

Supplementary Material for

## At the turn of the tide: space use and habitat partitioning in two sympatric shark species is driven by tidal phase

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## Supplementary Figures

Figure S1: Two example two-week plots comparing real water depth (determined using a calibrated pressure logger, HOBO Water Level Data Logger, Onset, Bourne, USA) to model water depth (determined using the Oregon State University Tidal Model Driver (Egbert and Erofeeva 2002)). Over the entire six-month deployment of the pressure logger, the water depth produced by the model only differed from the actual water depth by  $0.1 \text{ m} \pm 0.08 \text{ (s.d.)}$ .

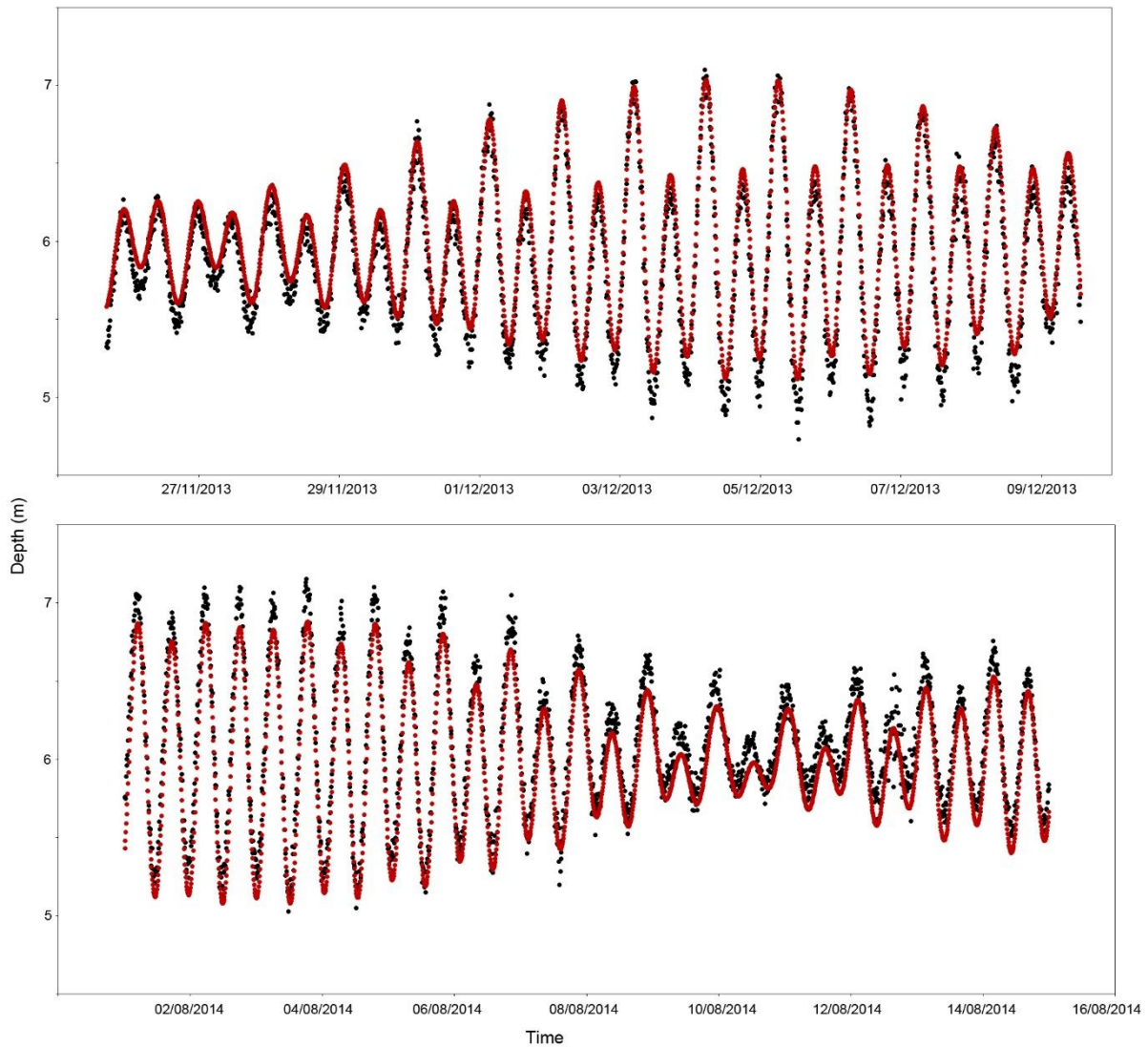


Figure S2: High resolution drone imagery (1 pixel = 15 cm) of St Joseph Atoll at a 0.1 m low tide is available at the following link, courtesy and Copyright © of Drone Adventures for the Save Our Seas Foundation:

[https://a.tiles.mapbox.com/v4/droneadv.oh05ml7b/page.html?access\\_token=pk.eyJ1IjoiZlZlYmVhZHYiLCJhIjoiYmU0ZXQtcyJ9.8Fh95YZQ\\_WdYEDlgtmH95A#15/-5.4270/53.3358](https://a.tiles.mapbox.com/v4/droneadv.oh05ml7b/page.html?access_token=pk.eyJ1IjoiZlZlYmVhZHYiLCJhIjoiYmU0ZXQtcyJ9.8Fh95YZQ_WdYEDlgtmH95A#15/-5.4270/53.3358)

Figure S3: High resolution drone imagery (1 pixel = 15 cm) of St Joseph Atoll at a 1.4 m high tide is available at the following link, courtesy and Copyright © of Drone Adventures for the Save Our Seas Foundation:

[https://a.tiles.mapbox.com/v4/droneadv.oh069ib0/page.html?access\\_token=pk.eyJ1IjoiZlZlYmVhZHYiLCJhIjoiYmU0ZXQtcyJ9.8Fh95YZQ\\_WdYEDlgtmH95A#15/-5.4270/53.3358](https://a.tiles.mapbox.com/v4/droneadv.oh069ib0/page.html?access_token=pk.eyJ1IjoiZlZlYmVhZHYiLCJhIjoiYmU0ZXQtcyJ9.8Fh95YZQ_WdYEDlgtmH95A#15/-5.4270/53.3358)

## Kernel Density Probability

The method used to perform kernel density estimation used the same algorithm as ArcGIS, with a Quartic kernel density function:

$$density = \frac{1}{radius^2} \cdot \sum_{i=1}^n \left[ \frac{3}{\pi} \cdot pop_i \left( 1 - \left( \frac{distance_i}{radius} \right)^2 \right)^2 \right]$$

Where  $i = 1, \dots, n$  are the input points;  $pop_i$  is the occupancy value of point  $i$ ;  $distance_i$  is the distance between point  $i$  and the location.

Silverman's rule of thumb (Silverman 1986), adapted for two dimensions, was also used for the radius (or bandwidth):

$$SearchRadius = 0.9 * \min \left( SD, \sqrt{\frac{1}{\ln 2}} * D_m \right) * n^{-0.2}$$

$$SD = \sqrt{\frac{\sum_{i=1}^n x_i - \bar{x}}{n} + \frac{\sum_{i=1}^n y_i - \bar{y}}{n}}$$

Where  $D_m$  is the median distance to the mean centre of all occupied grid cells

Figure S4: Fast Fourier Transformation (FFT) analysis of peak frequency in overlap magnitude between blacktip reef sharks *Carcharhinus melanopterus* and sicklefin lemon sharks *Negaprion acutidens*, for real and random sharks, using a  $250 \times 250$  m grid cell ( $0.0625 \text{ km}^2$ ) instead of the conservative  $500 \times 500$  m grid cell ( $0.25 \text{ km}^2$ ).

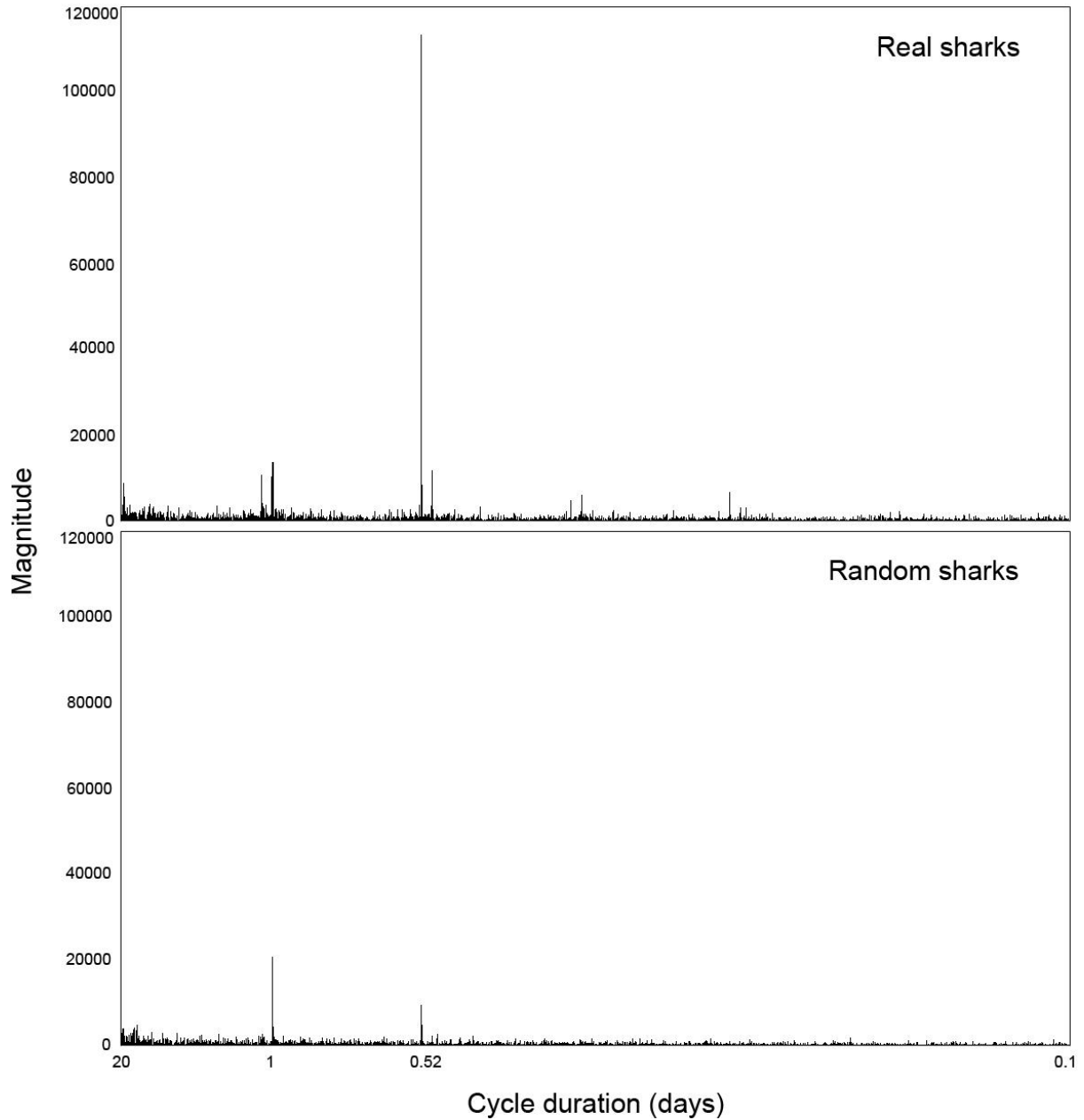
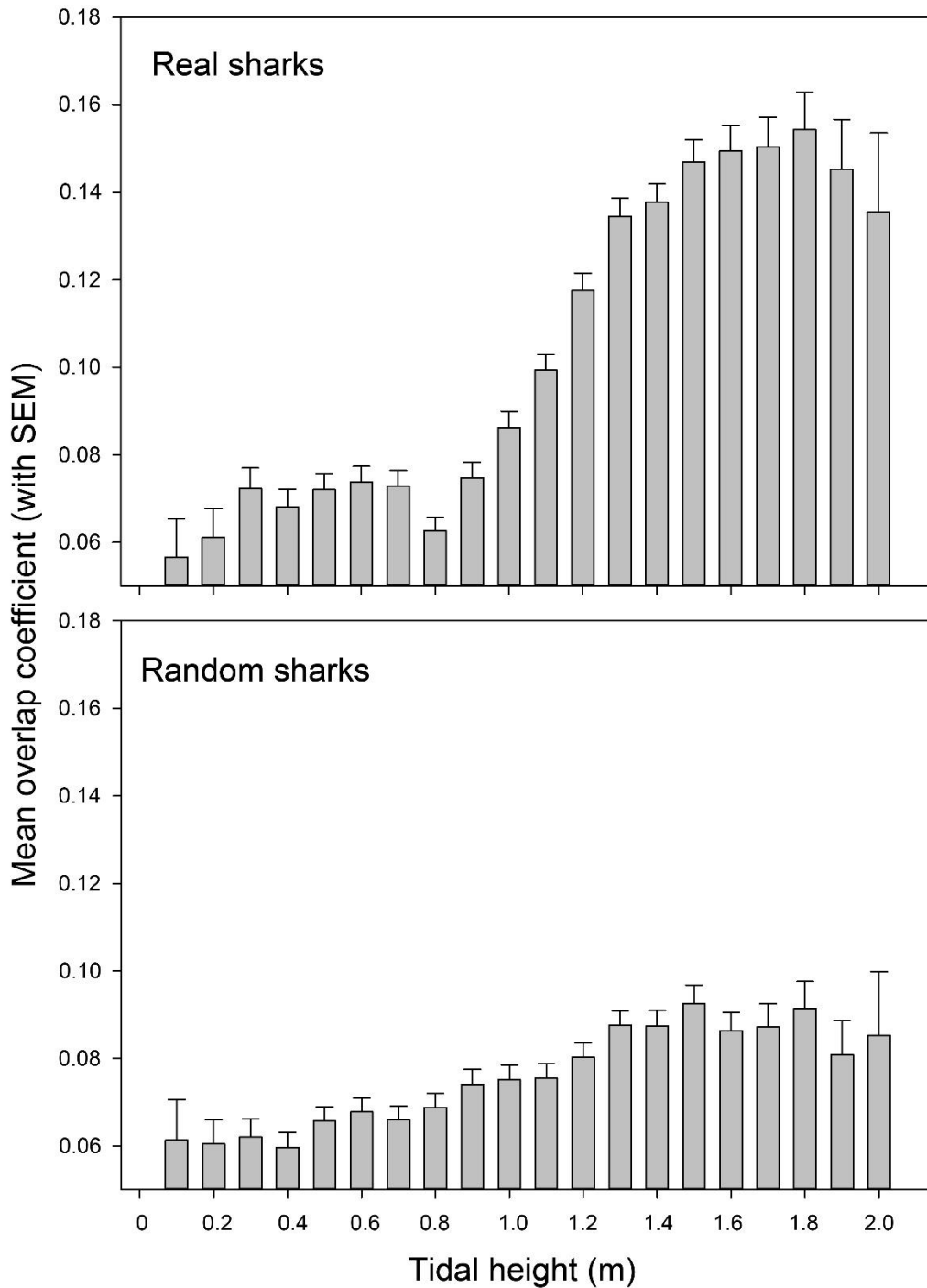


Figure S5: Mean overlap coefficient between blacktip reef sharks *Carcharhinus melanopterus* and sicklefin lemon sharks *Negaprion acutidens* over the course of the tidal cycle for both real and random sharks, using a  $250 \times 250$  m grid cell ( $0.0625 \text{ km}^2$ ) instead of the conservative  $500 \times 500$  m grid cell ( $0.25 \text{ km}^2$ ). For real sharks, mean overlap for tides  $<1.4$  m was  $0.09 \pm 0.14$  (SD), and  $0.149 \pm 0.15$  (SD) for tides  $>1.4$  m ( $0.07 \pm 0.12$  (SD) and  $0.09 \pm 0.18$  (SD), respectively for random sharks).



## Supplementary Tables

**Table S1: Results of one sample signed rank tests testing whether the relative difference of detection proportions between the lagoon versus flats differs from 0 (no difference) for each tidal bin.**

Blacktip reef shark				Sicklefin lemon shark			
Tidal height	Z	n	p	Tidal height	Z	n	p
0.1	-0.54	31	0.597	0.1	-2.16	28	0.032
0.2	-2.25	31	0.025	0.2	-3.22	28	0.001
0.3	-1.49	31	0.14	0.3	-2.68	28	0.008
0.4	-2.82	31	0.005	0.4	-3.32	28	<0.001
0.5	-2.28	31	0.023	0.5	-4.23	28	<0.001
0.6	-0.64	31	0.531	0.6	-3.41	28	<0.001
0.7	-0.73	31	0.473	0.7	-3.94	28	<0.001
0.8	-1.87	31	0.063	0.8	-3.49	28	<0.001
0.9	0.182	31	0.864	0.9	-3.8	28	<0.001
1.0	0.843	31	0.406	1.0	-3.1	28	0.002
1.1	1.327	31	0.188	1.1	-2.43	28	0.016
1.2	0.097	31	0.931	1.2	-0.84	28	0.407
1.3	1.935	31	0.054	1.3	2.095	28	0.037
1.4	2.355	31	0.019	1.4	2.547	28	0.011
1.5	1.914	31	0.057	1.5	3.695	28	<0.001
1.6	2.757	31	0.006	1.6	4.457	28	<0.001
1.7	1.979	31	0.049	1.7	3.363	28	<0.001
1.8	2.595	31	0.01	1.8	4.305	28	<0.001
1.9	2.629	31	0.009	1.9	4.381	28	<0.001
2.0	0.363	31	0.726	2.0	4.345	28	<0.001

## Acoustic Telemetry Data Processing

The raw data downloaded from the acoustic receivers (VR2W, Vemco Ltd, Bedford, Canada) is simply a list of detection IDs (the decoded 'ping' numbers from the tag) coupled with the time each detection was received. For the data to be useful the ping numbers must be translated to project specific fish IDs, the timestamp must be corrected for clock drift and the location ID that identifies where the receiver was deployed at the time the ping was received must be determined. The resulting triplet of Fish ID, Location ID and Timestamp represent a single acoustic telemetry datum and must be stored in a database that will allow large numbers of detections (potentially millions) to be selected and analysed to address the questions relevant to the research.

At the D'Arros and St Joseph project site, receivers (VR2W) have been deployed since 2012 and are downloaded approximately every six months. The array is large (>80 receivers) so to streamline the logistical task of downloading receivers at the surface and replacing them, the receivers are swapped *in situ* underwater, so that a new receiver with a fresh battery can be installed and the data downloaded on the service vessel. There is therefore an ongoing rotation of receivers, with almost seamless receiver coverage in the array, and the number of scuba dives required to perform the downloads is minimised. The rotation of receivers could present considerable problems in the analysis of the data and therefore a database and a suite of supporting programs have been written to manage the deployment of tags and receivers, to import the downloaded data and perform the necessary filtering and corrections and to store the data in a manner amenable to complex analytical methods, such as network analysis.

Although the single datum of Location, Fish Id and Timestamp is simple, processing millions of these detections to perform robust analysis can be complex and problematic. Consequently, the software includes a number of functions that combine complex selection criteria with multiple analysis options to ensure that extracting the wealth of information from the data can be achieved quickly and reliably. The software is written in C#, in the Windows Forms desktop framework providing a graphical user interface for all functions and can operate using either an Access or SQL Server database. While many researchers will have Access as part of Microsoft Office, an Access database is limited to a maximum size of 2 Gb. The 2 Gb limit is unlikely to represent a problem except for very large and long running arrays however, SQL Server Express (or LocalDb) is a free download with a limit of 10 Gb and offers much better overall performance.

The key features of the software are as follows:

### **Data import**

Data can be imported directly from the downloaded \*.vrl files from VR2 receivers or from the text files downloaded from the older VR3 receivers. Checks are included to prevent files, or detections, being inadvertently imported more than once. Firstly, using the VRx receiver serial number and the download date, a device deployment table is cross referenced to resolve the 'Deployment ID' that records the geographic location at which the receiver was deployed when the download was performed.

Using deployment and clock reset dates from the device deployment table and the \*.vrl file together with the time of download on the PC (which is used as an accurate reference), a clock drift correction is performed, assuming a linear drift function, as recommended by Vemco. If required, the timestamp is converted from UTC to the local time, to simplify later analysis.



Ping numbers are translated first to tag numbers using a table of all tag numbers deployed by the project. Any unmatched numbers could represent pings from tags deployed by other groups and therefore these are written to an error table from which 'mystery tag' data can be exported. Tag numbers are then cross referenced to a tagged fish table to determine the Fish Id. This last step allows for tags having been retrieved and redeployed by checking the tag deployment dates on the Fish table.

A record, comprising Deployment Id, Fish Id and Timestamp is then written to the Detections table. When all pings for the download have been processed, the import history table is updated to maintain a record of the data imported and to allow checks to be performed to prevent duplicate pings being imported if the receiver data is not cleared prior to redeployment. While this is not likely to be the case with VR2 receivers, that are typically retrieved, serviced and redeployed, it can occur with VR3 and VR4 receivers that are downloaded via an acoustic modem.

Import errors resulting from incorrect configurations, such as incorrect receiver deployment dates are clearly identified and can be easily reprocessed and imported once the errors are corrected.

### **Data Analysis**

The software to analyse the data, although provided essentially in a single program, is best considered in two parts: Selection and Data analysis.

#### *Selection*

Selection of the data is organised into three categories, relating to the three elements of the detection datum, Pings, Geographic location and Fish.

**Ping selection.** Pings can be selected using combinations of date ranges, hour of the day or month of the year. It is possible to update the detections table with Tide heights and Temperatures, when these are available, and these too can be used to select pings.

**Geographic location.** As well as latitudinal and longitudinal ranges, selection criteria can specify depth ranges, habitats, or select specific subsets of receiver deployments. For example, for D'Arros and St Joseph, it might be necessary to select detections only from those receivers located in the lagoon.

**Fish.** Fish can be selected using combinations of taxonomic affiliations, morphometrics (size, age, sex), or individual fish can be selected using the Fish ID. Once selections are complete the program constructs an SQL statement to select the required data from the database. The details of the selection depend in part on the analysis to be performed, some options for which are described below.

#### *Analysis*

The following data extraction or analytical methods are currently provided.

**Simple ping data extracts.** A number of straightforward functions are provided to extract lists of detections in the form of .csv files. Optionally tagging and morphometric data can be appended. Additional extracts are provided to give summary data (i.e. one entry per tagged fish), data formatted for use in GLM or GAM models, data formatted for uploading to the Wildlife Computers portal to merge with satellite data, or 'Mystery Tag' exporting.

**Track files.** Detections can be exported in the form of reconstructed tracks as a time series of locations for individual fish for the analysis of movement.

**Network analysis.** Network analysis methods lend themselves very well to the analysis of passive acoustic telemetry data, where receivers can be treated as nodes and movement between receivers as edges in the network. Networks can be constructed with a number of optional parameters, for example, the minimum speed of movement between consecutive receivers that can be considered a connection – if the time between consecutive detections is high (and consequently the speed low and the movement path likely to be meandering), then this is probably not a directed movement between receivers and therefore should not be considered to be a meaningful connection. Networks are therefore constructed by summarising movement and occupancy from the reconstructed tracks from all selected detections.

To aid with significance testing, the program can generate randomisations of the networks. Randomised networks are constructed by using randomised track reconstructions from all selected fish. For each track randomisation, the first ping at the first receiver is kept, and then a swim distance is calculated based on the time between detections and a 1 m/s swim speed. Receivers are then selected at random until two are found within range of the swim distance. The closer of the two is selected as the next receiver in the random track. If no receiver was found in range after 100 random selections then no move is deemed to occur and the current receiver is assigned (i.e. the animal is deemed not to have moved). This is repeated for the duration of the track, producing a random walk through the array with steps constrained by the observed detection intervals. By repeating this process typically 100 times for each track, mean randomised network metrics are produced that can be used to compare to the observed real track network metrics.

Networks can be output in a number of file formats for use in other software (e.g ArcGIS or UCINet) or can be sent to another program in the suite written specifically for the visualisation of networks. This ‘Visualiser’ (Figure S6**Error! Reference source not found.**) will display appropriately scaled and colour shaded nodes and edges, with optionally, nodes located in their correct relative geographical locations, greatly facilitating data exploration. Layout can currently be either geographical or topological.

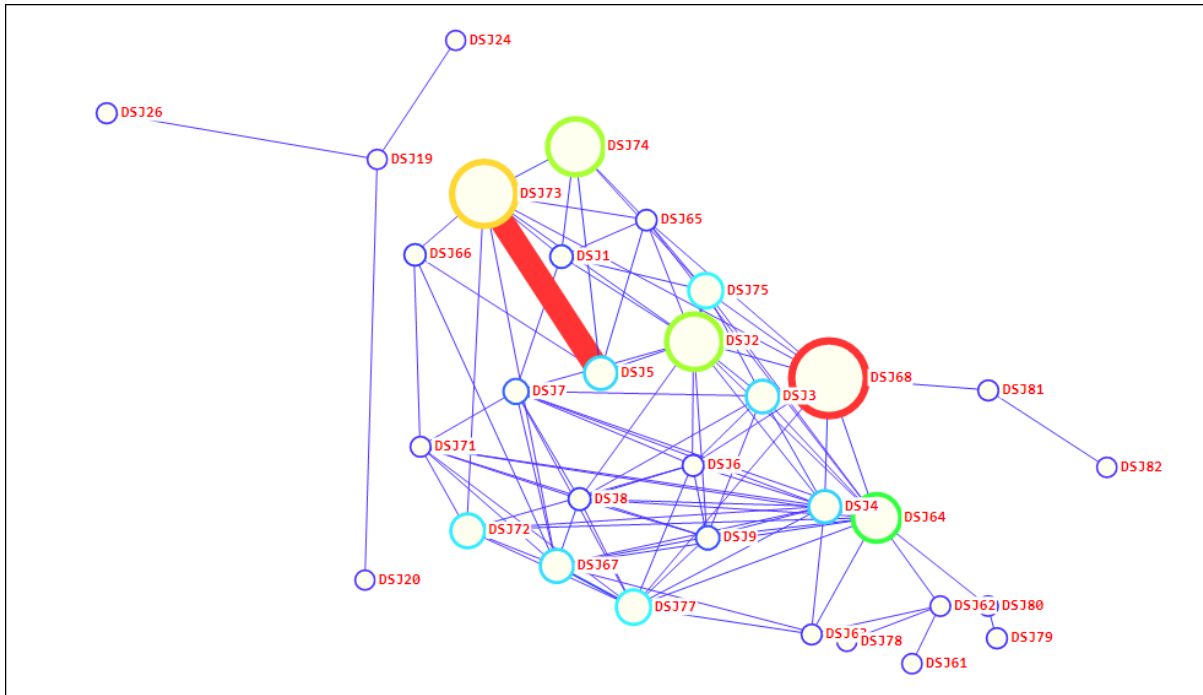


Figure S6: An example network as displayed in the visualiser with geographic layout.

**Time in Area Analysis.** This analysis computes for each fish the time spent inside, outside and transiting between the array and a selected subset of the array, e.g. for D’Arros, the lagoon. Time inside or outside is computed from consecutive pings occurring inside or outside the subset of the array respectively, while transit is computed from pairs of detections where one is inside and the other outside.

In addition, there are other analyses available, such as an interactive detection matrix (abacus plot) and single or double plot actograms. The design of the analysis program ensures that new analytical methods can be added as required.

#### Database maintenance

To ensure that database tables can be updated easily and accurately, graphical user interfaces are provided, e.g. *WorkWithFish* that provides update facilities for the tagged fish table and *WorkWithDeployments* that provides updates for deployment locations and the deployed devices. These programs perform extensive validation as data are entered and offer important functions, such as deployment receiver swap overs, that greatly simplify the maintenance of the data that are essential to the correct processing and analysis of the detections.

The software has been written Nicolas Humphries at the Marine Biological Association UK and are currently still in development and testing phases. It is intended that the software suite will be published for general use at a later date.

#### References

- Egbert G, Erofeeva S (2002) Efficient inverse modeling of barotropic ocean tides. *J Atmospheric Ocean Technol* 19:183–204
- Silverman, B. W. (1986). *Density estimation for statistics and data analysis*. Chapman and Hall, New York.