Sea glider navigation around a circle using distance measurements to a drifting acoustic source

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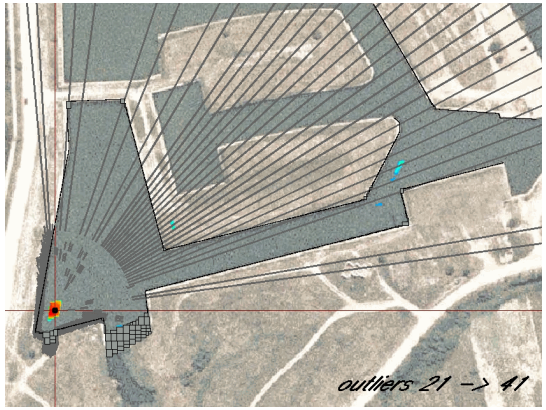
ENSTA Bretagne

Our activities in applied interval analysis to underwater robotics

SAUC'E robot competition

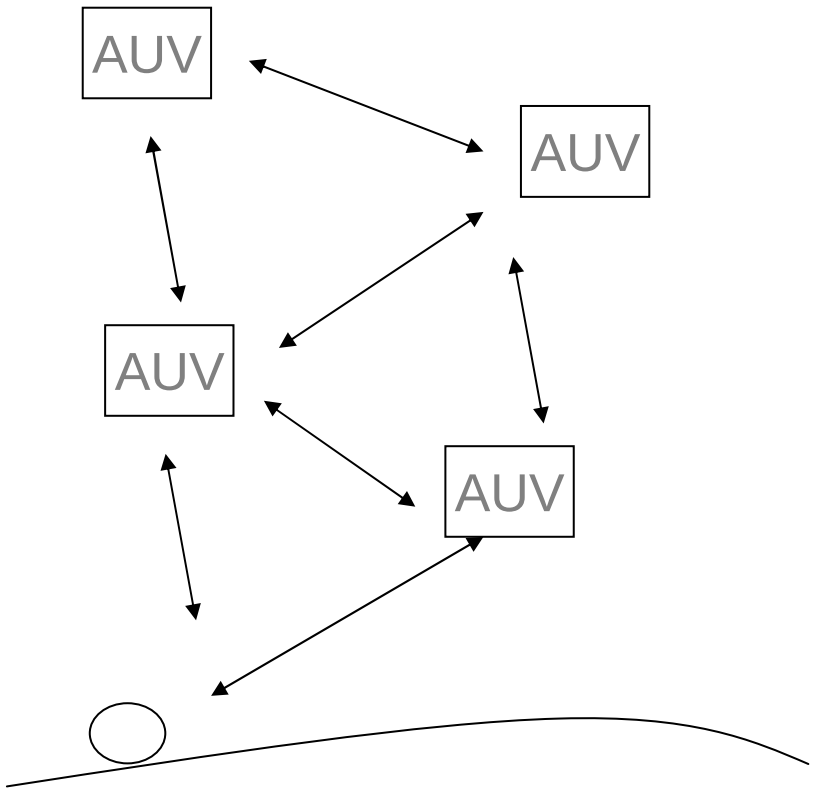
- SAUC-E (Student Autonomous Underwater Challenge - Europe)



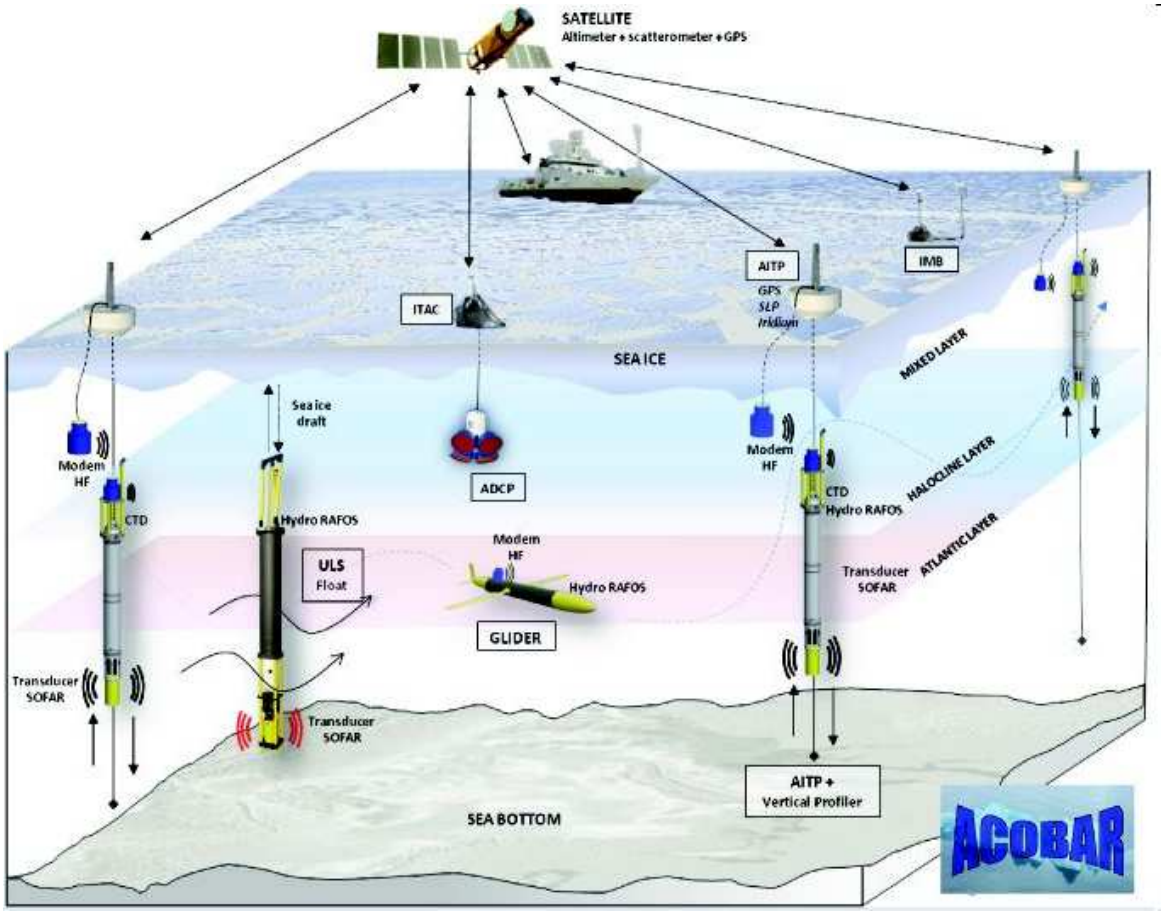
Robot Swarms

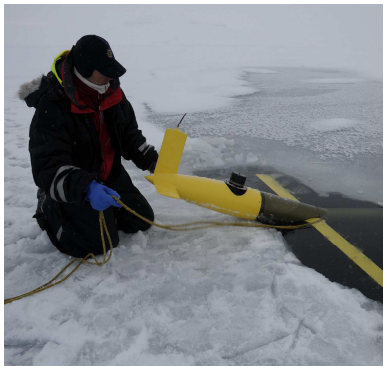
- 4 CISCREA robots

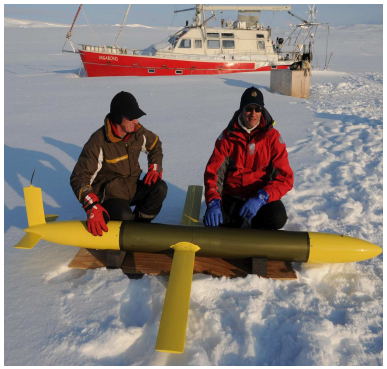
SLAM



ENSTA Bretagne's Glider



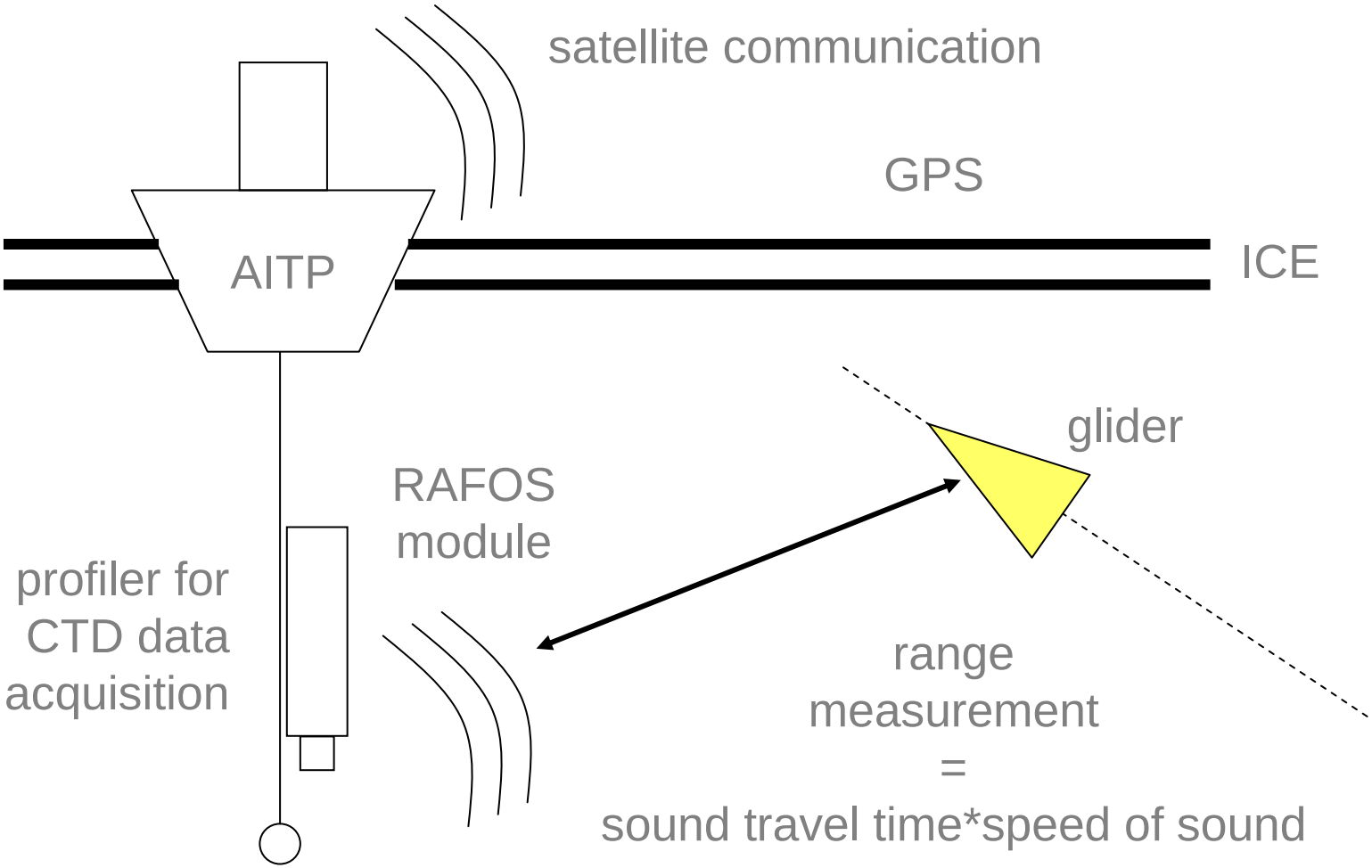




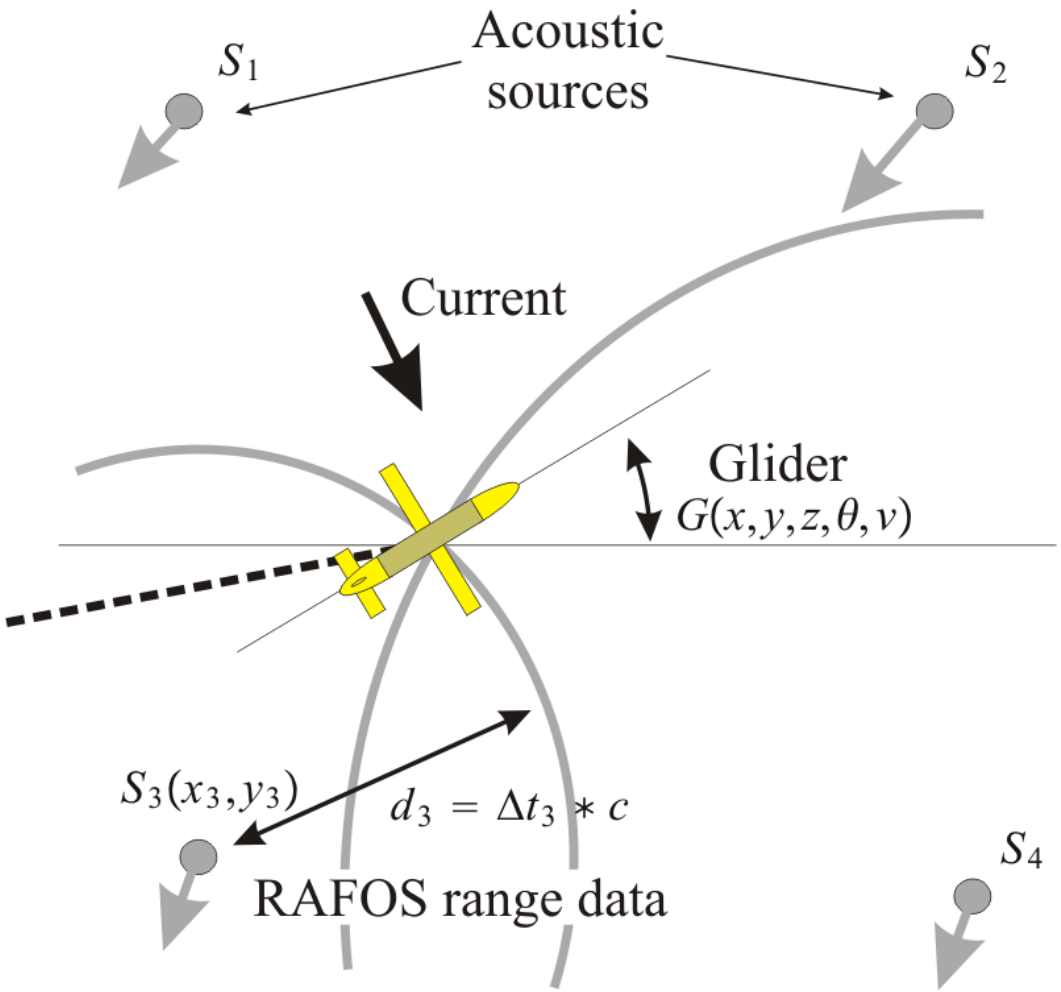
A campaign of several months under the polar ice cape

Problems to solve : No GPS

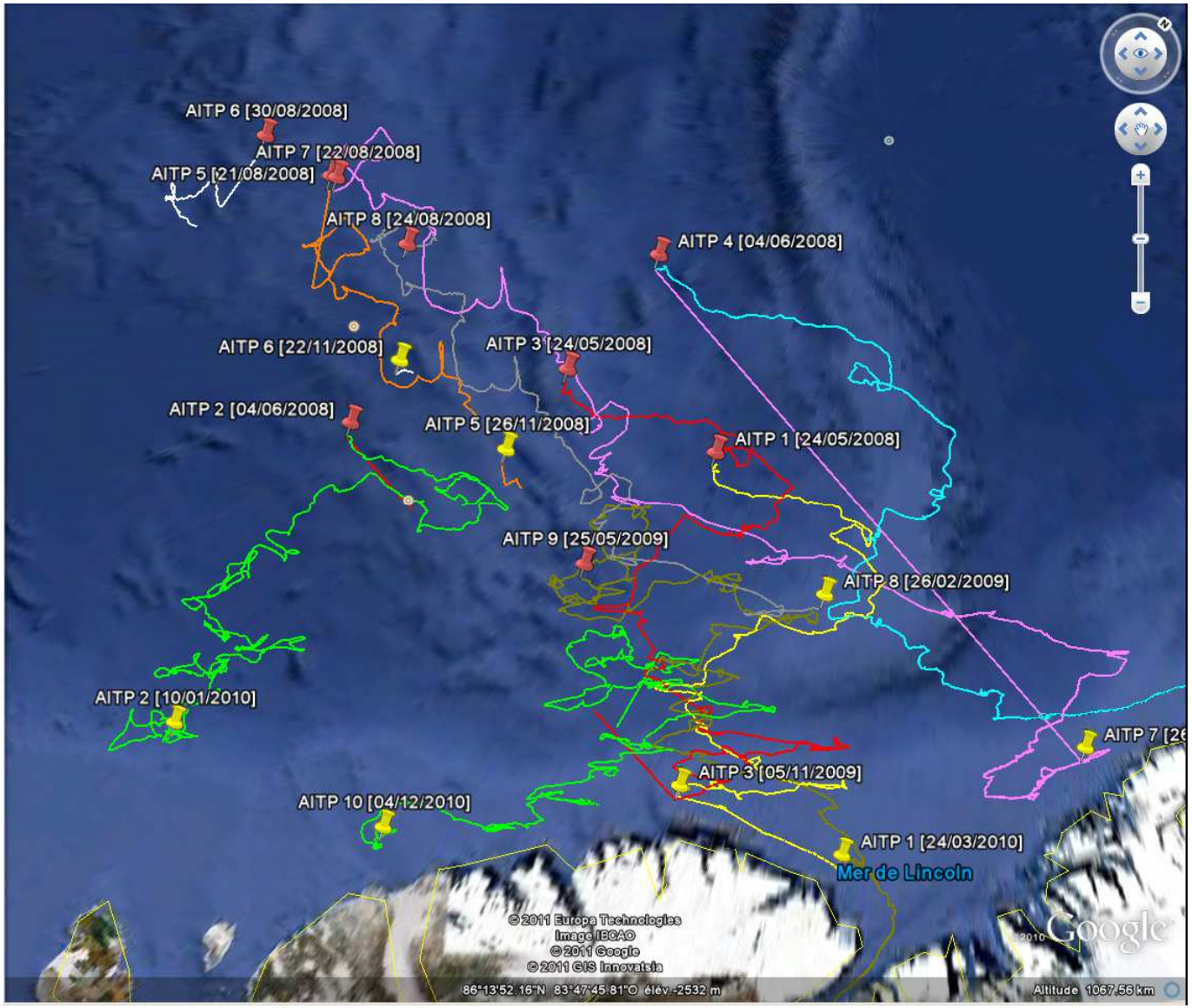
- Localization of the vehicle?



Classical approach: (lon,lat) localization



Problems to solve : Sources are drifting

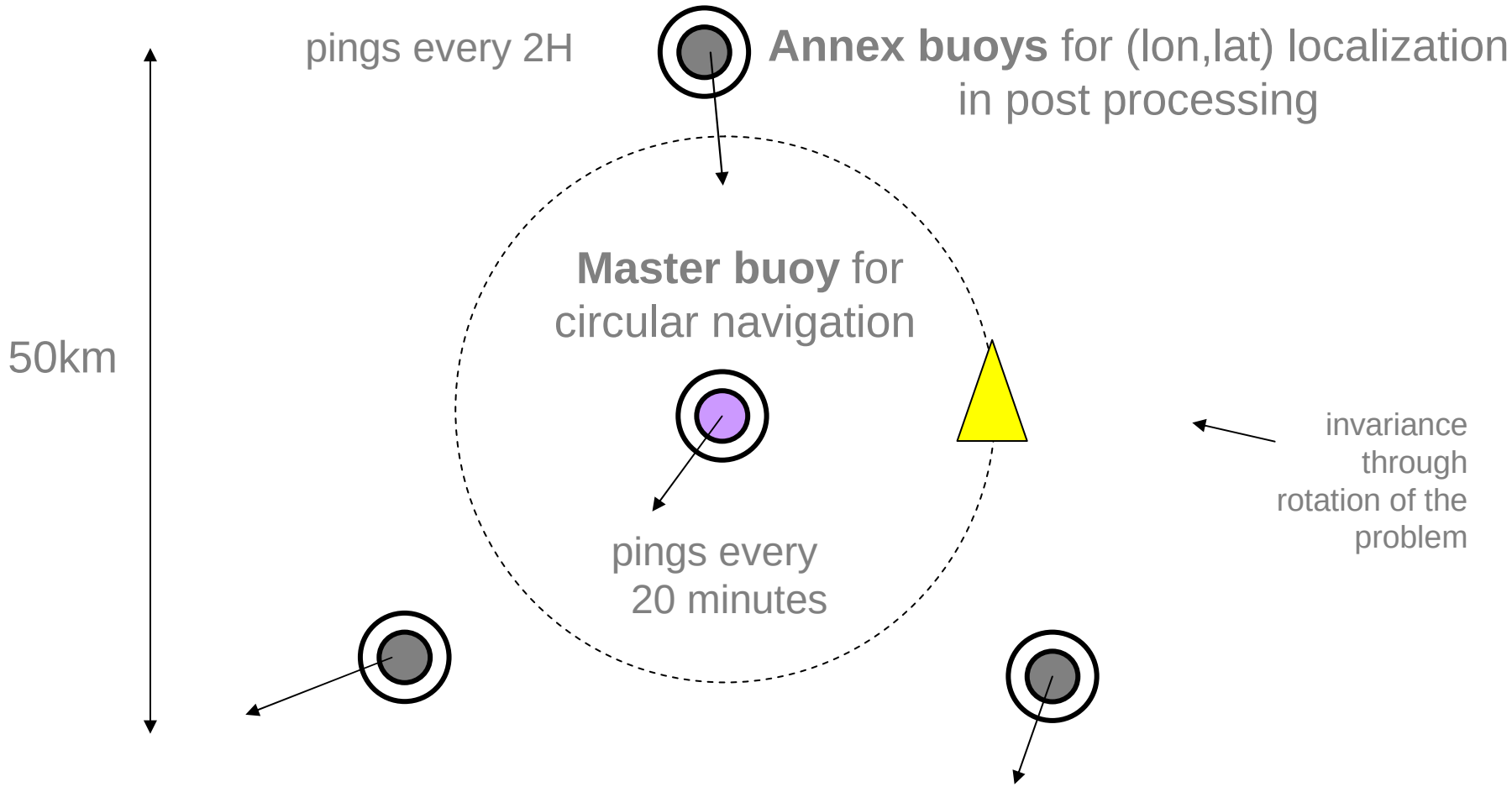


Other problems

- The pings are rare (to economize the energy) → little redundancy of data
- The readings of the compass are poor in the North Pole
- …

Solution

- Split the localization (longitude, latitude) and navigation

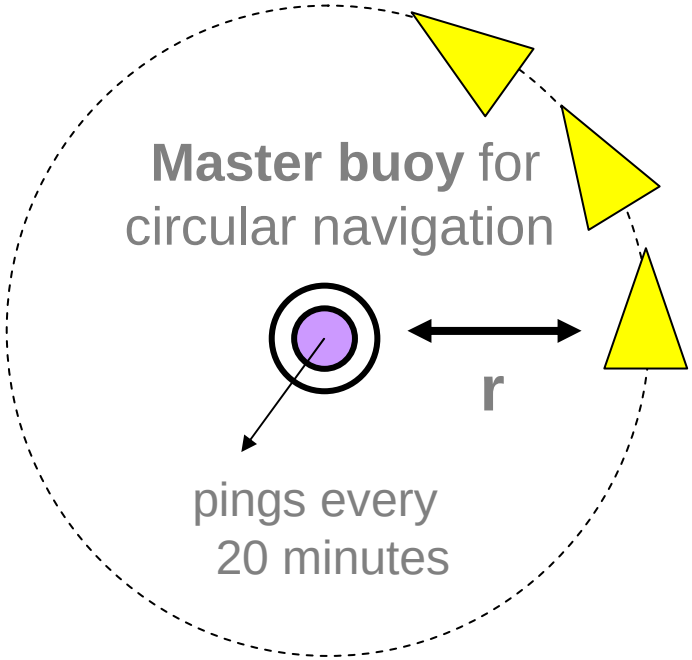


Plan of the presentation

- Navigation around a single acoustic beacon using set membership methods
  - General idea about the control
  - Setting up the equations
  - Setting up the problem as a set inversion problem
  - Estimate error and its derivative using robust regression
  - Simulation results of the PID control loop
- Results of (lon,lat) localization also using set membership methods
- Conclusion

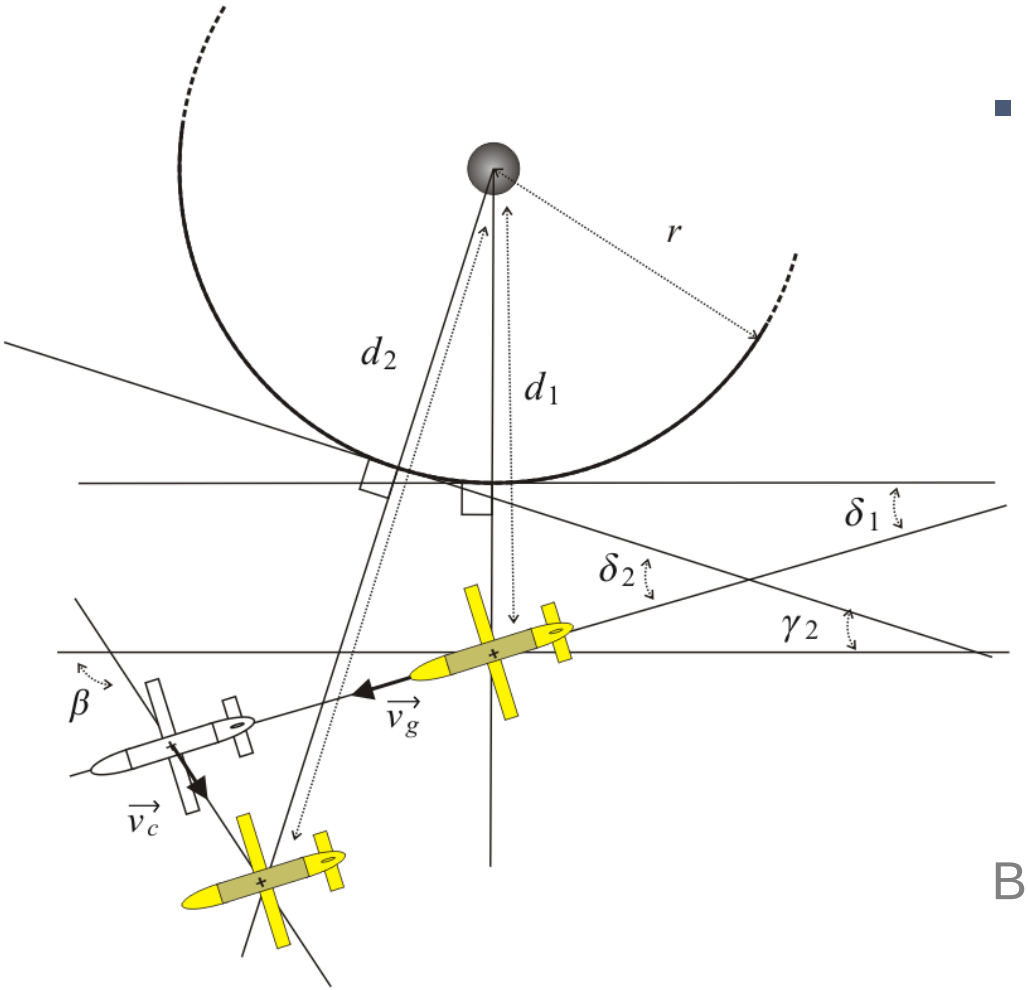
Single acoustic beacon navigation

The controller of the glider



Video

State equations

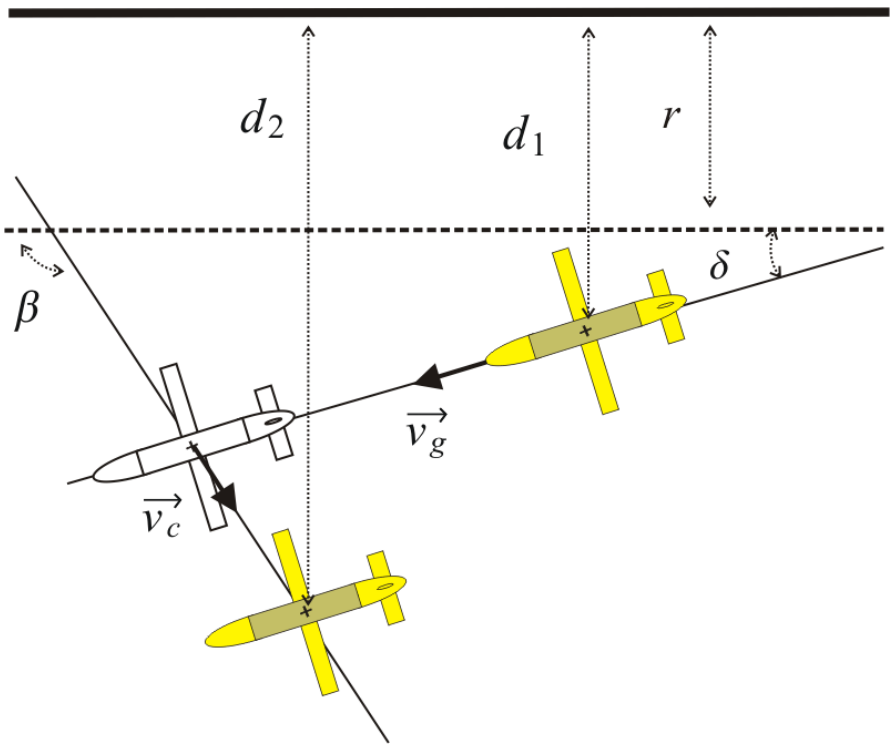


- Circle following case

$$\dot{d} = v_c \sin\beta + v_g \sin\delta$$
$$\dot{\delta} = \arctan \frac{v_c \cos\beta + v_g \cos\delta}{d} + \omega$$
$$\dot{\psi} = \omega.$$

Big radius (>5km) with respect to glider's speed (1km/h)

State equations: approximation



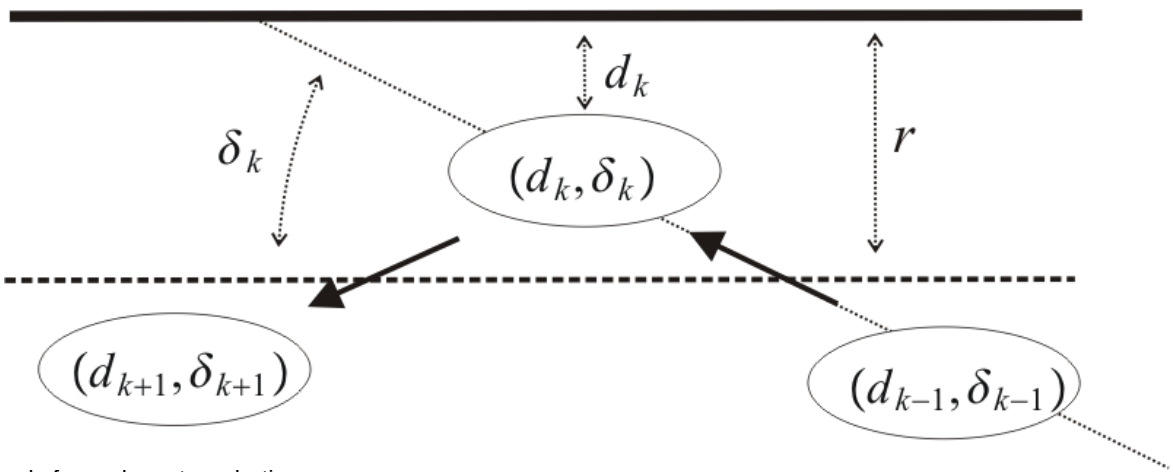
- Approximation by a line

$$\dot{d} = v_c \sin\beta + v_g \sin\delta$$
$$\dot{\delta} = \omega$$
$$\dot{\psi} = \omega.$$

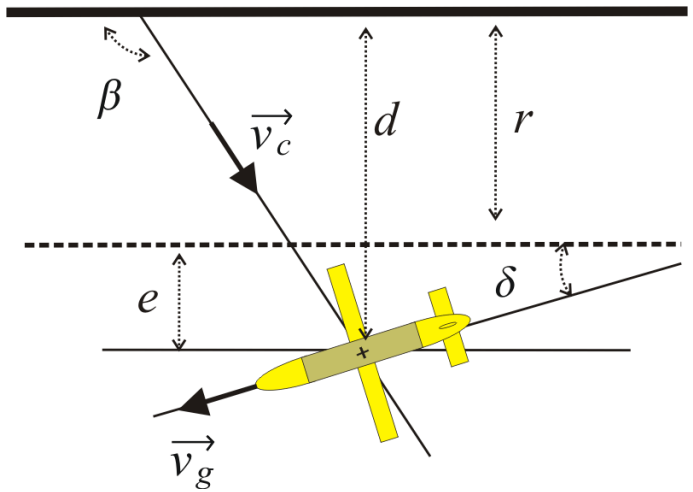
Big radius (>5km) with respect to glider's speed (1km/h)

Discrete regulation

- **Step 1** : Make a range measurement
- **Step 2** : Compute heading correction
- **Step 3** : Correct the heading (using a compass or gyroscope) – this step takes several minutes -
- **Step 4** : Go strait until the next measurement (~20 minutes)
- **Step 5** : Go to **Step 1**



PID control



The error

$$e_k = d_k - r$$

The PID controller for the rotation speed

$$\omega_k = K_1 \sum_{i \in \{0,..,k\}} e_i + K_2 e_k + K_3 \dot{e}_k$$

Filtering a **noisy signal** with outliers

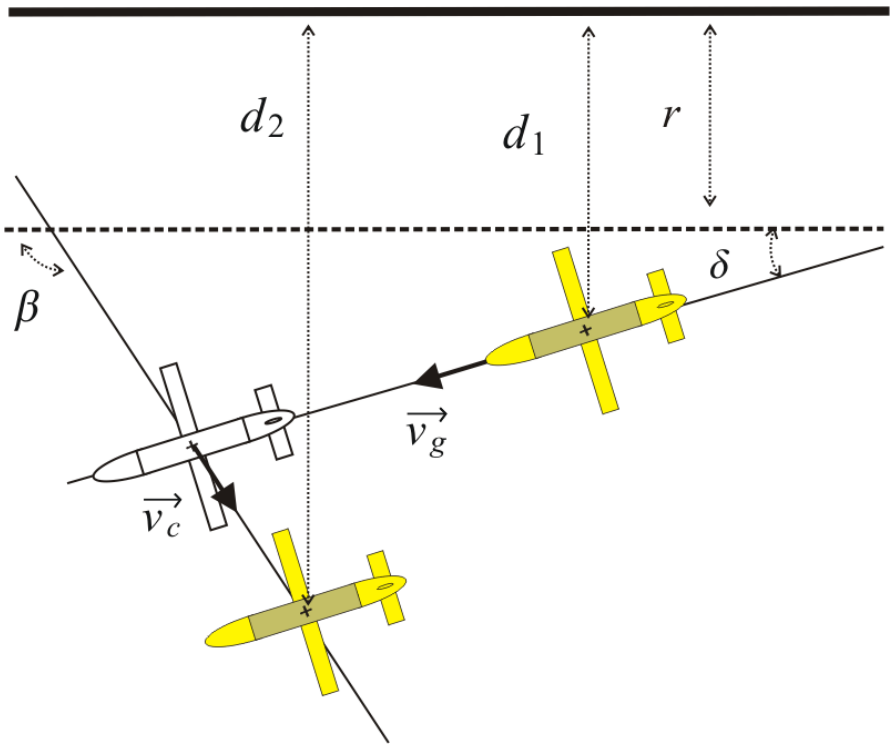
Derivative of a **noisy** signal with **outliers**

complicated

Method 1 : state estimation

State estimation

- We estimate all the variables which can be estimated



$$d_n, \delta_n, v_c \sin\beta$$

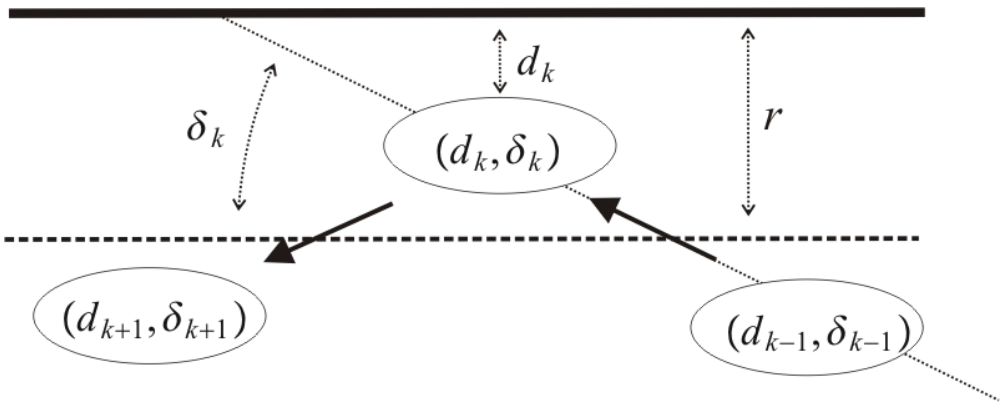
Discrete form of the state equations

The state equations for the case of line following are

$$\boxed{\begin{aligned} \dot{d} &= v_c \sin\beta + v_g \sin\delta \\ \dot{\delta} &= \omega \end{aligned}}$$

The discrete form of those state equations can be written

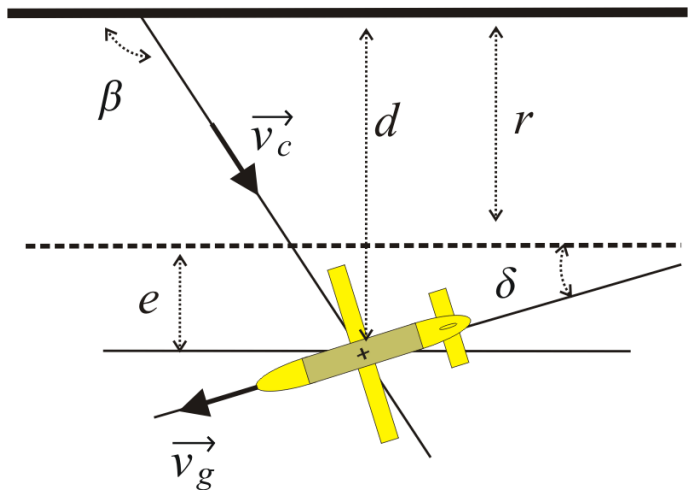
$$\boxed{\begin{aligned} d_{k+1} &= (v_c \sin\beta + v_g \sin\delta_{k+1})\Delta t + d_k \\ \delta_{k+1} &= \delta_k + u_k + w_k \\ \tilde{d}_k &= d_k + \tilde{w}_k \end{aligned}}$$



Set up the problem as a set inversion

The **discrete** form of those state equations can be written

$$
\begin{aligned}
d_{k+1} &= (v_c \sin\beta + v_g \sin\delta_{k+1})\Delta t + d_k \\
\delta_{k+1} &= \delta_k + u_k + w_k \\
\tilde{d}_k &= d_k + \tilde{w}_k
\end{aligned}
$$



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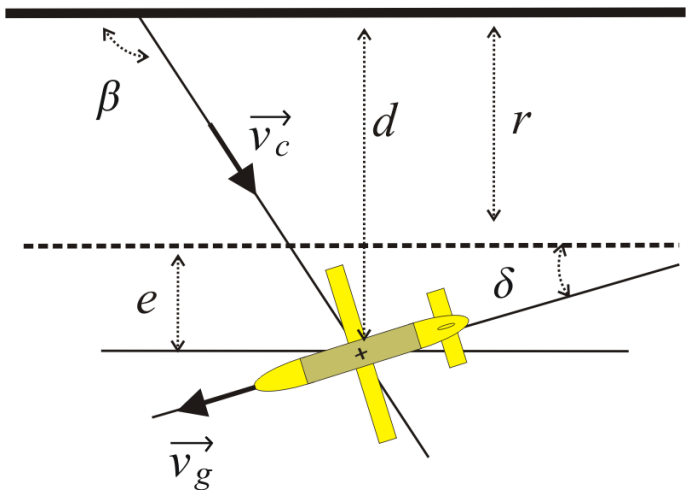


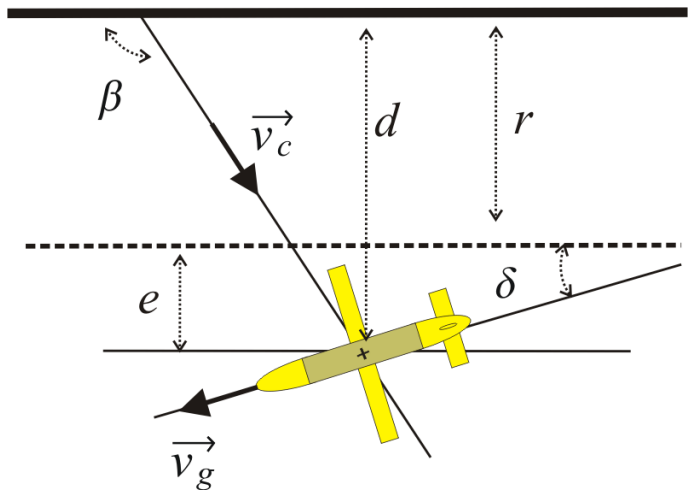
For each time step n we search for

$$d_n, \delta_n, v_c \sin\beta$$

Set up the problem as a set inversion

The **discrete** form of those state equations can be written

$$\begin{aligned} d_{k+1} &= (v_c \sin\beta + v_g \sin\delta_{k+1})\Delta t + d_k \\ \delta_{k+1} &= \delta_k + u_k + w_k \\ \tilde{d}_k &= d_k + \tilde{w}_k \end{aligned}$$



For each time step n we search for

$$d_n, \delta_n, v_c \sin\beta$$

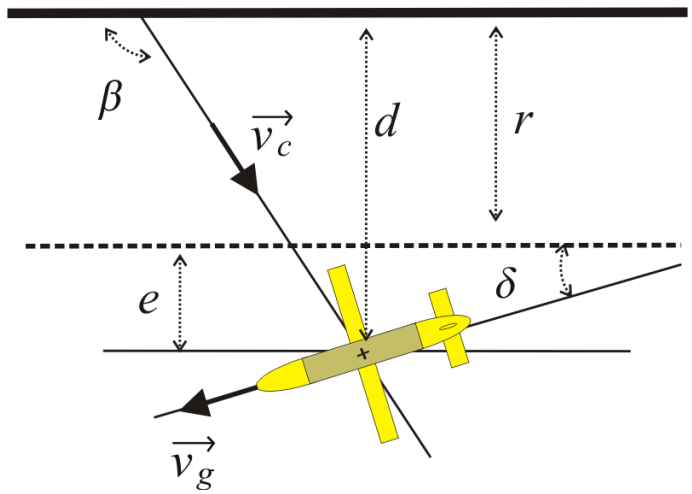
We obtain equations in the form of

$$d_n - k v_c \Delta t \sin\beta - \sum_{i=0}^{k-1} v_g \Delta t \sin\left(\delta_n - \sum_{j=1}^{i} (u_{n-j} + w_{n-j})\right) + \tilde{w}_{n-k} = \tilde{d}_{n-k}$$

Set up the problem as a set inversion

The **discrete** form of those state equations can be written

$$\begin{aligned} d_{k+1} &= (v_c \sin\beta + v_g \sin\delta_{k+1})\Delta t + d_k \\ \delta_{k+1} &= \delta_k + u_k + w_k \\ \tilde{d}_k &= d_k + \tilde{w}_k \end{aligned}$$



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$$\mathbf{f}(d_n, \delta_n, v_c \sin\beta) = \begin{pmatrix} [\tilde{d}_n] \\ \dots \\ [\tilde{d}_{n-N}] \end{pmatrix}$$

3D
Multi-occurrence
…

Set up the problem as a set inversion

The **discrete** form of those state equations can be written

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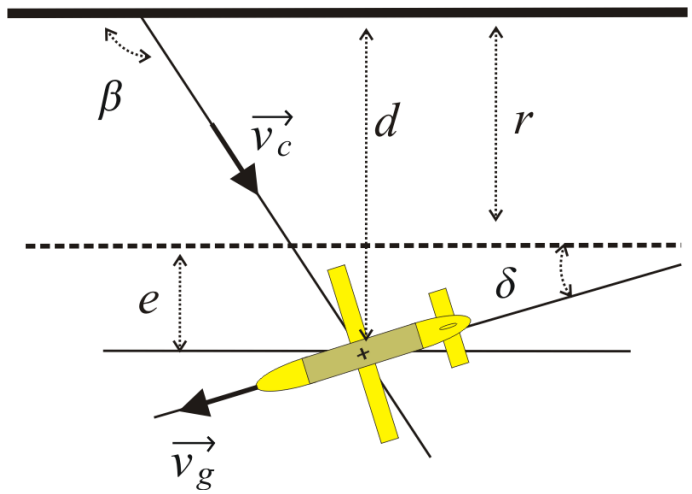

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$$\frac{d_n - d_{n-1}}{\Delta t} = v_c \sin\beta + v_g \sin\delta_n \quad \blacktriangleleft \quad \mathbf{f}(d_n, \delta_n, v_c \sin\beta) = \begin{pmatrix} [\tilde{d}_n] \\ \dots \\ [\tilde{d}_{n-N}] \end{pmatrix}$$

3D
Multi-occurrence
…

Waiting for IBEX 2

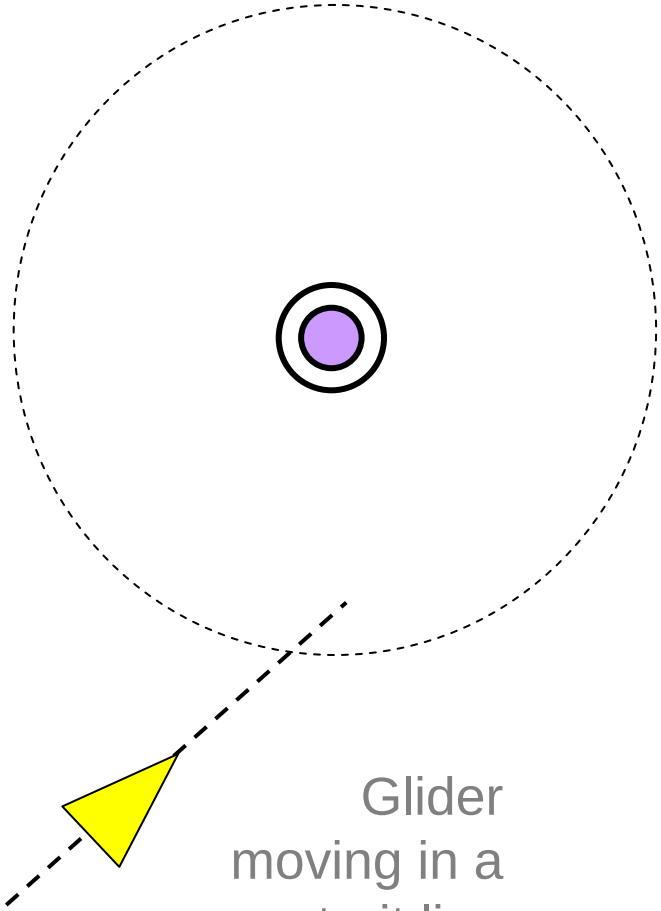
- Constraint in the form

$$d_n - kv_c \Delta t \sin\beta - \sum_{i=0}^{k-1} v_g \Delta t \sin\left(\delta_n - \sum_{j=1}^{i} (u_{n-j} + w_{n-j})\right) + \tilde{w}_{n-k} = \tilde{d}_{n-k}$$

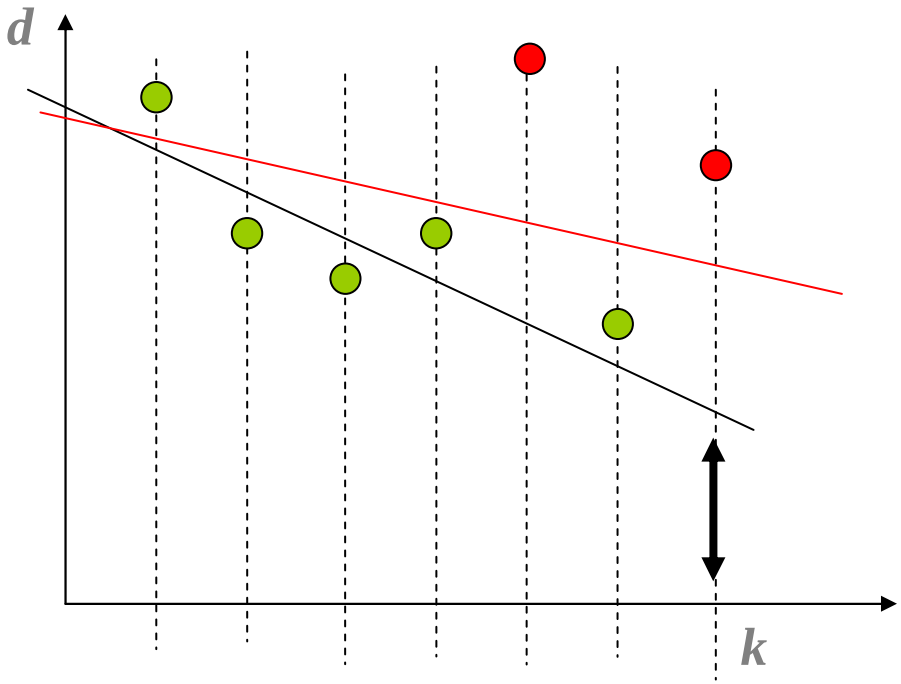
Simple

Method 2 : linear regression

Numerical differentiation : linear regression

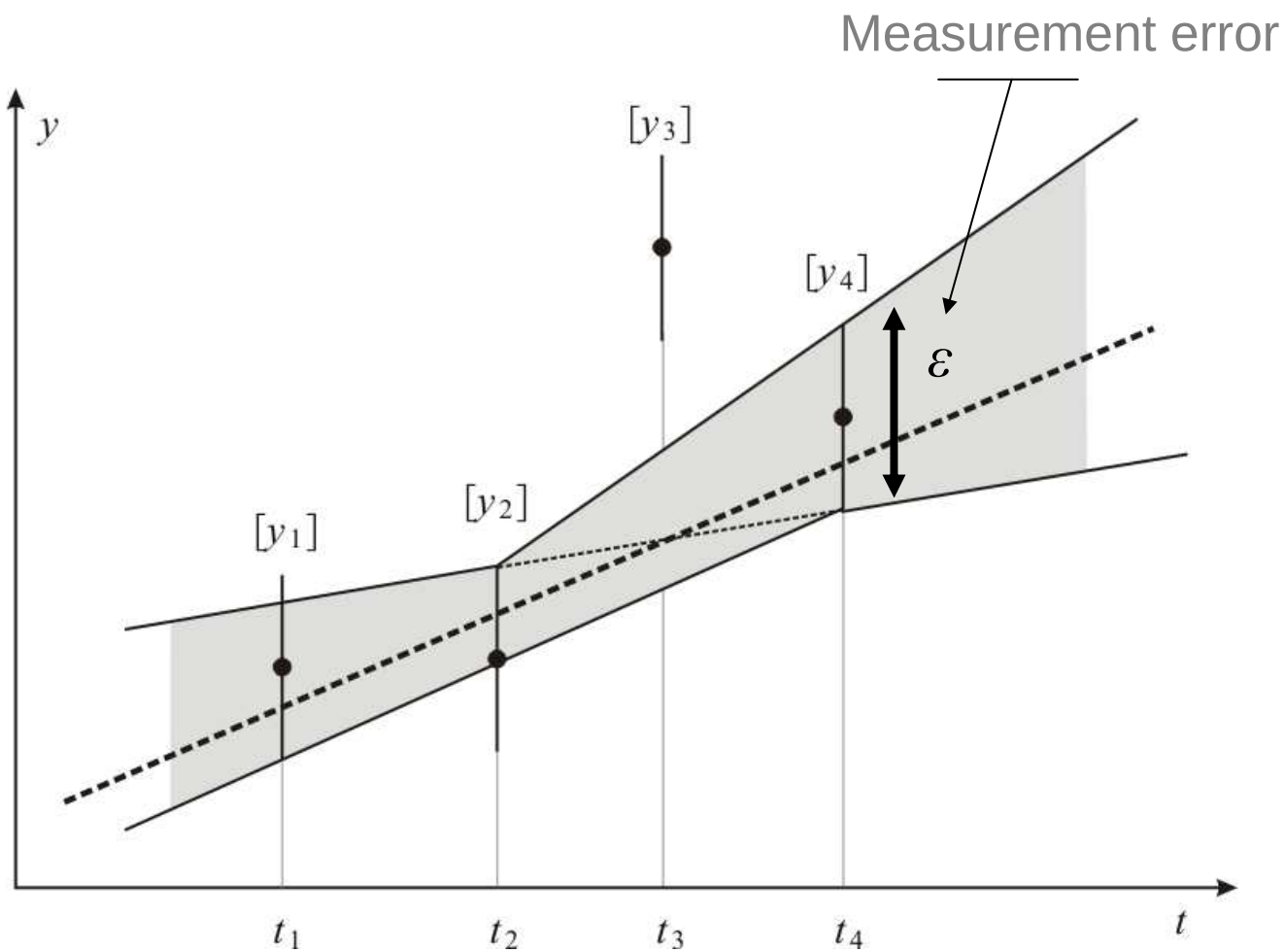


Glider moving in a strait line



Least squares?

Robust linear regression



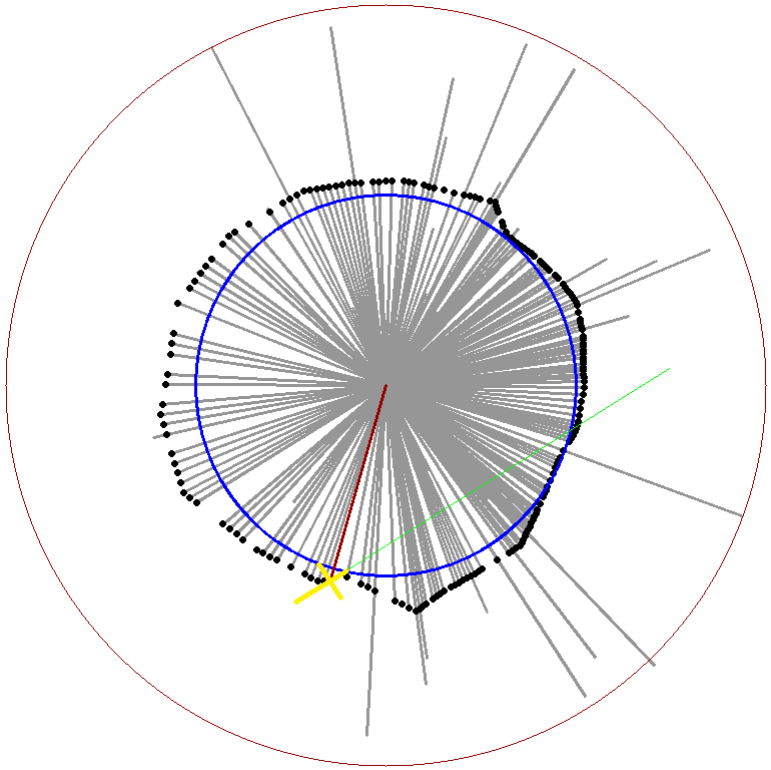
Find the lines which pass through a maximum number of intervals $[y_i]$

Simulation results

- Go strait line
- Every N measurements (N=7 -> 2 hours) perform PID control
- → use frequent measurements !

Simulation result

- 20% **outliers**
- 20% **missing data**
- 1 measurement every 20 minutes
- speed 0.3m/s
- north current 0.15m/s
- circle radius 10km



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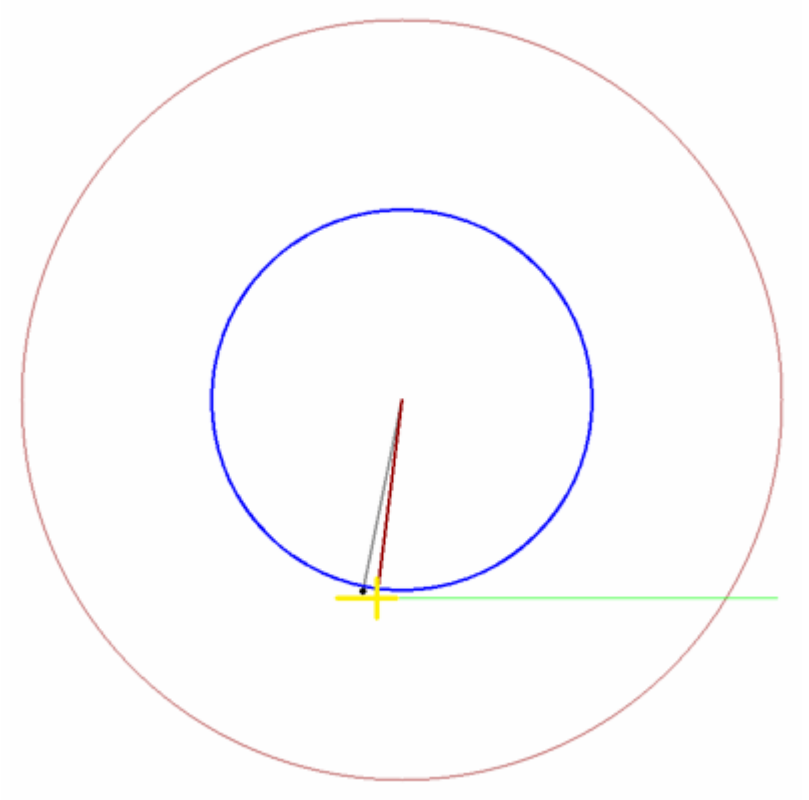
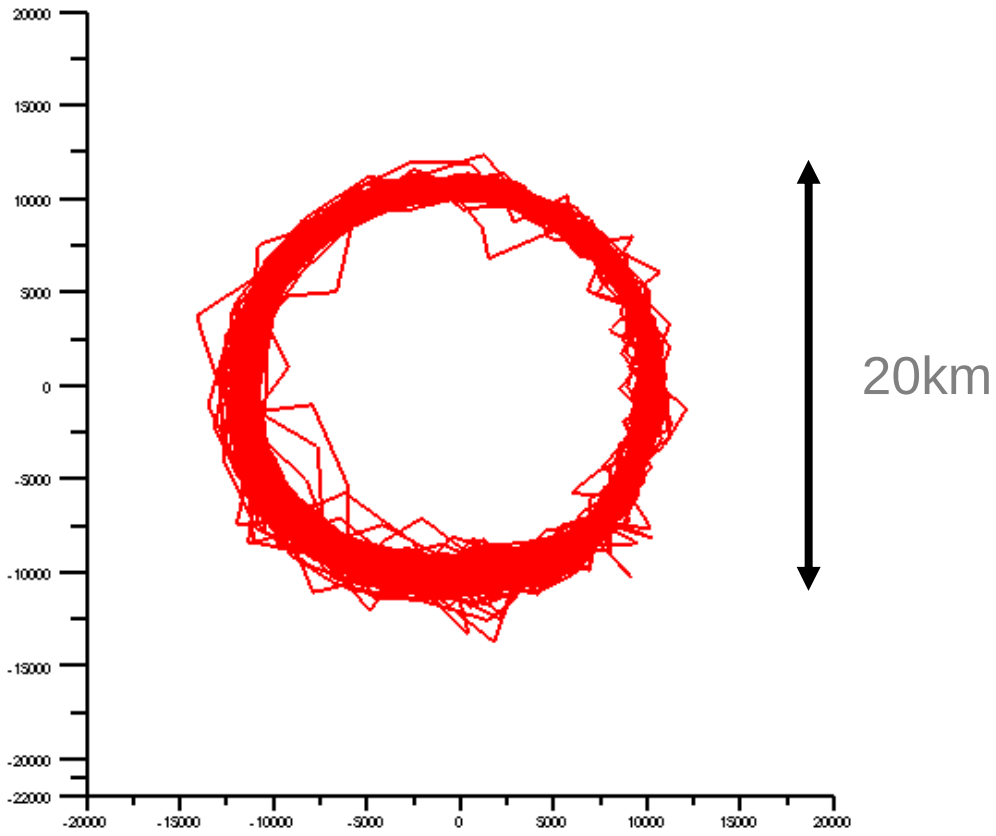
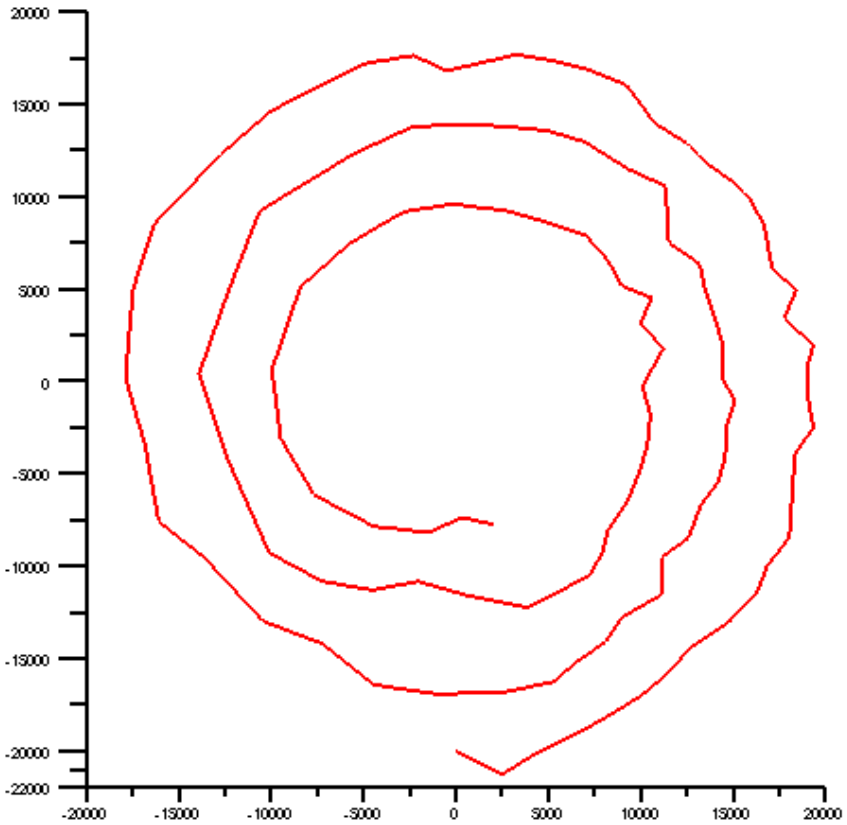
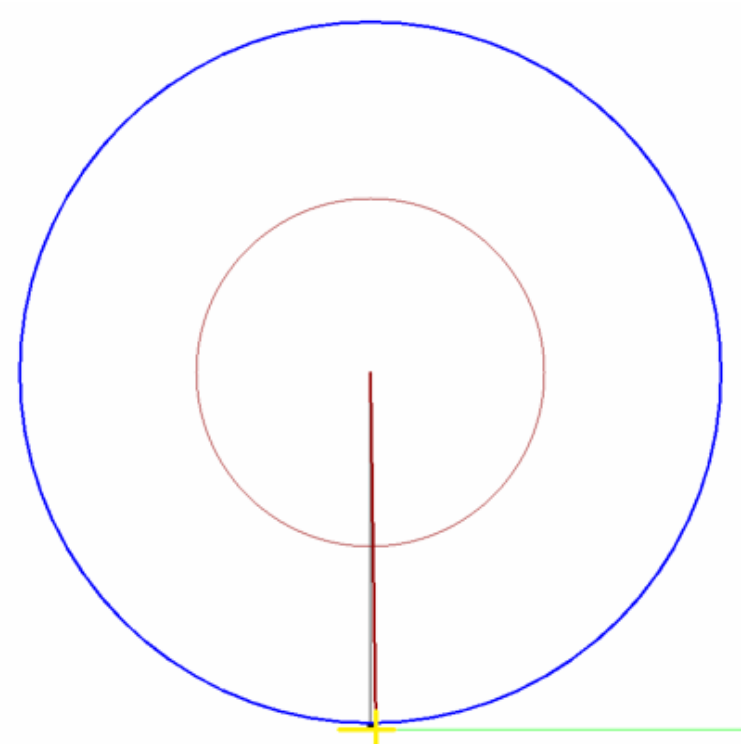


One year navigation



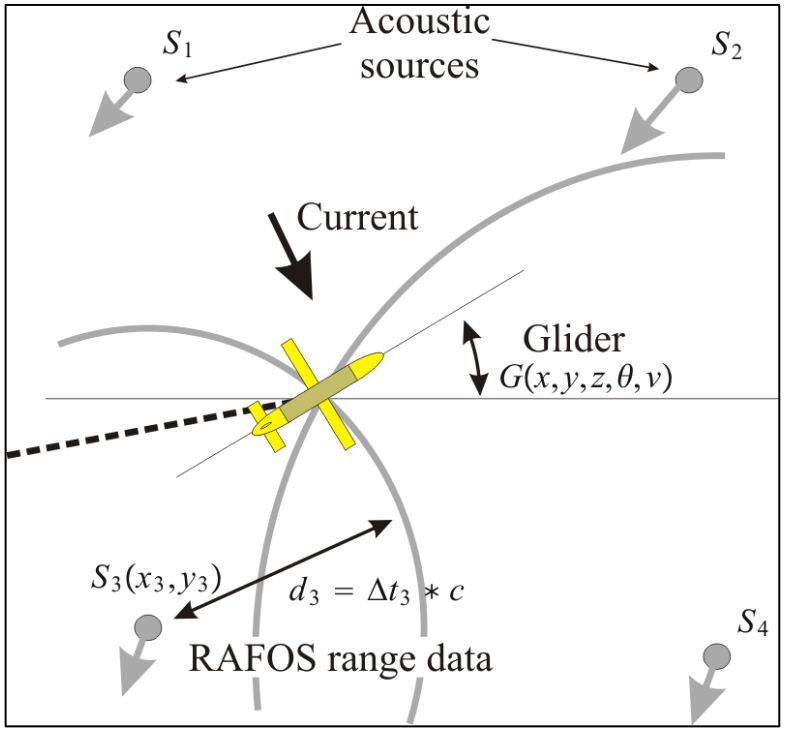
The spiral


20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-22000
-20000
-15000
-10000
-5000
0
5000
10000
15000
20000

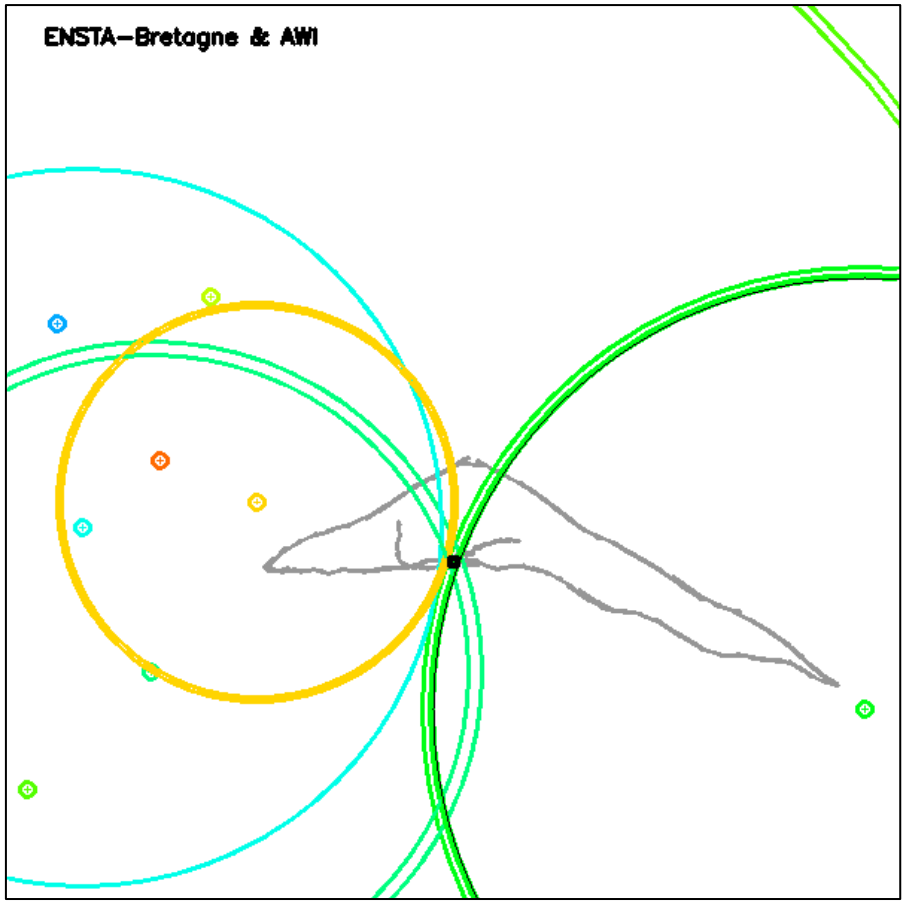


Offline longitude / latitude localization

Localization using acoustic beacons

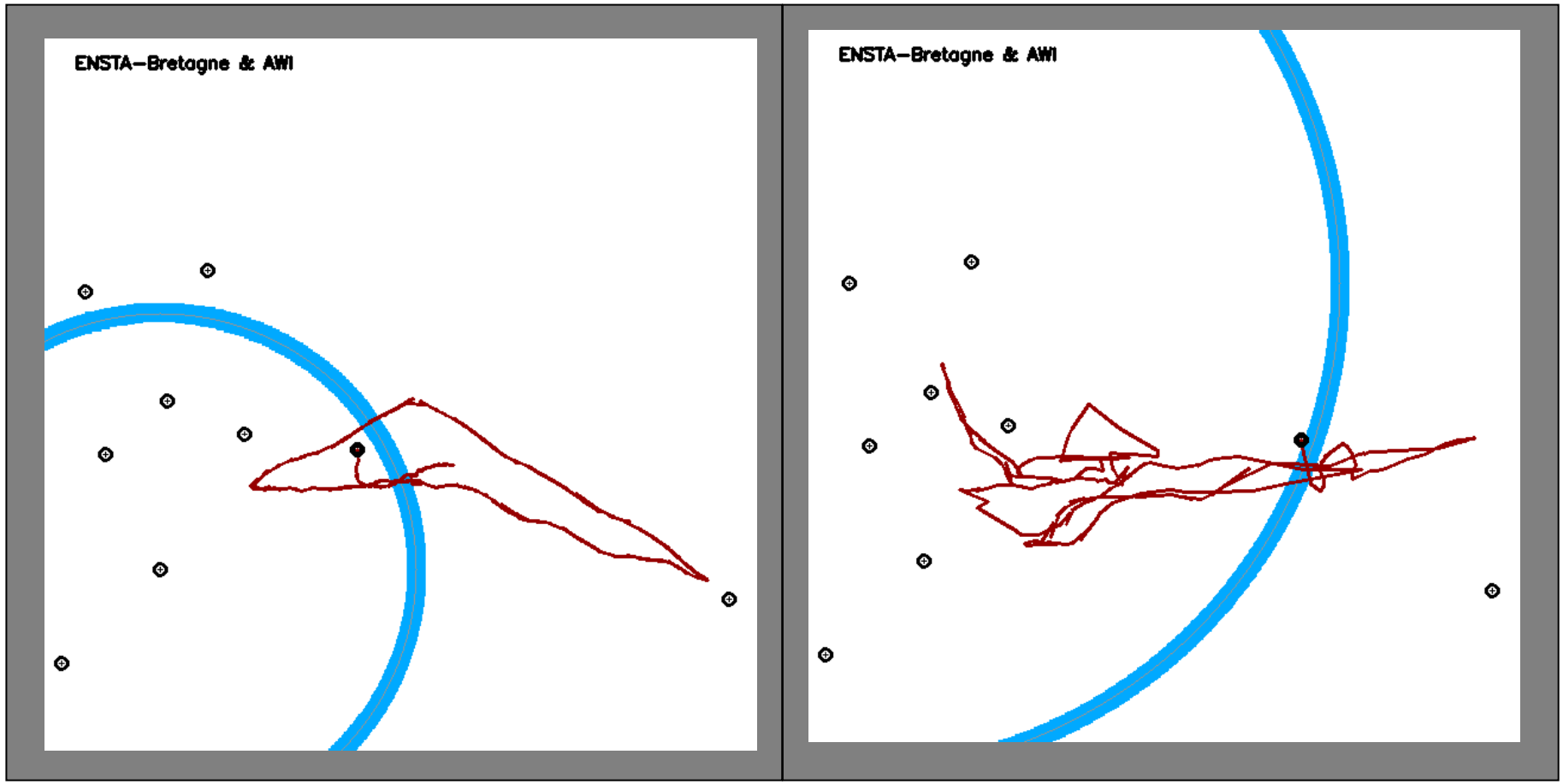


Localization by trilateration



Dataset from AWI (Allemagne) taken in the Fram strait

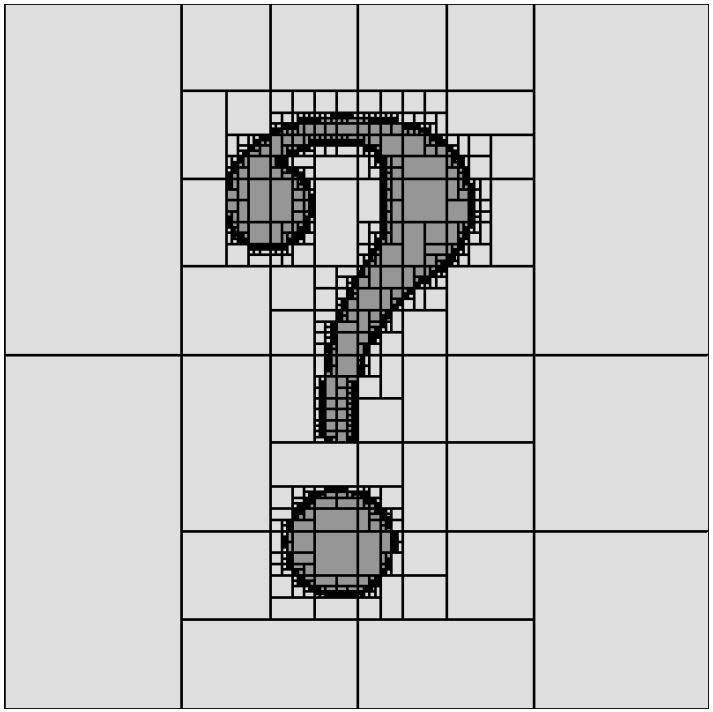
Localization using acoustic beacons



Conclusion

- A system for oceanic survey
  - A real-time method for navigation
  - A method for data geo-localization performing offline computation
- Using set membership methods allow to handle outliers and non-linear equations
- Perspectives : decrease the rate of measurements as much as possible

Questions?



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