Movement-Assisted Localization in Acoustic Monitoring Studies

J. Andrew Royle

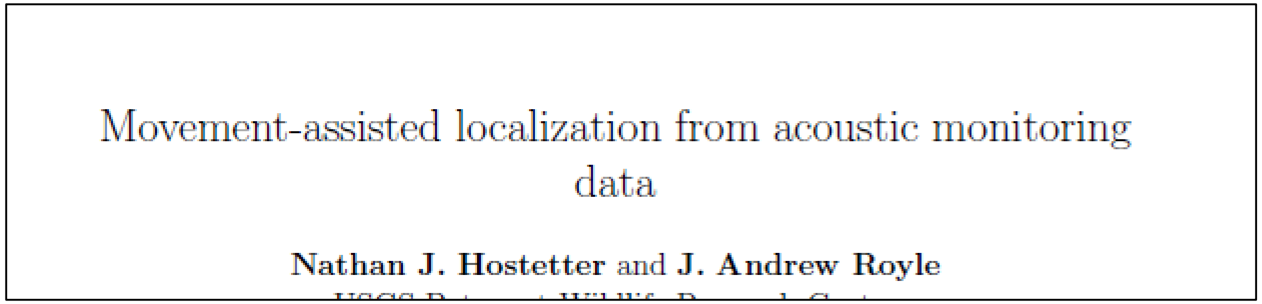
USGS Patuxent Wildlife Research Center

Nathan J. Hostetter

UW School of Aquatic and Fishery Sciences

NJH: polar bear postdoc with S Converse: Integrating movement models and unmarked sightings with SCR data

Paper: (almost submitted)



Movement-assisted localization from acoustic monitoring data

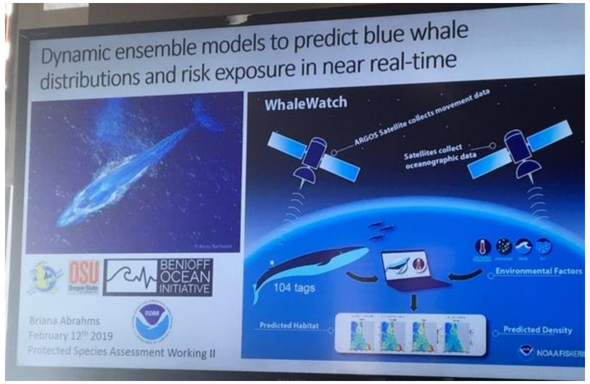
Nathan J. Hostetter and **J. Andrew Royle**

Outline

1. Capture-recapture and SCR
2. SCR as a framework for integration of data and models: Space is the mode of integration.
3. Acoustic monitoring: passive and active
4. Movement-assisted localization in acoustic telemetry studies
5. Toward passive acoustics
    - uncertain identity (or none at all)

Why integrated models, movement, localization, SCR?

Briana Abrahms

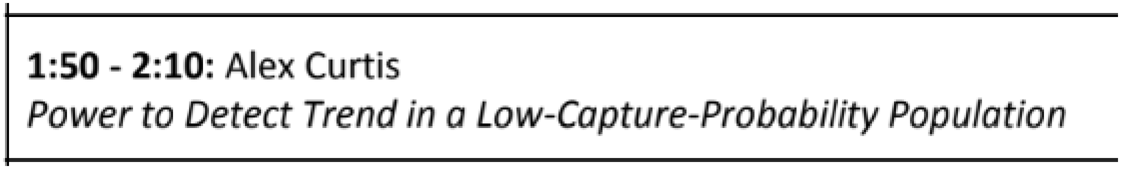


Dynamic ensemble models to predict blue whale distributions and risk exposure in near real-time

Briana Abrahms
February 12th 2019
Protected Species Assessment Working II

Species distribution models

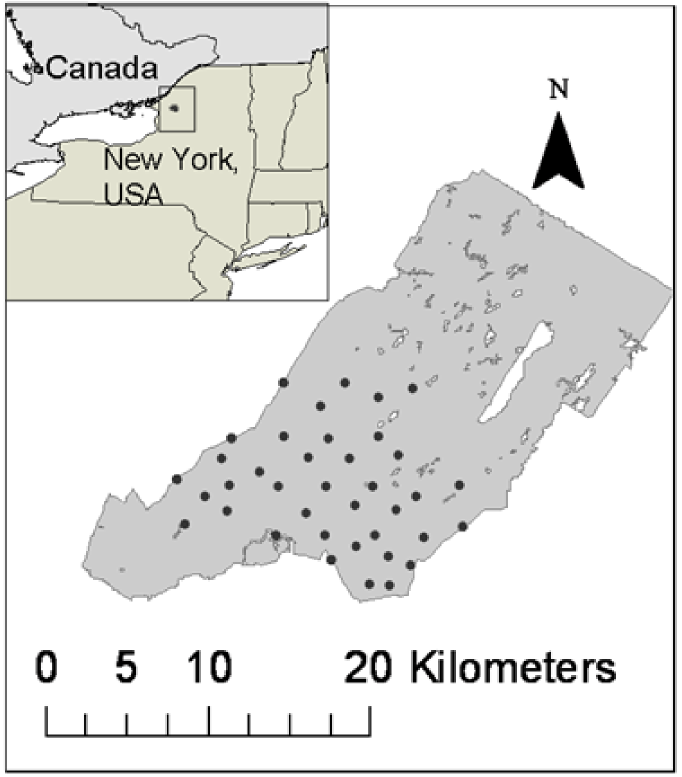
Individual-based models



1:50 - 2:10: Alex Curtis
Power to Detect Trend in a Low-Capture-Probability Population

1. Capture-recapture models

- Models for estimating population size, N, and other demograhpic parameters from *individual encounter history data* – usually obtained from an array of traps or similar devices



Individual encounter history data

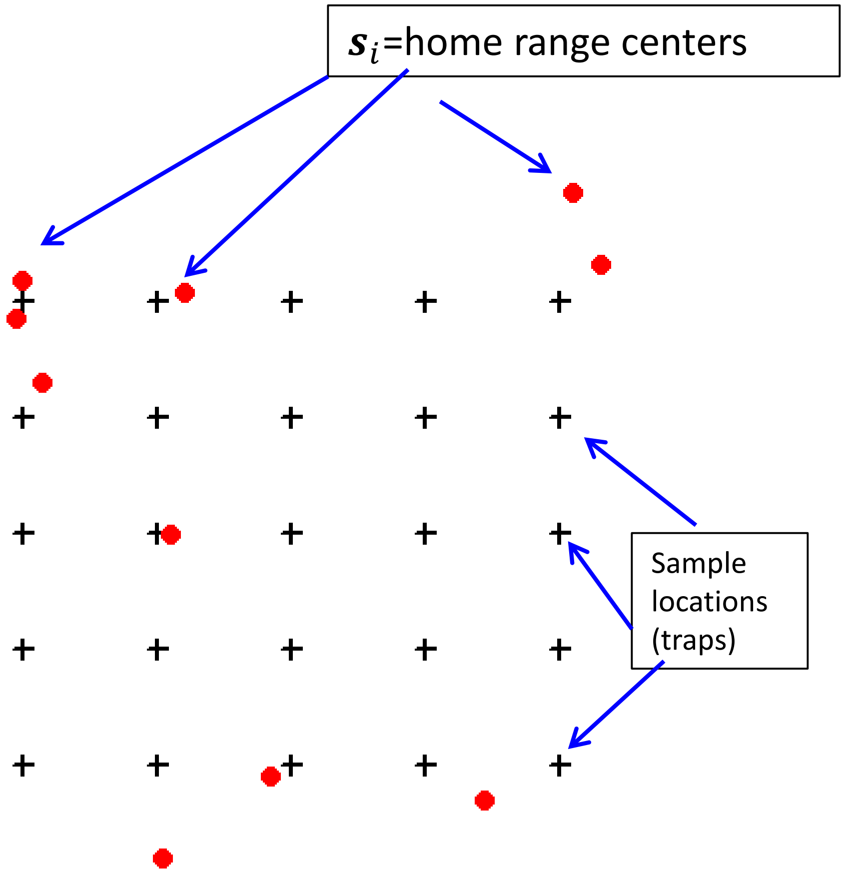
```
                 Occasion
individual  1   2   3   4   5
------------------------------
    1       1   0   1   0   1
    2       0   1   0   0   0
    3       0   1   1   1   0
    4       0   0   1   0   1
    5       0   1   0   0   0
    …       . . . .     . .
    …
```

encountered

NOT encountered

Getting SPACE into capture-recapture

- Describe distribution of individuals by a *Poisson point process* (Efford, 2004)
  - $\boldsymbol{s}_i$ = activity center or home range center fo individual *i*
  - *LATENT VARIABLES*
- Describe Pr(*encounter in trap*) conditional on "where an individual lives", $\boldsymbol{s}_i$



$\boldsymbol{s}_i$=home range centers

Sample locations (traps)

Essential Elements of Spatial capture-recapture

1. Point process model for home range centers

$\{ \boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_N \}$ = realization of a point process

$\boldsymbol{s}_i \sim \text{Uniform}(\mathcal{S})$; $\mathcal{S}$ = state-space of point process

2. Observation model (trap and individual specific encounter)

$y_{ij} | \boldsymbol{s}_i \sim \text{Bernoulli}(\, p(\boldsymbol{x}_j, \boldsymbol{s}_i) \,)$

$\boldsymbol{x}_j$ = trap location

3. Detection probability

linked by allowing
probability of encounter
to depend on s:

$p(\boldsymbol{x}_j, \boldsymbol{s}_i) = p_0 * \exp(-dist(\boldsymbol{x}, \boldsymbol{s})^2/\sigma^2)$

[or some other function]

The spatial encounter model

Observation model:

$$y_{ijk} \sim Bernoulli(p_{ijk})$$

i = individual
j = trap
k = occasion

Encounter probability model: p_{ijk} is a function of distance from individual to trap (or where an individual lives and trap locations).

- "half normal" model:

$$p_{ij} = \boldsymbol{p_0} \exp\left(-\frac{dist(\boldsymbol{s}_i, \boldsymbol{x}_j)^2}{2\boldsymbol{\sigma^2}}\right)$$

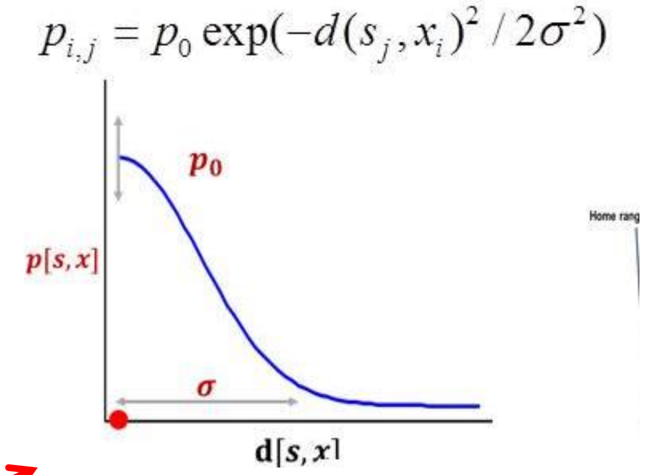
- $\boldsymbol{x}_j$ = location of trap j
- $\boldsymbol{s}_i$ = location of individual i's home range center

The spatial encounter model

Observation model:

$$y_{ijk} \sim Bernoulli(p_{ijk})$$

i = individual
j = trap
k = occasion

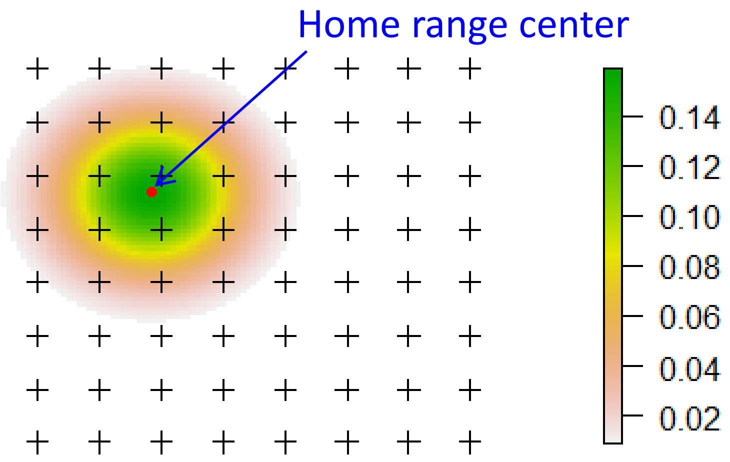


Encounter probability model: p_{ijk} is a function of distance from individual to trap (or where an individual lives and trap locations).

- “half normal” model:

$$p_{ij} = \boldsymbol{p_0} \exp\left(-\frac{dist(\boldsymbol{s}_i, \boldsymbol{x}_j)^2}{2\boldsymbol{\sigma^2}}\right)$$

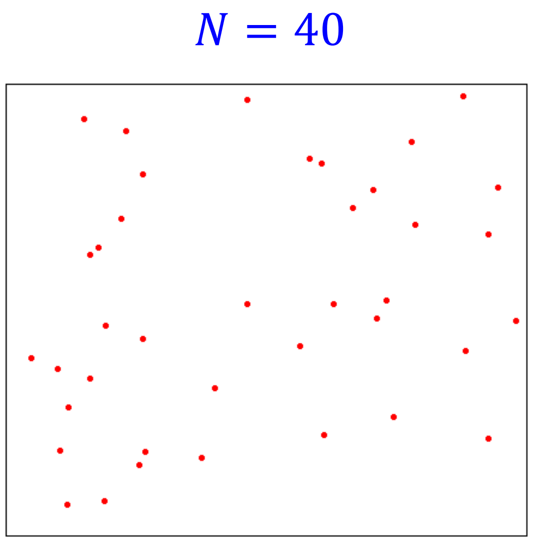
- $\boldsymbol{x}_j$ = location of trap j
- $\boldsymbol{s}_i$ = location of individual i's home range center



The latent point process model

$$p_{ij} = p_0 \exp(-\frac{dist(\boldsymbol{s}_i, \boldsymbol{x}_j)^2}{2\sigma^2})$$

A latent feature of the individual



Point process model for the individual activity centers $\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_N$:

- homogeneous point process – “*complete spatial randomness*”

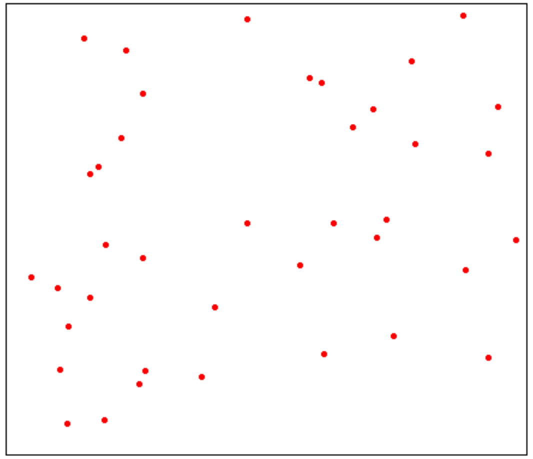
$$\Pr(\boldsymbol{s}_i) = const$$

The latent point process model

$$p_{ij} = p_0 \exp(-\frac{dist(\boldsymbol{s}_i, \boldsymbol{x}_j)^2}{2\sigma^2})$$

A latent feature of the individual

$N = 40$



Point process model for the individual activity centers $\boldsymbol{s}_1, \boldsymbol{s}_2, \dots, \boldsymbol{s}_N$:

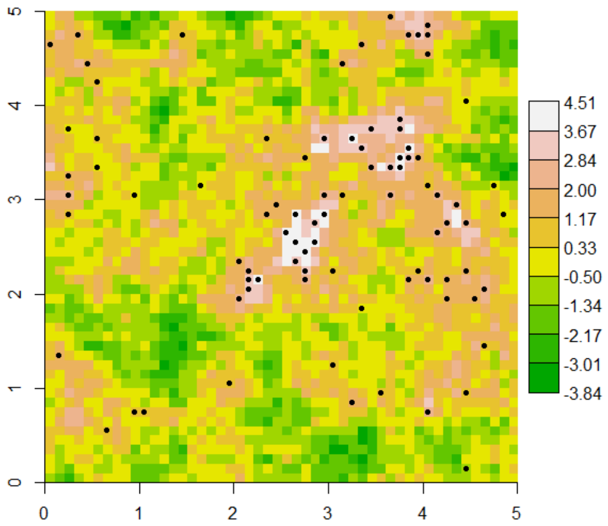
- homogeneous point process – *"complete spatial randomness"*

$$\Pr(\boldsymbol{s}_i) = const$$

- Inhomogeneous point process – local point density depends on some landscape or habitat covariate

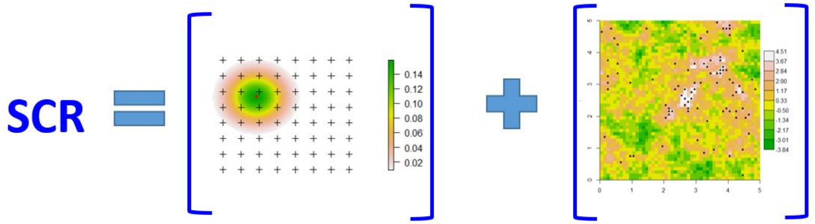
$$\Pr(\boldsymbol{s}) \propto \exp(\beta z(\boldsymbol{s}))$$

Forest structure



SCR in a nutshell

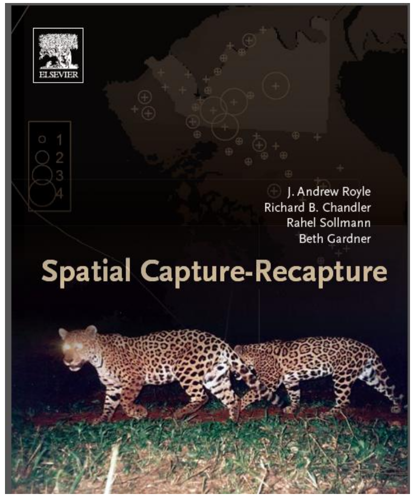
- Spatial observation model + spatial model for the distribution of individuals within a population



spatially explicit model for encounter history data

spatially explicit model for the distribution of individuals

SCR book with R. Chandler, Rahel Sollmann & Beth Gardner



- SCR has space in it – a description of where individuals are, were and will be
- Ideal framework for integrating data and models – where space is the mode of integration

2. SCR as a framework for integration

Data integration:

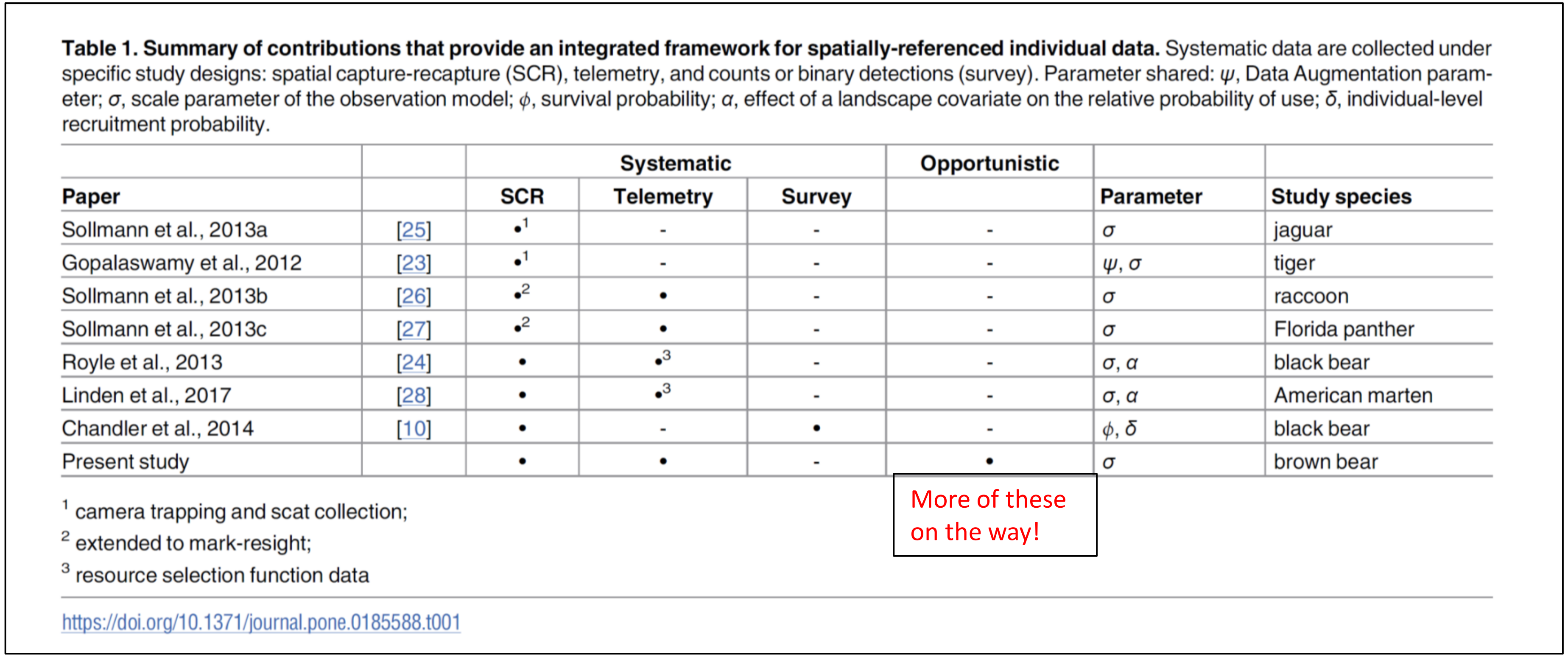


Table 1. Summary of contributions that provide an integrated framework for spatially-referenced individual data. Systematic data are collected under specific study designs: spatial capture-recapture (SCR), telemetry, and counts or binary detections (survey). Parameter shared: ψ, Data Augmentation parameter; σ, scale parameter of the observation model; ϕ, survival probability; α, effect of a landscape covariate on the relative probability of use; δ, individual-level recruitment probability.

		Systematic			Opportunistic		
Paper		**SCR**	**Telemetry**	**Survey**		**Parameter**	**Study species**
Sollmann et al., 2013a	[25]	•[1]	-	-	-	σ	jaguar
Gopalaswamy et al., 2012	[23]	•[1]	-	-	-	ψ, σ	tiger
Sollmann et al., 2013b	[26]	•[2]	•	-	-	σ	raccoon
Sollmann et al., 2013c	[27]	•[2]	•	-	-	σ	Florida panther
Royle et al., 2013	[24]	•	•[3]	-	-	σ, α	black bear
Linden et al., 2017	[28]	•	•[3]	-	-	σ, α	American marten
Chandler et al., 2014	[10]	•	-	•	-	ϕ, δ	black bear
Present study		•	•	-	•	σ	brown bear

[1] camera trapping and scat collection;

[2] extended to mark-resight;

[3] resource selection function data

https://doi.org/10.1371/journal.pone.0185588.t001

More of these on the way!

Tenan et al. 2017

Integrated models:

SCR + occupancy

SCR + point counts

SCR + distance sampling

SCR + movement

Integrating movement with SCR

SCR is a population movement model. A population of “trajectories”

Simple version

$$u_{i,t} \sim Normal(s, \sigma^2)$$

Even better

$$u_{i,t} \sim Normal(u_{i,t-1}, \sigma^2)$$

- SCR data = type of thinned telemetry (non-uniform thinning)
- Telemetry = a type of SCR with p = 1

Acoustic monitoring data

- So SCR is a framework for data integration including movement and telemetry…. can it be made to work with bioacoustics? That's our research objective.
- Key issues:
  - locations are imprecisely observed
  - Ping frequency is often not known precisely (or at all)
  - Individual ID: Not known for passive acoustics

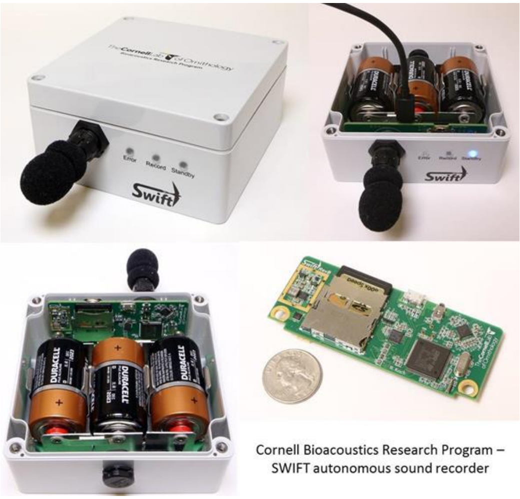
3. Bioacoustic monitoring technology

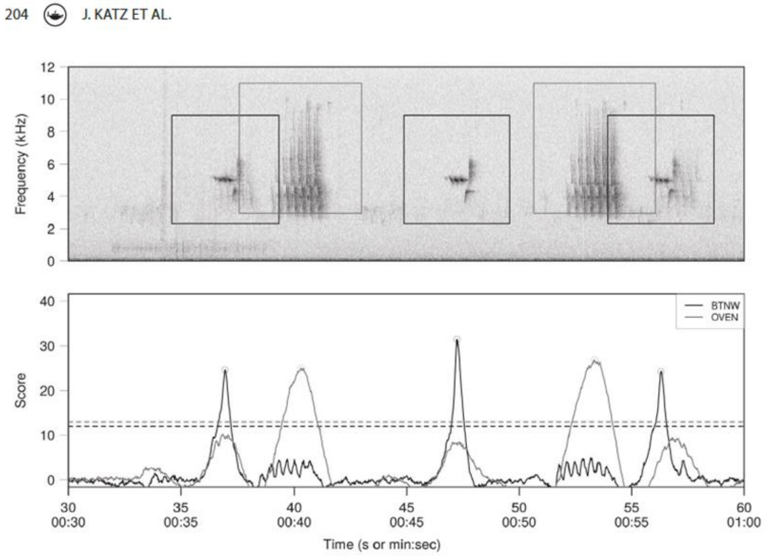
Rapidly adopted and deployed for many taxa: birds, frogs, bats, fish, sharks, sea turtles, whales

- Passive acoustics
  - Individual vocalizations are detected
- Active acoustics
  - Implanted device that emits sound (“ping”)
  - Telemetry

Passive acoustics: terrestrial

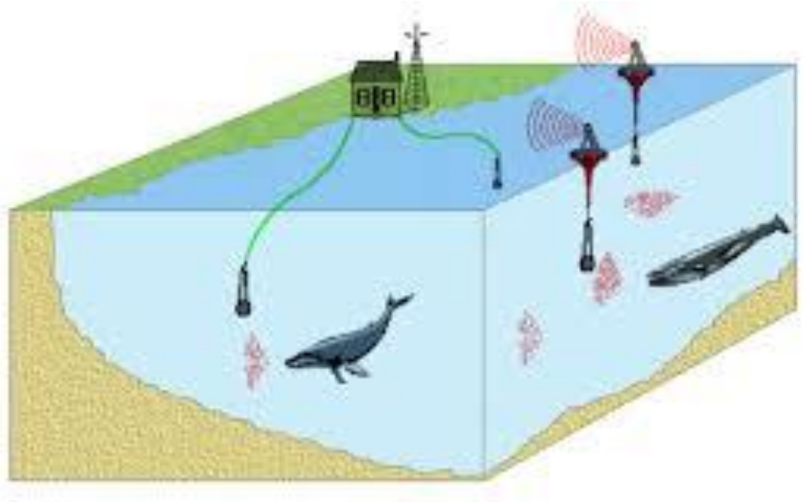
- Autonomous recording device
- Digital representation of animal vocalizations (spectrogram)
- Widely used for birds and frogs


Cornell Bioacoustics Research Program – SWIFT autonomous sound recorder

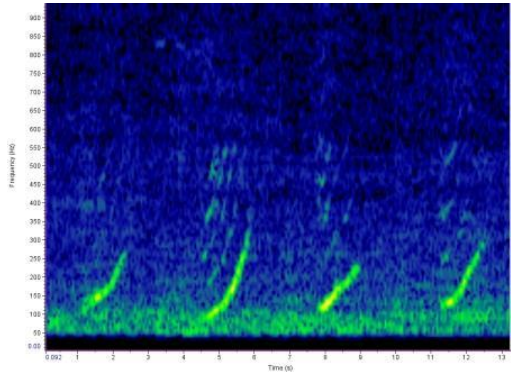


Passive acoustics: marine

- Whales, dolphins
- Individual vocalizations detected by a sensors deployed from buoys



Vocalization of a N. Atl. right whale (spectrogram)



Active acoustics: telemetry

Florida Fish and Wildlife Conservation Commission

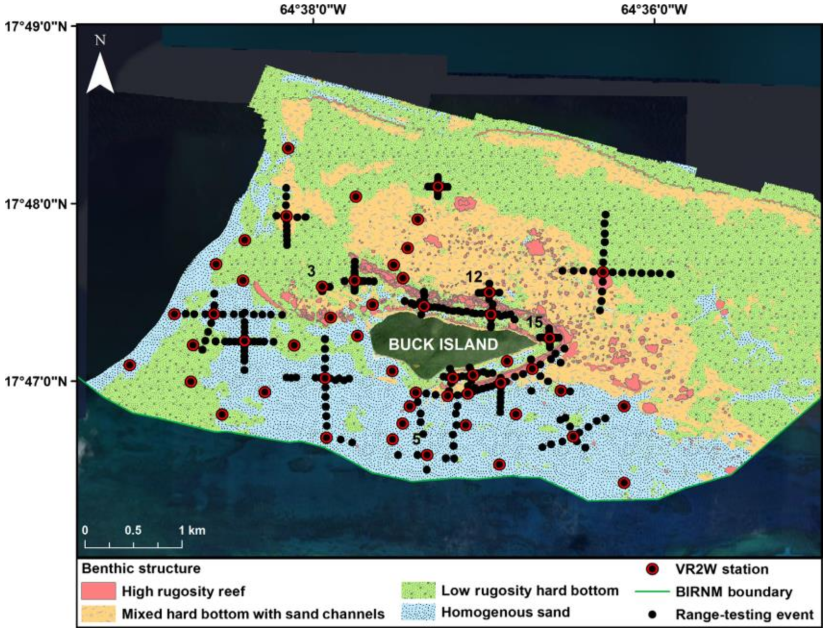
Acoustic tags, typically affixed externally or surgically implanted

Devices transmit acoustic signals (“pings”) on a programmed schedule (possibly random)

- Sea turtles, sharks, fish
- Great Lakes Acoustic Telemetry Observation System (GLATOS)
- Everywhere….

GLATOS
Great Lakes Acoustic Telemetry Observation System

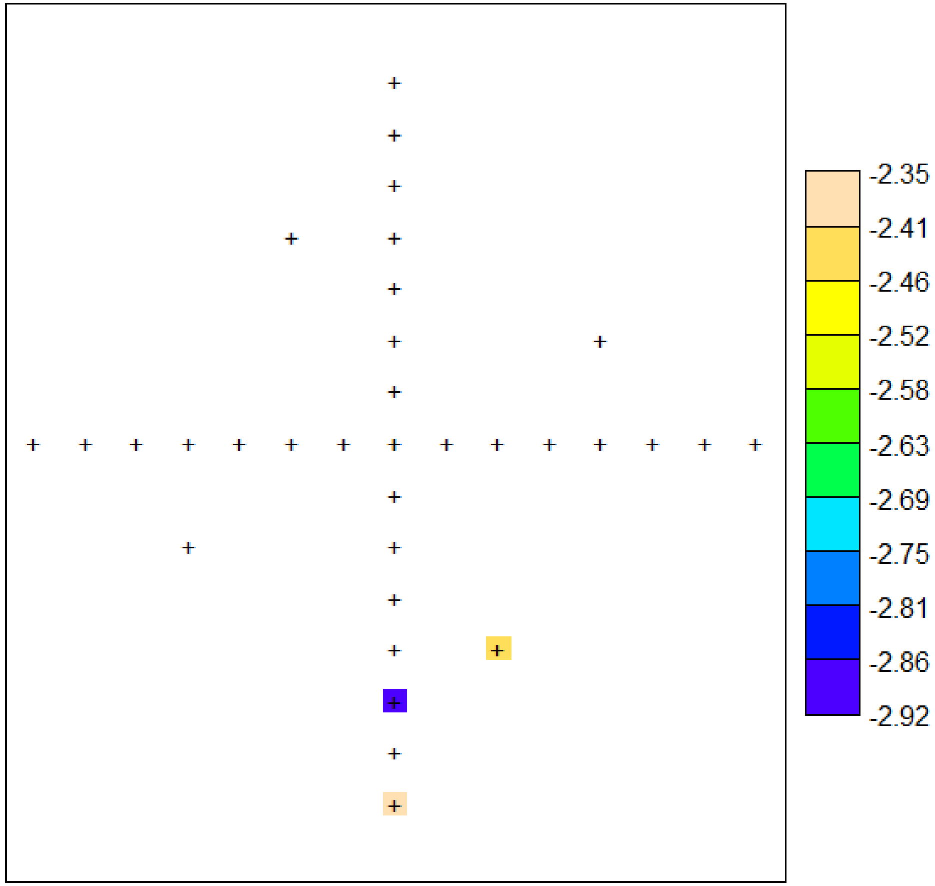
Buck Island acoustic monitoring array from Selby et al. 2016 (thanks K. Hart)



USGS
science for a changing world

Acoustic sampling: Localization

- Key objective: estimating the location of the individual or tag that emitted the acoustic signal: *localization*
- An array of acoustic sensors allows *estimation* of acoustic source location

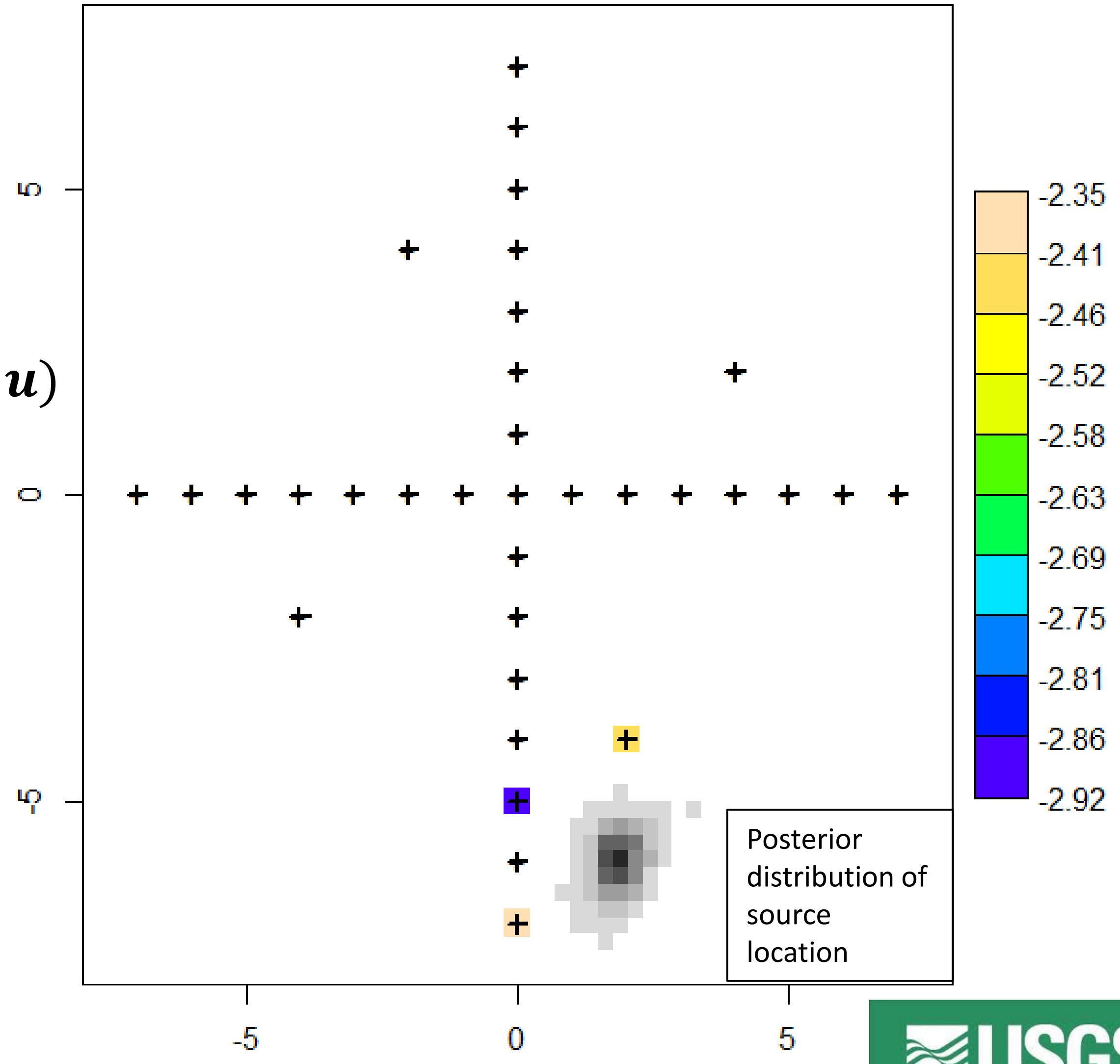


Received signal strength

Source localization

- Requires a model of probability of detection

$$p(\boldsymbol{x}|\boldsymbol{u}) = \Pr(\mathit{detect\ at\ sensor}\ \boldsymbol{x}|\ \mathit{location\ of\ source}\ \boldsymbol{u})$$



Posterior distribution of source location

Importance of localization

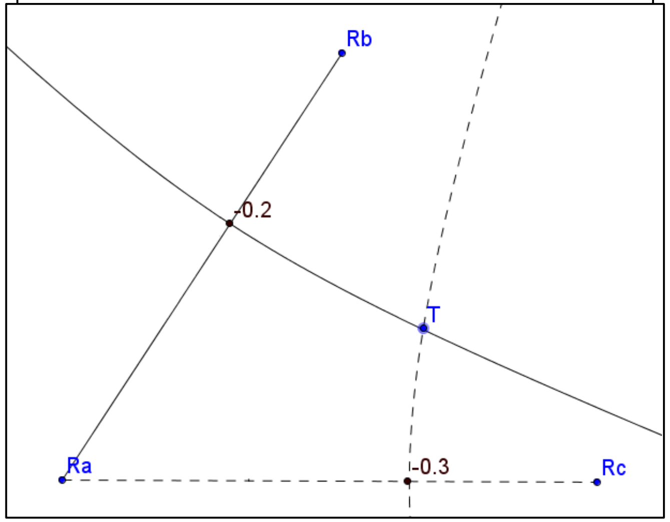
Inferring source locations is extremely important in all acoustic studies because acoustic methods do not provide precise location information (unlike GPS)

- Formal models of *movement, resource selection* and *occupancy* require source locations $\boldsymbol{u}_t$ as “data” …
- You need precise localizations: Mis-attribution of spatial location is like a “false positive” detection…. *Biases home-range size, distribution, habitat use… biases everything you care about*
- 2 methods of improving localization:
  - *More sensors, higher density (expensive)*
  - *Use better localization models*

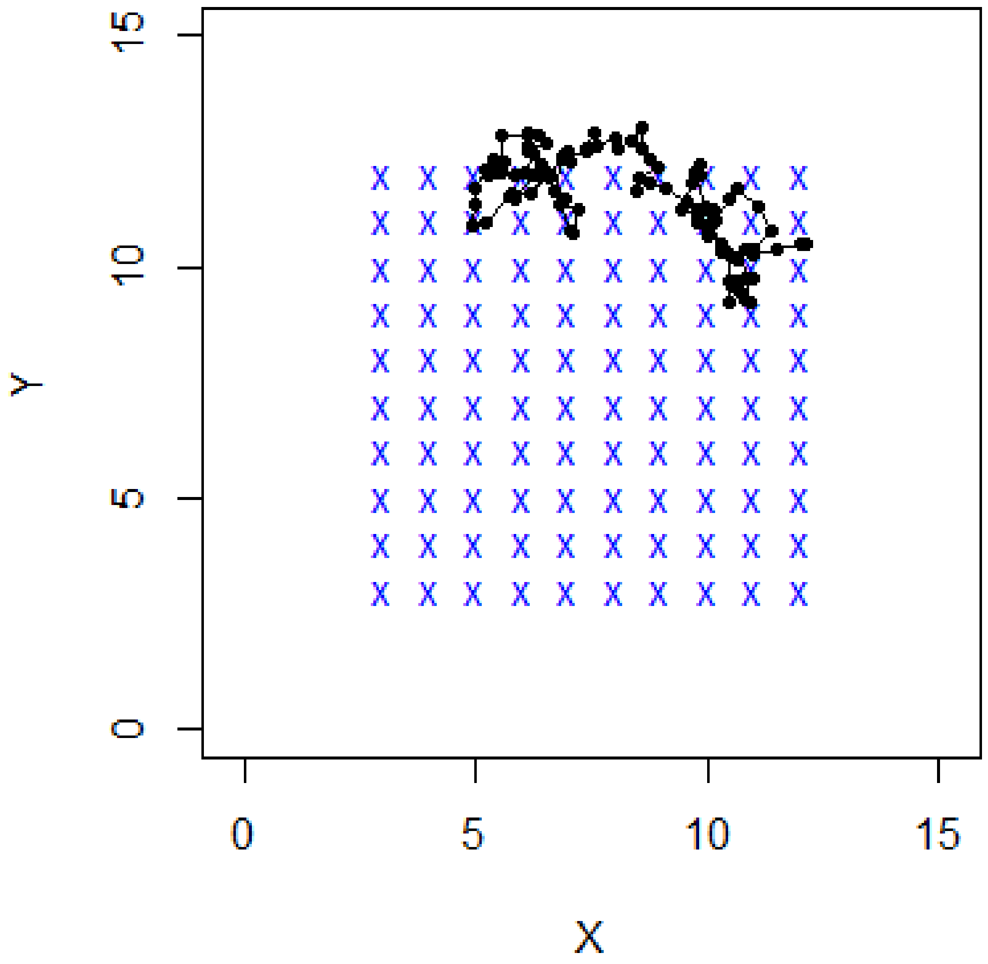
Acoustic telemetry

- Classical: hyperbolic positioning ("triangulation") –
    - Requires TDOA (very precise calibration)
    - Doesn't localize with < 3 detections
    - Doesn't use full encounter history (non-detections…)
    - ignores movement

Vemco positioning system uses a standard hyperbolic positioning argument based on TDOA



Sturgeon moving through a sensor array



- Statistical objective: recover the latent trajectory: “ensemble localization”

Statistical Localization

Posterior distribution of source location $\boldsymbol{u}$:

$$\Pr(\boldsymbol{u}_t \mid \boldsymbol{y}_t) \propto \Pr(\boldsymbol{y}_t \mid \boldsymbol{u}_t)\ \Pr(\boldsymbol{u}_t)$$

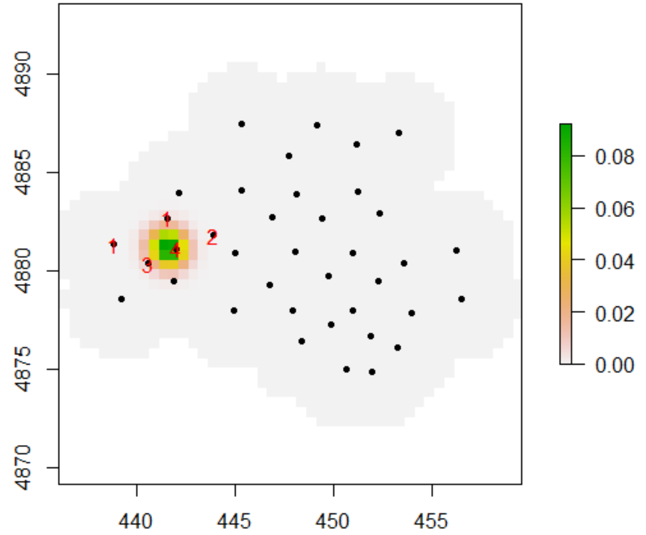
(i.e., *Bayes' rule*)

Spatial encounter information

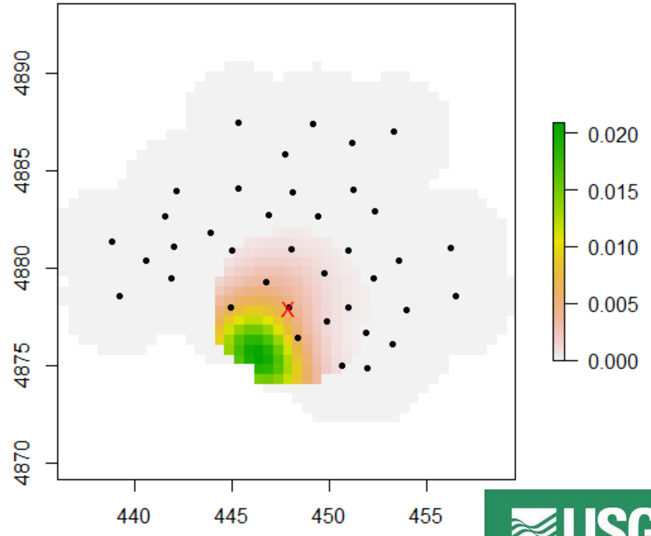
Spatial process model

- Provides a characterization of source location by combining information about where individuals are detected with a model for how sources are distributed in space
- Statistical localization USES THE ZEROS

Example 1: individual detected many times at interior traps.

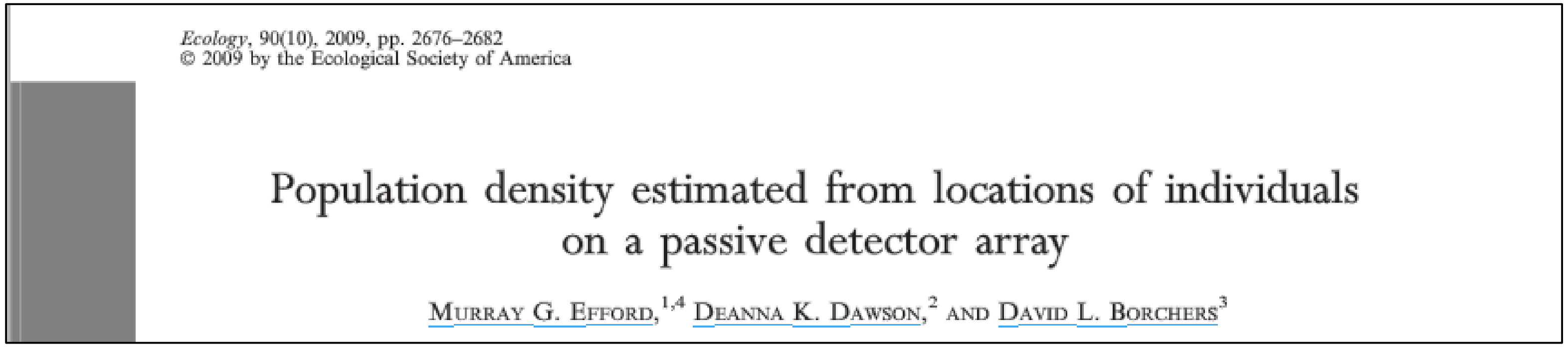


Example 2: individual captured one time near the edge.



How to localize: Spatial capture-recapture

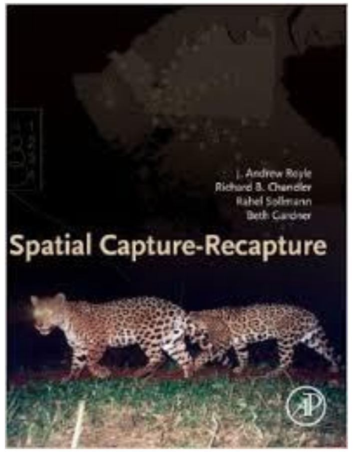
- Spatial capture-recapture (SCR)
- Efford et al (2009):



Ecology, 90(10), 2009, pp. 2676–2682
© 2009 by the Ecological Society of America

Population density estimated from locations of individuals on a passive detector array

Murray G. Efford,[1,4] Deanna K. Dawson,[2] and David L. Borchers[3]

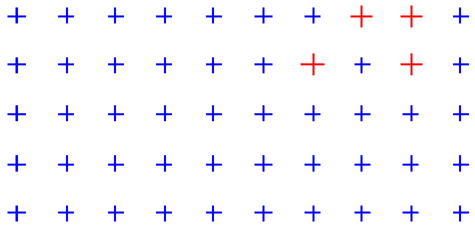


- SCR: A general framework for localization in acoustic and other studies… allows integrating localization models with spatial process models (resource selection, movement, connectivity, etc..)

Statistical localization from telemetry data

Posterior distribution of source location $\boldsymbol{u}$:

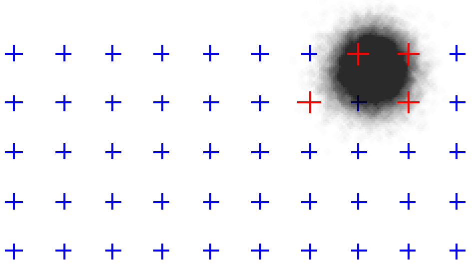
1 ping detected 4 times



Trajectory for a single fish

$$\Pr\left(\boldsymbol{u}_{i,t} \middle| \boldsymbol{y}_{i,t}\right) \propto \Pr\left(\boldsymbol{y}_{i,t} \middle| \boldsymbol{u}_{i,t}\right) \Pr\left(\boldsymbol{u}_{i,t}\right)$$

- $\Pr\left(\boldsymbol{y}_{i,t} \middle| \boldsymbol{u}_{i,t}\right)$: observation model
- $\Pr\left(\boldsymbol{u}_{i,t}\right) =$ uniform distribution



Posterior distribution of latent $\boldsymbol{u}_{i,t}$

The movement/localization synthesis

- Localization is not regarded as a “movement modeling problem” *per se* even though the objectives are analogous (inference about location)

- Therefore movement has not considered as part of the localization process and vice versa

Movement-assisted localization

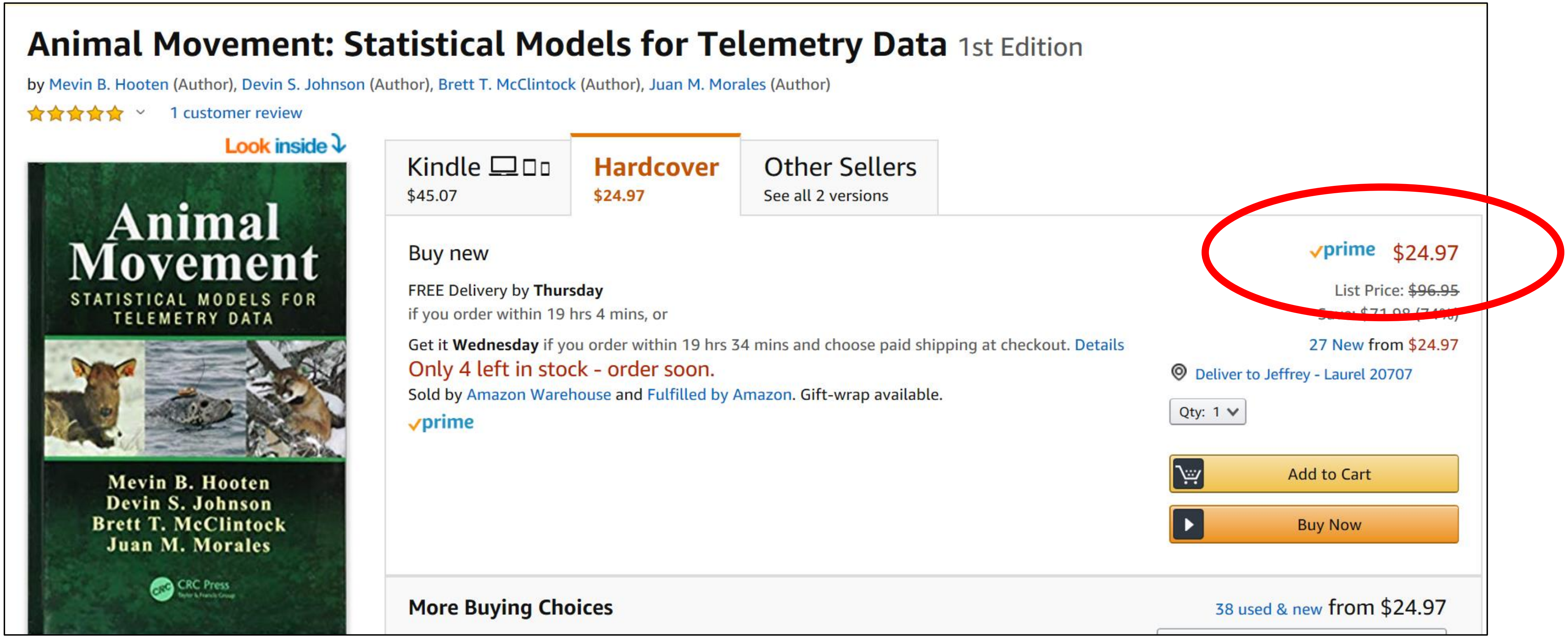
Posterior distribution of source location $\boldsymbol{u}$:

$$\Pr(\boldsymbol{u}_{i,t} \mid \boldsymbol{y}_{i,t}) \propto \Pr(\boldsymbol{y}_{i,t} \mid \boldsymbol{u}_{i,t}) \Pr(\boldsymbol{u}_{i,t})$$

- $\Pr(\boldsymbol{u}_{i,t}) =$ uniform distribution

$$\Pr(\boldsymbol{u}_{i,t} \mid \boldsymbol{y}_{i,t}) \propto \Pr(\boldsymbol{y}_{i,t} \mid \boldsymbol{u}_{i,t}) \Pr(\boldsymbol{u}_{i,t} | \boldsymbol{u}_{i,t-1})$$

- $\Pr(\boldsymbol{u}_{i,t} | \boldsymbol{u}_{i,t-1}) =$ a dynamic movement process model
- This propagates past and future information into localizations at time t [as the latent variable $\boldsymbol{u}_{i,t}$is updated using Markov chain Monte Carlo methods]



Animal Movement: Statistical Models for Telemetry Data 1st Edition

by Mevin B. Hooten (Author), Devin S. Johnson (Author), Brett T. McClintock (Author), Juan M. Morales (Author)

★★★★★ 1 customer review

Kindle	Hardcover	Other Sellers
$45.07	$24.97	See all 2 versions

Buy new

FREE Delivery by **Thursday**
if you order within 19 hrs 4 mins, or

Get it **Wednesday** if you order within 19 hrs 34 mins and choose paid shipping at checkout. Details

Only 4 left in stock - order soon.

Sold by Amazon Warehouse and Fulfilled by Amazon. Gift-wrap available.

✓prime

✓prime $24.97

List Price: ~~$96.95~~

Save: $71.98 (74%)

27 New from $24.97

Deliver to Jeffrey - Laurel 20707

More Buying Choices

38 used & new from $24.97

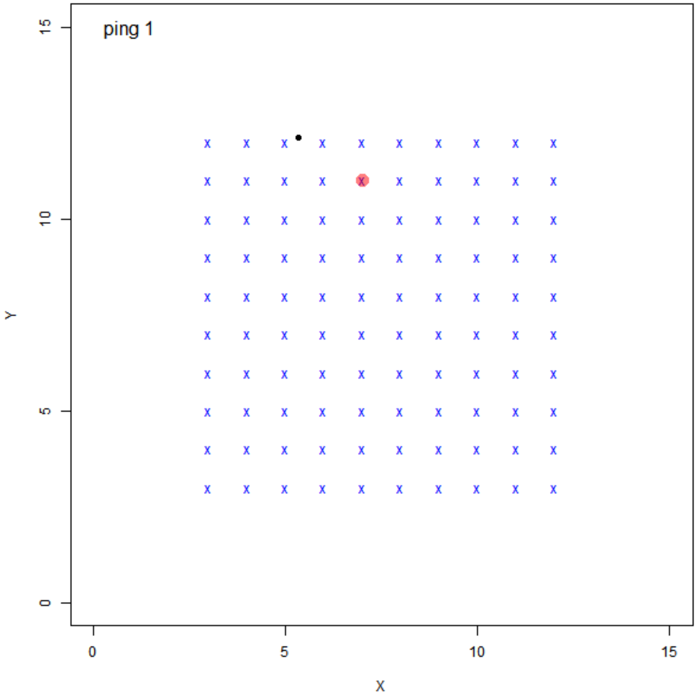
Movement-assisted localization

State process: Markovian conditional on ping interval T_t (i.e., Brownian motion)

$$\boldsymbol{u}_t \sim Normal(\boldsymbol{u}_{t-1}, \sigma^2 |T_t|)$$

Observation process:

$$\Pr(y_{tj} = 1) = \exp(-\frac{\left|\left|\boldsymbol{x}_j - \boldsymbol{u}_t\right|\right|^2}{2\sigma^2})$$

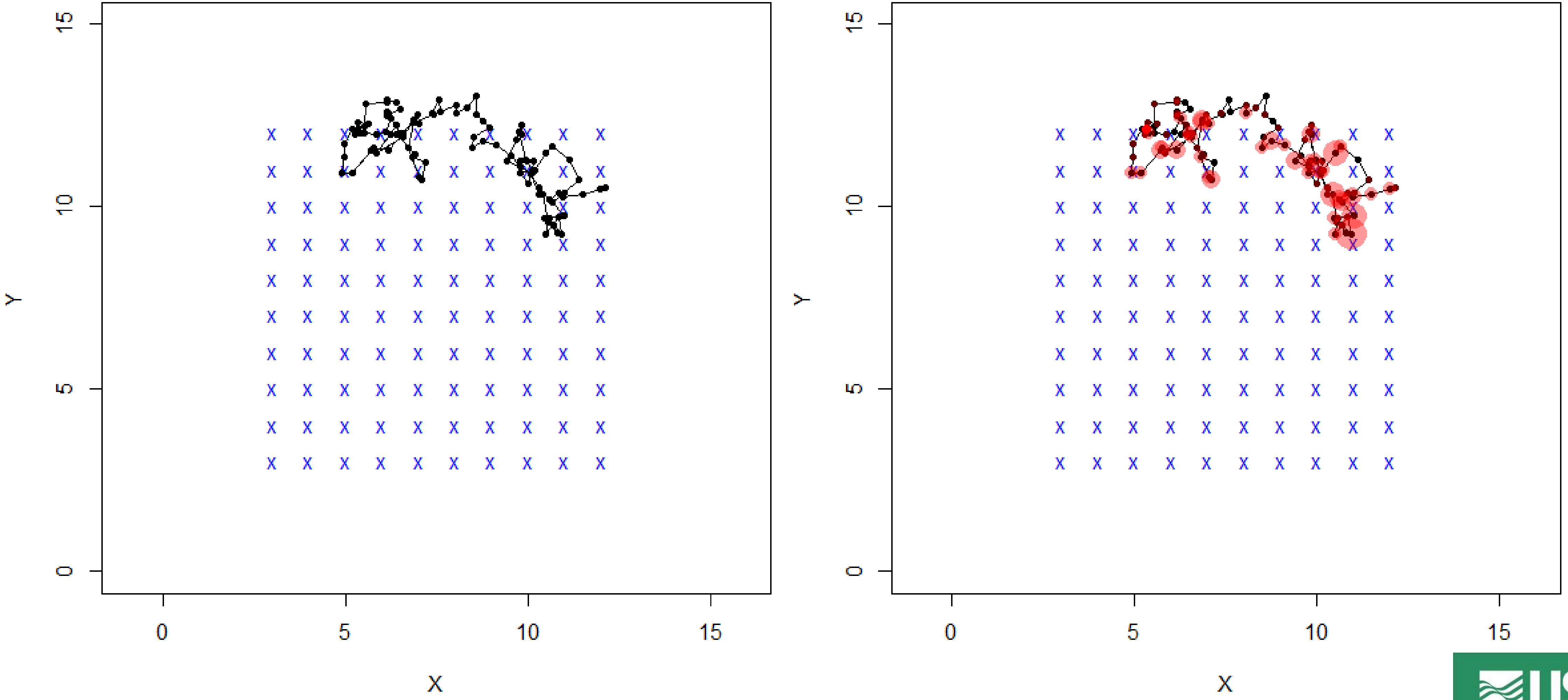


A single realization of this process

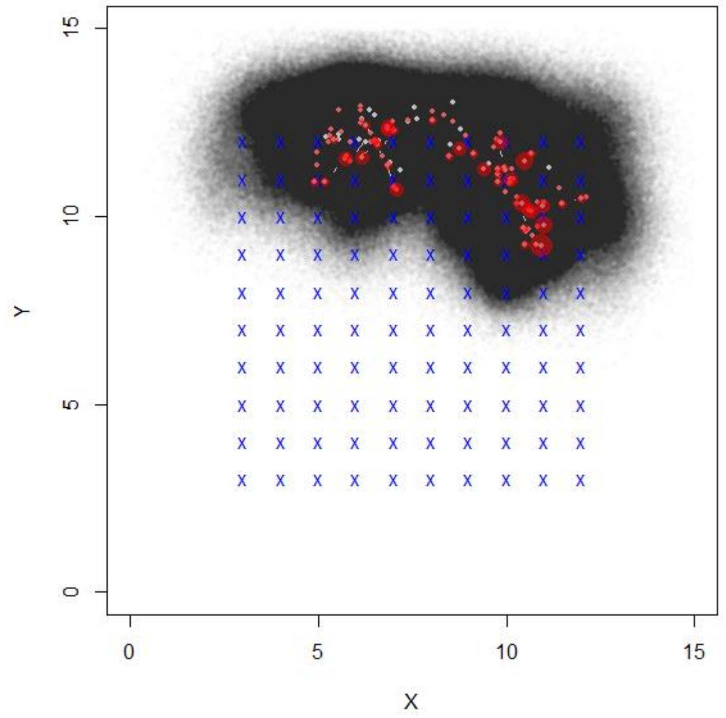
PING LOCATIONS AND DETECTIONS for fish #2

K = 100 pings

#pings	0	1	2	3	4	5
Frequency	22	38	24	12	3	1

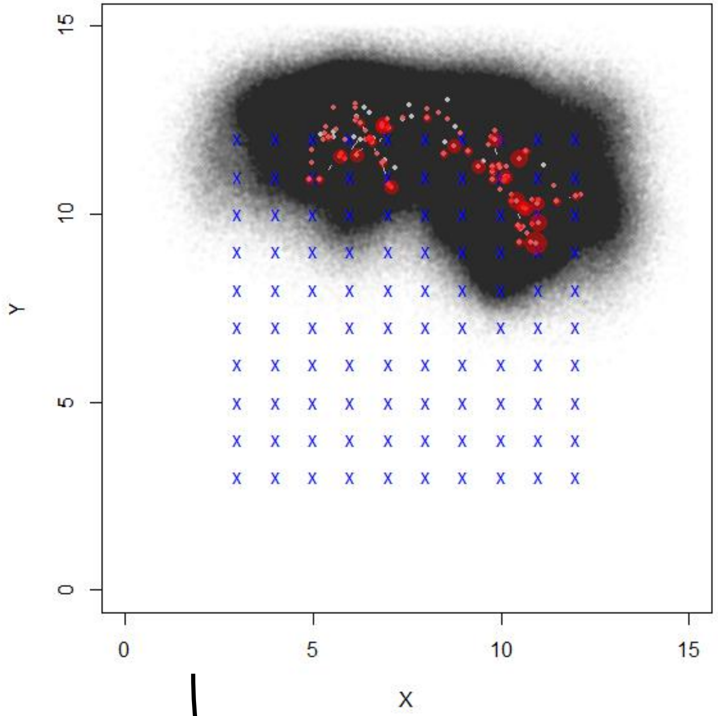


Uniform and independent localization

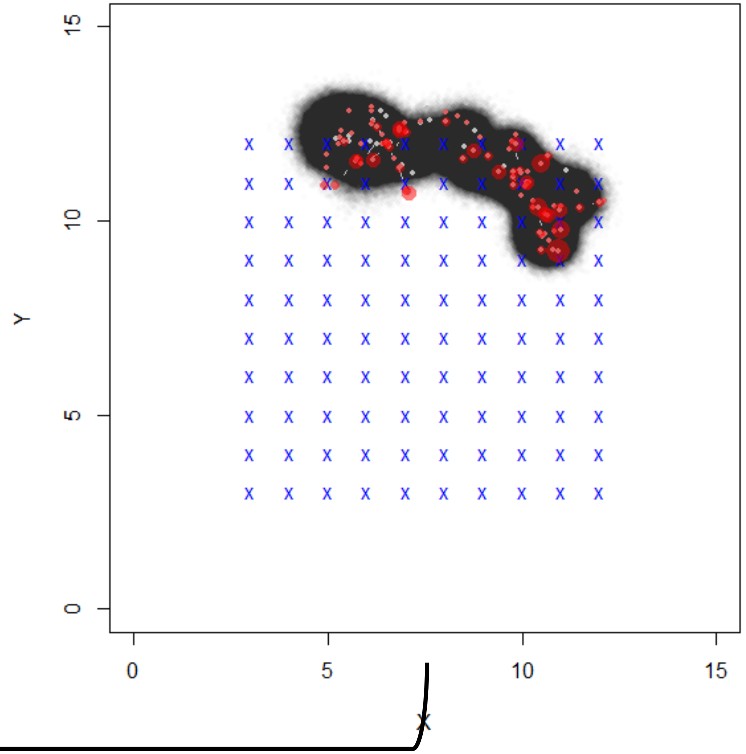


NO MOVEMENT MODEL: “independent and uniform prior” used to localize where at least 1 detection was made.

Uniform and independent localization



Movement assisted localization



Movement assisted localization improves localization precision:

#dets	RMSE reduction (%)
1	45
2	40
3	35
4	33
5	27
6	30
7	27

Compare these two:

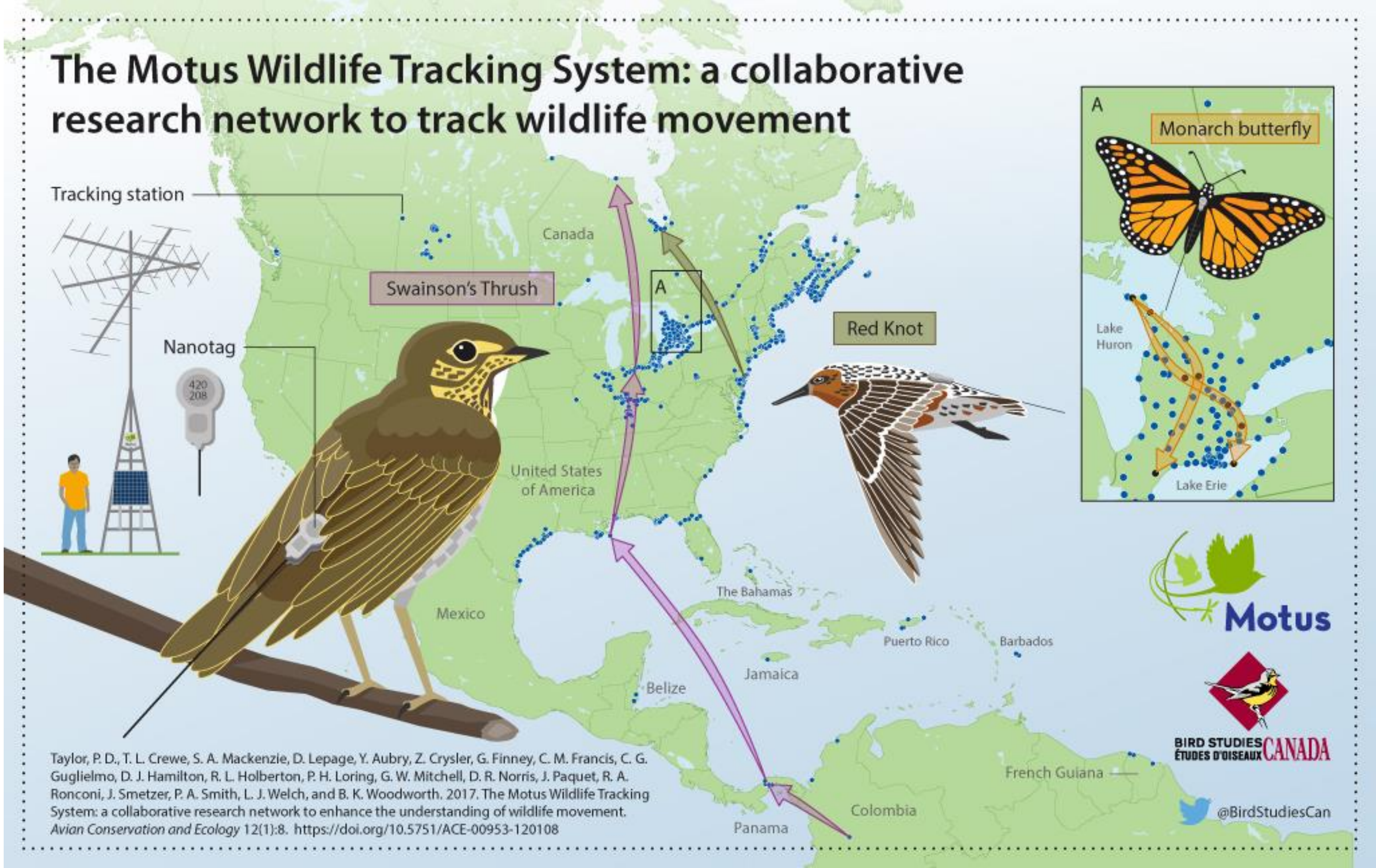
RIGHT: with movement model

LEFT: no movement model

Other applications and extensions

VHF Nanotags: Motus

- Seabirds , shorebirds and ducks
- Fixed sensor array + aircraft
- **Motus Wildlife Tracking System**
- Lots of interest in off-shore bird movement related to wind energy development

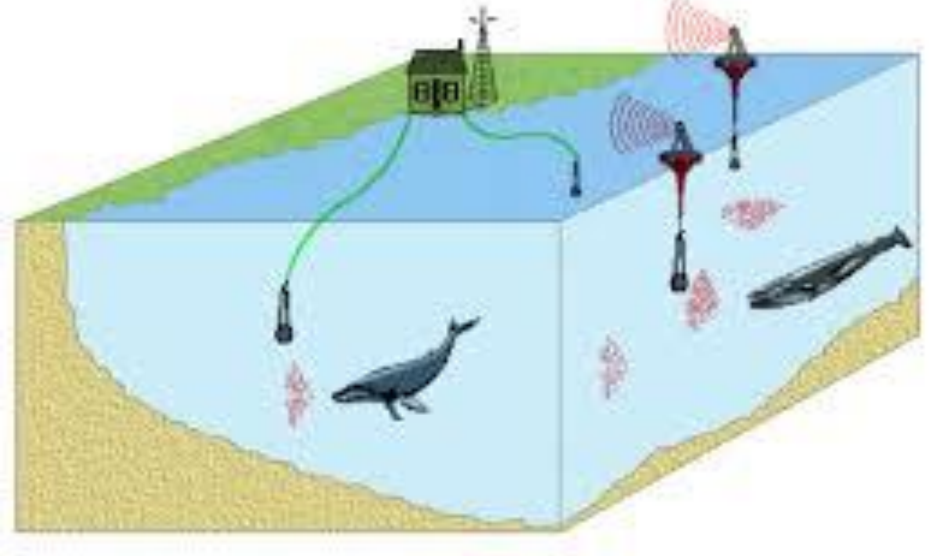


The Motus Wildlife Tracking System: a collaborative research network to track wildlife movement

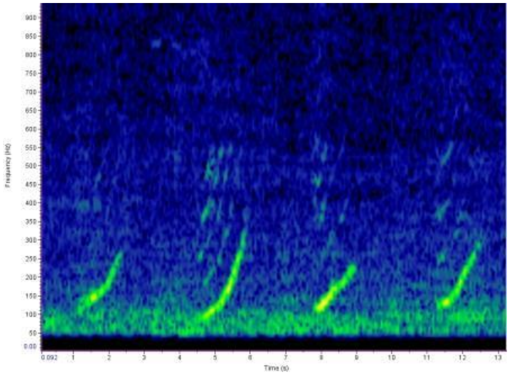
Taylor, P. D., T. L. Crewe, S. A. Mackenzie, D. Lepage, Y. Aubry, Z. Crysler, G. Finney, C. M. Francis, C. G. Guglielmo, D. J. Hamilton, R. L. Holberton, P. H. Loring, G. W. Mitchell, D. R. Norris, J. Paquet, R. A. Ronconi, J. Smetzer, P. A. Smith, L. J. Welch, and B. K. Woodworth. 2017. The Motus Wildlife Tracking System: a collaborative research network to enhance the understanding of wildlife movement. *Avian Conservation and Ecology* 12(1):8. https://doi.org/10.5751/ACE-00953-120108

Passive acoustics: marine

- Whales, dolphins
- Individual vocalizations detected by a sensor array
- Ping schedule is not knowable… vocalizations occur stochastically
- Individual identity is not known



Vocalization of a N. Atl. right whale (spectrogram)



Passive acoustics: Unknown ping schedule

- MAL model:

$$\boldsymbol{u}_t \sim Normal(\boldsymbol{u}_{t-1}, \sigma^2 |T_t|)$$

- Known ping schedule: T_t is known. Implies number of missed pings is known. This is achievable in acoustic telemetry applications but not always done!
- Unknown ping schedule requires another parameter, e.g.,

$$npings_t \sim Poisson(\theta)$$

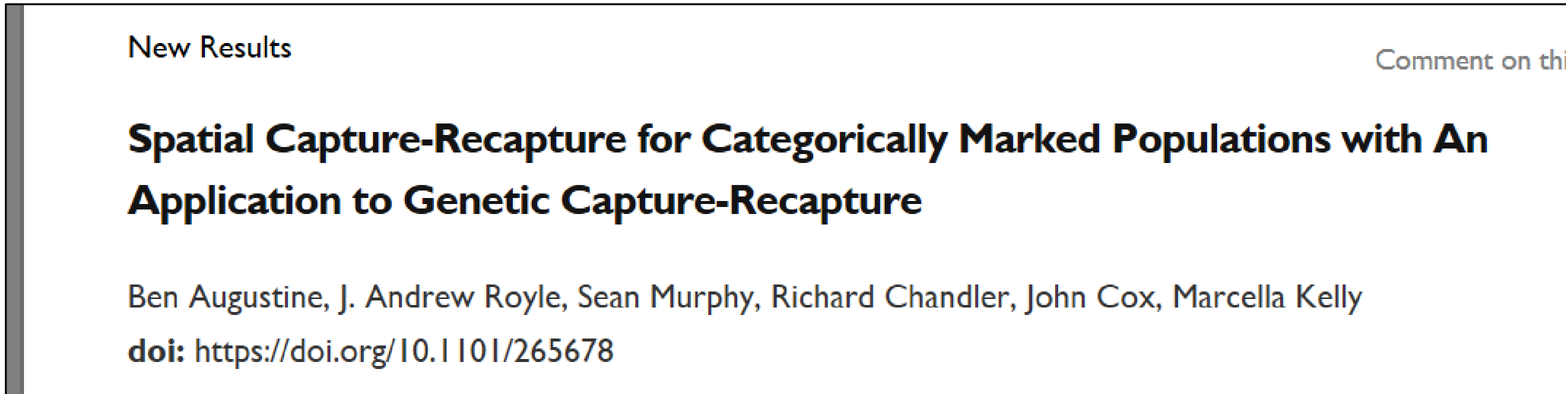
- Intermediate case: Stochastic ping interval

Passive Acoustics: no individual ID

- No ID information – can’t track individuals!
- The idea is: a movement model should serve as a prior distribution for associating observations to individuals – “clustering”
- Statistical framework: SCR with uncertain ID

Uncertain ID models

- “noID” model (Chandler & Royle 2013, AOAS) -- uses a latent SCR model to structure counts of unidentified individuals.
- With transient animals like whales, migrating fish, and polar bears, the latent SCR model has to be expanded to include Markovian movement (transience)
  - Has not been done yet
- CR model is a type of a statistical classification model...



New Results

Comment on thi

Spatial Capture-Recapture for Categorically Marked Populations with An Application to Genetic Capture-Recapture

Ben Augustine, J. Andrew Royle, Sean Murphy, Richard Chandler, John Cox, Marcella Kelly

doi: https://doi.org/10.1101/265678

Basic idea of partial ID (SPIM) models

```
sample       x    y   sex PC1   PC2
1          1.6 7.15   M 0.573 0.55
2          8.4 2.57   M 0.150 0.80
3          9.1 9.27   M 0.088 0.60
4          6.5 7.09   M 0.391 0.26
5          8.2 1.61   M 0.033 0.93
6          4.2 4.55   F 0.386 0.66
7          9.8 6.95   M 0.308 0.94
8          1.1 4.84   F 0.212 0.18
9          2.5 0.97   F 0.827 0.53
10         7.7 9.25   F 0.356 0.69
```

New Results

Comment on th

Spatial Capture-Recapture for Categorically Marked Populations with An Application to Genetic Capture-Recapture

Ben Augustine, J. Andrew Royle, Sean Murphy, Richard Chandler, John Cox, Marcella Kelly

doi: https://doi.org/10.1101/265678

Everything you could possibly want

Integrating opportunistic observations

- Current frontier in statistical ecology: integrating incidental observations in population models which integrate individual-level data
- Data: An observation of a species at location x
- One version of the integrated model formulation: Which individual does that belong to?
- Need a population level movement model… characterization of all trajectories in the population
    - How many individuals are there?
    - Where are those individuals?

Summary

- SCR as a framework for integration. Space is the mode of integration
- Integration of movement information – MAL one example
- Movement important for passive acoustics – a prior for clustering of observations with no ID
- This should be important for integrating incidental observations with capture-recapture and other kinds of structured data
- Research questions:
    - No-ID (passive acoustics)
    - Stochastic ping schedule (missed pings… how many? Needed to estimate detection probability unbiasedly)