**Supplementary Materials:**

# Animal Tracking Toolbox User Manual

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Passive telemetry studies use detection patterns of a tagged animal within a fixed array to understand movement patterns, habitat use and activity space. Raw detection data are typically used to calculate metrics of detection (i.e. number of detections, number of days detected, number of receivers tag was detected on, index of residence), dispersal (e.g. distances and bearings between consecutive detections; step distances and turning angles, distances and bearings between each detection and release site) and activity space (e.g. Minimum Convex Polygon [MCP] area, Kernel Utilisation Distribution area), however the techniques and parameters used to calculate these metrics are often customised to each study making cross-study comparisons unreliable. Here we provide a tool to enable standardisation of the calculation of these commonly used metrics and provide an analytical tool to facilitate.

The Animal Tracking Toolbox (ATT) is a wrapper function created in the R statistical environment (R Development Core Team 2016) that calculates standardised metrics of movement and activity space from passive telemetry to enable direct comparisons between animals tracked within the same study and between studies or locations. The function uses individual detection data files alongside tag metadata with user-defined parameters to calculate a range of standardised movement and activity space metrics (Fig S1). This function can be used to calculate and visualise standardised metrics of movement and activity space within and between species tracked at multiple locations (e.g. Fig S2).

The ATT was developed to pre-process and calculate standardised metrics of movement and activity space from large-scale detection data housed in the Integrated Marine Observing System's Animal Tracking Facility (IMOS ATF) national data repository. The ATT accepts detection data (referred to as 'tagdata' in the function) exported from the IMOS ATF database (can be accessed through the AODN portal: https://portal.aodn.org.au), however can also be configured to accept export formats from the VEMCO data management software VUE (see input data section). This manual will outline the required data formats for input 'tagdata' and associated tag metadata (referred to as 'taginfo' in the function). This manual will also demonstrate how to run the function for a single tag as well as running the function for a large number of tags within a coded loop and in parallel on a multi-core system.

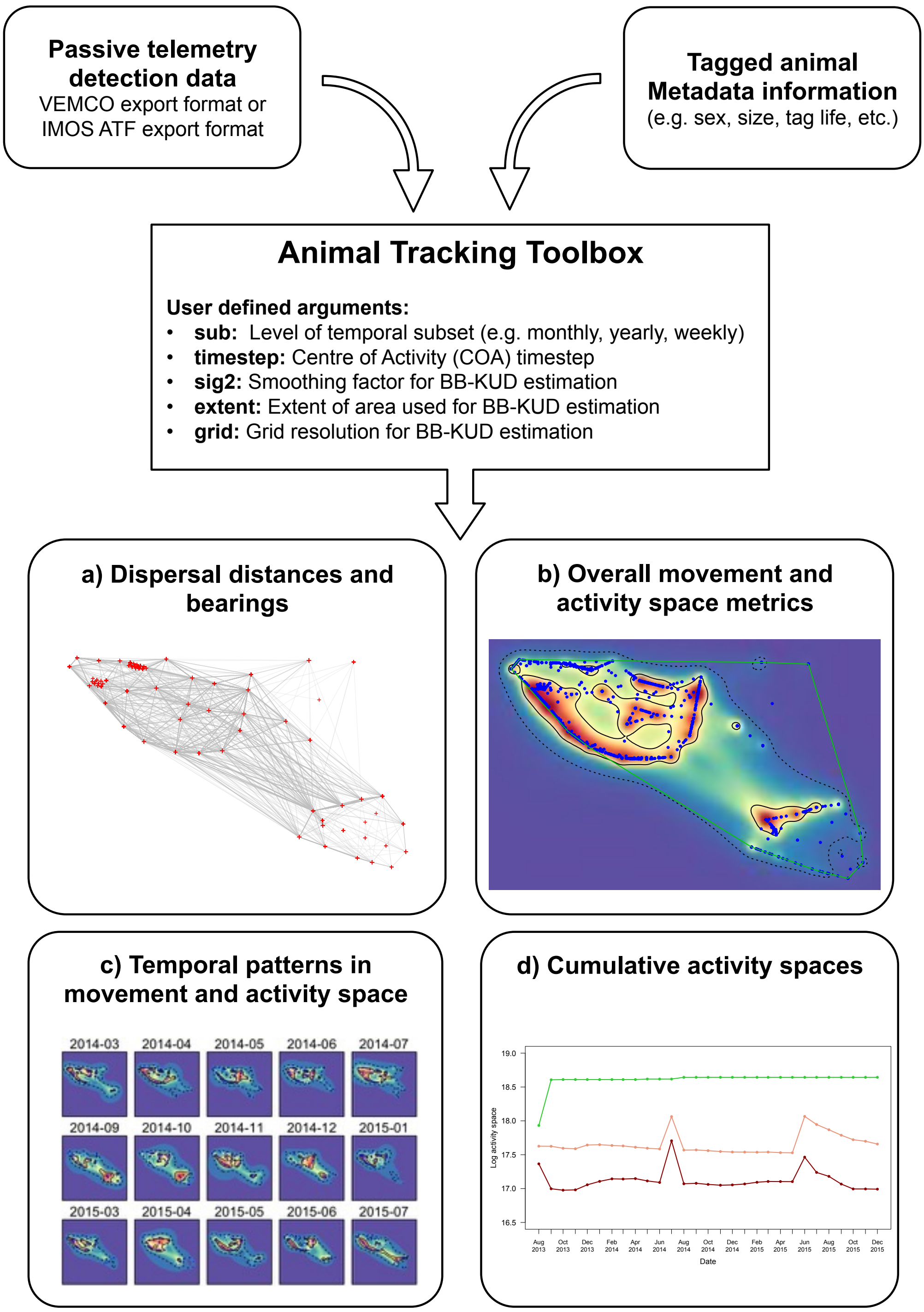



**Figure S1.** Visual summary of types of standardised metrics that can be calculated using the Animal Tracking Toolbox

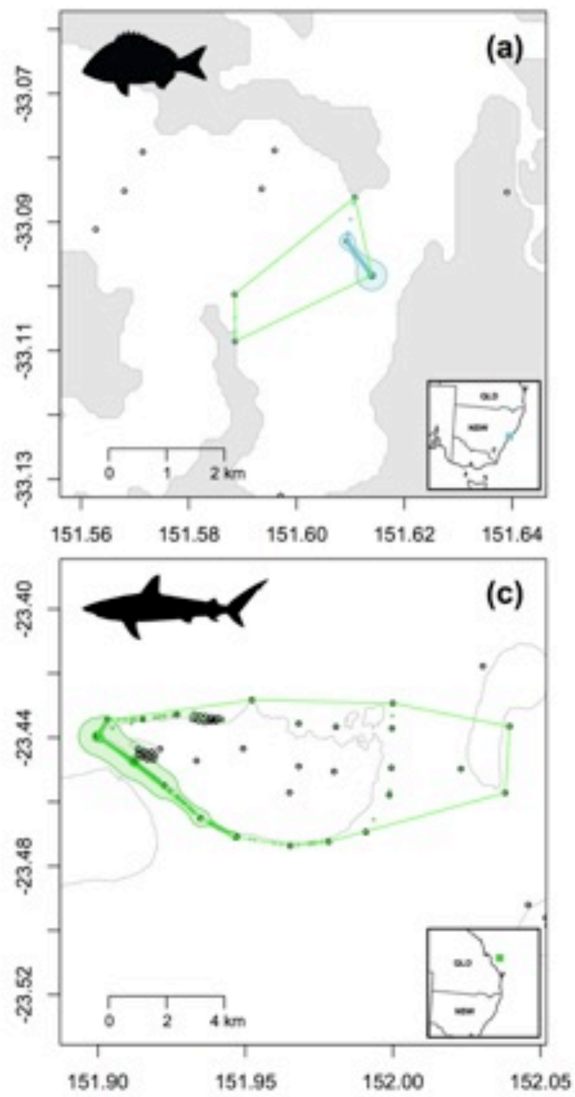



**Figure S2.** Overall activity space metric plots for multiple species tagged at multiple locations (a) Yellowfin Bream [n=1], (b) Yellowtail Kingfish [n=1], (c) Grey Reef Shark [n=1] and (d) Bull Shark [n=1] output using the ATT. Coloured points represent Centres of Activity (60 min time steps) with darker shapes representing core activity space (50% contour of Brownian bridge kernel utilisation distribution [BBKUD]) and lighter shapes representing the extent of activity space (95% contour of BBKUD). Green polygons represent overall Minimum Convex Polygons from detection data. Open circles represent locations of VR2W receivers deployed within the IMOS ATF infrastructure and associated research installations.

## Input data formats

There are two files associated with detection and tag information required to run the ATT, the input detection data ('tagdata') obtained from passive telemetry datasets and tag metadata information ('taginfo'). The ATT was developed to recognise field names from the IMOS ATF database and more generally from a VEMCO VUE database that is commonly used in the field of passive telemetry. These data formats are detailed below (Table S1), and can be used as a guide to configure the 'tagdata' input if the VEMCO or IMOS ATF data formats are not used. The 'taginfo' data format conforms to the metadata information stored on the IMOS ATF database (Table S2), and similar formats should be used to store metadata information on animals tagged for analysing passive telemetry data.

### *Input detection data format: 'tagdata'*

**Table S1.** Input data format follow standard VEMCO or IMOS ATF detection data output formats

| Data field | Description |
|---|---|
| ***VEMCO data format*** | |
| *Date and Time (UTC)* | Date and time of tag detection (yyyy-mm-dd HH:MM:SS) |
| *Receiver* | Name of static receiver, combines receiver model with its serial number (e.g. VR2W-123456) |
| *Transmitter* | Combination of code map and ping ID (eg. A69-1303-14503) |
| *Transmitter Name* | Ping ID of transmitter deployed (e.g. 14503) |
| *Transmitter Serial* | Manufacturers serial number for deployed transmitter (e.g. 1126413) |
| *Sensor Value* | Physical measurement recorded by a tag's sensor, if applicable (If sensor data hasn't been converted then sensor_unit = 'ADC' and values range from 0 to 255.) |
| *Sensor Unit* | Physical unit associated with sensor values (Either 'ADC', '°C', 'm' or '$m/s^2$') |
| *Station Name* | Name of receiving station on which the transmitter was detected. Receivers typically gets deployed multiple times at the same station |
| *Latitude* | Latitude at which receiver was deployed and tag was detected (d.ddd˚) |
| *Longitude* | Longitude at which receiver was deployed and tag was detected (d.ddd˚) |
| ***IMOS ATF data format*** | |
| *transmitter_id* | Combination of code map and ping ID. Dual sensor tags are associated with multiple transmitter IDs (e.g. A69-9002-12345) |
| *installation_name* | Name of installation on which the transmitter was detected. An installation typically consists of multiple receiving stations |
| *station_name* | Name of receiving station on which the transmitter was detected. Receivers typically gets deployed multiple times at the same station |
| *receiver_name* | Name of receiver station, combines receiver model with its serial number (e.g. VR2W-123456) |
| *detection_timestamp* | Date and time of tag detection (yyyy-mm-dd HH:MM:SS) |
| *longitude* | Longitude at which receiver was deployed and tag was detected (d.ddd˚) |
| *latitude* | Latitude at which receiver was deployed and tag was detected (d.ddd˚) |
| *sensor_value* | Physical measurement recorded by a tag's sensor, if applicable (If sensor data |

| | |
|---|---|
| | hasn't been converted then sensor_unit = 'ADC' and values range from 0 to 255.) |
| *sensor_unit* | Physical unit associated with sensor values (Either 'ADC', '°C', 'm' or 'm/s$^2$') |
| *FDA_QC* | Quality control flag for the false detection algorithm (1:passed, 2:failed) |
| *Velocity_QC* | Velocity from previous and next detections both 10 m.s$^{-1}$? (1:yes, 2:no) |
| *Distance_QC* | Distance from previous and next detections both < 1000 km? (1:yes, 2:no) |
| *DetectionDistribution_QC* | Detection occurred within expert distribution area? (1:yes, 2:no, 3:test not performed) |
| *DistanceRelease_QC* | Detection occurred within 500 km of release location? (1:yes, 2:no) |
| *ReleaseDate_QC* | Detection occurred before the tag release date? (1:yes, 2:no) |
| *ReleaseLocation_QC* | Tag release lat/long coordinates within expert distribution area and/or within 500 km from first detection? (1:yes, 2:no) |
| *Detection_QC* | Composite detection flag indicating the likely validity of detections (1:valid detection, 2:probably valid detection, 3:probably bad detection, 4:bad detection) |

***Tag Metadata format: 'taginfo'***

**Table S2.** Format of tag metadata format of IMOS ATF database and required for the ATT function ('taginfo' file)

| Data field | Description |
|---|---|
| *transmitter_id* | Combination of code map and ping ID (e.g. . A69-9002-12345) |
| *tag_id* | Unique tag ID. Dual sensor tags have different transmitter IDs but the same tag ID. |
| *release_id* | Unique tag release ID. A given tag ID may be associated with several release IDs if it has been re-deployed. |
| *tag_project_name* | Project name under which a tag was registered |
| *scientific_name* | Tagged species scientific name |
| *common_name* | Tagged species common name |
| *release_longitude* | Longitude at which tag was deployed (d.ddd˚) |
| *release_latitude* | Latitude at which tag was deployed (d.ddd˚) |
| *ReleaseDate* | Date and time at which tag was deployed (yyyy-mm-dd HH:MM:SS) |
| *sensor_slope* | Slope used in the linear equation to convert raw sensor measurements |
| *sensor_intercept* | Intercept used in the linear equation to convert raw sensor measurements |
| *sensor_type* | Type of sensor (Can be pinger, temperature, pressure, or accelerometer) |
| *sensor_unit* | Physical unit associated with sensor values (Either 'ADC', '°C', 'm' or 'm/s$^2$') |
| *tag_model_name* | Tag model (e.g. V9, V13-TP, V16-P, V9-A) |
| *tag_serial_number* | Manufacturers serial number for deployed transmitter (e.g. 1126413) |
| *tag_expected_life_time_day* | Tag expected life time (days) |
| *tag_status* | Tag status (e.g. deployed, lost, etc) |
| *sex* | Sex of tagged animal (if recorded) |
| *measurement* | Morphometric information of tagged animal (if recorded; e.g. Total length, weight) |
| *dual_sensor_tag* | Is the tag a dual sensor tag (TRUE/FALSE) |

### ***Animal Tracking Toolbox parameters:***

The ATT provides users with the flexibility to customise aspects of temporal subsetting for movement and activity space metric calculations and smoothing factor selection for Brownian bridge Kernel Utilisation Distribution estimation (BBKUD; Horne *et al.* 2007). Although the ATT allows customisation, default values are provided for all arguments to ensure standardisation of estimated metrics of movement and activity space.

**Table S3.** Summary of user-defined input parameters for the Animal Tracking Toolbox

| **Parameter name** | **Description** |
|---|---|
| *tagdata* | Individual detection data (IMOS/AODN or VEMCO output) [required] |
| *taginfo* | Tag metadata (e.g. sex, size, tag life, etc.)[reqired] |
| *IMOSdata* | (TRUE/FALSE) Sets column names based on data source [default = FALSE] |
| *sub* | Level of sub-setting for temporal analyses [default = "%Y-%m"] |
| *timestep* | Centre of Activity (COA) time step [default = 60] |
| *sig2* | Smoothing factor for BBKUD estimation related to imprecision of relocation [default = 200] |
| *extent* | Extent of area used for BB-KUD estimation [default = 2] |
| *grid* | Grid resolution for BB-KUD estimation [default = 200] |
| *storepoly* | (TRUE/FALSE) Store output polygons of overall activity space [default = FALSE] |
| *plotfull* | (TRUE/FALSE) Output plot showing overall activity space [default = FALSE] |
| *plotsub* | (TRUE/FALSE) Output plot showing temporally sub-setted activity space [default = FALSE] |

## Script Usage

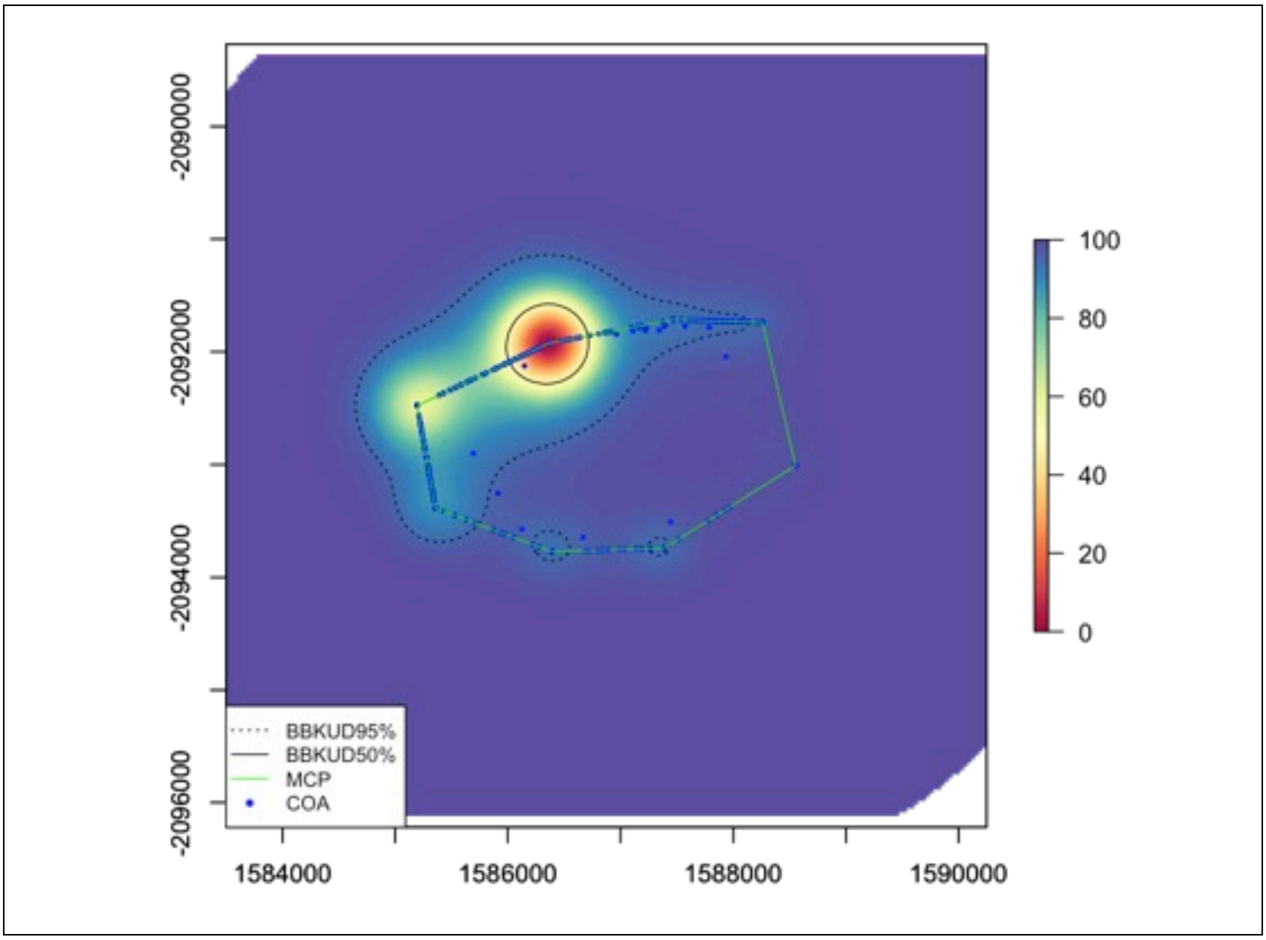
*Package requirements:*

The following R packages are required to run the ATT

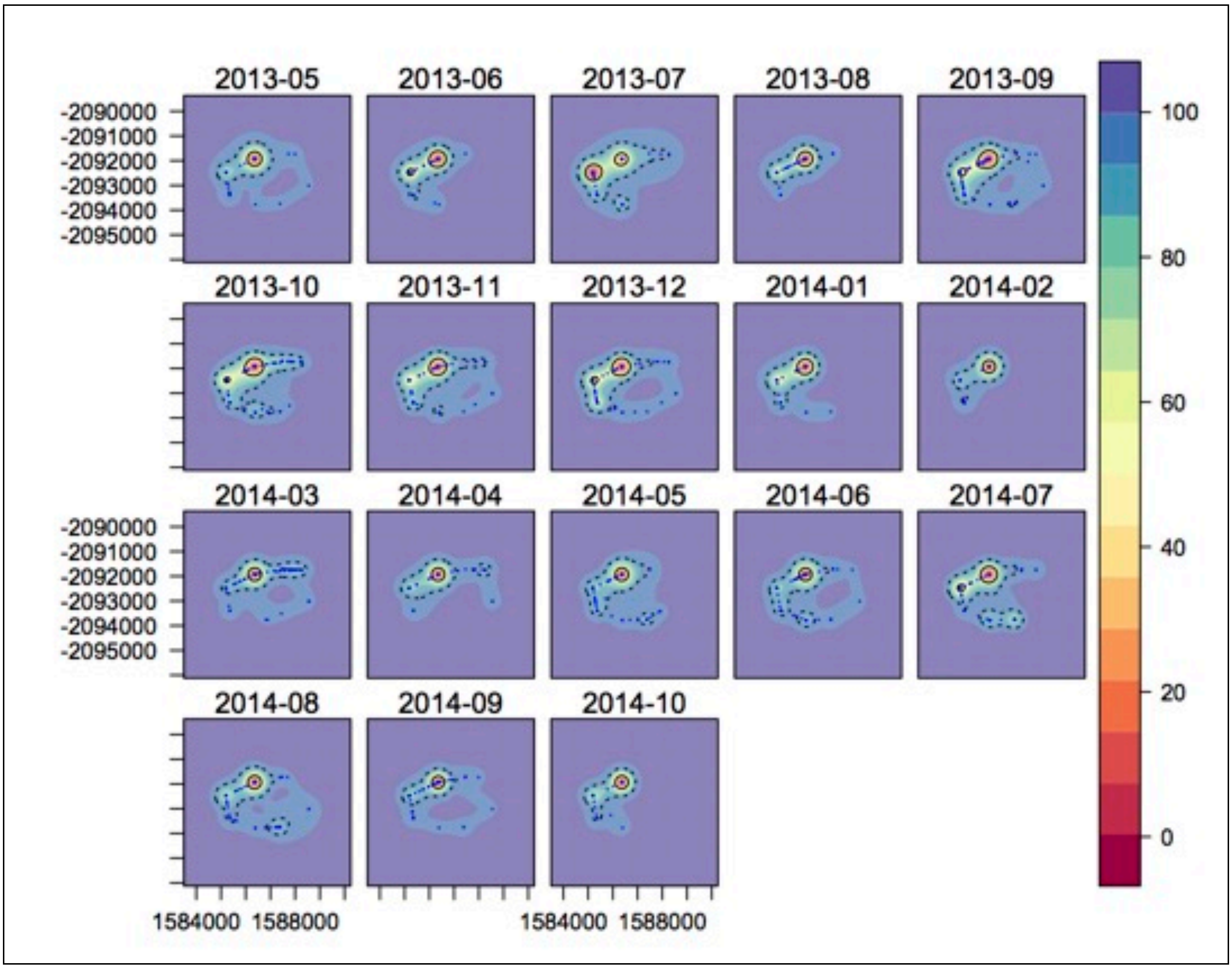
- `adehabitatHR`
- `sp`
- `raster`
- `rasterVis`
- `plyr`
- `lubridate`
- `maptools`
- `maps`

***Running ATT for a single tag***

```
## Source the Animal Tracking Toolbox R script to load the function
source("…/Animal Tracking Toolbox.R")

## Upload tagdata file from IMOS ATF database
IMOS_data<- read.csv ("…/IMOSdata.csv", header=TRUE)

## Upload detection data from VEMCO VUE software
VUE_data<-read.csv("…/VUEoutput.csv", header=TRUE)

## Upload Tag metadata file (format should follow Table S2 above)
metadata<- read.csv("…/TagMetadataFile.csv", header=TRUE)

## Run Animal Tracking Toolbox when using VEMCO VUE export format
VUE_output<-ATT(tagdata=VUE_data, taginfo=metadata)

## Run Animal Tracking Toolbox when using IMOS ATF export data
IMOS_output<-ATT(tagdata=IMOS_data, taginfo=metadata, IMOSdata=TRUE)

## Running the ATT to include calculation of cumulative metrics
## Warning: calculating cumulative metrics will increase the time taken
## to run the full function if the tag has a large number of detections
IMOS_output<-ATT(tadata=IMOS_data, taginfo=metadata, IMOSdata=TRUE,
cumulative=TRUE)

## Storing MCP polygon and BBKUD estimates as raster files
IMOS_output<-ATT(tagdata=IMOS_data, taginfo=metadata, IMOSdata=TRUE,
storepoly=TRUE)

## Running the ATT to produce plots of overall and subsetted activity
## space metrics
IMOS_output<-ATT(tagdata=IMOS_data, taginfo=metadata, IMOSdata=TRUE,
plotfull=TRUE, plotsub=TRUE)


## This will produce two pop-up windows with overall and subsetted plots:
```



-2090000
-2092000
-2094000
-2096000
1584000
1586000
1588000
1590000
100
80
60
40
20
0
BBKUD95%
BBKUD50%
MCP
COA

2013-05
2013-06
2013-07
2013-08
2013-09
2013-10
2013-11
2013-12
2014-01
2014-02
2014-03
2014-04
2014-05
2014-06
2014-07
2014-08
2014-09
2014-10
-2090000
-2091000
-2092000
-2093000
-2094000
-2095000
1584000 1588000
100
80
60
40
20
0

*Running ATT for multiple animals in a loop*

```
## Identify folder with multiple input files
indi<-list.files("…/folder with input files", full.names=TRUE)

## Upload Tag metadata file (format should follow Table S2 above)
metadata<- read.csv("…/TagMetadataFile.csv")

## Set up empty list to fill with ATT output
loop_output<-list(full=data.frame(matrix(ncol=12, nrow=0)),
                subset=data.frame(matrix(ncol=17, nrow=0)),
                COA=data.frame(matrix(ncol=7, nrow=0)),
                disp=data.frame(matrix(ncol=15, nrow=0)))

## Run ATT function for all files in folder and compile in loop_output
for(n in 1:length(indi)){
  tag<-read.csv(indi[n], header=T)
  tryCatch({
    a<-ATT(tagdata=tag, taginfo=metadata, cumulative=TRUE)
    }, error=function(e){cat("ERROR within ATT function ( n =", n, "):\n",
indi[n],"\n",conditionMessage(e), "\n")})
  loop_output<-mapply(rbind, loop_output, a, SIMPLIFY=F)
  a<-list(full=NA, subset=NA, COA=NA, disp=NA)
setTxtProgressBar(txtProgressBar(min = 0, max = length(indi), style = 3), n)
}


## Summarise output
summary(loop_output)
```

*Working in parallel*

```
## load libraries needed to run script in parallel
library(doParallel)
library(foreach)

## Identify folder with multiple input files
indi<-list.files("…/folder with input files", full.names=TRUE)

## Upload Tag metadata file (format should follow Table S2 above)
metadata<- read.csv("…/TagMetadataFile.csv")

## Set up back end for parallel computing
cl <- makeCluster(detectCores())
registerDoParallel(cl)
```

```
## Create function to combine parallel output
combfun <- function(x, ...) {
  mapply(rbind,x,...,SIMPLIFY=FALSE)
}

## Run ATT function for all file in folder and compile in loop_output
par_output<-foreach(n=1:length(indi), .combine='combfun',
                .multicombine=TRUE,
                .init=list(full=data.frame(matrix(ncol=12, nrow=0)),
                           subset=data.frame(matrix(ncol=17, nrow=0)),
                           COA=data.frame(matrix(ncol=7, nrow=0)),
                           disp=data.frame(matrix(ncol=15, nrow=0))))
            %dopar% {
                    tag<-read.csv(indi[n], header=T)
                    ATT(tagdata=tag, taginfo=metadata)
                     }
stopCluster(cl)

## Summarise output
summary(par_output)
```

## Outputs

Standardised metrics calculated by the ATT function are output as a list consisting of five objects:

i. `full`: a data frame consisting of summary information on detection performance, overall activity space areas (MCP, 50% and 95% BBKUD)
ii. `subset`: a data frame consisting of summary information on detection performance and activity space metrics (MCP, 50% and 95% BBKUD) temporally subsetted (e.g. Monthly, weekly, etc). Temporal subset is determined by the `sub` argument of the ATT function (defaulted as month of the year: "%Y-%m"). Cumulative metrics are included in this data frame if the argument `cumulative=TRUE` in the ATT function.
iii. COA: a data frame consisting of Centre of Activity positions calculated within a defined timestep. Time step defined by the `timestep` argument of the ATT function (defaulted to 60 min time step).
iv. `disp`: a data frame consisting of dispersal distances and bearings. Dispersal distances and bearings are calculated between consecutive detections and from dispersal from release site (if recorded in the taginfo metadata file).
v. `sp`: a list of three spatial objects consisting of:
   - `mcpcont`: Spatial polygon of overall Minimum Convex Polygon (in latitude and longitude)
   - `raster_full`: Raster object of overall BBKUD (in latitude and longitude)
   - `raster_sub`: Raster stack object of subsetted BBKUD (in latitude and longitude)

**Table S4.** Summary of user-defined input parameters for the Animal Tracking Toolbox, and summary of subsequent output list

| List title | Data field | Description |
|---|---|---|
| $full | *tag_id* | Unique tag identification number |
| | *transmitter_id* | Combination of code map and ping ID (eg. A69-1303-14503) |
| | *species* | Species of tagged animal (if recorded in taginfo file) |
| | *sex* | Sex of tagged animal (if recorded in taginfo file) |
| | *bio* | Biological attributes recorded in taginfo file |
| | *num_det* | Number of detected on full array |
| | *days_det* | Number of days detected on full array |
| | *num_stat* | Number of receiver stations detected on within full array |
| | *DI* | Detection Index (num_det/days_det) |
| | *mcp* | Minimum Convex Polygon area ($m^2$) |
| | *bbk50* | Brownian bridge Kernel Utilisation Distribution 50% contour area ($m^2$) |
| | *bbk50* | Brownian bridge Kernel Utilisation Distribution 95% contour area ($m^2$) |
| $subset | *yearmon* | Temporal subset, month of the year (yyyy-mm) |
| | *tag_id* | Unique tag identification number |
| | *transmitter_id* | Combination of code map and ping ID (eg. A69-1303-14503) |
| | *species* | Species of tagged animal (if recorded in taginfo file) |
| | *sex* | Sex of tagged animal (if recorded in taginfo file) |
| | *bio* | Biological attributes recorded in taginfo file |
| | *num_det* | Number of detection during each temporal subset |
| | *days_det* | Number of days detected during each temporal subset |
| | *num_stat* | Number of receiver stations detected on during each temporal subset |
| | *num_new_stat* | Number of new receiver stations detected on since last subset |
| | *DI* | Detection Index calculated for each temporal subset |
| | *mcp* | MCP area for each temporal subset ($m^2$) |
| | *bbk50* | BBKUD 50% contour area for each temporal subset ($m^2$) |
| | *bbk95* | BBKUD 95% contour area for each temporal subset ($m^2$) |
| | *cmcp* | Cumulative MCP area since last temporal subset ($m^2$) |
| | *ck50* | Cumulative BBKUD 50% area since last temporal subset ($m^2$) |
| | *ck95* | Cumulative BBKUD 95% area since last temporal subset ($m^2$) |
| $COA | *DateTime* | Date time for calculated Centre of Activity record (yyyy-mm-dd HH:MM:SS) |
| | *tag_id* | Unique tag identification number |
| | *transmitter_id* | Combination of code map and ping ID (eg. A69-1303-14503) |
| | *species* | Species of tagged animal (if recorded in taginfo file) |
| | *meanlat* | Mean latitude coordinate during COA timestep (d.dddd˚) |
| | *meanlon* | Mean longitude coordinate during COA timestep (d.dddd˚) |
| $disp | *tag_id* | Unique tag identification number |
| | *transmitter_id* | Combination of code map and ping ID (eg. A69-1303-14503) |
| | *species* | Species of tagged animal (if recorded in taginfo file) |
| | *installation_name* | Name of researcher installation (if recorded) |
| | *station_name* | Name of receiver station (if recorded) |
| | *ReleaseDate* | Date and time of tag release (yyyy-mm-dd HH:MM:SS; if recorded) |
| | *ReleaseLat* | Latitude coordinate of tag release (d.dddd˚; if recorded) |
| | *ReseaseLon* | Longitude coordinate of tag release (d.dddd˚; if recorded) |
| | *detection_timestamp* | Timestamp of raw detection (yyyy-mm-dd HH:MM:SS) |
| | *lat* | Latitude coordinate of raw detection (d.dddd˚) |
| | *lon* | Longitude coordinate of raw detection (d.dddd˚) |
| | *disrel* | Dispersal distance from release site (m; if release coordinates recorded) |
| | *Azrel* | Bearing of detection from release site (ddd.d˚; if release site recorded) |

| | | |
|---|---|---|
| | *discon* | Dispersal distance from consecutive detections (m) |
| | *azcon* | Bearing between consecutive detections (ddd.d˚) |
| $sp | $mcpcont | Spatial polygon of calculated overall MCP |
| | $raster_full | Gridded raster of full BBKUD estimation |
| | $raster_sub | Gridded raster stack of BBKUD estimates for all temporal subsets |

**References**


Horne, J.S., Garton, E.O., Krone, S.M. & Lewis, J.S. (2007) Analysing animal movements using brownian bridges. *Ecology,* **88,** 2354-2363.

R Development Core Team (2016) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.