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A Process for Evaluating Parametric Models for Mechanical Systems Simulation: the Case of a Sailboat

Context

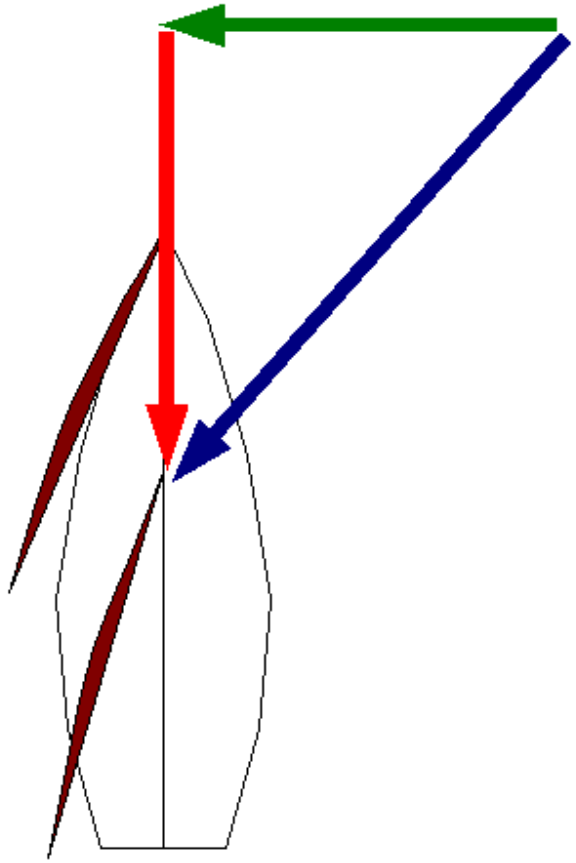
The wind

Absolute wind

TWD : True Wind Direction
TWA : True Wind Angle
TWS : True Wind Speed

Relative wind

AWA : Apparent Wind Angle
AWS : Apparent Wind Speed



The sailboat

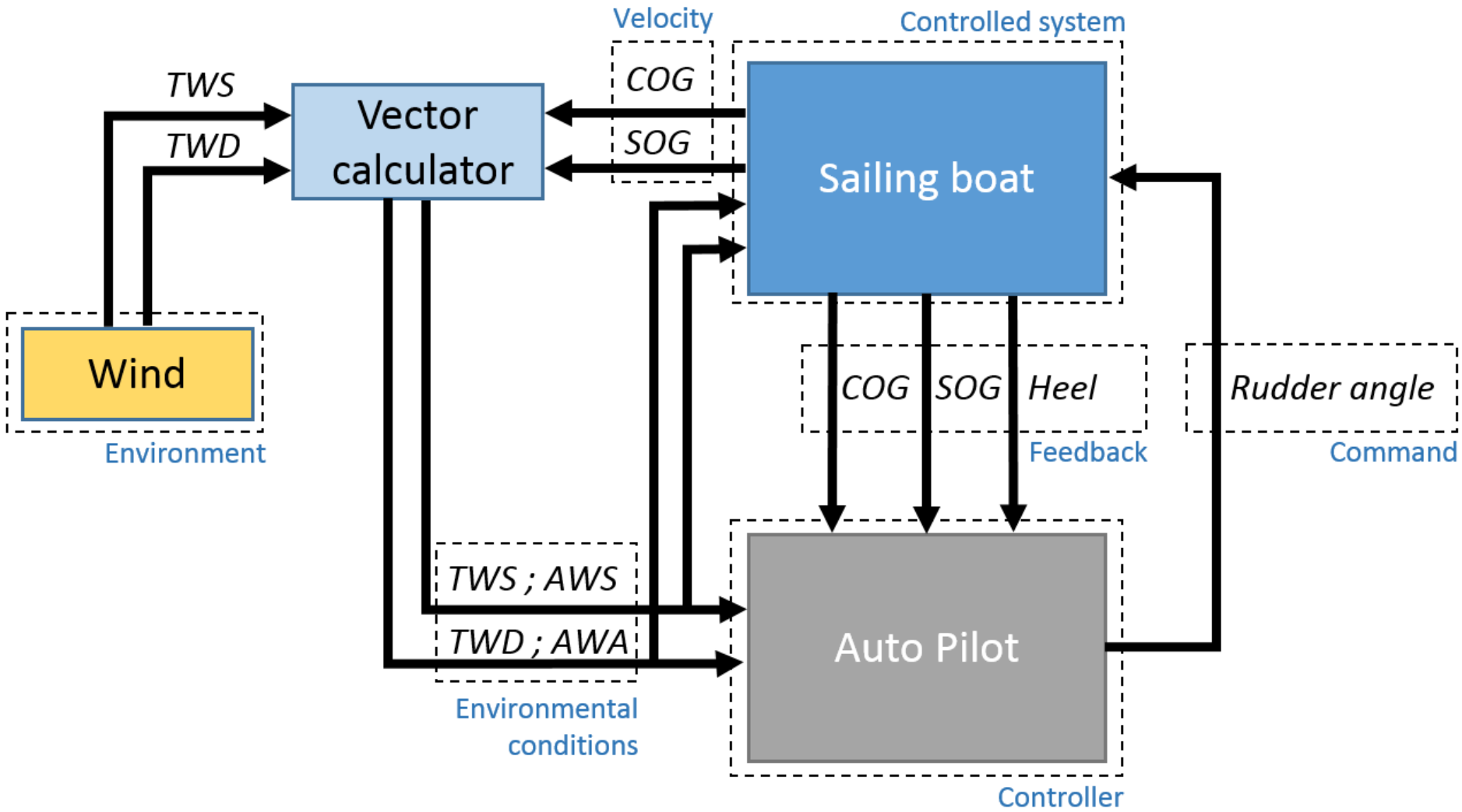
Speed

COG : Course Over Ground
SOG : Speed Over Ground

Behavior

Heel : heel angle

Sailboat modeling



Controlled system modeling

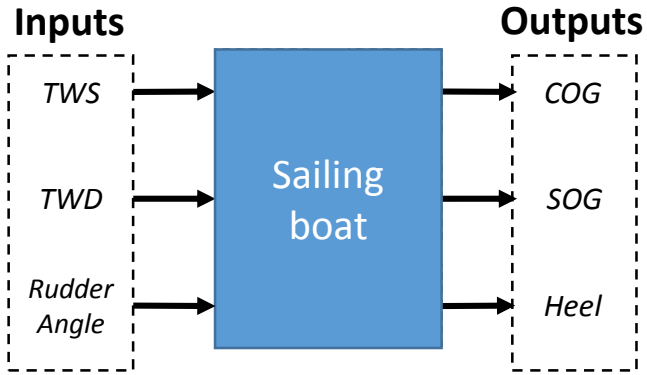
No efficient analytical model

Strongly nonlinear system

- ➢ fluid / structure interactions in aero and hydro
- ➢ CFD (complex and heavy computation)

Multiple and uncertain parameters

- ➢ Measured wind
- ➢ High sensitivity to settings



Dataset logged from the sail boat

→ Evaluation of a parametric model

Outlines

- Introduction
- Parametric models
- Proposition
- Evaluation
- Conclusion and future works

Model Family

MIMO systems : Multiple Inputs Multiple Outputs

State-space models

State-space approach

$$\begin{cases} x_{i+1} = [A] \cdot x_i + [B] \cdot u_{i+1} \\ y_i = [C] \cdot x_i + [D] \cdot u_i \end{cases}$$

Autoregressive models

Transfer function approach

$$y_i(z) = \frac{b_1 \cdot z^{-1} + b_2 \cdot z^{-2} + \cdots + b_p \cdot z^{-p}}{1 + a_1 \cdot z^{-1} + a_2 \cdot z^{-2} + \cdots + a_n \cdot z^{-n}} u_i(z)$$

Model order

Influence on the number of parameters

State-space models

State-space approach

→ Size of the state vector

Autoregressive models

Transfer function approach

→ Order of each transfer function

Nonlinearities of the system

- Linear equation of motion

$$\frac{\partial m \cdot \vec{V}}{\partial t} = \sum \vec{F}$$

- Nonlinear parameters

$$F_v = \frac{1}{2} \rho \cdot V^2 \cdot S \cdot C$$

Referential choice

Relative referential

Work with apparent wind
→ AWA and AWS

Work on cap variation
→ Yaw rate

VS

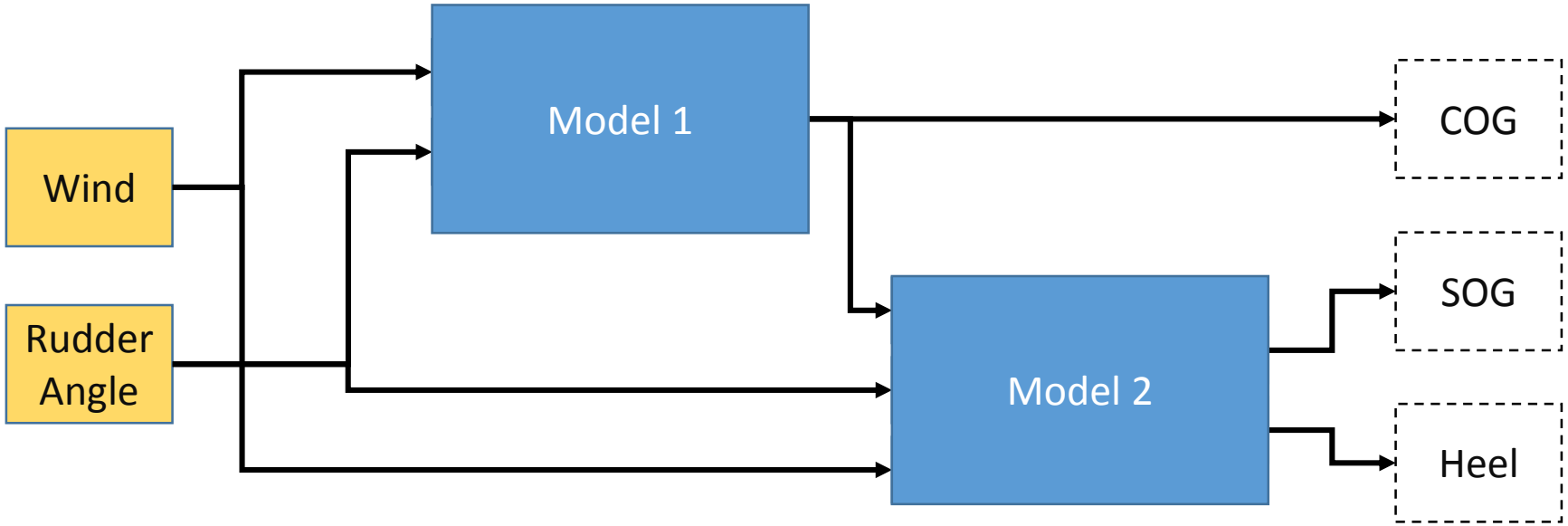
Absolute referential

Work with real wind
→ TWS et TWD

Work on absolute position
→ COG and SOG

Rem : *relevant for nonlinear systems and to deal with bad conditioned system*

Chained models



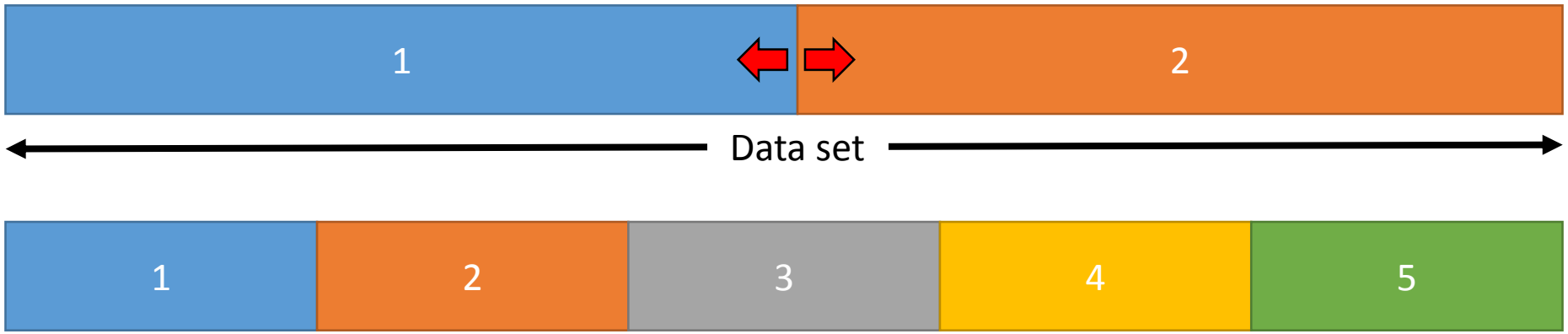
Window size choice

Classical approach in identification method

Split the data set in two parts :

- One part to compute the model
- One part to validate the model

Question of the size of each part



Model issues and options

- **Choice of a model family**
- **Choice of the referential**
- **Choice of the model order**
- **Choice of the number of used models**
- **Choice of the window size**
- **Choice of additional inputs to deal with nonlinearities**

Model evaluation and setting

- **Family and referential**
  - → Criteria (distance) to compare models
- **Choice of the number of used models**
  - → Testing different combinations
- **Choice of the model order**
  - → Mathematical tools to find best order : Matlab
- **Choice of additional inputs to deal with nonlinearities**
  - → Add exponentiation inputs
- **Choice of the window size**
  - → Split the set into several parts of different size

Evaluation

Measure set from a racing multihull

All inputs and output data logged during a sailing navigation:

- TWS, TWD, rudder angle, AWS, AWA, COG, SOG, Heel
- Length of data set : 2500 s
- Sample frequency : 1 Hz

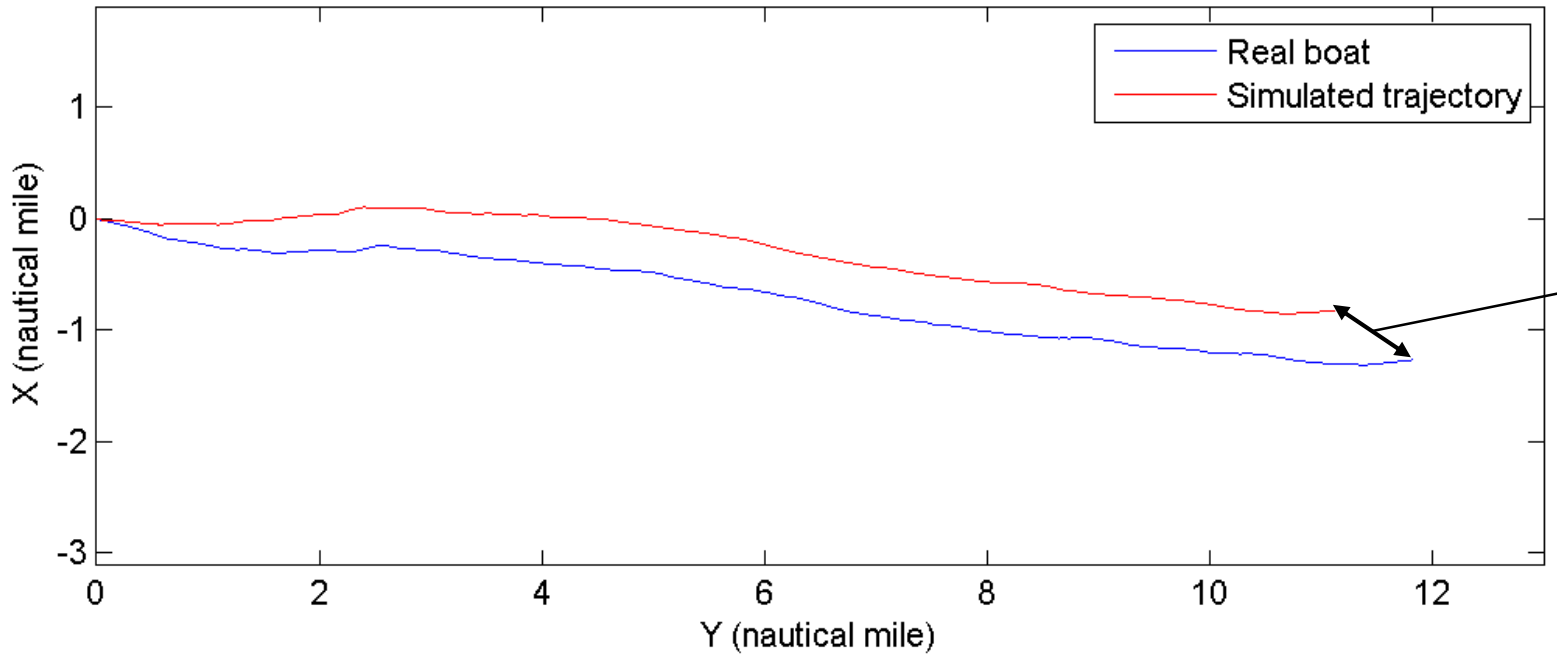
Model choice

Name	Referential	Model family
A	absolute	State-space
B	absolute	Autoregressive
C	relative	State-space
D	relative	Autoregressive

→ **Numerical criteria to compare model performances**

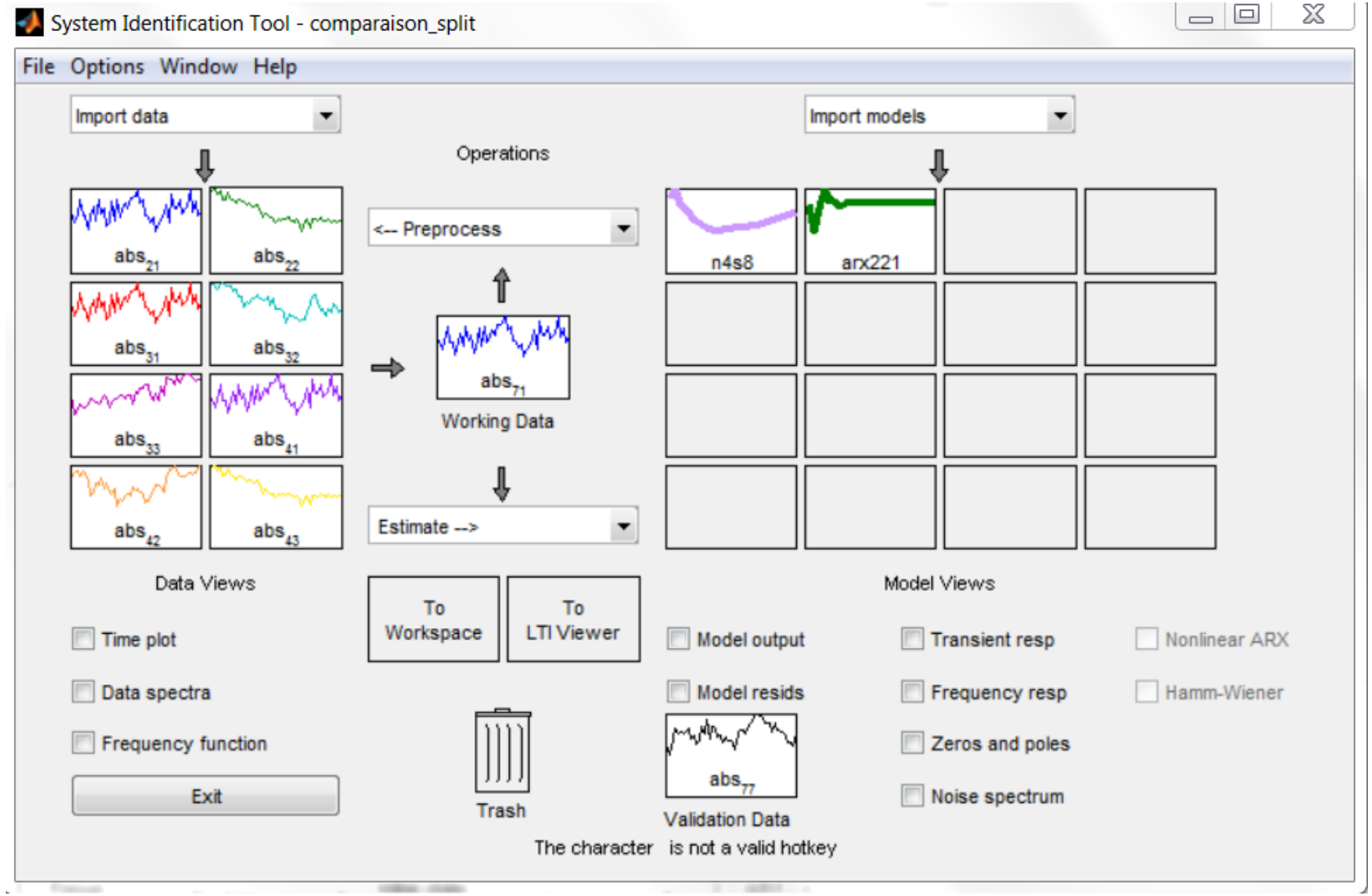
Numerical criteria

$$C1 = \left(1 - \frac{\|COG_m - COG_s\|_2}{\|COG_m - mean(COG_m)\|_2}\right) \times 100$$



C2

Order choice



Computation time : ~1 s

Inputs and outputs

Inputs

- Wind speed
  TWS or AWS
- Wind direction
  TWD or AWA
- Rudder angle

Outputs

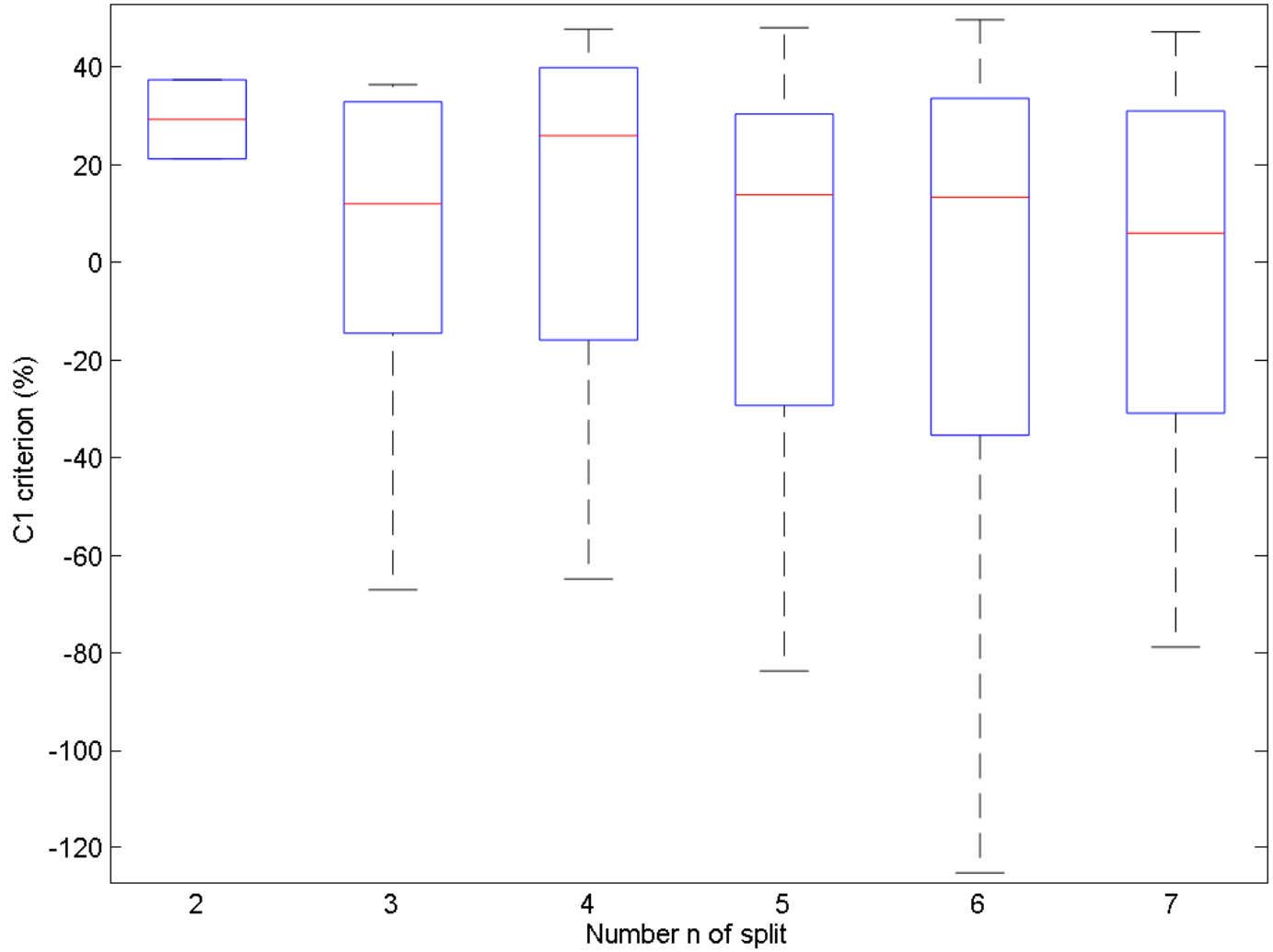
- Boat speed
  SOG
- Boat direction
  COG
- Heel

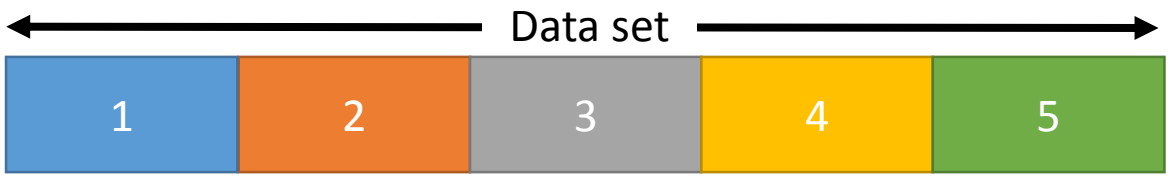
Taking into account nonlinearities

$$F_v = \frac{1}{2}\rho \cdot V^2 \cdot S \cdot C$$

- *Additional inputs*
  TWS² or AWS²

Impact of window size





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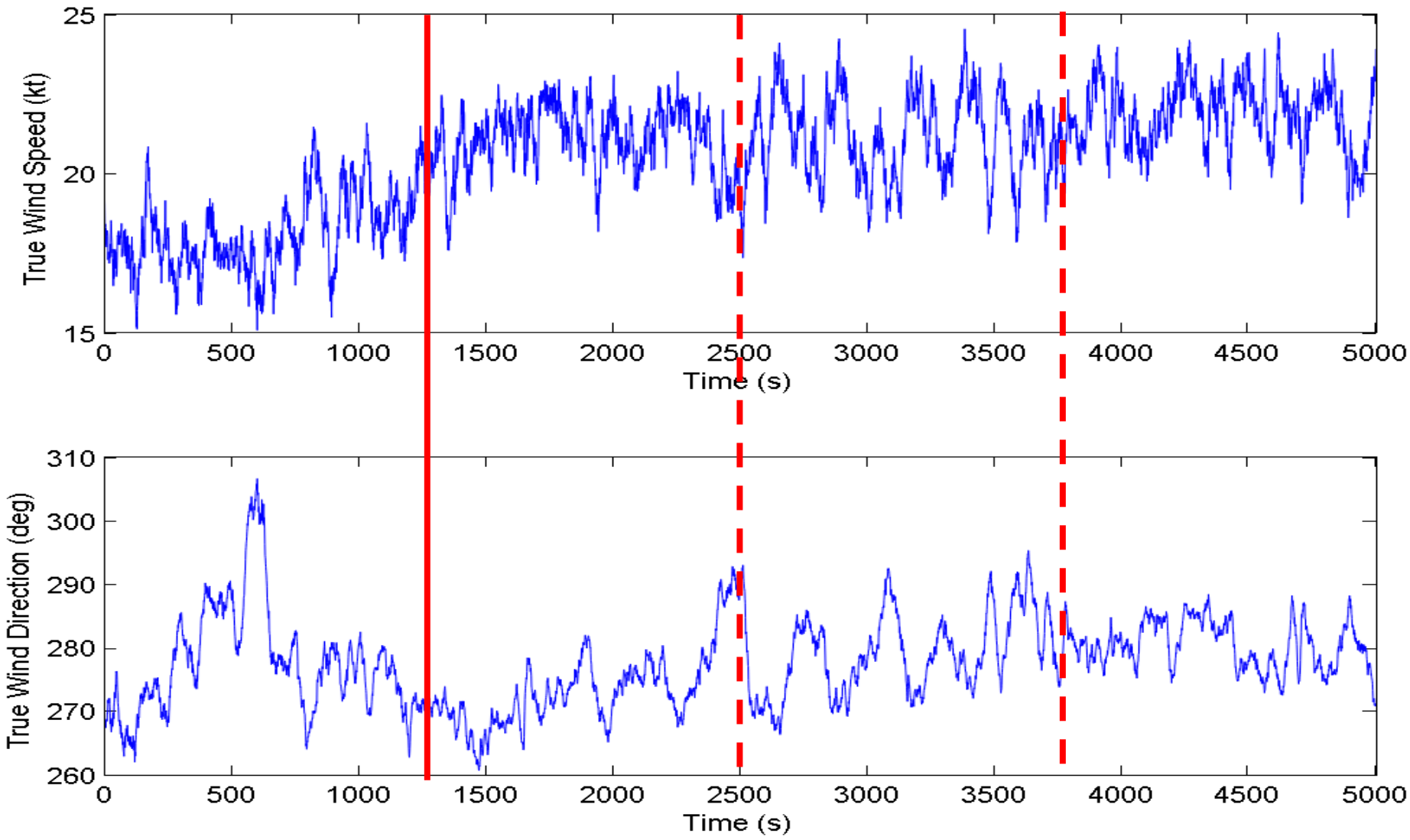
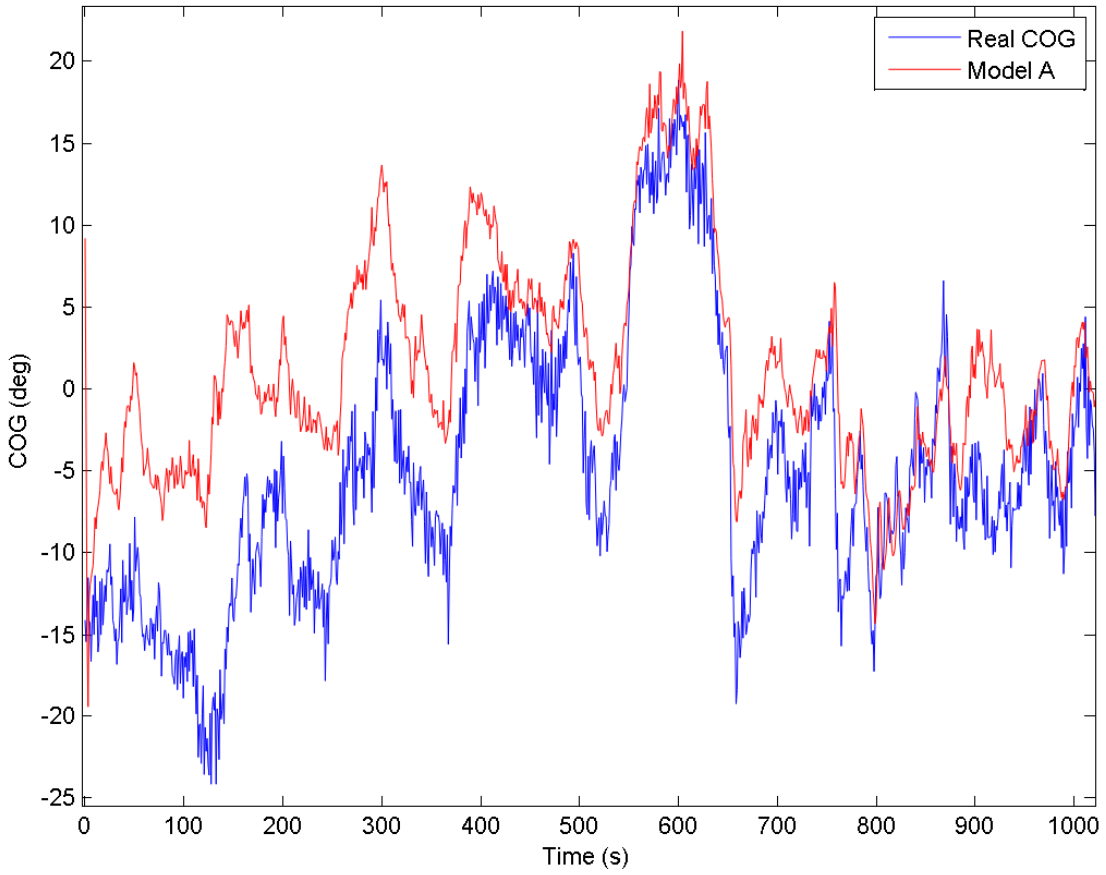
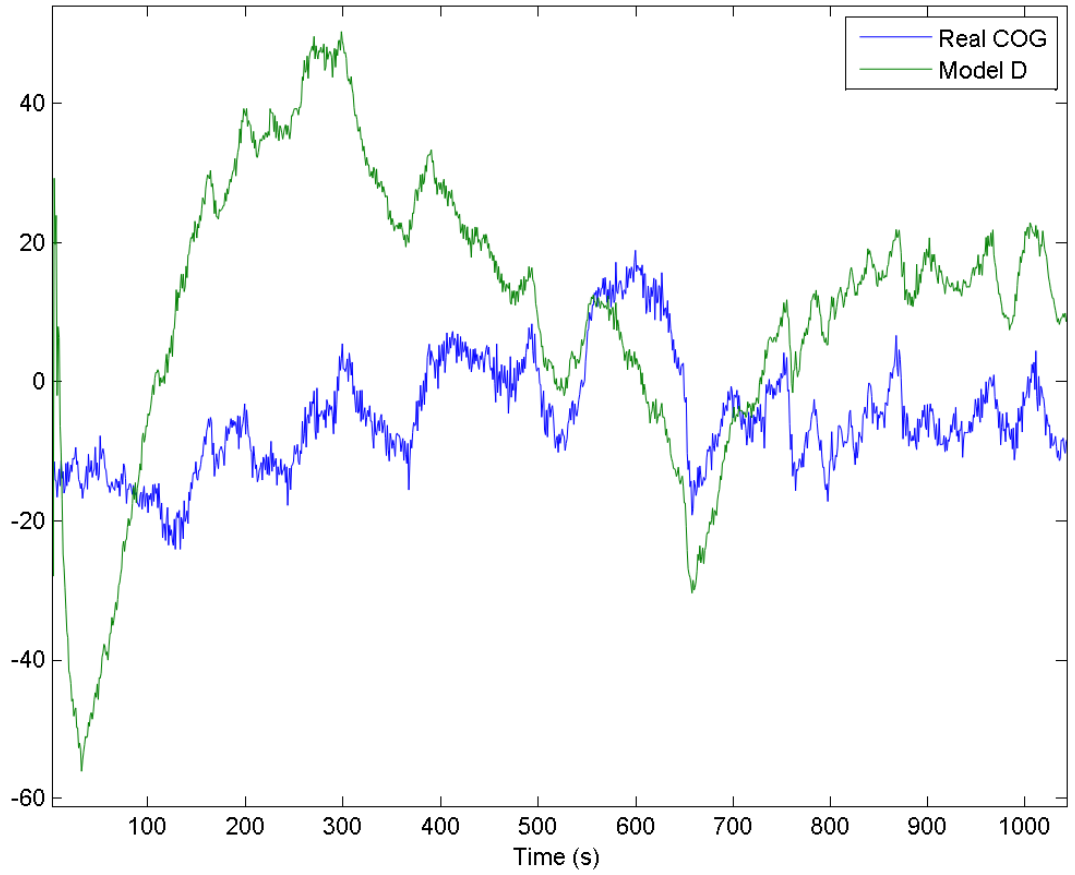


Numerical results

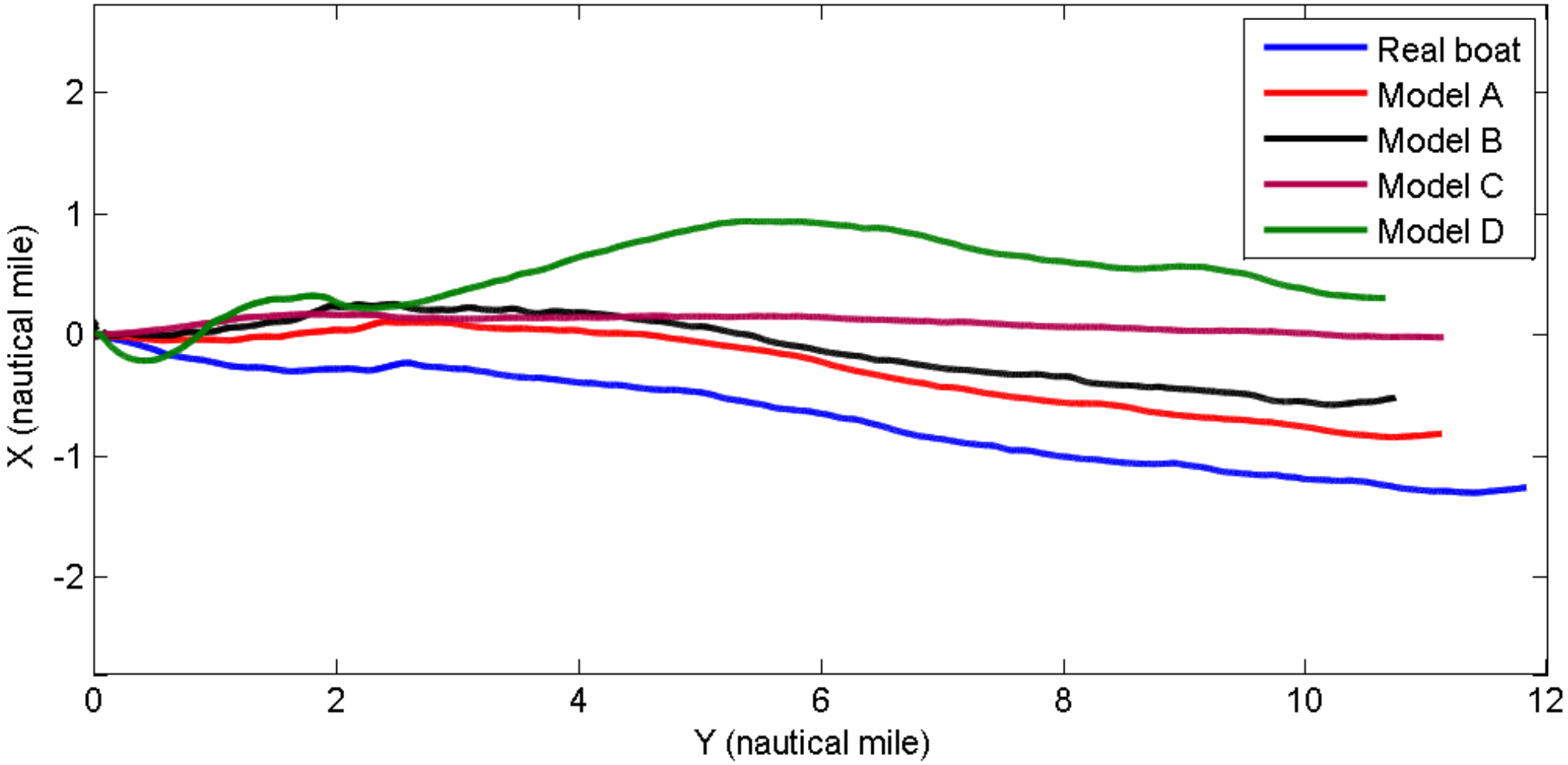
Model name	C1 (%)	C2 (NM)
A	36.6	0.8261
B	4.39	1.3089
C	-2.95	1.4157
D	-110	1.9528

Simulated COG





Simulated trajectories



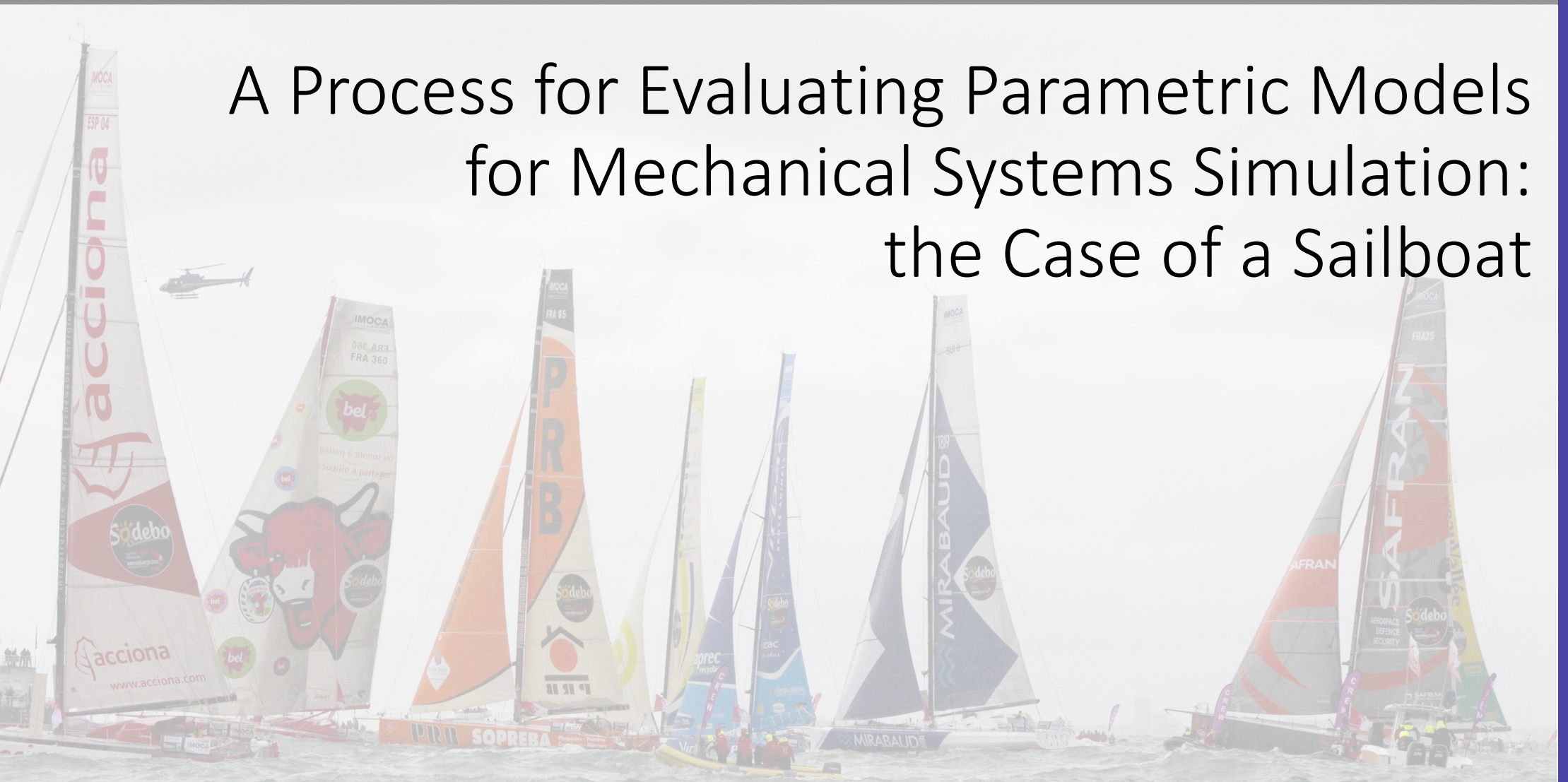
Conclusion and Future works

- Solution to simulate the system behavior
- Choice between accurate and versatile model

Future works

- Models with new inputs : new sensors on the boat
- Other measurements to validate the model
- Automation of regime detection
- Automation of optimal model setting

Any question ?



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