Supplementary Material for: A Rough Guide to Pre-processing High-Frequency Animal Tracking Data

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1 Processing calibration data

Here we show how the residence patch method (Barraquand and Benhamou 2008; Bijleveld et al. 2016; Oudman et al. 2018) accurately estimates the duration of known stops in a track collected as part of a calibration exercise in the Wadden Sea.

1.1 Prepare libraries

First we prepare the libraries we need. Libraries can be installed from CRAN if necessary.

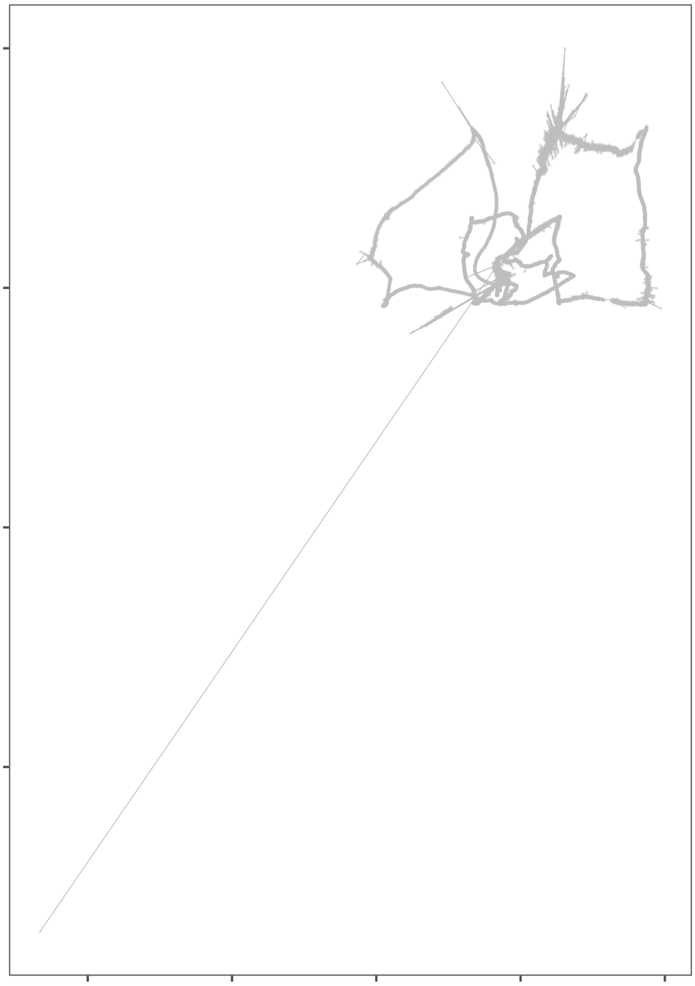
```
# load libs
library(data.table)
library(atlastools)
library(ggplot2)
library(patchwork)

# prepare a palette
pal <- RColorBrewer::brewer.pal(4, "Set1")
```

1.2 Access data and preliminary visualisation

First we access the data from a local file using the `data.table` package (Dowle and Srinivasan 2020). We then visualise the raw data.

```
# read and plot example data
data <- fread("data/atlas1060_allTrials_annotated.csv")
data_raw <- copy(data)
```



1.3 Filter by bounding box

We first save a copy of the data, so that we can plot the raw data with the cleaned data plotted over it for comparison.

```r
# make a copy using the data.table copy function
data_unproc <- copy(data)
```

We then filter by a bounding box in order to remove the point outlier to the far south east of the main track. We use the `atl_filter_bounds` functions using the `x_range` argument, to which we pass the limit in the UTM 31N coordinate reference system. This limit is used to exclude all points with an X coordinate < 645,000.

We then plot the result of filtering, with the excluded point in black, and the points that are retained in green.

```r
# remove inside must be set to falses
data <- atl_filter_bounds(data = data,
                          x = "x", y = "y",
                          x_range = c(645000, max(data$x)),
                          remove_inside = FALSE)
```

1.4 Filter trajectories

Handle time

Time in ATLAS tracking is counted in milliseconds and is represented by a 64-bit integer (type `long`), which is not natively supported in R; it will instead be converted to a `numeric`, or `double`.

This is not what is intended, but it works. The `bit64` package can help handle 64-bit integers if you want to keep to intended type.

A further issue is that 64-bit integers (whether represented as `bit64` or `double`) do not yield meaninful results when you try to convert them to a date-time object, such as of the class `POSIXct`.

This is because `as.POSIXct` fails when trying to work with 64-bit integers (it cannot interpret this type), and returns a date many thousands of years in the future (approx. 52,000 CE) if the time column is converted to `numeric`.

There are two possible solutions. The parsimonious one is to convert the 64-bit number to a 32-bit short integer (dividing by 1000), or to use the `nanotime` package.

The conversion method loses an imperceptible amount of precision. The `nanotime` requires installing another package. The first method is shown here.

In the spirit of not destroying data, we create a second lower-case column called `time`.

```r
# divide by 1000, convert to integer, then convert to POSIXct
data[, time := as.integer(TIME / 1000)]
```

Add speed and turning angle

```r
# add incoming and outgoing speed
data[, `:=` (speed_in = atl_get_speed(data,
                                      x = "x",
                                      y = "y",
                                      time = "time"),
             speed_out = atl_get_speed(data, type = "out"))]
```

```
# add turning angle
data[, angle := atl_turning_angle(data = data)]
```

Get 95th percentile of speed and angle

```
# use sapply
speed_angle_thresholds <-
  sapply(data[, list(speed_in, speed_out, angle)],
       quantile, probs = 0.9, na.rm = T)
```

Filter on speed

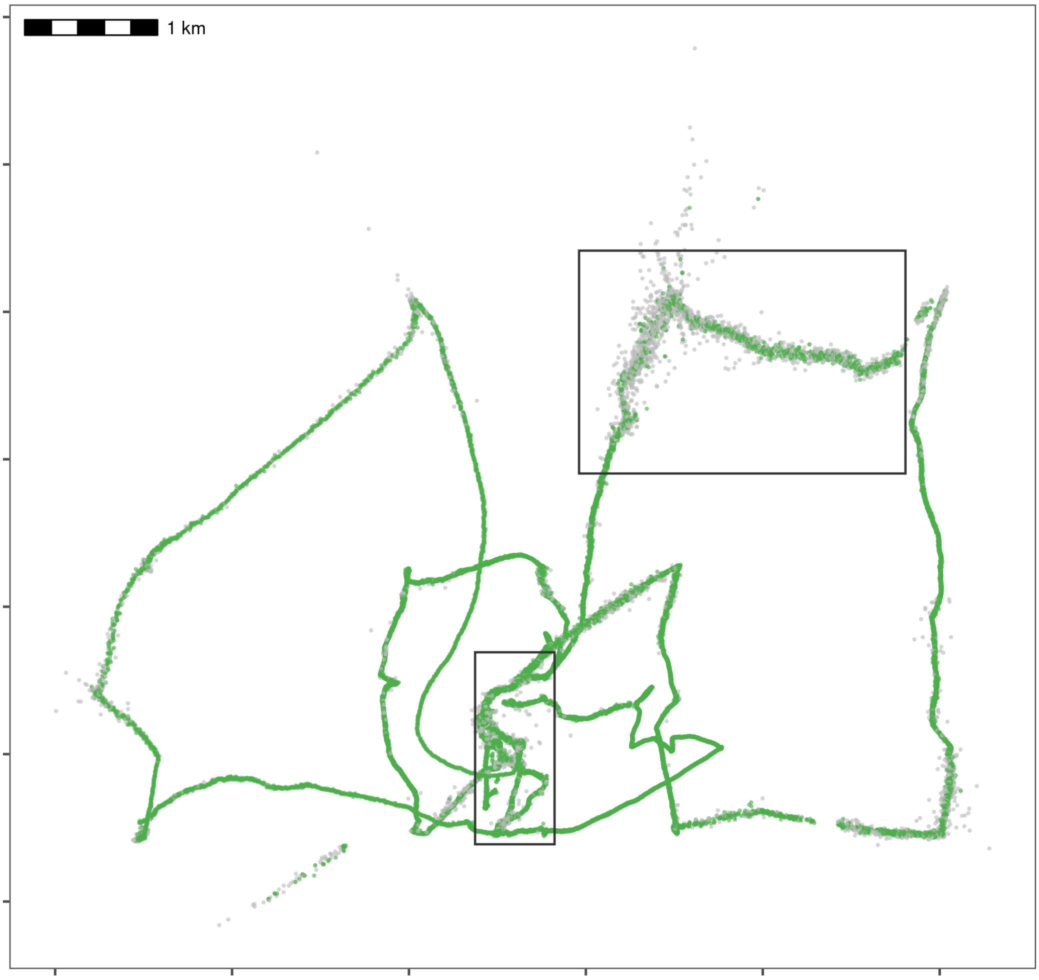
Here we use a speed threshold of 15 m/s, the fastest known boat speed. We then plot the data with the extreme speeds shown in grey, and the positions retained shown in green.

```
# make a copy
data_unproc <- copy(data)

# remove speed outliers
data <- atl_filter_covariates(data = data,
            filters = c("(speed_in < 15 & speed_out < 15)"))

# recalculate speed and angle
data[, `:=` (speed_in = atl_get_speed(data,
                                      x = "x",
                                      y = "y",
                                      time = "time"),
             speed_out = atl_get_speed(data, type = "out"))]

# add turning angle
data[, angle := atl_turning_angle(data = data)]
```

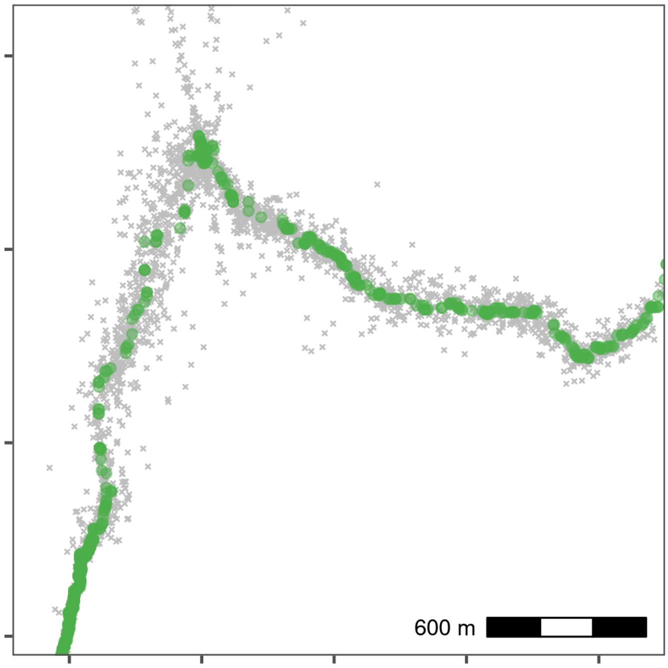


1.5 Smoothing the trajectory

We then apply a median smooth over a moving window ($K = 5$). This function modifies in place, and does not need to be assigned to a new variable. We create a copy of the data before applying the smooth so that we can compare the data before and after smoothin.

```
# apply a 5 point median smooth, first make a copy
data_unproc <- copy(data)

# now apply the smooth
atl_median_smooth(data = data,
                  x = "x", y = "y", time = "time",
                  moving_window = 5)
```



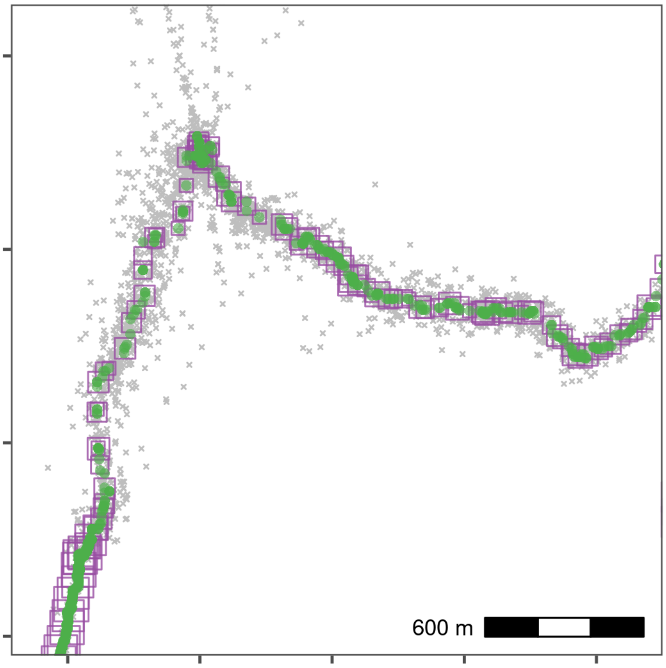
1.6 Thinning the data

Next we thin the data to demonstrate thinning by median smoothing. Following this, we plot the median smooth and thinning by aggregation.

```
# save a copy
data_unproc <- copy(data)

# remove columns we don't need
data <- data[, setdiff(colnames(data),
                        c("tID", "Timestamp", "id", "TIME", "UTCtime")),
             with = FALSE]

# thin to a 30s interval
data_thin <- atl_thin_data(data = data,
                           interval = 30,
                           method = "aggregate",
                           id_columns = "TAG")
```



1.7 Residence patches

Get waypoint centroids

We subset the annotated calibration data to select the waypoints and the positions around them which are supposed to be the locations of known stops. Since each stop was supposed to be 5 minutes long, there are multiple points in each known stop.

```
library(stringi)
data_res <- data_unproc[stri_detect(tID, regex = "(WP)")]
```

From this data, we get the centroid of known stops, and determine the time difference between the first and last point within 50 metres, and within 10 minutes of the waypoint positions' median time.

Essentially, this means that the maximum duration of a stop can be 20 minutes, and stops above this duration are not expected.

```
# get centroid
data_res_summary <- data_res[, list(x_median = round(median(x), digits = -2),
                                    y_median = round(median(y), digits = -2)),
                                    t_median = median(time)),
                             by = "tID"]

# now get times 10 mins before and after
data_res_summary[, `:=`(t_min = t_median - (10 * 60),
                        t_max = t_median + (10 * 60))]

# make a list of positions 10min before and after
wp_data <- mapply(function(l, u, mx, my) {
  tmp_data <- data_unproc[inrange(time, l, u)]
  tmp_data[, distance := sqrt((mx - x)^2 + (my - y)^2)]
```

```
    # keep within 50
    tmp_data <- tmp_data[distance <= 50, ]

    # get duration
    return(diff(range(tmp_data$time)))

  }, data_res_summary$t_min, data_res_summary$t_max,
     data_res_summary$x_median, data_res_summary$y_median,
  SIMPLIFY = TRUE)
```

Prepare data

An indicator of individual residence at or near a position can be useful when attempting to identify residence patches. Positions can be filtered on a metric such as residence time (Bracis, Bildstein, and Mueller 2018).

Calculate residence time

First we calculate the residence time with a radius of 50 metres. For this, we need a dataframe with coordinates, the timestamp, and the animal id. We save this data to file for later use.

```
# load recurse
library(recurse)

# get 4 column data
data_for_patch <- data_thin[, list(x, y, time, TAG)]

# get recurse data for a 10m radius
recurse_stats <- getRecursions(data_for_patch,
                               radius = 50, timeunits = "mins")

# assign to recurse data
data_for_patch[, res_time := recurse_stats$residenceTime]

# save recurse data
fwrite(data_for_patch, file = "data/data_calib_for_patch.csv")
```

Run residence patch method

We subset data with a residence time > 5 minutes in order to construct residence patches. From this subset, we construct residence patches using the parameters: `buffer_radius` = 5 metres, `lim_spat_indep` = 50 metres, `lim_time_indep` = 5 minutes, and `min_fixes` = 3.

```
# assign id as tag
data_for_patch[, id := as.character(TAG)]

# on known residence points
patch_res_known <- atl_res_patch(data_for_patch[res_time >= 5, ],
                                 buffer_radius = 5,
                                 lim_spat_indep = 50,
                                 lim_time_indep = 5,
                                 min_fixes = 3)
```

Get spatial and summary objects

We get spatial and summary ouput of the residence patch method using the `atl_patch_summary` function using the options `which_data` = "spatial" and `which_data` = "summary. We use a buffer radius here of 20 metres for the spatial buffer, despite using a buffer radius of 5 metres earlier, simply because it is easier to visualise in the output figure.

```
# for the known and unkniwn patches
patch_sf_data <- atl_patch_summary(patch_res_known,
                                   which_data = "spatial",
                                   buffer_radius = 20)

# assign crs
sf::st_crs(patch_sf_data) <- 32631

# get summary data
patch_summary_data <- atl_patch_summary(patch_res_known,
                                        which_data = "summary")
```

Prepare to plot data

We read in the island's shapefile to plot it as a background for the residence patch figure.

```
# read griend
griend <- sf::st_read("data/griend_polygon/griend_polygon.shp")
```

1.8 Compare patch metrics

We then merge the annoated, known stop data with the calculated patch duration. We filter this data to exclude one exceedingly long outlier of about an hour (WP080), which how

```
# get known patch summary
data_res <- data_unproc[stringi::stri_detect(tID, regex = "(WP)"), ]

# get waypoint summary
patch_summary_real <- data_res[, list(nfixes_real = .N,
                                      x_median = round(median(x), digits = -2),
                                      y_median = round(median(y), digits = -2)),
                               by = "tID"]

# add real duration
patch_summary_real[, duration_real := wp_data]

# round median coordinate for inferred patches
patch_summary_inferred <-
  patch_summary_data[,
                     c("x_median", "y_median",
                       "nfixes", "duration", "patch")
                     ][, `:=`(x_median = round(x_median, digits = -2),
                              y_median = round(y_median, digits = -2))]

# join with respatch summary
patch_summary_compare <-
```

```r
  merge(patch_summary_real,
        patch_summary_inferred,
        on = c("x_median", "y_median"),
        all.x = TRUE, all.y = TRUE)

# drop nas
patch_summary_compare <- na.omit(patch_summary_compare)

# drop patch around WP080
patch_summary_compare <- patch_summary_compare[tID != "WP080", ]
```

7 patches are identified where there are no waypoints, while 2 waypoints are not identified as patches. These waypoints consisted of 6 and 15 (WP098 and WP092) positions respectively, and were lost when the data were aggregated to 30 second intervals.

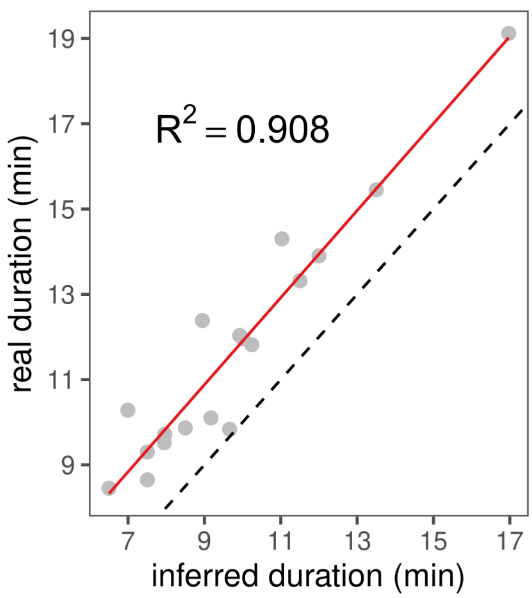
Linear model durations

We run a simple linear model.

```r
# get linear model
model_duration <- lm(duration_real ~ duration,
                     data = patch_summary_compare)

# get R2
summary(model_duration)

# write to file
writeLines(
  text = capture.output(
    summary(model_duration)
  ),
  con = "data/model_output_residence_patch.txt"
)
```



2 Processing Egyptian fruit bat tracks

We show the pre-processing pipeline at work on the tracks of three Egyptian fruit bats (*Rousettus aegyptiacus*), and construct residence patches.

2.1 Prepare libraries

Install the required R libraries that are required from CRAN if not already installed.

```
# load libs
library(data.table)
library(RSQLite)
library(ggplot2)
library(patchwork)

# prepare a palette
pal <- RColorBrewer::brewer.pal(4, "Set1")
```

2.2 Install `atlastools` from Github.

`atlastools` is available from Github and is archived on Zenodo (Gupte 2020). It can be installed using `remotes` or `devtools`. Here we use the `remotes` function `install_github`.

```
install.packages("remotes")

# installation using remotes
remotes::install_github("pratikunterwegs/atlastools")
```

2.3 Read bat data

Read the bat data from an `SQLite` database local file and convert to a plain text csv file. This data can be found in the "data" folder.

```
# prepare the connection
con <- dbConnect(drv = SQLite(),
                 dbname = "data/Three_example_bats.sql")

# list the tables
table_name <- dbListTables(con)

# prepare to query all tables
query <- sprintf('select * from \"%s\"', table_name)

# query the database
data <- dbGetQuery(conn = con, statement = query)

# disconnect from database
dbDisconnect(con)
```

Convert data to csv, and save a local copy in the folder "data".

```
# convert data to datatable
setDT(data)
```

```r
# write data for QGIS
fwrite(data, file = "data/bat_data.csv")
```

2.4 A First Visual Inspection

Plot the bat data as a sanity check, and inspect it visually for errors (Figure 1). The plot code is hidden in the rendered copy (PDF) of this supplementary material, but is available in the `Rmarkdown` file "06_bat_data.Rmd". The saved plot is shown below as Figure 1.

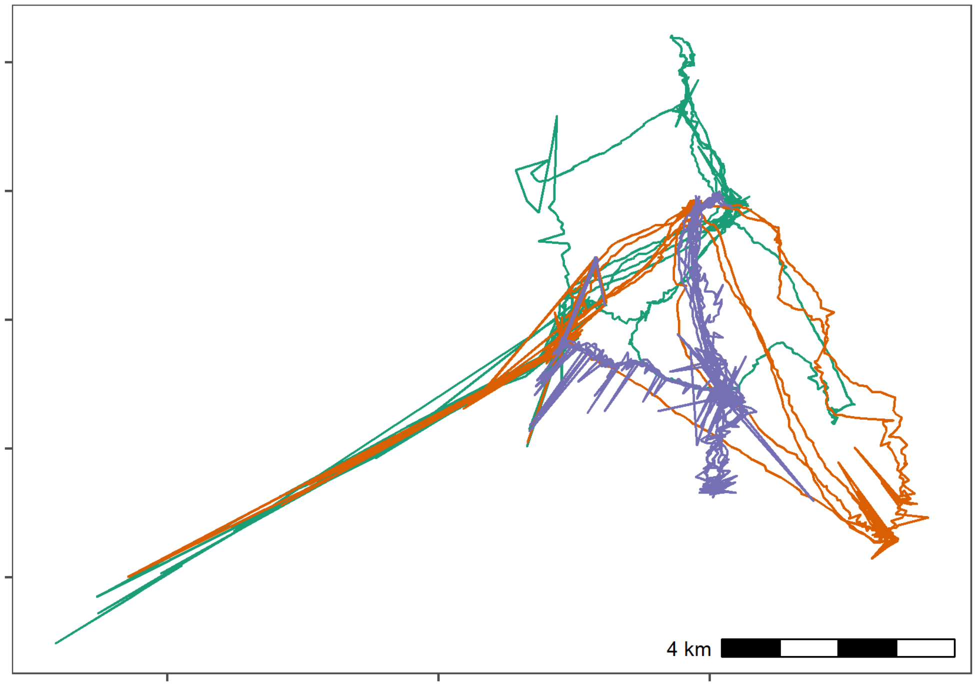


Figure 1: Movement data from three Egyptian fruit bats tracked using the ATLAS system (*Rousettus aegyptiacus*; (Toledo et al. 2020; Shohami and Nathan 2020)). The bats were tracked in the Hula Valley, Israel (33.1°N, 35.6°E), and we use three nights of tracking (5th, 6th, and 7th May, 2018), for our demonstration, with an average of 13,370 positions (SD = 2,173; range = 11,195 – 15,542; interval = 8 seconds) per individual. After first plotting the individual tracks, we notice severe distortions, making pre-processing necesary

2.5 Prepare data for filtering

Here we apply a series of simple filters. It is always safer to deal with one individual at a time, so we split the data.table into a list of data.tables to avoid mixups among individuals.

Prepare data per individual

```r
# split bat data by tag
# first make a copy using the data.table function copy
# this prevents the orignal data from being modified by atlastools
# functions which DO MODIFY BY REFERENCE!
data_split <- copy(data)
```

```
# now split
data_split <- split(data_split, by = "TAG")
```

2.6 Filter by covariates

No natural bounds suggest themselves, so instead we proceed to filter by covariates, since point outliers are obviously visible.

We use filter out positions with `SD > 20` and positions calculated using only 3 base stations, using the function `atl_filter_covariates`.

First we calculate the variable SD.

```
# get SD.
# since the data are data.tables, no assignment is necessary
invisible(
  lapply(data_split, function(dt) {
    dt[, SD := sqrt(VARX + VARY + (2 * COVXY))]
  })
)
```

Then we pass the filters to `atl_filter_covariates`. We apply the filter to each individual's data using an `lapply`.

```
# filter for SD <= 20
# here, reassignment is necessary as rows are being removed
# the atl_filter_covariates function could have been used here
data_split <- lapply(data_split, function(dt) {

  dt <- atl_filter_covariates(
    data = dt,
    filters = c("SD <= 20",
                "NBS > 3")

  )
})
```

Sanity check: Plot filtered data

We plot the data to check whether the filtering has improved the data (Figure 2). The plot code is once again hidden in this rendering, but is available in the source code file.

2.7 Filter by speed

Some point outliers remain (Figure 2), and could be removed using a speed filter.

First we calculate speeds, using `atl_get_speed`. We must assign the speed output to a new column in the data.table, which has a special syntax which modifies in place, and is shown below. This syntax is a feature of the `data.table` package, not strictly of `atlastools` (Dowle and Srinivasan 2020).

```
# get speeds as with SD, no reassignment required for columns
invisible(
  lapply(data_split, function(dt) {
```

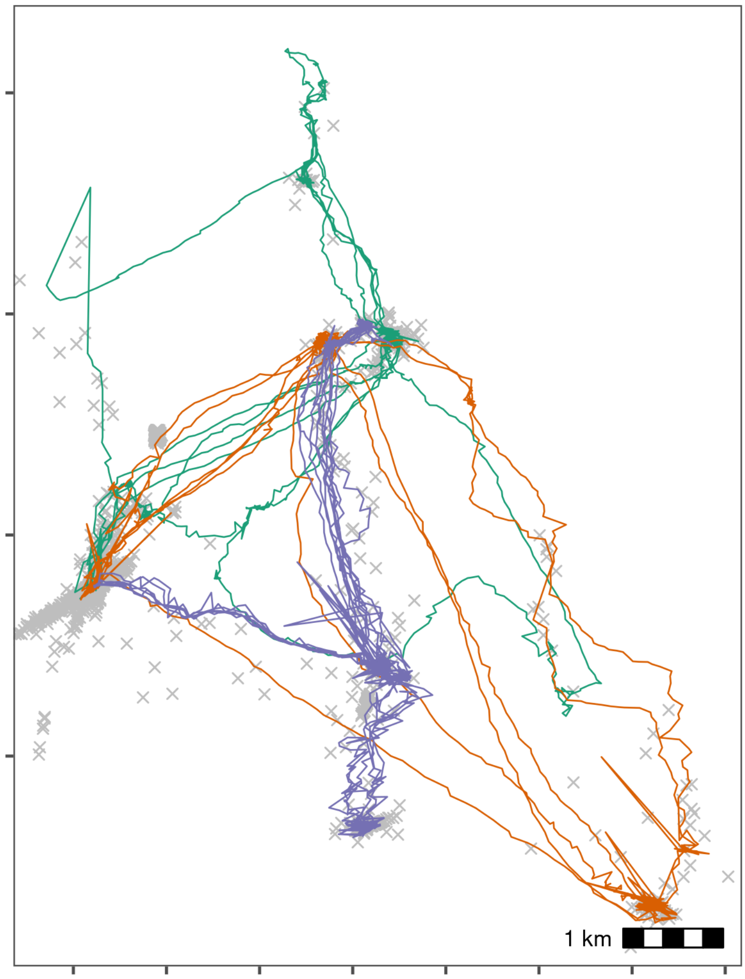


Figure 2: Bat data filtered for large location errors, removing observations with standard deviation > 20. Grey crosses show data that were removed. Since the number of base stations used in the location process is a good indicator of error (Weiser et al. 2016), we also removed observations calculated using fewer than four base stations. Both steps used the function `atl_filter_covariates`. This filtering reduced the data to an average of 10,447 positions per individual (78% of the raw data on average). However, some point outliers remain.

```
    # first process time to seconds
    # assign to a new column
    dt[, time := floor(TIME / 1000)]

    dt[, `:=`(speed_in = atl_get_speed(dt,
                                         x = "X", y = "Y",
                                         time = "time",
                                         type = "in"),
              speed_out = atl_get_speed(dt,
                                         x = "X", y = "Y",
                                         time = "time",
                                         type = "out"))]
  })
)
```

Now filter for speeds > 20 m/s (around 70 km/h), passing the predicate (a statement return TRUE or FALSE) to `atl_filter_covariates`. First, we remove positions which have `NA` for their `speed_in` (the first position) and their `speed_out` (last position).

```
# filter speeds
# reassignment is required here
data_split <- lapply(data_split, function(dt) {
  dt <- na.omit(dt, cols = c("speed_in", "speed_out"))

  dt <- atl_filter_covariates(data = dt,
                              filters = c("speed_in <= 20",
                                          "speed_out <= 20"))
})
```

Sanity check: Plot speed filtered data

The speed filtered data is now inspected for errors (Figure 3). The plot code is once again hidden.

2.8 Median smoothing

The quality of this data (Figure 3) is relatively high, and a median smooth is not strictly necessary. We demonstrate the application of a 5 point median smooth to the data nonetheless.

Since the median smoothing function `atl_median_smooth` modifies in place, we first make a copy of the data, using `data.table`'s `copy` function. No reassignment is required, in this case. The `lapply` function allows arguments to `atl_median_smooth` to be passed within `lapply` itself.

In this case, the same moving window K is applied to all individuals, but modifying this code to use the multivariate version `Map` allows different K to be used for different individuals. This is a programming matter, and is not covered here further.

```
# since the function modifies in place, we shall make a copy
data_smooth <- copy(data_split)

# split the data again
data_smooth <- split(data_smooth, by = "TAG")
```

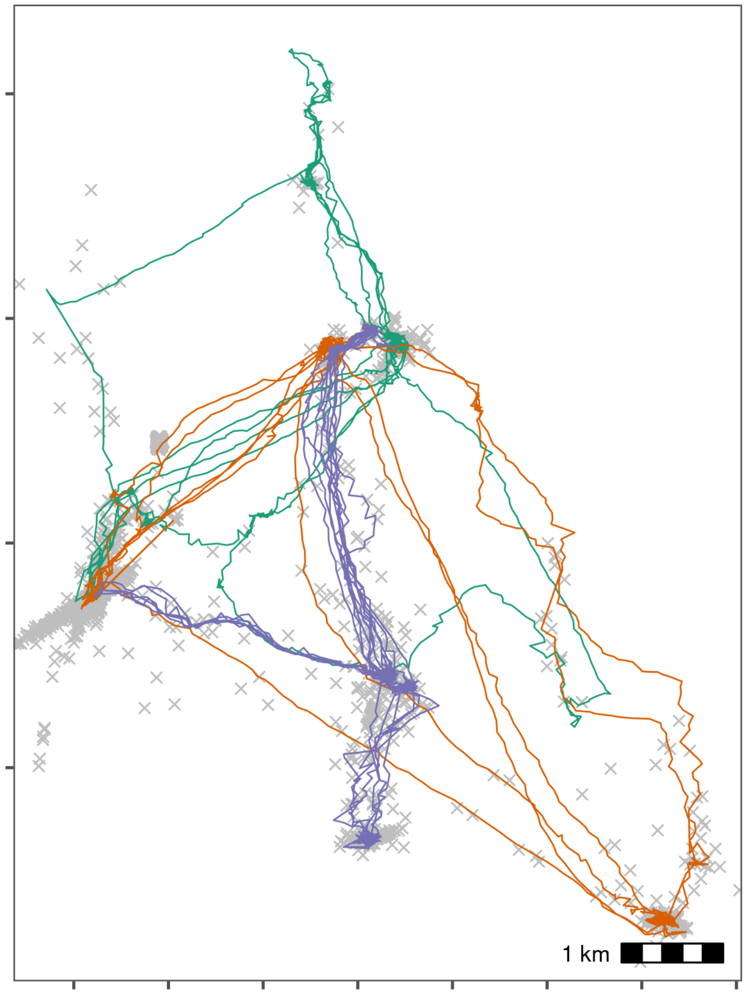


Figure 3: Bat data with unrealistic speeds removed. Grey crosses show data that were removed. We calculated the incoming and outgoing speed of each position using `atl_get_speed`, and filtered out positions with speeds > 20 m/s using `atl_filter_covariates`, leaving 10,337 positions per individual on average (98% from the previous step).

```r
# apply the median smooth to each list element
# no reassignment is required as THE FUNCTION MODIFIES IN PLACE!
invisible(

  # the function arguments to atl_median_smooth
  # can be passed directly in lapply

  lapply(X = data_smooth,
         FUN = atl_median_smooth,
         time = "time", moving_window = 5)
)
```

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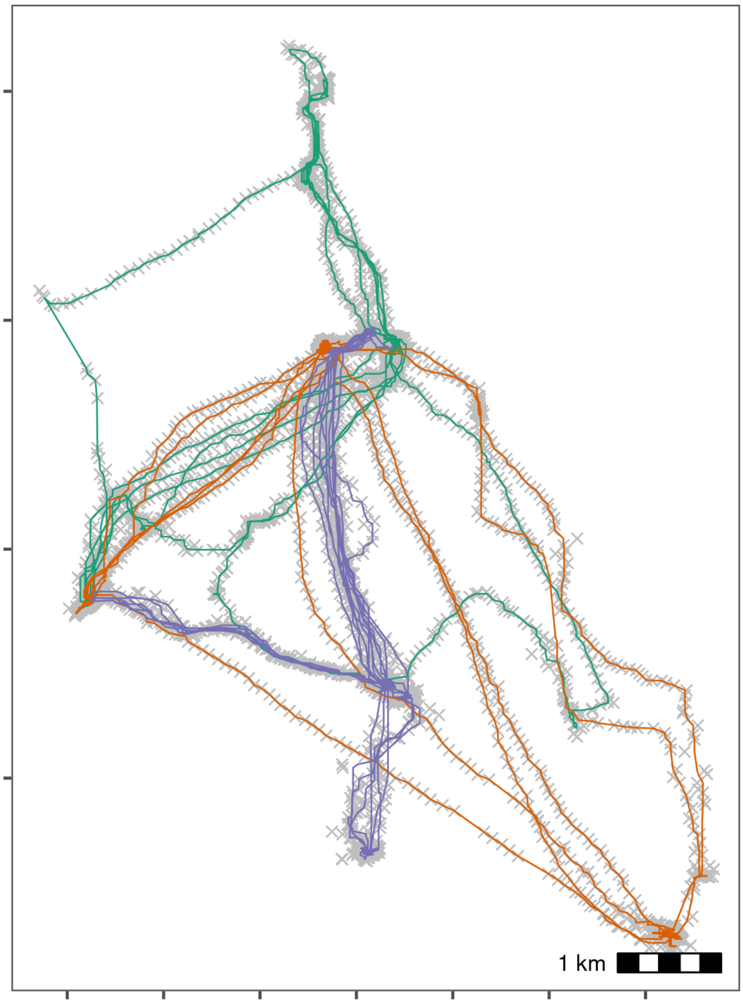

Figure 4: Bat data after applying a median smooth with a moving window $K = 5$. Grey crosses show data prior to smoothing. The smoothing step did not discard any data.

2.9 Making residence patches

Calculating residence time

First, the data is put through the `recurse` package to get residence time (Bracis, Bildstein, and Mueller 2018).

```
# load recurse
library(recurse)

# split the data
data_smooth <- split(data_smooth, data_smooth$TAG)
```

We calculated residence time, but since bats may revisit the same features, we want to prevent confusion between frequent revisits and prolonged residence.

For this, we stop summing residence times within Z metres of a location if the animal exited the area for one hour or more. The value of Z (radius, in `recurse` parameter terms) was chosen as 50m.

This step is relatively complicated and is only required for individuals which frequently return to the same location, or pass over the same areas repeatedly, and for which revisits (cumulative time spent) may be confused for residence time in a single visit.

While a simpler implementation using total residence time divided by the number of revisits is also possible, this does assume that each revisit had the same residence time.

```
# get residence times

data_residence <- lapply(data_smooth, function(dt) {
  # do basic recurse
  dt_recurse <- getRecursions(
    x = dt[, c("X", "Y", "time", "TAG")],
    radius = 50,
    timeunits = "mins"
  )

  # get revisit stats
  dt_recurse <- setDT(
    dt_recurse[["revisitStats"]]
  )

  # count long absences from the area
  dt_recurse[, timeSinceLastVisit :=
          ifelse(is.na(timeSinceLastVisit), -Inf, timeSinceLastVisit)]
  dt_recurse[, longAbsenceCounter := cumsum(timeSinceLastVisit > 60),
             by = .(coordIdx)
             ]
  # get data before the first long absence of 60 mins
  dt_recurse <- dt_recurse[longAbsenceCounter < 1, ]

  dt_recurse <- dt_recurse[, list(
    resTime = sum(timeInside),
    fpt = first(timeInside),
    revisits = max(visitIdx)
```

```r
    ),
    by = .(coordIdx, x, y)
    ]

    # prepare and merge existing data with recursion data
    dt[, coordIdx := seq(nrow(dt))]

    dt <- merge(dt,
                dt_recurse[, c("coordIdx", "resTime")],
                by = c("coordIdx"))

    setorderv(dt, "time")
})
```

We bind the data together and assign a human readable timestamp column.

```r
# bind the list
data_residence <- rbindlist(data_residence)

# get time as human readable
data_residence[, ts := as.POSIXct(time, origin = "1970-01-01")]
```

Constructing residence patches

Some preparation is required. First, the function requires columns `x`, `y`, `time`, and `id`, which we assign using the `data.table` syntax. Then we subset the data to only work with positions where the individual had a residence time of more than 5 minutes.

```r
# add an id column
data_residence[, `:=`(id = TAG,
                      x = X, y = Y)]

# filter for residence time > 5 minutes
data_residence <- data_residence[resTime > 5, ]

# split the data
data_residence <- split(data_residence, data_residence$TAG)
```

We apply the residence patch method, using the default argument values (`lim_spat_indep = 100` (metres), `lim_time_indep = 30` (minutes), and `min_fixes = 3`). We change the `buffer_radius` to 25 metres (twice the buffer radius is used, so points must be separated by 50m to be independent bouts).

```r
# segment into residence patches
data_patches <- lapply(data_residence, atl_res_patch,
                       buffer_radius = 25)
```

Getting residence patch data

We extract the residence patch data as spatial `sf-MULTIPOLYGON` objects. These are returned as a list and must be converted into a single `sf` object. These objects and the raw movement data are shown in Figure 5.

```r
# get data spatials
data_spatials <- lapply(data_patches, atl_patch_summary,
                        which_data = "spatial",
                        buffer_radius = 25)

# bind list
data_spatials <- rbindlist(data_spatials)

# convert to sf
library(sf)
data_spatials <- st_sf(data_spatials, sf_column_name = "polygons")

# assign a crs
st_crs(data_spatials) <- st_crs(2039)
```

Write patch spatial representations

```r
st_write(data_spatials,
         dsn = "data/data_bat_residence_patches.gpkg")
```

Write cleaned bat data.

```r
data_clean <- fwrite(rbindlist(data_smooth),
                     file = "data/data_bat_smooth.csv")
```

Write patch summary.

```r
# get summary
patch_summary <- lapply(data_patches, atl_patch_summary)

# bind summary
patch_summary <- rbindlist(patch_summary)

# write
fwrite(patch_summary,
       "data/data_bat_patch_summary.csv")
```

3 References

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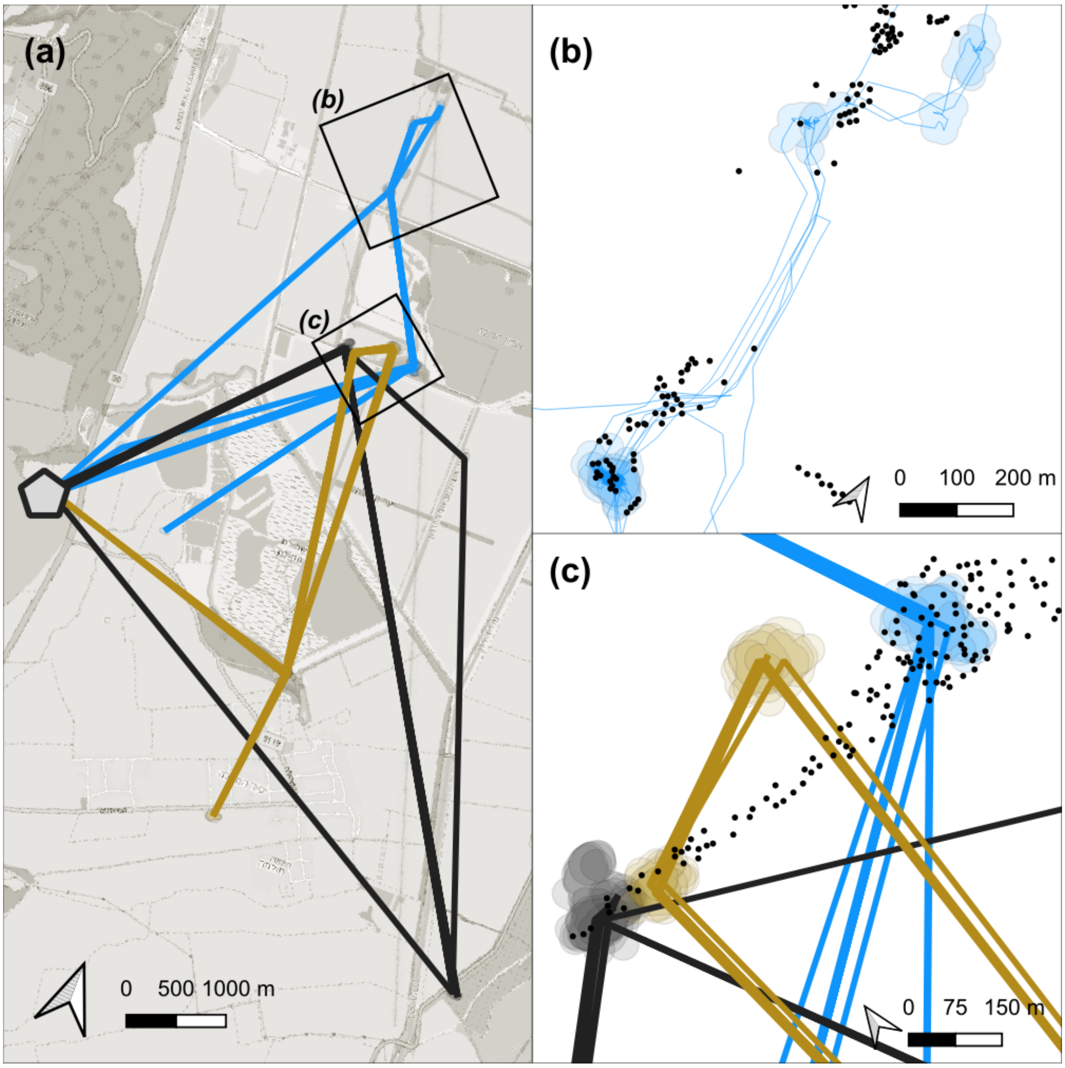

Figure 5: A visual examination of plots of the bats' residence patches and linear approximations of paths between them showed that though all three bats roosted at the same site, they used distinct areas of the study site over the three nights **(a)**. Bats tended to be resident near fruit trees, which are their main food source, travelling repeatedly between previously visited areas **(b, c)**. However, bats also appeared to spend some time at locations where no fruit trees were recorded, prompting questions about their use of other food sources **(b, c)**. When bats did occur close together, their residence patches barely overlapped, and their paths to and from the broad area of co-occurrence were not similar **(c)**. Constructing residence patches for multiple individuals over multiple activity periods suggests interesting dynamics of within- and between-individual overlap **(b, c)**.

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