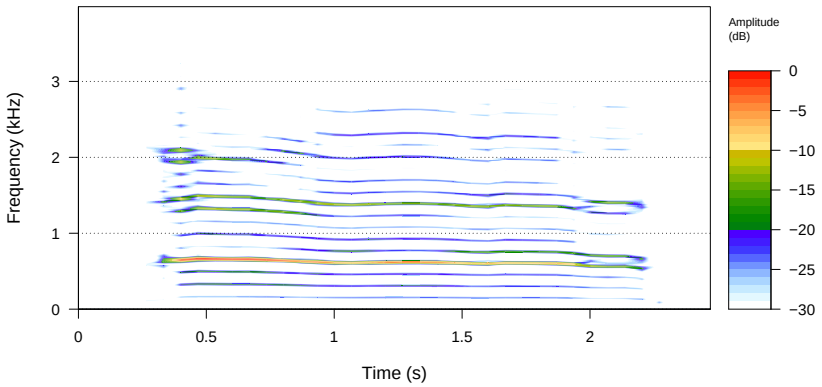

Figure 4.5: Spectrogram

4.2.2.1 Settings for a FFT

Chapter 5

Dynamic digital visualisations

5.1 Video spectrograms

5.2 zcjs: Zero-crossing File Visualisation

The zcjs JavaScript library was originally developed for displaying zero-crossing audio files (1.3.3) on the web as part of the BioAcoustica project (https://bio.acousti.ca; Baker et al. [2015]). The `zcjs` package [Baker, 2022] imports this visualisation functionality into R.

The following code installs the `zcjs` package.

```
install.packages("devtools")
devtools::install_github("bioacoustica/zcjs-r")
```

To load the package:

```
library(zcjs)
```

The package comes with a demonstration file for testing the package's functionality.

5.2.1 Customising a zcjs plot

x-compress

Chapter 6

Representing Soundscapes

6.1 False Colour Index Spectrograms

Chapter 7

Patterns of activity

Many organismal activities are tied to the cycles of the day, particularly in temperate zones, cycles of the year. These cycles bring regular fluctuations in light levels, day lengths, temperatures, and various other influences. Often these cycles interact, with the dawn chorus peaking in the early daylight hours and its timing and intensity fluctuating on a yearly cycle. This chapter looks at visualising these cycles and the effects of lunar cycles.

These plots are created using the SonicScrewdriver package [Baker, 2021], which uses the suncalc package [Thieurmel and Elmarhraoui, 2019] to perform the required sun and moon position calculations. The Plotrix package [Lemon, 2006] is used for creating the visualisation. These packages are installed as shown below.

```
install.packages(c("plotrix", "sonicscrewdriver"))
```

The SonicScrewdriver package must be loaded before constructing a visual.

```
library(sonicscrewdriver)
```

7.1 Daily Cycles

Broughton (1963) contests the term diel for daily cycles as an incorrectly formed, unnecessary neologism. However, it sees greater use (according to the online Oxford English Dictionary) than his suggested nycthemeral.

The design for these plots came from a desire to compare the dawn chorus at various locations around the UK. However, they also offer great potential for comparing locations with greater longitudinal or latitudinal separation. The

plots show the times of day, night, twilight (7.1.1), sunrise, sunset, nadir and solar noon. The day part of the plot shows the altitude (angle of the sun above the horizon) throughout the day, with the maximum value representing the sun directly overhead.

7.1.1 The Types of Twilight

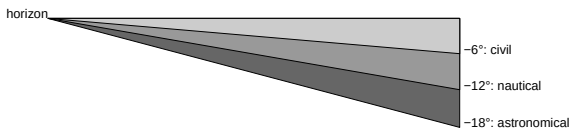

Figure 7.1: Different types of twilight as the sun sets below the horizon

7.1.1.1 Civil Twilight

Civil twilight occurs when the sun's geometric centre (as seen from Earth) passes between 0° and 6° below the horizon. During this time, it is normal for humans not to need the assistance of artificial light for everyday tasks.

7.1.1.2 Nautical Twilight

Nautical twilight occurs when the sun is between 6° and 12° below the horizon. During this time, there is sufficient light to distinguish the horizon without illumination from the moon (allowing the determination of position at sea through star sightings).

7.1.1.3 Astronomical Twilight

Many astronomical observations are possible when the sun is between 12° and 18° below the horizon. Some light from the sun is visible through the atmosphere. Often considered a dark sky in urban areas with light pollution.

7.1.2 Diel Plots

As the times of the solar day are dependent both on the date and location these must be passed to the `dielPlot()` function.

```
dielPlot("2022-08-08", lat=53, lon=0.1)
```

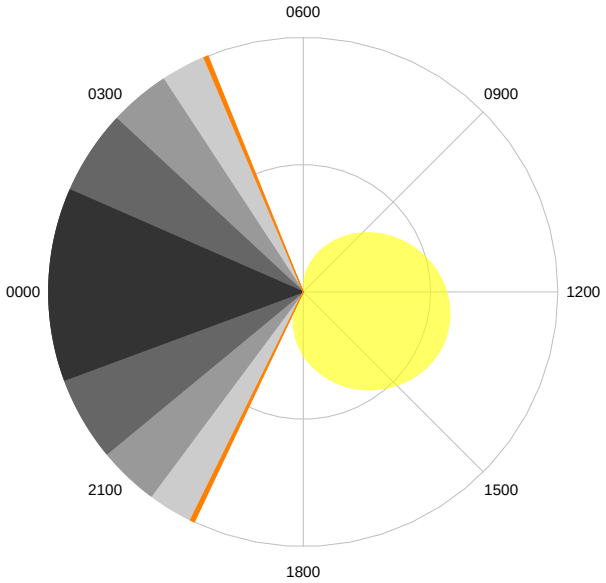

Figure 7.2: Example of a diel plot

7.1.2.1 Rotations of a `dielPlot()`

By default the information is plotted in the UTC timezone, so locations in other timezones will have an overall rotation.

```
par(mfrow=c(1,3))
dielPlot(Sys.Date(), lat=53, lon=-50)
dielPlot(Sys.Date(), lat=53, lon=-0)
dielPlot(Sys.Date(), lat=53, lon=50)
```

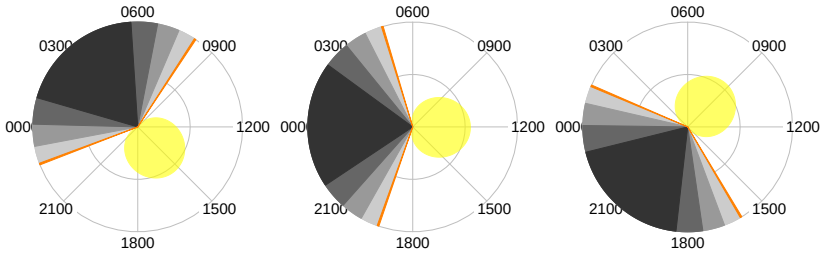

Figure 7.3: Diel plots in UTC.

Plots can be made in any timezone by using the `rot` parameter to `dielPlot()` and the `tz()` function.

```
par(mfrow=c(1,3))
dielPlot(Sys.Date(), lat=53, lon=-50, rot=tz(3))
dielPlot(Sys.Date(), lat=53, lon=-0, rot=tz(3))
dielPlot(Sys.Date(), lat=53, lon=50, rot=tz(3))
```

By setting the `rot` parameter to `Solar Noon` it is possible to align the plots to solar noon. Notice that this rotates the plot labels.

```
par(mfrow=c(1,3))
dielPlot(Sys.Date(), lat=53, lon=-50, rot="Solar Noon")
dielPlot(Sys.Date(), lat=53, lon=-0, rot="Solar Noon")
dielPlot(Sys.Date(), lat=53, lon=50, rot="Solar Noon")
```

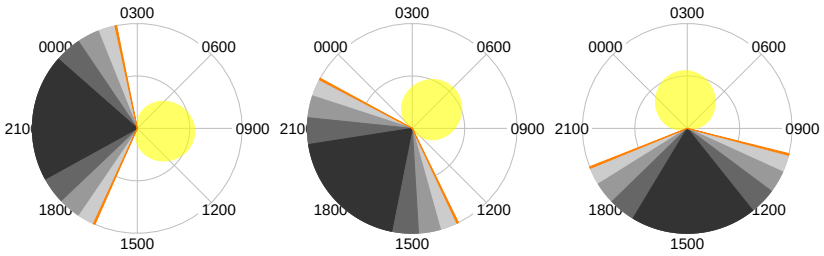

Figure 7.4: The same diel plots in UTC +3

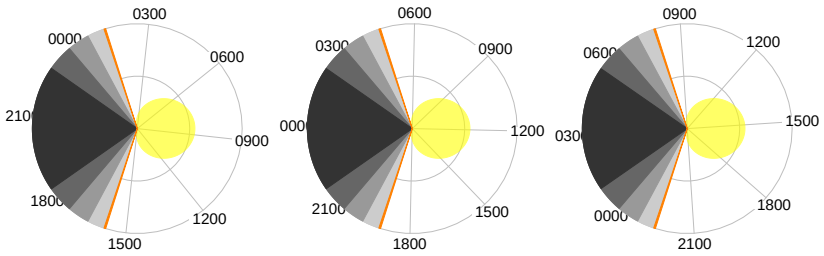

Figure 7.5: The same diel plots aligned to solar noon

7.1.2.2 Customising a `dielPlot()`

In addition to the `date`, `lat` and `lon` parameters to `dielPlot()` it is possible to make additional customisations to how the information is presented.

Legend

A legend can be added to the plot by setting `legend=TRUE`.

```
dielPlot("2022-08-08", lat=53, lon=0.1, legend=TRUE)
```

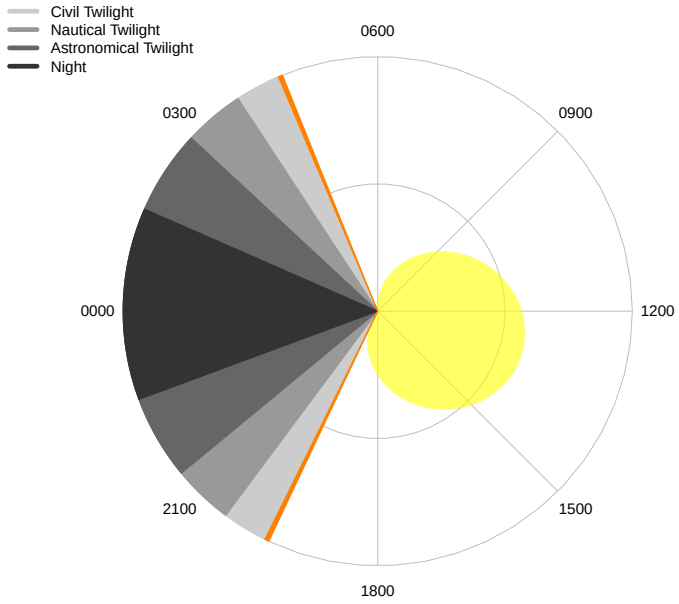

Figure 7.6: Example adding a legend to a diel plot

Plotting Components

The components that can be plotted are listed below. By default all are plotted except for `Solar Noon` and `Nadir`.

Name	Notes
Astronomical Twilight	
Nautical Twilight	
Civil Twilight	
Sunrise	
Solar Noon	The time when the sun is highest in the sky

Name	Notes
Sunset	
Nadir	

The components that are plotted can be specified using the `plot` parameter.

```
components <- c("Sunrise", "Sunset", "Solar Noon", "Nadir")
dielPlot("2022-08-08", lat=53, lon=0.1, plot=components)
```

7.2 Yearly Cycles

The `yearlyPlot()` function from the SonicScrewdriver package shows daylight changes throughout a year. It behaves in a very similar fashion to `dielPlot` but takes a single year rather a date as input.

```
yearlyPlot(2022, lat=53, lon=0.1)
```

7.3 Lunar Cycles

7.4 Core and ring plots

These visualisations for cyclical data plot their information onto a circle with a radius of two units. It is possible to limit the plot either to the centre of the circle (a 'core' plot) or to the edge (a 'ring plot'). These alternative forms may be more useful when these plots are used to visualise addition variables (7.7).

```
dielPlot("2022-08-08", lat=53, lon=0.1, limits=c(0,1))
```

```
dielPlot("2022-08-08", lat=53, lon=0.1, limits=c(1,2))
```

7.5 Behind the scenes

7.5.1 `radialPolygon()`

The `radialPolygon()` function handles most of the plotting functionality for cyclical data in `SonicScrewdriveR`. It handles sectors, annuli, horizon plots and

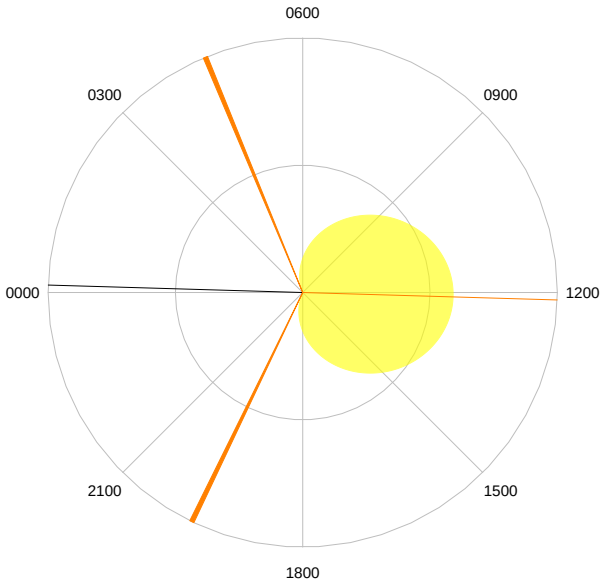

Figure 7.7: Selecting the components to plot

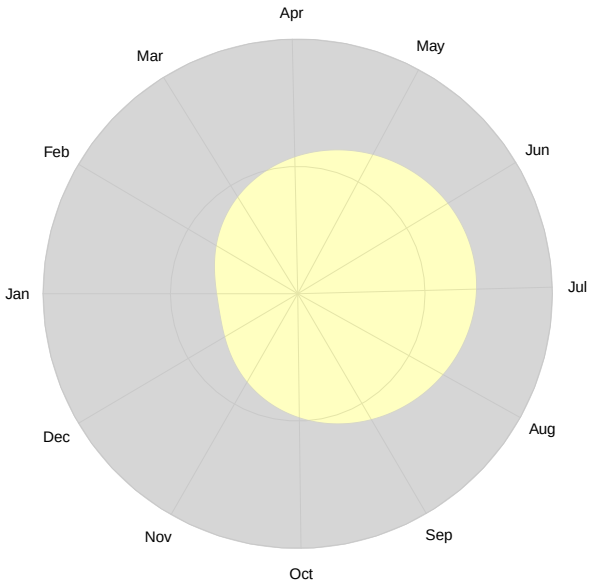

Figure 7.8: Example of a yearly plot

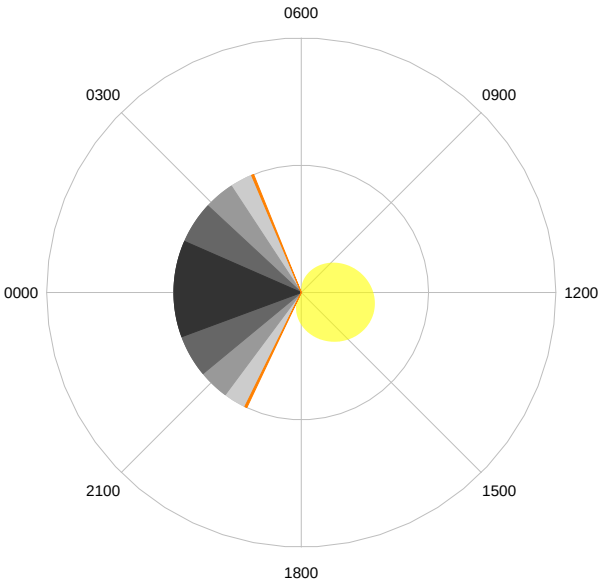

Figure 7.9: A 'core' diel plot.

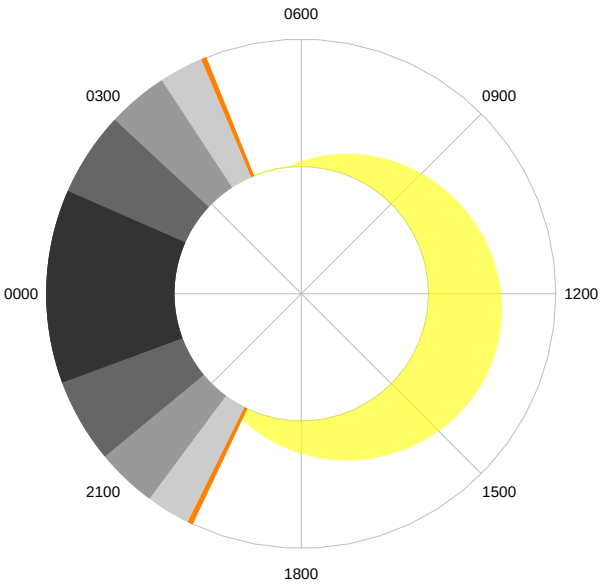

Figure 7.10: A 'ring' diel plot.

irregular polygons. It is used by the plotting functions such as `dielPlot()` and helper functions such as `dielRings()` to add data to cyclical plots.

For simple use cases, knowledge of the operation of `radialPolygon()` may not be needed. Several helper functions cover the most common uses. However, understanding how this function works will allow for far greater customisation of cyclical plots than would otherwise be possible.

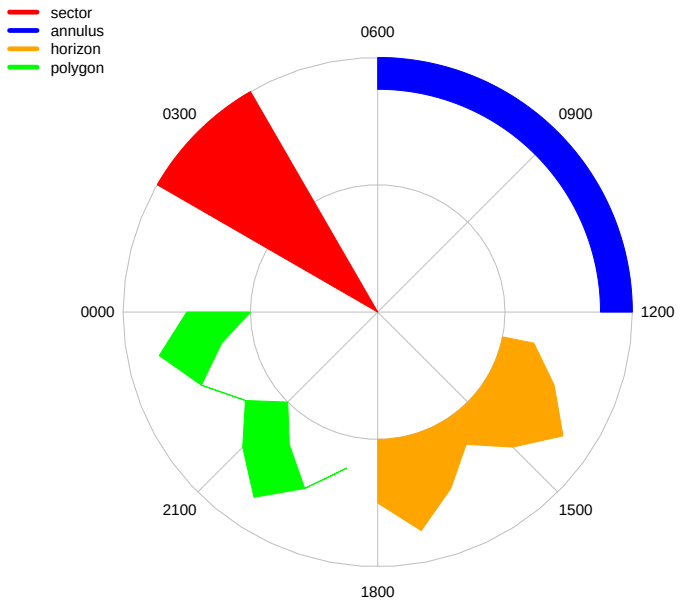

Figure 7.11: Types of radial polygon plot

The various types of plots are created by changing the angle and radius parameters to `radialPolygon()`.

```
radialPolygon(angle1, angle2, radius1, radius2, col)
```

7.5.1.1 Orientation

Unlike traditional polar plots, diel and yearly plots start their periods on the left hand horizontal, and proceed clockwise. This orientation is assumed by `radialPolygon()`, although it may be modified (e.g. the parameters `reverse=FALSE` and `rot=0` will plot using the standard conventions for polar coordinate systems.)

7.5.1.2 Sectors

A sector is a section of a circle defined by two radii and an arc between them. Sectors are used widely in the default settings of `dielPlot()` to plot the times of night and twilight.

```
emptyDiel()
radialPolygon(pi/6, 2*pi/3, 0, 2, col="red")
```

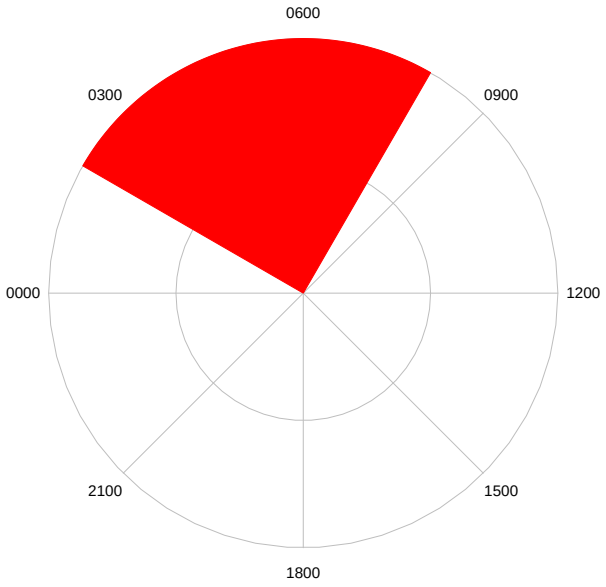

Figure 7.12: Plotting a sector

Reversing the angle arguments allows the complementary sector to be drawn.

```
emptyDiel()
radialPolygon(2*pi/3, pi/6, 0, 2, col="blue")
```

7.5.1.3 Annuli

An annulus is the region between two concentric circles. Annuli and annular sectors are generated by `radialPolygon()` when the parameter `radius` is greater than zero.

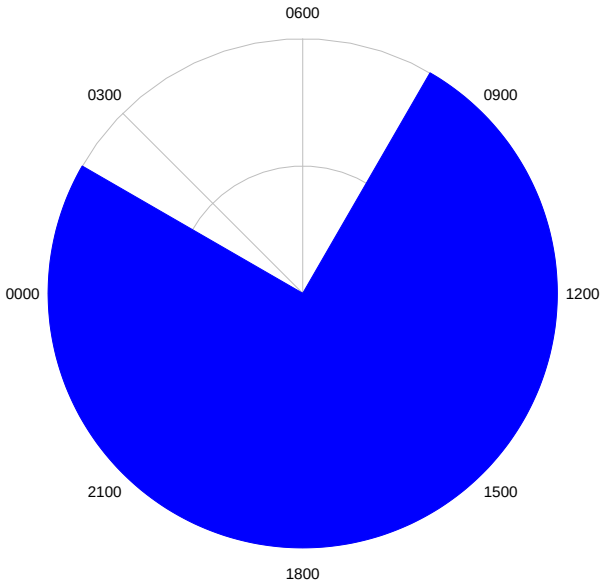

Figure 7.13: Plotting a sector

```
emptyDiel()
radialPolygon(0, 2*pi, 1.75, 2, col="blue")
radialPolygon(pi, 4*pi/3, 1, 1.5, col="red")
legend(
  -3,2.5,
  c("annulus", "annuluar sector"),
  col=c("blue", "red"),
  lty=1,
  lwd=5,
  bty = "n",
  cex = 1)
```

7.5.1.4 Horizons

Horizons have one circular edge, and one that represents data, they are named as they often resemble a landscape or cityscape horizon. The example below uses a generated sine pattern to form the data edge.

```
library(tuneR)
```

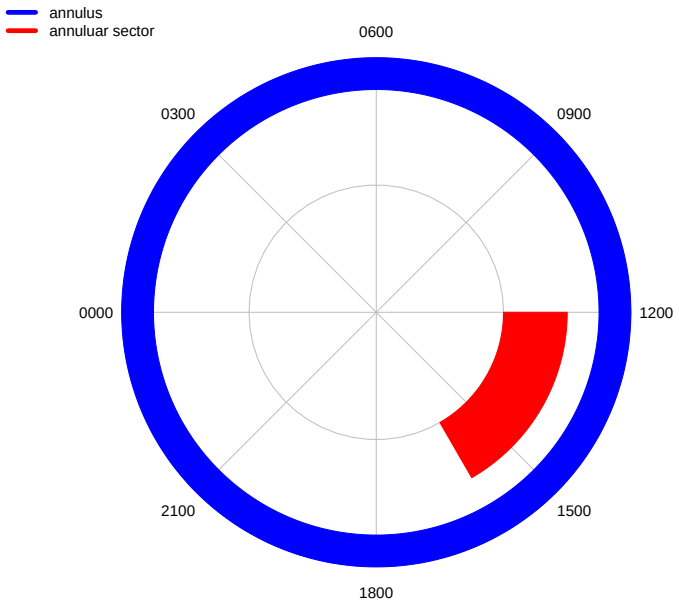

Figure 7.14: Plotting an annulus and an annular sector

```
angles <- (0:200)*pi/200 + pi/2
values <- 0.05*sine(10, samp.rate=201)@left

emptyDiel()
radialPolygon(NA,angles,0.5,1+values)
```

Setting the first angle parameter to `NA` uses the range of the second to calculate the inner edge.

The inner edge can be used to show data by swapping the order of the angle and radius parameters.

```
library(tuneR)

angles <- (0:200)*pi/200 + pi/2
values <- 0.05*sine(10, samp.rate=201)@left

emptyDiel()
radialPolygon(angles,NA,1+values,2)
```

The `yearlyPlot()` function uses two horizon plots, with a shared data edge.

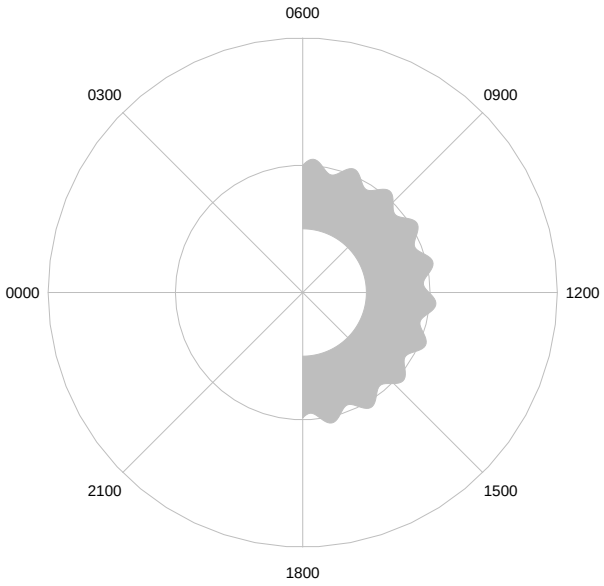

Figure 7.15: Plotting a horizon polygon.

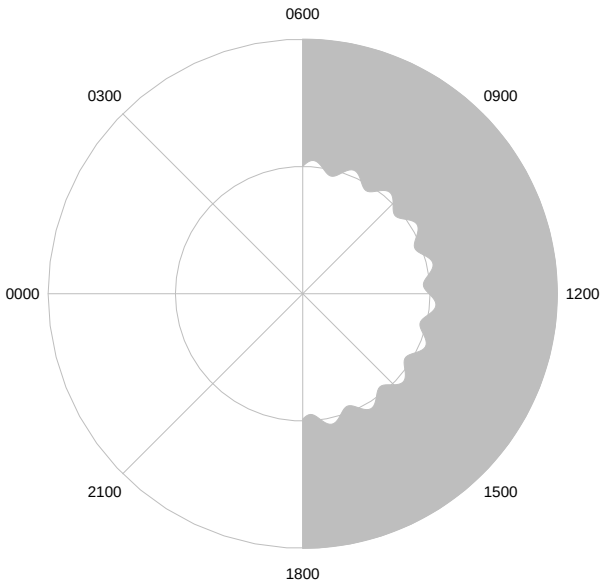

Figure 7.16: Plotting a horizon polygon.

7.5.1.5 Polygons

7.6 Empty plots

The uses of daily and yearly plots extend beyond linking data to earthly cycles. The following functions provide the basic coordinate system without any data plotted (these functions are used intenally by `dielPlot()` and `yearlyPlot()` to establish their coordinate system).

7.6.1 `emptyDiel()`

```
emptyDiel()
```

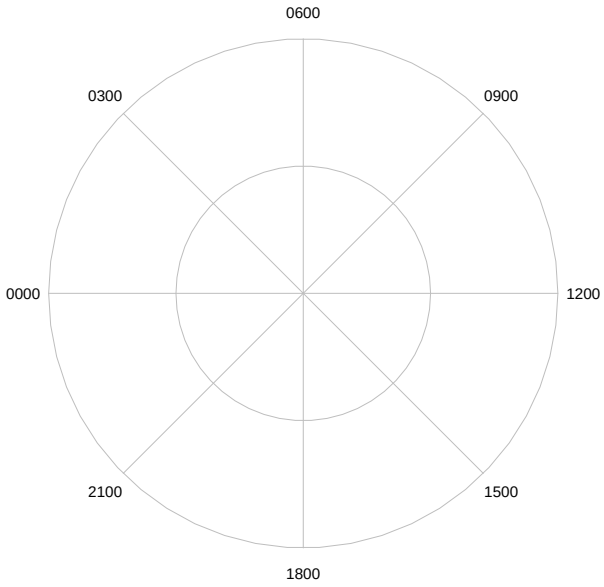

Figure 7.17: An empty dielPlot().

7.6.2 `emptyYearly()`

The `emptyYearly()` function takes an option `year` parameter that automatically adjusts the grid positions for leap years, although the visual effect is marginal.

```
emptyYearly(year=2000)
```

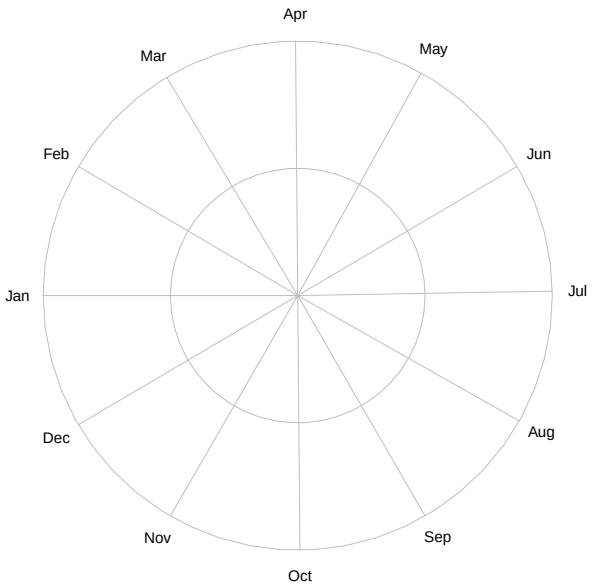

Figure 7.18: An empty yearlyPlot().

7.7 Adding data to the visualisation

7.7.1 Periodic data: rings

The ring functions (`dielRing()`,...) plot ring segments on top of a base cyclical plot. These rings are useful for showing typical periods of activity for a species, or events that happen continuously for a specified period of time.

By defaults the limits for the rings are `1,2` for use with a *core* type plot, but this can be changed by specifying the `limits` parameter to the ring function. Similarly, the plot legend may be removed with the paramater `legend=FALSE`.

7.7.1.1 `dielRings()`

```
names <- c("activity 1", "activity 2", "activity 3")
starts <- c("0600", "0900", "1500")
```

```
ends <- c("1200", "1700", "1900")
cols <- c("red", "green", "blue")

dielPlot("2022-08-08", lat=53, lon=0.1, limits=c(0,1))
dielRings(names, starts, ends, cols=cols)
```

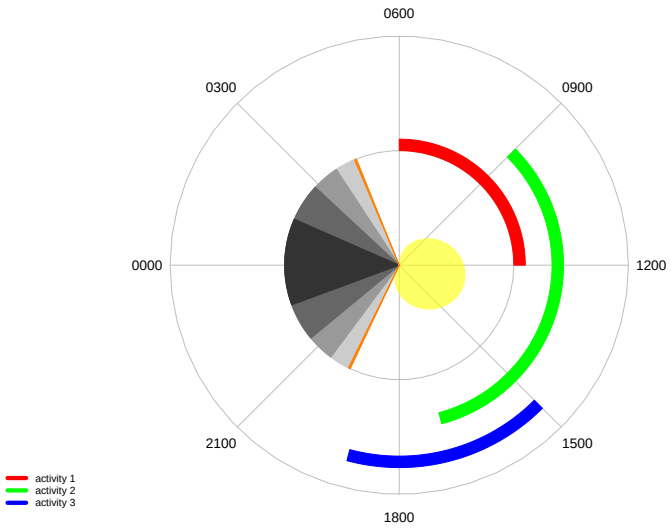

Figure 7.19: A 'core' diel plot with diel rings.

```
names <- c("activity 1", "activity 2", "activity 3")
starts <- c("0600", "0900", "1500")
ends <- c("1200", "1700", "1900")
cols <- c("red", "green", "blue")

dielPlot("2022-08-08", lat=53, lon=0.1, limits=c(1,2))
dielRings(names, starts, ends, cols=cols, limits=c(0,1))
```

7.7.2 Periodic data: horizons

In this example we will plot the average monthly minimum and maximum temperatures for Lyme Regis, UK onto a `yearlyPlot()`. This example introduces three small helper functions; `yearlyLabels()`, `yearlyPositions()` and `circularise()`.

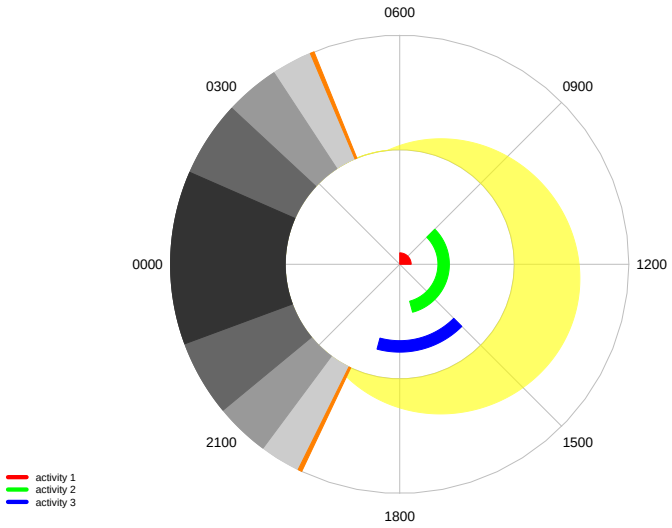

Figure 7.20: A 'ring' diel plot with diel rings.

7.7.2.1 `yearlyLabels()` and `yearlyPositions`

These two functions are closely related, and used internally by `SonicScrewdriveR` to label a yearly plot.

```
yearlyLabels()
```

```
##  [1] "Jan" "Feb" "Mar" "Apr" "May" "Jun" "Jul" "Aug" "Sep" "Oct" "Nov" "Dec"
```

The related `yearlyPositions()` gives angular positions for the data around the plot (in radians).

```
yearlyPositions(year=2022)
```

```
##  [1] 0.0000000 0.5336404 1.0156382 1.5492786 2.0657048 2.5993452 3.1157713
##  [8] 3.6494117 4.1830521 4.6994783 5.2331187 5.7495449
```

The temperature data we have for Lyme Regis is monthly, however we would like to plot the values at the middle of the respective month. For this we add the parameter `format="mid-month"` to get the appropriate radial angles.

```
yearlyPositions(year=2022, format="mid-months")
```

```
##  [1] 0.2668202 0.7746393 1.2824584 1.8074917 2.3325250 2.8575582 3.3825915
##  [8] 3.9162319 4.4412652 4.9662985 5.4913318 5.9733296
```

If we now plot this data we see that the output is not quite a complete ring or horizon data as we might have expected.

```
# Temperature data for Lyme Regis
t_min <- c(3, 2.7, 3.4, 5.2, 8.2, 11.2, 13.1, 13, 14.4, 9.2, 5.8, 3.8)
t_max <- c(7.9,8, 9.8, 12.4, 15.4, 18.2, 20.1, 19.5, 17.8, 14.4, 10.6, 8.4)

# Scale the data
sf <- max(t_max)
t_min <- t_min/sf
t_max <- t_max/sf

angles <- yearlyPositions(format="mid-months")

yearlyPlot(lat=50.7, lon=-2.9)
radialPolygon(angles, angles, t_min, t_max, col="orange")
```

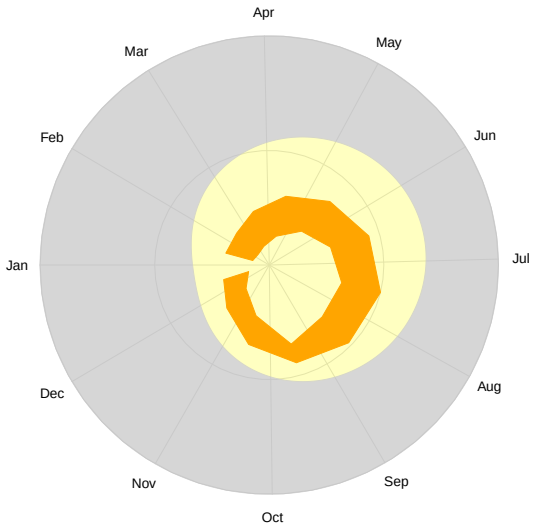

Figure 7.21: Horizon data plot without circularise().

7.7.2.2 `circularise()`

In order to join the horizons into a complete ring we can use the `circularise()` function on the angle and temperature vectors.

```
# Temperature data for Lyme Regis
t_min <- c(3, 2.7, 3.4, 5.2, 8.2, 11.2, 13.1, 13, 14.4, 9.2, 5.8, 3.8)
t_max <- c(7.9,8, 9.8, 12.4, 15.4, 18.2, 20.1, 19.5, 17.8, 14.4, 10.6, 8.4)

# Scale the data
sf <- max(t_max)
t_min <- t_min/sf
t_max <- t_max/sf

angles <- yearlyPositions(format="mid-months")

# Circularise
t_min <- circularise(t_min)
t_max <- circularise(t_max)
angles <- circularise(angles)

yearlyPlot(lat=50.7, lon=-2.9)
radialPolygon(angles, angles, t_min, t_max, col="orange")
```

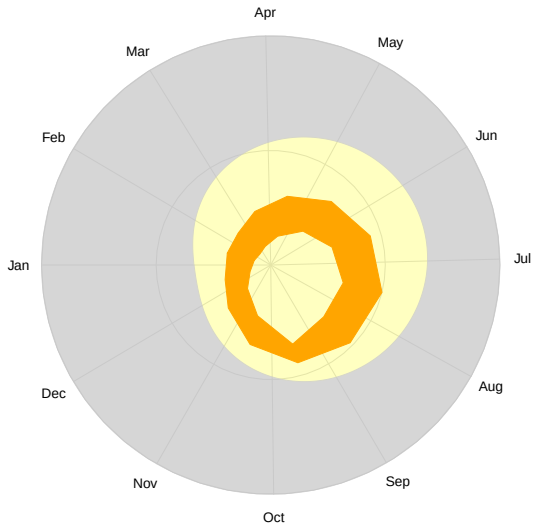

Figure 7.22: Horizon data plot with circularise().

7.7.3 Helper functions

7.7.3.1 `dielFraction()`

The `dielFraction()` function is used to convert a POSIX time, or a time in `HHMM` string format, into a radial fraction. This function is called by `dielPlot()` and `dielRings()`. By default the output is multiplied by 2 π to output a position round a circle.

```
time <- Sys.time()
print(time)
```

```
## [1] "2024-01-24 19:11:32 GMT"
```

```
frac <- dielFraction(time)
print(frac)
```

```
## [1] 5.024525
```

The raw fraction can be specified using the parameter `unit="fraction"`.

```
time <- Sys.time()
print(time)
```

```
## [1] "2024-01-24 19:11:32 GMT"
```

```
frac <- dielFraction(time, unit="fraction")
print(frac)
```

```
## [1] 0.7996782
```

7.7.3.2 `yearlyFraction()`

Similarly to `dielFraction()`, `yearlyFraction()` by default returns a fraction of a cycle. It can take either a number representing a day of the year, or an object that can be coerced into `POSIXlt` format.

```
frac <- yearlyFraction(31, input="day")
print(frac)
```

```
## [1] 0.5336404
```

```
date <- Sys.Date()
print(date)
```

```
## [1] "2024-01-24"
```

```
frac <- yearlyFraction(date, input="POSIXlt")
print(frac)
```

```
## [1] 0.3959267
```

7.8 Interactive Plots

These plots can be used to create Shiny apps

- shiny-diel is an example that shows diel plots for a number of locations, and can be animated using the play button under the date slider.

Chapter 8

Displaying annotations

Chapter 9

Shiny: Interactive Web Apps

Chapter 10

The Future

Chapter 11

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