Supporting Online File for: not final!

Simulation and Analysis of Animal Movement Paths using Numerus Model Builder

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1 MATHEMATICAL DESCRIPTION MBCRW MODEL

We now introduce the MBCRW model. It describes a biased walk with alternating centres of attraction O and P_i. Each daily movement will present a different P_i. The movement will start from and around O, to move to and around P_i and back to O.

$$P = \begin{cases} O & \text{if } cos(\frac{2\pi t}{T}) > 0 \\ P_i & \text{otherwise} \end{cases}$$

where t indicates the elapsed time and T represents the length of the day. At time $t = 0$ P will be equal to O, switching after $\frac{T}{4}$ to P_i and to O again after $\frac{3}{4}T$.

Location data Given the initial position (x_0, y_0), the location coordinates are updated as follows:

$$x_{t+1} = x_t + s_t \cos\theta_t \tag{1}$$
$$y_{t+1} = y_t + s_t \sin\theta_t \tag{2}$$
$$\tag{3}$$

where s_t is the step length and θ_t is the absolute heading. Note that an equivalent description could define θ_{t+1} as function of the turning angle α_t, as follows:

$$\theta_{t+1} = \theta_t + \alpha_t \tag{4}$$

and apply the trigonometric functions to $(\theta_t + \alpha_t)$.

Step-length: s_t is uniformly distributed in $[s_{min}, s_{max}]$:

$$s_t \sim \text{UNIFORM}(s_{min}, s_{max}) \tag{5}$$

Absolute heading: θ_t varies with time and location. We define θ_t as follows, where P represents the centre of attraction at time t:

$$\theta_{t+1} = \begin{cases} \theta^{c_P} & \text{if } z^u > f(d_t^P) \\ \theta_t + \theta^n & \text{otherwise} \end{cases}$$

θ^{c_P} is drawn from the distribution:

$$\theta^{c_P} \sim \text{UNIFORM}(\theta^P - (1 - corrP) \times \frac{\pi}{2}, \theta^P + (1 - corrP) \times \frac{\pi}{2}) \tag{6}$$

where θ^P is the absolute heading towards the point P (function of the animal current position) and *corrP* defines the heading correlation (0: no correlation, 1: maximum correlation).

z^u is drawn from the uniform distribution on $[0,1]$:

$$z^u \sim \text{UNIFORM}(0,1) \tag{7}$$

while the function f is defined as follows:

$$f(d_t^P) = \frac{1}{1+(d_t^P/d^{\text{crit}_P})^{\eta_P}} \tag{8}$$

It defines where the attraction is felt and therefore the range of movement. d_t^P is the distance from point P at time t, with $d^{\text{crit}_P} > 0$ and $\eta_P > 1$.

The random variable θ^n is drawn from the distribution:

$$\theta_n \quad \sim \quad \begin{cases} \text{UNIFORM}(-\pi,\pi) & \text{if } m=1 \\ \text{UNIFORM}(-(1-corrH)\times\pi,(1-corrH)\times\pi) & \text{if } m=2 \end{cases}$$

with heading correlation *corrH*. m describes 2 different modes: the first mode represents a complete random movement, within the critical distance, while the second one represents a walk with heading correlation greater than 0. The value of m can switch between the 2 values accordingly to the following transition matrix:

$$\begin{pmatrix} \theta_{11} & 1-\theta_{11} \\ 1-\theta_{22} & \theta_{22} \end{pmatrix}$$

with $\theta_{11}, \theta_{22} \in [0,1]$.

2 SIMULATION PARAMETERS

To define the parameters of our model, we established 5s as a time unit (17280 in one day) and one space unit equal to 100m. In 5s, the distance is around 7m (assuming straight walk). We run the simulation for 172800 time units (10 days); we set as initial location the origin O: (0,0), initial mode $m = 1$ and the centres of attraction as shown in Figure 1.

We use the following set of parameters:

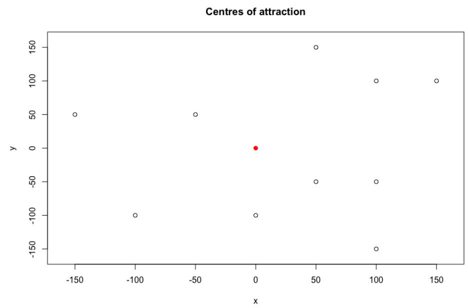

Figure 1: Centers of attraction O (in red) and P_i. Note that the scale represents the spatial units in NMB.

Param name	Value	Param name	Value
s_{min}	0.05	η_P	3
s_{max}	0.09	corrH	0.8
T	17280	corrO	0.8
d^{crit_O}	50	corrP$_i$	0.8
$d^{crit_{P_i}}$	50	θ_{11}	0.995
η_O	3	θ_{22}	0.995

3 HMM ANALYSIS

The results of the HMM path segmentation are illustrated in Figure 2.

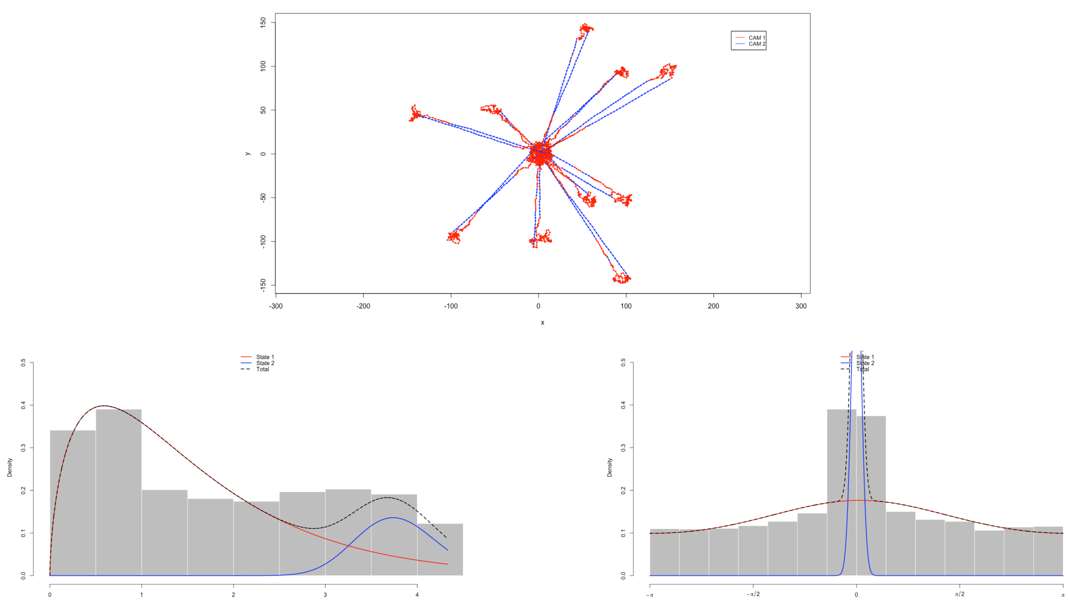

Figure 2: Results of the CAM extraction through HMM analysis

4 CLUSTERING ANALYSIS

The elbow method results are shown in Figure 3.

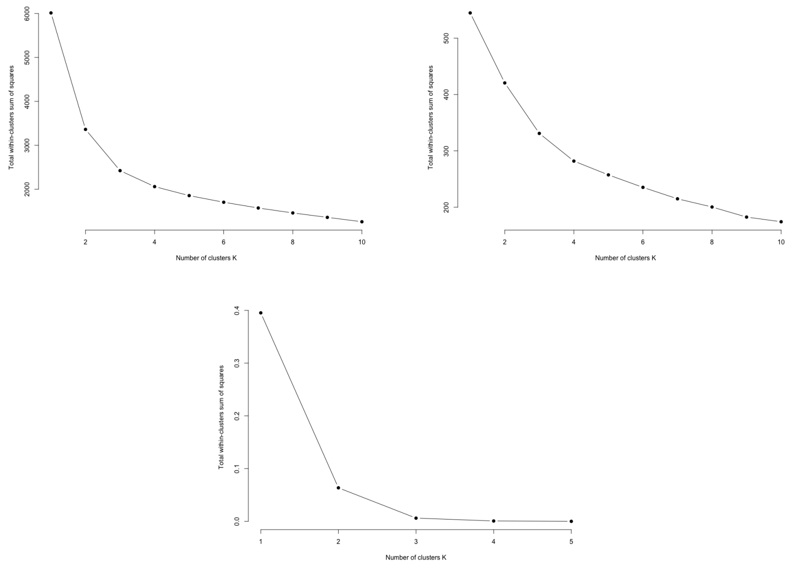

Figure 3: Elbow method - CAM and global

In this table we represent the number of metaFuMes in each CAM, from the analysis of the subsampled data of the MBCRW model.

CAM	metaFuME 1	metaFuME 2	metaFuME 3
1	11541	12478	0
2	3425	0	895

5 MODEL COMPARISON

Step length and turning angle distributions for MBCRW model (Figure 4) and M^3 model (Figure 10)

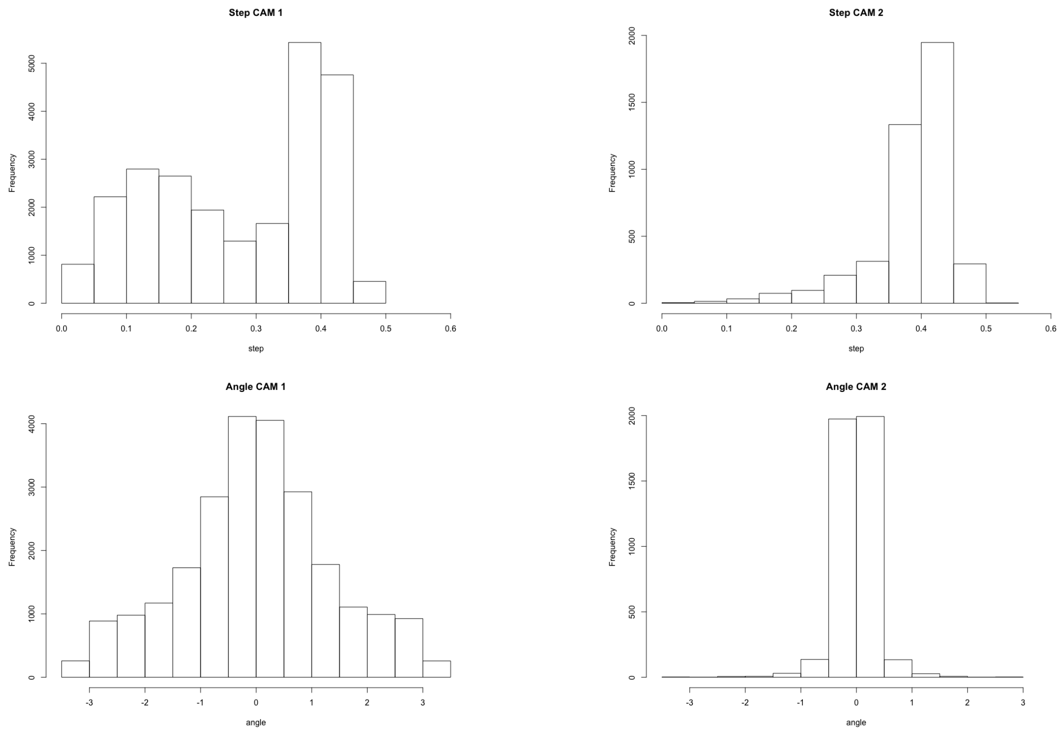

Figure 4: Step length and turning angle distribution for each CAM - MBCRW model

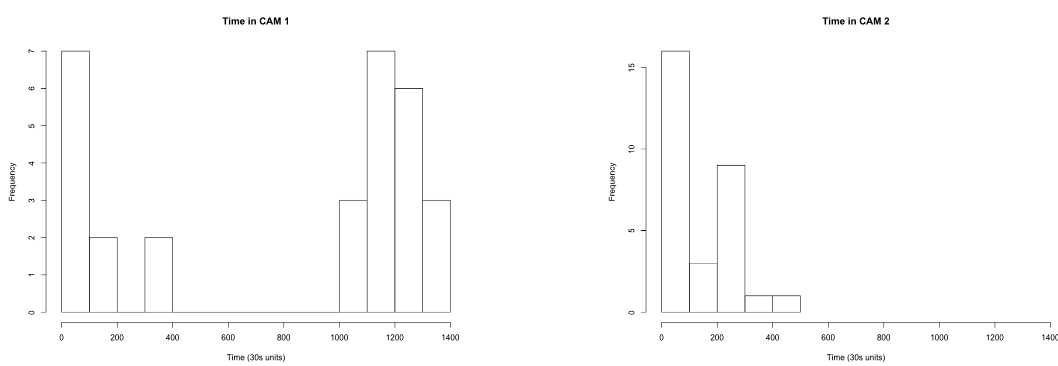

Figure 5: Distribution of time steps in each CAM, from MBCRW data

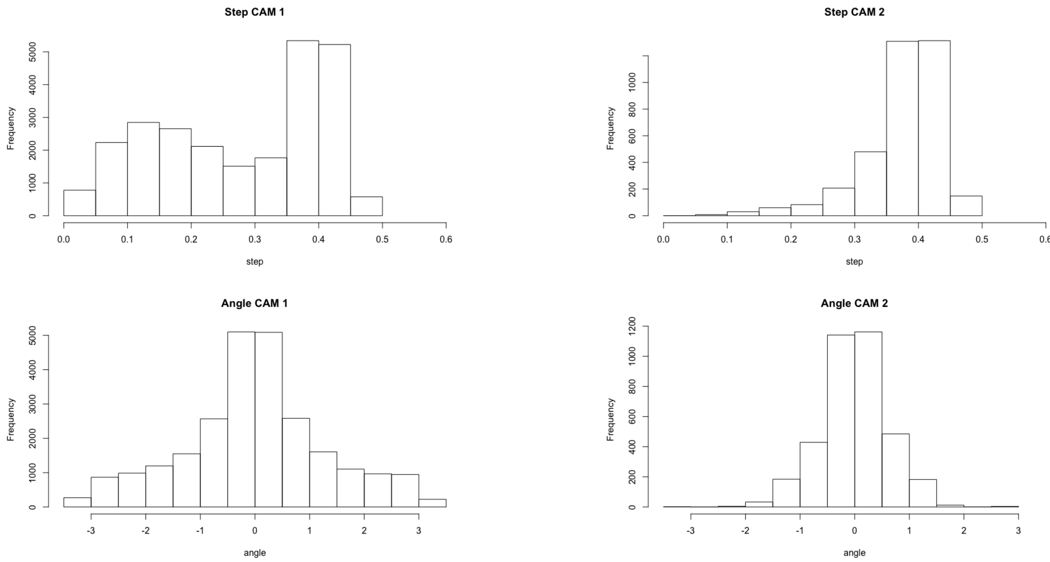

Figure 6: Step length and turning angle distribution for each CAM - M^3 model - to be changed

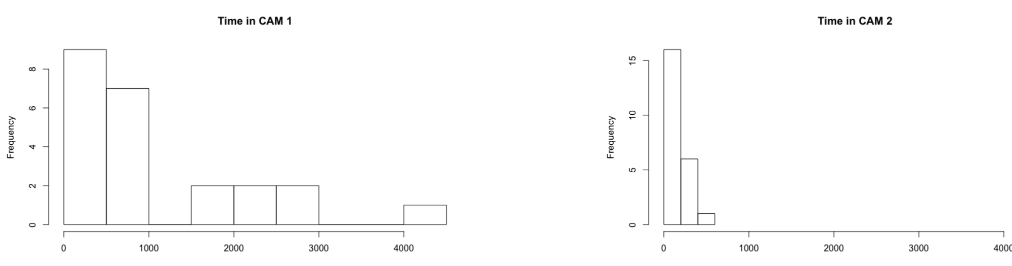

Figure 7: Distribution of time steps in each CAM, from M^3 data - to be changed

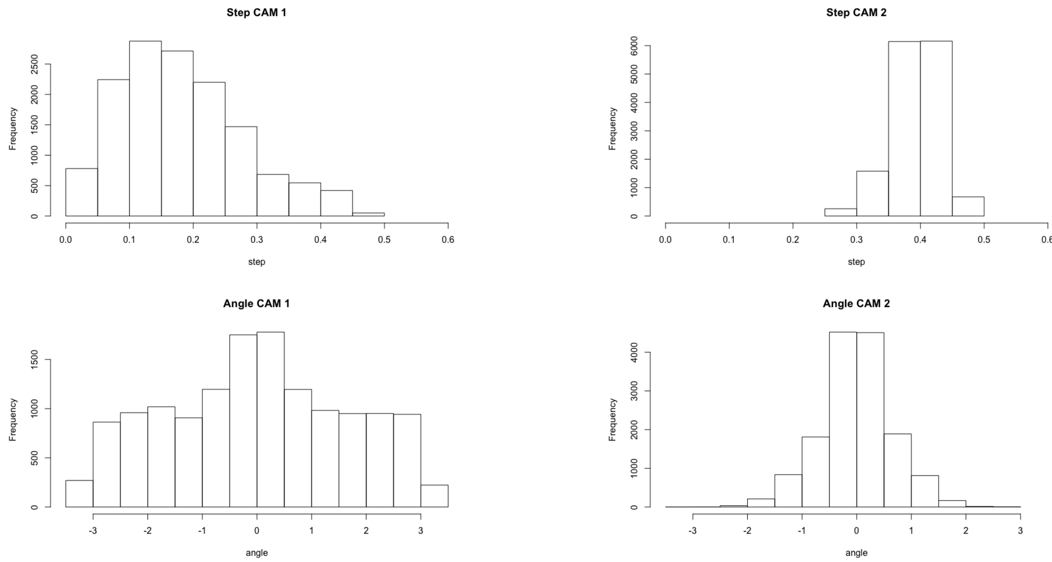

Figure 8: Step length and turning angle distribution for each CAM - M^3 model - HMM analysis - to be changed

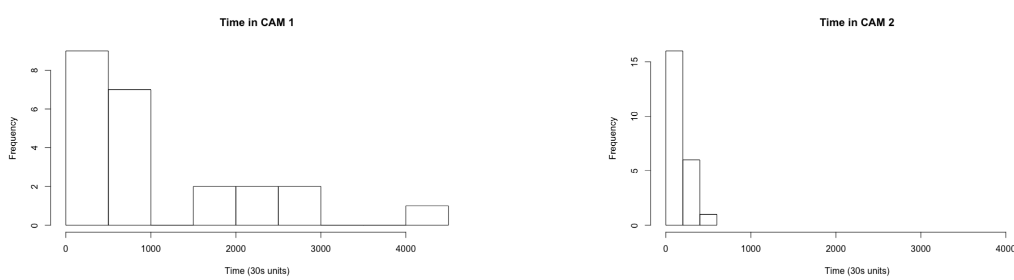

Figure 9: Distribution of time steps in each CAM, from M^3 data - to be changed

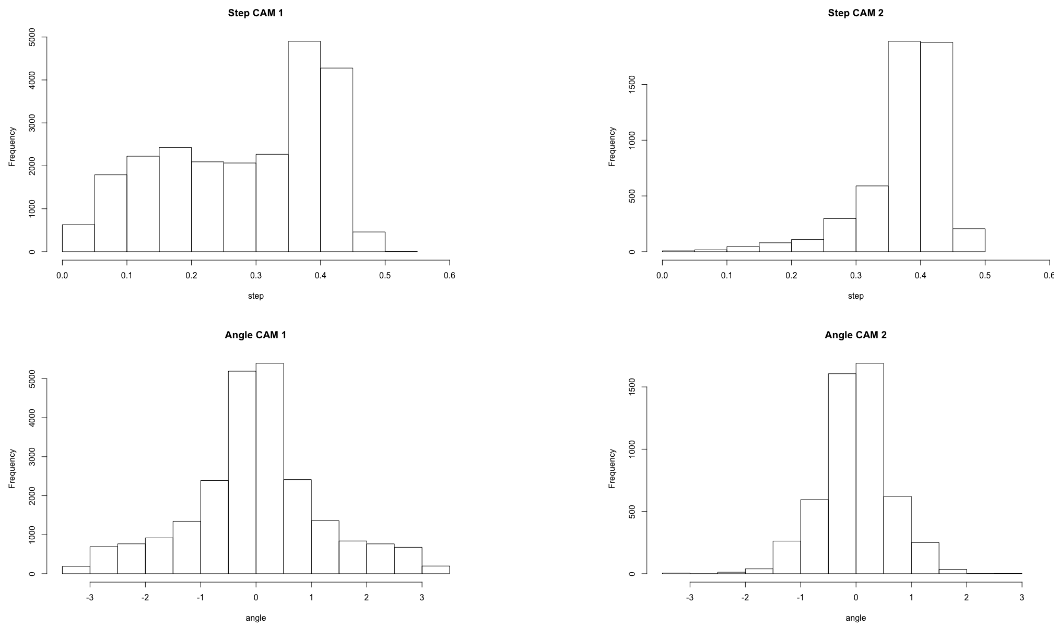

Figure 10: Step length and turning angle distribution for each CAM - M^3 model

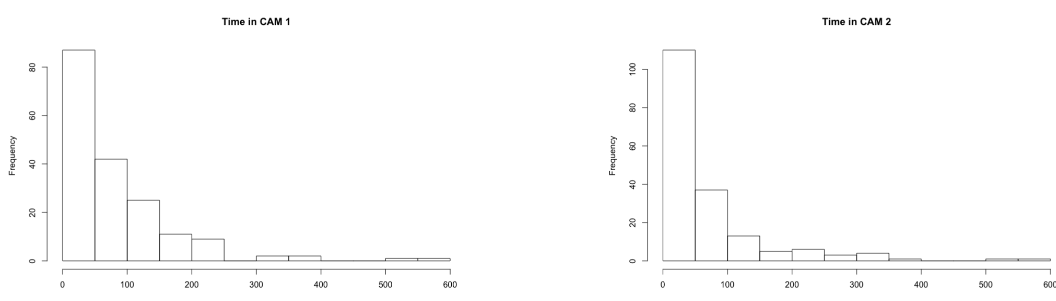

Figure 11: Distribution of time steps in each CAM, from M^3 data - HMM analysis

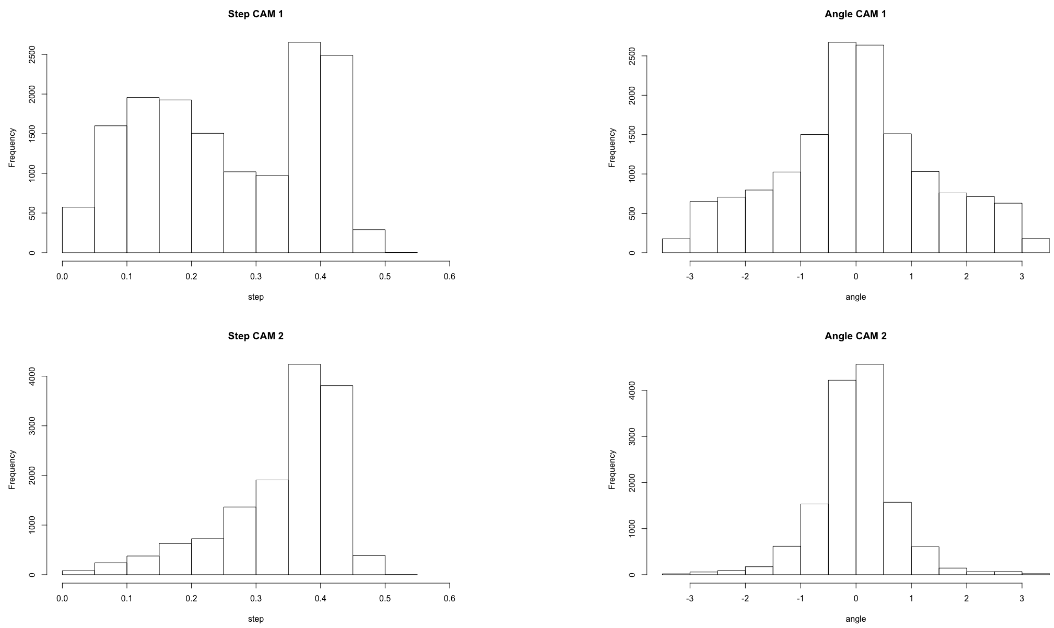

Figure 12: Step length and turning angle distribution for each CAM - M^3 model - HMM analysis

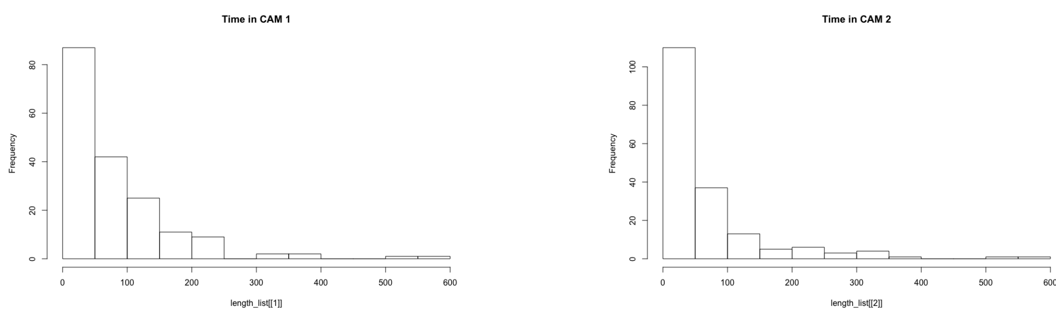

Figure 13: Distribution of time steps in each CAM, from M^3 data - HMM analysis

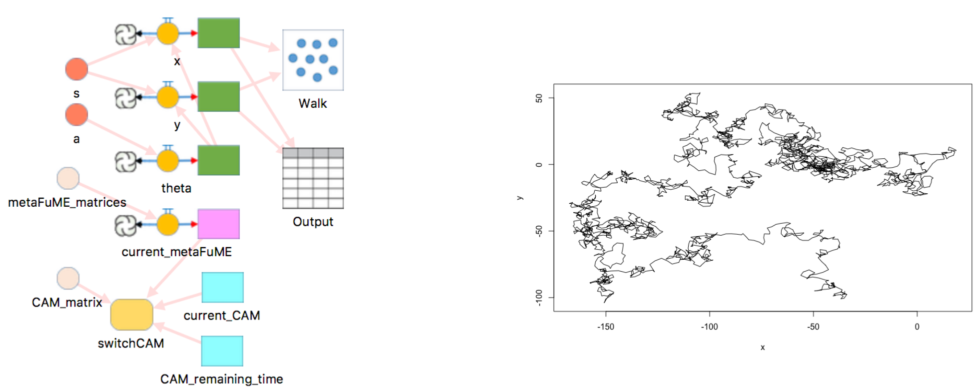

Figure 14: NMB implementation (left) and output of the simulation of the M^3 model

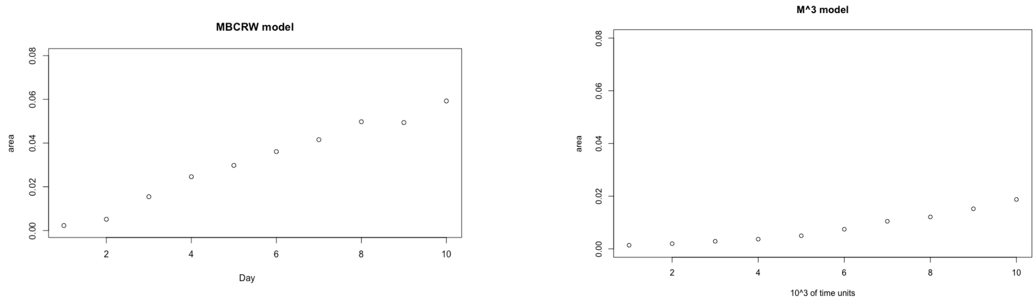

Figure 15: Total area coverage over time (each day) for the 2 models

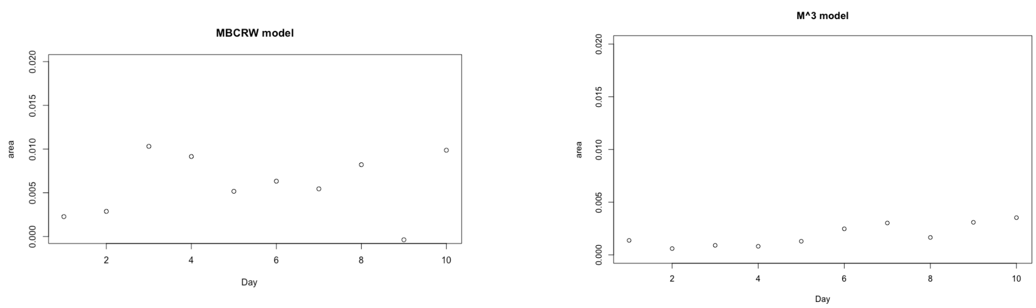

Figure 16: Area coverage over time (each day) for the 2 models

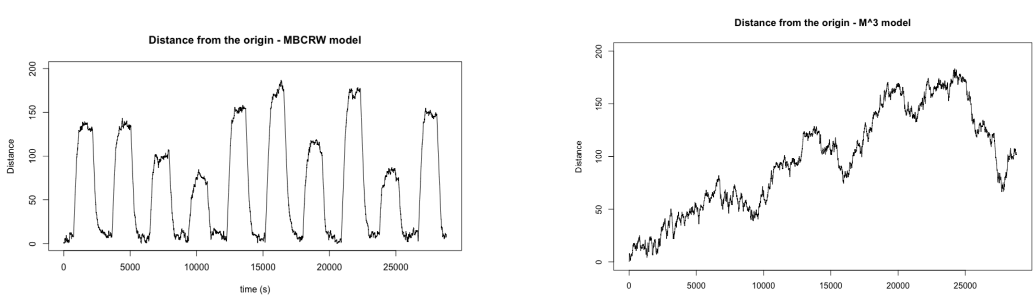

Figure 17: Distance from the origin over time for the 2 models