Orange-bellied Parrot Migration Tracking

VHF DATA PROCESSING PROTOCOLS 2024

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Summary

This document outlines the methods used by the Department of Natural Resources and Environment Tasmania (NRE Tas) to filter raw data downloaded from VHF receivers during tracking of Orange-bellied Parrots (*Neophema chrysogaster*; OBPs) over the 2024 northbound migration. These protocols are developed based on internationally recognised best-practice methods for analysing data of this type and contain two main steps: 1) distinguishing true-positive detections of OBPs from background radio noise and false-positive detections; and 2) estimating a location and positional accuracy of the location for each true-positive detection.

Background

Coded-VHF tracking utilises small VHF tags attached to an animal of interest that emit short burst radio signals that are unique to each tag. This allows for multiple animals to be individually detected and identified by a receiver monitoring a single VHF radio frequency. Data recorded by VHF receivers during coded-VHF tracking surveys however, also contain radio signals from various other sources including radio interference (noise), false-positive detections (a signal incorrectly attributed to a coded-VHF tag being used in the study) as well as true-positive detections (an actual signal emitted by a coded-VHF tag from the study). In this study we are solely interested in true-positive detections and therefore require a method to filter out interference and false-positive records from the data downloaded from VHF receivers.

In addition to recording the unique identifier of coded-VHF tags, receivers also record a Relative Signal Strength Indicator (RSSI) value for each observation which, for directional antennas such as those used in the 2024 OBP Migration Tracking survey, varies in relation to the distance and direction of the VHF tag to the VHF antenna location. Generally, the greater the RSSI value the closer the tag is to the antenna and more in line with the direction of directional antennas, while weaker signals are further from the antenna and further from the centre line of directional antennas. This should in theory allow for RSSI to be used as a proxy for a location estimate for each record; however, RSSI is also influenced by numerous other factors including wind, temperature, line-of-sight (e.g. obscuring vegetation or topography), proximity of the VHF tag to the ground, orientation of the tag relative to the antenna, battery power and individual performance of the VHF tag (Carlson *et al.* 2022; Desrochers *et al.* 2018). Because of these multiple influences there is still a large degree of uncertainty when using RSSI values to determine location estimates even when RSSI values are standardised against ground-truthing surveys that calibrate RSSI to VHF tags in known locations within the antenna radiation pattern (Taylor *et al.* 2011).

The aim of these protocols is to develop a standardised ruleset for processing raw data downloaded from VHF receivers to produce:

- A filtered dataset containing only true-positive detections; and
- A conservative estimate of location for each true-positive detection.

This will be achieved by:

- defining a set of rules that separate true-positive detections from false-positive detections and interference based on an internationally recognised and peer-reviewed best practice ruleset; and

- generating a location estimate (and positional accuracy) from the theoretical range and radiation pattern of antennae used in the project and RSSI values of detections.

Data filtering

The first step in processing raw data is defining what is a true-positive detection from interference and false-positives. Because each record is stamped with a unique numeric identifier, removing interference (those records not stamped with an identifier associated with a tag used in the survey) is straightforward both in R (R Core Team 2023) and Excel. For instance, in R using the tidyverse package (Wickham *et al.* 2019) a simplified version of how this could be completed is as follows:

```
# install.packages(“tidyverse”)
library(“tidyverse”)

# read in tag metadata containing tag ids
taginfo <- read_csv(“taginfo.csv”)

# read in data downloaded from receiver
data <- read_csv(“receiver_data_download.csv”)

# filter out interference data
true_data <- data%>%filter(tagid %in% taginfo%>%pull(tagid))
```

With interference removed, the next step is to define which observations assigned an identifier associated with an actual tag are true-positive detections and which are false-positive detections. To do this we use protocols developed for use in the Motus Wildlife Tracking System (Motus) by Birds Canada and over 2,400 international research collaborators and partners. Since 2012, Motus protocols represent the best-practice approach to analysing VHF tracking data and have been used on more than 47,000 animals and 374 species across 34 countries in over 800 projects (Motus 2024).

The basis of these protocols relies on the association of records with the same identifier across time and space. For example, if a tag is detected at two receivers 200 km apart, only one of these records can be correct. Actual detections are orders of magnitude more likely than false-positive detections so protocols for defining true-positive detections rely on a weight of evidence (Motus 2022).

Motus protocols group detections at a receiver into *runs* of detections. A run is defined as a series of detections without a gap between sequential detections of more than 60 missed detections (Motus 2022). The tags used in the 2024 OBP Migration Tracking survey emit radio bursts at a set interval of every 5 sec so the gap to define a new run was 5 min (= 5 sec x 60).

As we would expect a burst from a tag within range of an antenna to be detected every 5 sec, the first step in defining a run of true-positive detections is to omit detections that are not recorded at roughly 5 sec or multiple of (e.g. at 5, 10, 15, 20, $n_{t+1} = 5n_t$… sec) from the previous detection. This must also account for small drifts in the timing of bursts that may affect burst interval length.

We considered these protocols at every antenna (as receivers can have multiple independent antennae). Before grouping into runs at each antenna, we removed detections that occurred simultaneous with another detection (0 sec burst interval), or outside the 5 sec burst interval (±1 sec to allow for drift) up to a 20 sec burst interval. All detections with burst intervals greater than 20 sec were included to account for cumulative drift. Note this was undertaken using a supervised approach (all potential removals were vetted prior to removal) to ensure no valid runs were removed due to a leading false detection occurring outside the 5 sec interval. Under supervision, all potential removals were removed. This removed ~7% of all detections assigned to an actual tag number. In this way runs were specific to antennae and not receivers, therefore a run could never be defined across two antennae at the same receiver.

With true-positive detections occurring far more frequently than false-positive detections, Motus protocols define true-positive detections based on run length. False-positives are isolated or infrequent events and can therefore be filtered out of the data based on a shorter run length. Typical Motus filtering defines runs of 4 or more detections (in sites with low radio noise) or runs of 5 or more detections (in sites with high radio noise) as true-positive detections (Motus 2023a). For our purposes and because our sites contain a mix of low and high levels of radio interference, we have opted for the more conservative estimate of defining true-positive detections as runs of 5 or more detections across all sites.

Finally, filtered data is then plotted and visually checked to assess spatial relationships between runs of true-positive detections to ensure their distributions are biologically plausible (e.g. a bird does not appear in Stanley and then 2 hrs later in Melaleuca and then back in Stanley an hour after that). Using the ruleset defined above, no biologically implausible true-positive detections have been observed in 2024 surveys.

To recap, true-positive detections are defined as detections that:

- are assigned a unique identifier known from the tag series;
- occur within the burst interval of tags while accounting for burst interval drift i.e. an interval of 5 sec (±1 sec) from the previous detection up to a burst interval of 20 sec, with all detections with a burst interval greater than 20 sec included to account for cumulative burst interval drift;
- occur within a run of 5 or more consecutive detections without a gap of 5 min between sequential detections; and
- are biologically plausible in their spatiotemporal distribution.

Location estimation and positional accuracy

Background

Remote tracking using VHF comes with an inherent level of location uncertainty, which can be reduced with intensive receiver deployments, appropriate antenna arrays, multiple antennas and multiple antenna types (omnidirectional and directional) (Baldwin *et al.* 2018). This is because even with multiple directional and omnidirectional antennae and a measure of signal strength, the angle of a tag to the receiver is unknown and could be anywhere along the isopleth for that signal strength (Janaswamy *et al.* 2018). Therefore, determining an approximate location of the tag relies on using signal strength as a proxy for distance in trilateration (locating a tag based on its distance from three or more receivers) (Paxton *et al.* 2022) or triangulation (locating a tag based on its angle from two or more receivers) (Janaswamy *et al.* 2018).

Even in well-designed surveys over small areas location uncertainty remains higher in VHF tracking than other more precise telemetry methods such as GPS (Taylor *et al.* 2017). Although still an imperfect measure of location uncertainty, the accuracy of estimating location is greatly improved in VHF tracking studies by ground truthing the relationship between distance of a tag to a receiver and signal strength (Janaswamy *et al.* 2018). This can be achieved by placing tags in the range of antennae at differing distances and angles to directional antenna and leaving them in location for the duration of the study. Tags need to be left in place throughout the study as this relationship can vary over study period with changing environmental conditions and tag deterioration. This was not practicable in our study for numerous reasons. 1) signal strength can vary between sites and the number of receivers in our study increased the survey effort needed to achieve this; 2) ground truthing was not possible within our study's timeframe and short turnaround; and 3) as our study was tracking a flying animal and signal strength varies with height from the ground, the range of altitudes that could be utilised by birds in flight limits the reliability of ground truthing using tags placed on the ground.

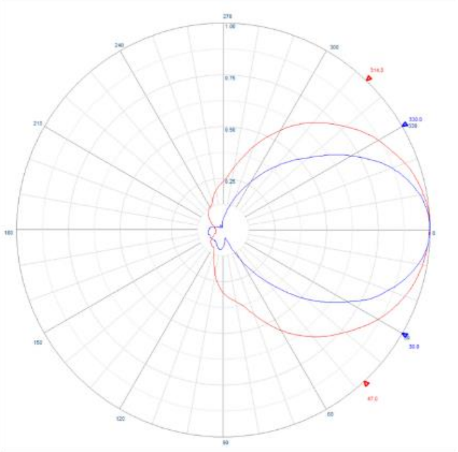


Figure 1. The theoretical radiation pattern of antennas used in this project, illustrating the near circular ellipsoid shape and lack of back and side lobes.

Issues with location estimation specific to this project design

In our surveys we used two directional antennas with a theoretical range of ~5km at each receiver (Motus 2023b). Because the array of twenty receivers in this project was placed across a large extent, most had non-overlapping coverage with other receivers making it difficult to determine a location for a tracked OBP using trilateration or similar methods that utilise RSSI and distance or angle to a signal. Because of this, each detection represented a non-georeferenced observation of an OBP. Nonetheless, an estimate of location (and an estimate of positional accuracy associated with a location) is important for entering data into databases of observational data (e.g. the Natural Values Atlas, NRE Tas).

Preliminary methods

A crude approach would be to use the location of the receiver as the location estimate for the observation (± the positional accuracy of the location), however, this would be misleading as we are often certain this was not the location of the detected OBP particularly for detections with a low RSSI. In addition, a small (GPS derived) positional accuracy (e.g. ~4-6 m) of the receiver location would give a misleading sense of location certainty to the observation.

Given the antennae used in this project were directional and had a theoretical range and radiation pattern, a slightly more nuanced approach would be to project out from the receiver location to find the centre of the antenna range and use the theoretical range of the antennae as the positional accuracy (Fig 1). However, the actual range of the antenna can vary from the theoretical range and therefore this method would under- or over-estimate the positional accuracy of each detection.

Refined method for location estimation and positional accuracy

Location estimation

Both the antenna location and the centre of its range are coarse-scale localizations of tag position. An extension of this method is to further account for shifts in location estimates by modelling the relationship between distance from the mast and RSSI values using the density distribution of RSSI values. If we assume 1) a circular radiation pattern (Fig 1) with constant detection probability inside the theoretical range of the antenna (~5 km) and decreasing detection probability at

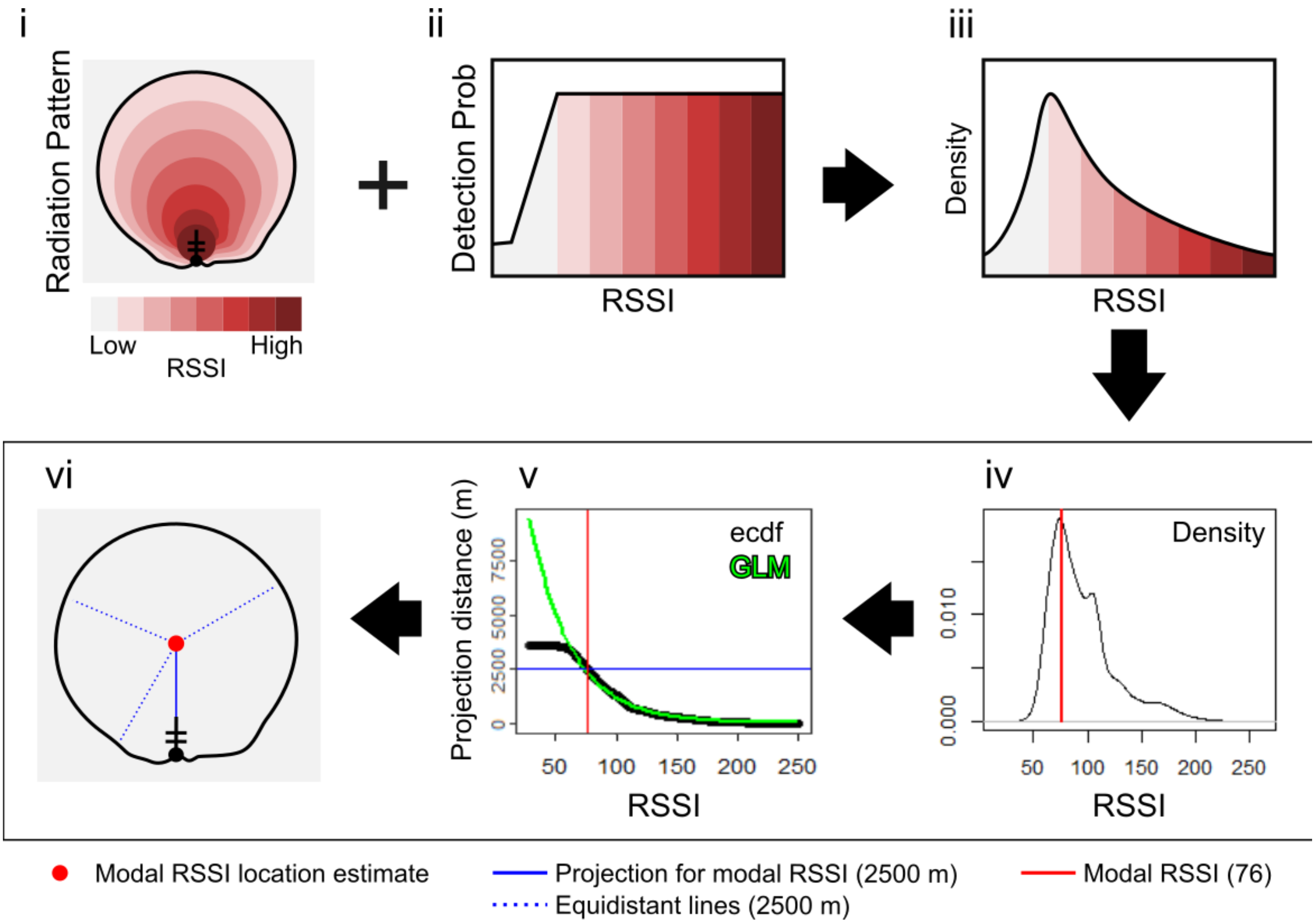


Figure 2. Assuming (i) a 5km range and circular radiation pattern with RSSI diminishing with distance; and (ii) a constant detection probability within the range and diminishing detection probability outside this range; then the density distribution of RSSI values would be positively skewed with modal RSSI values associated with transmitters that were detected on the perimeter of the radiation pattern (being the RSSI isopleth with the largest surface area and constant detection probability) (iii illustrative; iv actual). Standardising the empirical cumulative distribution function of RSSI values to distance from the mast with the maximum RSSI value at 0 km from the mast and modal value at 2.5 km from the mast (the radius of the circular 5 km range) and modelled projection distances (v) would allow for location estimates (without a measure of positional accuracy) to be calculated as a distance projected from the location of the antenna mast (vi). Location estimates are close to equidistant to all the possible actual locations of the transmitter in x, y and z directions along the given RSSI isopleth but do not contain a measure of position accuracy.

distances beyond the theoretical range; and 2) that birds (detections) were randomly distributed throughout the possible detectability space of the antenna, then we would predict RSSI values to be positively skewed and have a modal value corresponding to detections at the perimeter of the nominal range (being the RSSI isopleth with the greatest surface area and constant detection probability; Fig 2). The distance of location estimates from the antenna mast (projected in the direction of the antenna bearing) can then be calculated using the empirical cumulative distribution function (*ecdf*) of RSSI values, with a distance of 0 km for maximum values and 2.5 km for modal values (Fig 2v). 0 km was chosen as the location projection distance for maximum values based on test tag data collected during mast installation that showed RSSI values for tags at or near the base of the mast to be at or below the maximum RSSI value recorded during tracking. To account for variation in detection probability affecting projection distances beyond the theoretical range of the antenna (see Fig 2v), projection distances used to calculate location estimates were modelled from all *ecdf* derived distances with RSSI ≥ modal RSSI using a log-linked Gamma distribution GLM. Location estimates are close to equidistant to all the possible actual locations of the transmitter in x, y and z directions along a given RSSI isopleth but require a measure of positional accuracy.

It is important to note that this method is intended to improve location estimates of tracked OBPs beyond the preliminary methods outlined above; however, still relies on a theoretical and highly simplified antenna radiation pattern (Fig 2 I and Fig 2 ii). While this simplified radiation pattern model is supported by the data (cf. Fig 2iii & Fig 2. iv) it should nonetheless be treated with caution during interpretation and analysis and used as a guide only.

The utility of co-detections

As well as refining location estimates of tagged OBPs, the RSSI of detections could also be used to estimate positional accuracy as positional accuracy has an inverse relationship with RSSI. Positional accuracy is smaller for detections with high RSSI (e.g. when a tag is closer to the antenna) and larger for detections with low RSSI (e.g. when a tag is far from the antenna). However, this requires a method of calibrating RSSI with distance. One potential method for calibrating RSSI with distance is by estimating the location of tags that were co-detected at the same time by two different receivers using bilateration (locating a tag based on its distance from two receivers).

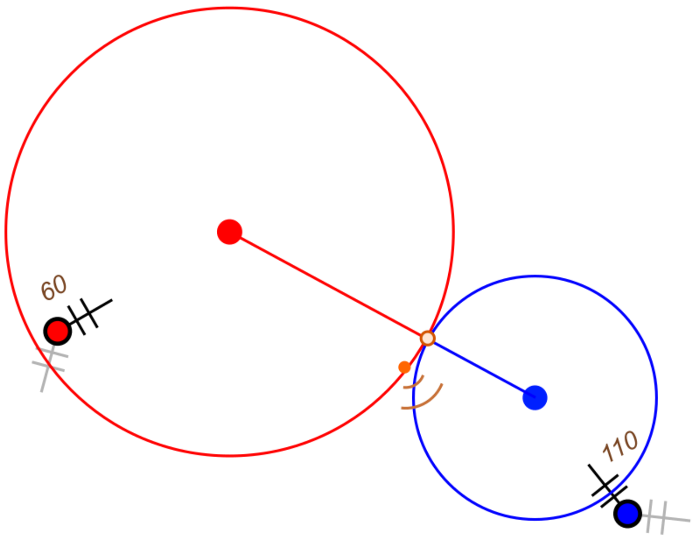


Figure 3. An example bilateration to determine an approximate location (light orange point) of a co-detected tag (orange point) using relative RSSI values (red and blue circles). Distances in bilateration are calculated as proportion of the total distance between the two centre points based on relative RSSI values. In this case the distance to the red centre point is around two-thirds of the total distance as $RSSI_{RED}$ is slightly weaker than $RSSI_{BLUE}$ ($Distance_{RED}$ = total distance x $RSSI_{BLUE} / \sum RSSI$). This distance is a measure of the positional accuracy of the location estimate at the centre of the theoretical antenna range (red and blue lines). Theoretical RSSI values are shown next to the antennae.

In a few cases, two receivers were in close enough proximity to each other to allow co-detection of a tag at both receivers at the same time. Co-detections highlighted the degree to which the actual range of antennas can vary with environmental conditions. In one instance, a co-detection of two confirmed true-positive detections occurred between receivers 14 km apart. In this case the bird would have been at least 7 km from both receivers (assuming the bird was detected exactly halfway between the two receivers), however it is likely the bird was further than this distance from one or both towers. In another example a bird was detected at two receivers 20 km apart within a 5 sec interval. Given the distance covered even at a maximum likely speed of travel (< 150 m) and the scale of location uncertainty involved in VHF tracking (> 1 km) we could reasonably consider this to be a co-detection between towers for our purposes.

Because location estimates of co-detected tags record two separate locations for the same tag at the same time, the distance between the two locations could be used to measure positional accuracy. Using co-detections, we measured a geodesic distance to an approximate tag location between the two location estimates using bilateration for a subset of tags. RSSI was used as a proxy for distance in bilateration calculations by scaling the distance between the two location estimates by their relative RSSI values. This method assumed the actual tag was roughly between the two location estimates. The difference between the location estimate and the tag location calculated using bilateration was then used to model positional accuracy based on RSSI.

Estimating positional accuracy

The difference (in km) between location estimates and tag locations calculated using bilateration was modelled against RSSI values for all co-detected tags using a using a log-link Gamma distribution GLM. The 95% quantile in GLM quantile regression from this model was then used as the measure of positional accuracy based on RSSI for all detections including those that were only recorded at a single receiver.

Key assumptions in these estimates of positional accuracy are:

1. That the theoretical range for antennae is a near circular ellipsoid, with minimal back and side lobes.
2. RSSI has an exponential decay with distance.
3. That the tag is located close to the line connecting the shortest distance between the two location estimates.

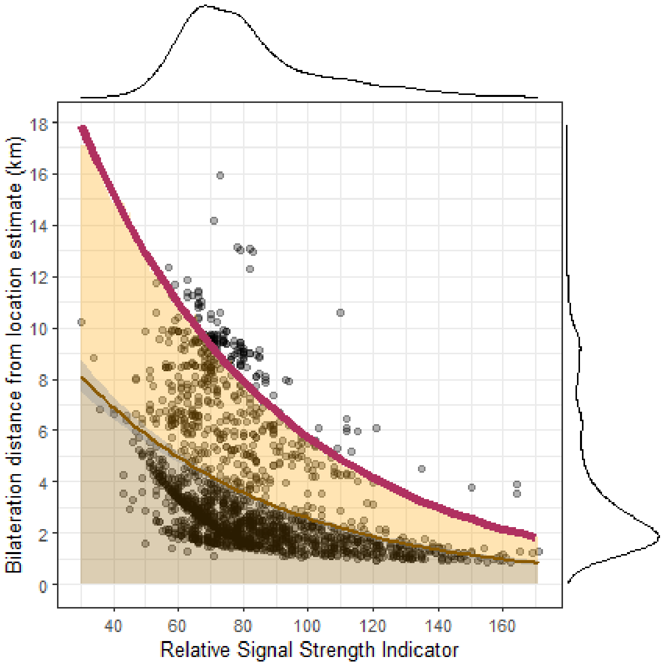


Figure 4. The distance from location estimates to tag location calculated using bilateration as a function of RSSI and modelled using a log-link Gamma distribution GLM. Dark orange shaded area shows the median 50% quantile. Orange line and grey shaded area shows the predicted mean and 95% Confidence Interval. Maroon line and all orange shaded area shows the 95% quantile or positional accuracy.

Assumption 1 is based on the ellipsoid shape of the theoretical radiation pattern for the type of antenna used in the 2024 OBP Migration Tracking survey (Fig 1). Assumption 2 is based on studies that have shown RSSI has a theoretical exponential decay relationship with distance over the range of distances used in this study (Paxton *et al.* 2022). Assumption 3 is likely to have been violated in some cases. However, the greater the distance between the two antenna the more likely that assumption 3 is valid. This is because as the distance between two antennae increases the overlap in their ranges diminishes until the tangent of the two ranges lies directly along the line connecting the shortest distance between the centres of the two theoretical ranges of the pair of antennae (under Assumption 1 being that radiation pattern is near circular, Fig 1). For this reason, a minimum distance cut-off between paired location estimates in co-detections was used to filter out cases where the actual tag's location had a greater chance of not being directly between the two location estimates due to their close proximity to each other. 2.5 km was chosen based on the theoretical range of the antennae used in this project (~5 km). With this cut-off in place, it seems plausible that most remaining co-detected tags were actually located close to the line connecting the shortest distance between the two location estimates. This assumption is necessary because locations predicted with bilateration using RSSI values as a proxy for distance will always lie on the line connecting the shortest distance between the two location estimates.

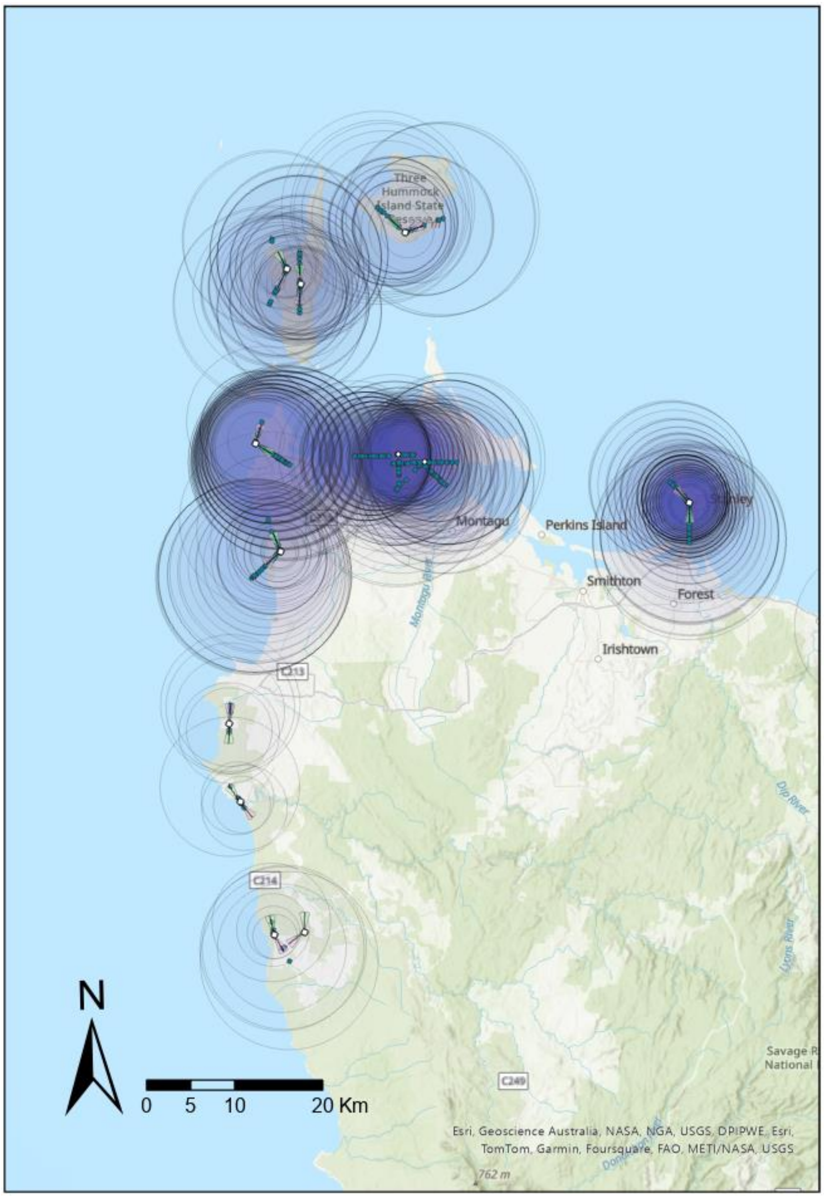
Steps in modelling postional accuracy were as follows:

1. Classify two true-positive detections within a 5 sec interval of each other at two separate antennae as co-detections.
2. Remove any co-detections with location estimates within 2.5 km of each other.

3. Determine a tag location using bilateration by calculating a distance from the two location estimates to an approximate tag location along the shortest geodesic path between the two location estimates with the two distances scaled by their relative RSSI values (Fig 3).
4. Model bilateration distance from location estimate as a function of RSSI and plot the 95% quantile to estimate with (95% confidence) the positional accuracy of the location estimates (Fig 4).
5. Table positional accuracy by binned RSSI values (in intervals of 5) for use in generating positional accuracy for the entire dataset, with each bin receiving the positional accuracy value (in m) of the bin's lowest RSSI value (Table 1).
6. Plot location estimates with position accuracy for each observation (run of detections) based on the median RSSI value in each run (Fig 5).

Table 1. Positional accuracy of detections based on their RSSI values.

RSSI Limits		Position accuracy (± m)
Lower	Upper	
-Inf	34	17882
35	39	16485
40	44	15196
45	49	14008
50	54	12913
55	59	11904
60	64	10973
65	69	10115
70	74	9325
75	79	8596
80	84	7924
85	89	7305
90	94	6734
95	99	6207
100	104	5722
105	109	5275
110	114	4862
115	119	4482
120	124	4132
125	129	3809
130	134	3511
135	139	3237
140	144	2984
145	149	2751
150	154	2536
155	159	2337
160	164	2155
165	169	1986
170	Inf	1831



Esri, Geoscience Australia, NASA, NGA, USGS, DPIPWE, Esri, TomTom, Garmin, Foursquare, FAO, METI/NASA, USGS

Figure 5. An example of plotted location estimate and positional accuracy for each observation at NW Tasmania sites in 2024 OBP migration tracking.

Conclusion

The methods described in this document represent the current best-practice approach for defining true-positive detections, filtering raw data from VHF receivers and defining location estimates and positional accuracy of true-positive detections based on RSSI values (signal strength). Steps in data filtering are a conservative approach based on internationally recognised best practice methods. Steps in location accuracy are specific to the antennae array deployed for tracking of OBPs during the 2024 migration season and may be subject to change in future years. These steps may be improved somewhat by calibrating RSSI values against a subset of standards (an array of tags placed around each receiver to record fluxes in RSSI values throughout the season and at different directions and distances from antennae). Further improvement may be made by augmenting antenna arrays with a greater number of antennae at a site and a mix of directional and omnidirectional antennas.

It is important to note that the methods used for modelling location estimates and positional accuracy are intended to improve estimates beyond the preliminary methods that use the location of the receiver station and theoretical radiation pattern of antenna by incorporating signal strength into model estimates. While these methods are supported by the raw data, they still use a simplified interpretation of the antenna radiation pattern and should therefore be treated with caution during interpretation and further analysis. It is recommended these spatial outputs are regarded as a conservative guide for location and position accuracy only.

Acknowledgments

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Tasmanian
Government

Department of Natural Resources and Environment Tasmania
Orange-bellied Parrot Tasmanian Program

Email:
OBP.Program@nre.tas.gov.au

www.nre.tas.gov.au