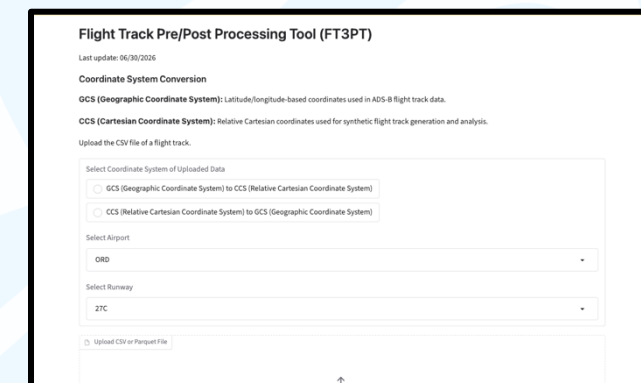
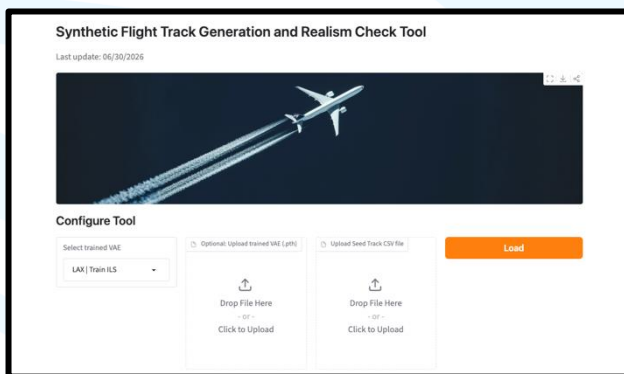




AI-Enabled Modeling and Simulation for Airspace Safety Analysis: A Digital Framework for Synthetic Flight Track Generation, Validation, and Collision Risk Assessment

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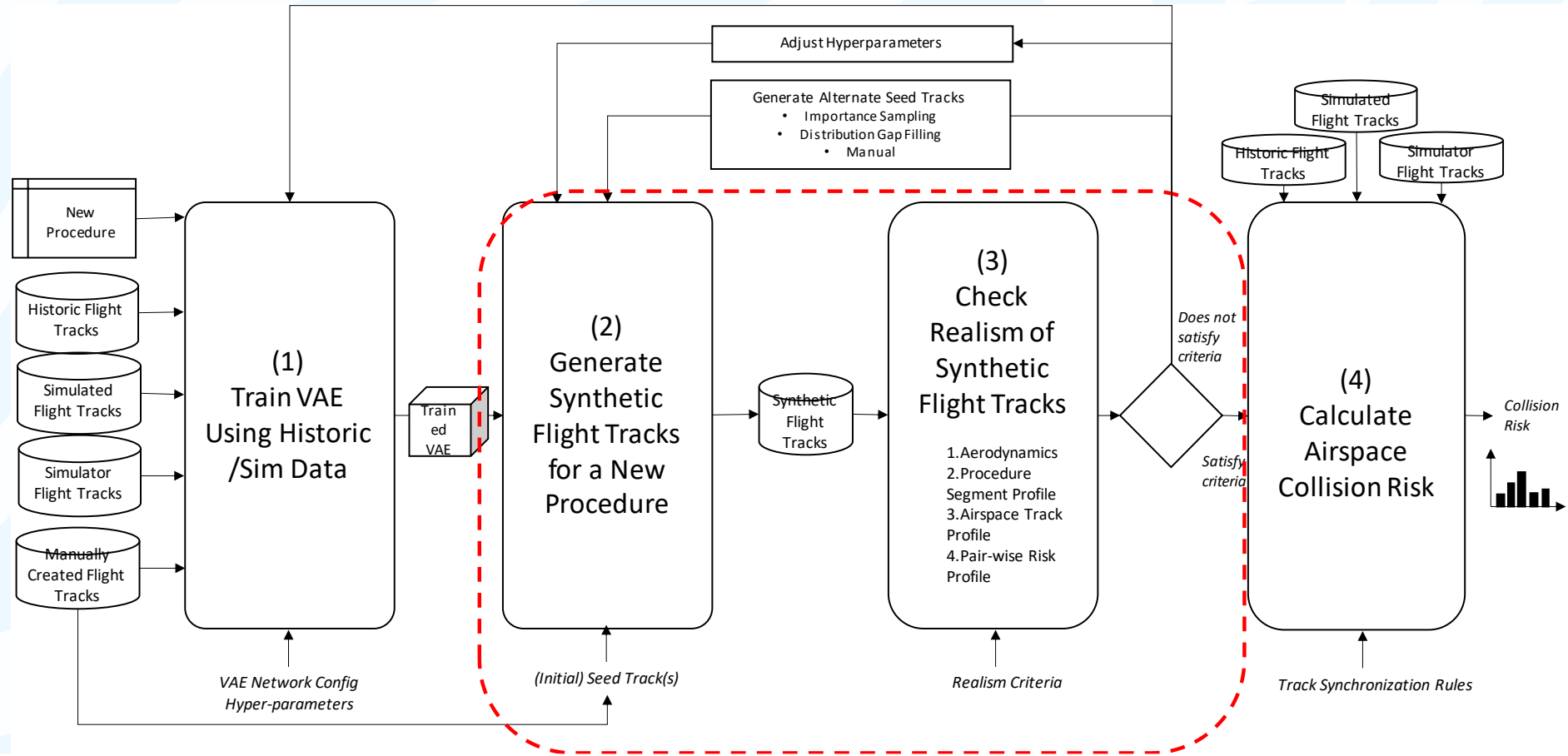
Outline

- I. Introduction
- II. Functional Architecture For Collision Risk Modelling Using Synthetic Flight Tracks
- III. System Specification
 - I. Use Case
 - II. System Requirements
 - III. Tool Functional Architecture
 - IV. User-Interface/Front End Design
 - V. Algorithms/Back-End Design
- IV. Tool Demonstration
- V. Conclusion

I. Introduction

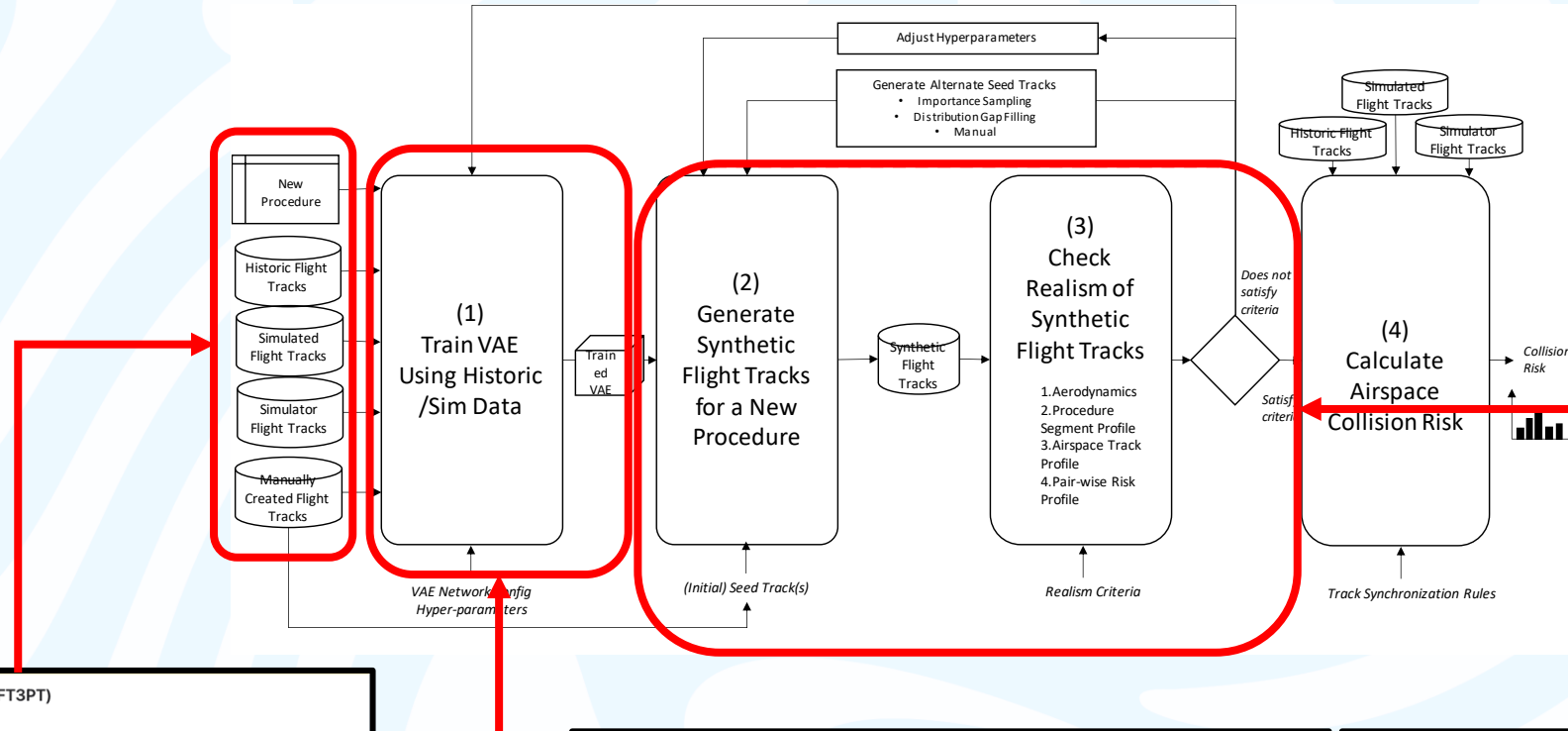
- New navigation procedures and air traffic control technologies require collision risk modelling (CRM) to assess their safety.
- CRM supports evaluation against a Target Level of Safety (TLS), an acceptable upper bound on collision rates.
- Historical flight tracks describe existing operations but may not represent new procedures.
- Because collisions are rare events, reliable risk estimation requires **large, representative flight-track datasets** ($2 \times 3 \times 10^9$ flight tracks).
- Variational Autoencoders (VAEs) can generate synthetic flight tracks using learned patterns and seed tracks.
- This work presents an analyst-oriented tool for **generating, inspecting, and validating synthetic flight tracks** for specific airport arrival and approach procedures.

II. Functional Architecture For Collision Risk Modelling Using Synthetic Flight Tracks



Architecture CRM analysis using synthetic flight tracks

II. Functional Architecture For Collision Risk Modelling Using Synthetic Flight Tracks



Flight Track Pre/Post Processing Tool (FT3PT)

Last update: 06/30/2026

Coordinate System Conversion

GCS (Geographic Coordinate System): Latitude/longitude-based coordinates used in ADS-B flight track data.

CCS (Cartesian Coordinate System): Relative Cartesian coordinates used for synthetic flight track generation and analysis.

Upload the CSV file of a flight track.

Select Coordinate System of Uploaded Data

- ☐ GCS (Geographic Coordinate System) to CCS (Relative Cartesian Coordinate System)
- ☐ CCS (Relative Cartesian Coordinate System) to GCS (Geographic Coordinate System)

Select Airport

ORD

Select Runway

27C

Upload CSV or Parquet File

Variational Autoencoder Training Tool (VAETT)

Upload Variational Autoencoder Training Data

Select the airport and runway and then upload the CSV file.

Select Airport

LAX

Select Runway

24R

Upload CSV File



Drop File Here

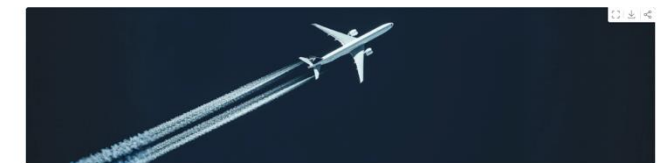
- Or -

Click to Upload

Upload and Prepare Flight Tracks for Training

Synthetic Flight Track Generation and Realism Check Tool

Last update: 06/30/2026



Configure Tool

Select trained VAE

LAX | Train ILS

Optional: Upload trained VAE (.pth)

Upload Seed Track CSV File

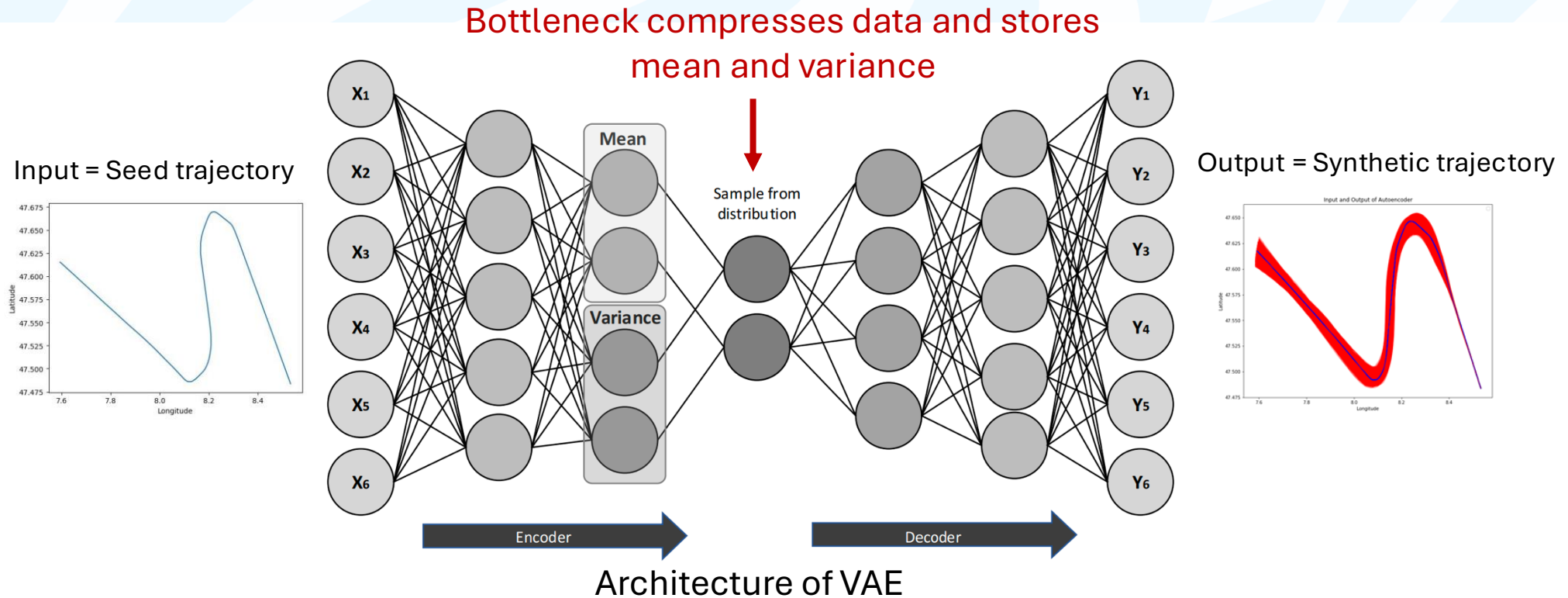
Drop File Here

- Or -

Click to Upload

Load

II. Functional Architecture For Collision Risk Modelling Using Synthetic Flight Tracks



$$Loss = \alpha \times \text{Reconstruction loss} + \beta \times \text{KL loss} + \gamma \times \text{Monotonicity loss}$$

II. Functional Architecture For Collision Risk Modelling Using Synthetic Flight Tracks

- **Train the VAE:** Use historical flight tracks, supplemented by simulated or manually created tracks.
- **Generate synthetic tracks:** Provide seed tracks representing the proposed procedure, preferably similar to the training data.
- **Check realism:** Evaluate aerodynamic behavior, procedural consistency, track-set characteristics, and proximity metrics.
- **Refine the output:** Adjust model loss coefficients or add seeds through importance sampling, distribution gap filling, or manual selection.
- **Calculate collision risk:** Use tracks that meet the analysis criteria to evaluate proximity and projected proximity.

III. System Specification

- This section describes the following:
 - A. Use Case
 - B. System Requirements
 - C. Tool Functional Architecture
 - D. User-Interface/Front End Design
 - E. Algorithms/Back-End Design

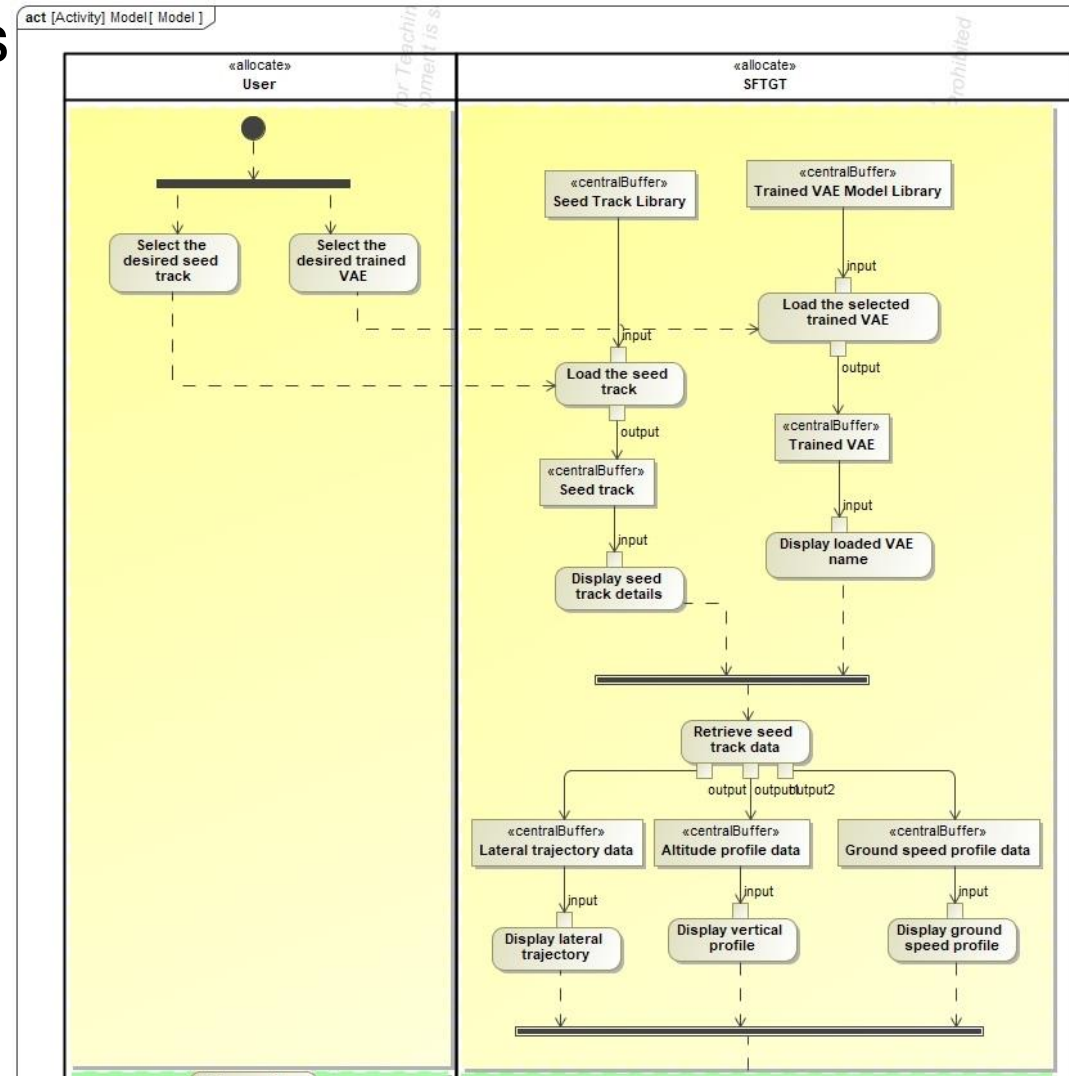
III. System Specification

A. Use Case: Analyst Needs and Inputs

- **Scenario:** Assess collision risk for a proposed arrival and approach procedure.
- **Objective:** Generate sufficient synthetic tracks ($2 \times 3 \times 10^9$ flight tracks) to support the required statistical confidence in the safety assessment.
- **Trained VAE Library:** Models for specific airports, runways, and procedures.
- **Seed Track Library:** Historical, simulator, simulated, or manually created tracks.
- **Historic Track Library:** Reference datasets for evaluating synthetic tracks.

III. System Specification

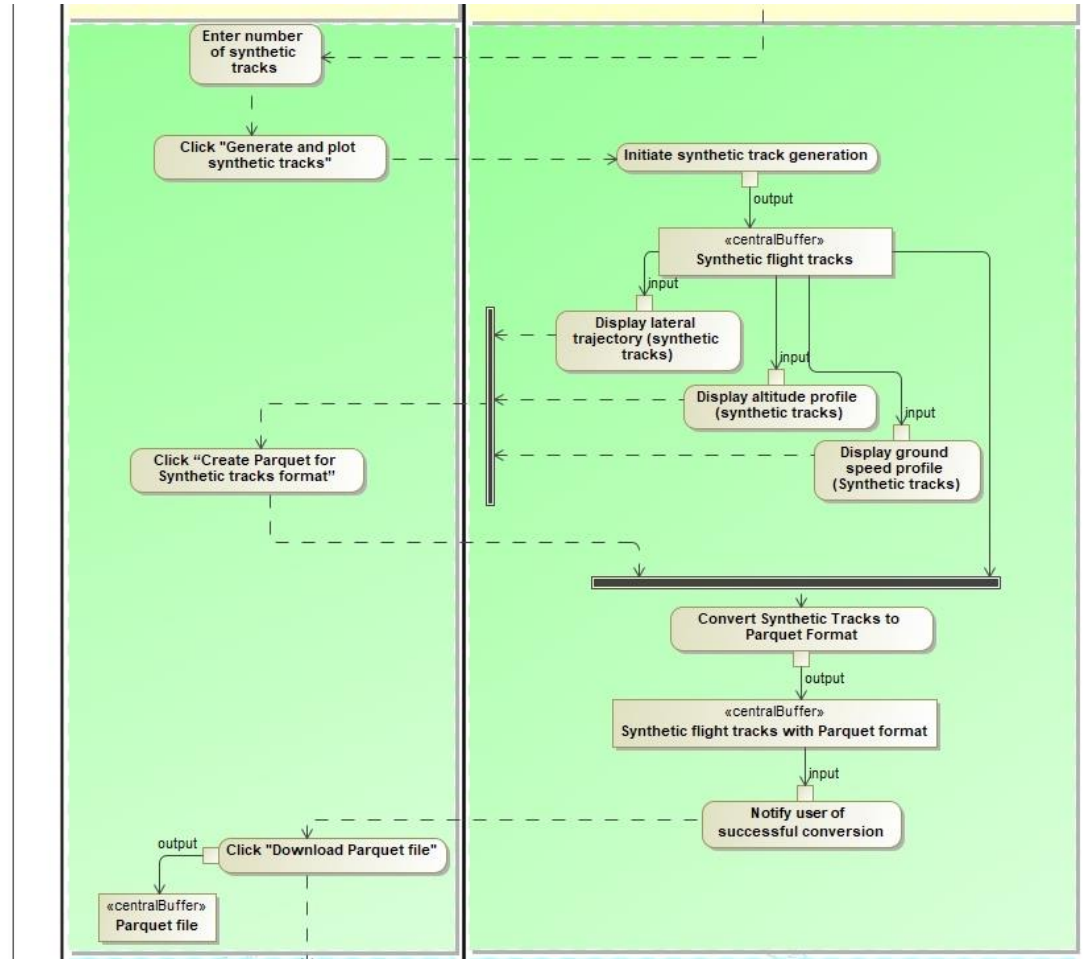
- Configuration: User and Tool roles
- User actions:
 - Select a trained VAE
 - Select seed track
- Tool actions:
 - Process VAE
 - Process seed track
 - Visualize lateral trajectory, altitude, and ground speed profiles



Configuration

III. System Specification

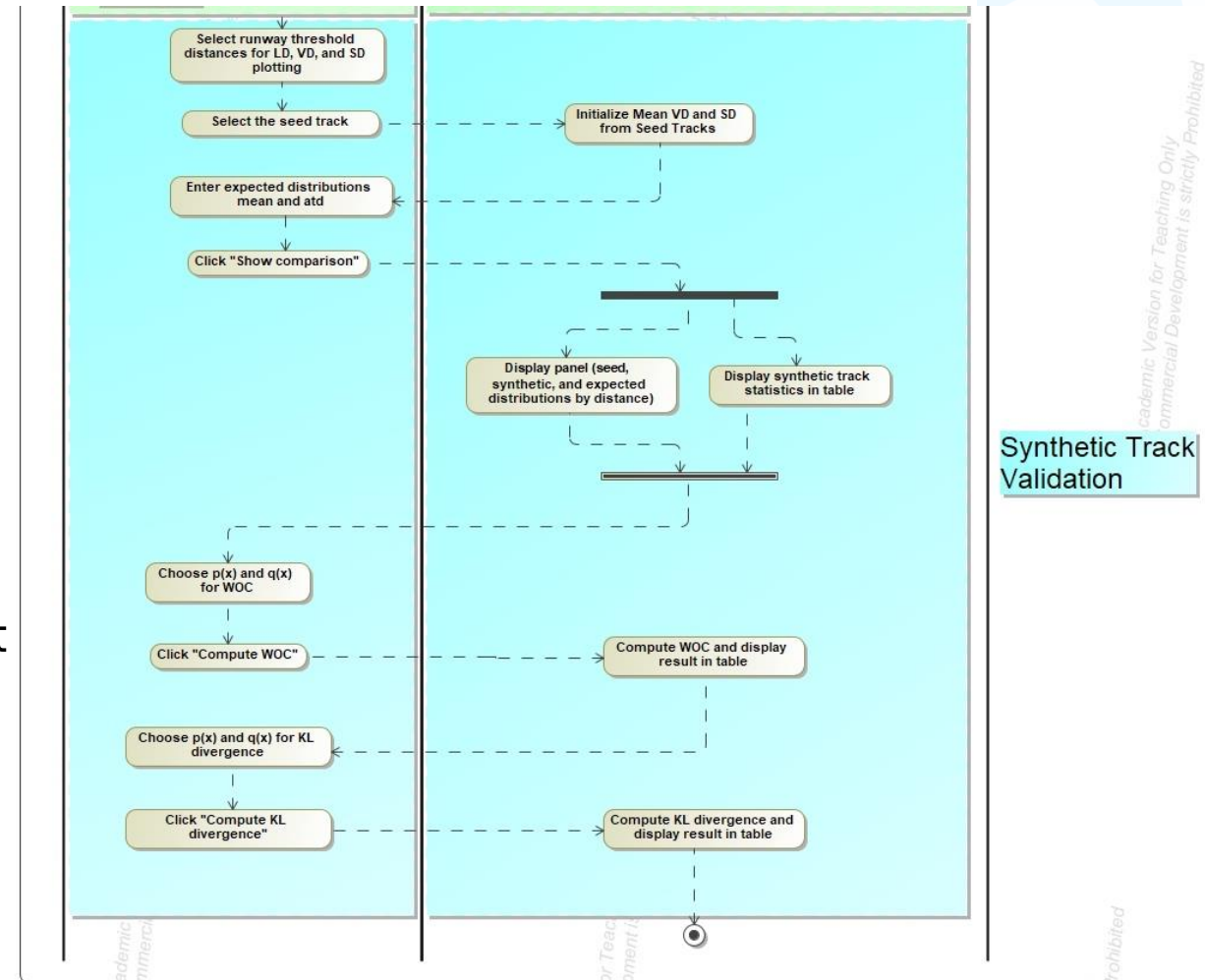
- Synthetic Track Generation
- User actions:
 - Specify the number of synthetic tracks
- Tool actions:
 - Generate and visualize (lateral trajectory, altitude and ground speed profiles) synthetic tracks
 - Export synthetic data



Synthetic Track Generation

III. System Specification

- Synthetic Track Validation
- User actions:
 - Specify the mean and standard deviation of the expected flight tracks for Lateral Dispersion (LD), Vertical Dispersion (VD), and Ground Speed Dispersion (SD)
- Tool actions:
 - Compute the overlap between the synthetic and expected using Weitzman Overlap Coefficient (WOC) and Kullback-Leibler (KL) Divergence



III. System Specification

- Synthetic Track Validation
- Weitzman Overlap Coefficient (WOC):

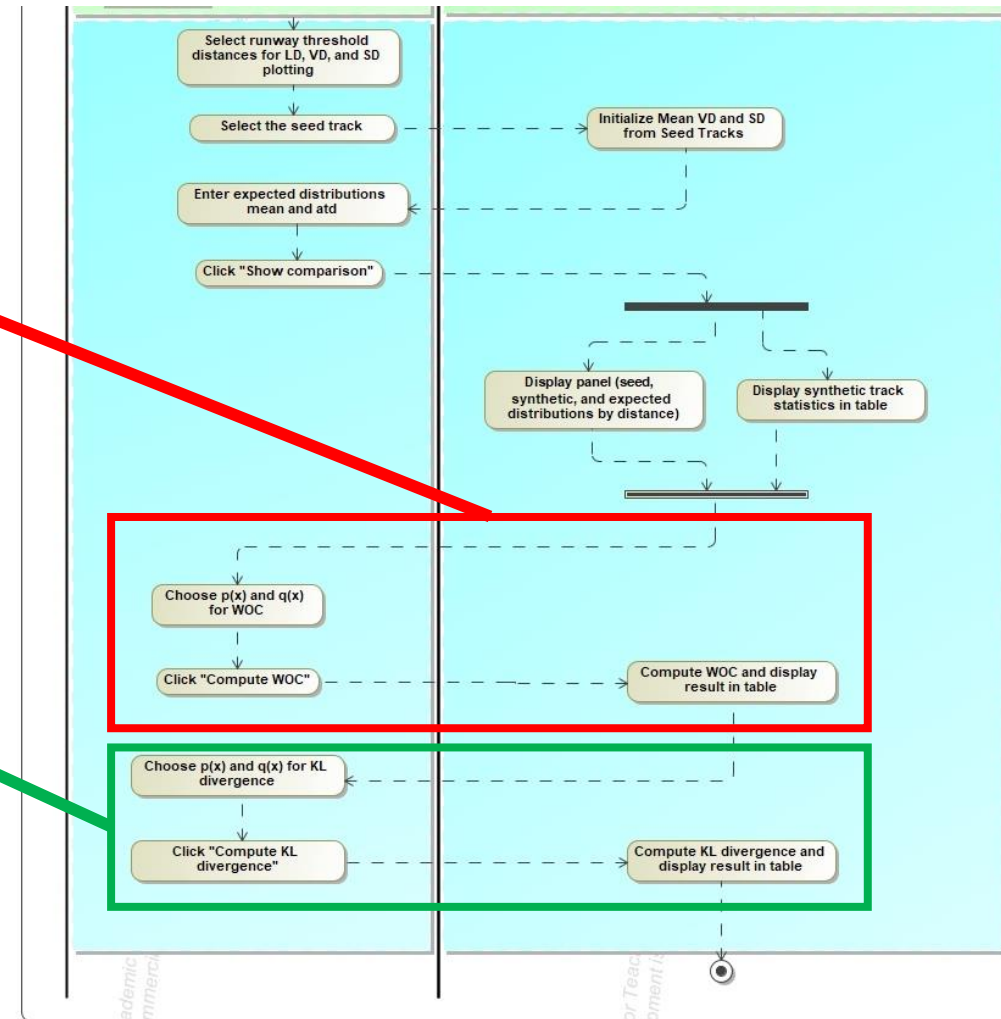
$$WOC = \int_{-\infty}^{+\infty} \min(p(x), q(x)) dx$$

- $P(x)$ and $q(x)$ are probability density functions

- KL Divergence:

$$D_{KL}(p \parallel q) = \int p(x) \log\left(\frac{p(x)}{q(x)}\right) dx$$

- $P(x)$ and $q(x)$ are probability density functions



Synthetic Track Validation

III. System Specification

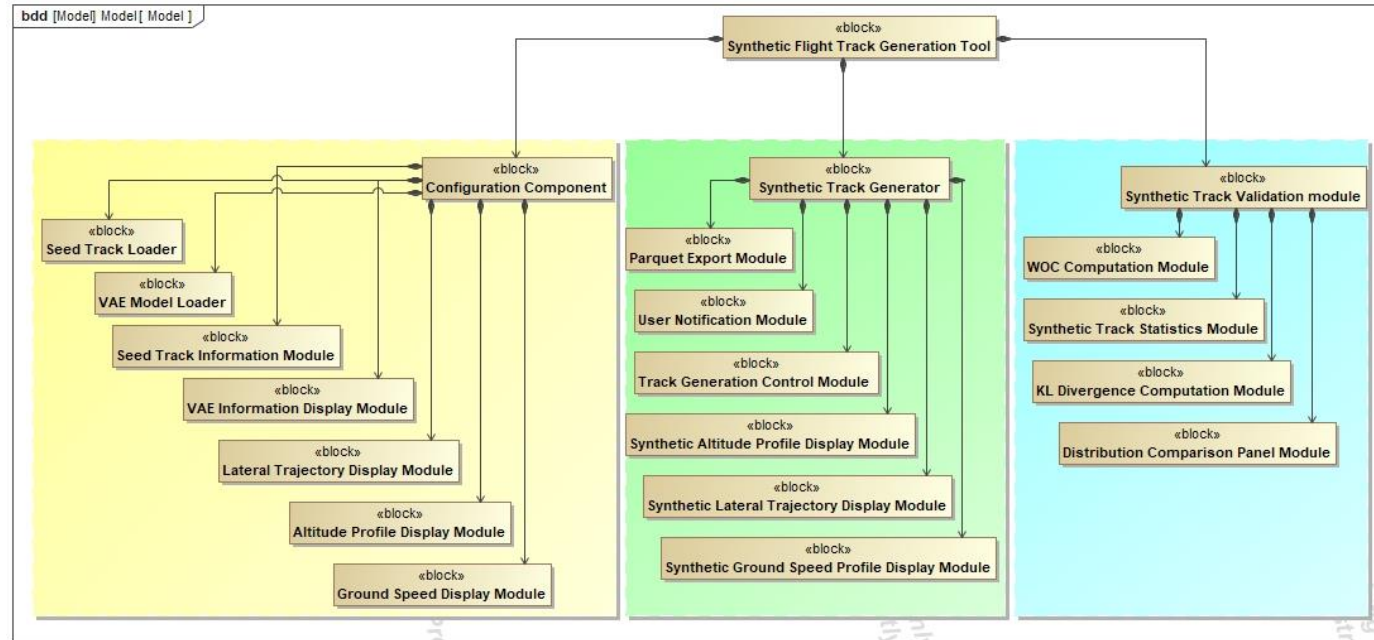
- System Requirements: Generation and Output
 - Generate tracks for specified arrival/approach procedures using **analyst-defined distributions or historical data with offsets**.
 - Support **pretrained VAEs and historical or newly defined seed tracks**.
 - Allow analyst-selected sample sizes, with design targets of **up to $2 \times 3 \times 10^9$ tracks**.
 - Run as a **stand-alone laptop application** with minimal installation and configuration.
 - Export uniquely named files containing **point index, latitude, longitude, altitude, and velocity**, with a model-defined number of points per track (e.g., 200).

III. System Specification

- System Requirements: Refinement and Validation
 - Support **multiple-seed selection and model fine-tuning** to achieve the required variability.
 - Compute distributions of **course changes, bank angles, and constant-speed/deceleration segment characteristics**.
 - Evaluate **lateral position, altitude, and speed at specified runway distances**.
 - Plot synthetic and historical distributions and quantify their agreement using **overlap metrics such as WOC**.

III. System Specification

- Tool Functional Architecture:



- **Configuration:** Load pretrained VAEs and seed tracks, display model and dataset information, and plot seed lateral trajectories, altitude profiles, and ground-speed profiles.
- **Synthetic Track Generation:** Specify the number of tracks, generate and visualize synthetic trajectories, export them, and report completion or errors.
- **Track Validation:** Calculate track statistics, compare synthetic distributions with seed, historical, or expected distributions, and assess agreement using **WOC** and **KL divergence**.

III. System Specification

• User-Interface/Front End Design

Configure Tool

Select trained VAE

Upload seed track

Load

Status:
Loaded model:
File:
Device:
Number of tracks:
Data shape:

Which seed track to plot?

Plot seed track(s)

Lateral trajectory

Altitude profile

Ground speed profile

Generate Synthetic Tracks

Seed track index

How many synthetic tracks?

Generate and plot synthetic tracks

Synthetic track generation status:

Lateral trajectory
(Synthetic and seed)

Altitude profile
(Synthetic and seed)

Ground speed profile
(Synthetic and seed)

Download Synthetic Tracks

Export status

Download Parquet file

Create Parquet for Synthetic Tracks

Track Validation

Distance (NM) to evaluate:
2 ☒ 3 ☒ 3.5 ☒ 4 ☒ 6 ☒ 9 ☒

Uploaded seed tracks:

Seed track(s) dispersion summary:

Synthetic dispersion summary:

Seed vs. Synthetic Comparison

Expected tracks distribution:

Show Comparison

Comparison panel:

Lateral dispersion

Vertical dispersion

Ground speed dispersion

Weitzman Overlap Coefficient (WOC):

WOC p(x)
Expected

WOC q(x)
Synthetic

Compute WOC

WOC results:

Kullback-Leibler (KL) Divergence:

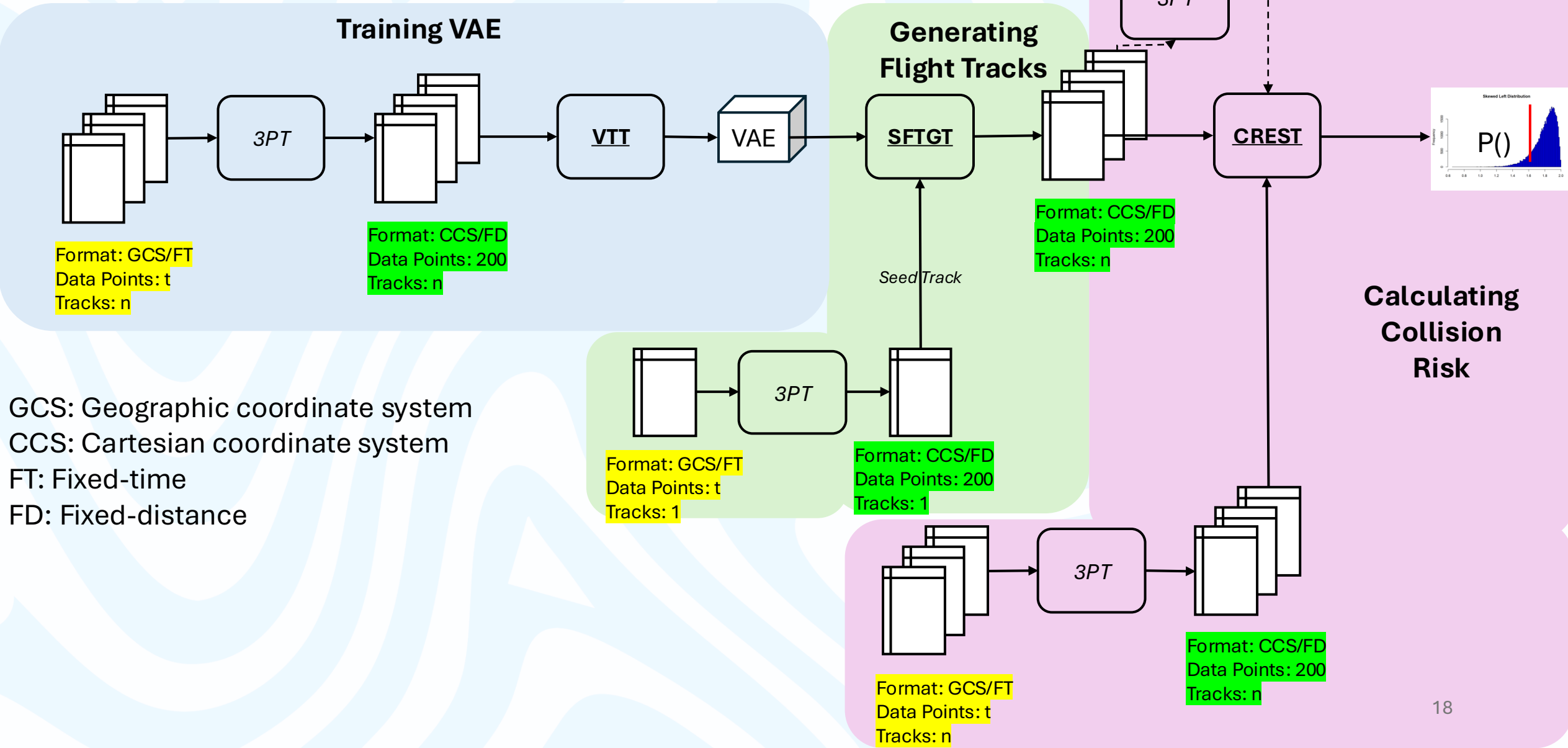
KL p(x)
Expected

KL q(x)
Synthetic

Compute KL Divergence

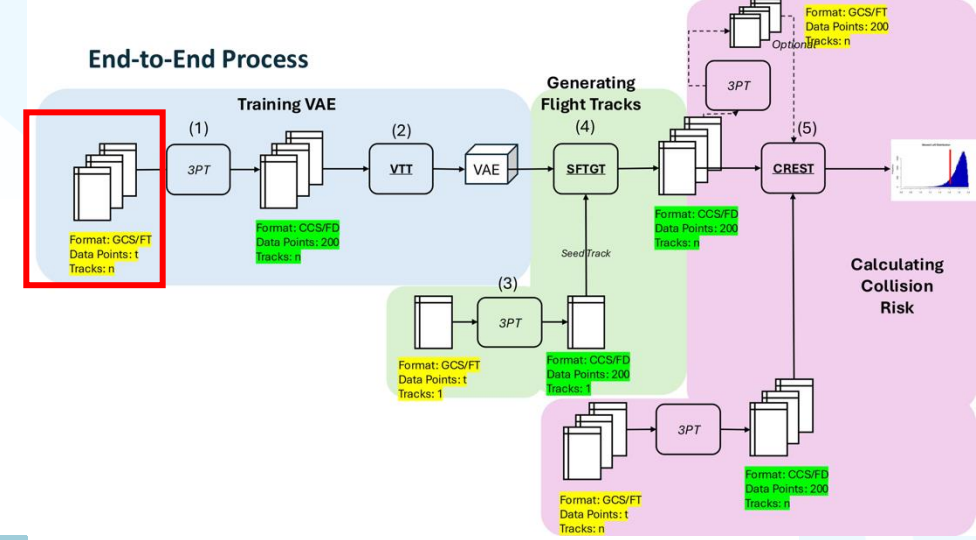
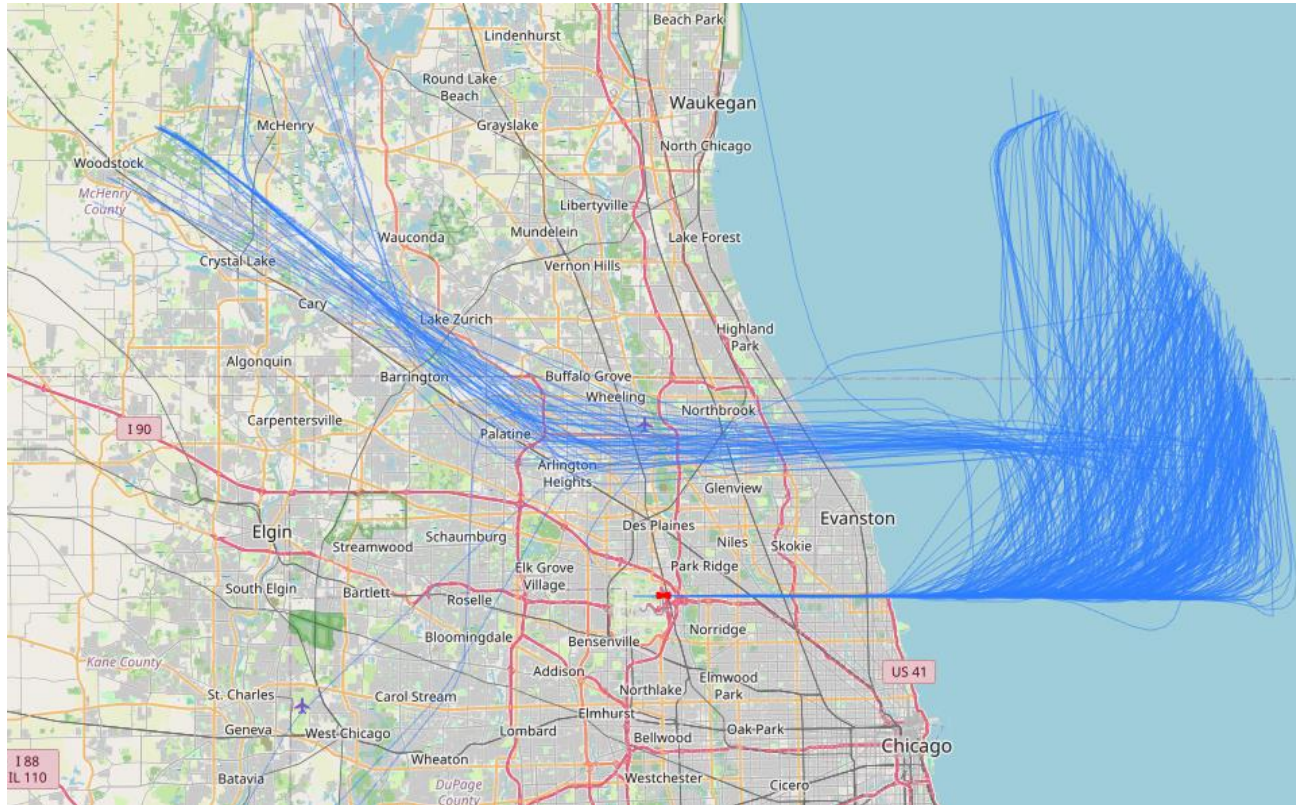
KL results:

IV. Tool Demonstration



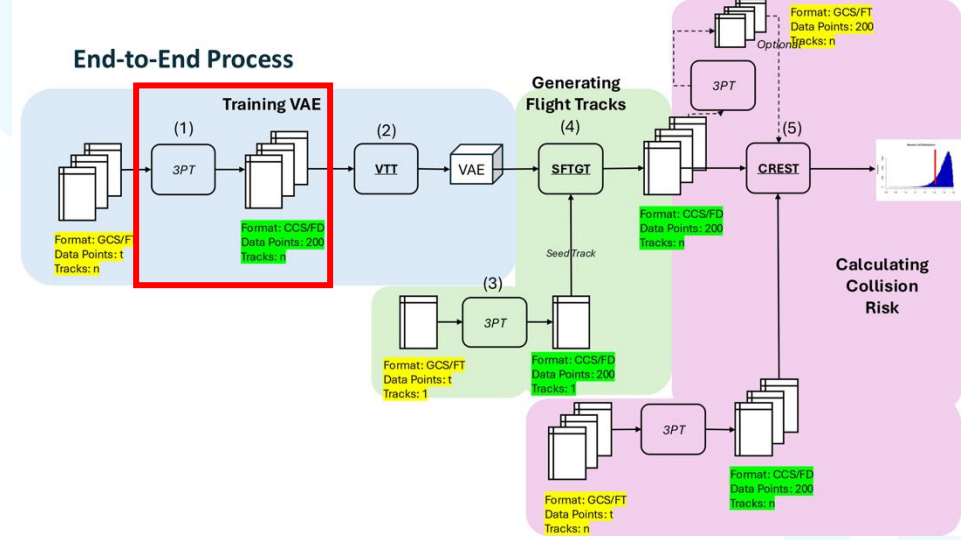
IV. Tool Demonstration

- Case Study of Chicago O'Hare Runway 27C
 - Dataset consists of 429 arrival flight tracks to ORD Runway 27C



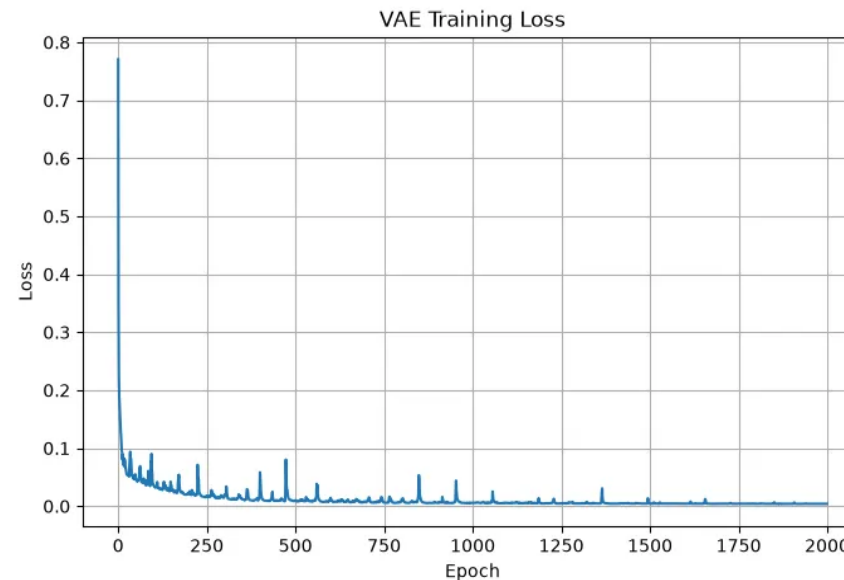
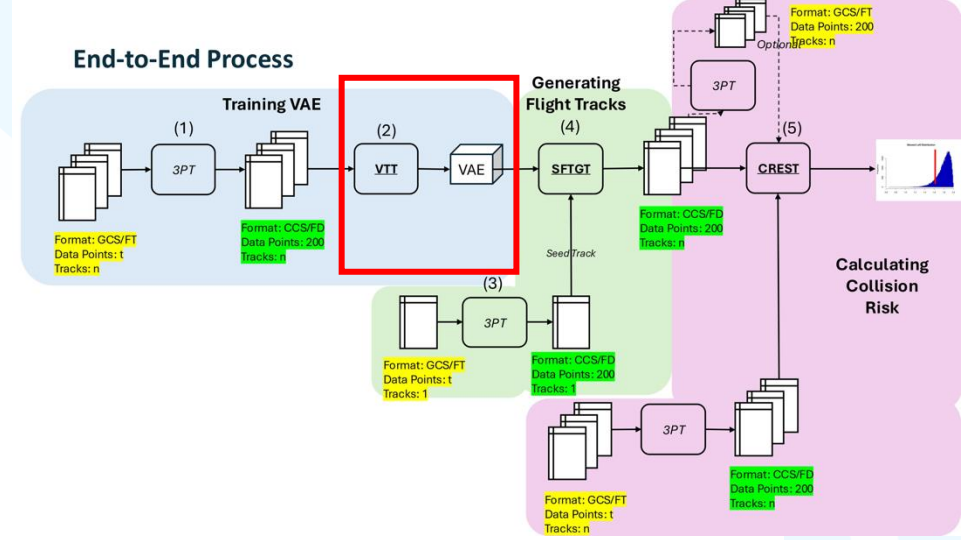
IV. Tool Demonstration

- Flight Track Pre/Post Processing Tool:
 - Upload raw ADS-B arrival flight tracks and group them into individual trajectories using unique flight identifiers.
 - Convert the grouped flight tracks from GCS to CCS
 - Standardize each flight track into a fixed-distance representation with 200 equally spaced points.
 - Represent each standardized flight track as a 200×4 matrix for VAE training.



IV. Tool Demonstration

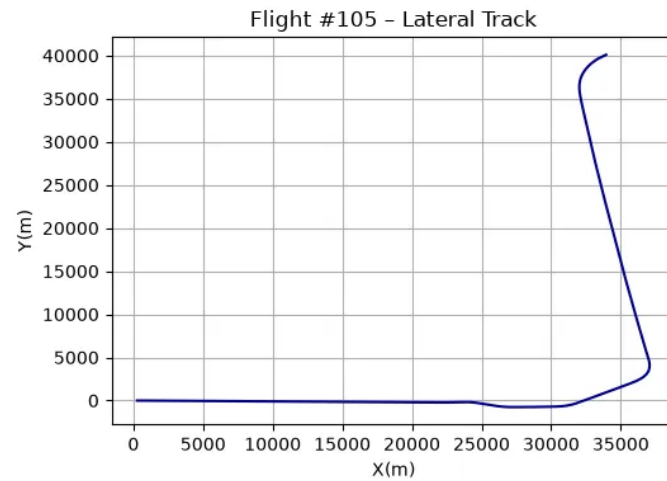
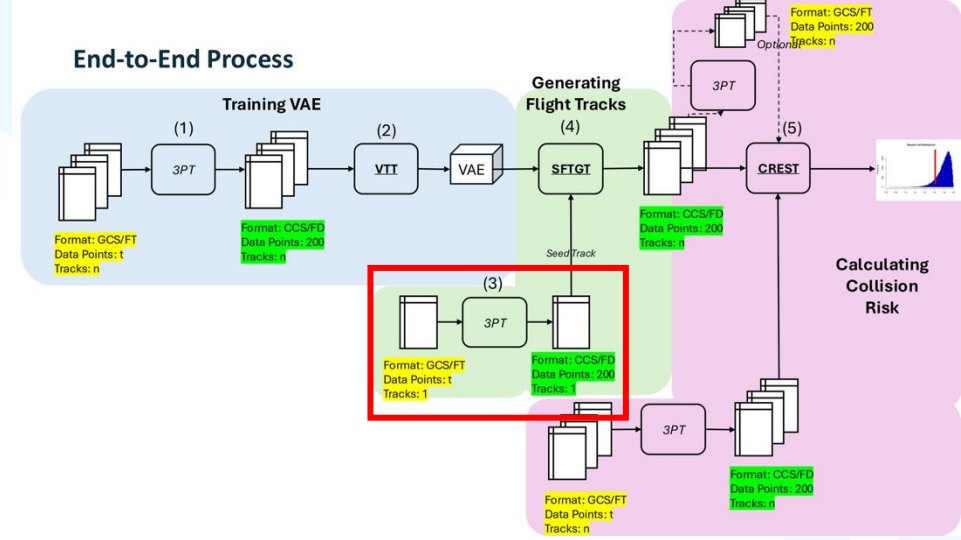
- Variational Autoencoder Training Tool:
 - Upload the standardized flight tracks to VTT and normalize them before VAE training.
 - Configure the VAE architecture, training hyperparameters, and loss function coefficients.
 - Train the VAE
 - Export the trained VAE and normalization parameters for synthetic flight track generation.



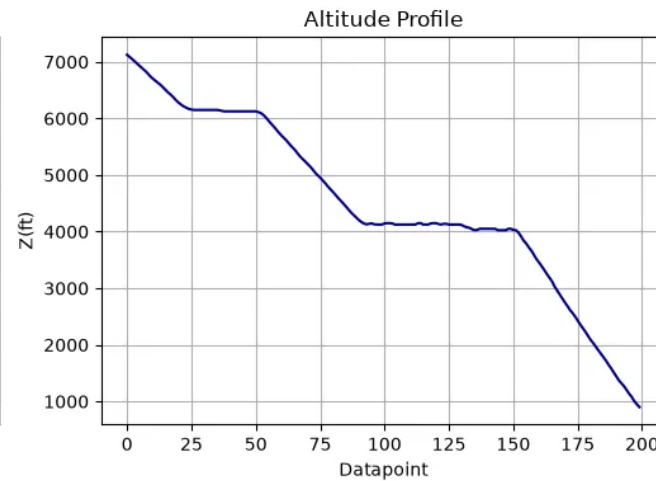
VAE training loss for the ORD Runway 27C case study

IV. Tool Demonstration

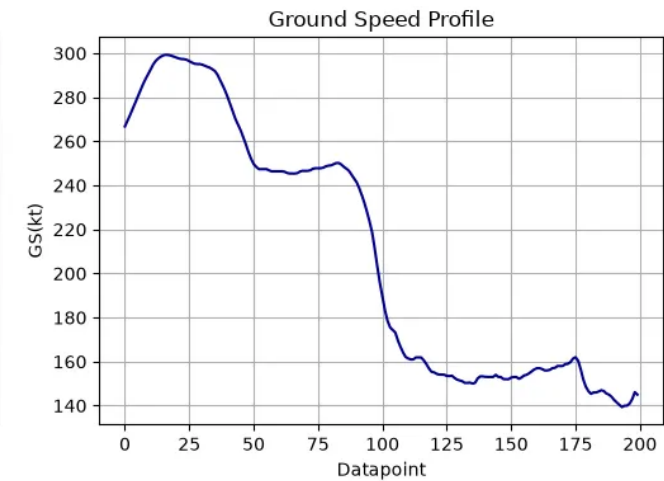
- Flight Track Pre/Post Processing Tool:
 - Select and upload a seed flight track to 3PT.
 - Standardize the seed flight track into a fixed-distance representation with 200 equally spaced (FD) points.
 - Export the seed track



(a)



(b)

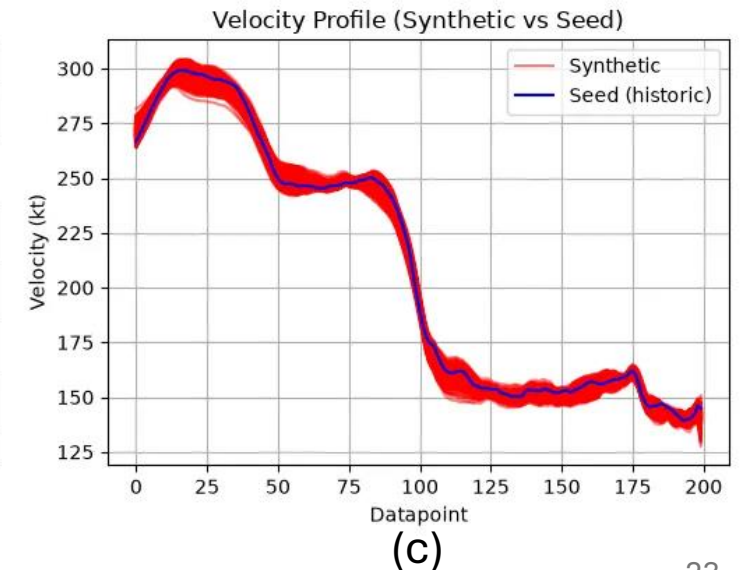
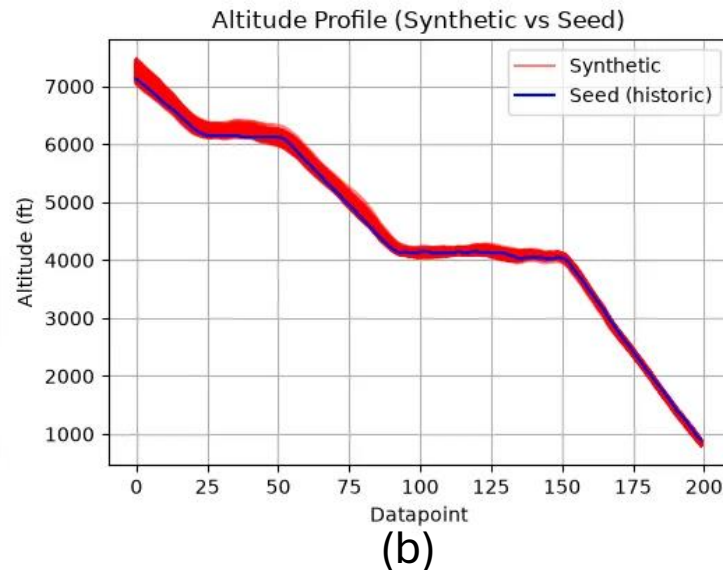
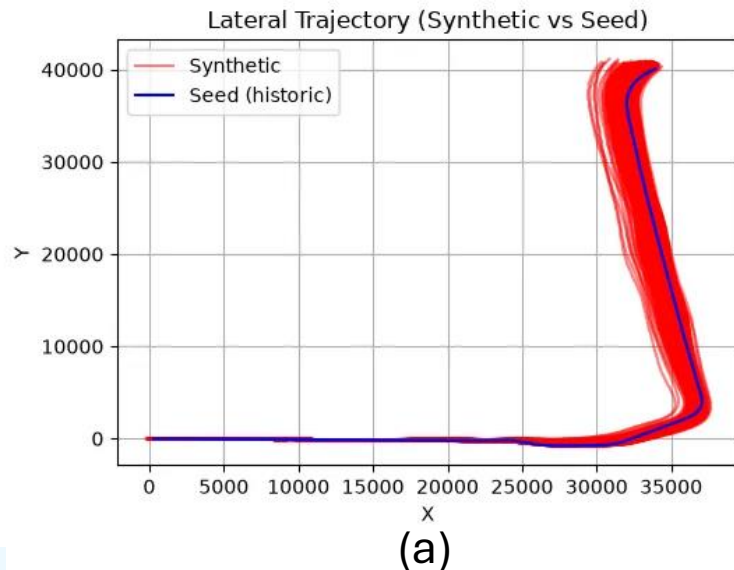
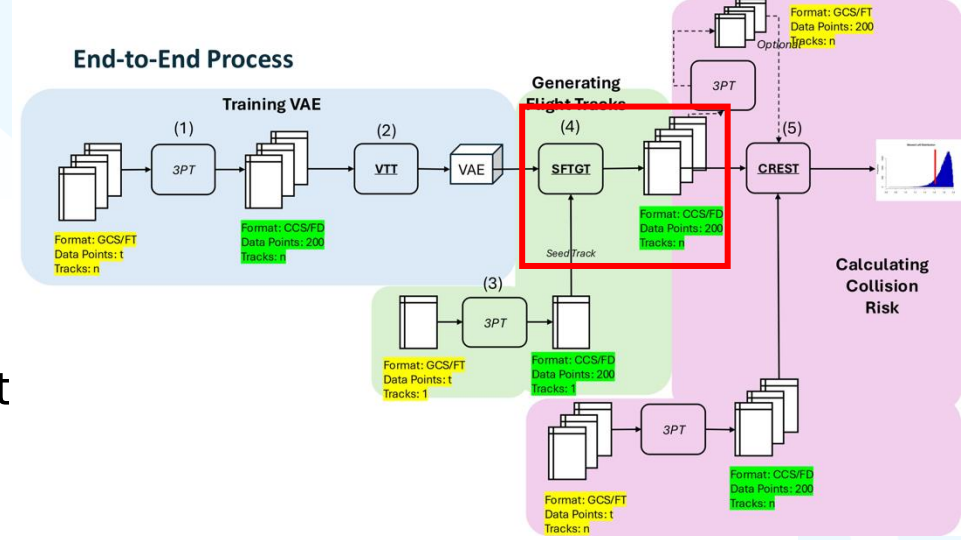


(c)

Seed flight track. (a) Lateral trajectory (b) Vertical profile (c) Groundspeed profile

IV. Tool Demonstration

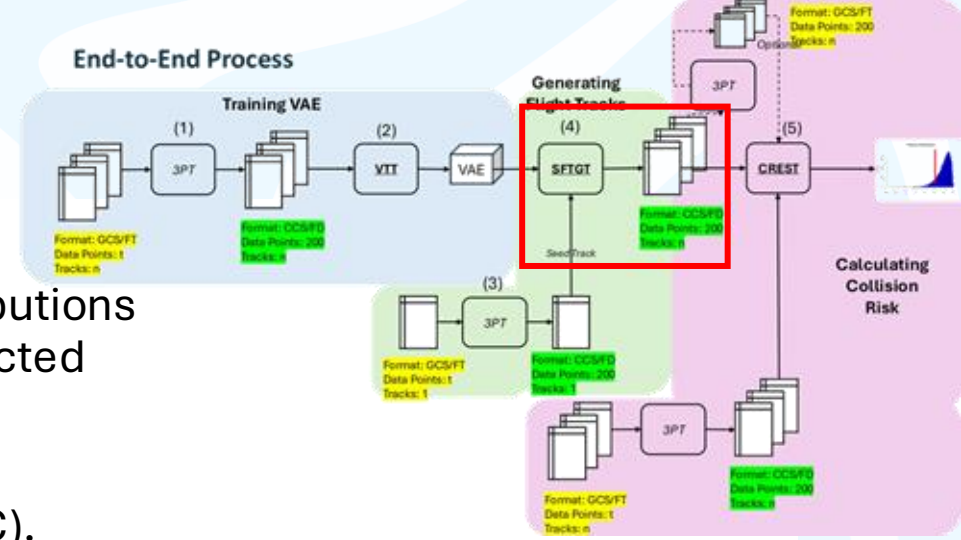
- Synthetic Flight Track Generation and Realism Check Tool:
 - Upload the trained VAE and the standardized seed flight track to SFTGT.
 - Generate 1,000 synthetic flight tracks from the seed flight track.
 - Compare the lateral, vertical, and ground speed profiles of the seed and synthetic flight tracks to verify realistic variations.



Seed and 1000 synthetic flight tracks. (a) Lateral trajectory (b) Vertical profile (c) Groundspeed profile

IV. Tool Demonstration

- Synthetic Flight Track Generation and Realism Check Tool:
 - Calculate the lateral (LD), vertical (VD), and speed (SD) distributions of the synthetic flight tracks and compare them with the expected distributions.
 - Evaluate the agreement between the synthetic and expected distributions using the Wasserstein Overlap Coefficient (WOC).
 - Quantify the similarity between the synthetic and expected distributions using KL divergence.



WOC

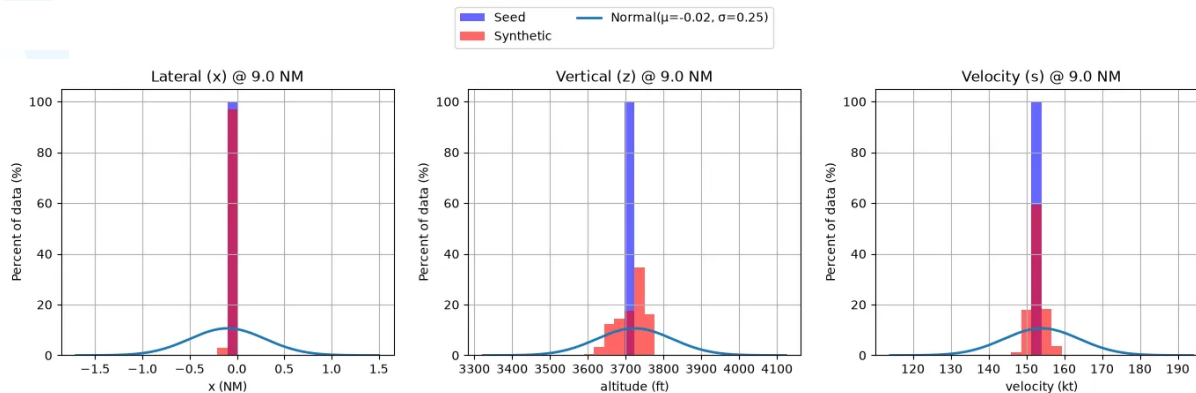
WOC results

Distance (NM)	A	B	WOC lateral x	WOC vertical z	WOC velocity s
2	Normal	Synthetic	0.02	0.48	0.53
3	Normal	Synthetic	0.02	0.35	0.28
3.5	Normal	Synthetic	0.04	0.25	0.87
4	Normal	Synthetic	0.02	0.76	0.64
6	Normal	Synthetic	0.02	0.57	0.33
9	Normal	Synthetic	0.06	0.56	0.32

KL Divergence

KL results

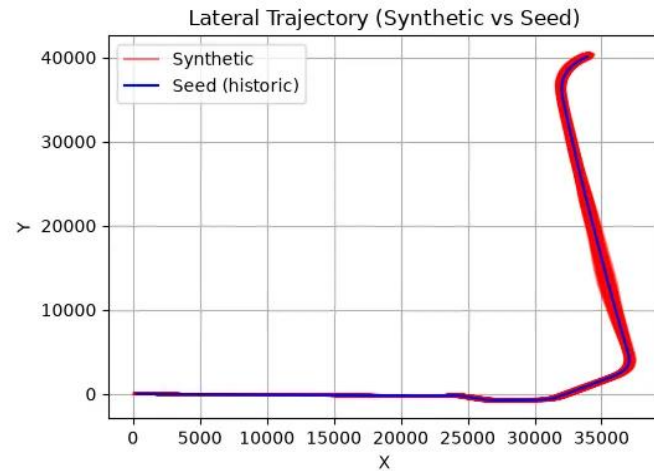
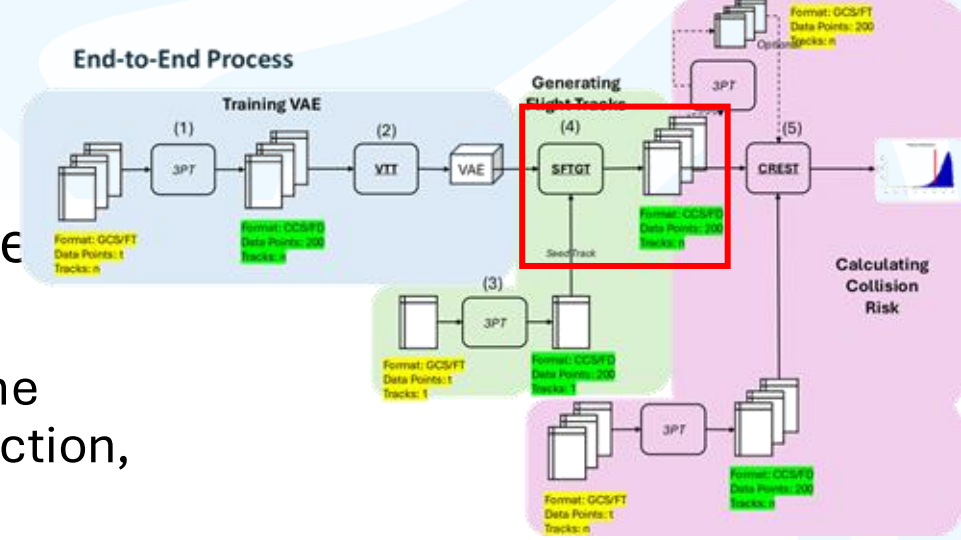
Distance (NM)	p	q	KL(p q) lateral x	KL(p q) vertical z	KL(p q) velocity s
2	Normal	Synthetic	26.65	1.58	3.44
3	Normal	Synthetic	26.8	4.75	7.13
3.5	Normal	Synthetic	25.94	5.62	0.27
4	Normal	Synthetic	26.88	0.59	2.73
6	Normal	Synthetic	26.71	3.9	10.18
9	Normal	Synthetic	24.63	4.18	10.07



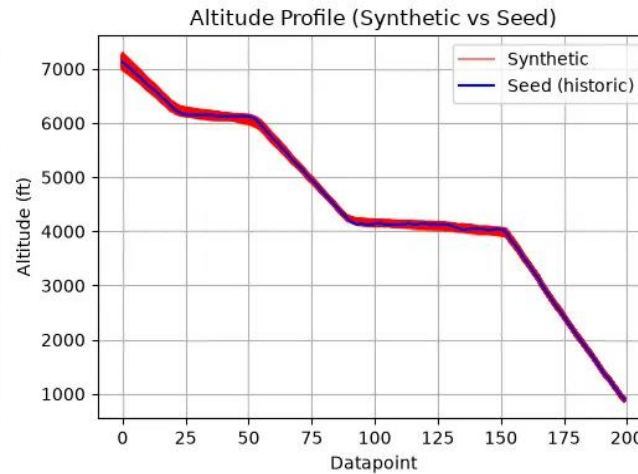
LD, VD, and SD of 1,000 synthetic flight tracks, the seed track, and expected tracks

IV. Tool Demonstration

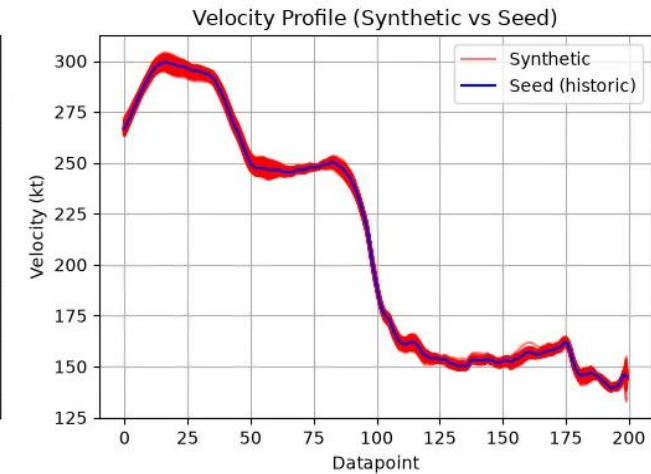
- Synthetic Flight Track Generation and Realism Check Tool:
 - Configure the fine-tuning hyperparameters, including the number of epochs and the coefficients of the reconstruction, KL divergence, and monotonicity losses.
 - Fine-tune the VAE to adapt the learned latent space to the seed track characteristics while preserving realistic trajectory generation.



(a)



(b)



(c)

Seed and 1000 synthetic flight tracks after fine-tuning. (a) Lateral trajectory (b) Vertical profile (c) Groundspeed profile

IV. Conclusion

- Developed an **analyst-oriented tool** that combines pretrained VAEs and seed tracks to generate synthetic flight trajectories for collision risk modelling.
- Integrated **configuration, generation, and validation** into a single workflow.
- Generate a **large set of flight tracks** in a short time (10^6 flight tracks in 4 minutes.)
- Enabled comparison with historical or expected distributions using **WOC and KL divergence**.
- Demonstrated the workflow through **ORD, LAX, SFO, and ATL** case study.