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Probabilistic Constraints Prediction with Uncertainty Quantification in Trajectory Based Operations (TBO)

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SUPPORTED BY sesar JOINT UNDERTAKING

This project has received funding from the SESAR Joint Undertaking (JU) under grant agreement No 101114701. The JU receives support from the European Union's Horizon Europe research and innovation programme and the SESAR JU members other than the Union.

The Challenge

SESAR3 Network TBO Solution 1

*Let's calculate the **probability** of ATCO applying the ATC LoA **constraint** by using **machine learning***

Want to fly the optimum trajectory.
Not sure that the ATCO will apply the constraint, no need to comply.
It is expensive to comply

Flight Dispatcher

Pilot

There is an ATC LoA constraint, TOD shall be later, I will apply, and inform ANSPs accordingly

Network Manager

ATCO

It is quiet today, I will give a better flight level to the Pilot

Ah, Pilot expects another TOD, cannot ask descend at TOD, must coordinate with the Pilot!!!

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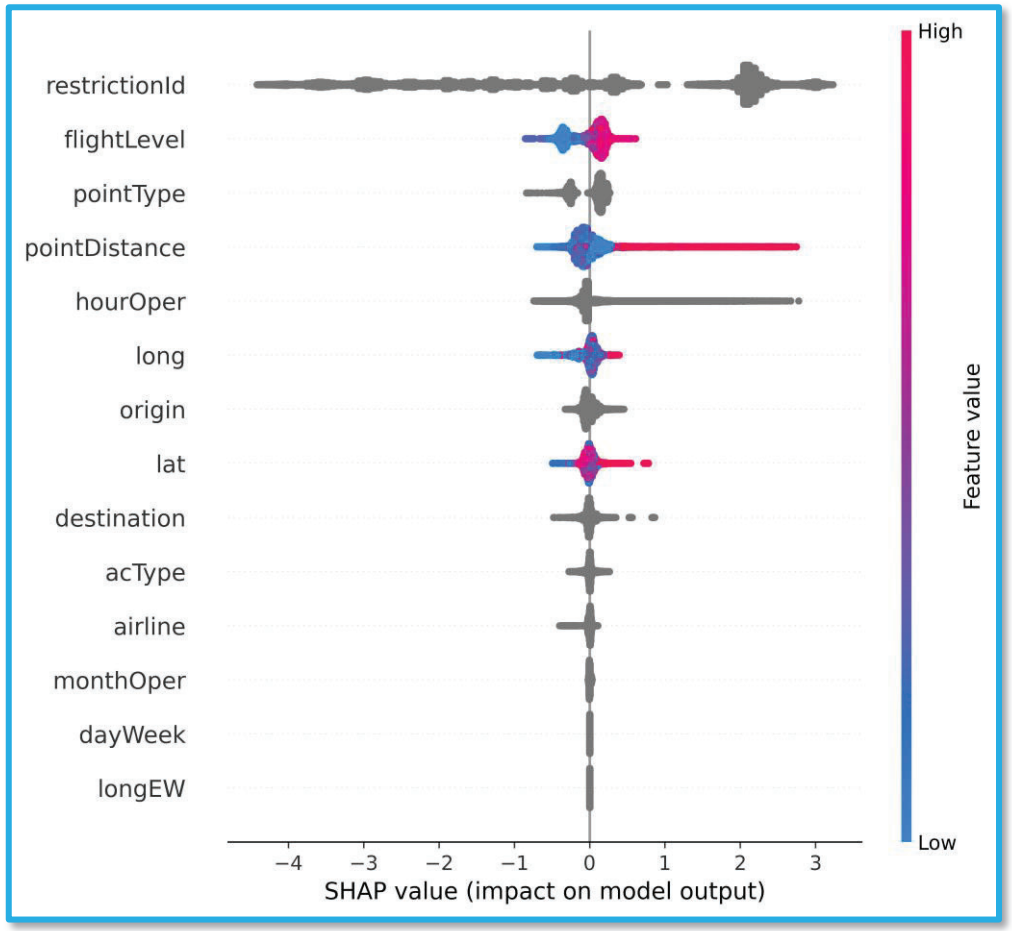
Probabilistic Machine Learning Approach

- Data from the entire 2024
- Pre-processing agreed and flown flight trajectories to label single way points with possible constraints
- Only trajectory input data
- Binary classifier CatBoost algorithm
- Main output: probability of a constraint to be applied (positive class) and not (negative class)



Model metrics (macro average)		
Precision	**Recall**	**Accuracy**
0.82	0.85	0.86

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Uncertainty Quantification in Machine Learning

- We can improve the **user's decision making** by providing **more insights** into the quality of **individual predictions**
- Predictions can be affected by **data uncertainty** and **knowledge uncertainty**
- Data uncertainty occurs due to noise and class overlap in the data
- Knowledge uncertainty happens due to mismatch between training and testing dataset. It can be reduced by increasing the training data
- Different techniques to quantify uncertainties: single model *vs* ensembles (*), (**), (***)
- The entropy of a discrete probability distribution is a measure of uncertainty
- Data and total uncertainties can be quantified
- $Knowledge\ uncertainty = Total\ uncertainty - Data\ uncertainty$
- Our approach: Bootstrapping with 50 models

(*) Malinin, Andrey. Uncertainty estimation in deep learning with application to spoken language assessment. Diss. 2019.

(**) De Falco, P., & Karaarslan, M. Probabilistic Constraints Prediction with Uncertainty Quantification in Trajectory Based Operations (TBO). SESAR Innovation Days 2024

(***) Roadmap, E. A. I. (2021). EASA Concept Paper: First usable guidance for Level 1 machine learning applications.

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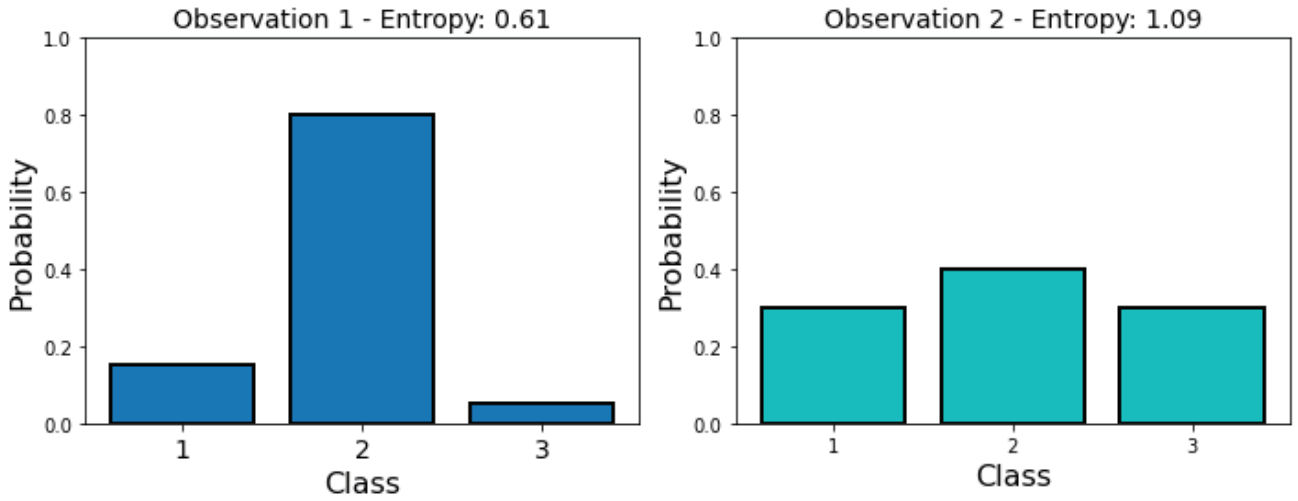
Uncertainty Quantification in Classification

- In classification machine learning (ML), models can produce probabilities that represent the likelihood of an input being associated with each possible class



Uncertainty of single observations

- Low entropy
- High entropy

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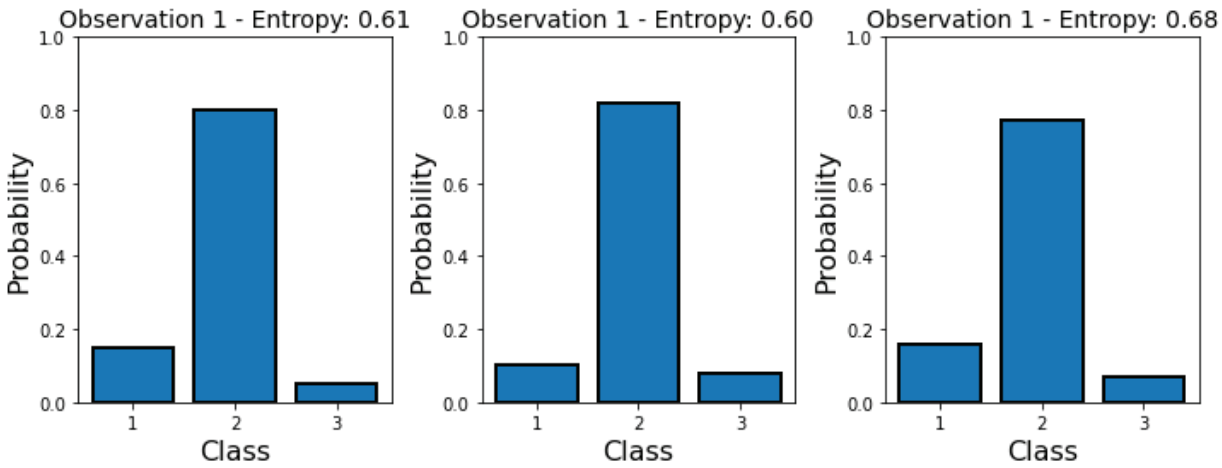
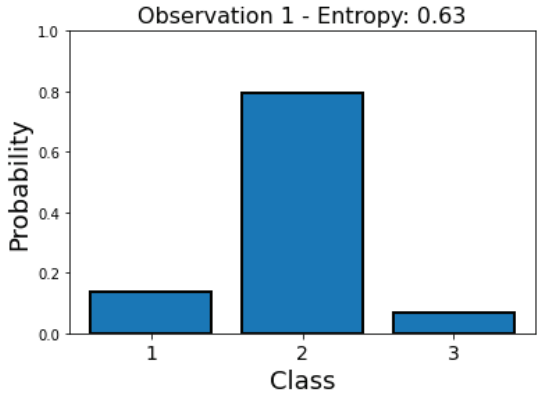
Uncertainty Quantification in Classification





Expected distribution

Uncertainty quantification in ensembles

- **Low** entropy of each prediction
- **Low** data uncertainty (average of entropies) in ensemble
- **Low** total uncertainty in ensemble
- **Low** knowledge uncertainty in ensemble

Data uncertainty = 0.631 nats
Total uncertainty = 0.632 nats
Knowledge uncertainty ≈ 0.001 nats

$$Knowledge\ uncertainty = Total\ uncertainty - Data\ uncertainty$$

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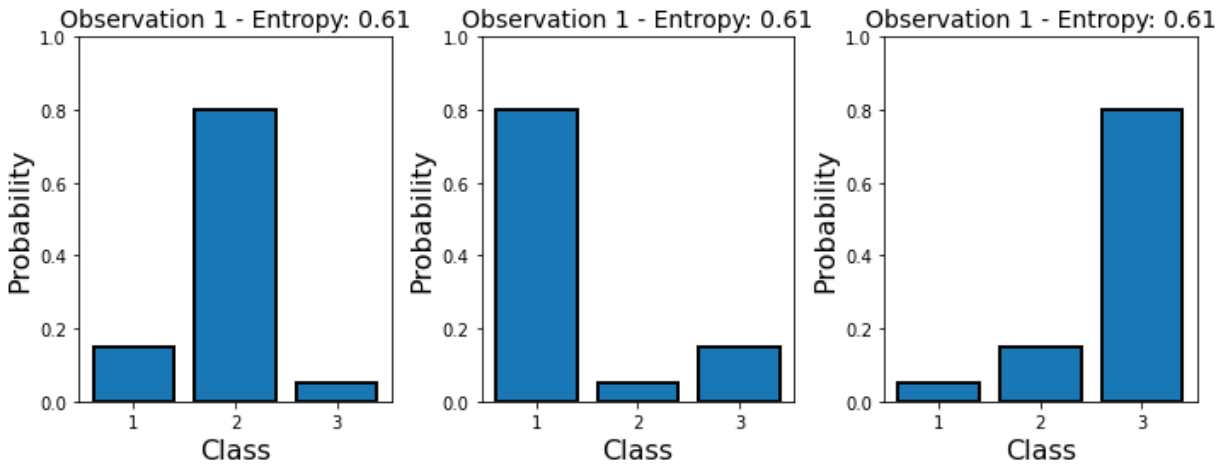
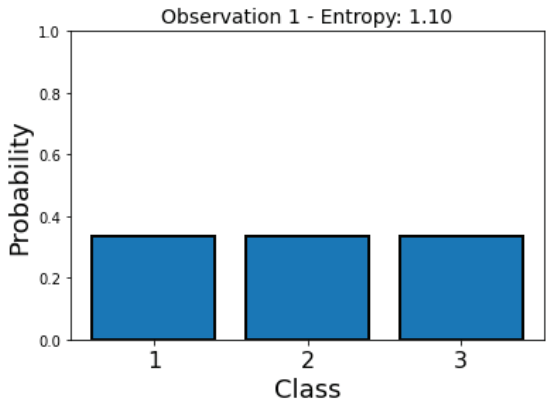
Uncertainty Quantification in Classification





Expected distribution

Uncertainty quantification in ensembles

- **Low** entropy of each prediction
- **Low** data uncertainty (average of entropies) in ensemble
- **High** total uncertainty in ensemble
- **High** knowledge uncertainty

Data uncertainty = 0.61 nats
Total uncertainty = 1.10 nats
Knowledge uncertainty ≈ 0.40 nats

$$Knowledge\ uncertainty = Total\ uncertainty - Data\ uncertainty$$

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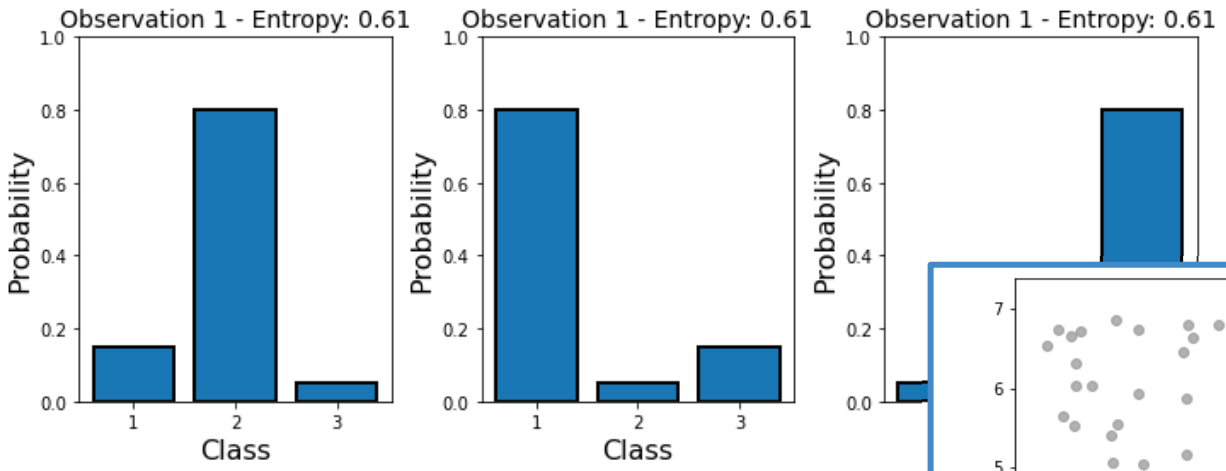
Uncertainty Quantification in Classification



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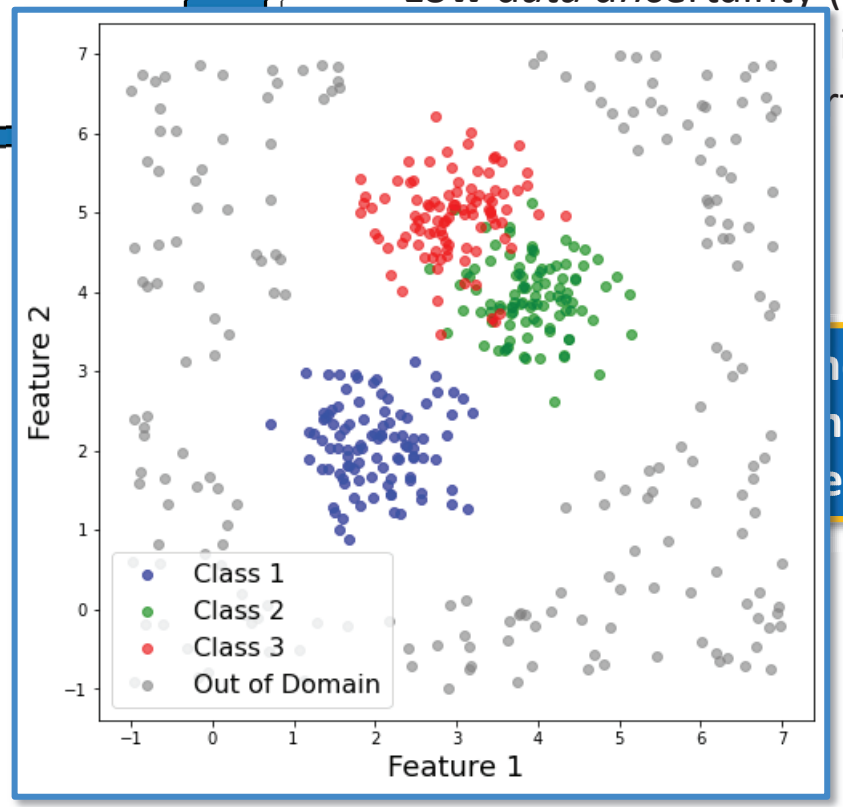

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Detecting unusual inputs using knowledge uncertainty

- Knowledge uncertainty values are **relatively low** for “standard” inputs
- Knowledge uncertainty values **increase significantly** for “unusual” inputs
- Knowledge uncertainty-based alerting system
  - Detects anomalies
  - Increase the level of user’s confidence in model usage
- Threshold selection to **minimise false alerts** while **maximising true alerts**

Applied constraint probability = 80%

Applied constraint probability = 80%

Applied constraint probability = 80%

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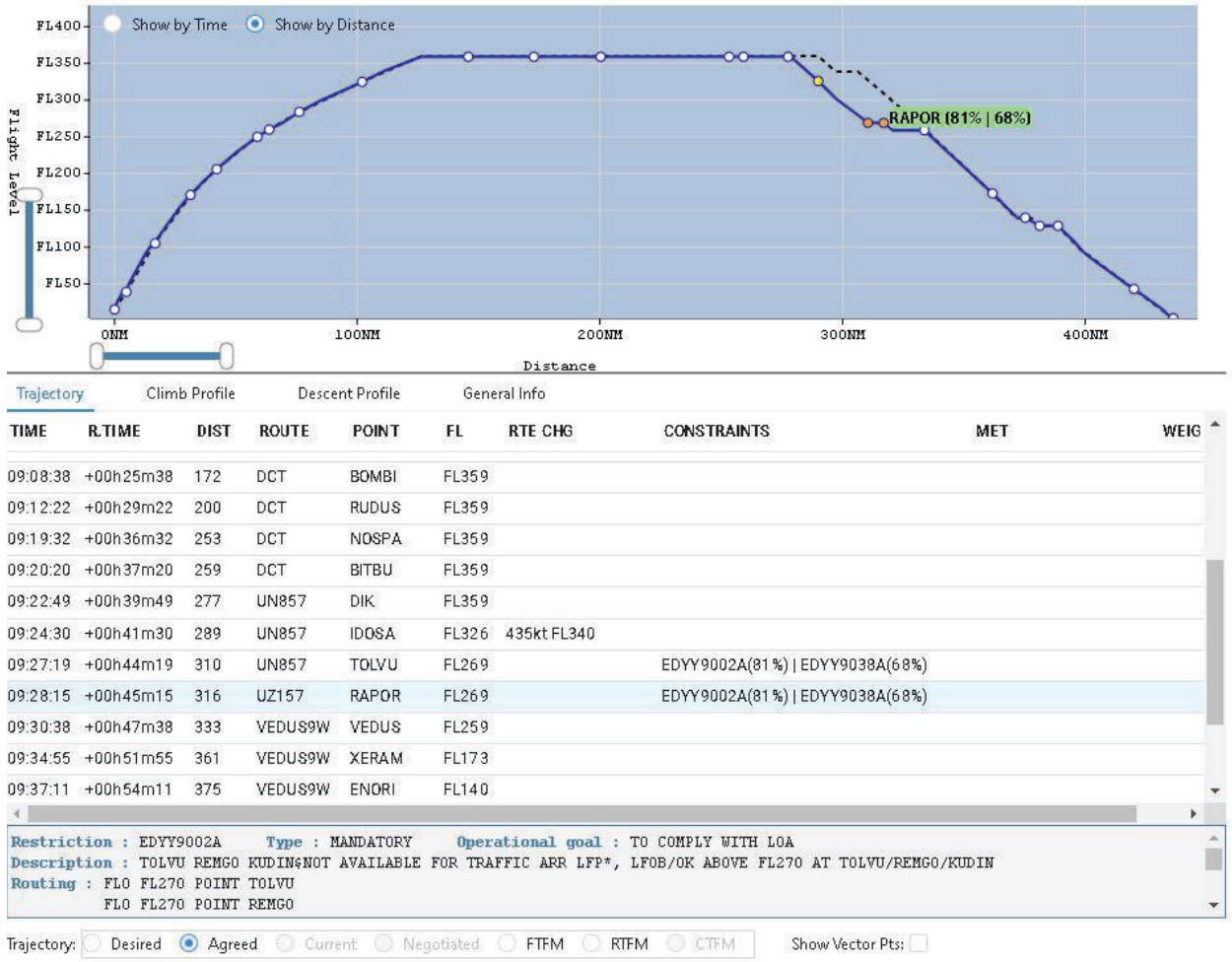
Next Steps

SESAR 3 Network TBO – Solution 1

- *Demonstrate that the trajectories are more aligned and predictable*

- Validation June 2025
- Visualize on real-time data
- Questions to answer
  - Is the probability information acceptable/reliable?
  - How can the AU use it?
  - Which probability threshold to use?
  - Which other ATM actors can use it?
  - If and how the knowledge uncertainty can be used?



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Thank you!

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