Model-Based Simulation for Design of an Airport ***Autonomous*** Approach and Landing System: *Stochastic Design-Space*

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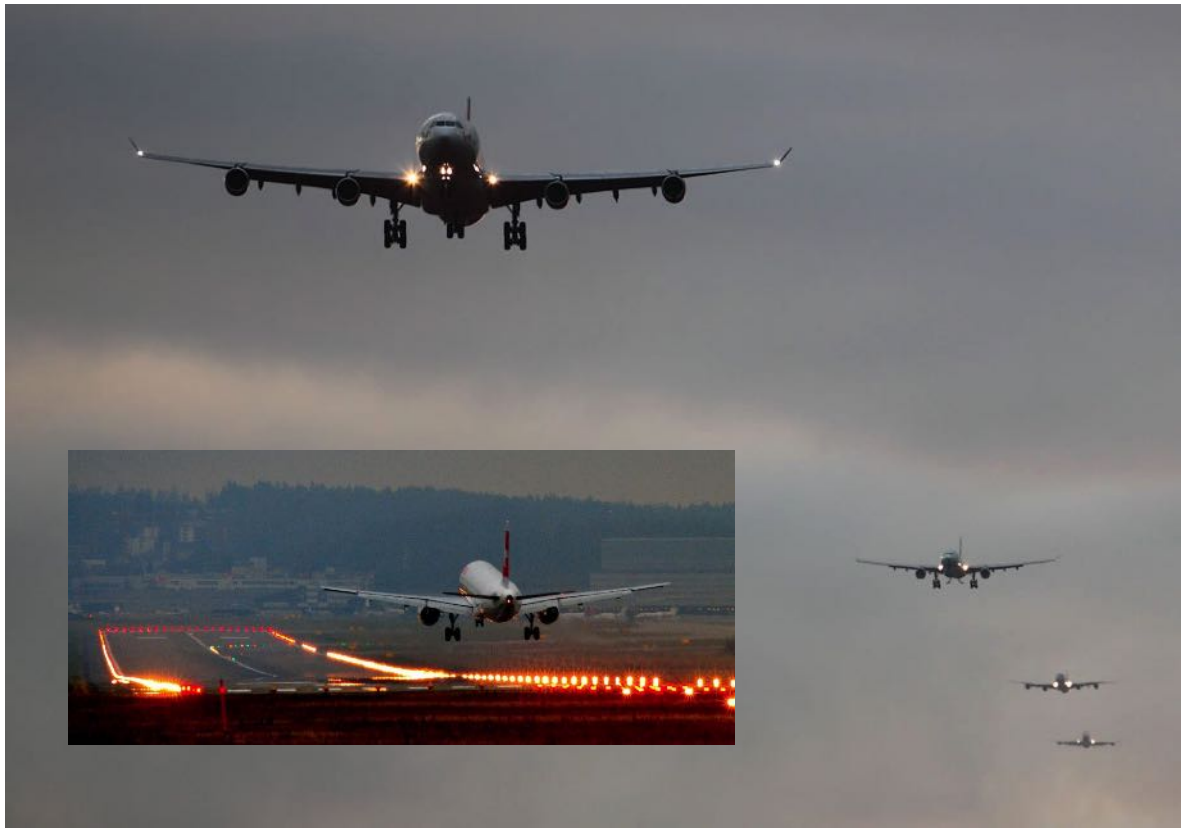

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MBSE & Simulation

- MBSE lower costs, improve efficiency and increase flexibility in design of complex systems
- Challenge to *seamlessly* leverage simulation in the Requirements Analysis and Design

Case Study: MBSE Simulation

- Tasked with design of Airport Autonomous Approach & Landing System
- Multiple components of system developed by different teams
- Component design affects overall system performance
  - **Stochastic design space**
- Simulation assess the impacts of component performance on overall system performance

Challenge #1: Discrete vs **Stochastic Design-Space**

- Discrete Design Space
  - Aircraft Weight Budget
    - Accumulated component weights
    - Error budget
- Stochastic Design Space
  - Performance affected by component design is stochastic
    - Confidence Interval

How to integrated Stochastic Simulation into MBSE Tool Environment?

Challenge #2: Multiple Component Req's Contribute to System Performance

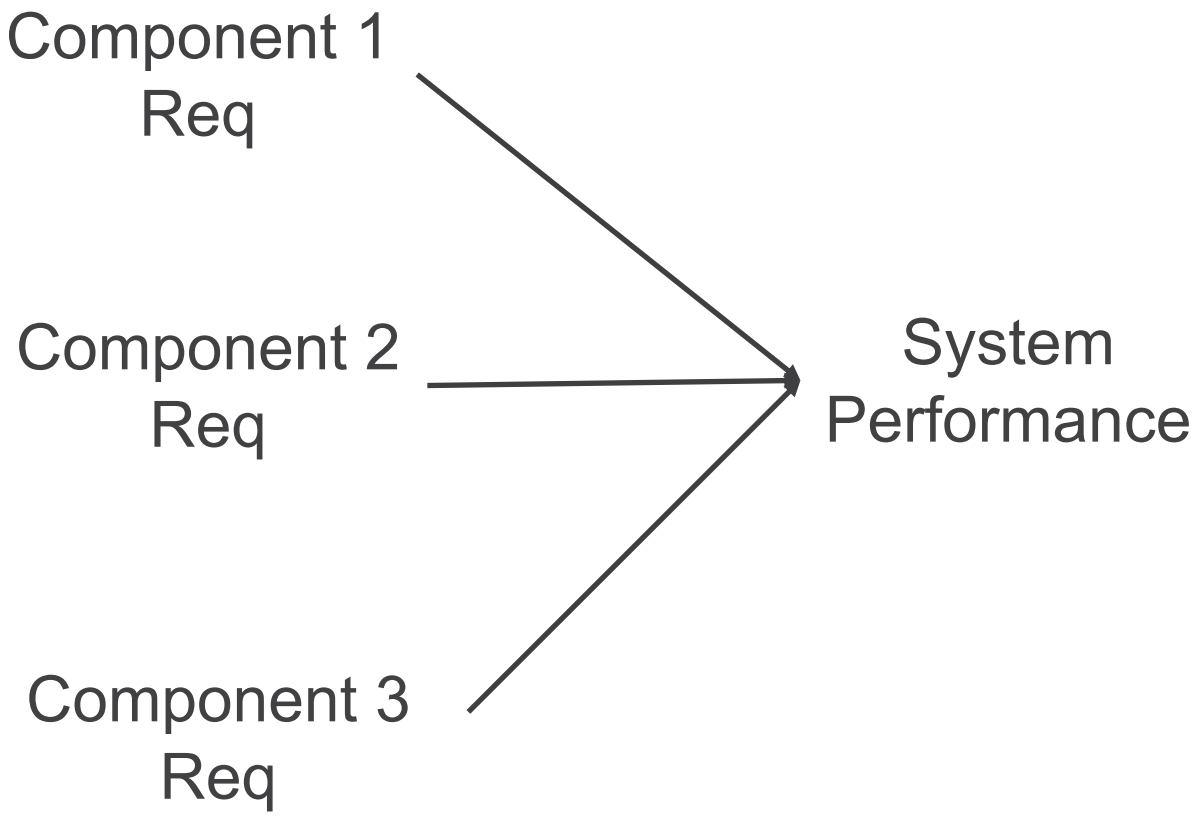
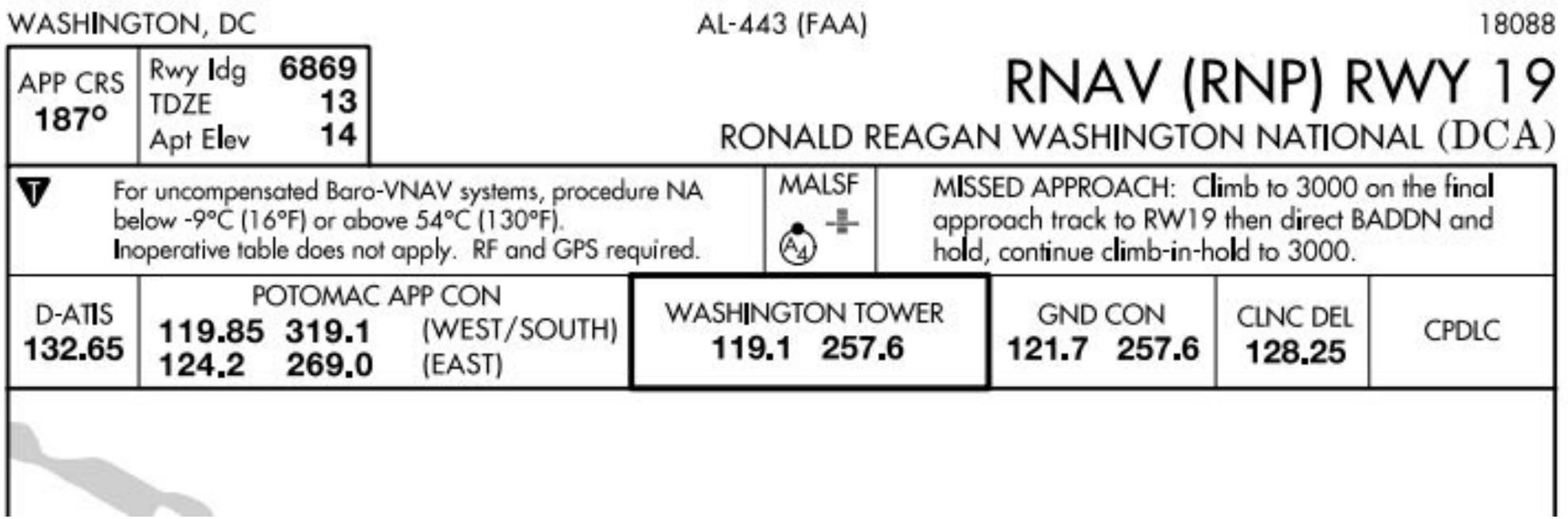


Table of Contents

Airport Approach and Landing - Procedure



WASHINGTON, DC | AL-443 (FAA) | 18088

RNAV (RNP) RWY 19

RONALD REAGAN WASHINGTON NATIONAL (DCA)

APP CRS	Rwy Idg	TDZE	Apt Elev
187°	6869	13	14

For uncompensated Baro-VNAV systems, procedure NA below -9°C (16°F) or above 54°C (130°F). Inoperative table does not apply. RF and GPS required.

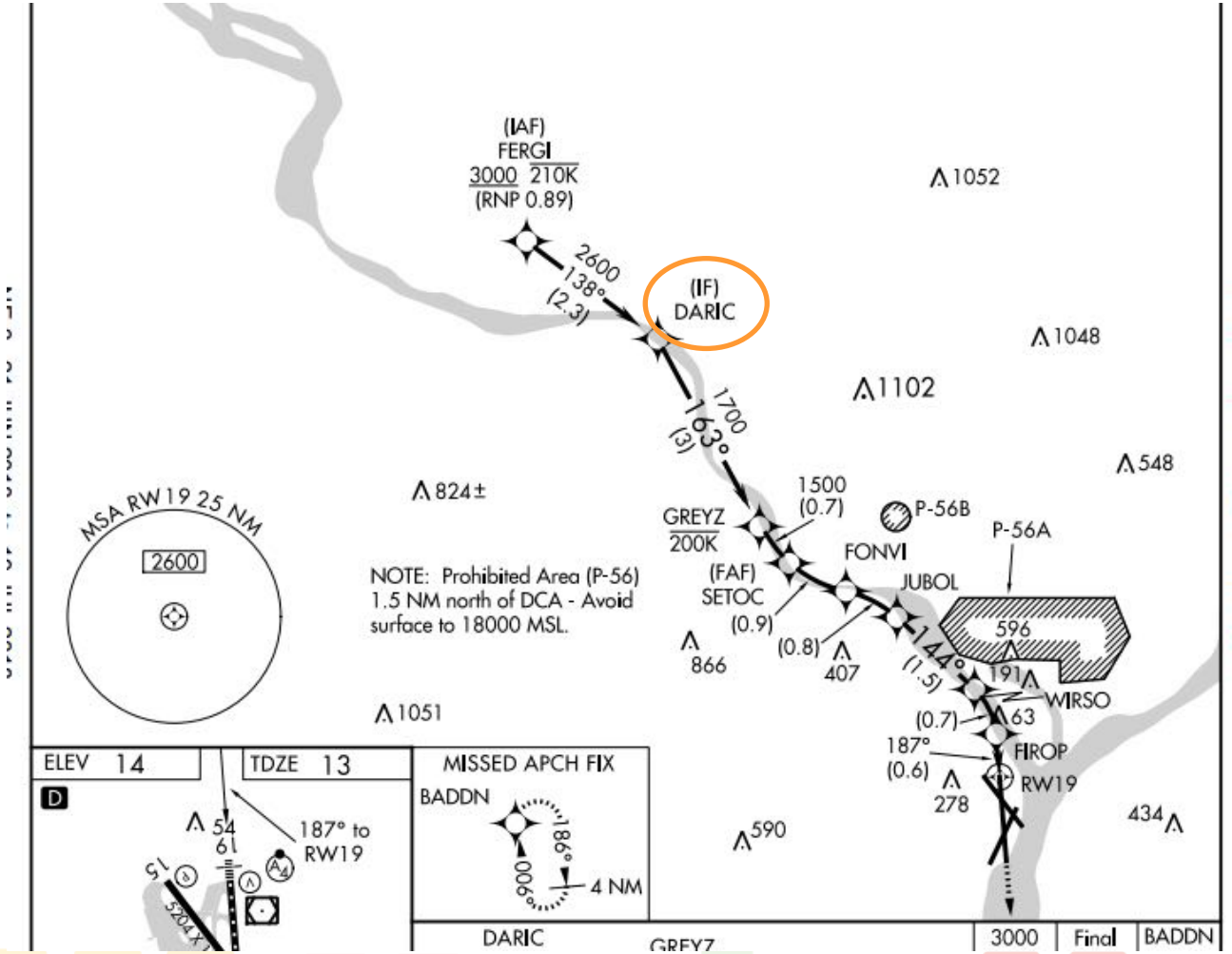
MALSF

MISSED APPROACH: Climb to 3000 on the final approach track to RW19 then direct BADDN and hold, continue climb-in-hold to 3000.

D-ATIS	POTOMAC APP CON	WASHINGTON TOWER	GND CON	CLNC DEL	CPDLC
132.65	119.85 319.1 (WEST/SOUTH) 124.2 269.0 (EAST)	119.1 257.6	121.7 257.6	128.25	

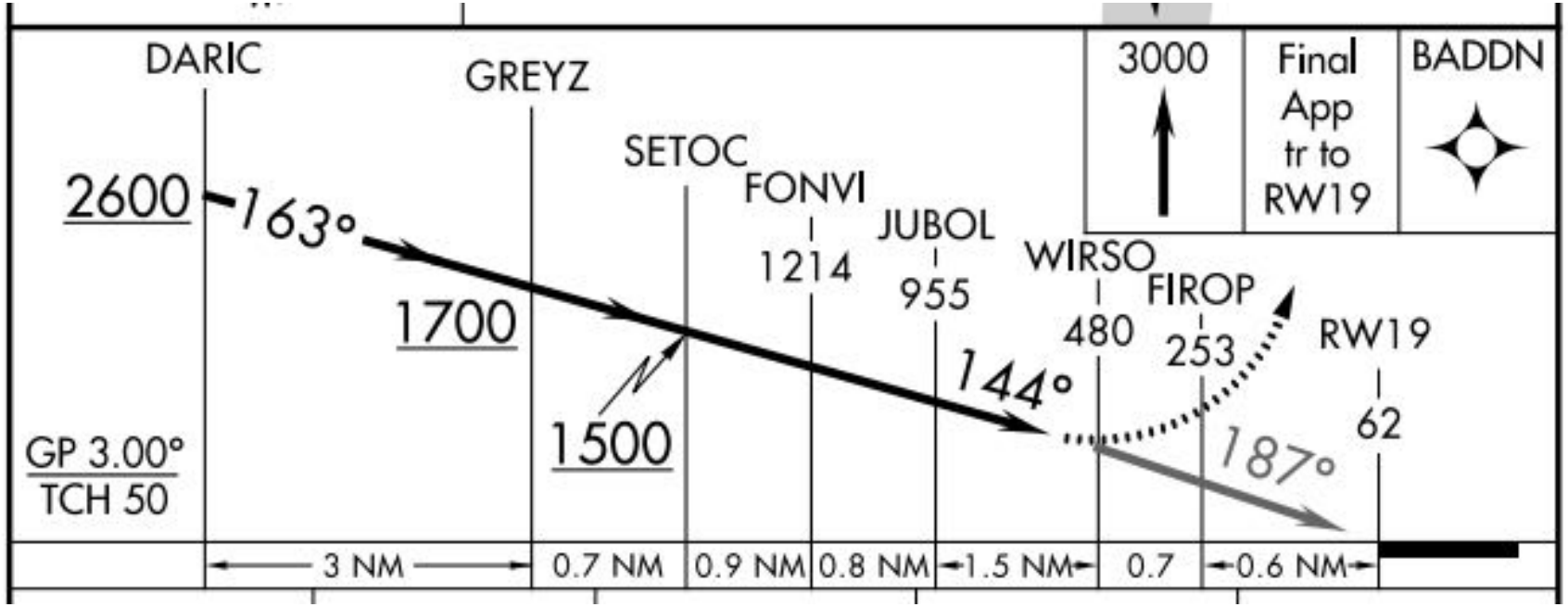
Airport Approach and Landing - Procedure

Lateral trajectory
Follows Potomac River



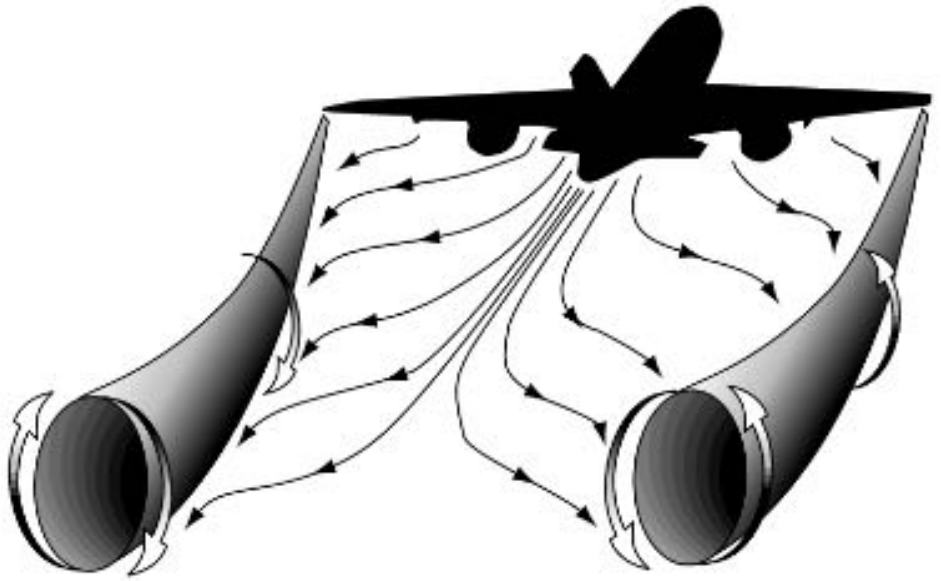
Airport Approach and Landing - Procedure

Vertical trajectory
2600’ to 13’
Rate of descent



Airport Approach & Landing

- Air Traffic Control sequences flights on Final Approach Segment
- Sequential aircraft must be separated by Minimum Safe Separation Distance (MSSD)
  - Avoid wake vortex encounter



Functions Performed by Air Traffic Controller

1. Automated Weather Reporting
2. Automated Traffic Collision (e.g. Mahboubi & Kochenderfer, 2015)
3. Active Runway Surveillance (e.g. Öztürk & EminKuzucuoglu, 2016)
4. Runway Assignments and Flight Sequencing (e.g. Erzberger, Davis & Green, 1993; Kim et.al. 2014)
5. Taxiway Guidance (Xin-min, et.al., 2010)
6. ***Spacing and Landing*** (Snisarevska, Sherry, Shortle, 2017)

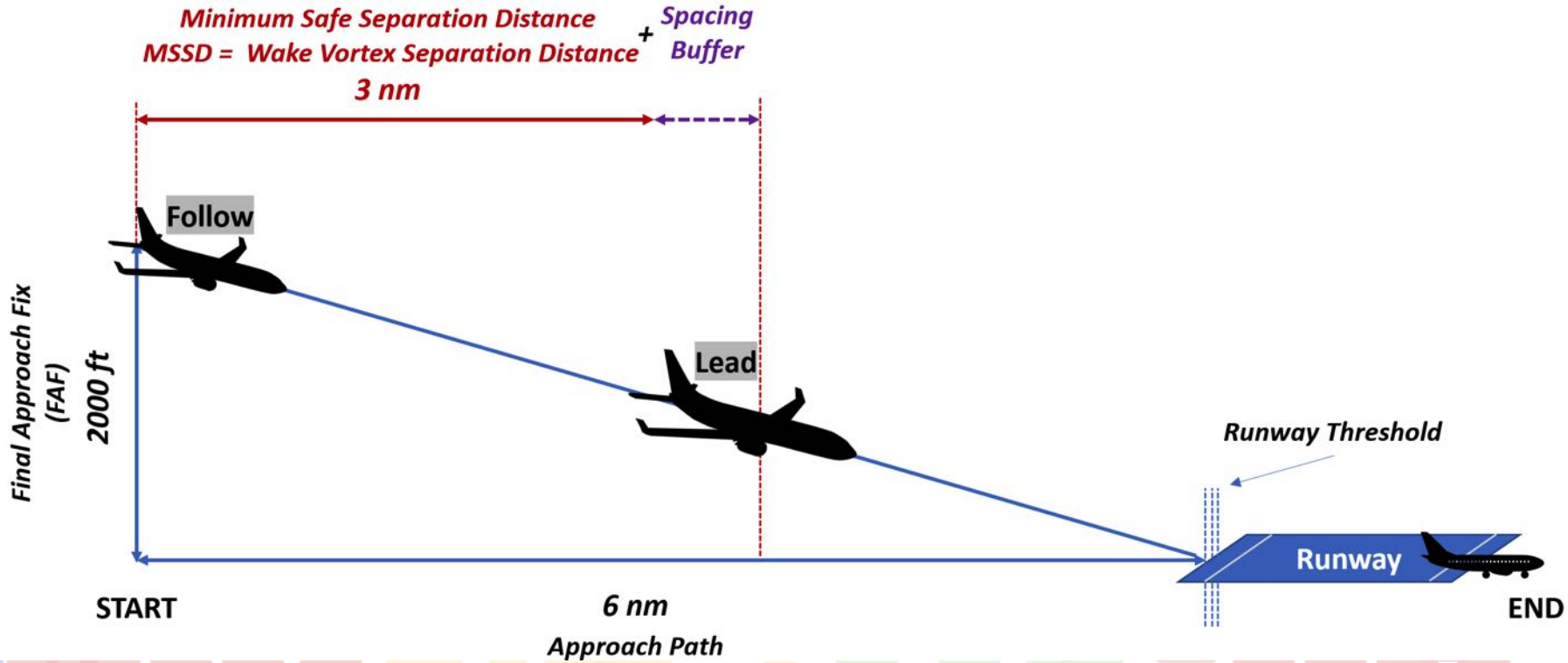
Spacing is Candidate for Autonomy

- Uni-directional flight
- Controlled airspace
- Repetitive control instructions

- … but highly stochastic

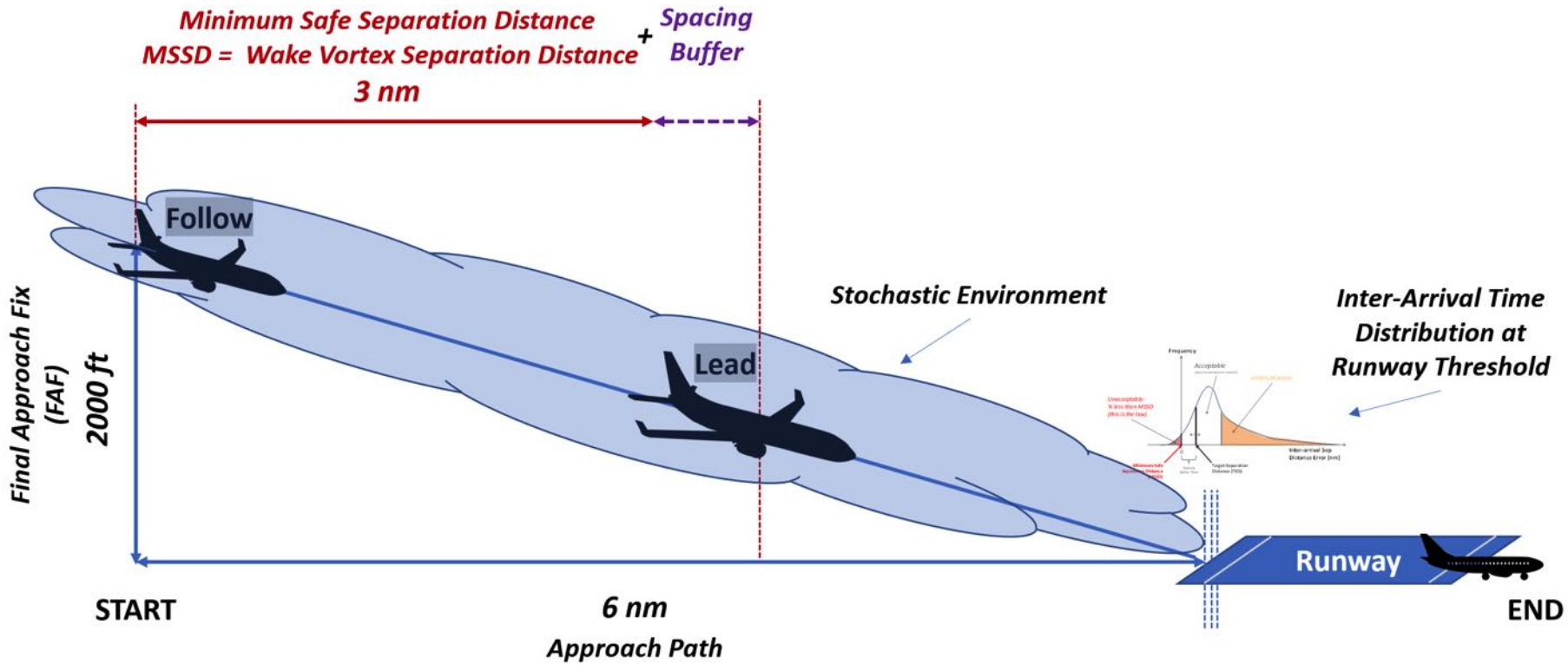
Approach & Landing Spacing

- Final approach segment and runway
- Flights must be sequenced and spaced before the Final Approach Fix (FAF)
  - 6nm from Runway Threshold, 2000’ AGL
- Flights are at their lowest speed for the approach and landing phase

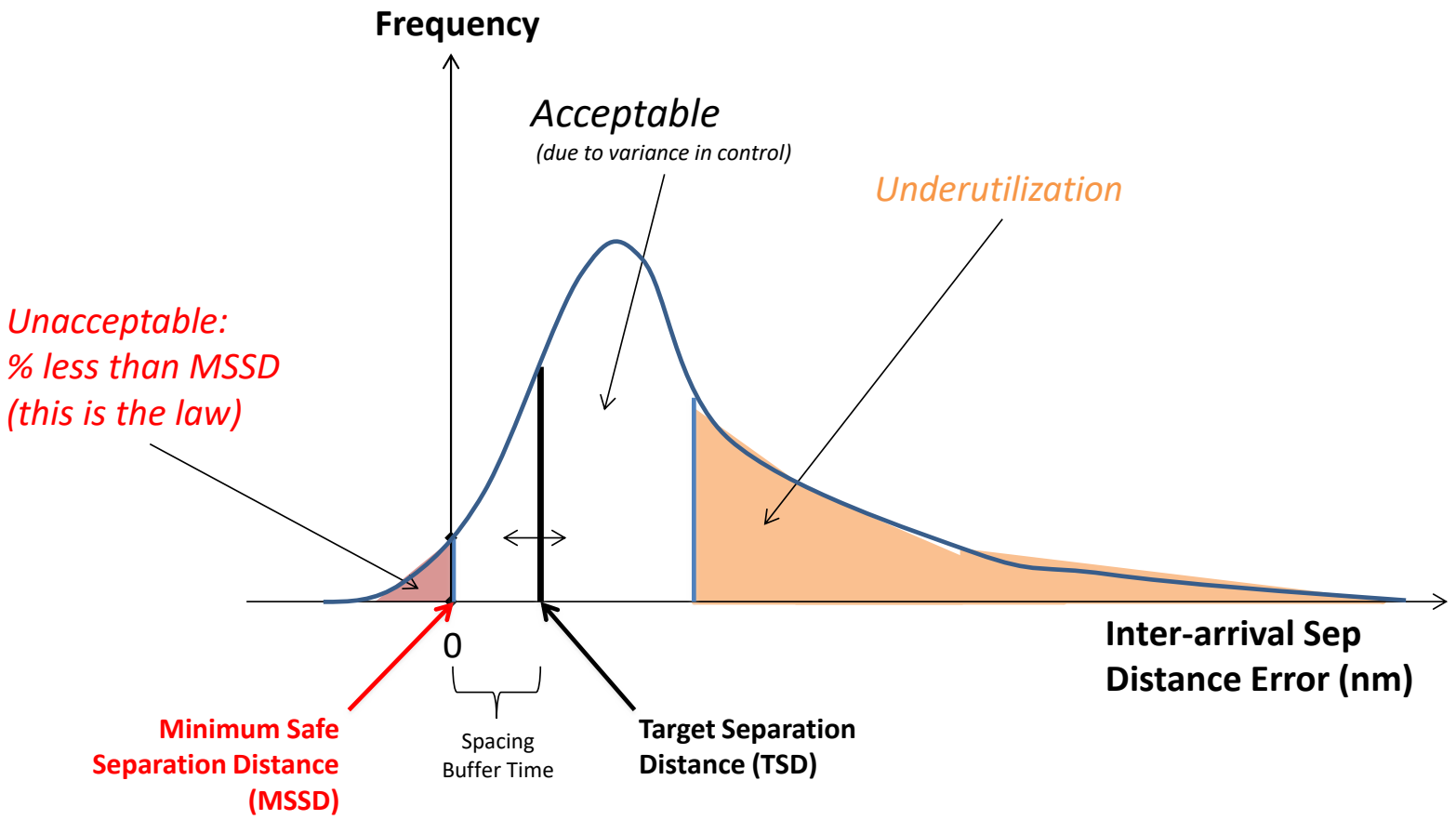


Approach & Landing Spacing

- Highly **stochastic** environment impacts time at Runway Threshold
- Air Traffic Controllers **manually** insert "*Buffer Time*" between the wake vortex separation distance of the lead and the follow aircraft
  - Too short Buffer Time → reduced safety margins
  - Too long Buffer Time → reduced runway throughput

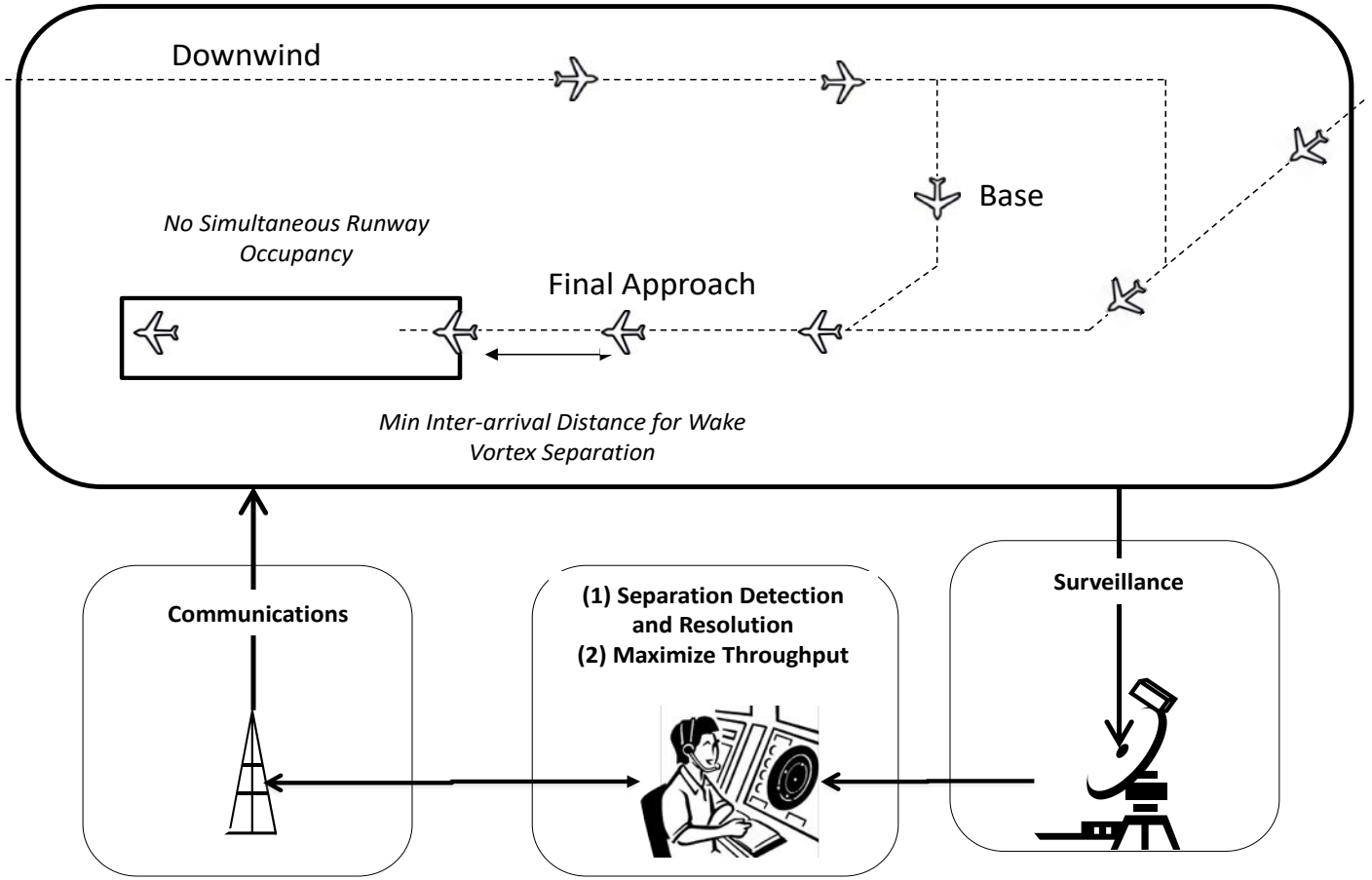


Approach & Landing Spacing

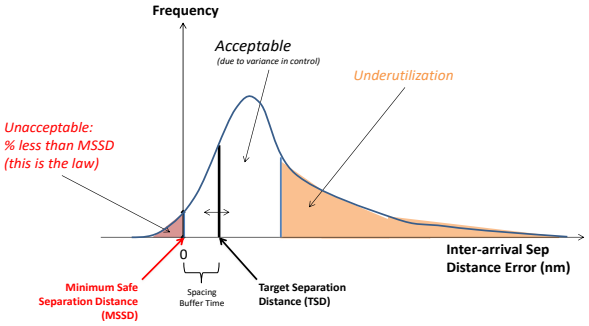


- The magnitude of the **left-tail** of the distribution determines **safety margins** of the approach process.
- The magnitude of the **right tail** of the distribution represents **gaps in the flow** and **reduced runway throughput**.

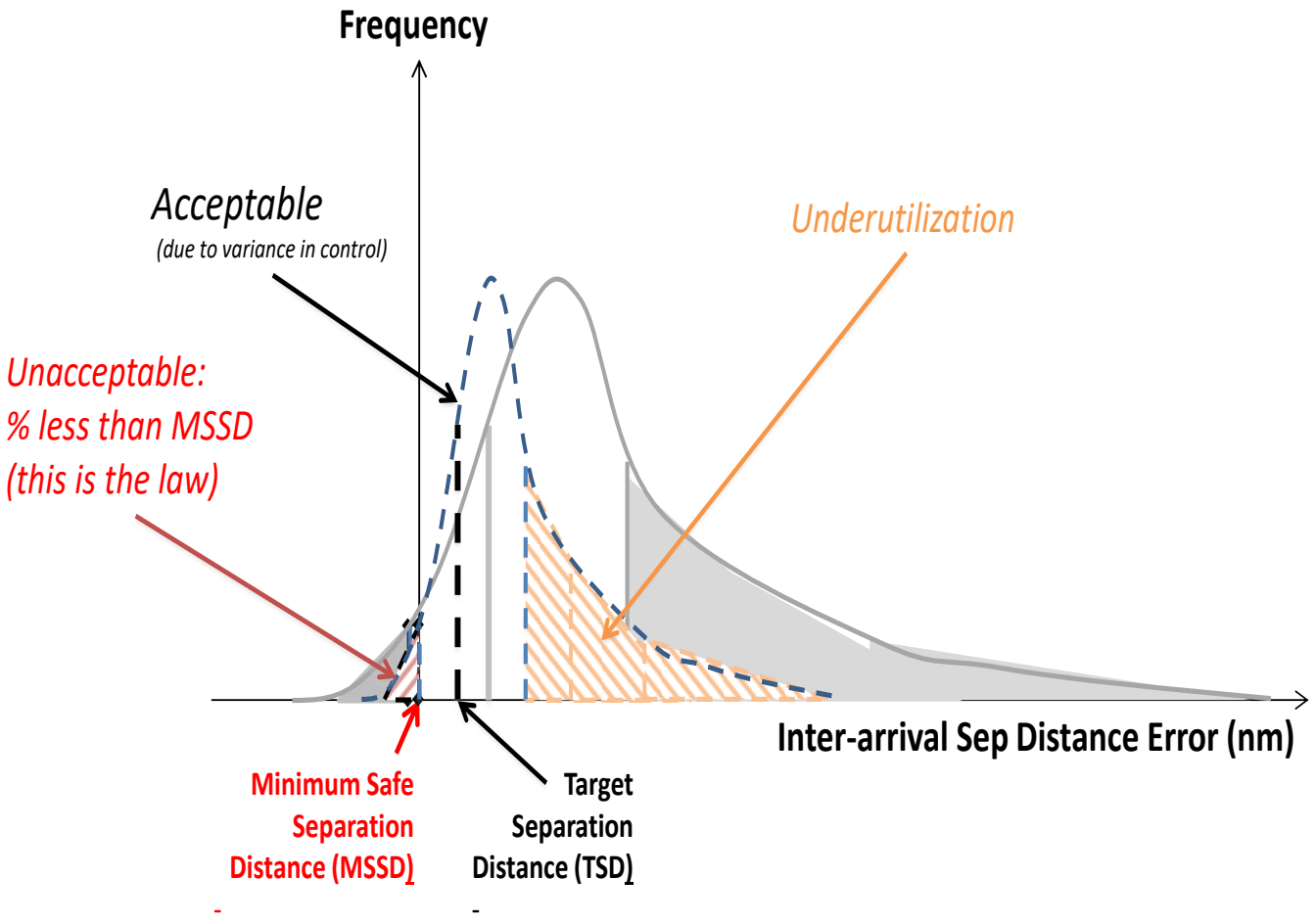
As-Is Spacing for Approach and Landing



- Air Traffic Controller introduces Spacing Buffer (SB) by controlling o the Target Separation Distance (TSD)
- Not supported by distribution

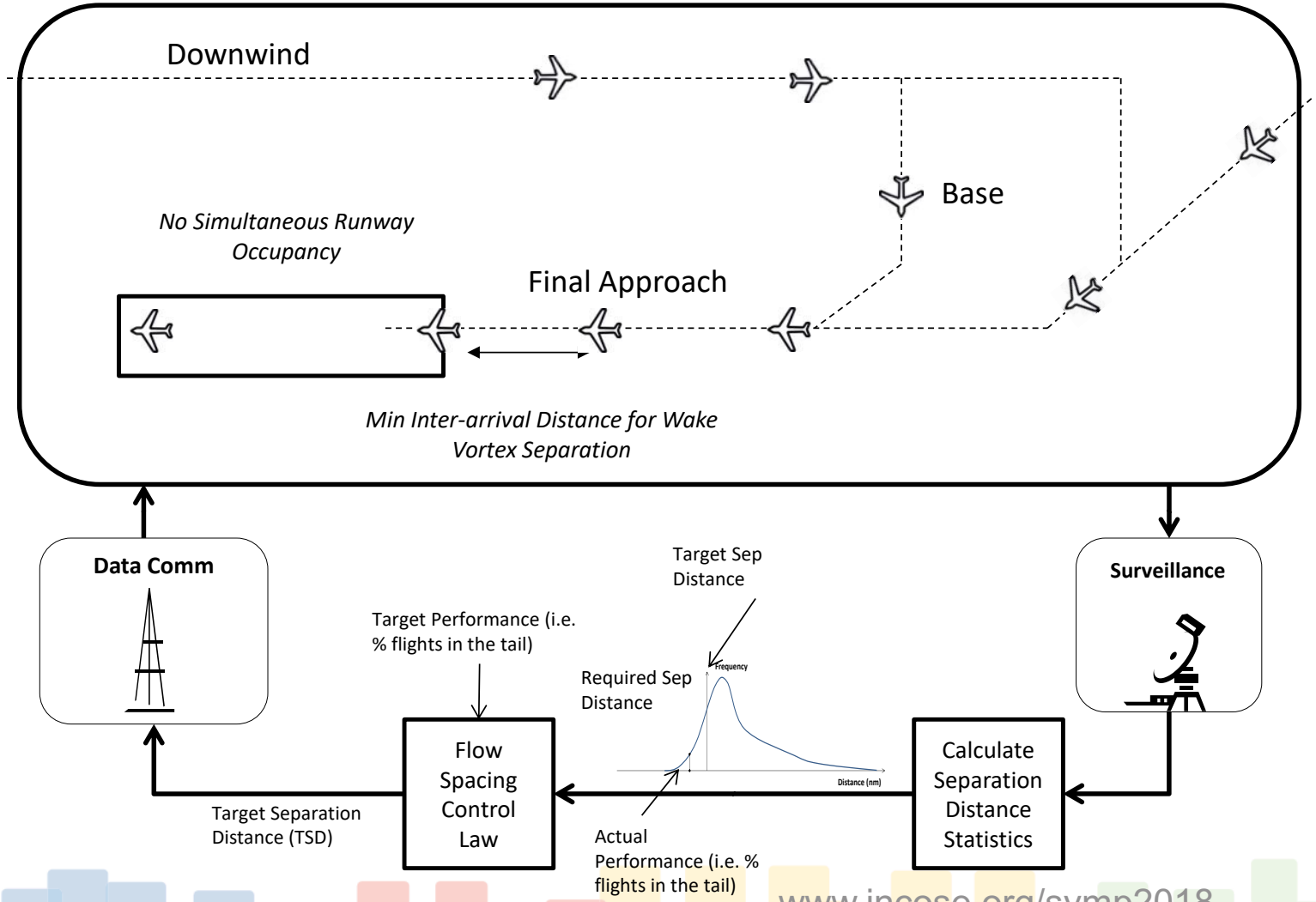


Con-Ops & Reqs



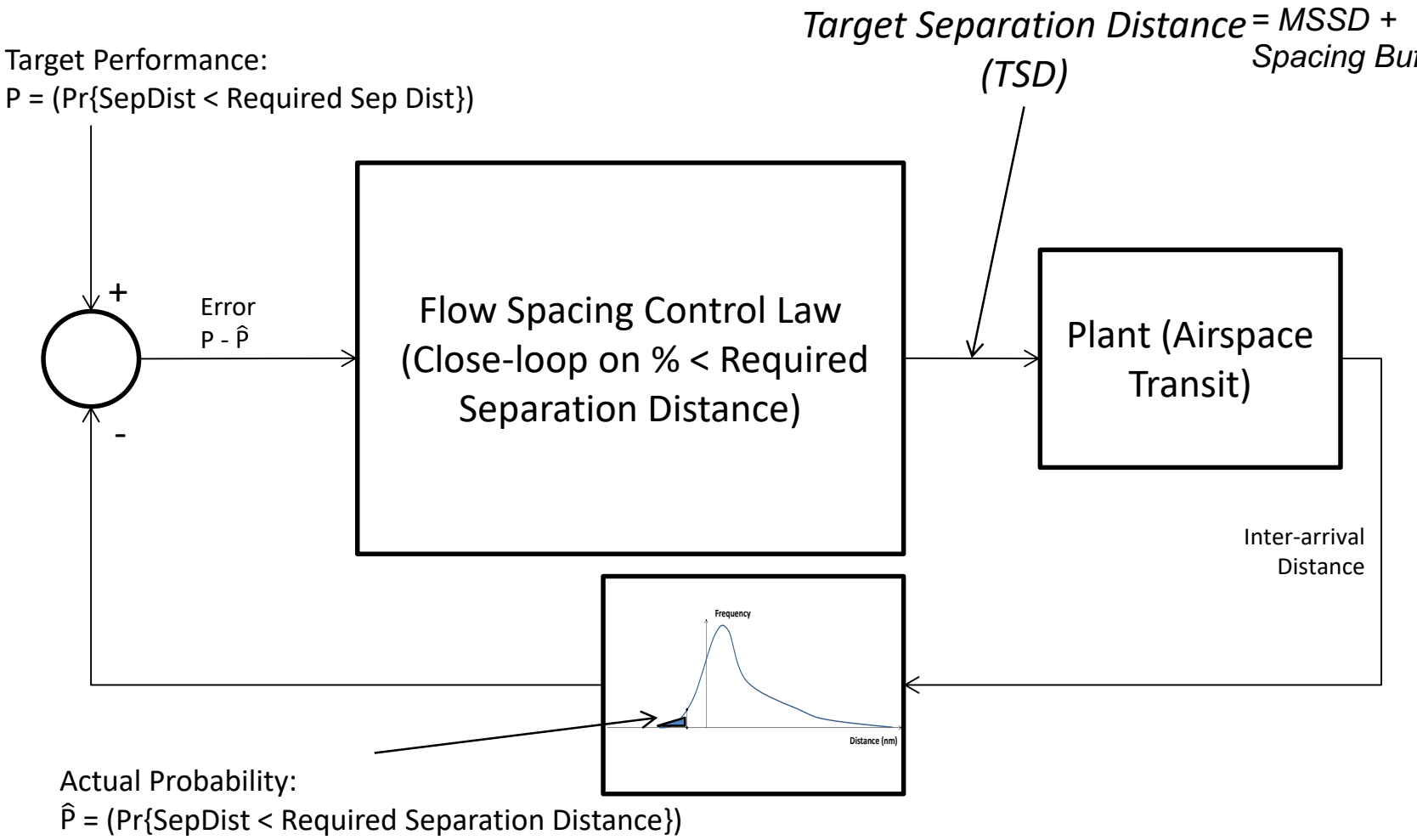
- Increase Throughput & Utilization *and* Maintain Safety margins
  - Knowledge of stochasticity
  - Eliminate voice communication delays
  - Reduce pilot technique
- Reduce right tail (Underutilization):
  - **Required Time of Arrivals (RTA)** places flights at the FAF according to a pre-defined time schedule;
  - **Self-separation** "pulls" sequential flights with a specified time/distance separation;
- Reduce left tail (Safety Margins):
  - **Autonomous Approach & Landing System (AALS)** monitors the inter-arrival times at the runway threshold and sets the buffer-time in excess of the wake vortex separation time to meet a Target Level of Safety (TLS).

Con-Ops & Reqs



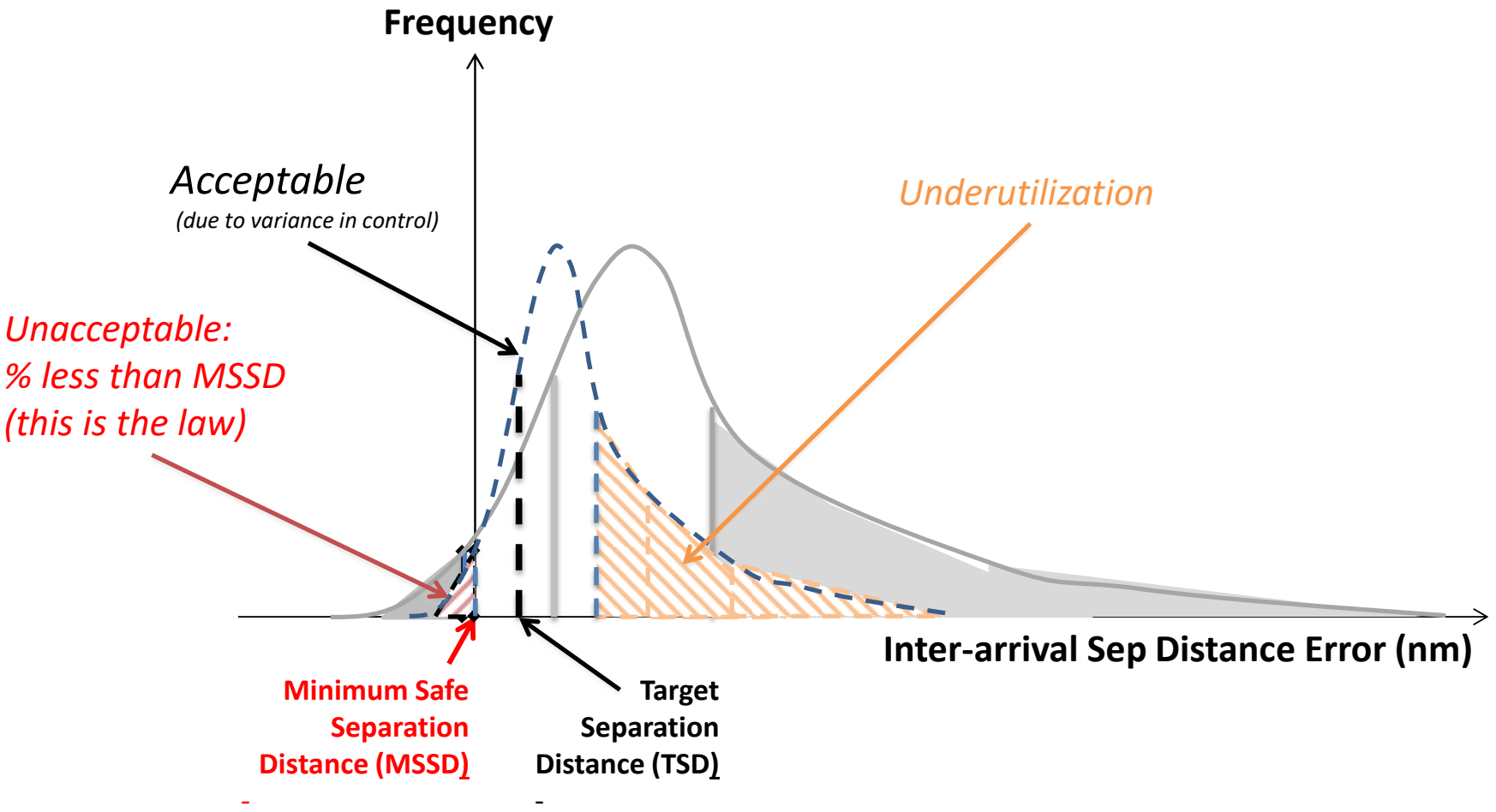
- Replace Air Traffic Controller with automation to perform *Flow Spacing Control*

Con-Ops & Reqs



- The control law continuously adjusts the Spacing Buffer based on the stochastic performance of the system to maximize throughput and maintain the TLS.

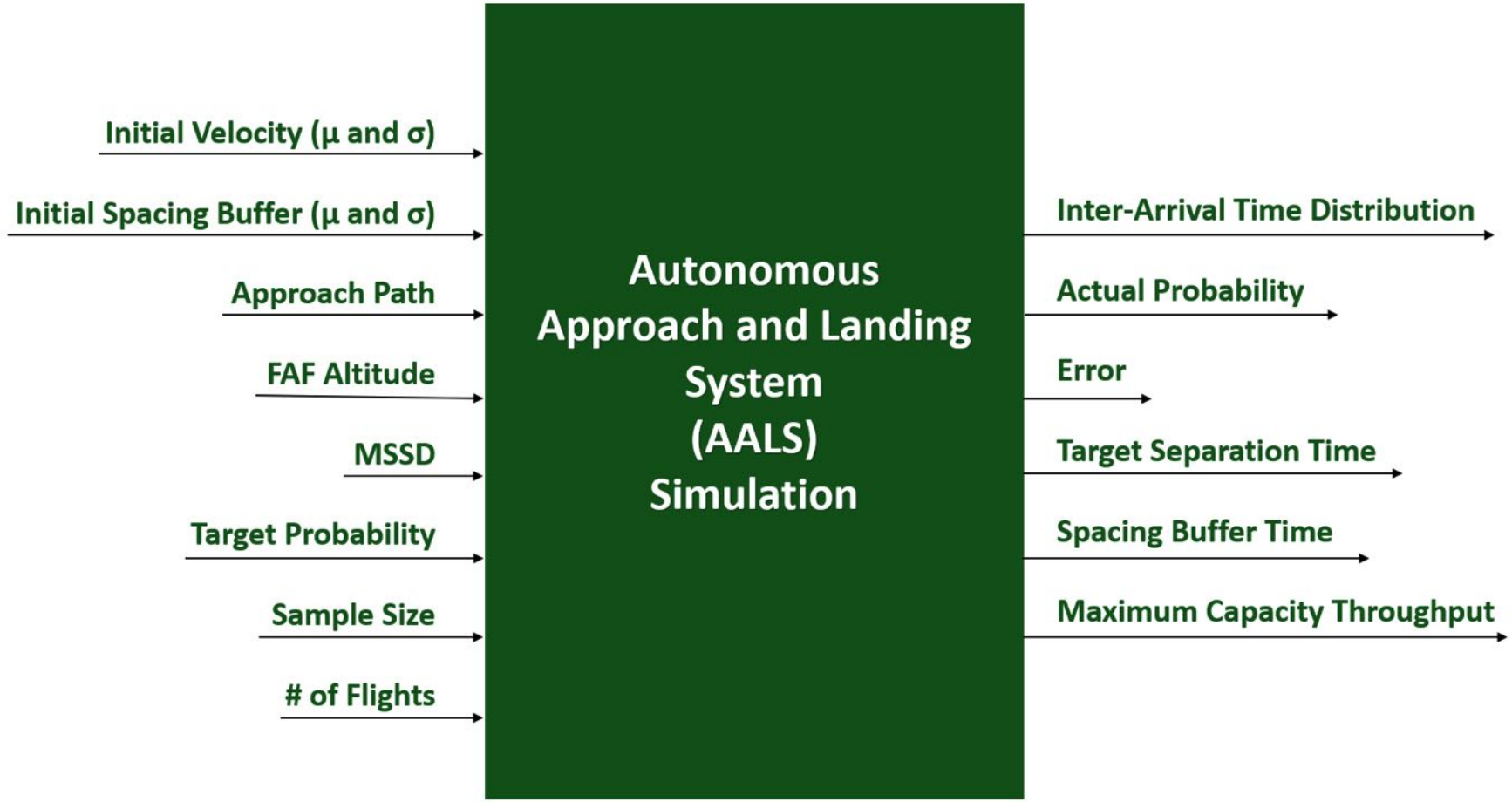
Con-Ops & Reqs



- The result of the AALS is an *inter-arrival time distribution* that continuously balances the trade-off between *utilization and safety* to actively maintain the TLS

MBSE Simulation

Function of Components Reqs

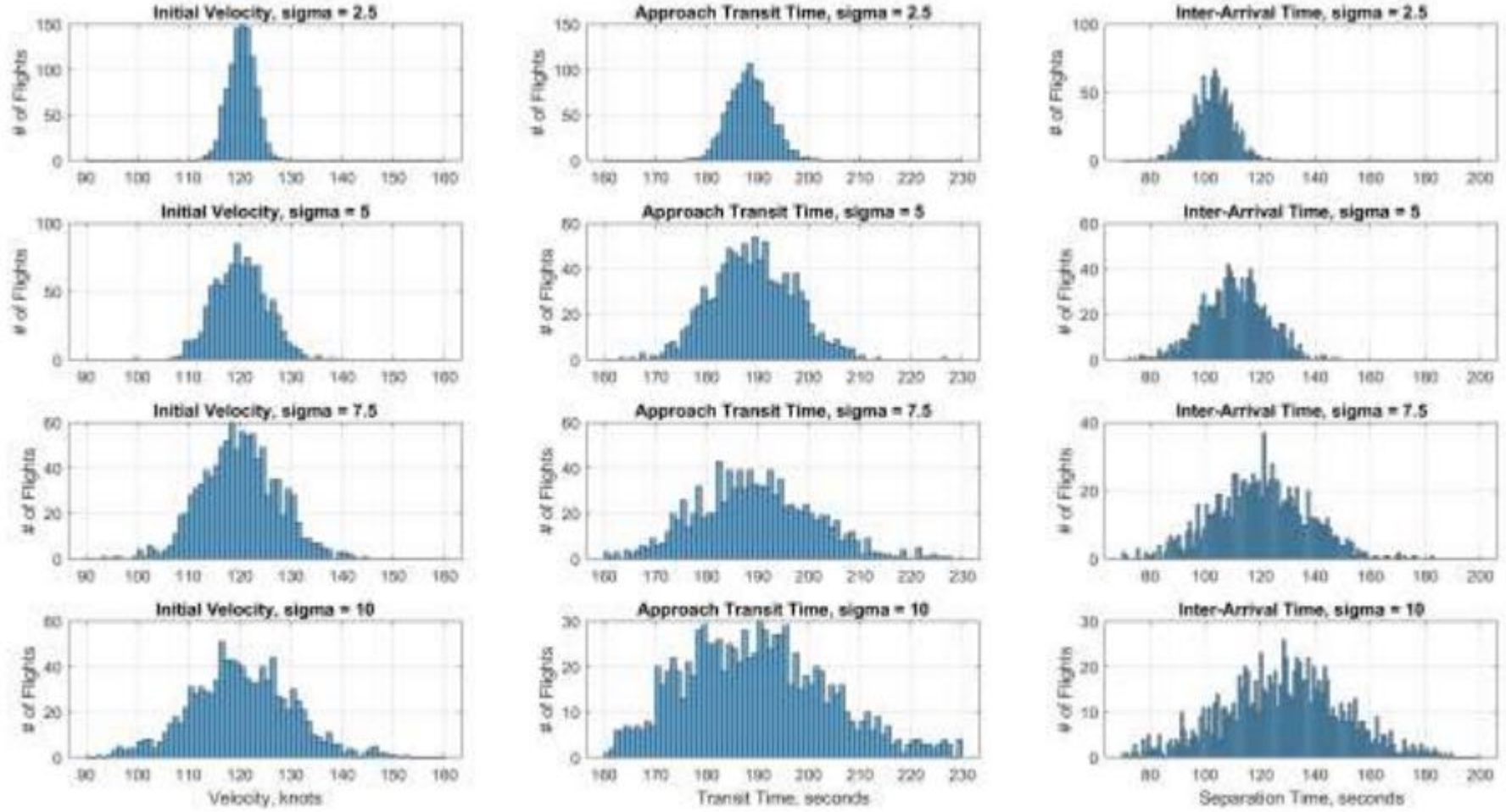


Approach and Landing Spacing Simulation

- **Initial Velocity Distribution** (μ and σ)
  - Models stochasticity in final segment approach
- **Initial Spacing Buffer Distribution** (μ and σ)
  - Models gaps in arrival flow at FAF

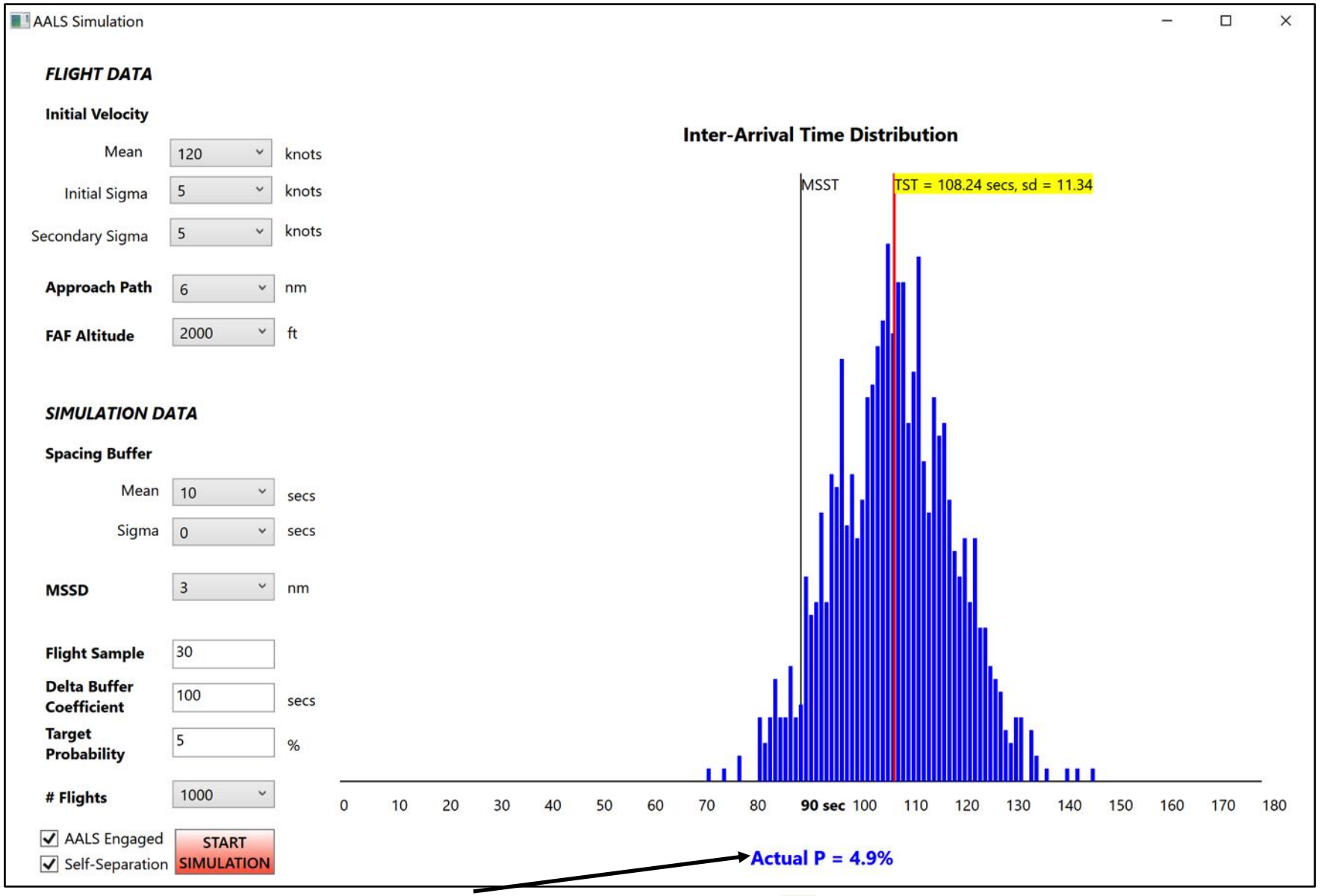
- **Maximum Capacity Throughput (MCT)** is a rate of number of flights that have landed on a runway per given period of time.

Approach and Landing Spacing Simulation



Increasing Stochasticity during Approach

Simulation GUI



Actual Probability after simulation

Fixed Spacing at FAF (Baseline)

Input:

V = 120 knots

σ_{IV} = 10 knots

Buffer = 10 s

σ_{SB} = 0

Output:

P = 30.5%

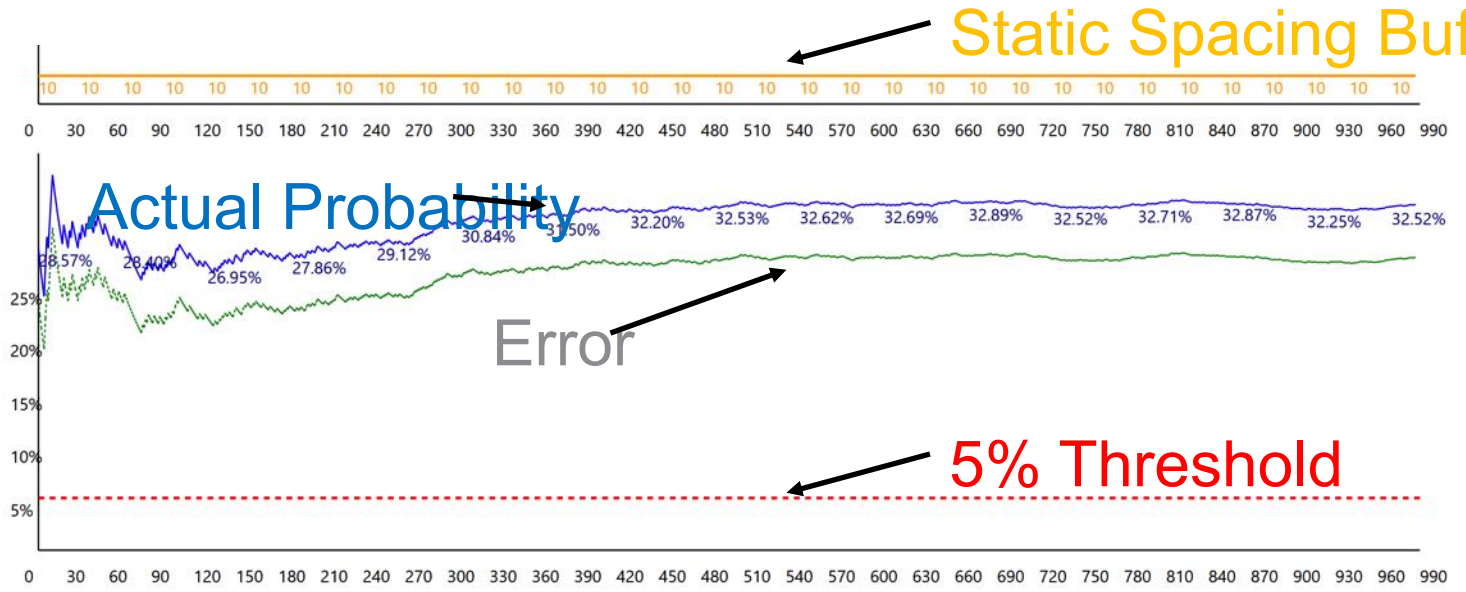
Buffer = 10 s

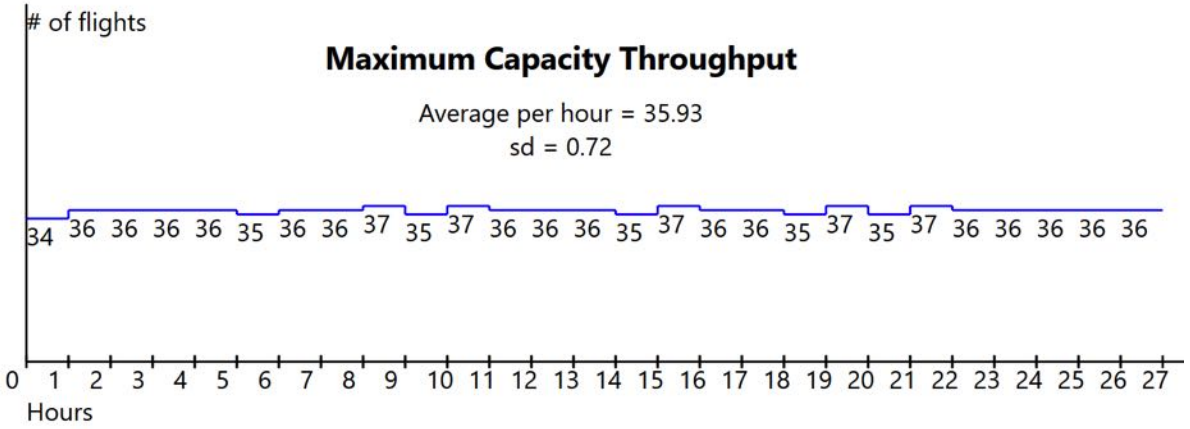
MCT = 36

IAT = 102.17 s

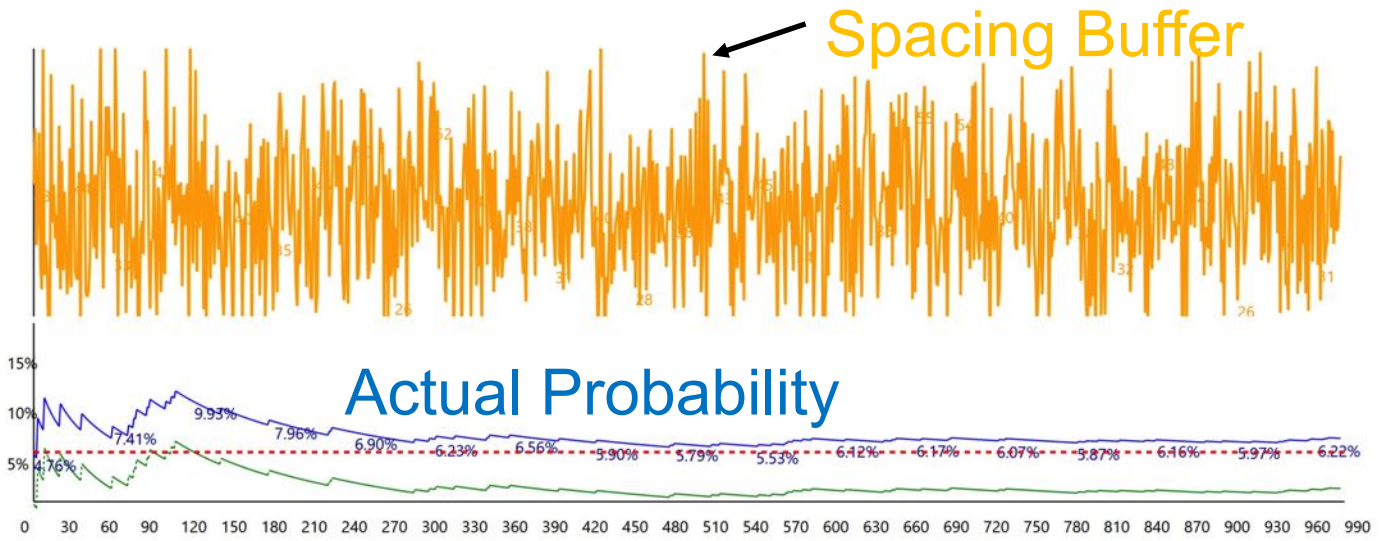
σ_{IAT} = 23.21 s

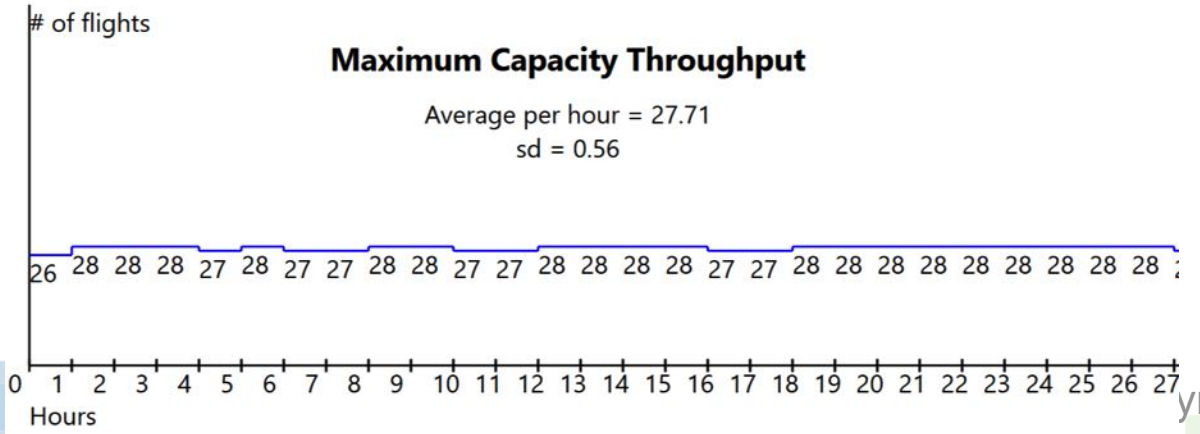
This scenario leads to extreme ***safety violations****.*





Manual Spacing at FAF (Spacing Buffer = 40 s, σ_{SB} = 10 s)





Input:

V = 120 knots

σ_{IV} = 10 knots

Buffer = 40 s

σ_{SB} = 10 s

Output:

P = 6.1%

Buffer = 39.99 s

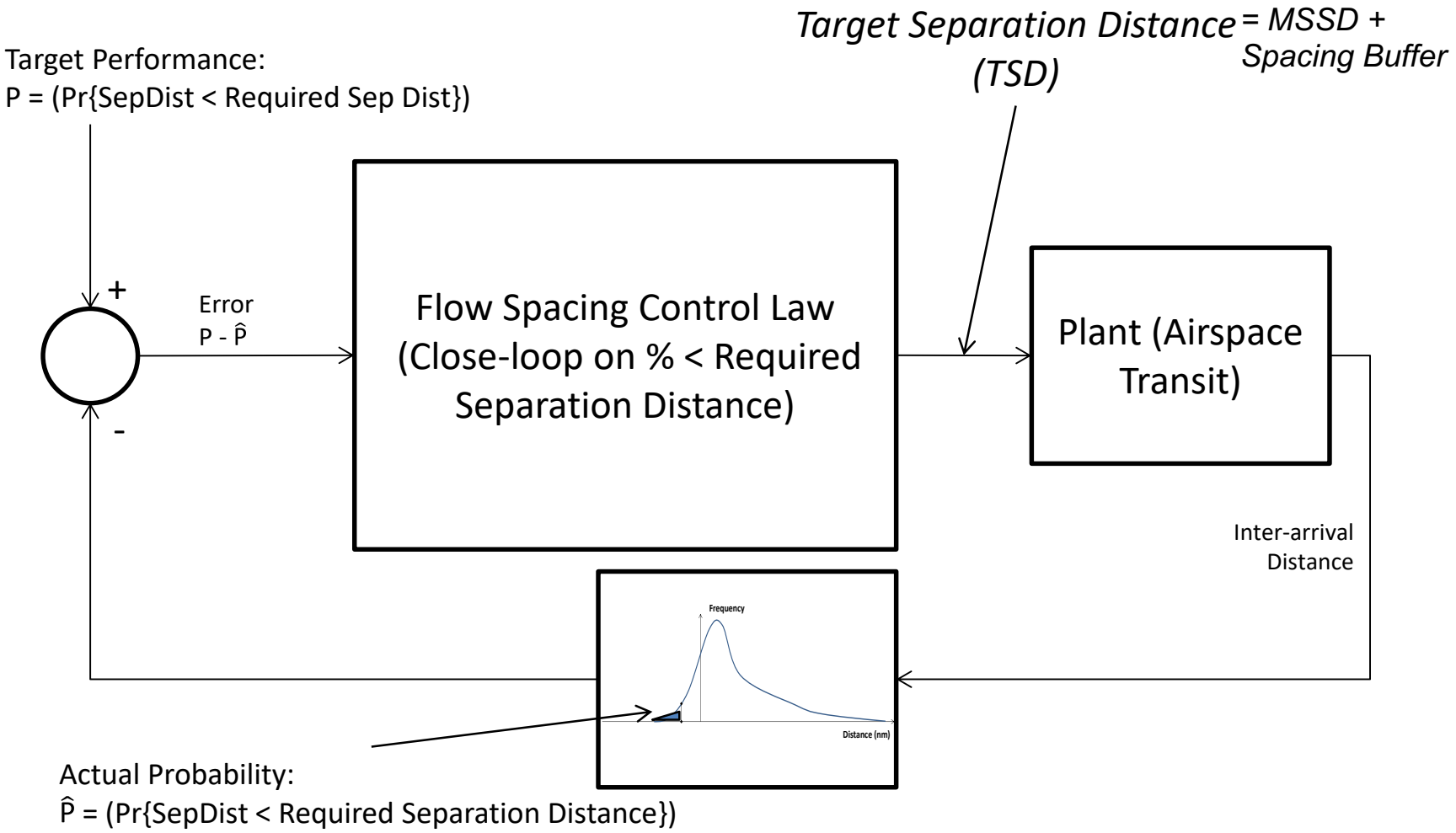
σ_{SB} = 9.75 s

MCT = 28

IAT = 129.75 s

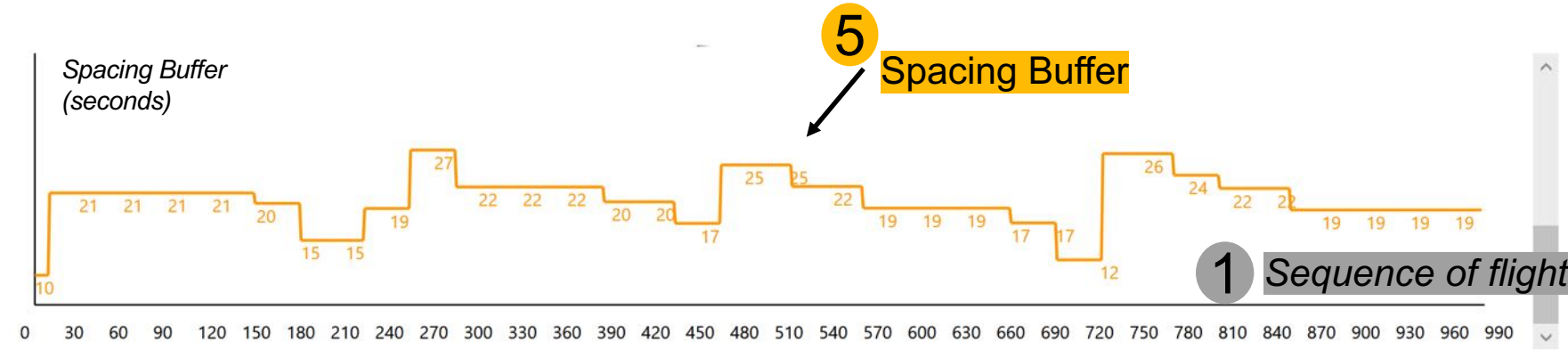
σ_{IAT} = 25.49 s

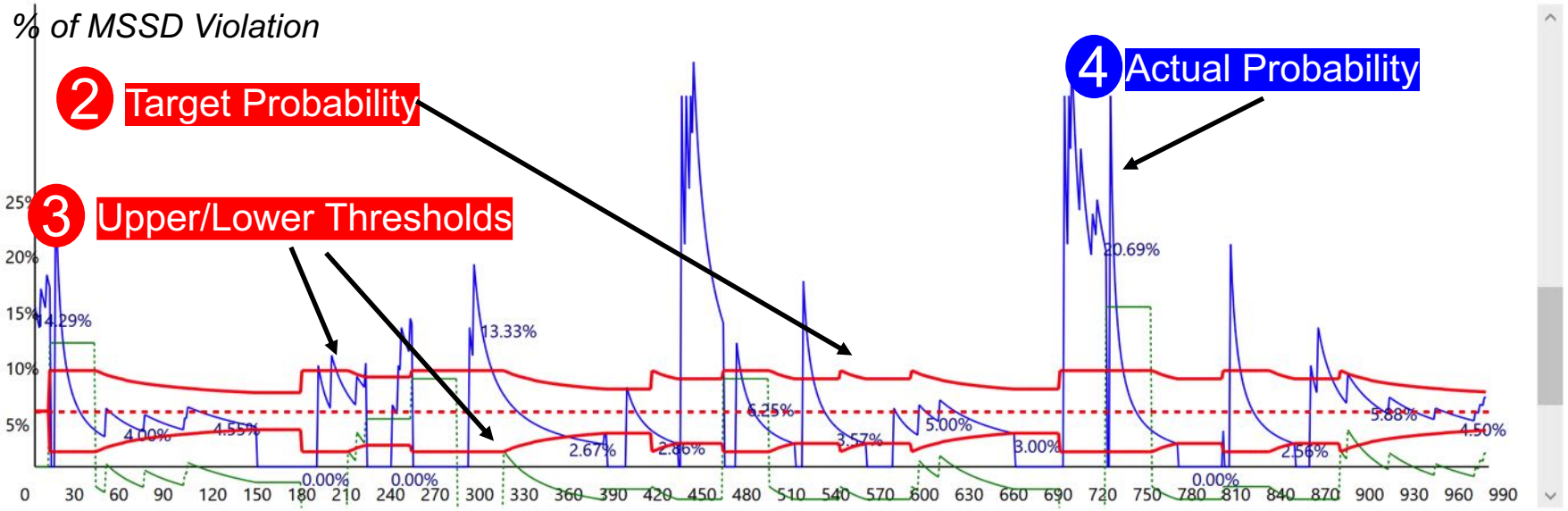
Autonomous Spacing Control



- **Actual Probability** is the current probability of "hitting" an acceptable region:
  - *Actual Probability = # of flights that violated MSSD / Flight Counter*
- **Target Probability** is the desired TLS, set to 5%.
- **Upper/Lower Thresholds** approach Target Probability as number of flights increased:
  - *Upper / Lower Threshold = Target Probability +/-*
  - *($t_{1-\alpha}$* (1 / SQRT(# of flights)))*

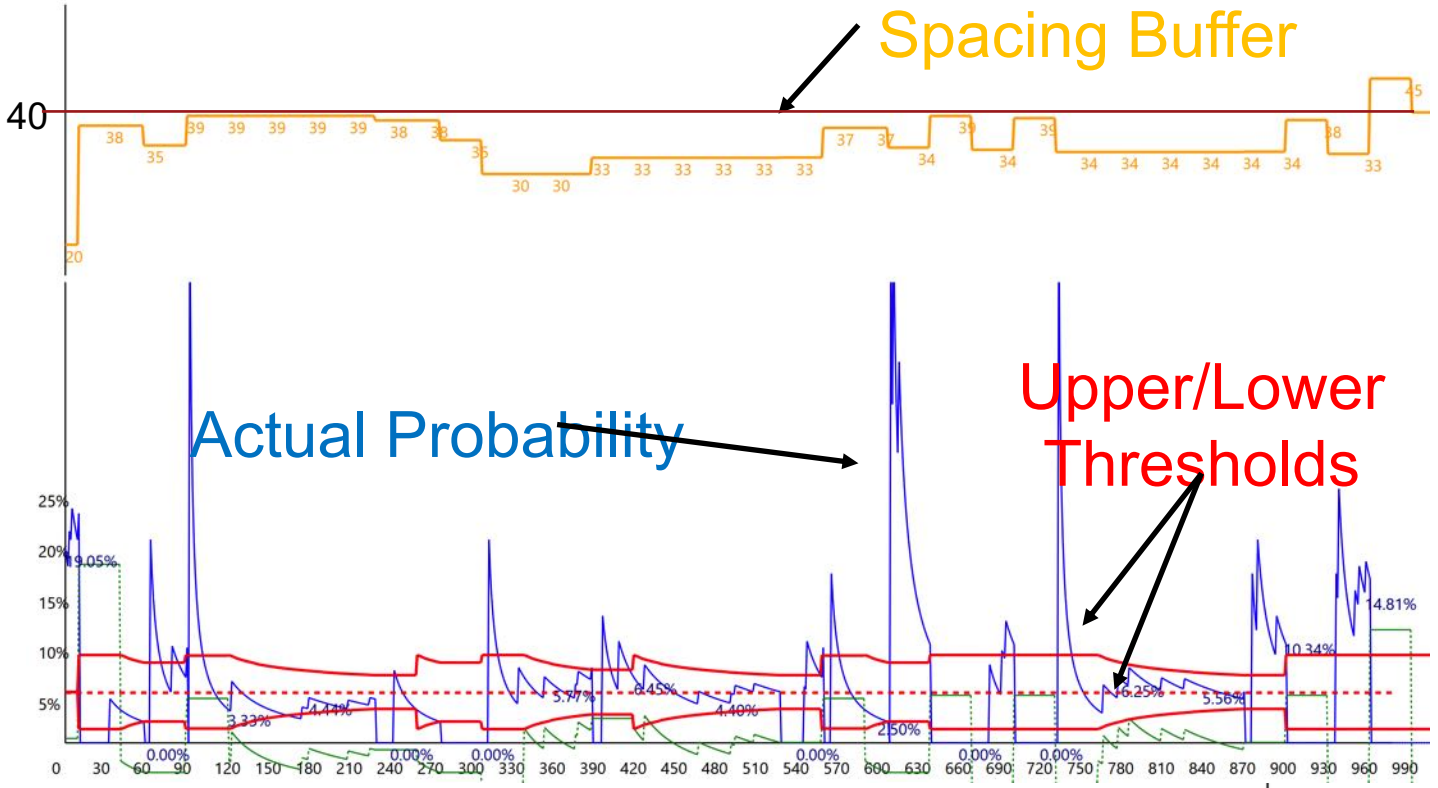
Autonomous Spacing Control





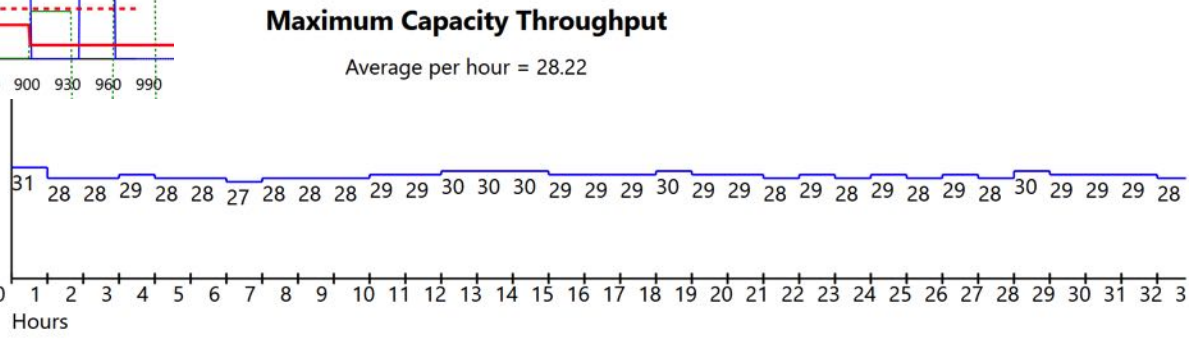
- Average Spacing Buffer = 20.16 seconds with standard deviation of 3.59 s
- Maximum Capacity Throughput = 32.6 flights per hour
- Actual Probability = 4.9% (<5% of Target Probability).

Automated Spacing Control



Input:
V = 120 knots
σ_{IV} = 10 knots
Buffer = AALS
σ_{SB} = 10 s

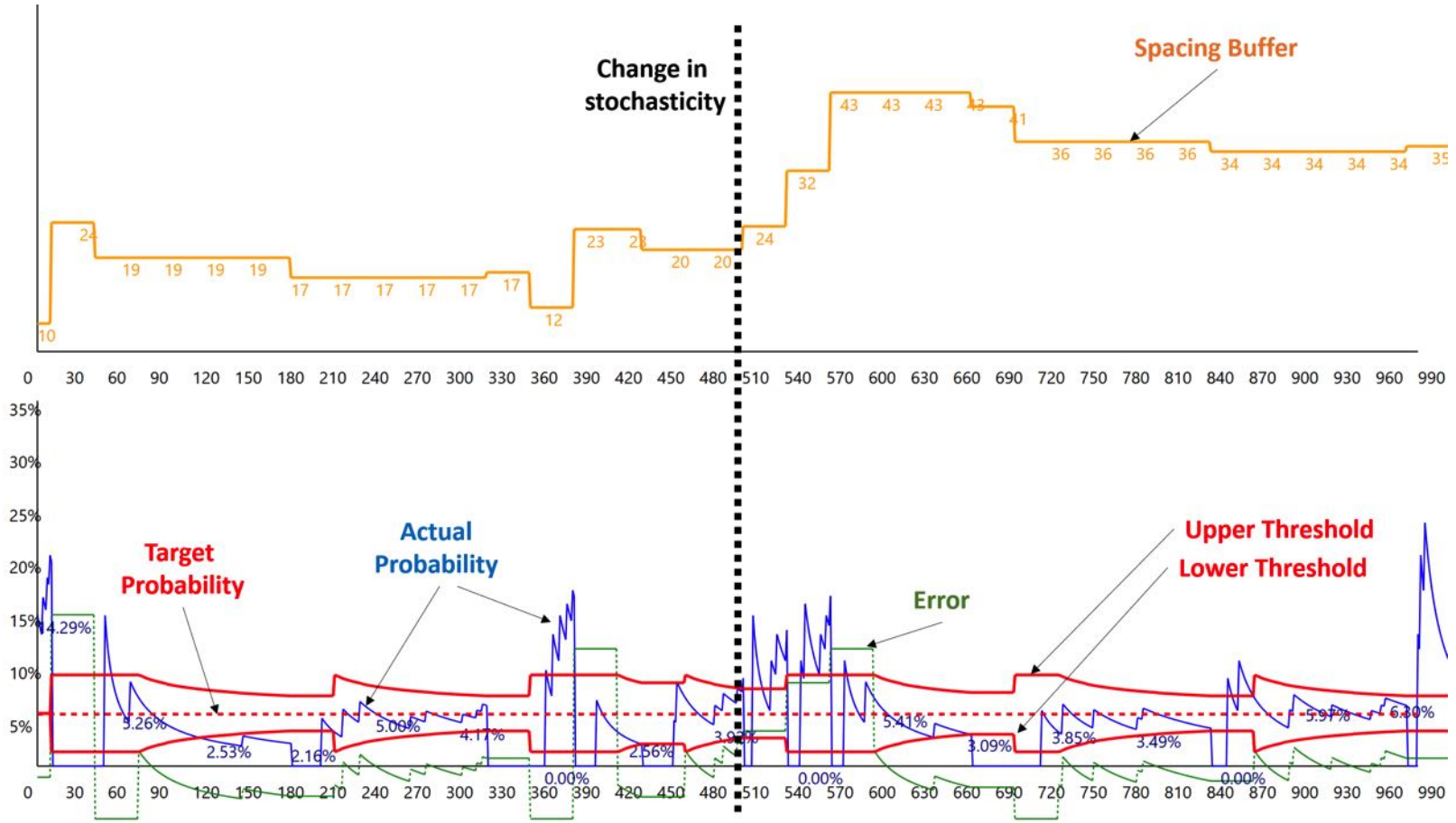
Output:
P = 4.72%
Buffer = 37.55 s
σ_{SB} = 4.31 s



Configuration Design

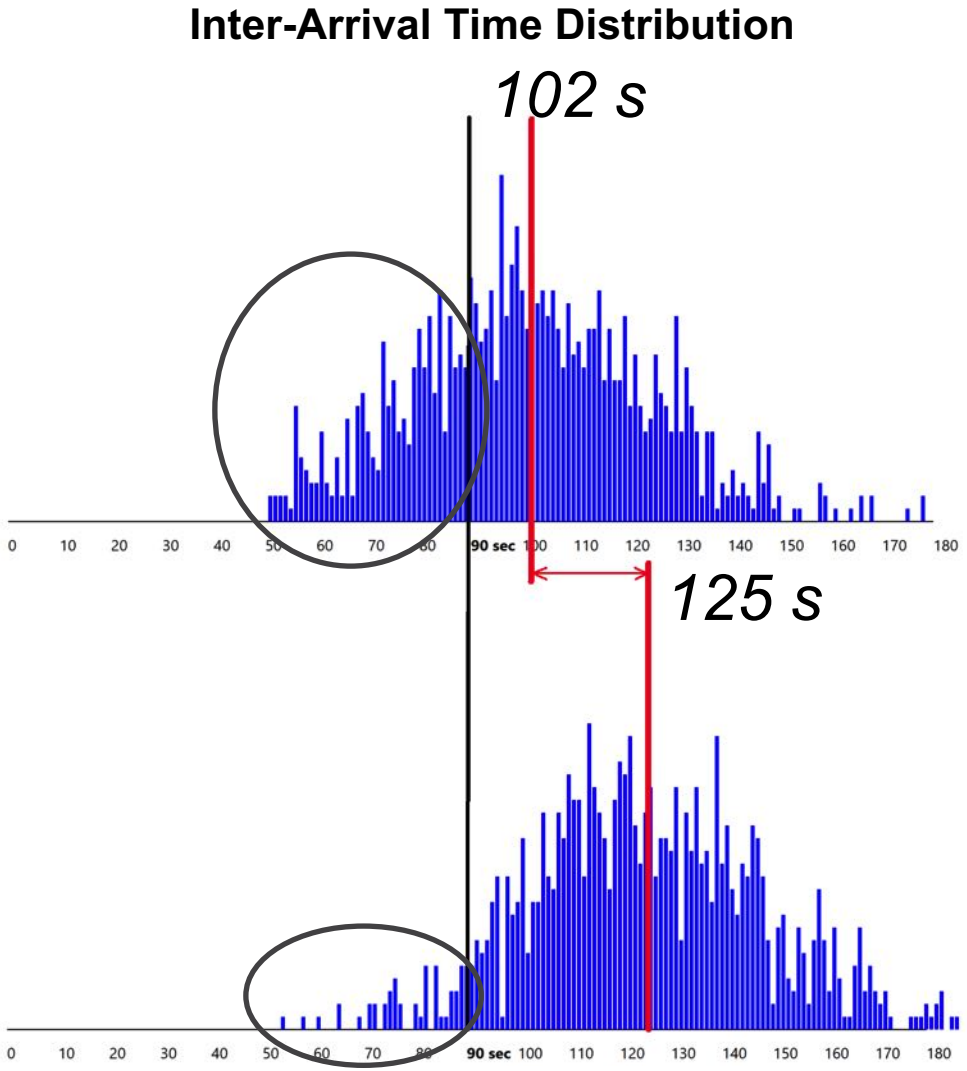
High Approach Stochasticity V = 120 knots, σ = 10		Input		Output						
		Spacing Buffer, secs		Inter-Arrival Time, secs		Excess Spacing Buffer, secs		Throughput		P (Left-tail)
Run	Configuration	μ	σ	μ	σ	μ	σ	μ	σ	
11	Self Sep (Ideal) with AALS	AALS	0	130.11	22.9	40	0	27.69	0.49	*3.92%*
12	Self-Sep with AALS	AASL	5	130.06	23.07	39.95	4.97	27.69	0.52	*3.91%*
13	RTA with AALS	AALS	10	130.25	24.57	40.01	9.99	27.67	0.62	**6.1%**
14	RTA/Self-Sep with AALS	**AALS**	**10**	**128.37**	**23.41**	**38.19**	**4.41**	**28.07**	**1.05**	**4.76%**

Automated Spacing Control (Adaptive)



Conclusions

- Stochastic simulation integrated into MBSE tools
  - Not a *seamless* process
- Provided necessary means to evaluate design trades



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