UCC

University College Cork, Ireland

Coláiste na hOllscoile Corcaigh

Supporting Information: Jones-Todd, C. M., E. Pirotta, J. W. Durban, D. E. Claridge, R. W. Baird, E. A. Falcone, G. S. Schorr, S. Watwood, and L. Thomas. Discrete-space continuous-time models of marine mammal exposure to Navy sonar. *Ecological Applications.*

Appendix S1. Atlantic Undersea Test and Evaluation Center

This section contains supplementary material relating to Blainville's beaked whale AUTEC data discussed in the manuscript. Fig. S1 shows the estimated and the raw ARGOS locations of the seven Blainville's beaked whales introduced in Section Telemetry data and exposure information; see Table S1 for a summary of each individual.

Tables S2 and S3 give the number of observations per Argos location class per individual and the estimated measurement standard deviation for each location class averaged across individuals, respectively. Table S4 gives the number of observations per individual, after the CTCRW model was fitted, classified as on- or off-range (black polygon in Fig. 1 of the manuscript).

Estimated individual-level random effects for the fitted model given by Equation 2 are shown in Fig. S2. For the baseline model, (a) in Section Discrete-space continuous-time Markov model, our package `mmre`, `https://doi.org/10.5281/zenodo.4876540` (Jones-Todd, 2021), returns the same parameter estimates and log-likelihood as the package `msm` (Jackson, 2011) in Table S5.

A multiple imputation procedure was used to show how the uncertainty associated with the Argos tracks could be propagated to the Markov model (Section Discrete-space continuous-time Markov model); Fig. S3 shows an example of twenty simulated tracks for three individuals. The root mean squared error (RMSE) and bias for each parameter in the simulation study (Section Simulation) are shown in Table S6; percentage errors are shown in Fig. S4a. Fig. S4b gives the values of the estimated parameters from the multiple imputation (Section Discrete-space continuous-time Markov model). Fig. S4c shows the aggregated residuals for each individual. Residuals are calculated as the difference between the observed number of transitions and those expected, between each state. Observations are partitioned based on quantiles, [0%–25%), [25%–50%), [50%–75%), and [75%–100%], of the observation times and the covariate (using the estimated transition rates as recommended by Aguirre-Hernández and Farewell (2002)); the observed number of transitions are the sum of each transition observed in each category. The estimated number of transitions are calculated as the sum of the transition probabilities in each bin.

Tag IDs	93232	111664	111670	129715	129719	129720	129721
Sex	Male	Female	Female	Female	Unknown	Female	Female
Age class	Adult	Adult	Adult	Adult	Subadult	Adult	Adult
Start date	2009-05-07	2012-05-06	2012-05-06	2013-11-11	2015-10-30	2015-10-30	2015-10-30
End date	2009-06-02	2012-05-23	2012-06-02	2013-11-28	2015-12-31	2015-11-25	2016-01-26
Duration (days)	25.96	16.74	26.84	17.24	61.44	25.59	87.91
Av. #	6.51	8.54	7.67	2.44	6.93	12.31	6.68
Tag type	SPOT	SPLASH	SPLASH	SPOT	SPOT	SPOT	SPOT

Table S1: Sex and age class for each tagged Blainville's beaked whale (see Fig. 1) along with tag start and end times, duration of tagging, average number of observations per day (Av. #), and tag types.

Tag IDs	3	2	1	0	A	B
93232	3	13	25	23	30	75
111664	5	13	31	29	16	49
111670	5	18	33	63	25	62
129715	0	1	0	0	4	37
129719	10	29	51	88	61	187
129720	13	42	58	89	40	73
129721	26	77	97	156	73	158

Table S2: Number of observations per Argos location class per individual Blainville's beaked whale. Note that any Z-class observation was removed prior to fitting the movement model.

	3	2	1	0	A	B
Latitude	0.87	4.53	20.26	19.74	36.45	112.68
Longitude	1.04	3.36	8.33	9.04	17.28	106.47

Table S3: Standard deviation for the measurement error for each observed Argos location class averaged across the seven individual Blainville's beaked whales.

Tag IDs	off-range	on-range
93232	104	65
111664	86	57
111670	173	33
129715	13	29
129719	420	6
129720	101	214
129721	535	52

Table S4: Number of observations on- and off-range for each tagged Blainville's beaked whale, see Fig. 1 of the manuscript.

Method	$\mathbf{P}(\mathbf{t} = \mathbf{1})$	log-likelihood
msm	$\begin{bmatrix} 0.877 & 0.123 \\ 0.505 & 0.495 \end{bmatrix}$	-257.042
mmre	$\begin{bmatrix} 0.877 & 0.123 \\ 0.505 & 0.495 \end{bmatrix}$	-257.042

Table S5: Comparison of the baseline `mmre` model, (a) in Section Discrete-space continuous-time Markov model, fitted to Blainville's beaked whale tracks, with the equivalent model in `msm` (Jackson, 2011).

	RMSE	bias
$\beta_{0,12}$	1.67	1.60
$\beta_{0,21}$	1.58	1.55
$\beta_{1,12}$	0.94	-0.33
$\beta_{1,21}$	0.60	-0.14
$\beta_{2,12}$	3.04	1.59
$\beta_{2,21}$	1.97	0.65

Table S6: Root mean squared error (RMSE), $\sqrt{\overline{(\hat{\theta}-\theta)^2}}$, and bias for each estimated parameter, θ, in the simulation study discussed in Section Simulation.

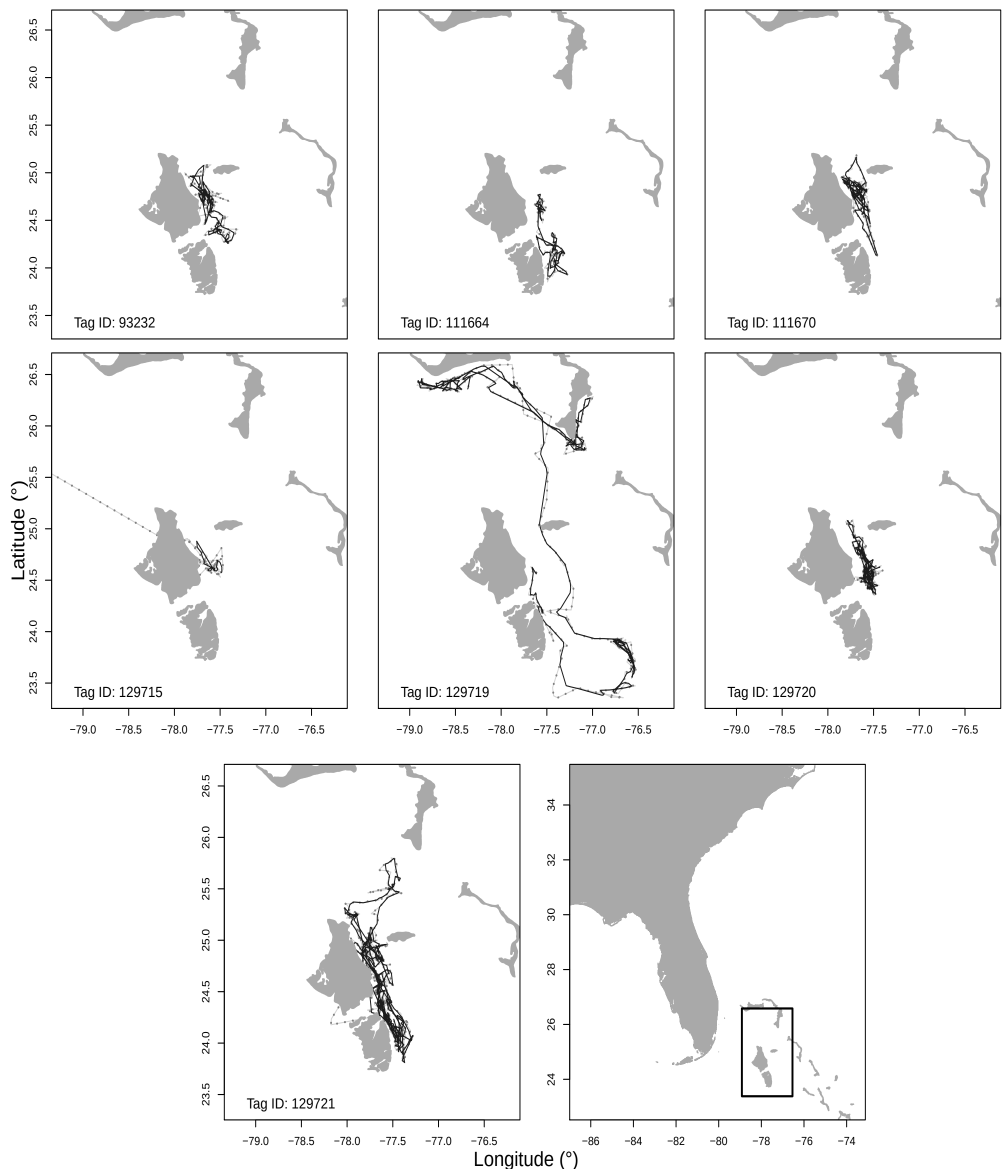

Figure S1: Estimated tracks, shown in black, and the raw ARGOS locations, dotted grey lines, of the seven Blainville's beaked whales *(Mesoplodon densirostris)*, at the AUTEC range, Bahamas (see Fig. 1).

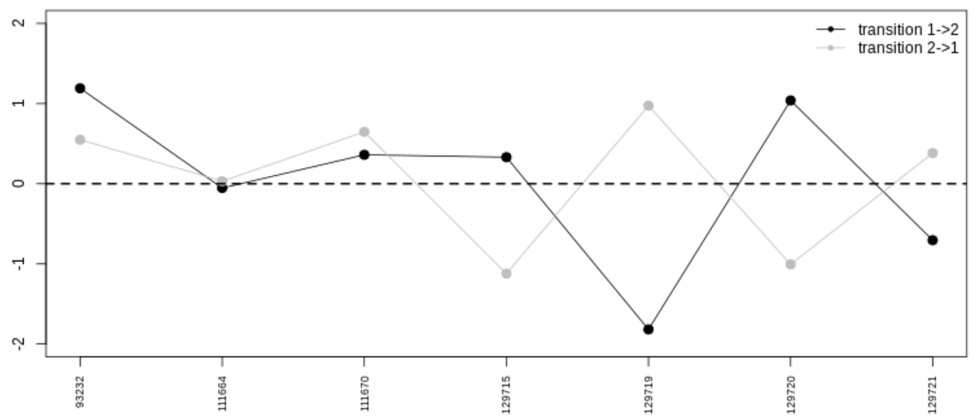

Figure S2: Estimated individual-level random effects for each of the seven Blainville's beaked whales for the model given by Equation 2 and discussed in Sections Discrete-space continuous-time Markov model and Results.

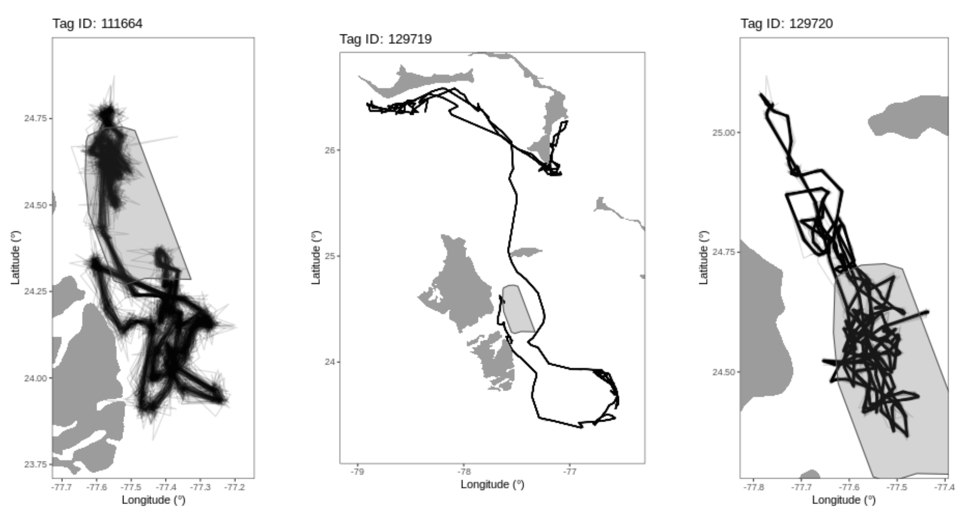

Figure S3: An example of twenty simulated tracks, assuming a bivariate t-distribution for the measurement error on the location of three individuals tagged on the AUTEC range (dark grey polygon), Bahamas. Tracks are semi-transparent and are overlain on one another.

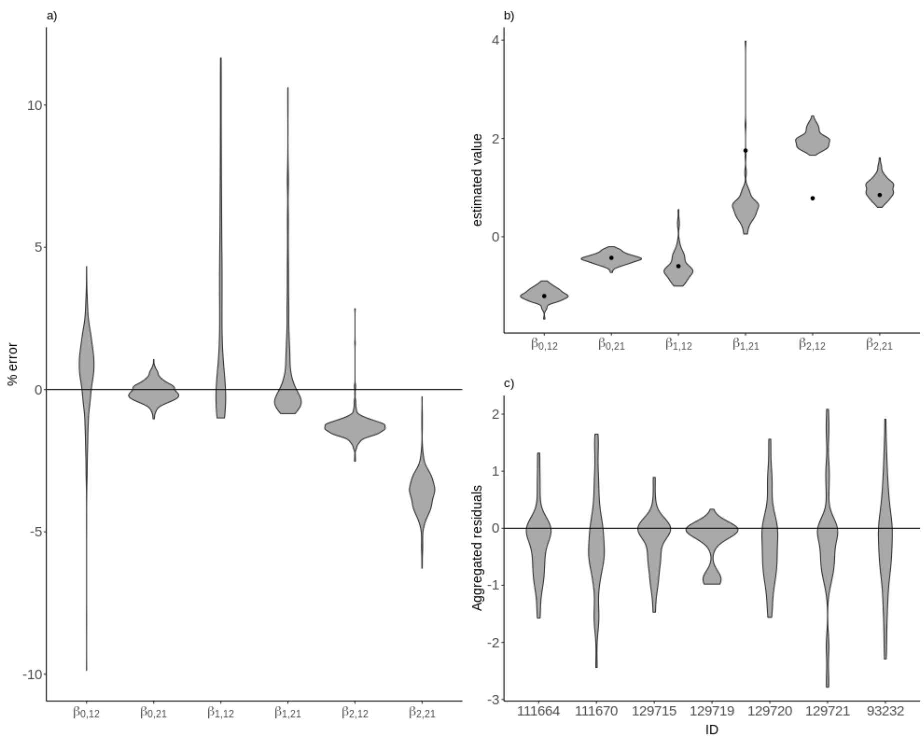

Figure S4: a) simulation errors for each estimated parameter, $\hat{\theta}$, expressed as a percentage of the true parameter value, θ, calculated as $\frac{\hat{\theta}-\theta}{\theta}$. b) parameter estimates from the models (Equation (2)) fitted to the imputed Blainville's beaked whale tracks; the black points show the estimated parameters from Table 1. c) aggregated residuals for each individual.

References

Aguirre-Hernández, R. and Farewell, V. (2002). A Pearson-type goodness-of-fit test for stationary and time-continuous Markov regression models. *Statistics in Medicine*, 21(13): 1899–1911.

Jones-Todd, C. M. (2021). cmjt/mmre: Release for accepted manuscript. *Zenodo*. `https://doi.org/10.5281/zenodo.4876540`.

Jackson, C. H. (2011). Multi-State Models for Panel Data: The `msm` Package for R. *Journal of Statistical Software*, 38(8): 1–29.