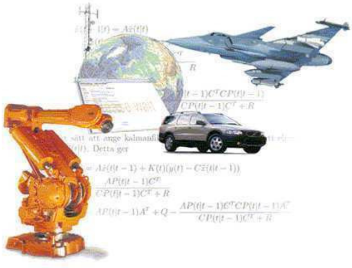
Licentiate seminar

Localization using Magnetometers and Light Sensors



Niklas Wahlström

Division of Automatic Control
Linköping University
Linköping, Sweden

Automatic control

Automatic control is about making a system to behave in the way you want.

Example: Unmanned Aerial Vehicle (UAV)

Automatic control

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Example: Unmanned Aerial Vehicle (UAV)

- The system has to sense its surrounding (for example in order to determine its position)

Automatic control is about making a system to behave in the way you want.

Example: Unmanned Aerial Vehicle (UAV)

- The system has to sense its surrounding (for example in order to determine its position)
- The control has to be accomplished automatically

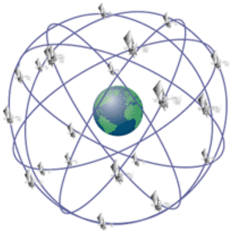
Localization can be defined as

The process of automatically determining a position of an object

In this thesis we will investigate two different localization techniques

- *Magnetic localization*
- Localization with *light levels*

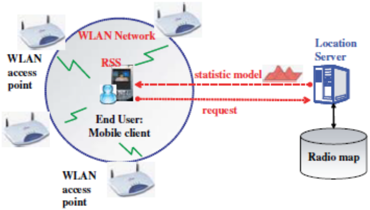
- Satellite navigation



Source: NASA

Standard Localization Techniques

- Satellite navigation
- Radio navigation



Ivanov, S., Nett, E., Schemmer, S. **Automatic WLAN localization for industrial automation** *IEEE International Symposium on Intelligent Signal Processing*, 2009.

- Satellite navigation
- Radio navigation
- Radar

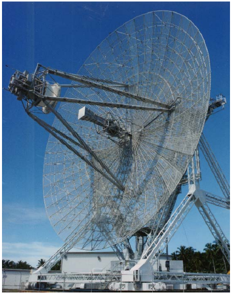
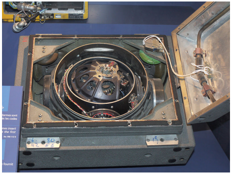


Photo: US army

- Satellite navigation
- Radio navigation
- Radar
- Computer vision

Lu, W.-L., Okuma, K. and Little, J. J. **Tracking and Recognizing Actions of Multiple Hockey Players using the Boosted Particle Filter**. *Image and Vision Computing*, 27(1–2):189–205, 2009.

- Satellite navigation
- Radio navigation
- Radar
- Computer vision
- Inertial navigation



Source: wikipedia

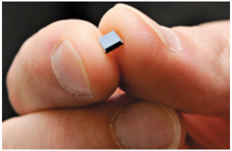
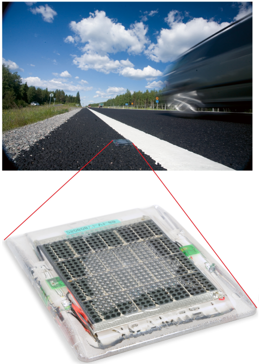
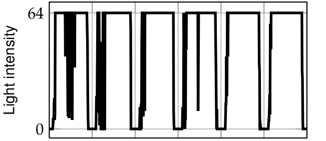


Photo: http://theenergycollective.com/

In this thesis, two alternative localization techniques are investigated.

Magnetic localization	Light levels
 Courtesy of Geveko ITS	 Source: Forskning & Framsteg 5/6 - 2012. 

Comparison

The two localization techniques have very different properties

	Magnetic localization	Light levels
Coverage	Vicinity of the sensor	The whole earth
Accuracy	> 5 mm	>150 km
Update frequency	100 Hz (sensor dependent)	Twice a day

Comparison

The two localization techniques have very different properties

	Magnetic localization	Light levels
Coverage	1×10^{1} m	1×10^{7} m
Accuracy	1×10^{-1} m	1×10^{5} m
Update frequency	1×10^{2} Hz	1×10^{-6} Hz

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Comparison

The two localization techniques have very different properties

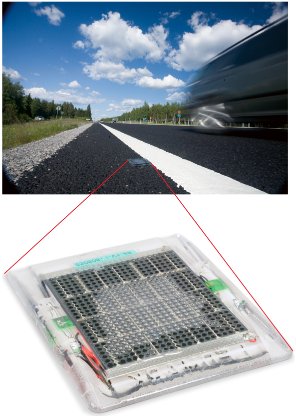
	Magnetic localization	Light levels
Coverage	1×10^{1} m	1×10^{7} m
Accuracy	1×10^{-1} m	1×10^{5} m
Update frequency	1×10^{2} Hz	1×10^{-6} Hz

They also have common advantages

- Cheap
- Small
- Low energy consumption

Applications

- Traffic surveillance



In Paper A and Paper B

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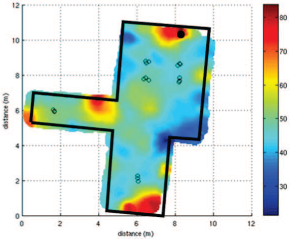
- Traffic surveillance
- Indoor navigation

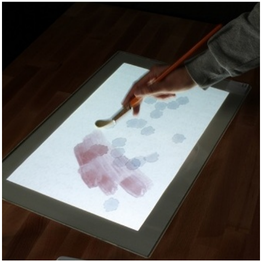


I. Vallivaara, J. Haverinen, A. Kemppainen, and J. Roning **Simultaneous localization and mapping using ambient magnetic field**. In *Proc. of the IEEE Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI)*, 2010

Models for magnetic maps are investigated in Paper C

Applications

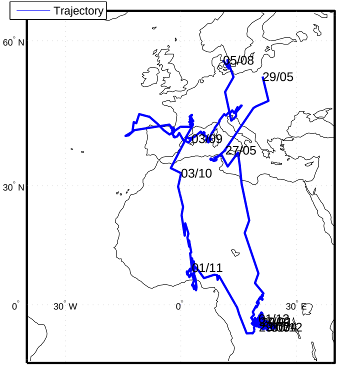
- Traffic surveillance
- Indoor navigation
- Localization in public environments



Visit *Visualiseringscenter C* in Norrköping!
This application is not further analyzed in this thesis.

Applications

- Traffic surveillance
- Indoor navigation
- Localization in public environments
- Bird localization



Presented in Paper D

Outline

Maxwell's equations

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= \mathbf{0} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{B} - \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} &= \mu_0 \mathbf{J}
\end{aligned}
$$

$\mathbf{E}$: Electric field
ρ: Charge density
$\mathbf{B}$: Magnetic field
$\mathbf{J}$: Current density

Maxwell's equations

Electrostatics

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \mathbf{E} + \cancel{\frac{\partial \mathbf{B}}{\partial t}} = \mathbf{0}$$

Magnetostatics

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} - \cancel{\mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}} = \mu_0 \mathbf{J}$$

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$\mathbf{E}$: Electric field

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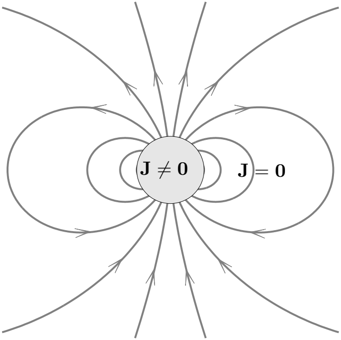
$\mathbf{B}$: Magnetic field

$\mathbf{J}$: Current density

The magnetostatic equations are difficult to solve...

...however, if the current density is localized, an analytical solution exists!



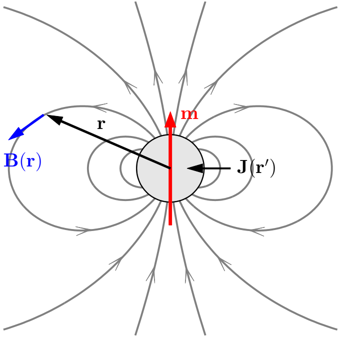
Magnetic dipole field

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \frac{3(\mathbf{r} \cdot \mathbf{m})\mathbf{r} - \|\mathbf{r}\|^2 \mathbf{m}}{\|\mathbf{r}\|^5}$$

Magnetic dipole moment

$$\mathbf{m} \triangleq \frac{1}{2} \int \mathbf{r}' \times \mathbf{J}(\mathbf{r}') d^3 r'$$

...however, if the current density is localized, an analytical solution exists!



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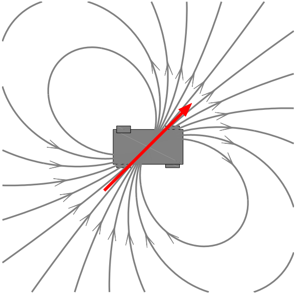
Magnetic dipole moment

$$\mathbf{m} \triangleq \frac{1}{2}\int \mathbf{r}' \times \mathbf{J}(\mathbf{r}')d^3r'$$

Application: Traffic surveillance

Contributions:

- Multiple sensors (Paper A)
  - Point target model

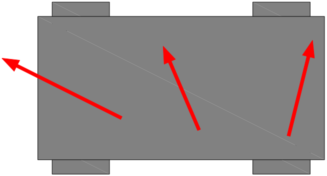


Idea: Model the vehicle as a magnetic dipole

Application: Traffic surveillance

Contributions:

- Multiple sensors (Paper A)
  - Point target model
  - Extended target model

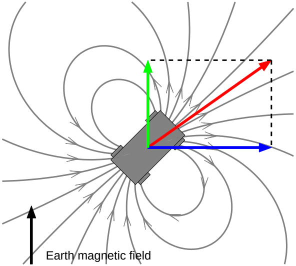


Idea: Use multiple magnetic dipoles to describe target extent

Application: Traffic surveillance

Contributions:

- Multiple sensors (Paper A)
  - Point target model
  - Extended target model
  - Target orientation dependent model



Idea: Decompose dipole moment into hard iron and soft iron components.

Application: Traffic surveillance

Contributions:

- Multiple sensors (Paper A)
  - Point target model
  - Extended target model
  - Target orientation dependent model
  - Observability analysis

Application: Traffic surveillance

Contributions:

- Multiple sensors (Paper A)
  - Point target model
  - Extended target model
  - Target orientation dependent model
  - Observability analysis
- One 2-axis sensor (Paper B)
  - Determine driving direction

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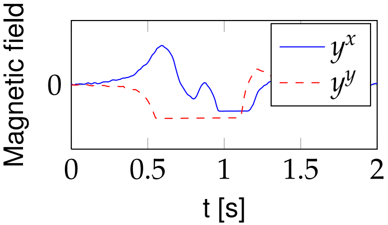
Problem formulation

- One 2-axis magnetometer has been deployed on the roadside

Magnetometer



- The magnetometer measures a distortion of the magnetic field.

We want to classify the driving direction of the vehicle!

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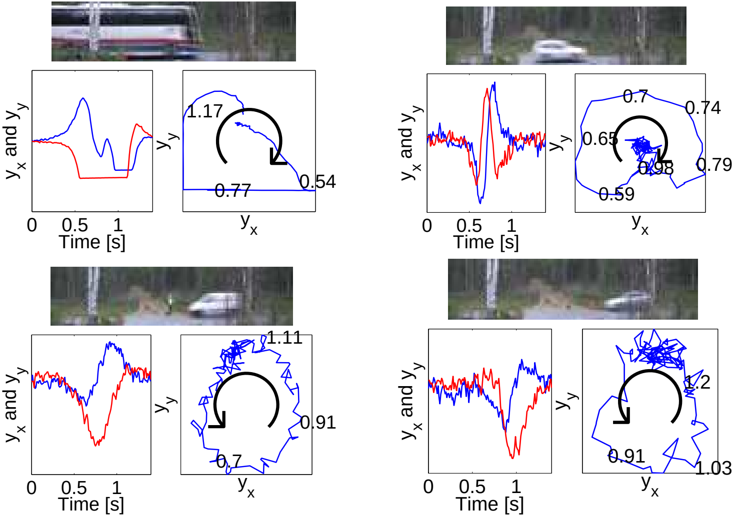
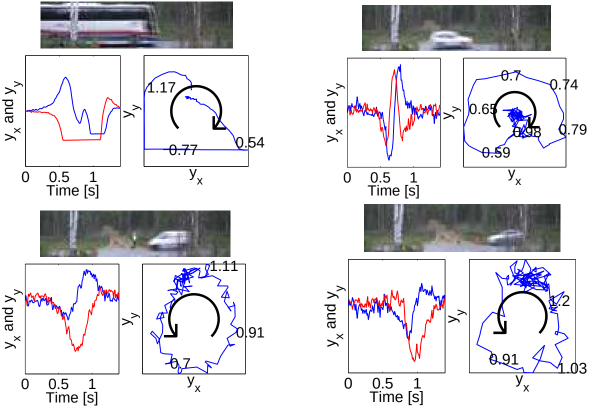
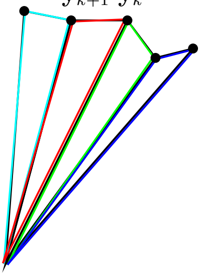

y_x and y_y
0
0.5
1
Time [s]
y_y
y_x
1.17
0.54
0.77
0.7
0.74
0.65
0.98
0.79
0.59
1.11
0.91
0.7
1.2
0.91
1.03



Classify driving direction by the turn of the measurement trajectory!

The area of one triangle is



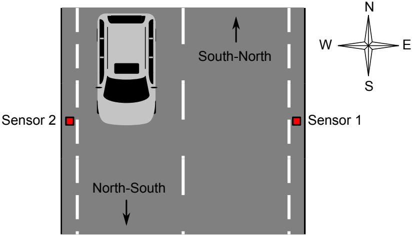
$$\frac{1}{2}\begin{vmatrix} y_k^{\mathsf{x}} & y_{k+1}^{\mathsf{x}} \\ y_k^{\mathsf{y}} & y_{k+1}^{\mathsf{y}} \end{vmatrix} = \frac{1}{2}(y_k^{\mathsf{x}} y_{k+1}^{\mathsf{y}} - y_k^{\mathsf{y}} y_{k+1}^{\mathsf{x}})$$

- Sum over all triangles
- The enclosed area can be computed as two inner products!

$$\hat{f} = \frac{1}{2}\left((\mathbf{y}_{1:N}^{\mathsf{x}})^T \mathbf{y}_{2:(N+1)}^{\mathsf{y}} - (\mathbf{y}_{1:N}^{\mathsf{y}})^T \mathbf{y}_{2:(N+1)}^{\mathsf{x}}\right)$$

- The sign of $\hat{f}$ determines the driving direction.

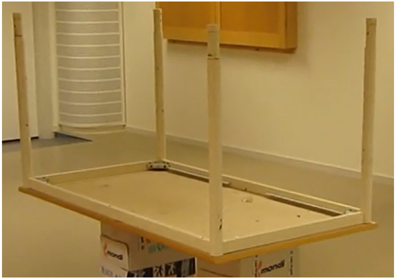
- 2 sensor nodes
- 158 min
- 291 vehicles travelling south-north
- 220 vehicles travelling north-south



Correct classification by the two sensors

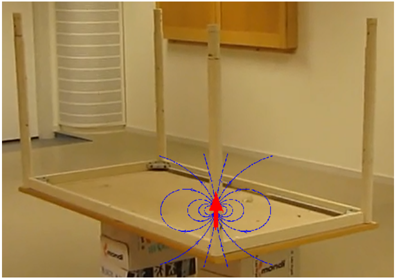
	South-North (Sensor 1)	North-South (Sensor 2)
Sensor 1	290/291	189/220
Sensor 2	265/291	220/220

Problem formulation



How should the map be modeled?

We want to find a magnetic map of this object!

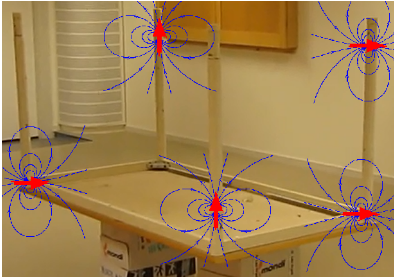


How should the map be modeled?

- Use the dipole model?

We want to find a magnetic map of this object!

Problem formulation

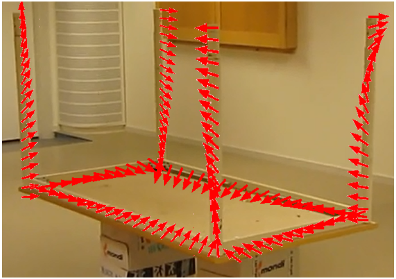


We want to find a magnetic map of this object!

How should the map be modeled?

- Use the dipole model?
- Use multiple dipoles?

← Parametric models

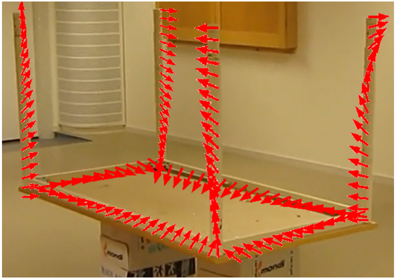


How should the map be modeled?

- ~~Use the dipole model?~~
- ~~Use multiple dipoles?~~ ← Parametric models
- Use a continuum of dipoles!

We want to find a magnetic map of this object!

Problem formulation



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- Use a continuum of dipoles! ← Nonparametric models!

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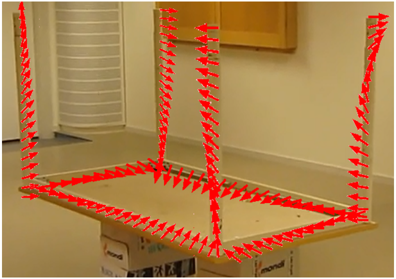
Problem formulation



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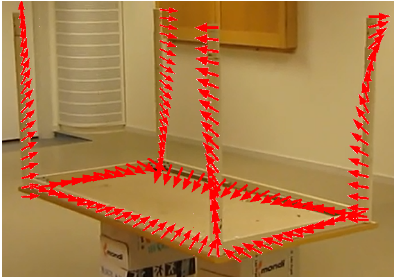
- ~~Use the dipole model?~~
- ~~Use multiple dipoles?~~ ← Parametric models
- Use a continuum of dipoles! ← Nonparametric models!
- Spatial correlation

Problem formulation



We want to find a magnetic map of this object!

How should the map be modeled?

- ~~Use the dipole model?~~
- ~~Use multiple dipoles?~~ ← Parametric models
- Use a continuum of dipoles! ← Nonparametric models!
- Spatial correlation ← Gaussian processes!

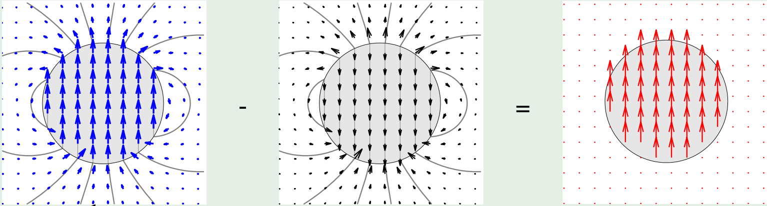
Magnetic fields

We use a slightly different version of the magnetostatic equations

$$\nabla \cdot \mathbf{B} = 0, \qquad \frac{1}{\mu_0}\mathbf{B} - \mathbf{H} = \mathbf{M},$$

$$\nabla \times \mathbf{H} = \mathbf{0}$$

Example



$$\frac{1}{\mu_0}\mathbf{B} \quad - \quad \mathbf{H} \quad = \quad \mathbf{M}$$

Gaussian processes can be seed as a distribution over functions

$$\mathbf{f}(\mathbf{u}) \sim \mathcal{GP}\big(\mu(\mathbf{u}), \mathrm{K}(\mathbf{u}, \mathbf{u}')\big),$$

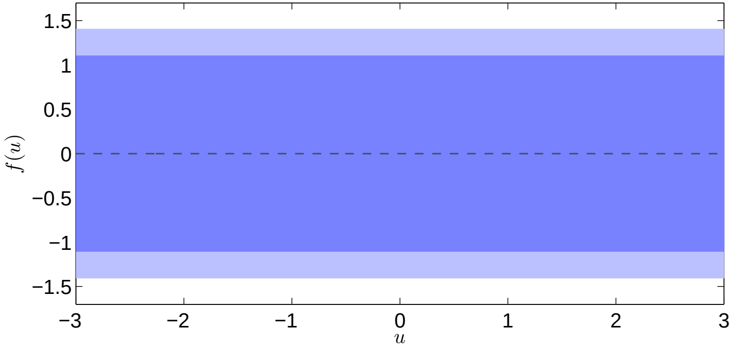
Mean function ↑ ↑ Covariance function

It is a generalization of the multivariate Gaussian distribution

$$\begin{bmatrix} \mathbf{f}(\mathbf{u}_1) \\ \vdots \\ \mathbf{f}(\mathbf{u}_N) \end{bmatrix} \sim \mathcal{N}(\mu, \mathrm{K}), \quad \text{where} \quad \mu = \begin{bmatrix} \mu(\mathbf{u}_1) \\ \vdots \\ \mu(\mathbf{u}_N) \end{bmatrix},$$

$$\mathrm{K} = \begin{bmatrix} \mathrm{K}(\mathbf{u}_1, \mathbf{u}_1) & \cdots & \mathrm{K}(\mathbf{u}_1, \mathbf{u}_N) \\ \vdots & & \vdots \\ \mathrm{K}(\mathbf{u}_N, \mathbf{u}_1) & \cdots & \mathrm{K}(\mathbf{u}_N, \mathbf{u}_N) \end{bmatrix}.$$

Objective: Estimate $\mathbf{f}(\mathbf{u})$ from noisy observations $\mathbf{y}_k = \mathbf{f}(\mathbf{u}_k) + \mathbf{e}_k$



Lindsten F. **A semiparametric Bayesian approach to Wiener system identification** *Presentation at SYSID12*

- The animation illustrated regression for one scalar function $f : \mathbb{R} \to \mathbb{R}$

- The animation illustrated regression for one scalar function $f : \mathbb{R} \to \mathbb{R}$
- We want to learn three different vector fields $\mathbf{f} : \mathbb{R}^3 \to \mathbb{R}^3$ In addition, these fields should obey

- The animation illustrated regression for one scalar function $f : \mathbb{R} \to \mathbb{R}$
- We want to learn three different vector fields $\mathbf{f} : \mathbb{R}^3 \to \mathbb{R}^3$ In addition, these fields should obey
  - $\nabla \cdot \mathbf{B}$ (divergence free)
  - $\nabla \times \mathbf{H}$ (curl free)

Gaussian process + magnetic fields

- The animation illustrated regression for one scalar function $f : \mathbb{R} \to \mathbb{R}$
- We want to learn three different vector fields $\mathbf{f} : \mathbb{R}^3 \to \mathbb{R}^3$ In addition, these fields should obey
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  - $\boldsymbol{\nabla} \times \mathbf{H}$ (curl free)

$\leftarrow$ There are covariance functions for this!

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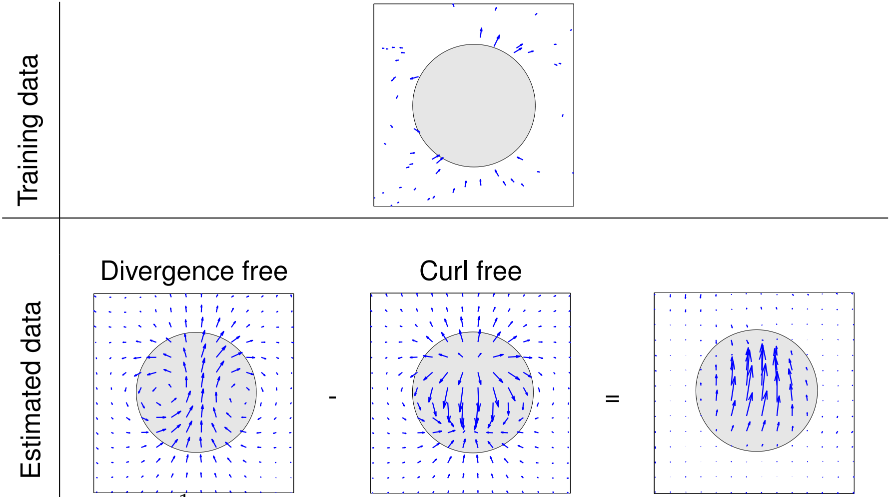
- We want to learn three different vector fields $\mathbf{f} : \mathbb{R}^3 \to \mathbb{R}^3$ In addition, these fields should obey
  - $\boldsymbol{\nabla} \cdot \mathbf{B}$ (divergence free)
  - $\boldsymbol{\nabla} \times \mathbf{H}$ (curl free)
  - $\frac{1}{\mu_0}\mathbf{B} - \mathbf{H} = \mathbf{M}$

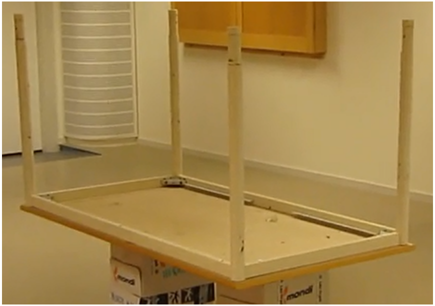
← There are covariance functions for this!



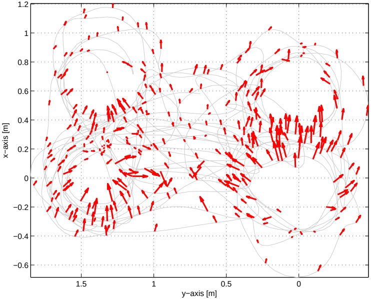
$$\frac{1}{\mu_0}\mathbf{B} - \mathbf{H} = \mathbf{M}$$

Real world experiment

- Measurements have been collected with a magnetometer
- An optical reference system (Vicon) has been used for determining the position and orientation of the sensor



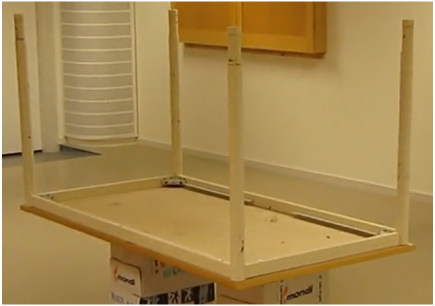
The magnetic environment



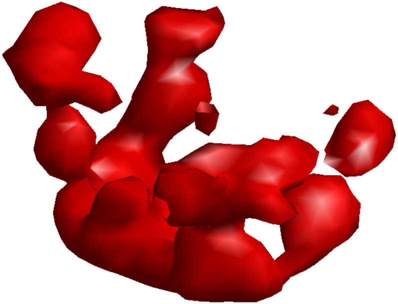
Training data

Real world experiment

- Measurements have been collected with a magnetometer
- An optical reference system (Vicon) has been used for determining the position and orientation of the sensor



The magnetic environment

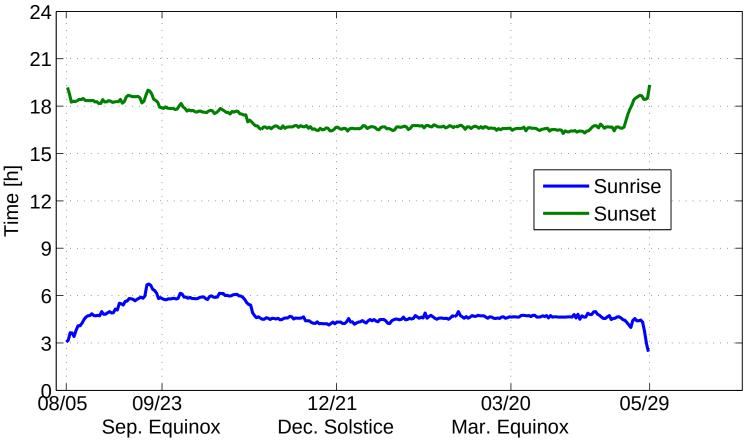


Estimated magnetic content

- Introduction
- Electromagnetic theory
- Localizing moving magnetic objects
- Mapping magnetic environments
- Geolocation using Light levels
- Concluding remarks

- Common swift, *Apus apus*. Weight: 40 g
- Equipped with light logger (light sensor, battery, memory, clock). Weight: 2g
- Released on Aug. 5, 2010, found 298 days later

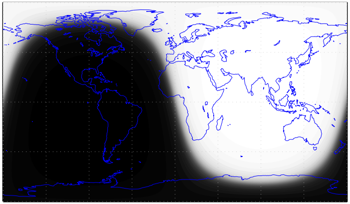
We want to localize Mr Swift!



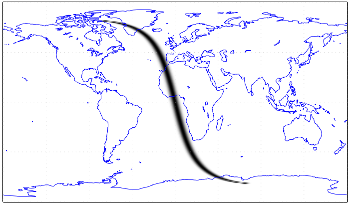
Time [h]
24
21
18
15
12
9
6
3
0
08/05
09/23
12/21
03/20
05/29
Sep. Equinox
Dec. Solstice
Mar. Equinox
Sunrise
Sunset

The likelihood - May 6

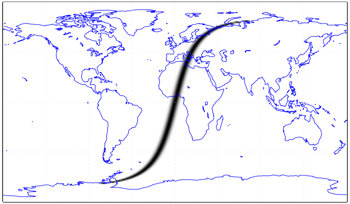
Daylight map, 06−May−2011 06:00:00



Likelihood, sunrise, 06−May−2011 06:00:00



Likelihood, sunset, 06−May−2011 18:00:00



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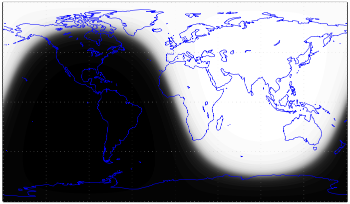
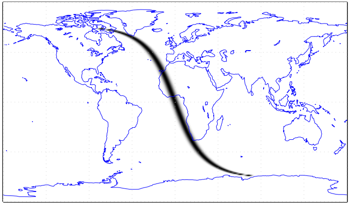
The likelihood - Summer solstice

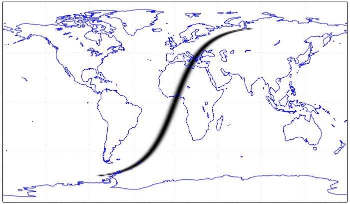
Daylight map, 21−Jun−2011 06:00:00



Likelihood, sunrise, 21−Jun−2011 06:00:00



Likelihood, sunset, 21−Jun−2011 18:00:00



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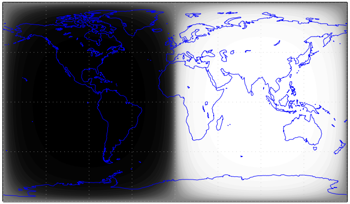
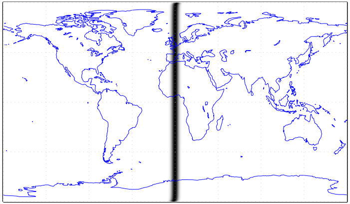
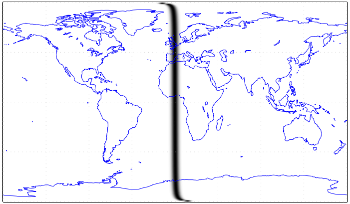
Daylight map, 21−Sep−2011 06:00:00



Likelihood, sunrise, 21−Sep−2011 06:00:00



Likelihood, sunset, 21−Sep−2011 18:00:00



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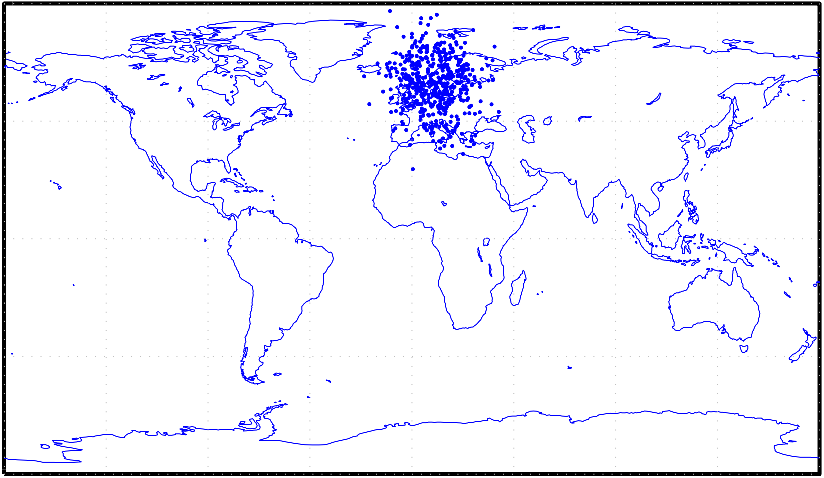
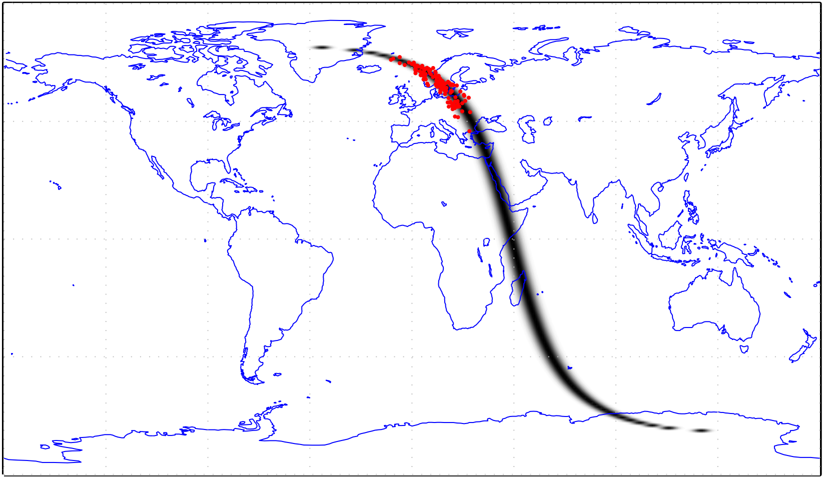
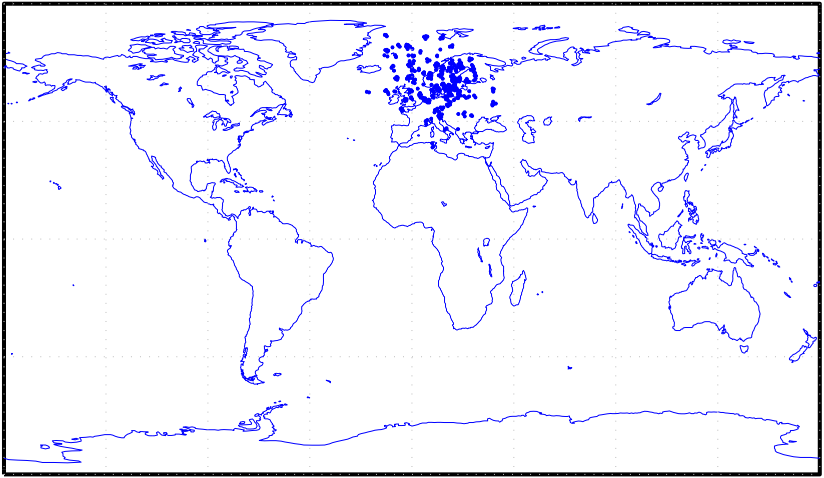
Prior

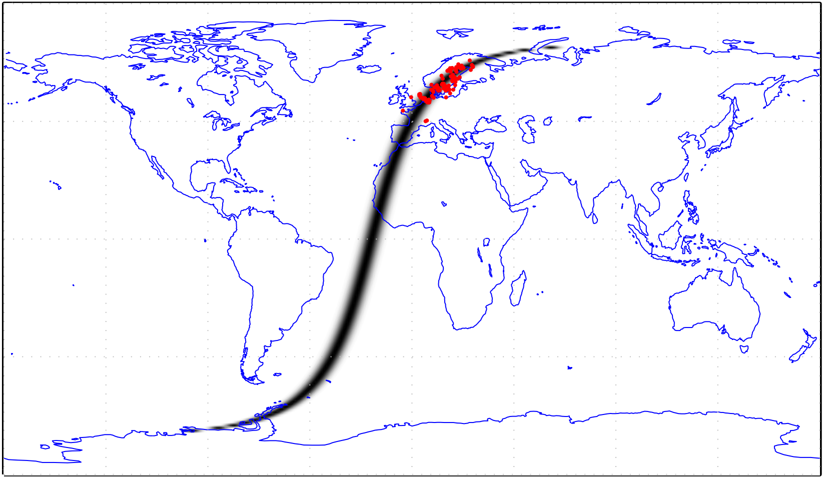


Measurement update - sunrise.
Time: 05-Aug-2010 03:04:00

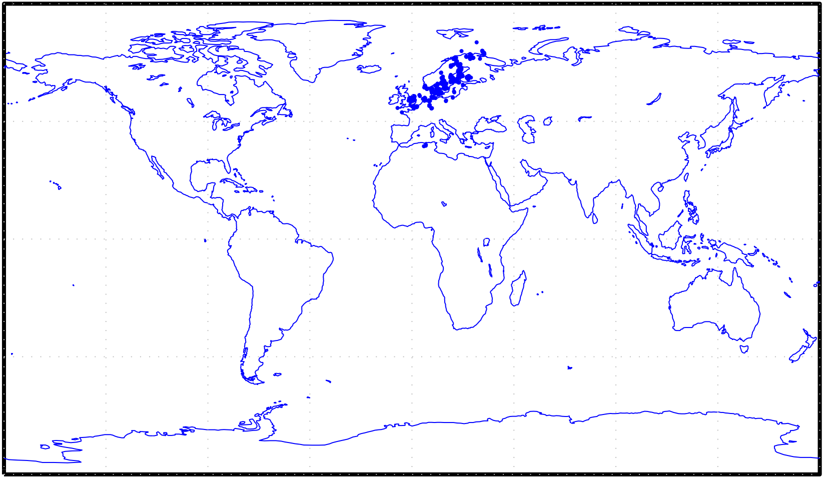


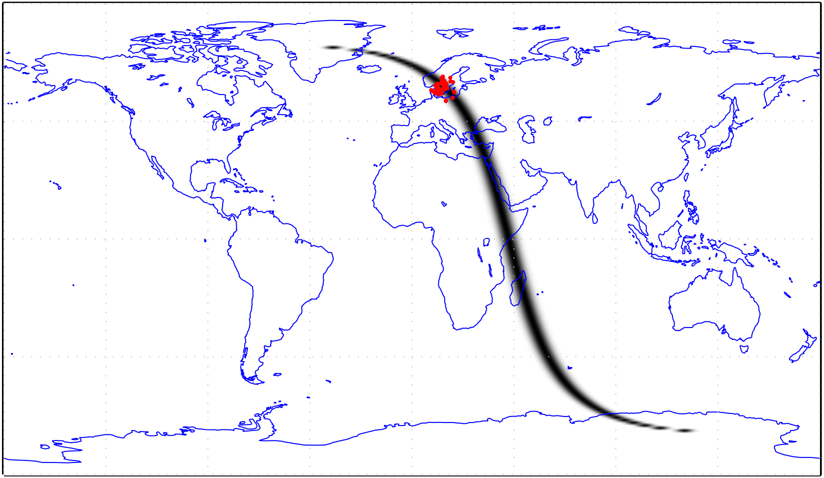
Time update.
Time: 05-Aug-2010 19:10:59



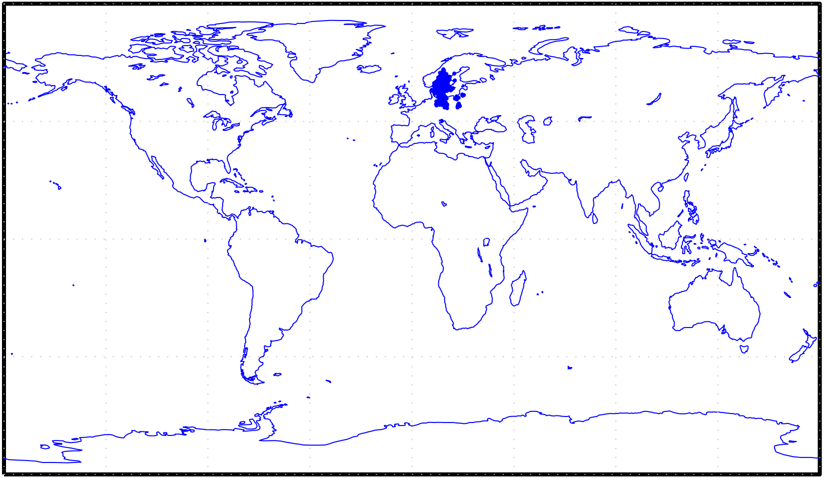


Time update.
Time: 06-Aug-2010 03:08:59

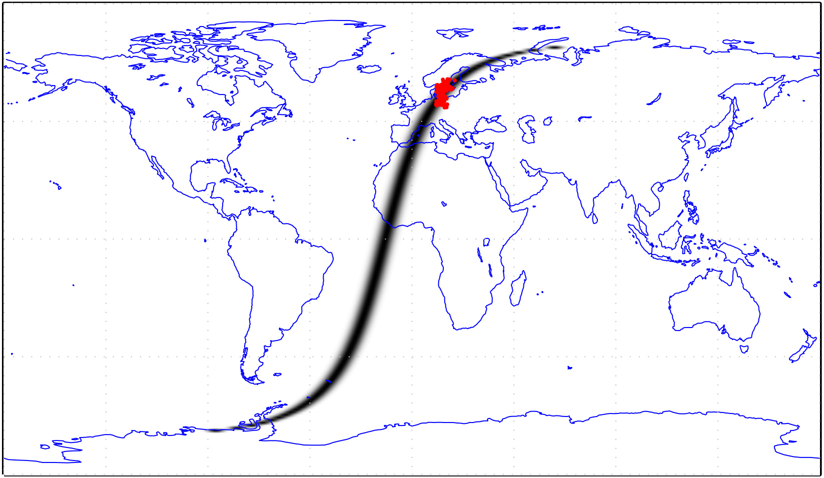




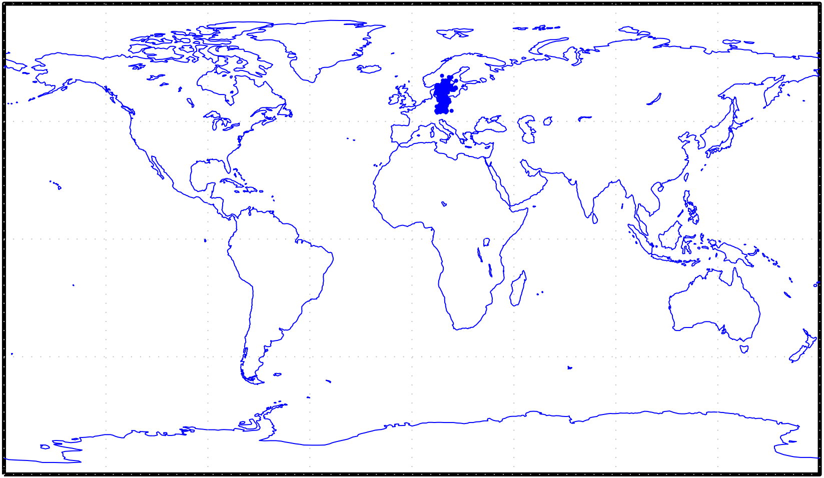
Time update.
Time: 06-Aug-2010 18:46:59



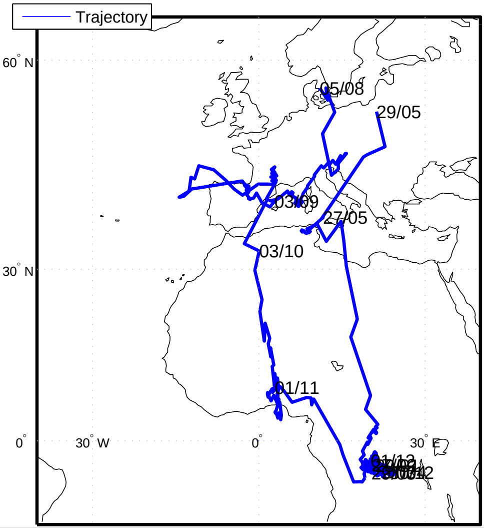
Measurement update - sunset.
Time: 06-Aug-2010 18:47:00



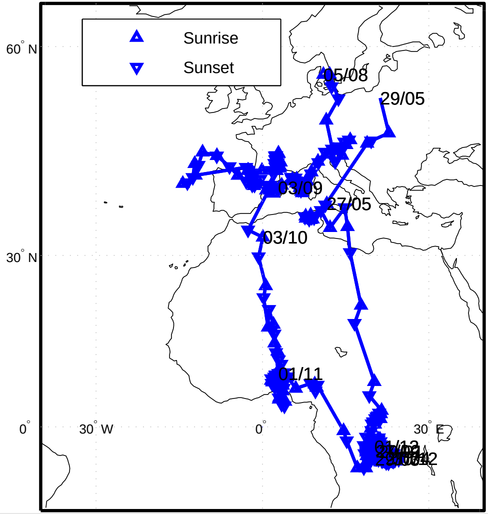
Time update.
Time: 07-Aug-2010 03:38:59



The Voyage



The Voyage



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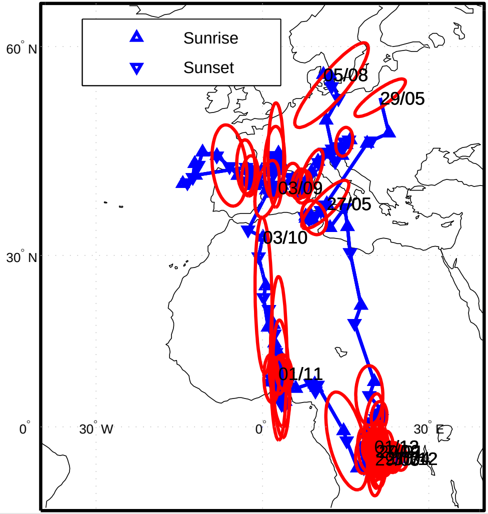

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Conclusions/contributions

- Localizing moving magnetic objects
  - Various parametric models: point target model, extended target model, target orientation dependent model
  - Classifying driving direction with only one 2-axis magnetometer

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- Localizing moving magnetic objects
  - Various parametric models: point target model, extended target model, target orientation dependent model
  - Classifying driving direction with only one 2-axis magnetometer
- Mapping magnetic environments
  - Bayesian nonparametric model of magnetic environments
- Geolocation using light levels
  - Filtering framework suitable for localizing migrating birds

Future work

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  - Full framework with detection integrated
  - Implementation in a real sensor network

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  - Full framework with detection integrated
  - Implementation in a real sensor network
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  - Final goal: Simultaneous Localization And Mapping

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- Localizing moving magnetic objects
  - Full framework with detection integrated
  - Implementation in a real sensor network
- Mapping magnetic environments
  - Extended the model to handle more complicated structures
  - Final goal: Simultaneous Localization And Mapping
- Localizing migrating birds using light levels
  - Do smoothing
  - Process light intensity data directly