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Pinzón: A Path Planner for Underwater Gliders

Jorge Cabrera Gámez

6th Biannual NRC-IOT Workshop on Underwater Vehicle Technology

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Credits

PINZON: A Path Planner for Underwater Gliders

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Outline

- Pinzón - The Path Planning Framework
  - ESEOO - The Regional Oceanic Model
  - Glider Motion Model
- Path Planning Algorithms
  - A*
  - CTS-A*
  - ABS CTS-A*
  - Optimization
- Conclusions and Future Works

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RU27 trans-Atlantic mission

Path Planning for gliders

PINZÓN

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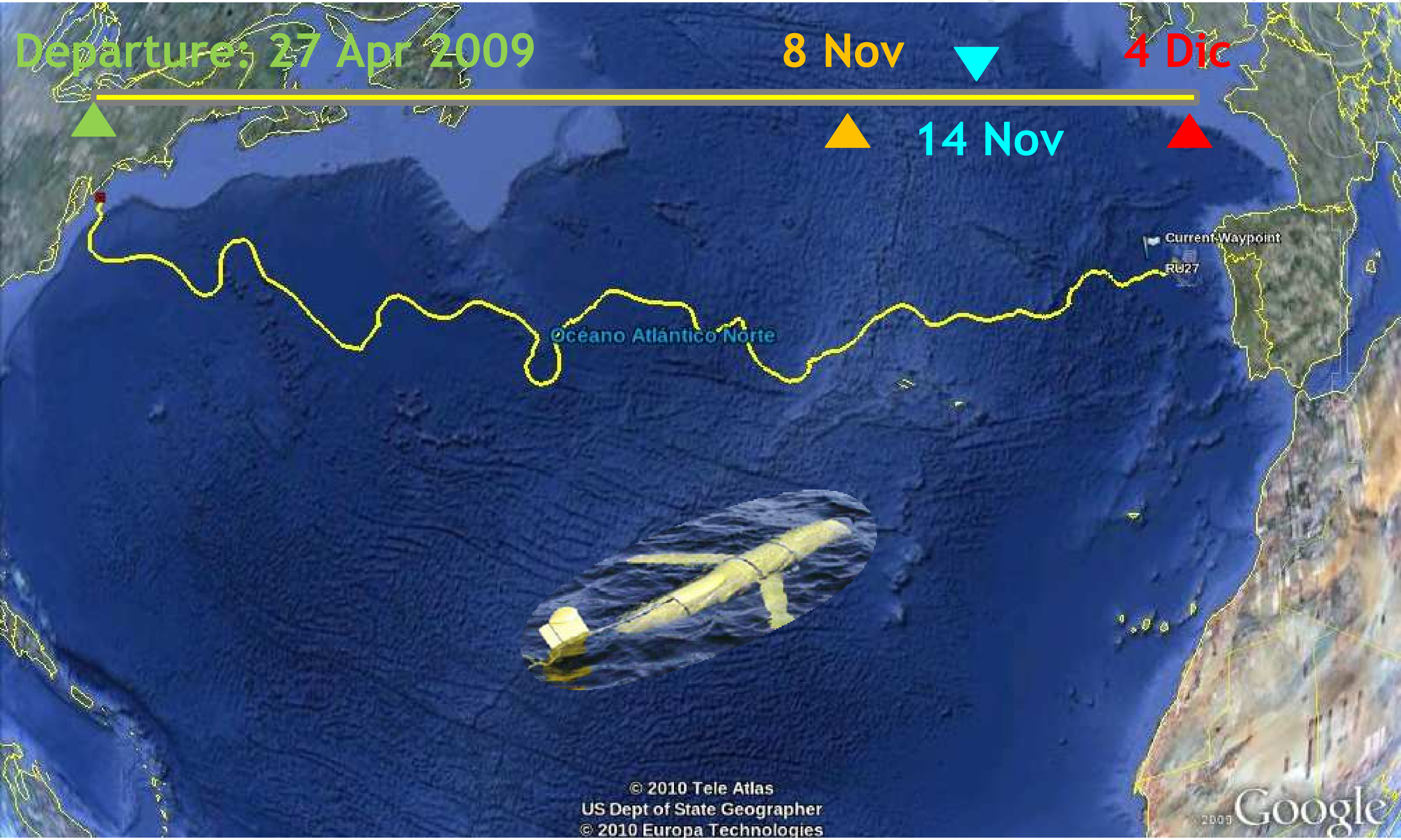

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Path Planning for gliders

- Path Planning
  - For gliders
  - Ocean currents given by Oceanic Models
- Pinzón Framework
  - Not only a path planner
  - Model Validation
    - Oceanic Model
    - Glider Motion Model
  - Ocean condition analysis

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Oceanic Models

Regional Oceanic Models. ESEOO

OCEANIC MODELS

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Oceanic Models

- Ocean Numerical Model
- Initialized with teledetection and *in situ* data
- Output
  - Ocean currents (geostrophic or total)
  - SSHA (Sea Surface Height Anomaly)
  - Temperature, Salinity (hence, Density)
- Global Oceanic Models
  - 2D day means data
  - NCOM 1/8°
  - NLOM 1/32°

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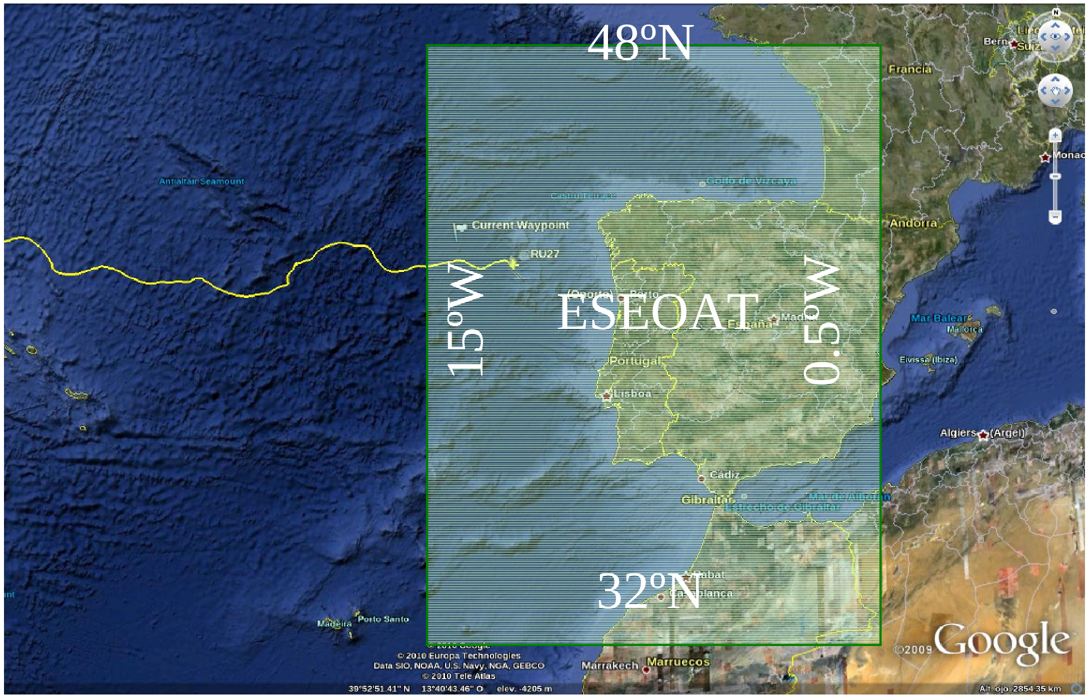
Regional Oceanic Models. ESEOO

- http://www.eseoo.org/
- POLCOMS model
- Buoys network, fresh water (river) discharges, …
- To be integrated in MyOcean system, http://www.myocean.eu.org
- Output: 2D + 1hour or 3D + day means



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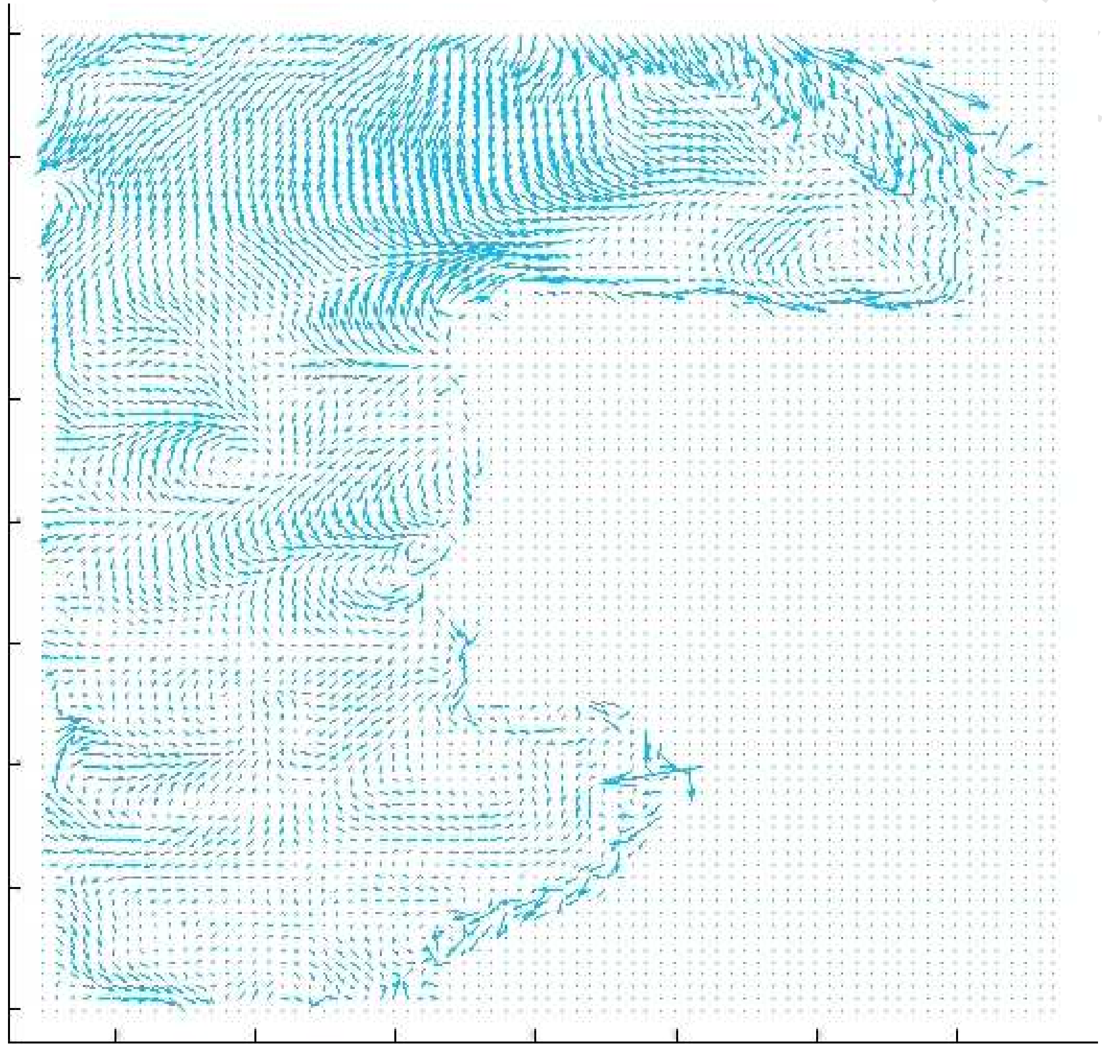
ESEOO total currents forecast, 29 Nov 2009



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Gliders

Kinematic Motion Models

Dynamic Motion Models

GLIDER MOTION MODEL

Gliders

- Autonomous Underwater Vehicle (AUV)
- Large Autonomy
  - Saw tooth pattern (dive, climb)
  - Surfacing
    - Communicate data
    - Receive bearing (next waypoint)
  - Low speed

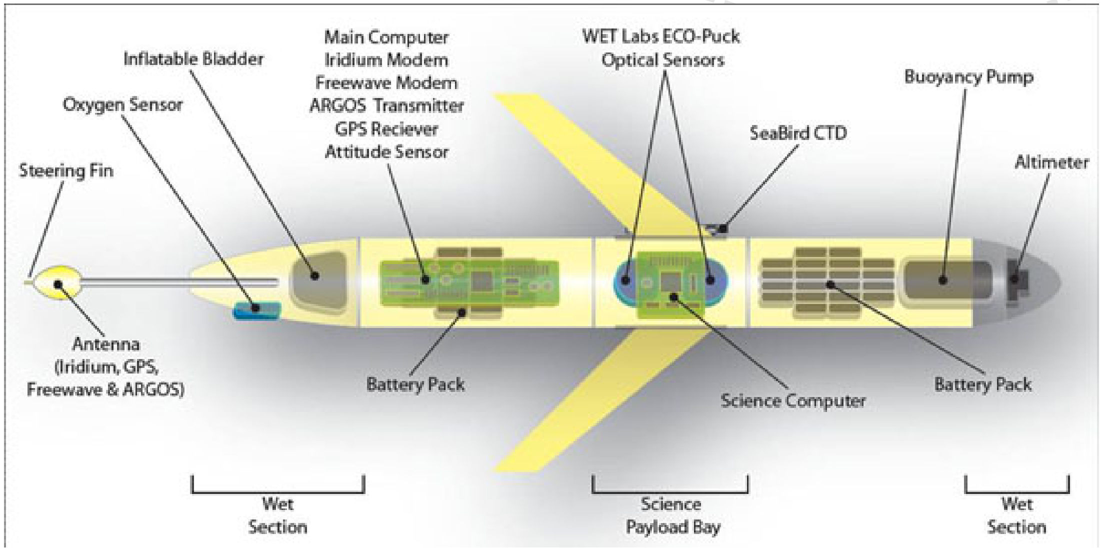

Figure courtesy of Integrated Marine Observing System (IMOS)

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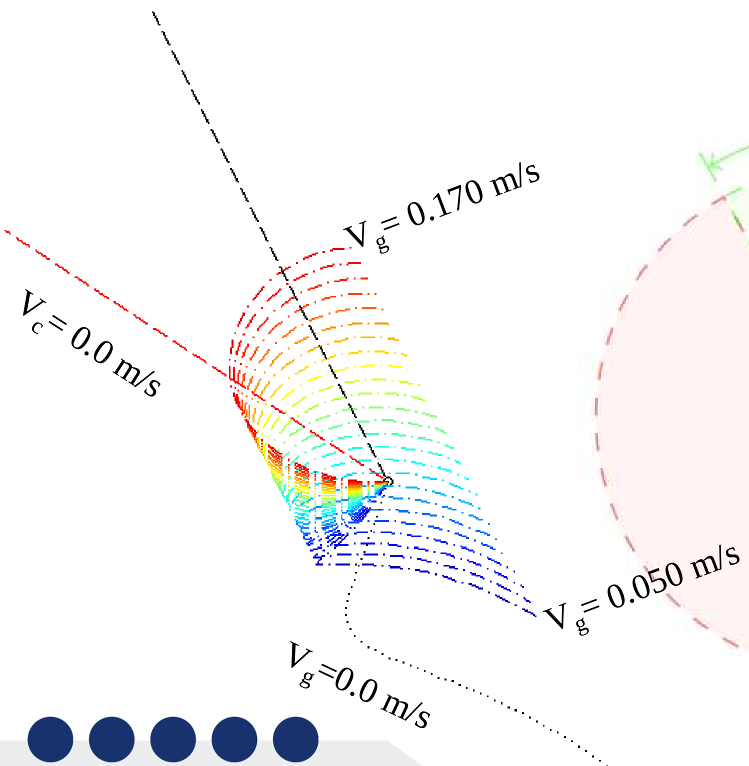
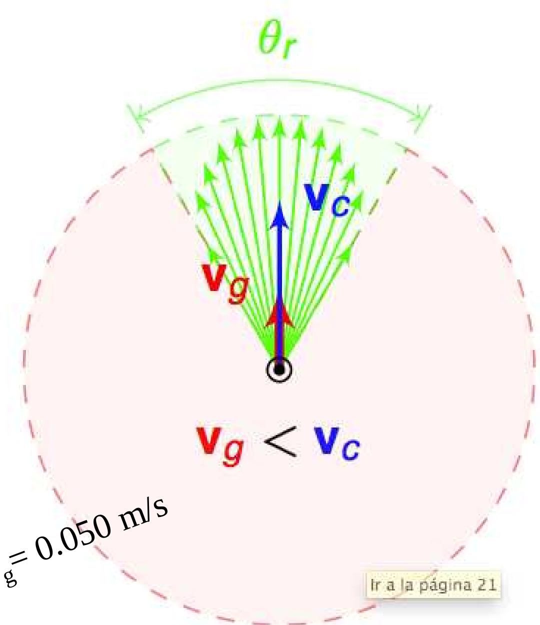
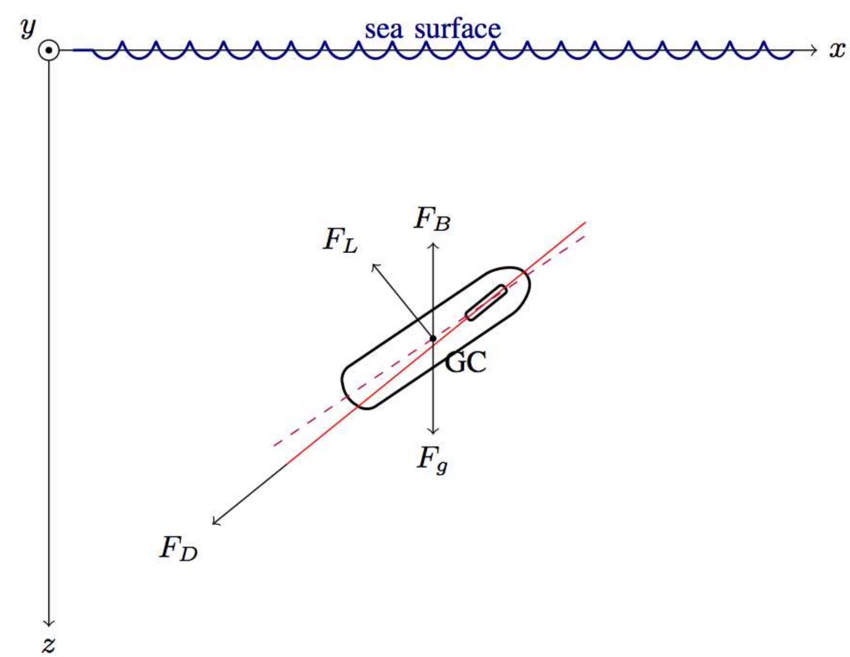
Kinematic Motion Models

- Vector composition + Trajectory integration
- Constrained motion model (feasible headings)
- Force balance (3D bouyancy model)







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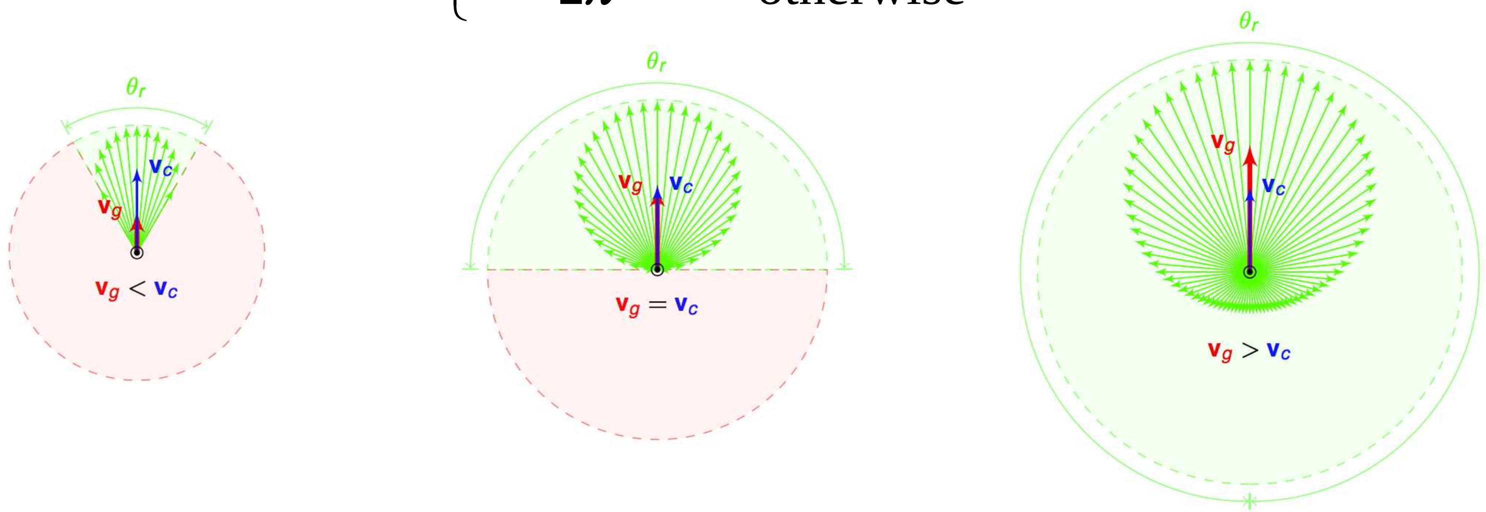
Kinematic Motion Models II

Constrained Motion Model equations:

$$\theta_g = \begin{cases} \theta_e + \arcsin s & \text{if } |s| \le 1 \\ \nexists & \text{otherwise} \end{cases} \qquad v_e = \begin{cases} v_g \sqrt{1-s^2} + v_c \cos\theta_{ec} & \text{if } |s| \le 1 \\ 0 & \text{otherwise} \end{cases} \quad \text{where} \quad \begin{aligned} s &= \frac{v_c}{v_g}\sin\theta_{ec} \\ \theta_{ec} &= \theta_e - \theta_c \end{aligned}$$

Accessibility Cone:

$$\theta_e \in [\theta_c - \frac{\theta_r}{2}, \theta_c + \frac{\theta_r}{2}] \quad \text{where} \quad \theta_r = \begin{cases} 2\arcsin\frac{1}{SR} & \text{if } SR \ge 1 \\ 2\pi & \text{otherwise} \end{cases}$$



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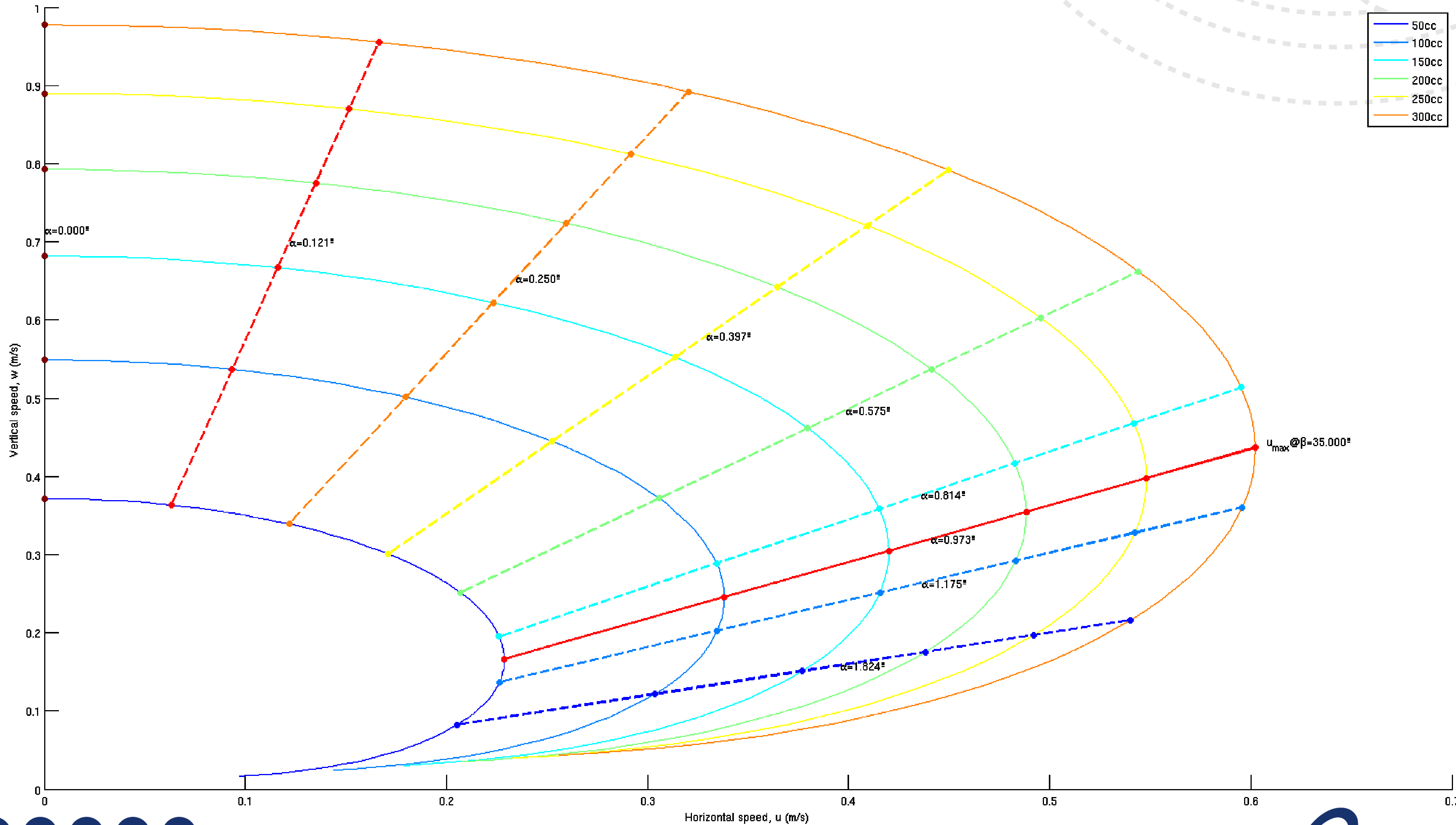
Kinematic Motion Models III



Force balance spider plot (velocity components)

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Path Planning Toolkit

OTHER CAPABILITIES

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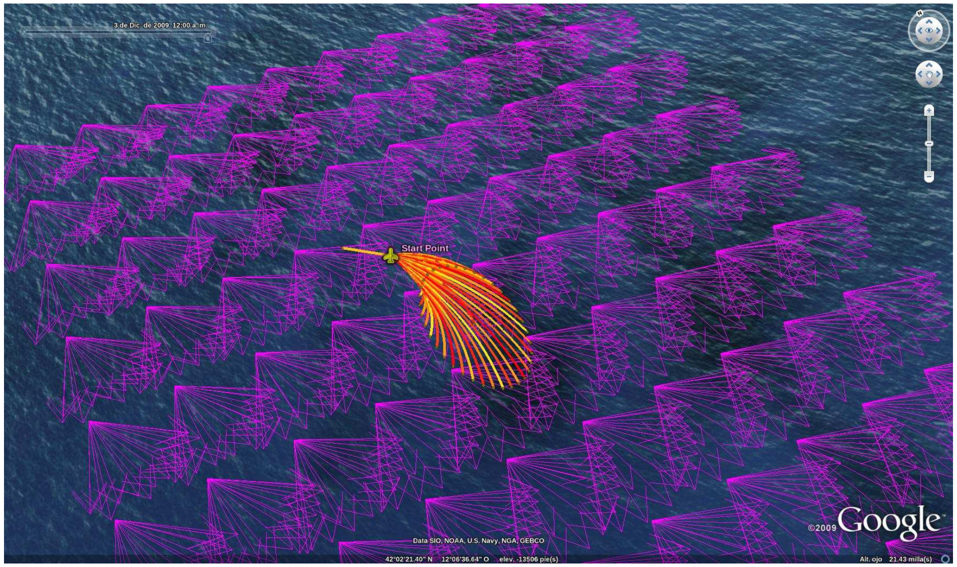
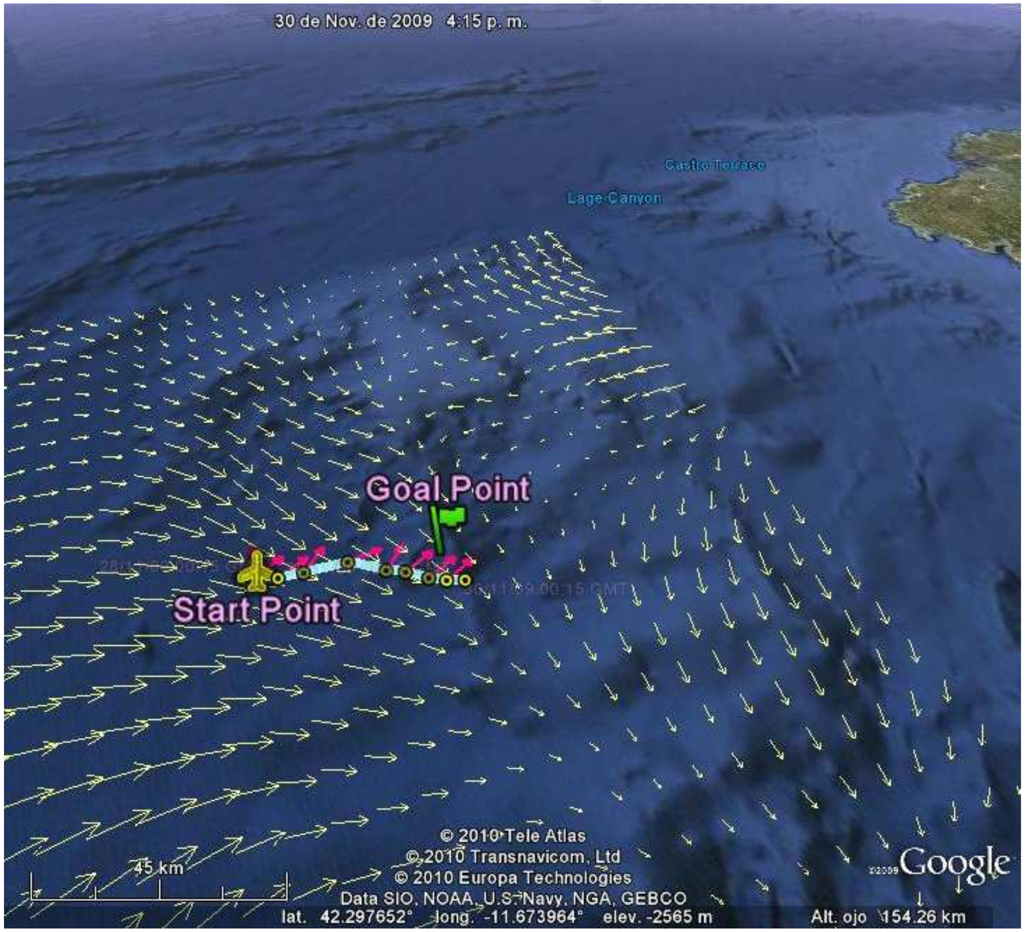
Path Planning Toolkit

- Not only Path Planning
- Data Analysis and Visualization
- Motion Models
- Path Planning for other vehicles





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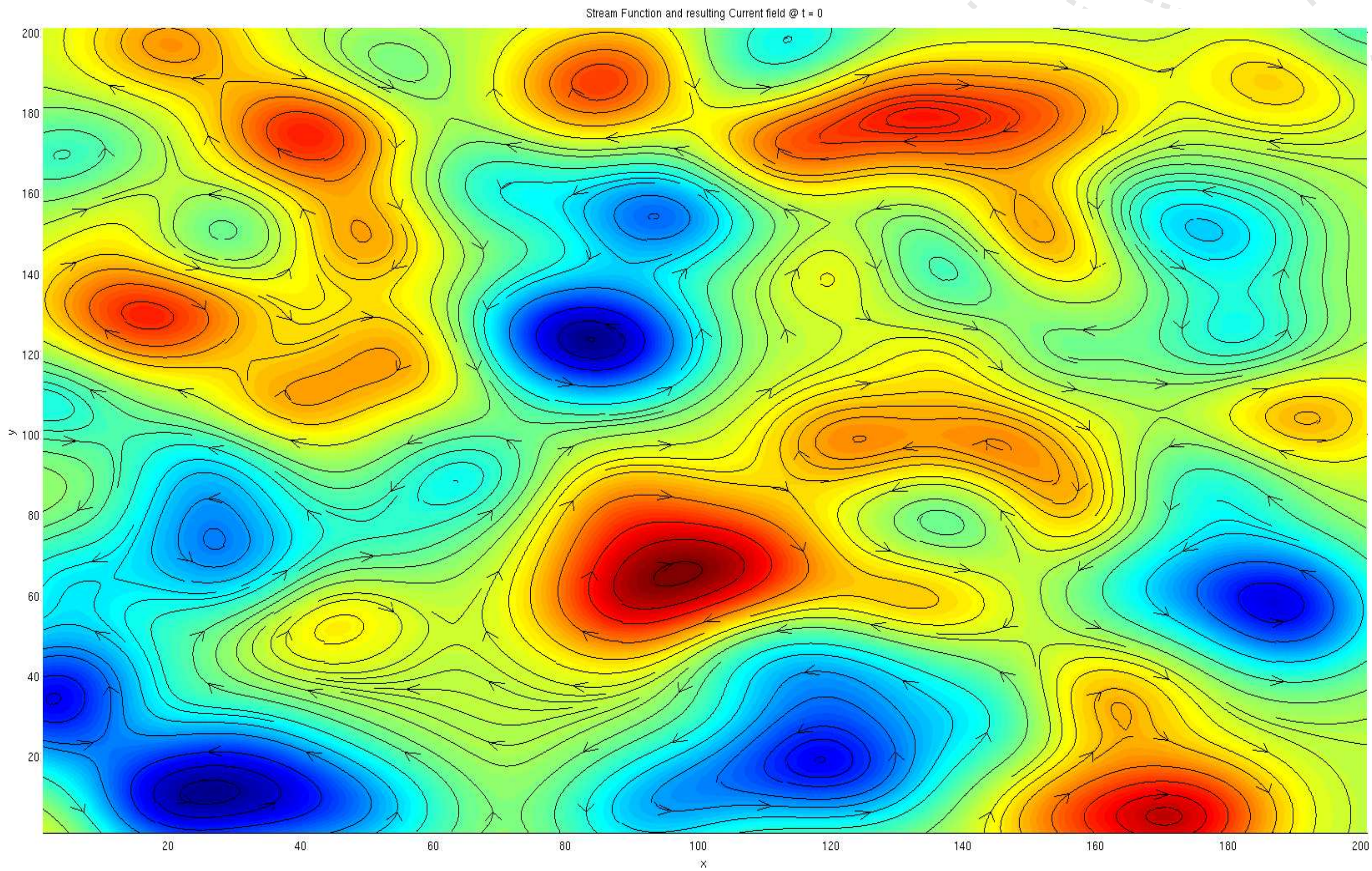
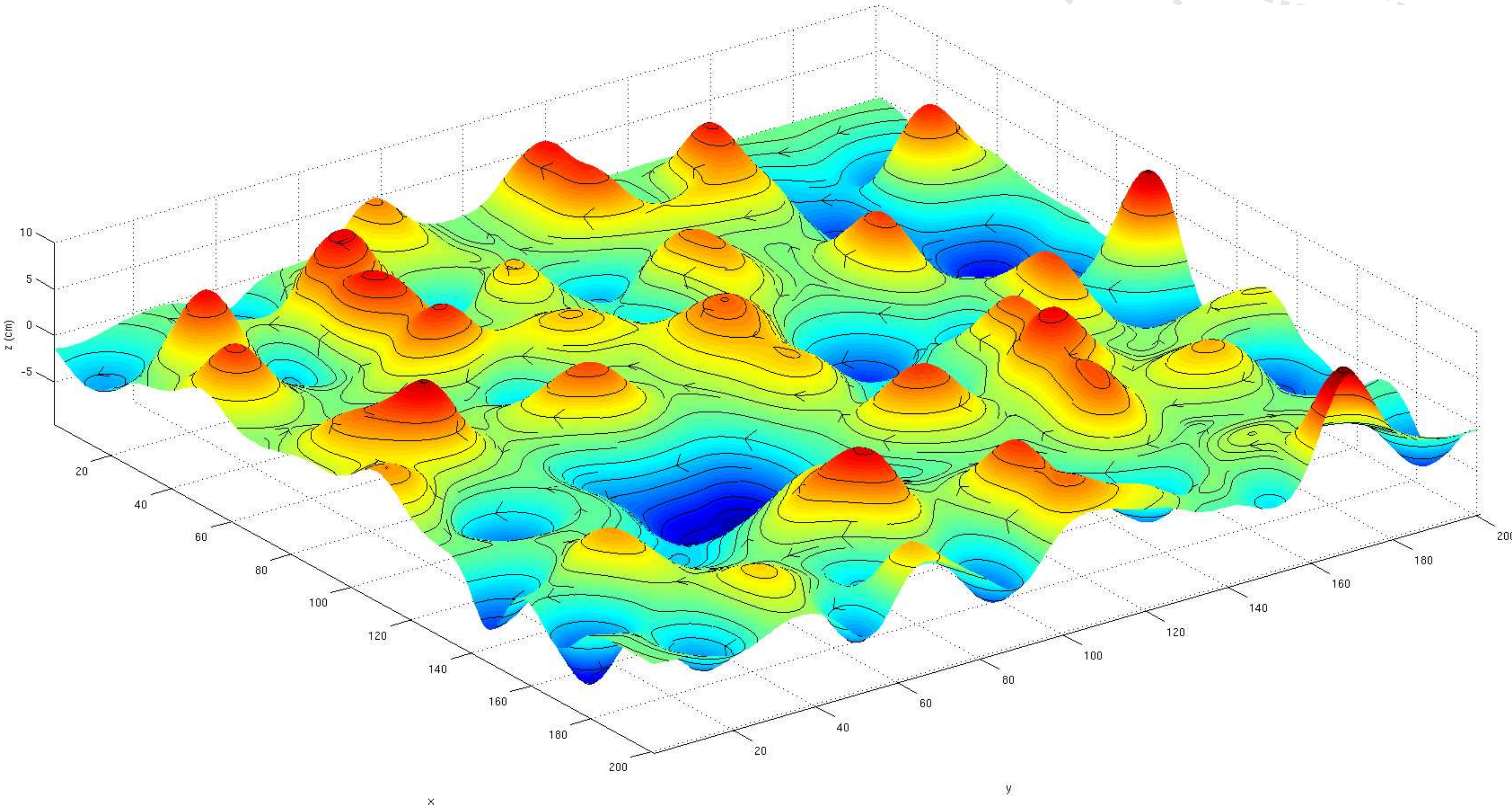
Generation of synthetic scenarios



Generation of synthetic scenarios



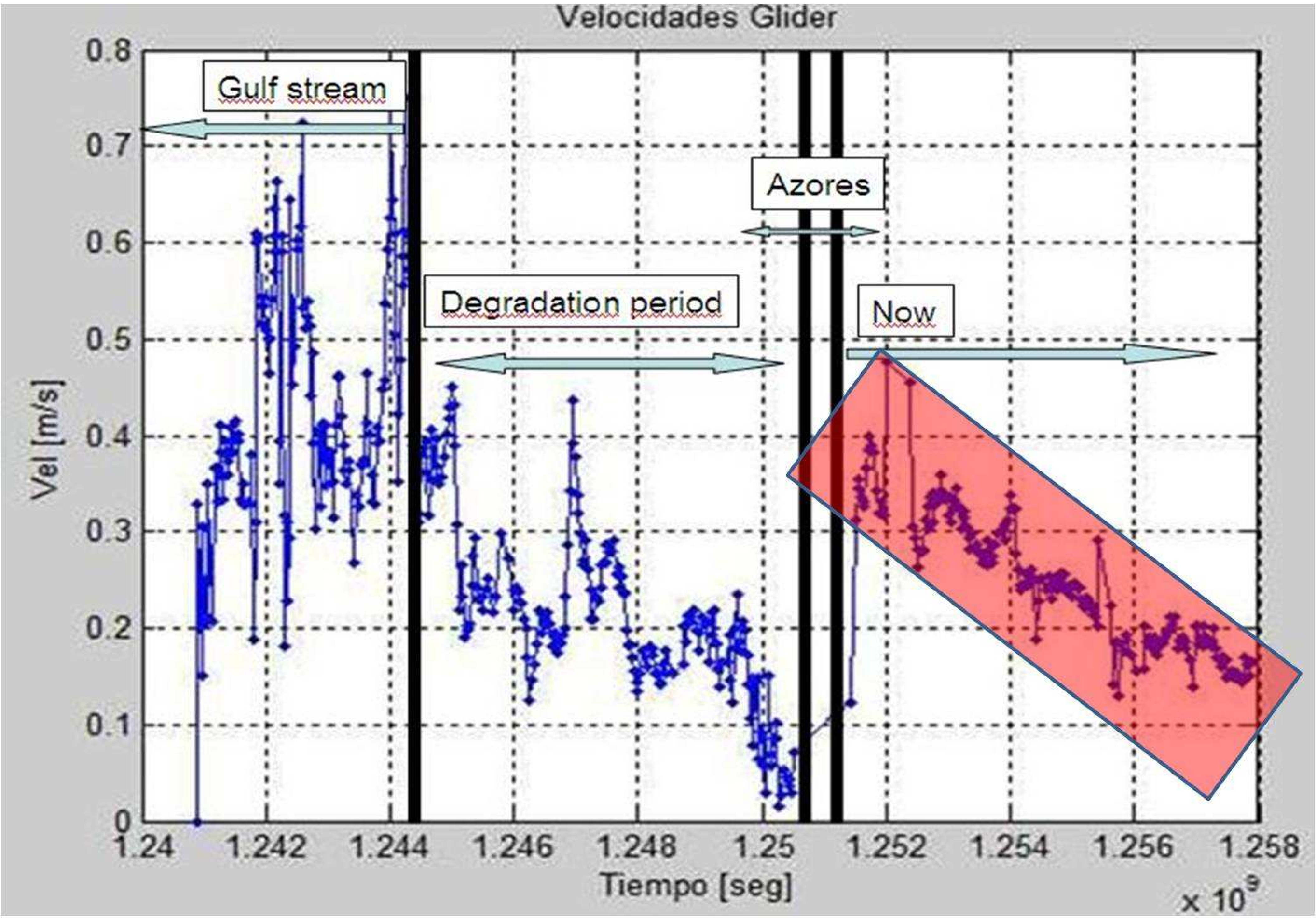


FIGURE 2. DRAGGING/BARNACLES EFFECT ON RU27 SPEEDS DURING THE 221 DAYS AT SEA.

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A*
Constant-Time Surfacing A*
Adaptive Bearing Sampling A*
Optimization
Results

PATH PLANNING ALGORITHMS

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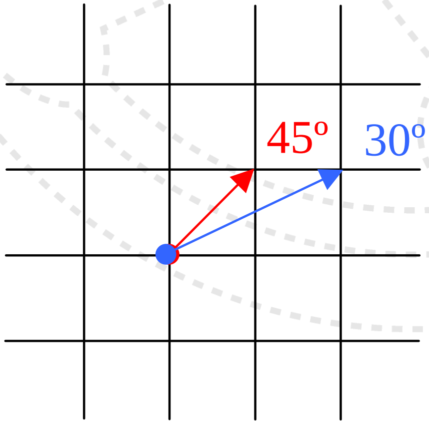
A* Algorithm



- Adaptation to the problem
  - Contrained motion model
- Limitations
  - Uniform grid discretization of the search space
  - Feasible headings: 0º, 45º, 90º, … 315º
    - Higher grid resolution does not help so much
    - Increase neighborhood, increase heading resolution, but also computational cost
  - Prone to lock (not feasible headings)
    - Particularly, for high Speed Ratios

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Algorithm: A*(n_{start}, n_{goal}) return $\mathcal{P}$

$g(n_{\text{start}}) = 0$
parent$(n_{\text{start}}) = n_{\text{start}}$ ▷ might assign null pointer $\varnothing$ too
$\mathcal{O} = \mathcal{C} = \varnothing$ ▷ empty open and closed lists
$\mathcal{O}$.**insert**$(n_{\text{start}}, g(n_{\text{start}}) + h(n_{\text{start}}))$
while $\mathcal{O} \neq \varnothing$ **do**
$n_i = \mathcal{O}$.**pop** ▷ retrieve node n_i with lowest cost
if $n_i = n_{\text{goal}}$ **then** ▷ goal n_{goal} reached
return $\mathcal{P}$ ▷ path found (extracted from parent$(\cdot)$)
end if
$\mathcal{C} = \mathcal{C} \cup \{n\}$
for all $n_{i+1} \in$ **successors**(n_i) **do**
if $n_{i+1} \notin \mathcal{C}$ **then**
if $n_{i+1} \notin \mathcal{O}$ **then**
$g(n_{i+1}) = \infty$
parent$(n_{i+1}) = \varnothing$
end if
if $g(n_i) + c(n_i, n_{i+1}) < g(n_{i+1})$ **then**
$g(n_{i+1}) = g(n_i) + c(n_i, n_{i+1})$ ▷ update
parent$(n_{i+1}) = n_i$
if $n_{i+1} \in \mathcal{O}$ **then**
$\mathcal{O}$.**remove**(n_{i+1})
end if
$\mathcal{O}$.**insert**$(n_{i+1}, g(n_{i+1}) + h(n_{i+1}))$
end if
end if
end for
end while
return $\varnothing$ ▷ no path found

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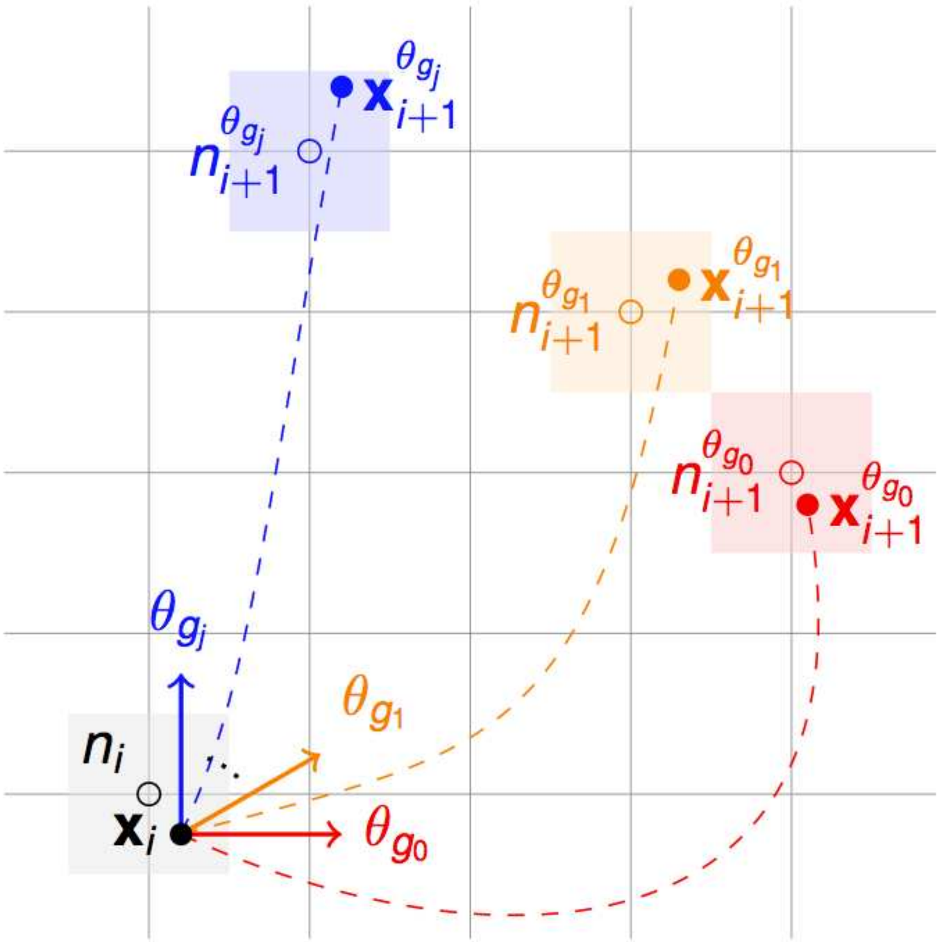
Constant-Time Surfacing A*

- Constant-Time Surfacings
- Bearing set
- Trajectory integration
- Continuous locations



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CTS-A* successors generation

Algorithm: successors$(n,\ k,\ t_s)$ **return** $\mathcal{N}$

$\mathcal{N} = \varnothing$
for all 1 to k **do**
$\theta_g \sim [0, 2\pi)$ ▷ sample bearing
$\mathbf{x}_{\theta_g} = \mathbf{trajectory}(t_s, dt, \mathbf{v}_g(\theta_g), \mathbf{v}_c(\mathbf{x}), \mathbf{x}_n)$
$m = \mathbf{NN}(\mathbf{x})$ ▷ Nearest Neighbor node m to $\mathbf{x}$
if $m \notin \mathcal{C}$ **then** ▷ m cannot be in the closed list $\mathcal{C}$
if m already labelled **then** ▷ labelled with $\mathbf{x}_m$
if $c(\mathbf{x}_{\theta_g}) < c(\mathbf{x}_m)$ **then** ▷ lower cost
label m with $\mathbf{x}_{\theta_g}$
else if $c(\mathbf{x}_{\theta_g}) = c(\mathbf{x}_m)$ **then** ▷ equal cost, but
if $d(\mathbf{x}_{\theta_g}, m) < d(\mathbf{x}_m, m)$ **then** ▷ closer
label m with $\mathbf{x}_{\theta_g}$
end if
end if
else
label m with $\mathbf{x}_{\theta_g}$
end if
$\mathcal{N} = \mathcal{N} \cup \{m\}$ ▷ add m to successors list $\mathcal{N}$
end if
end for
return $\mathcal{N}$

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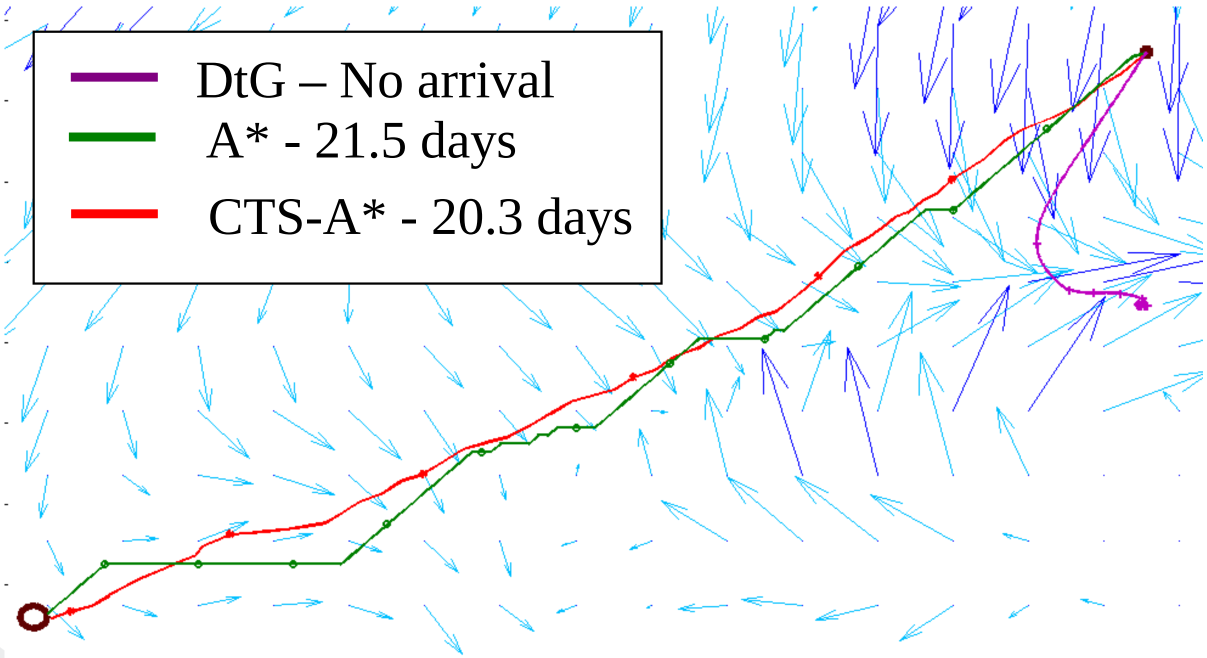
A* vs. CTS-A*

Mean number of days to reach the goal

Methods	All cases	Selected
Direct to goal	35% No arrival	18.0
A*	18.9	17.1
CTS-A*	18.7	16.9



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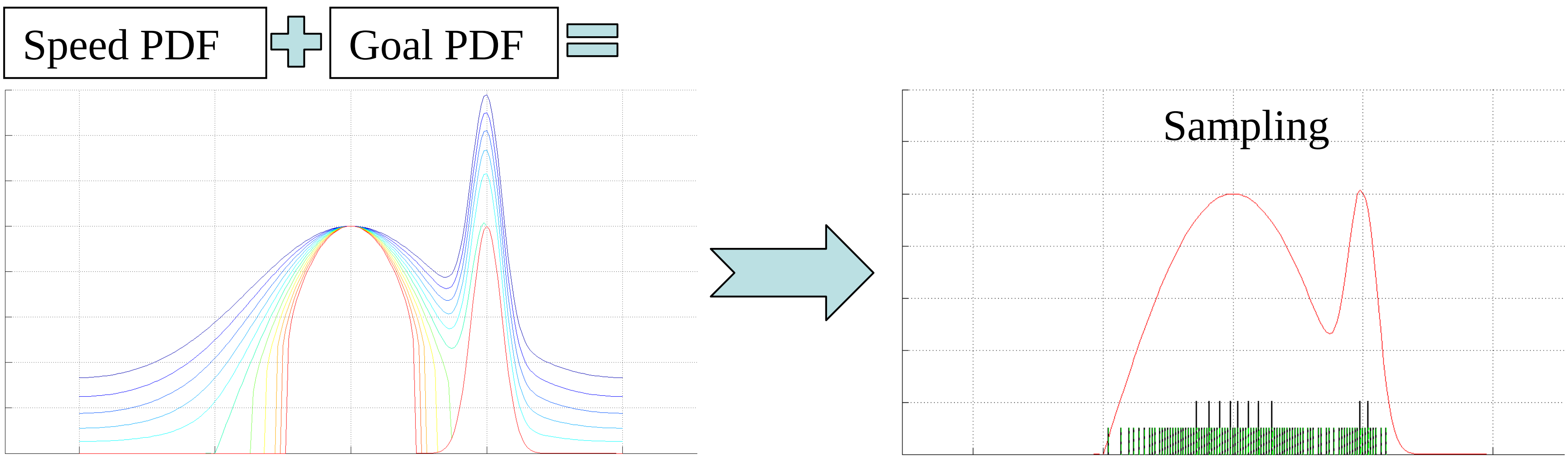
Adaptive Bearing Sampling

- Adaptive Bearing Sampling
  - Effective speed PDF distribution
  - Direction to the goal PDF distribution
  - Sequential Importance Sampling (SIS)



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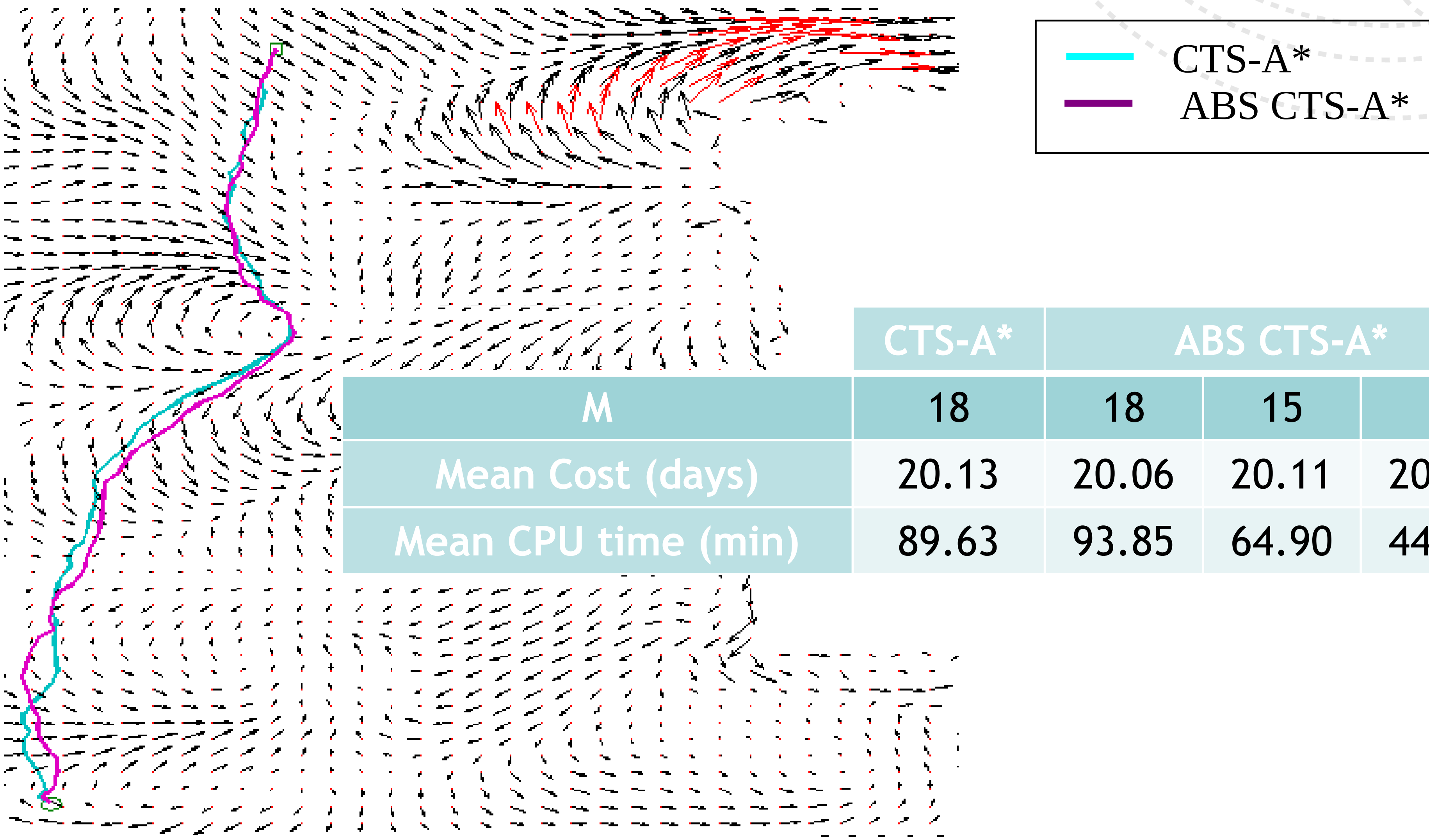
CTS-A* vs. ABS CTS-A*



	CTS-A*	ABS CTS-A*		
M	18	18	15	8
Mean Cost (days)	20.13	20.06	20.11	20.15
Mean CPU time (min)	89.63	93.85	64.90	44.39

Path planning with optimization techniques

Classical Levenberg-Marquardt, sequential quadratic programming or Quasi-Newton methods have been tested.

Objective function: optimize over a predefined number of bearings for …

Two different scenarios:

- **Fixed-time situations**: maximixation of distance traveled for a given period.
- **Fixed-time situations**: Minimize the time required to reach a target area.

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Path planning situations

- **Fixed-time problem** → Time varying scenario
  - Maximization of the distance traveled towards a distant way-point in a given period.
  - Short-term range planning, with a maximal duration of 3 days and a typical trajectory length below 100 Km.
  - Current models of high frequency predictions are used, as is the case of Regional Ocean Models (ROMs) with hourly outputs and forecasts to D+3.

- **Fixed-distance problem** → Quasi-stationary scenario
  - Minimization of the time required to reach a target area.
  - Long term or mission range planning, with durations from one to several weeks and trajectories durations above 200 Km.
  - Current model predictions are not available, and the planning must rely on historic mean current maps.

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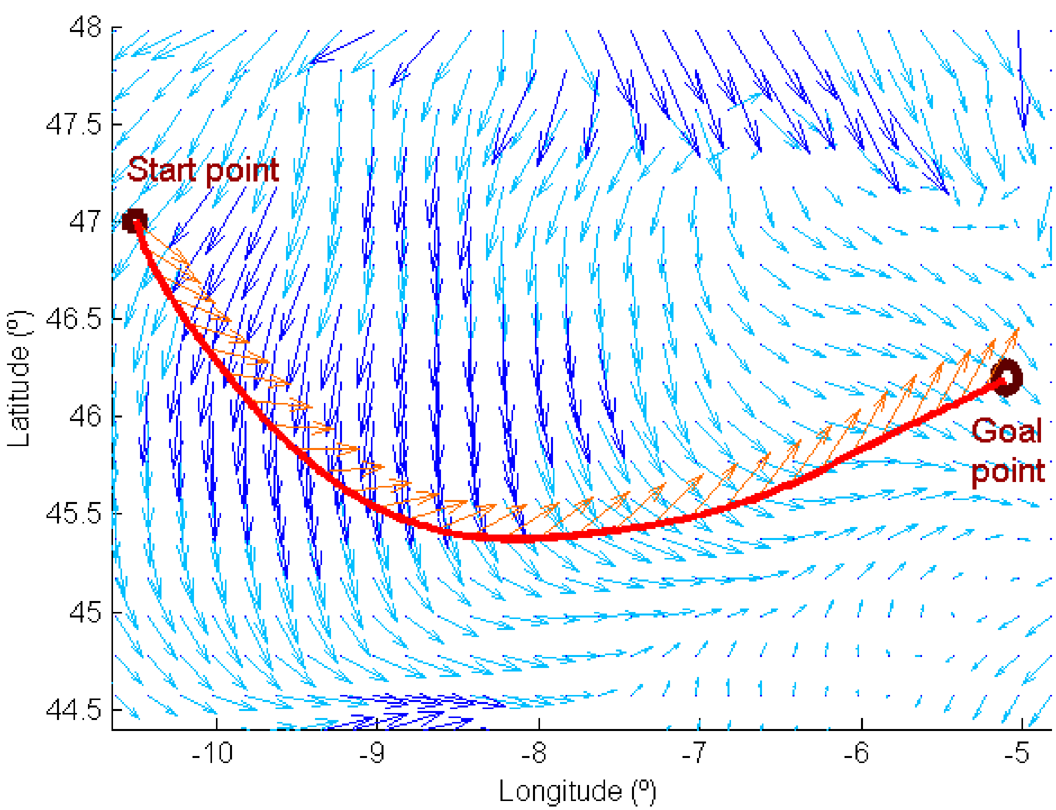
Example of path planning with optimization when the distance is fixed

Glider speed = 0.4 m/s
Distance: 423.22 km
Path time: 10.5 days
Computational cost: 24.9 secs



Glider trajectory

Bearings estimated in each surfacing

Ocean currents

Ocean currents that exceed glider velocity

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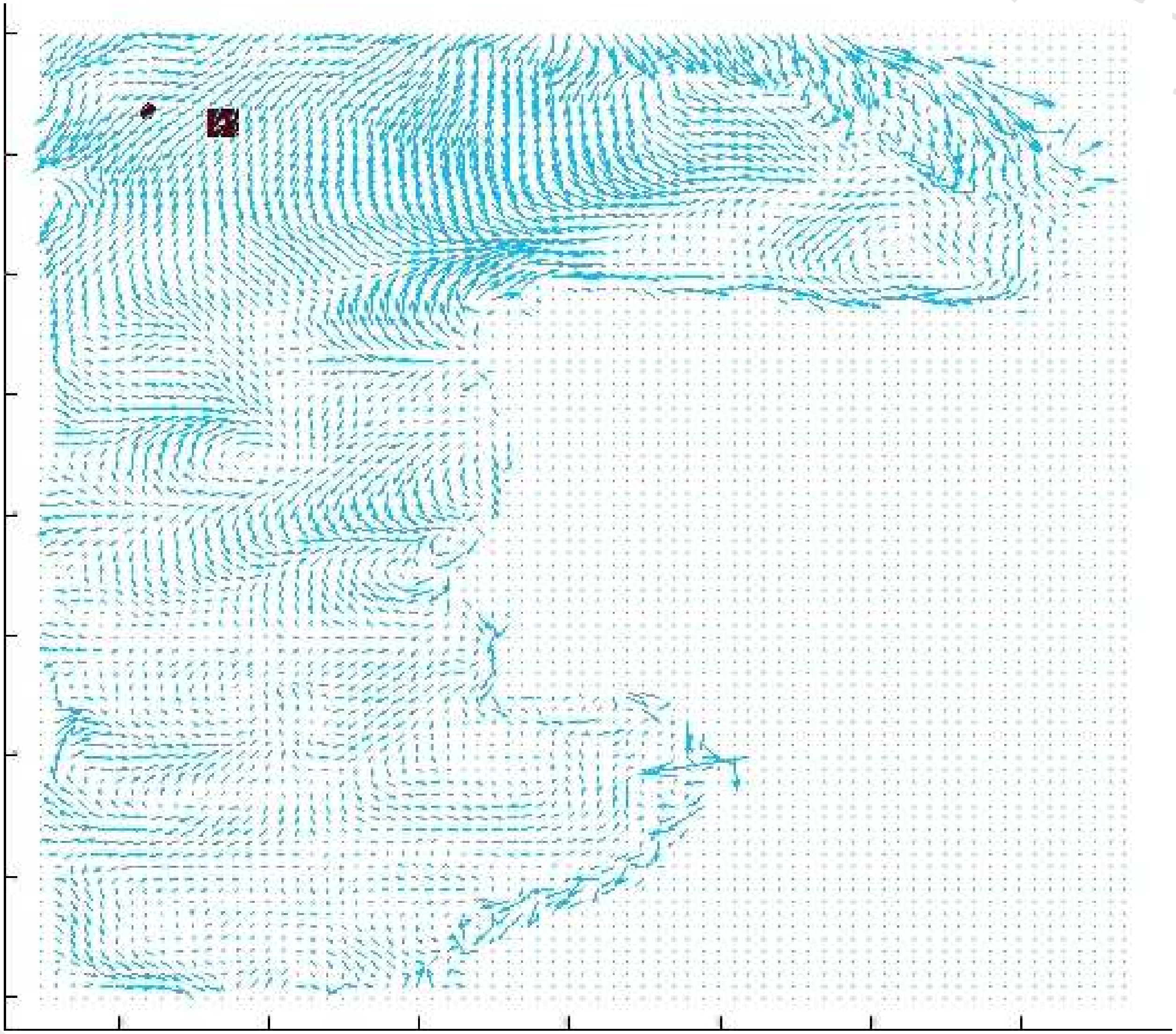
Fixed-time example (I)

ESEEO-AT Forecast



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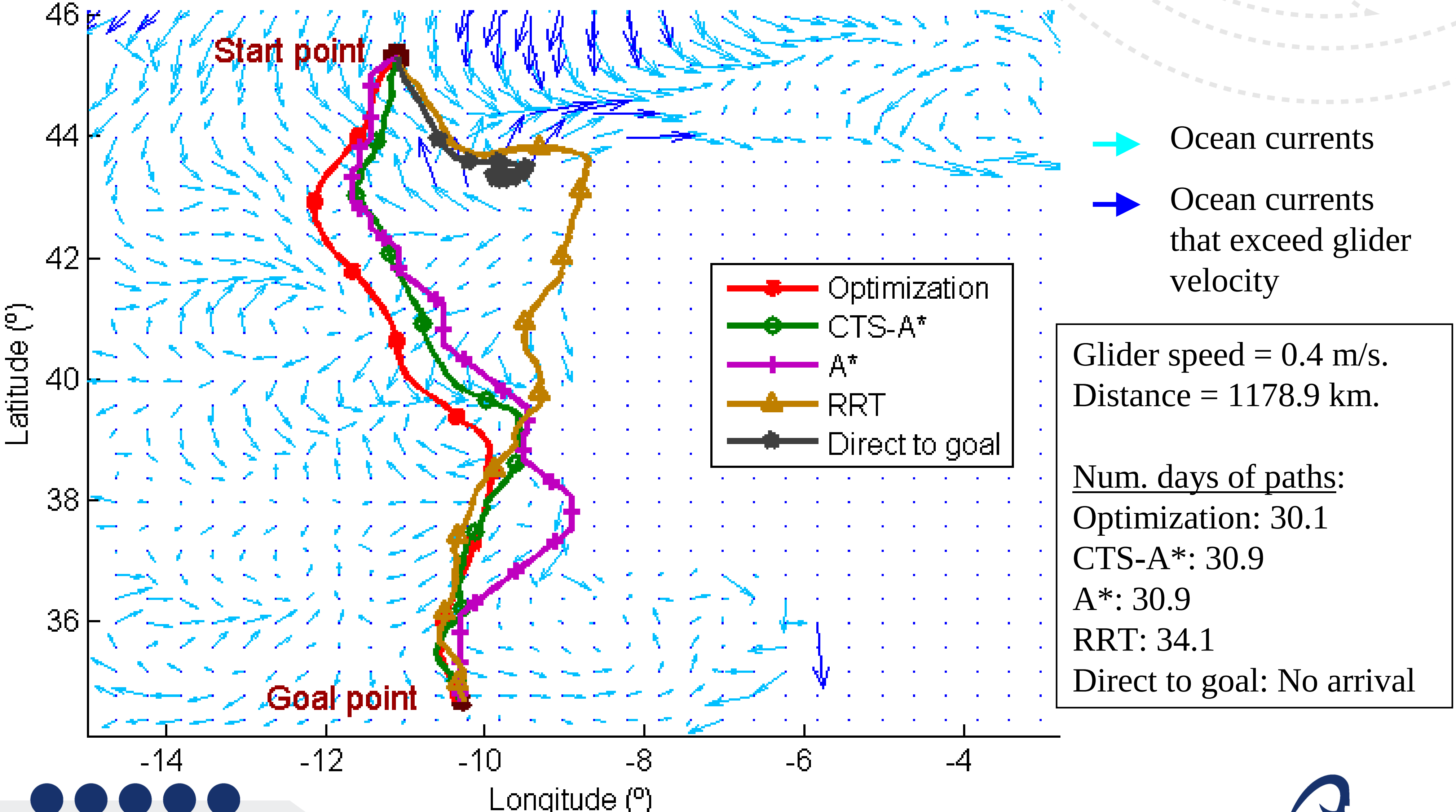
Comparative of trajectories



Glider speed = 0.4 m/s.
Distance = 1178.9 km.

Num. days of paths:
Optimization: 30.1
CTS-A*: 30.9
A*: 30.9
RRT: 34.1
Direct to goal: No arrival

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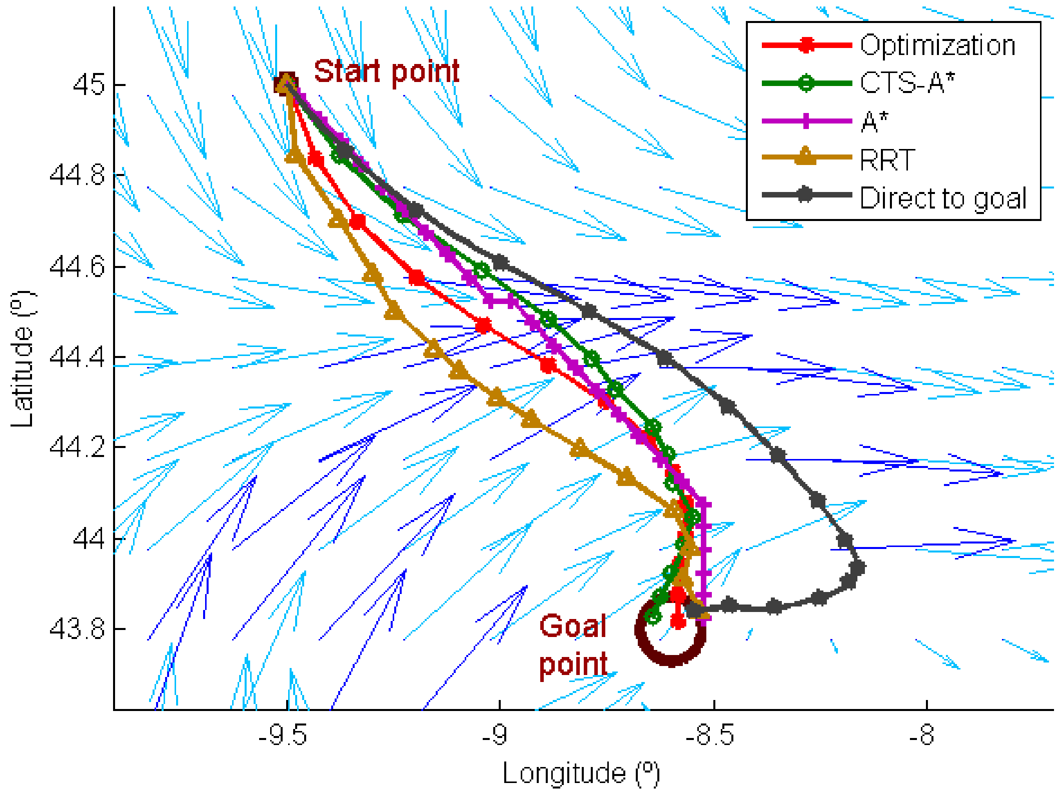
Comparative of trajectories



Glider speed = 0.4 m/s.
Distance = 151.4 km.

Num. days of paths:
Optimization: 4.0
CTS-A*: 4.3
A*: 4.5
RRT: 4.6
Direct to goal: 4.9

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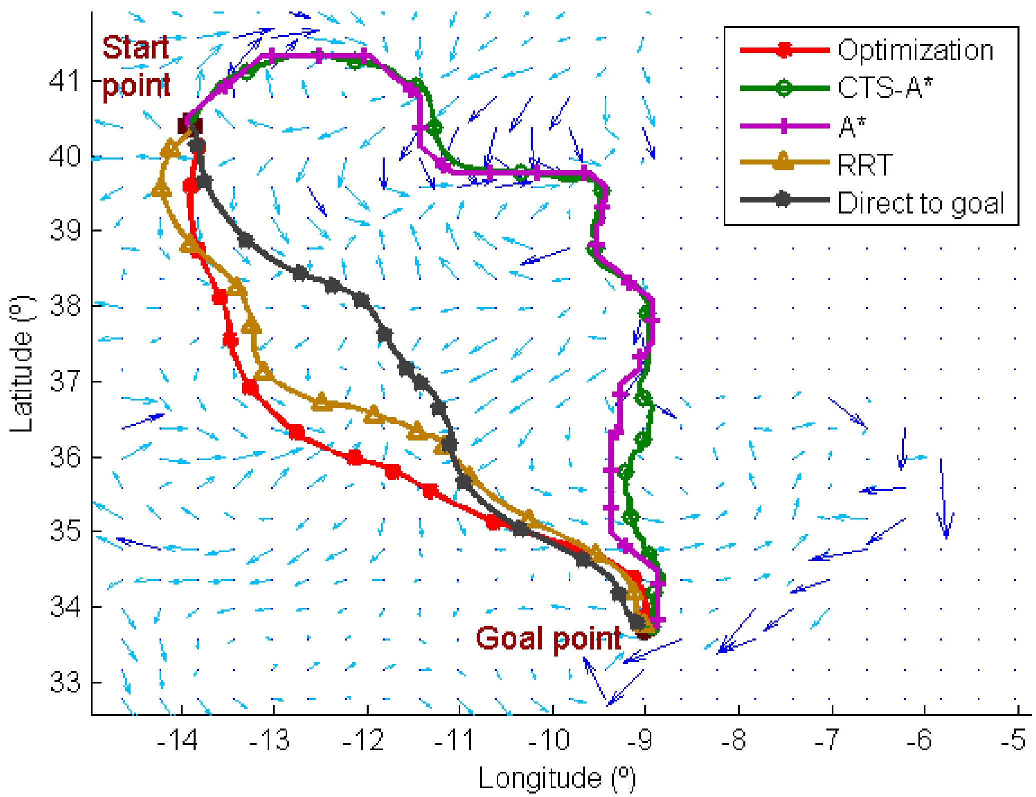
Comparative of trajectories



Ocean currents

Ocean currents that exceed glider velocity

Glider speed = 0.2 m/s.
Distance = 861.9 km.

Num. days of paths:
Optimization: 47.4
CTS-A*: 50.0
A*: 49.6
RRT: 49.7
Direct to goal: 53.8

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Other Approaches (I)

Mean of number of days to reach the goal

Methods	Mean of all cases	Mean of selected cases	Optimization mean improvemen
Direct to goal	No arrival in the 35% of cases	18.0	9.1%
RRT	No arrival in the 5% of cases	17.7	5.6%
A*	18.9	17.1	4.3%
CTS-A*	18.7	16.9	2.7%
Optimization	18.4	16.7	-

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Other Approaches (II)

Mean of computational costs (in minutes)

Method	Time
Direct to goal	<1
RRT	<1
A*	9.5
CTS-A*	77.1
Optimization	3.5

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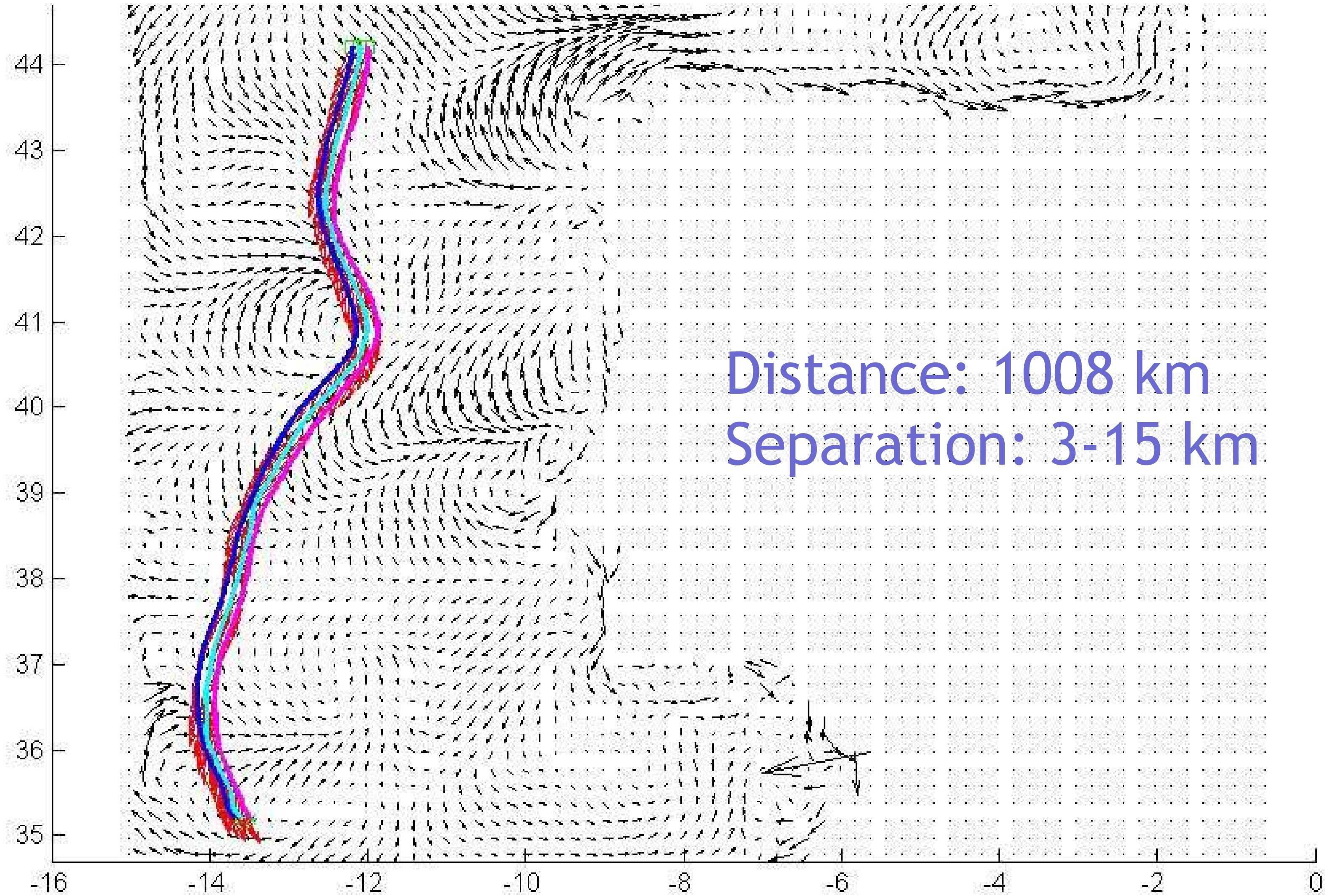
Path planning for three vehicles using optimization



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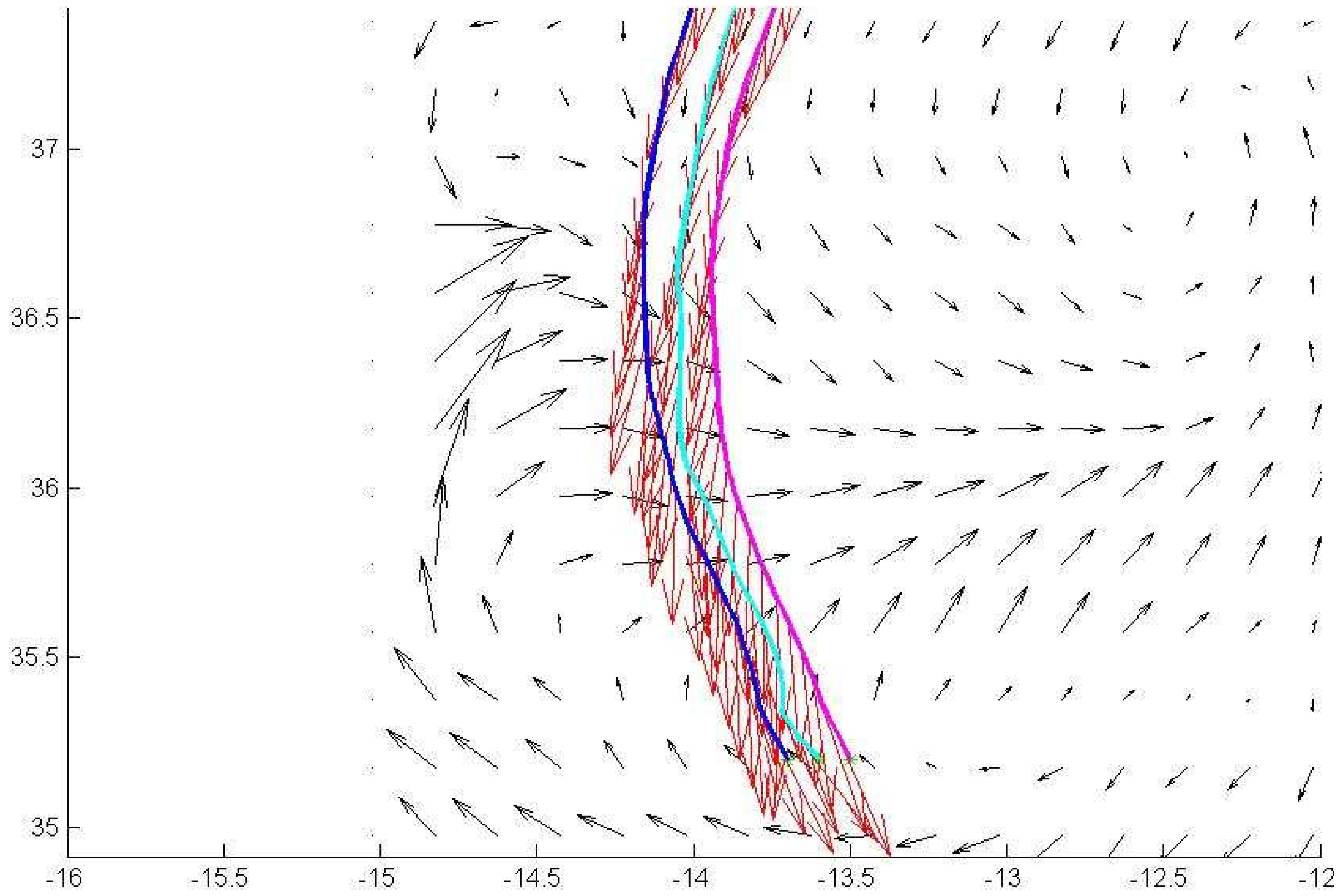
Path planning for three vehicles using optimization



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Conclusions and Future Works

CONCLUSIONS

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Conclusions

We have shown the evolution of Pinzon and the results achieved so far with several algorithms underwater glider path planning (A*, CTS-A*, βCTS-A*, RRT, Optimization).

Optimization method offers promising results and has revealed superior.

With this method we may address to different scenarios:

- The Fixed-time sc.(maximum distance in a given time)
- The Fixed-distance sc.(minimum time for given distance)

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Future Works

- 3D Path Planning
  - 3D Oceanic Model
  - Accurate vehicle model
- Multi-vehicle path planning
- Constraints

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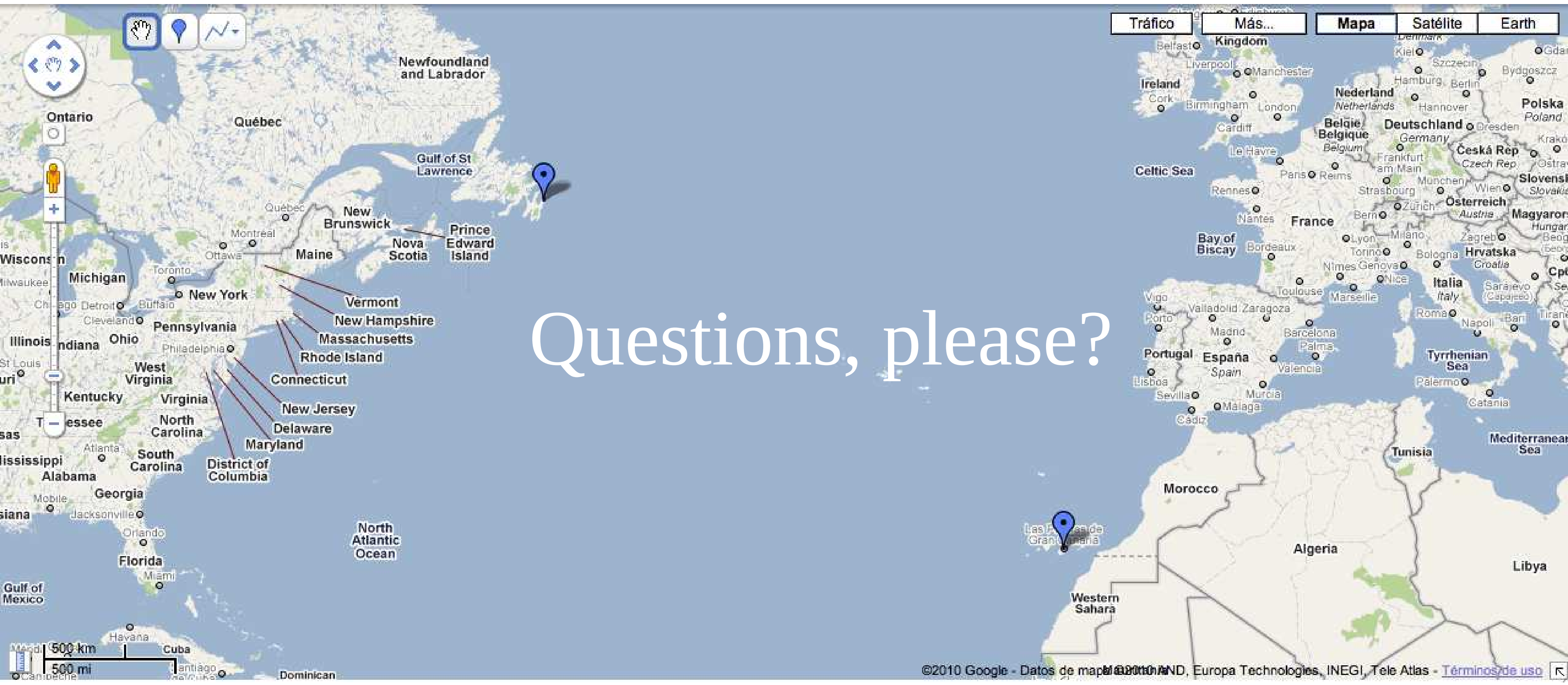
Thanks for your attention!



Questions, please?

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Glider and Ocean Models

MODEL VALIDATION

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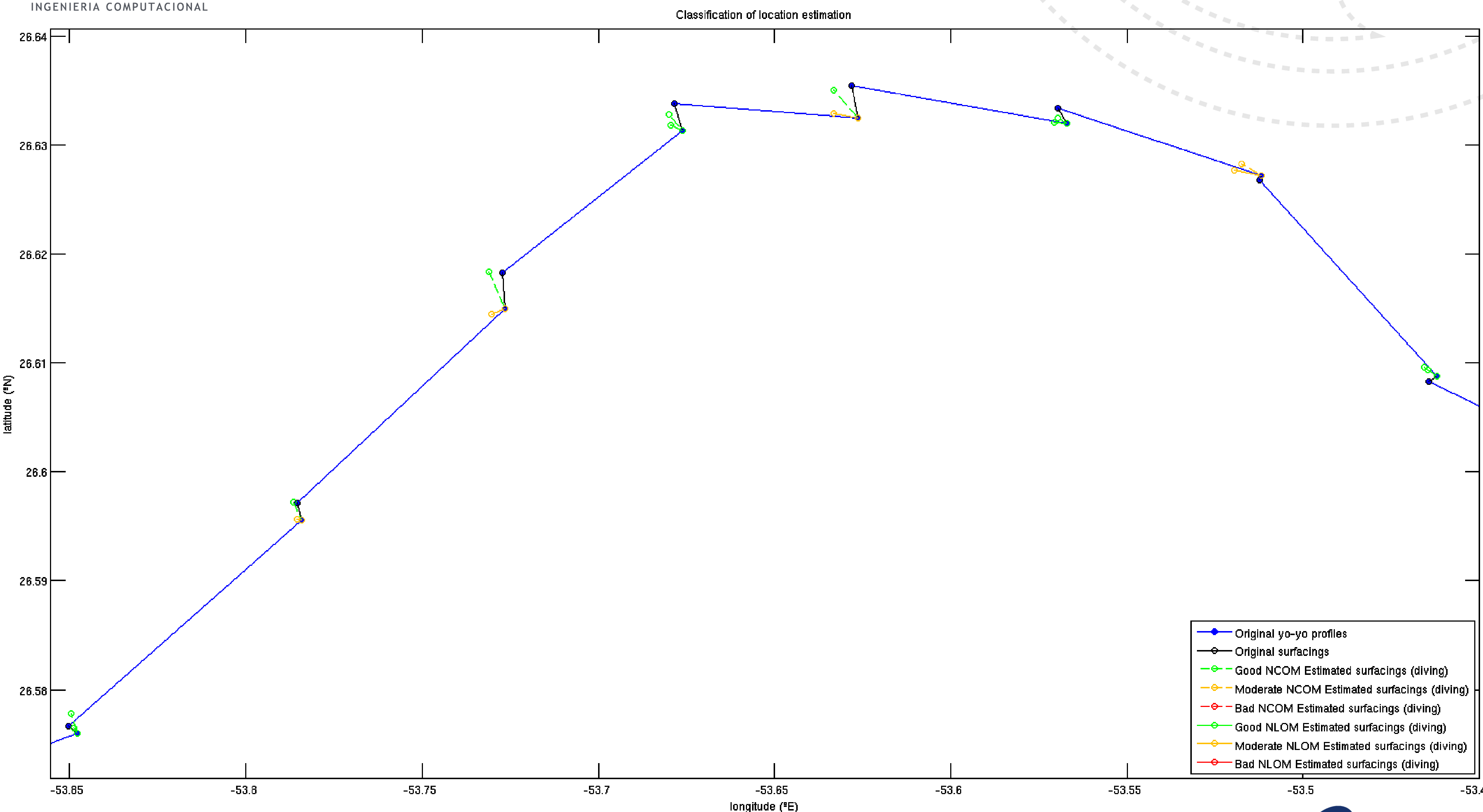
Glider and Ocean Models



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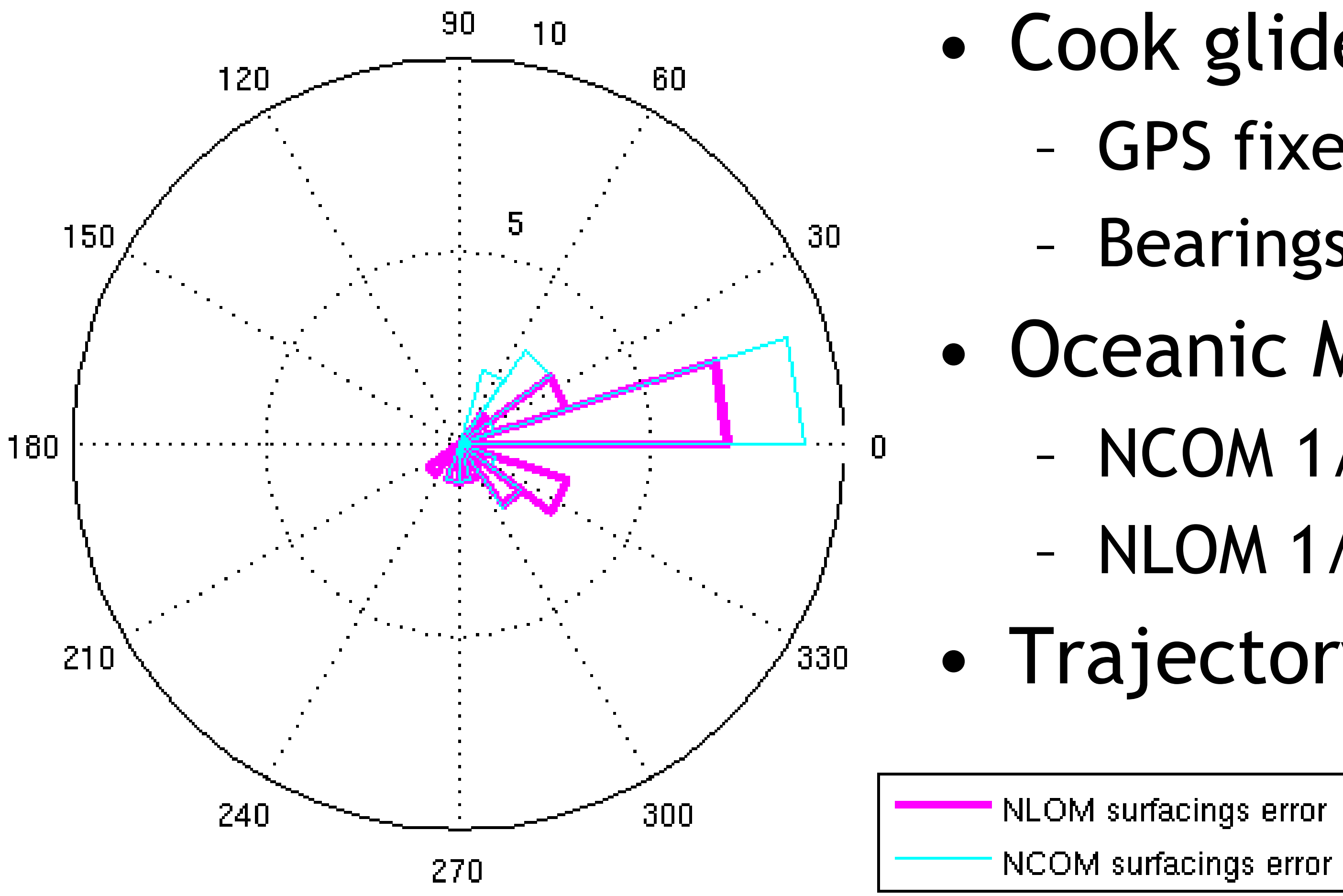
Glider and Ocean Models (II)



- Cook glider trajectory
  - GPS fixes
  - Bearings commanded
- Oceanic Models
  - NCOM 1/8°
  - NLOM 1/32°
- Trajectory simulation

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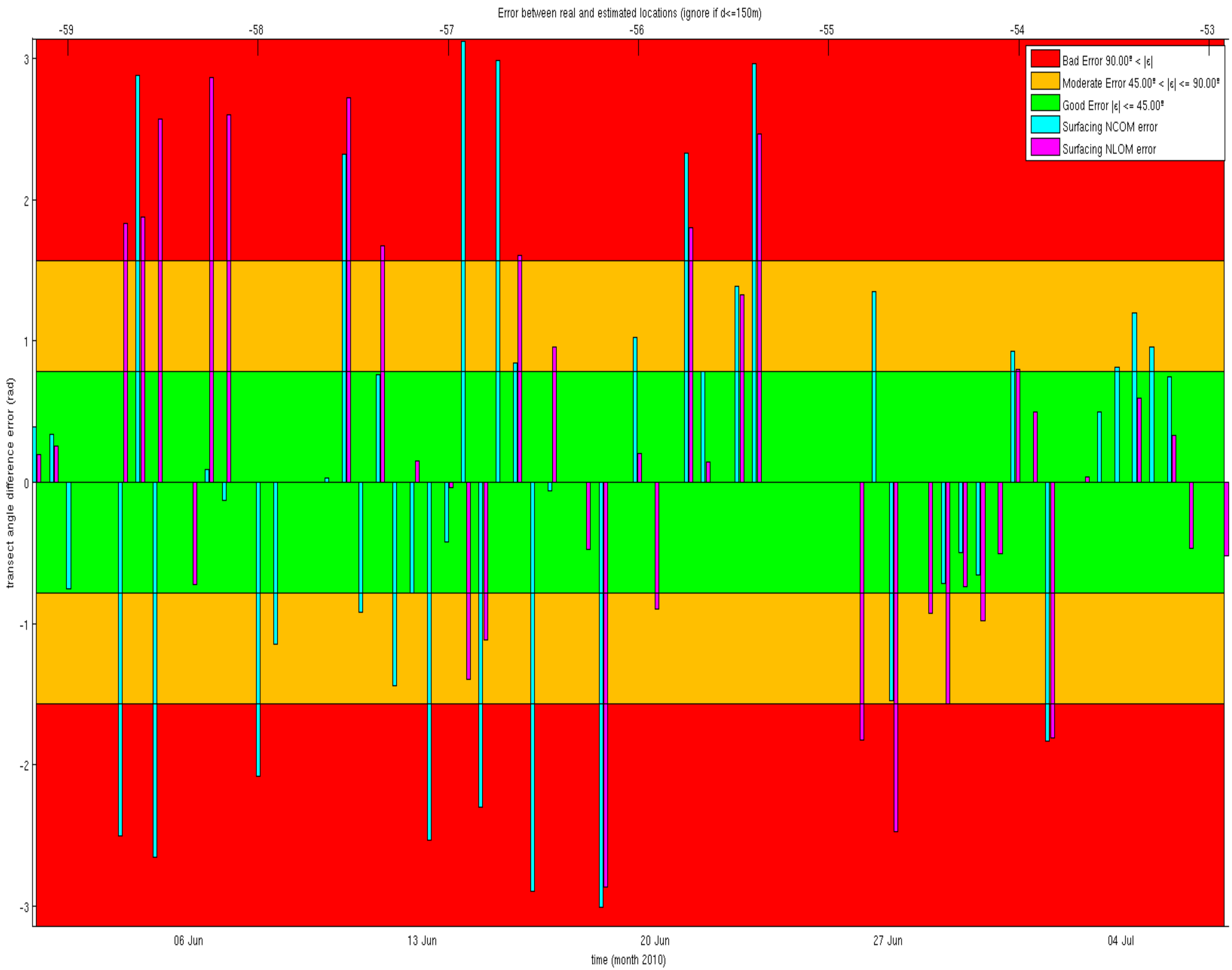
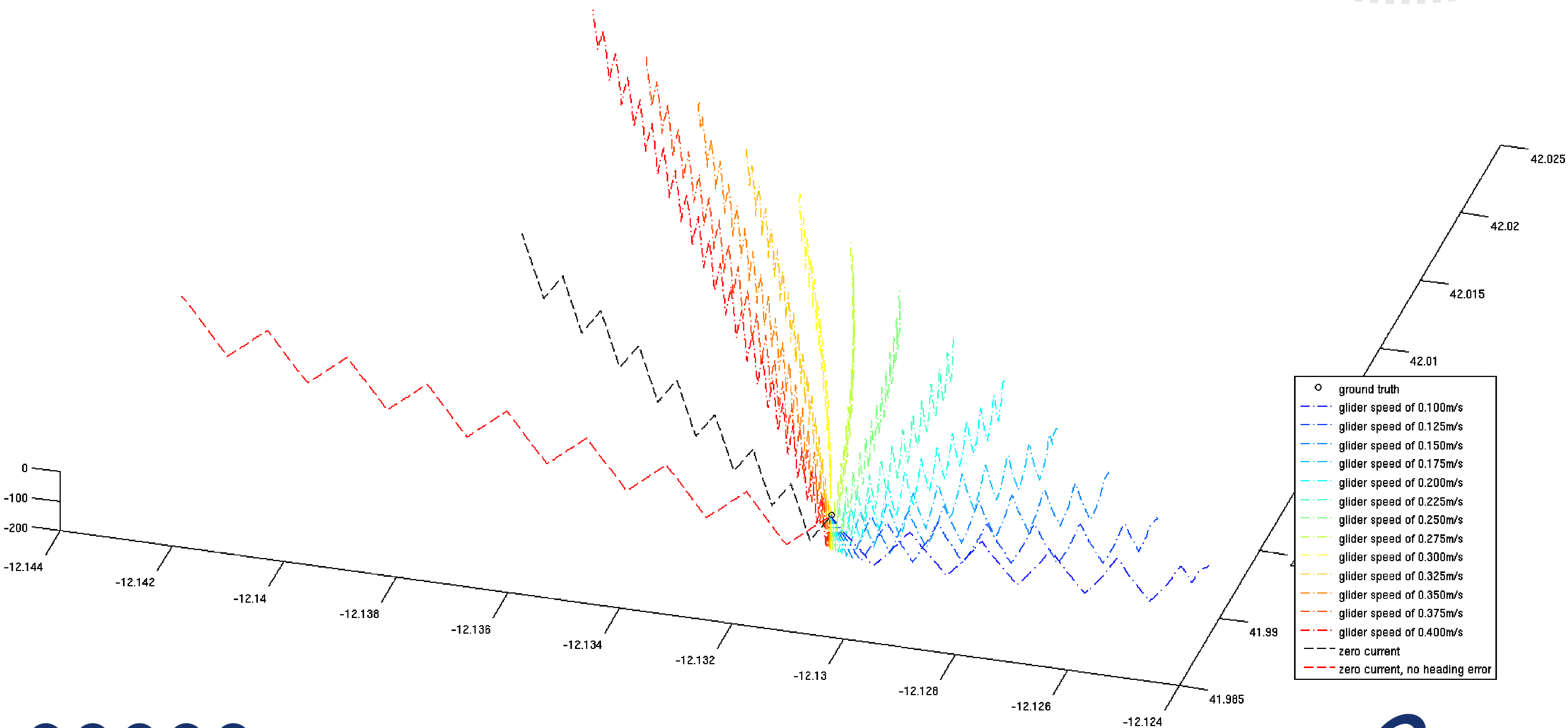


Error between real and estimated locations (ignore if d<=150m)
-59
-58
-57
-56
-55
-54
-53
Bad Error 90.00º < |ε|
Moderate Error 45.00º < |ε| <= 90.00º
Good Error |ε| <= 45.00º
Surfacing NCOM error
Surfacing NLOM error
3
2
1
0
-1
-2
-3
transect angle difference error (rad)
06 Jun
13 Jun
20 Jun
27 Jun
04 Jul
time (month 2010)

Kinematic Motion Models IV



Force balance trajectories for different glider speeds

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Dynamic Motion Models

- Consider accelerations (inertia)
  - Vehicle hull and wings shape (drag, lift)
  - 3D, accurate motion models
  - [Graver, 2005; Mahmoudian, 2008]
- **Assumption:** not significant for long-range missions

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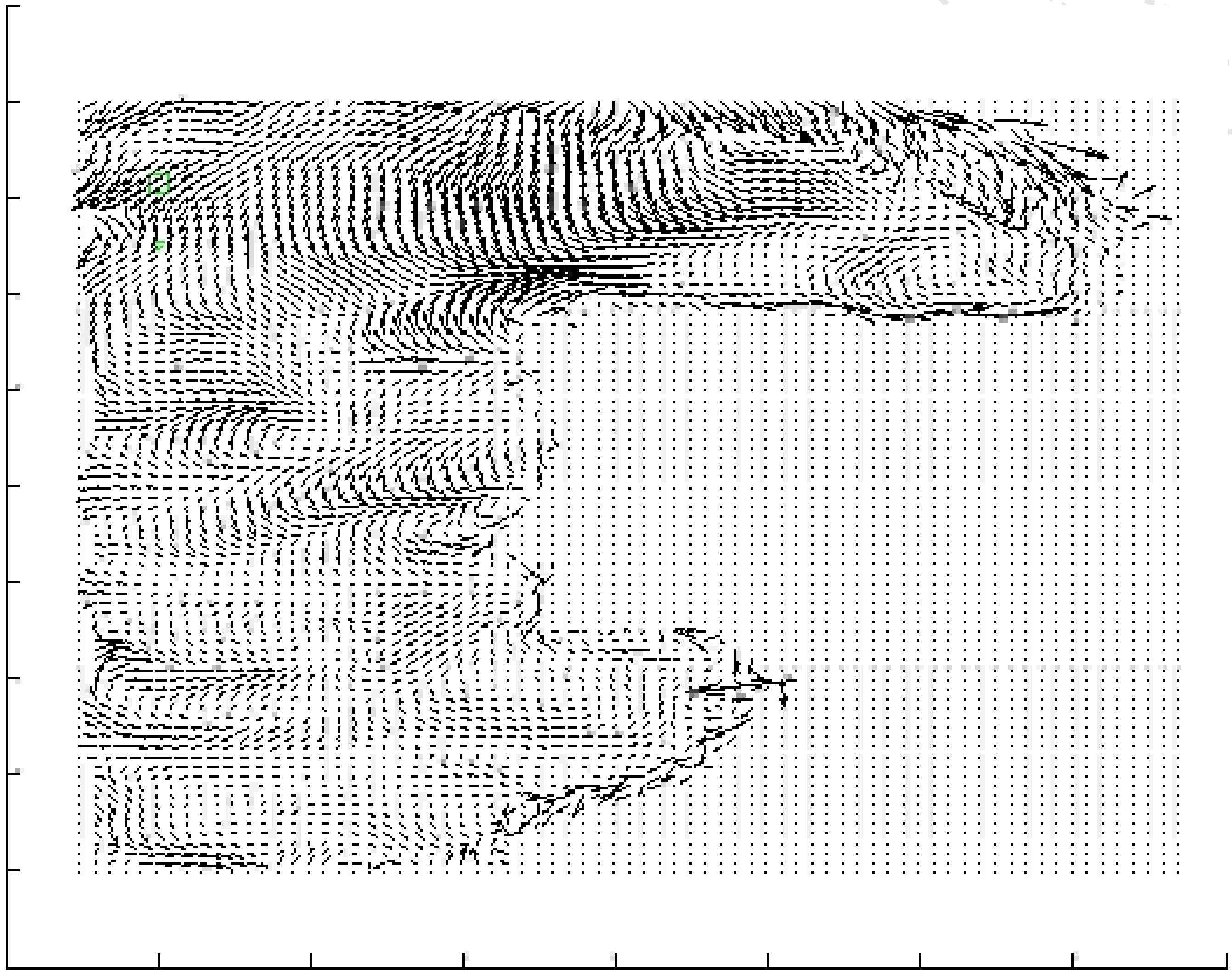
Fixed-time example (II)

ESEEO-AT Forecast



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```
Function RRT_Glider(Origin, Destination, TRAJ_TO_BE_FOUND)

    nodesFromOrigin={Origin}
    nodesFromDestination={Destination}
    numFoundTraj=0

    While numFoundTraj<TRAJ_TO_BE_FOUND

        wayPoint=Random(Destination)
        succ=GenerateSuccessors(nodesFromOrigin, wayPoint)
        Insert(NearestNeighbour(succ, wayPoint), nodesFromOrigin)

        wayPoint=Random(Origin)
        succ=GenerateSuccessors(nodesFromDestination, wayPoint)
        Insert(NearestNeighbour(succ, wayPoint), nodesFromDestination)

        traj=GetNewTrajectory(nodesFromOrigin, nodesFromDestination)
        If traj!=null
            numFoundTraj=numFoundTraj+1
            trajectories(numFoundTraj)=traj
        End

    End While

    return BestTraj(trajectories)
```

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