Imitating Trajectories in Aviation

Data-Driven Trajectory Imitation with Reinforcement Learning

Collaborating Organizations:

University of Piraeus Research Center, Greece

Boeing Research and Technology Europe, Spain

Objective

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- The objective of this project is to present algorithms for data-driven imitation of flown trajectories, following deep reinforcement learning techniques towards enhancing trajectory planning abilities.
- Treat historical data as data provided by “experts” that a machine learning algorithm should exploit.
- Imitate experts without going further on optimizing during the learning process.

Operational Goals

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- Approaching the trajectory planning problem as an imitation problem, using models learnt from historical data.
- Identify the features relevant to airspace users while planning, towards learning stakeholders' reward models.
- Increase enhanced trajectory prediction and planning abilities, by means of learning models of trajectories planned and flown by airspace users.
- Improved operations productivity by contributing to improved trajectory planning.

Data Sources (1/2)

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- Surveillance data
  - Flightradar24: historical trajectories for January, April, July 2019 above all Spanish Sectors

	January	April	July
BCN-MAD	746	704	626
MAD-BCN	740	693	618
ALL	154278	202552	242173

Data Sources (2/2)

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- Flight plan data
  - DDR ALLFT+: historical flight plans for January 2019 above all Spanish Sectors

BCN-MAD	MAD-BCN	ALL
778	779	20374

- Sector configuration data: Sectorization and active Sector Configurations
- Weather data
  - NOAA
  - METAR
  - TAF

Problem Formulation

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- Origin and Destination pair of Airports
- A set of historical trajectories
  - A trajectory is defined as a series of 4 dimensional points in the airspace
  - Samples every 5 seconds, achieved with interpolation
  - State parameters: longitude, latitude, altitude and timestamp
  - Actions: Δ State in spatial dimensions i.e. Δlongitude, Δlatitude, Δaltitude
- Every trajectory is further enriched with additional relevant data such as weather conditions, flight plans, air traffic information
  - Surface pressure, humidity, temperature, gust wind speed, u-component and v-component of wind

Overall Architecture

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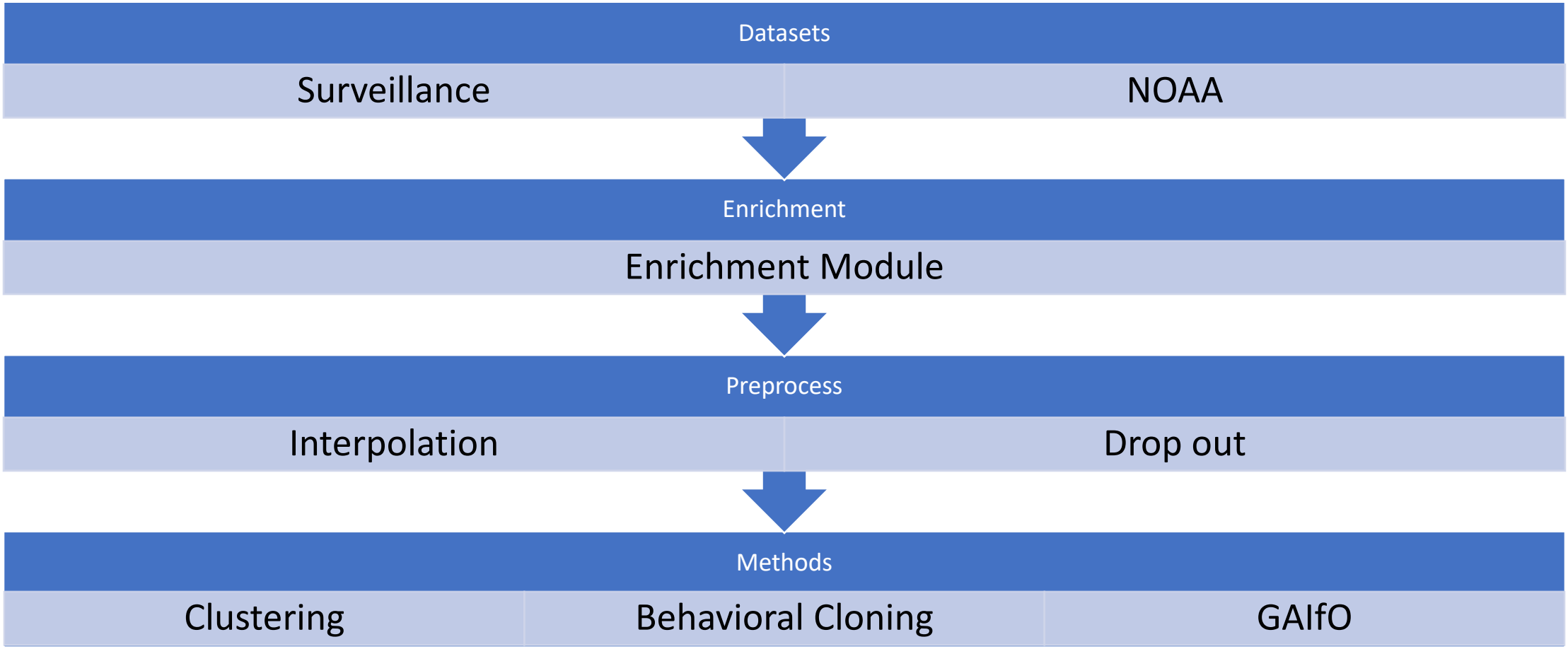
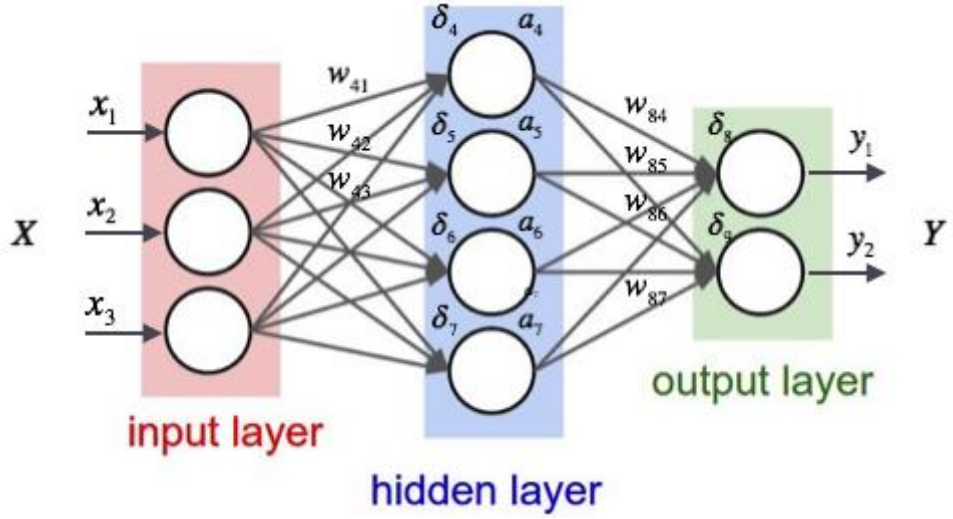


Clustering

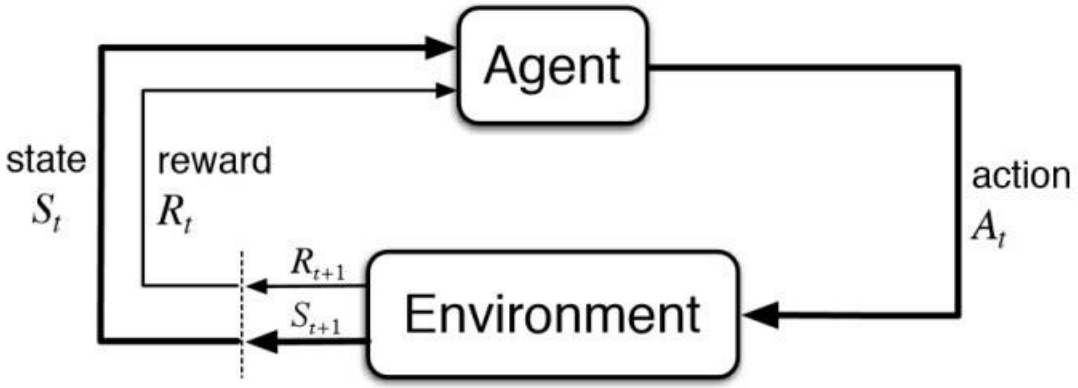
- ***k-means*** is a simple partitioning clustering algorithm, it groups similar objects in the same cluster and it minimizes an objective error function.
- ***Agglomerative clustering*** is a bottom-up (hierarchical) strategy for drawing the structure of data.
- Two types of distance functions have been studied to measure the dissimilarity between two multivariate trajectories.
  - DTW
  - RMSE
- ***Silhouette coefficient*** is an evaluation criterion that is based on the intra-class and inter-class distances of each object pair.

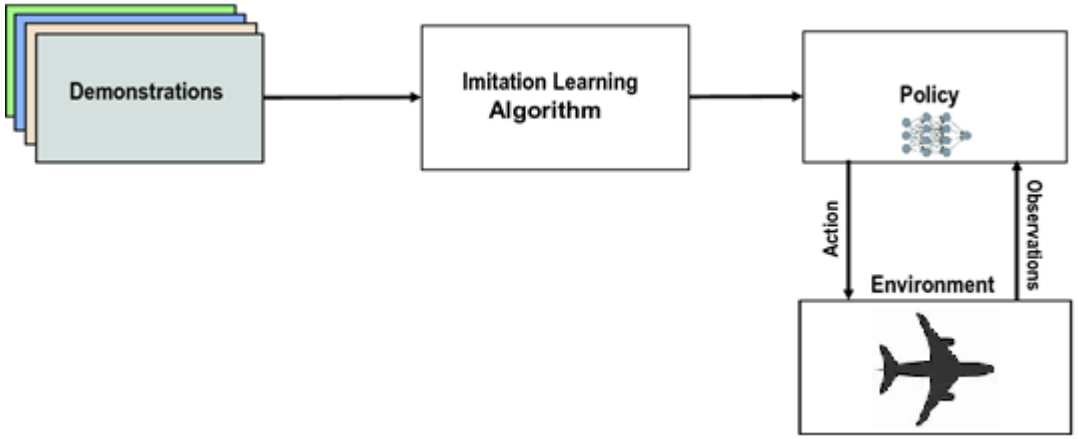
Behavioral Cloning

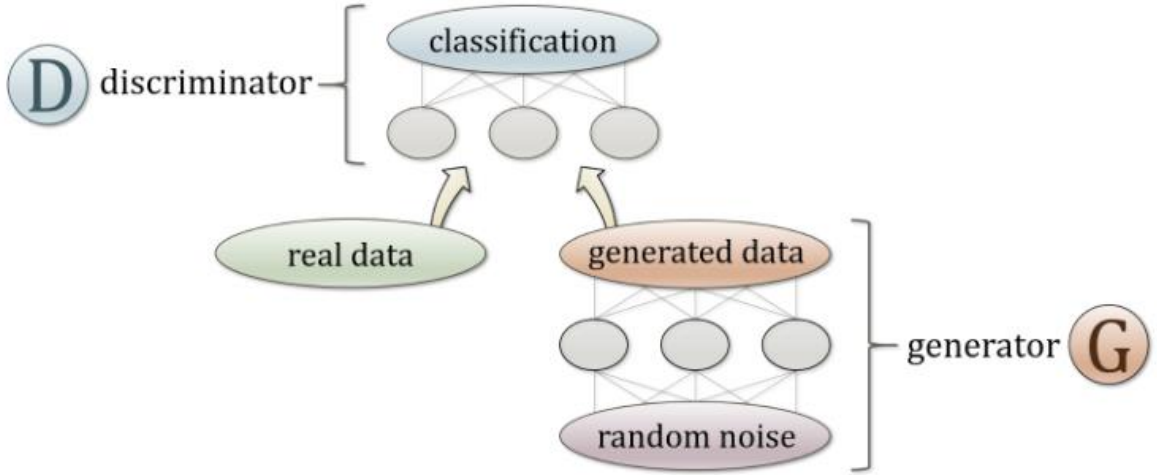
- Standard supervised learning techniques
- Bound to make mistakes
- Often used as a baseline



Generative Adversarial Imitation Learning from Observation (GAIfO)







Experimental Settings (1/2)

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- Surveillance with Spatiotemporal & Weather data
- Spatial Coverage:
  - Origin Airport: Barcelona
  - Destination Airport: Madrid
- Temporal Coverage:
  - April 1st – April 24th 2016
- Flights:
  - Total Flights: 530 flights
  - Training Set: 480 flights
  - Test Set: 50 flights

Training set

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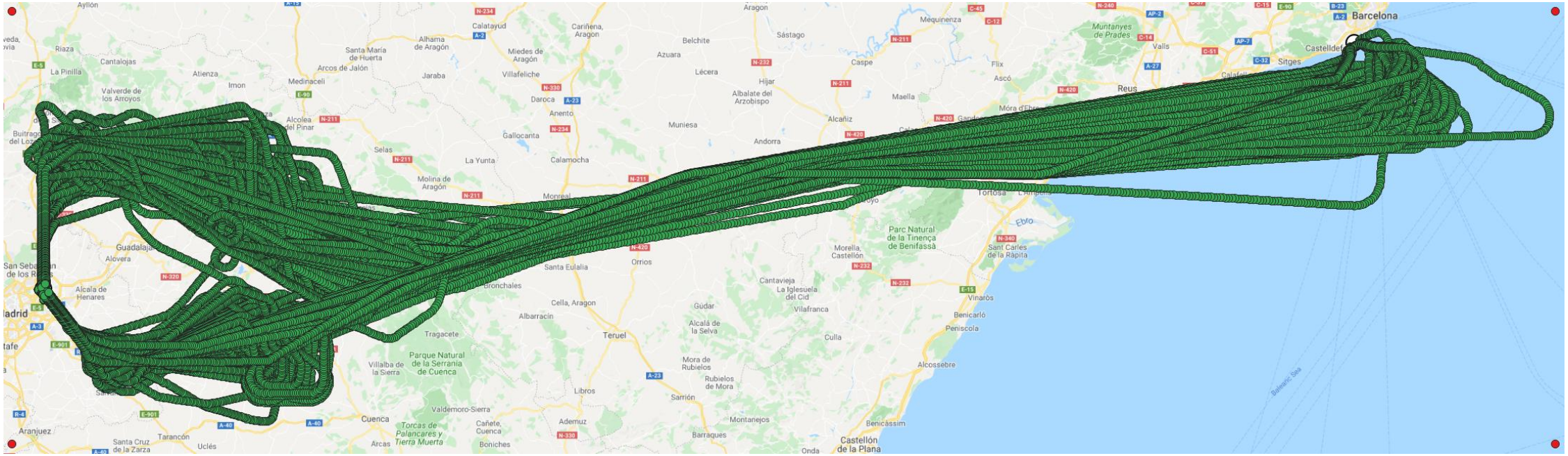
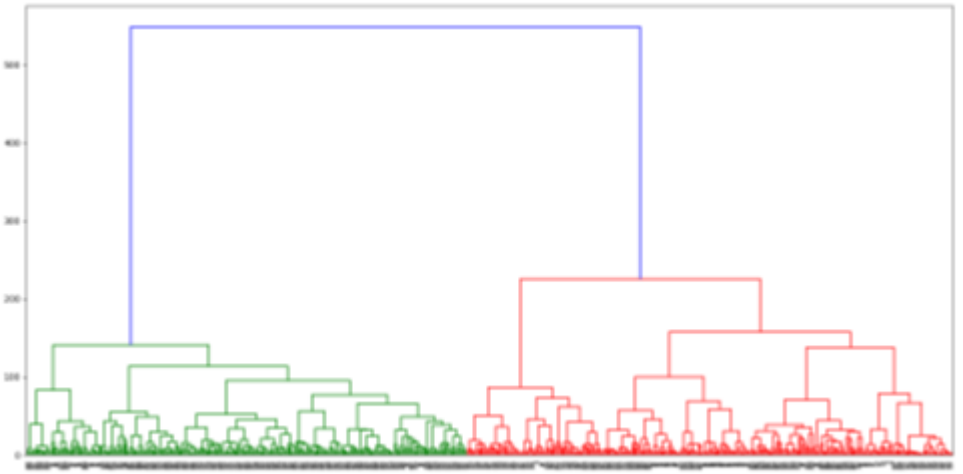
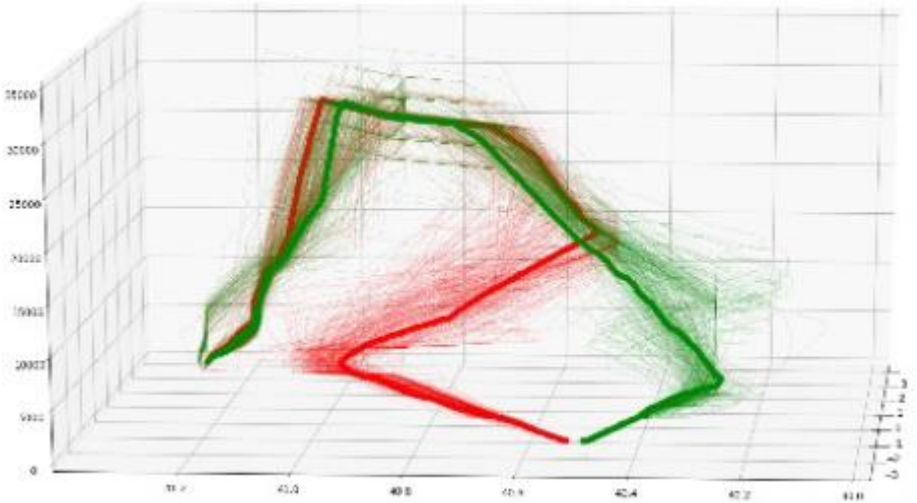


Clusters identified in the training set





Experimental Settings (2/2)

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Behavioral Cloning (BC)	Spatiotemporal (ST)	Spatiotemporal w/ Clustering (ST_CL)	Spatiotemporal + Weather (W)	Spatiotemporal + Weather w/ Clustering (W_CL)
GAIfO	Spatiotemporal (ST)	Spatiotemporal w/ Clustering(ST_CL)	Spatiotemporal + Weather (W)	Spatiotemporal + Weather w/ Clustering (W_CL)

Preliminary Experimental Results: DTW

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Method	State	DTW Mean	DTW Std
BC	Spatiotemporal (ST)	30.67	19.50
GAIfO	Spatiotemporal (ST)	13.01	10.55
BC	Spatiotemporal + Weather (W)	20.06	14.04
GAIfO	Spatiotemporal + Weather (W)	12.55	11.28

Method	State	DTW Mean	DTW Std
BC	Spatiotemporal (ST_CL)	6.88	5.98
GAIfO	Spatiotemporal (ST_CL)	4.84	1.288
BC	Spatiotemporal + Weather (W_CL)	27.53	19.75
GAIfO	Spatiotemporal + Weather (W_CL)	5.45	2.27

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Preliminary Experimental Results: RMSE

Method	State	RMSE Mean	RMSE Std
BC	Spatiotemporal (ST)	0.35	0.14
GAIfO	Spatiotemporal (ST)	0.18	0.13
BC	Spatiotemporal + Weather (W)	0.29	0.17
GAIfO	Spatiotemporal + Weather (W)	0.18	0.15

Method	State	RMSE Mean	RMSE Std
BC	Spatiotemporal (ST_CL)	0.13	0.11
GAIfO	Spatiotemporal (ST_CL)	0.08	0.02
BC	Spatiotemporal + Weather (W_CL)	0.36	0.18
GAIfO	Spatiotemporal + Weather (W_CL)	0.08	0.03

Preliminary Experimental Results: Visualization BC vs GAIfO W_CL

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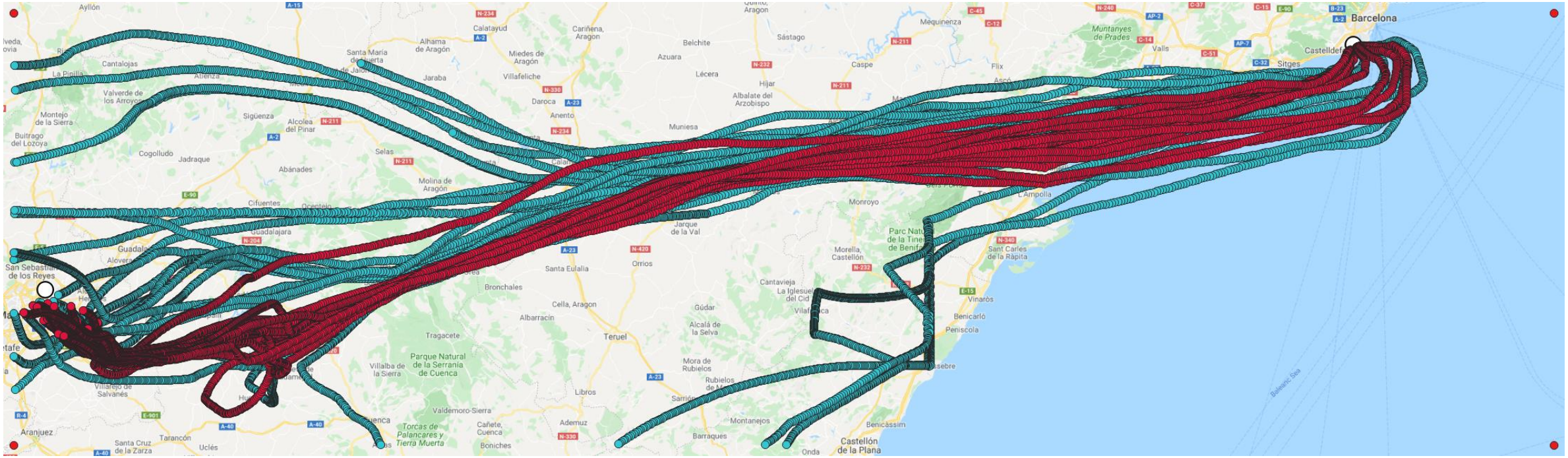

Preliminary Experimental Results: Horizontal Deviation GAIfO W_CL

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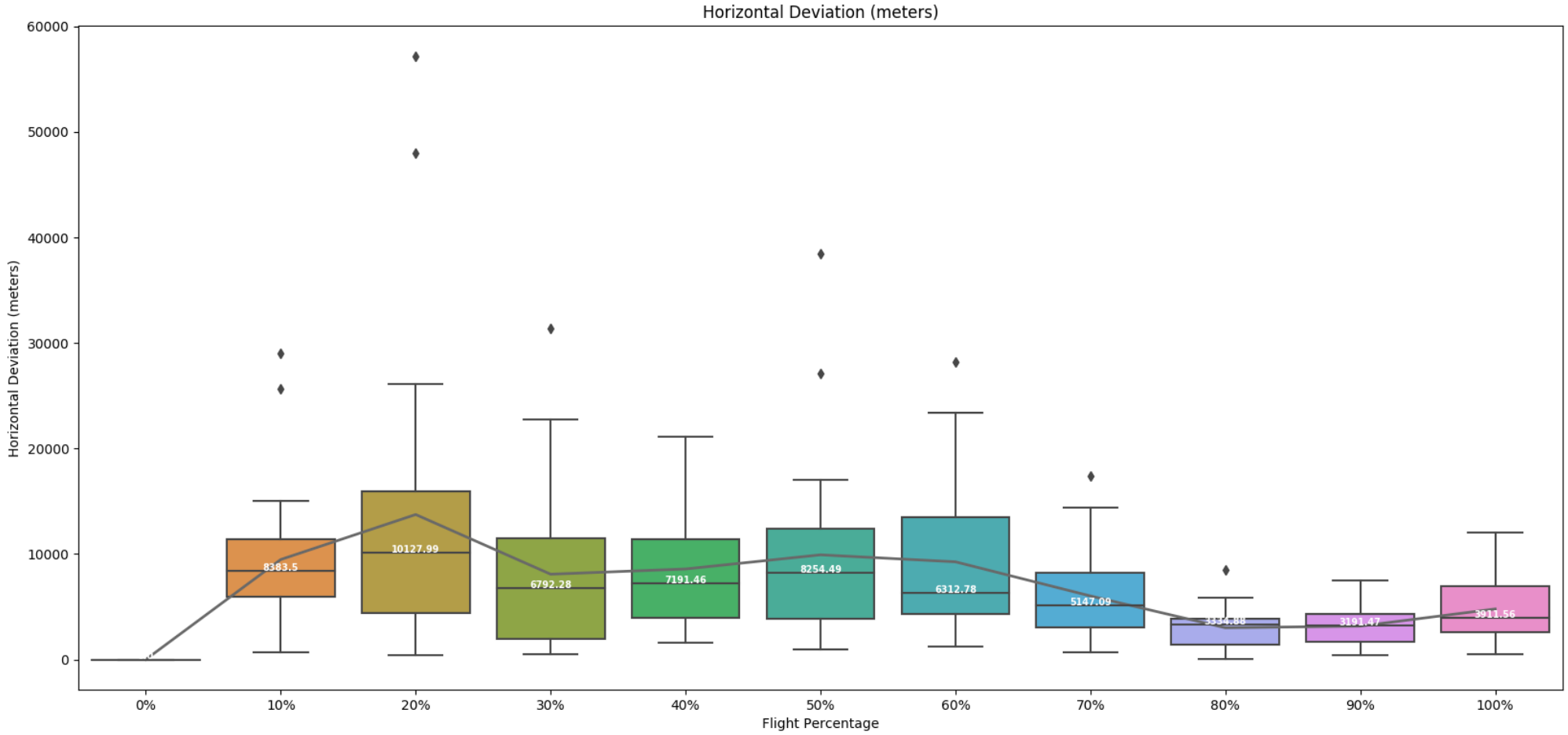

Preliminary Experimental Results: Vertical Deviation GAIfO W_CL

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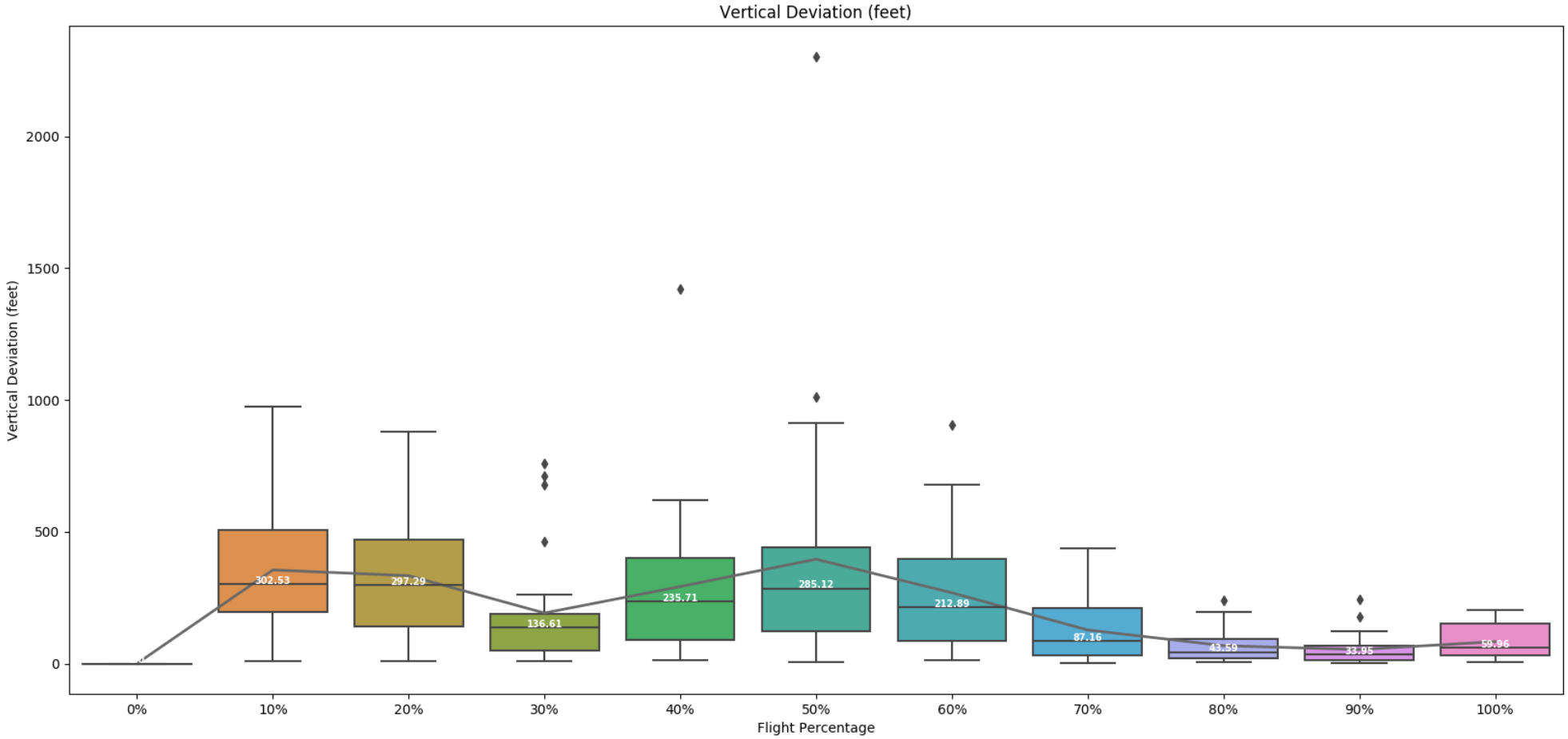

Preliminary Experimental Results: Worst Case GAIfO W_CL

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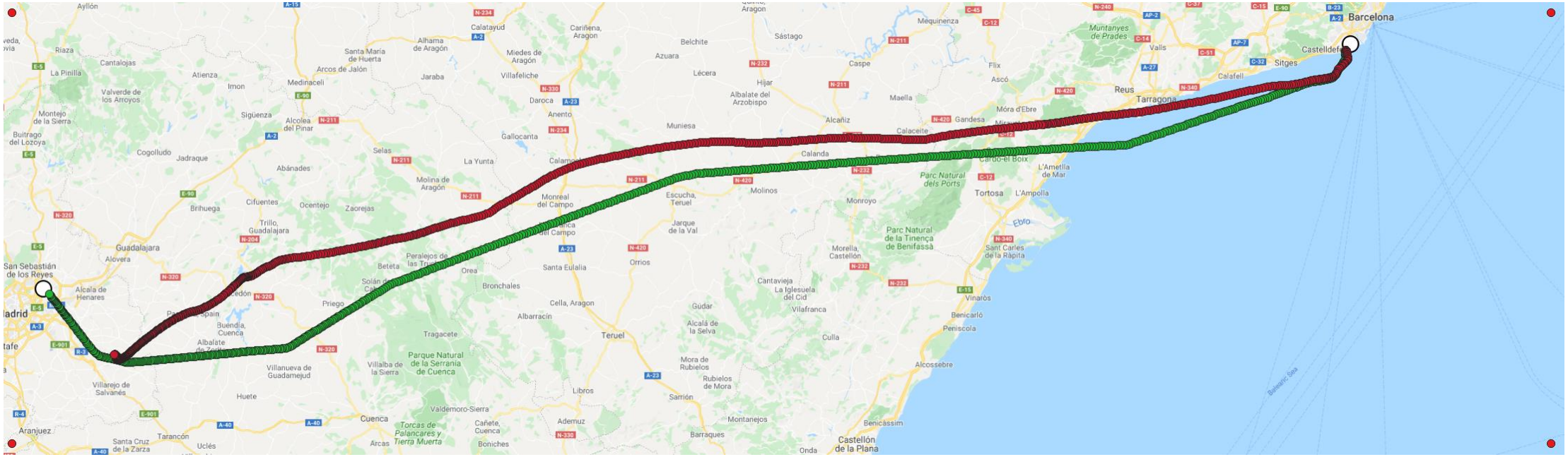

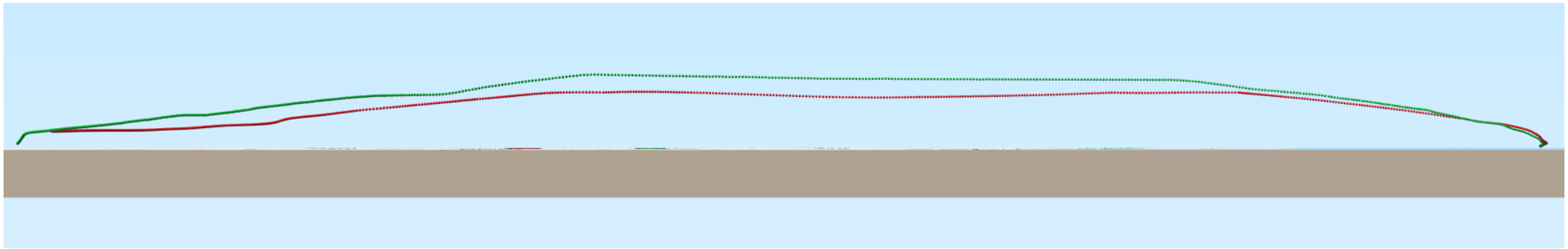

Preliminary Experimental Results: Average Case GAIfO W_CL

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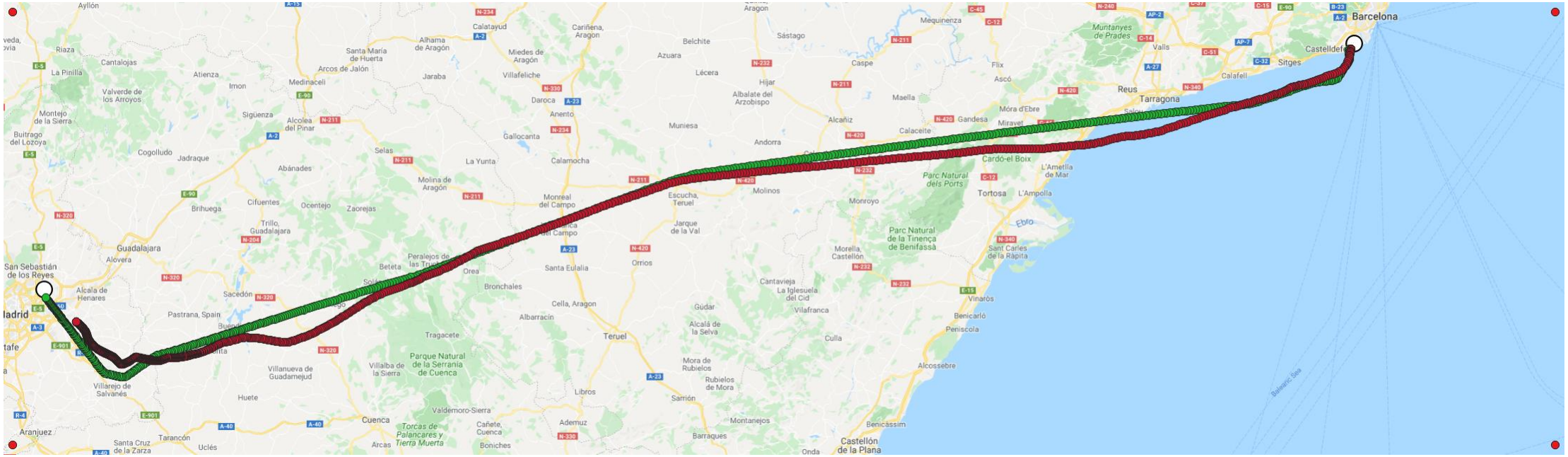

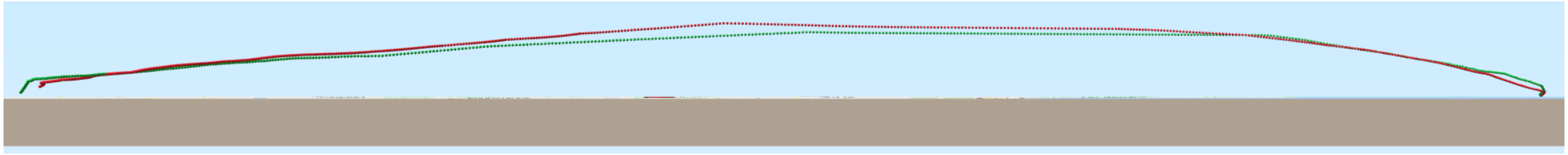

Preliminary Experimental Results: Best Case GAIfO W_CL

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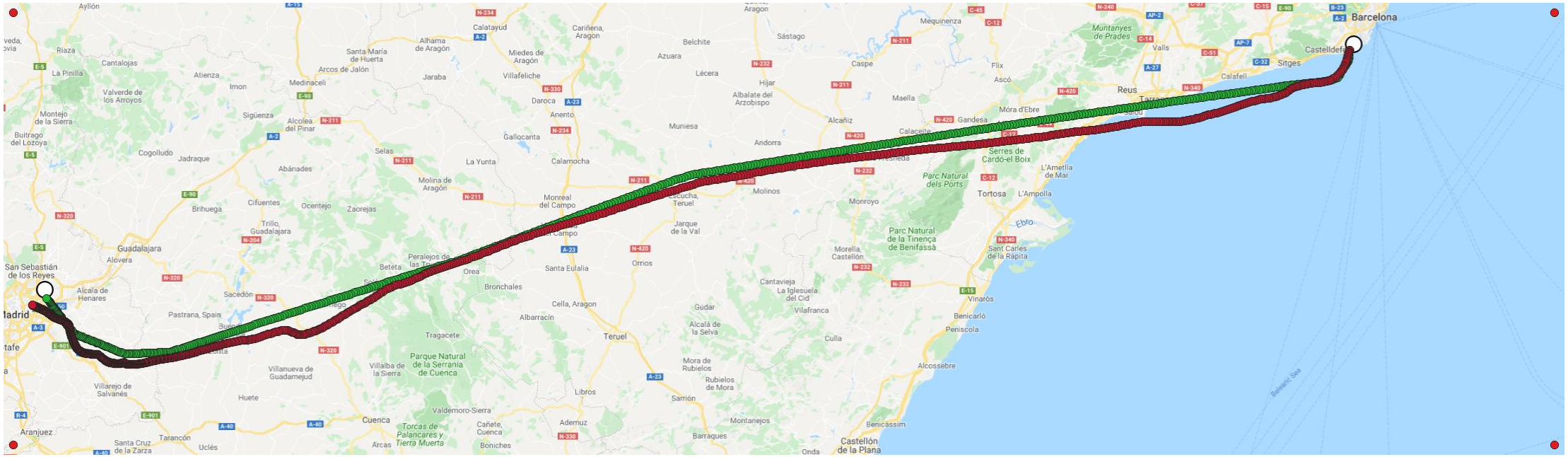

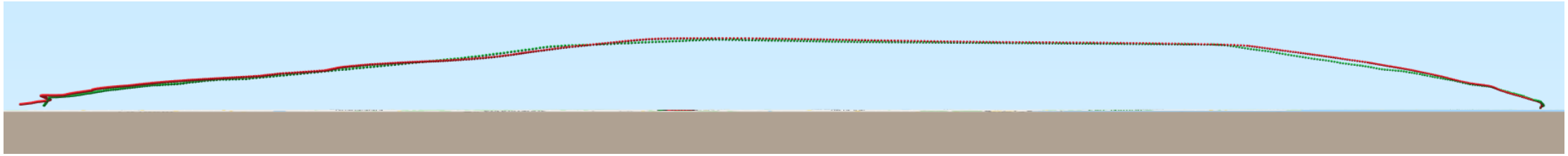

Preliminary Experimental Results: More Training

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Method	State	DTW Mean	DTW Std
GAIfO 1.5k	Spatiotemporal (ST_CL)	4.84	1.288
GAIfO 3k	Spatiotemporal (ST_CL)	4.10	1.31
GAIfO 1.5k	Spatiotemporal + Weather (W_CL)	5.45	2.27
GAIfO 3k	Spatiotemporal + Weather (W_CL)	5.08	1.85

Method	State	RMSE Mean	RMSE Std
GAIfO 1.5k	Spatiotemporal (ST_CL)	0.08	0.02
GAIfO 3k	Spatiotemporal (ST_CL)	0.06	0.02
GAIfO 1.5k	Spatiotemporal + Weather (W_CL)	0.08	0.03
GAIfO 3k	Spatiotemporal + Weather (W_CL)	0.08	0.02

Future Work

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- Further experiments and fine tuning, more origin/destinations
- Further trajectory enrichment
  - Weather conditions of the origin/destination airports
  - Bigger “line of sight” of the aircraft
  - Flight plans
  - Air traffic
- Utilizing Clustering’s promising results for unknown trajectories
- Recovering the experts’ cost function

Thank you

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Preliminary Experimental Results: Visualization BC vs GAIfO SP

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