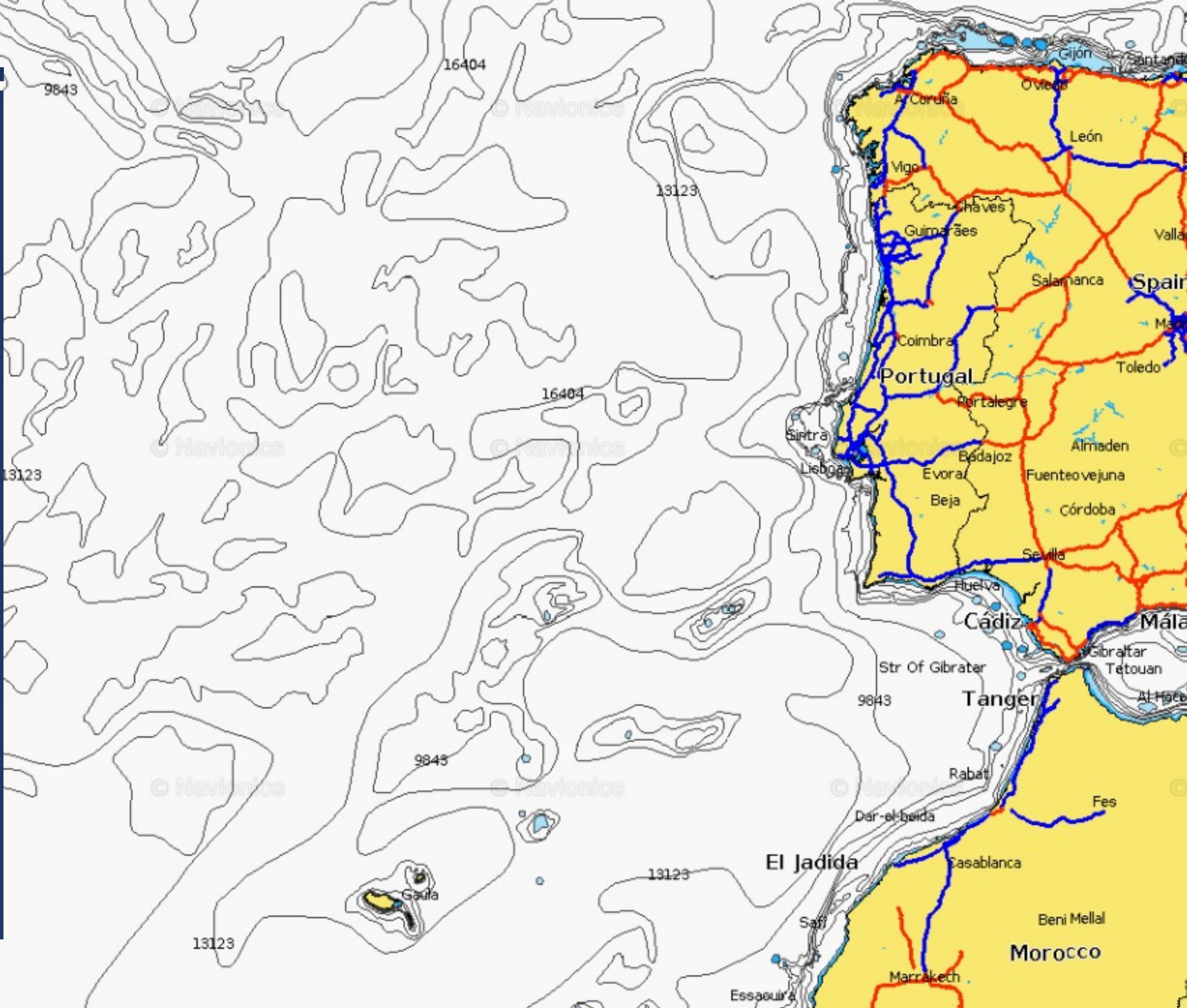
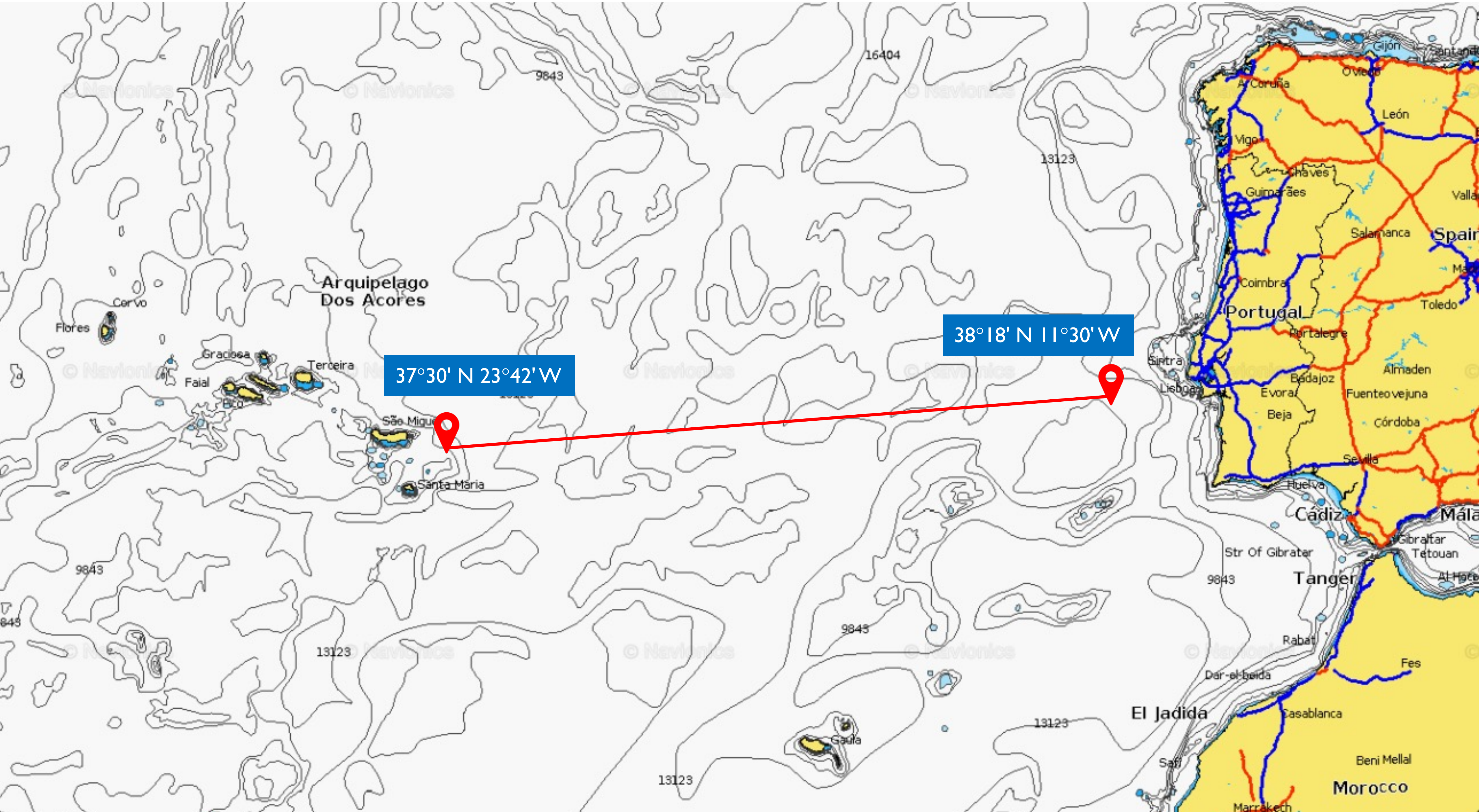
TIME-OPTIMAL AUTONOMOUS VESSEL ROUTE PLANNING IN DYNAMIC FLOW ENVIRONMENT IN OPEN OCEAN WATERS OFF THE PORTUGAL COAST

CLARA DAHILL

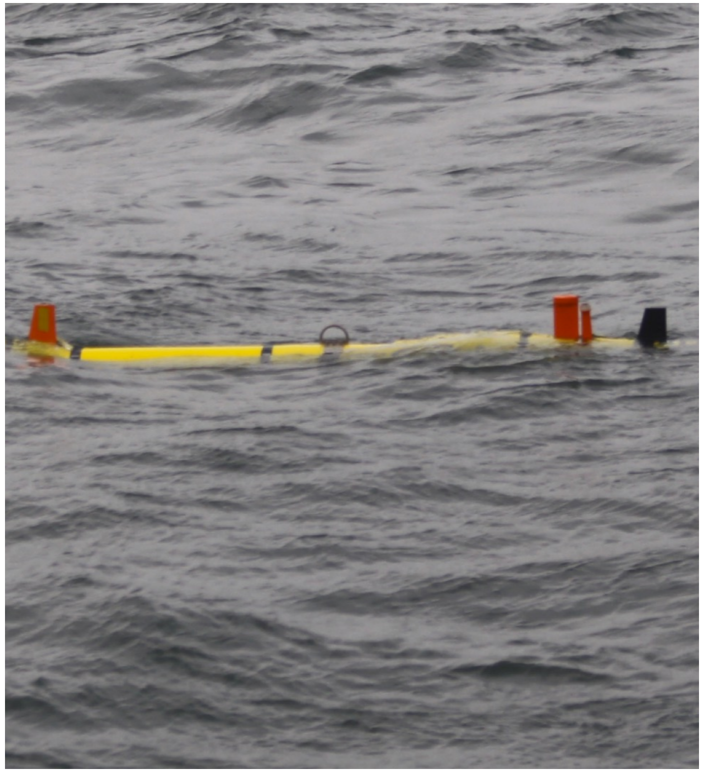
2.29 CLASS PROJECT





Arquipelago
Dos Acores
Cervo
Flores
Graciosa
Faial
Pico
Terceira
São Miguel
Santa Maria
37°30' N 23°42' W
38°18' N 11°30' W
Portugal
Spain
Gijón
Oviedo
Santander
A Coruña
León
Vigo
Chaves
Guimarães
Salamanca
Valla
Coimbra
Toledo
Portalegre
Sintra
Lisboa
Badajoz
Almaden
Evora
Fuenteovejuna
Beja
Córdoba
Sevilla
Huelva
Cádiz
Mála
Gibraltar
Tetouan
Str Of Gibratar
Tanger
Rabat
Fes
Dar-el-beida
Casablanca
El Jadida
Safi
Beni Mellal
Morocco
Marrakech
16404
9843
13123

BACKGROUND: VEHICLE



REMUS 600

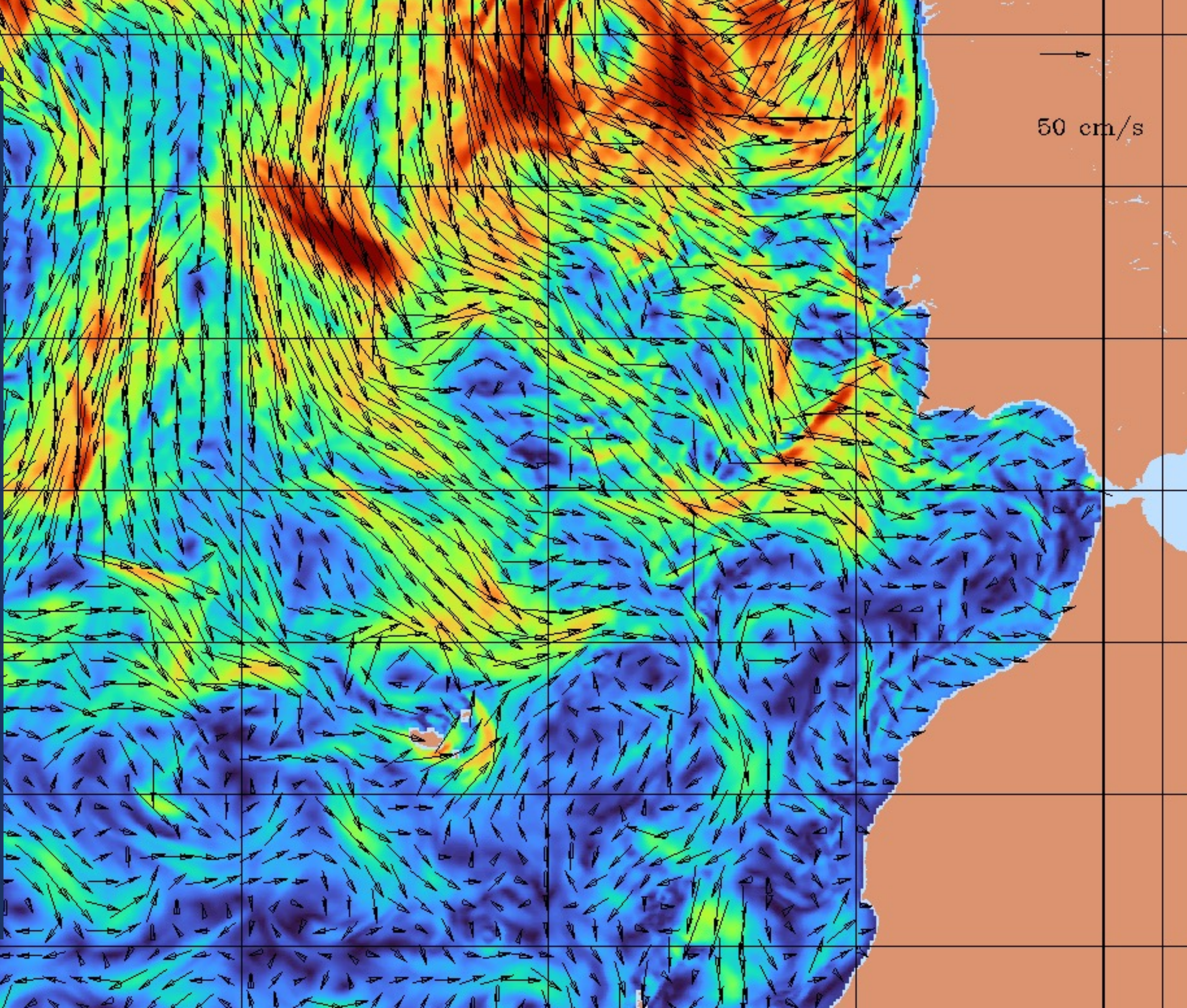
Subramani et al.

Autonomous Underwater Vehicles (AUV)

- Robotic path planning
- Executable path
- Slow speed of vehicle
- Effect of dynamic ocean environment

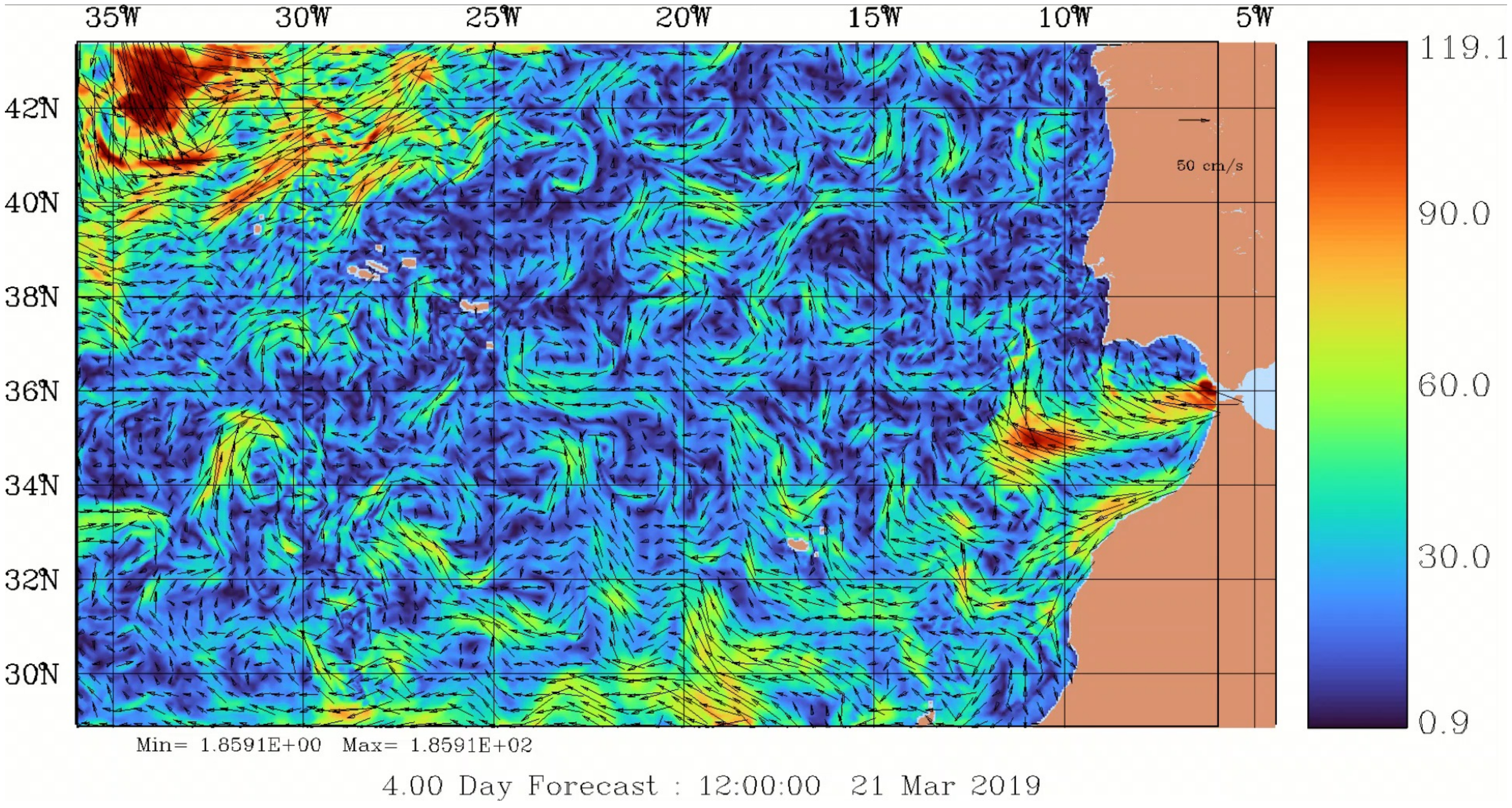
DYNAMIC OCEAN ENVIRONMENT

- Primitive Equation ocean modeling system (PE Model)
  - Bathymetry data sets
  - Coastline
  - Temperature
  - Salinity
  - Flow velocity
  - Initial condition
  - Boundary condition

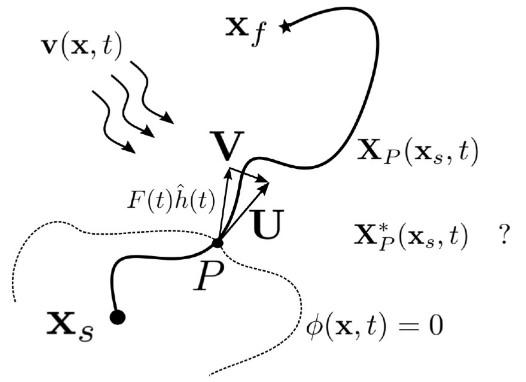


DYNAMIC FLOW ENVIRONMENT

- 30 Day Ocean PE Model
- March 21st – Apr 20th 2019
- Dynamic surface flow velocity



METHODS USED: COMPUTATIONAL SCHEMES

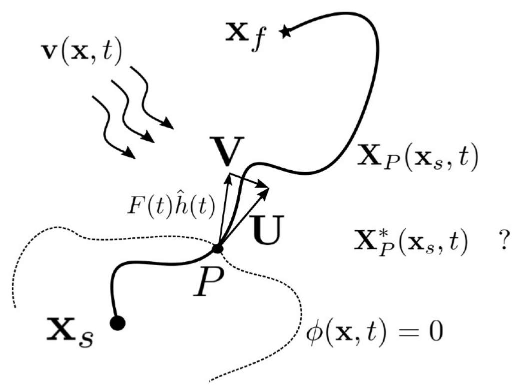


Schematic of time-optimal path planning, Subramani et al.

The goal of our path planning is to:

- for vehicle P
- on a voyage from starting point x_s to the destination x_f
- traveling at a nominal speed $F(t)$
- in a time dependent flow-field with dynamic ocean currents $v(x, t)$
- compute a time optimal path $X_P^*(x_s, t)$

METHODS USED: COMPUTATIONAL SCHEMES



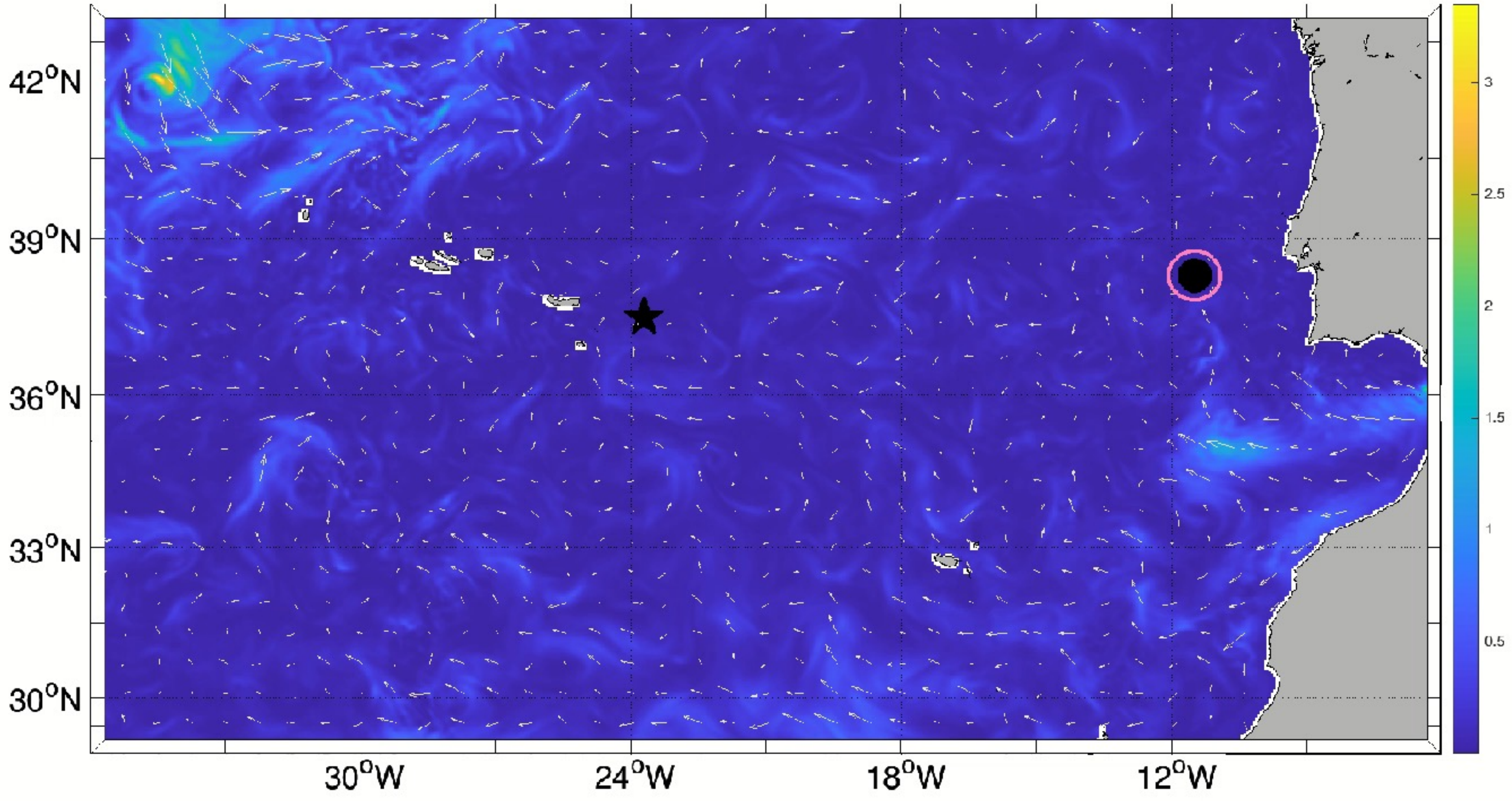
- Predict the evolving reachability front
- All the points that the vehicle can possibly reach at any given time
- $\phi(x,t)$ is the zero level-set contour, and defines the reachability front
- Defined by hyperbolic PDE (Hamilton-Jacobi-Bellman):

$$\frac{\partial \phi(\mathbf{x},t)}{\partial t} + F(t)|\nabla \phi(\mathbf{x},t)| + \mathbf{v}(\mathbf{x},t)\cdot\nabla\phi = 0$$

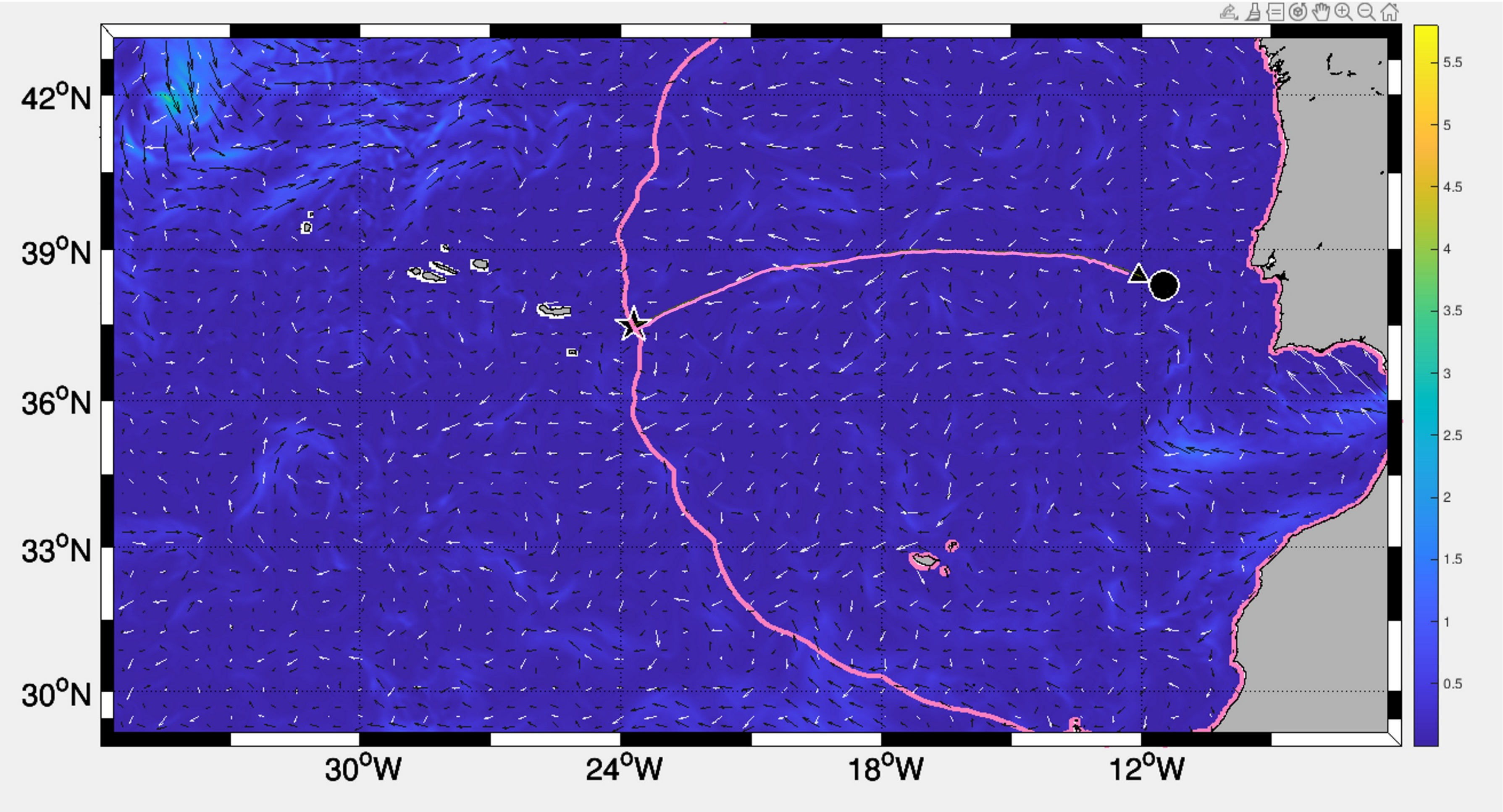
- Backtracking equation:

$$\frac{\mathrm{d}\mathbf{X}^*_P(\mathbf{x}_s,t)}{\mathrm{d}t} = -\mathbf{v}(\mathbf{X}^*_P(\mathbf{x}_s,t),t) - F(t)\frac{\nabla\phi(\mathbf{X}^*_P(\mathbf{x}_s,t),t)}{|\nabla\phi(\mathbf{X}^*_P(\mathbf{x}_s,t),t)|}$$

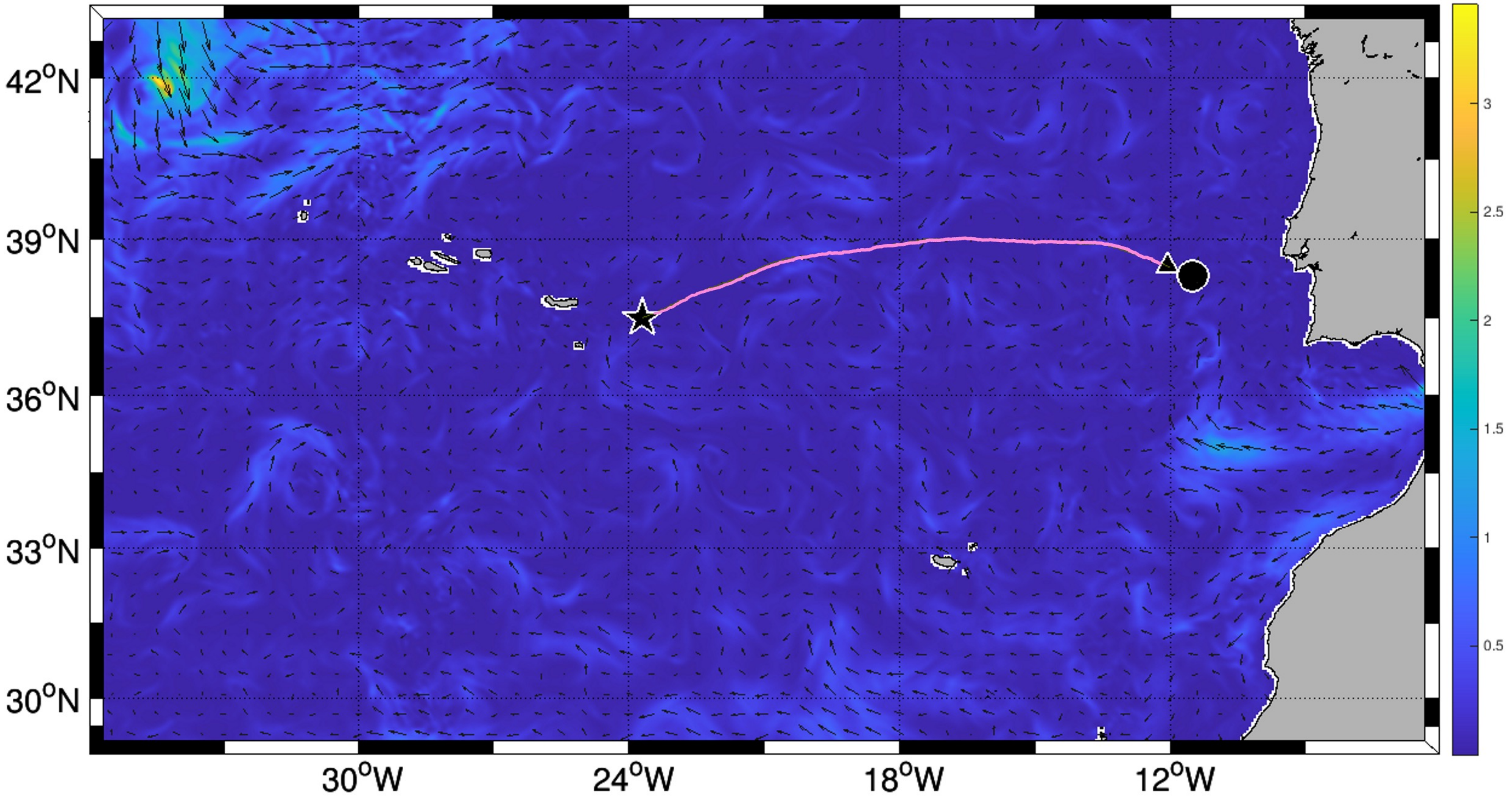
LEVEL SET PLOTS: FORWARD SOLVE



BACKWARD SOLVE

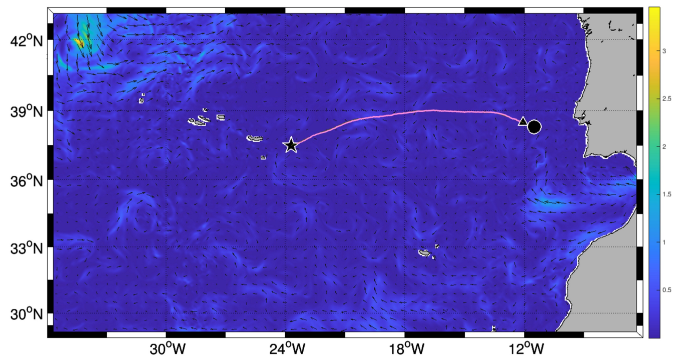


TIME-OPTIMAL PATH

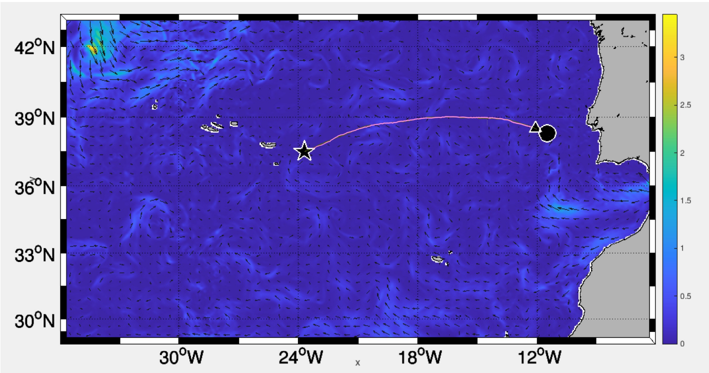


VALIDATION

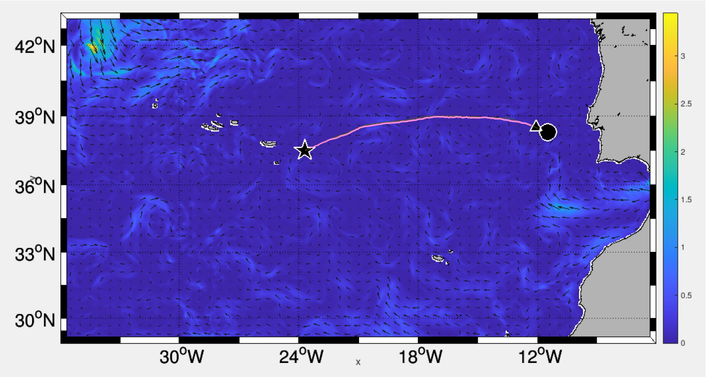
- L_∞ norm as a function of the time (does not explode)
- CFL: $C = \frac{c\Delta t}{\Delta x} < 1$
- Numerical solution converge towards true solution with changes in resolution, as the dt decreases



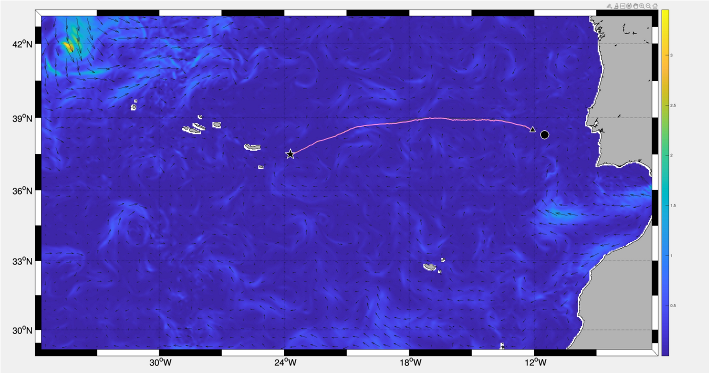
dt = 1000s



dt = 100s

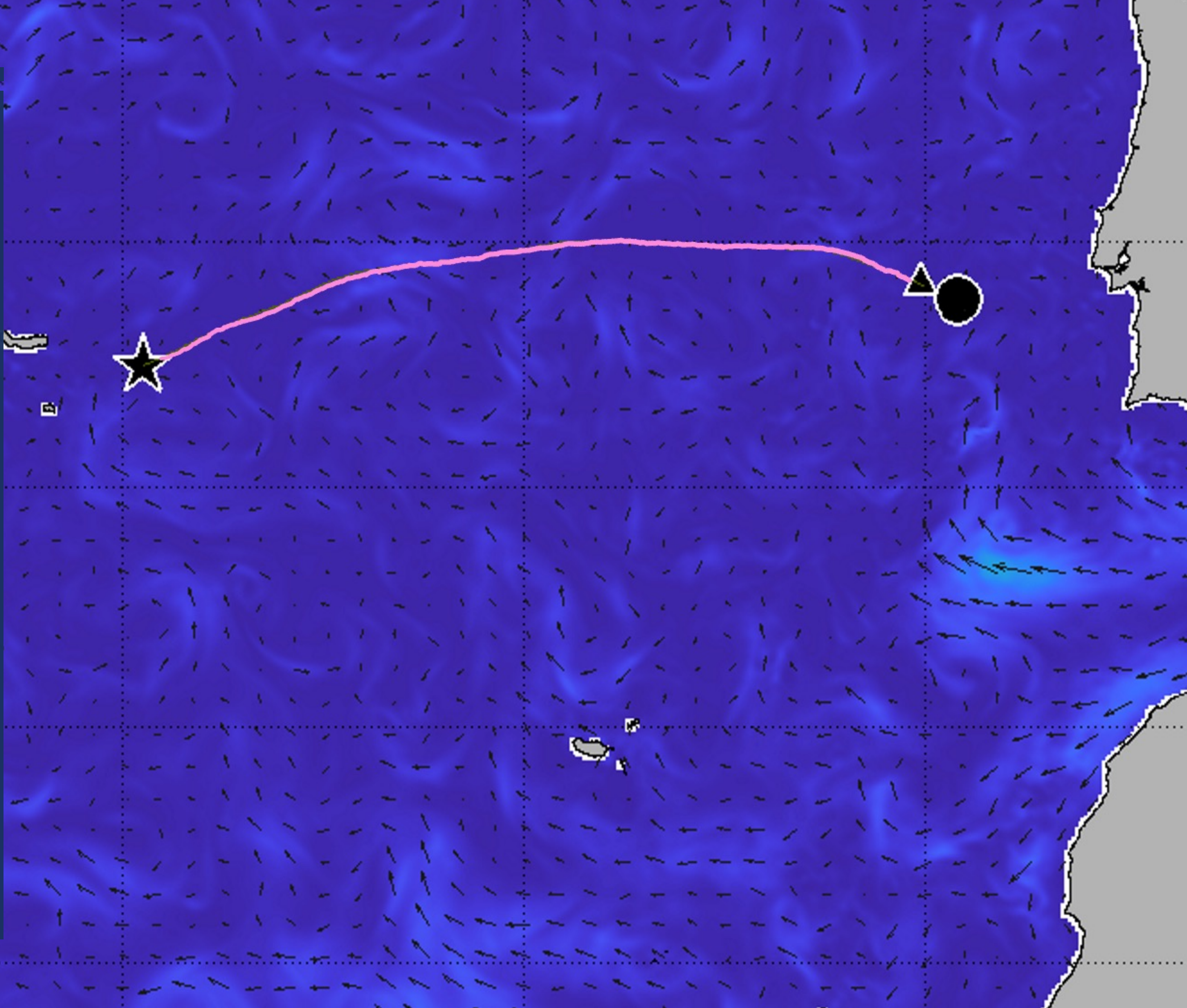


dt = 500s


dt = 250s

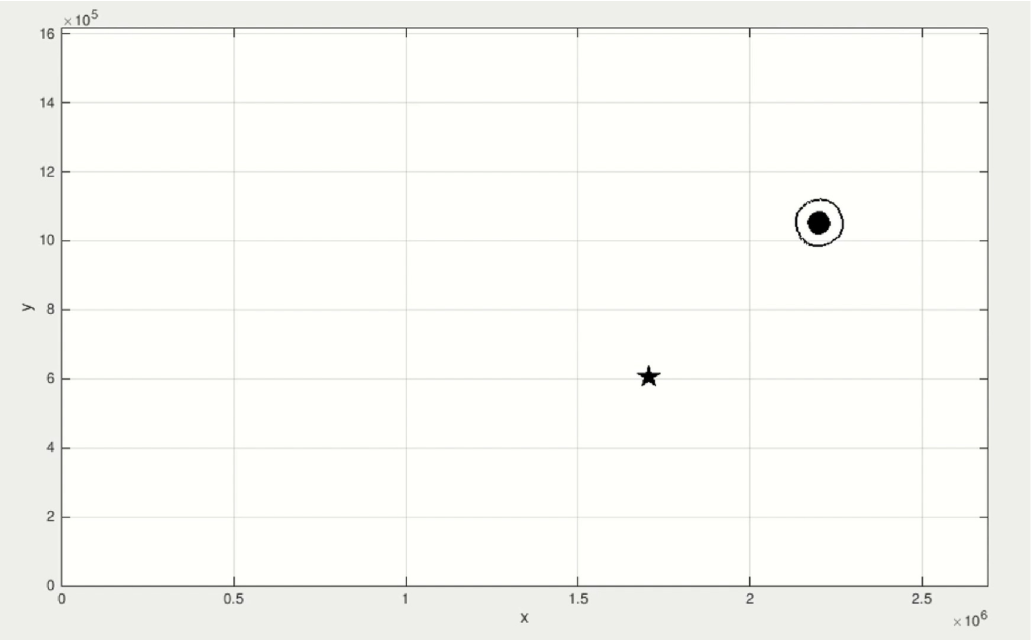
FUTURE APPLICATIONS

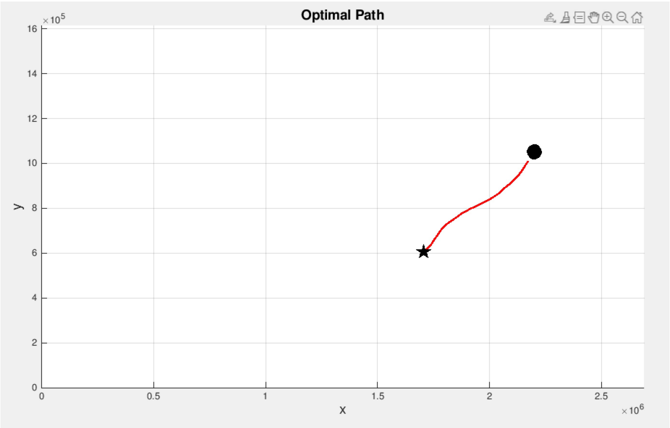
- Energy harvesting optimality
  - Wave
  - Wind
  - Solar
  - Ocean-thermal (3D) energy harvesting
- 3D time-optimal path planning



SOURCES

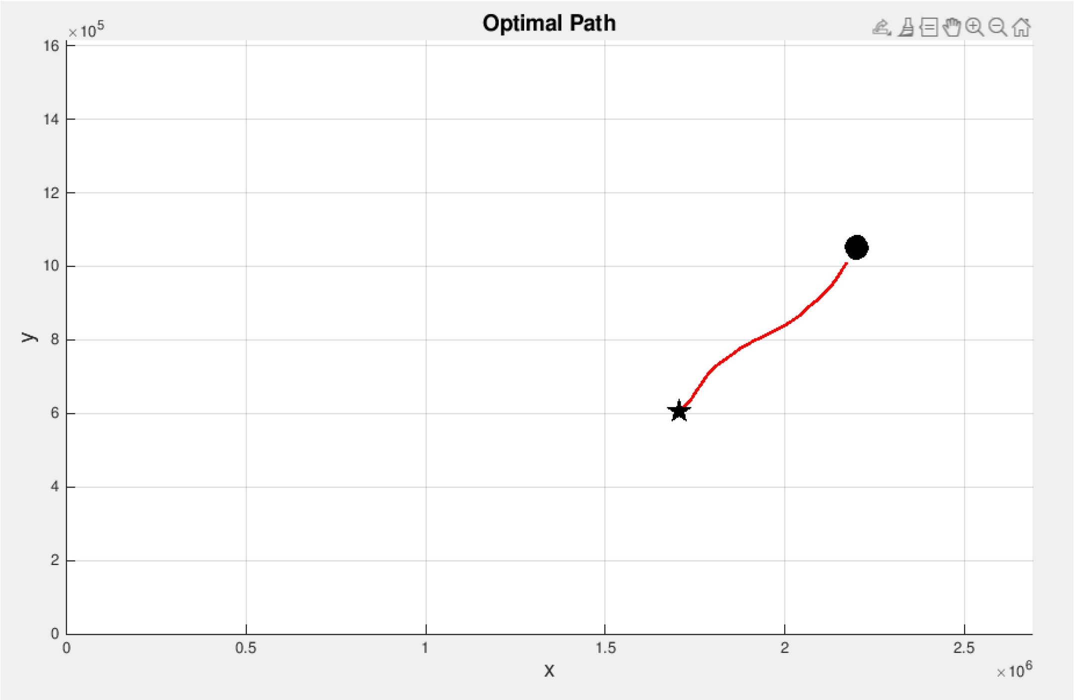
- Subramani, D. N., P. F. J. Lermusiaux, P.J. Haley, Jr., C. Mirabito, S. Jana, C. S. Kulkarni, A. Girard, D. Wickman, J. Edwards, J. Smith, 2017. Time-Optimal Path Planning: Real-Time Sea Exercises. In: Oceans '17 MTS/IEEE Aberdeen, 19-22 June 2017, DOI: 10.1109/OCEANSE.2017.8084776
- P. F. J. Lermusiaux, P.J. Haley, Jr., C. Mirabito, MSEAS Codes - Getting Started.
- Subramani, D. N., P. J. Haley Jr., and P. F. J. Lermusiaux, 2017. Energy-optimal path planning in the coastal ocean. Journal of Geophysical Research Oceans, 122, 3981–4003. doi:10.1002/2016JC012231
- Lermusiaux, P.F.J., D.N. Subramani, J. Lin, C.S. Kulkarni, A. Gupta, A. Dutt, T. Lolla, P.J. Haley Jr., W.H. Ali, C. Mirabito, and S. Jana, 2017. A Future for Intelligent Autonomous Ocean Observing Systems. The Sea. Volume 17, The Science of Ocean Prediction, Part 2, J. Marine Res. 75(6), pp. 765–813.



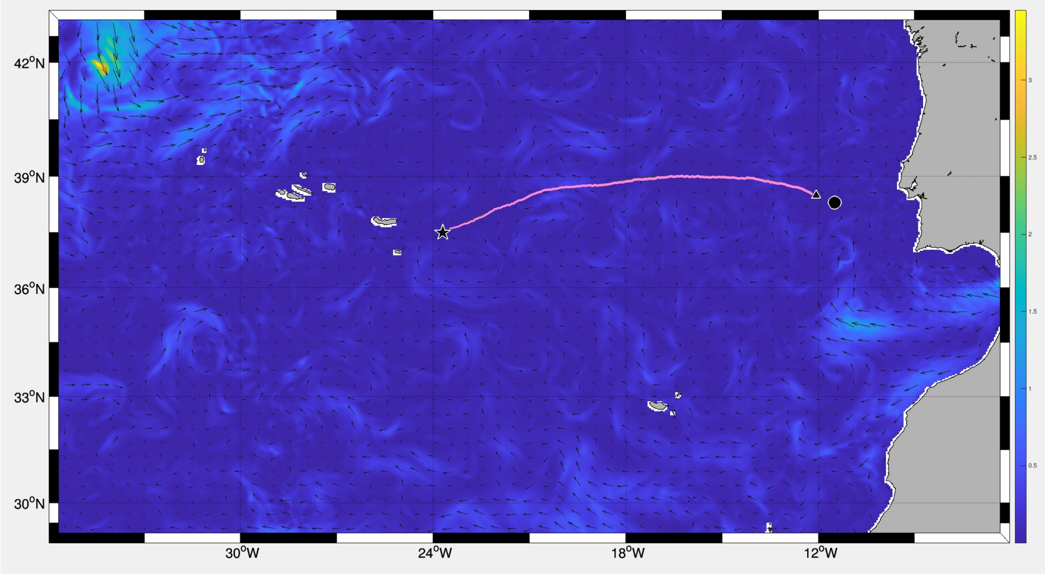


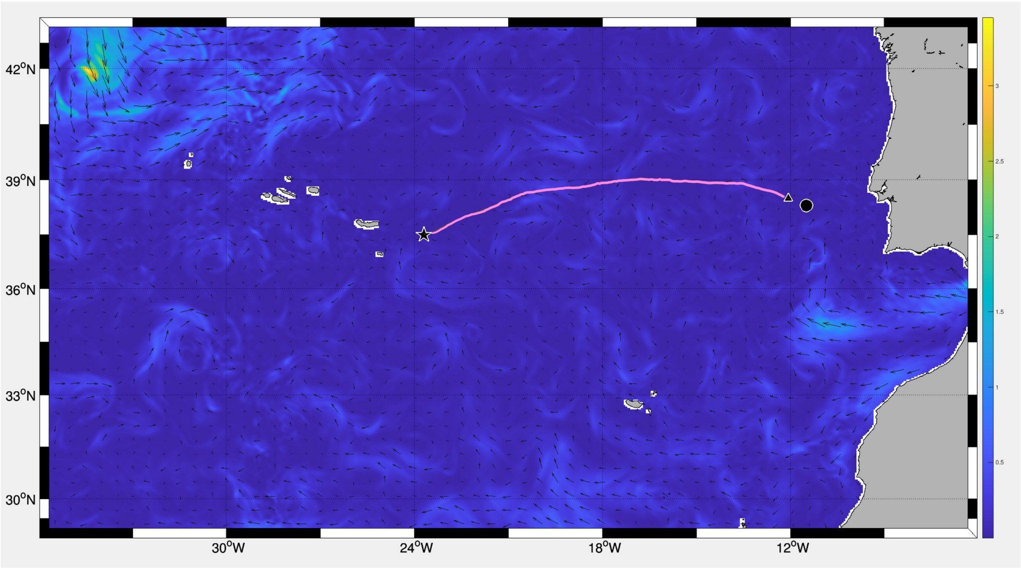
LEVEL SET PLOT: LISBON TO MADEIRA

LEVEL SET PLOT: LISBON TO MADEIRA



- L to M, 2 m/s, dt 1000, ir 50000





DIFFERENT SPEEDS

- 1 m/s
- 2 m/s
- 3 m/s