Society of Experimental Test Pilots (SETP) Symposium 2023

Urban Air Mobility (UAM)
Procedure Design and Flight Test Evaluation Methodology

David Zahn & Wayne Ringelberg
NASA Research Pilots

Overview

Importance of: Dynamic Procedure Design & Evaluation

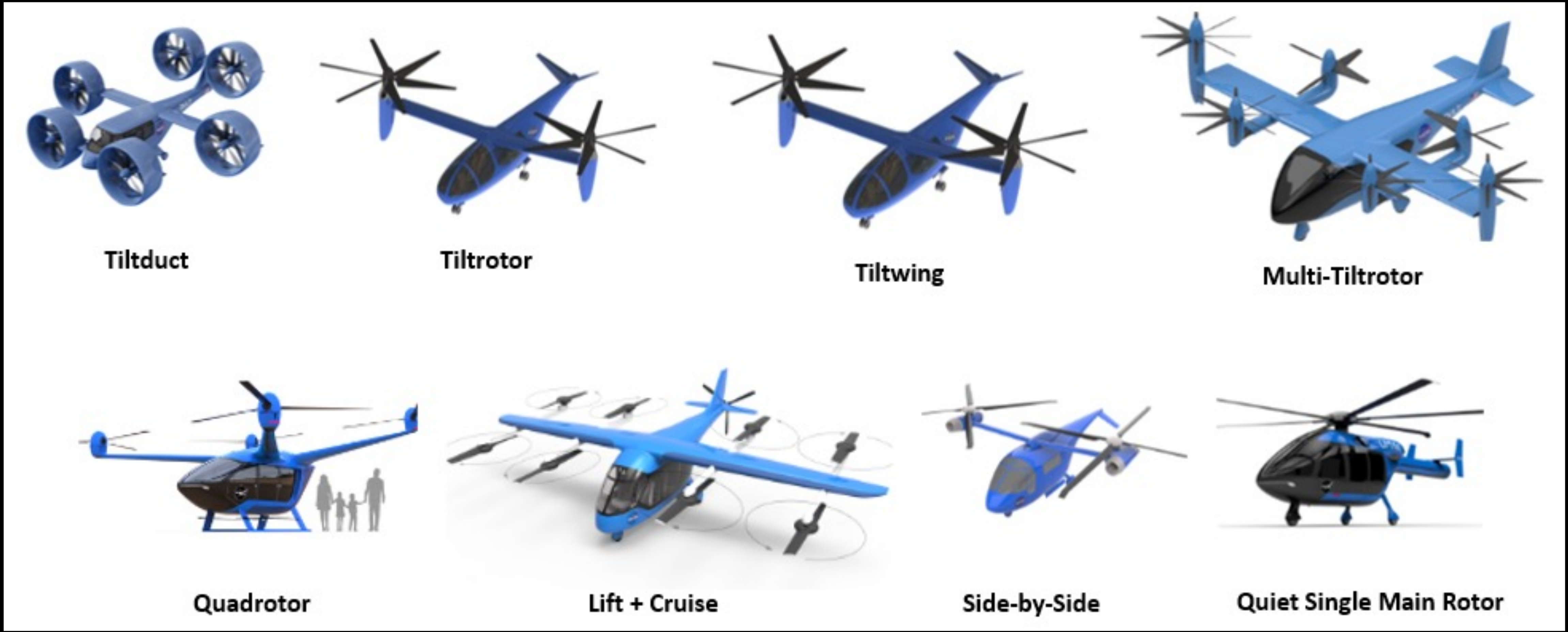
Technical Challenges: UAM Airspace Architecture

Lessons Learned: UAM Procedure Flight Test Evaluation

Conclusion: Future Model and Follow-on Research

Research Importance

Dynamic procedure design tailored for novel vehicles and operations



Credit: NASA

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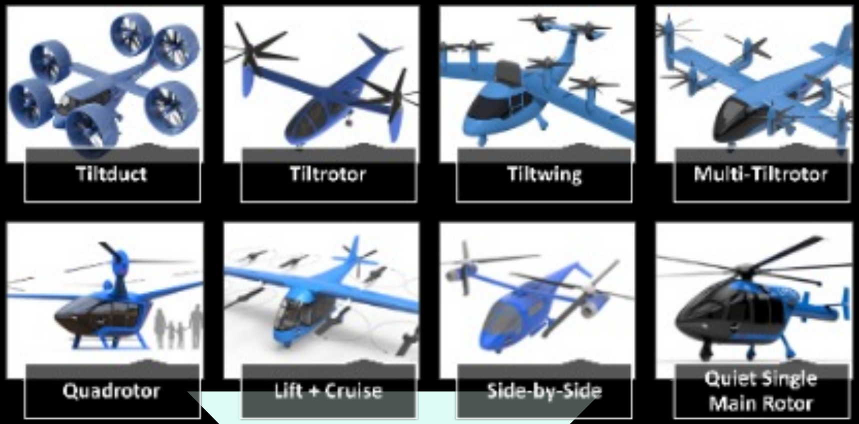

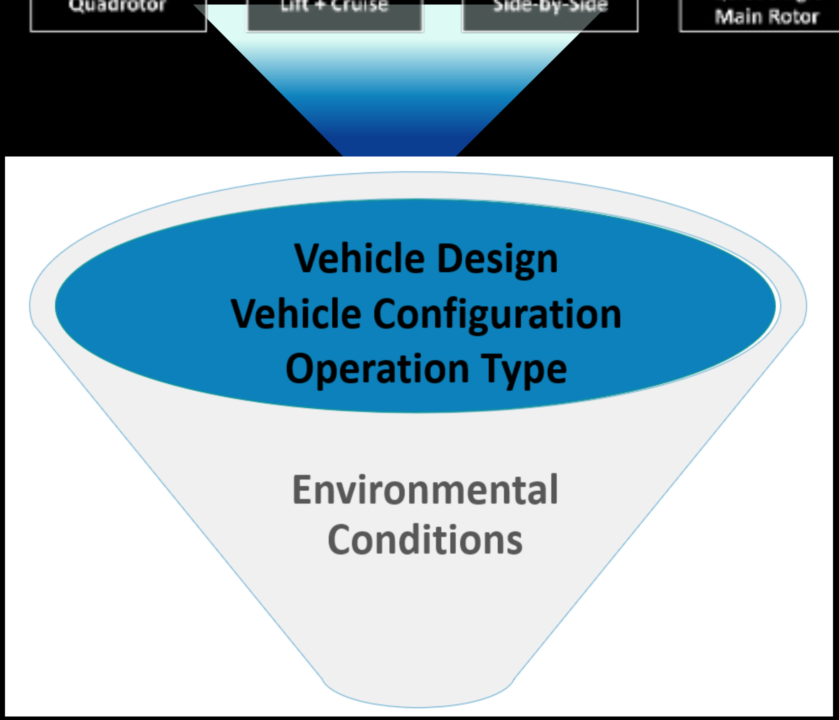

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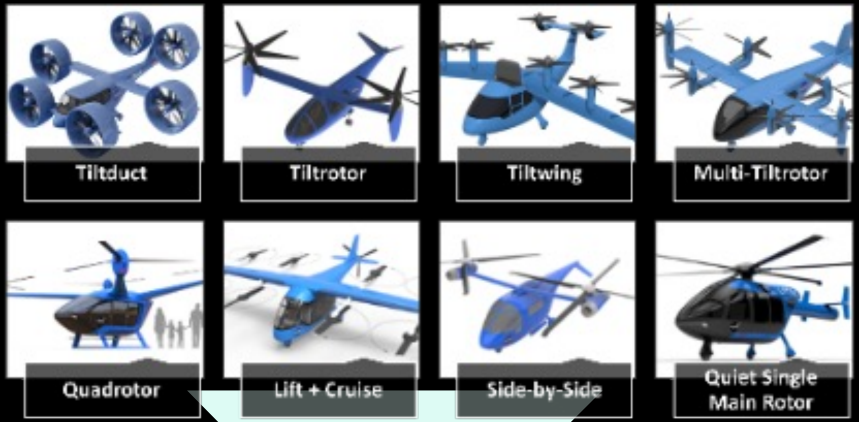
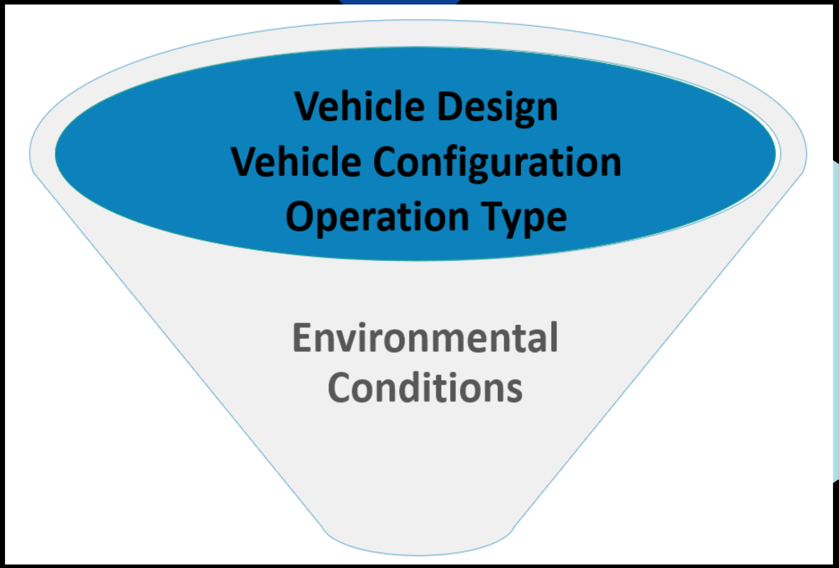




Safety

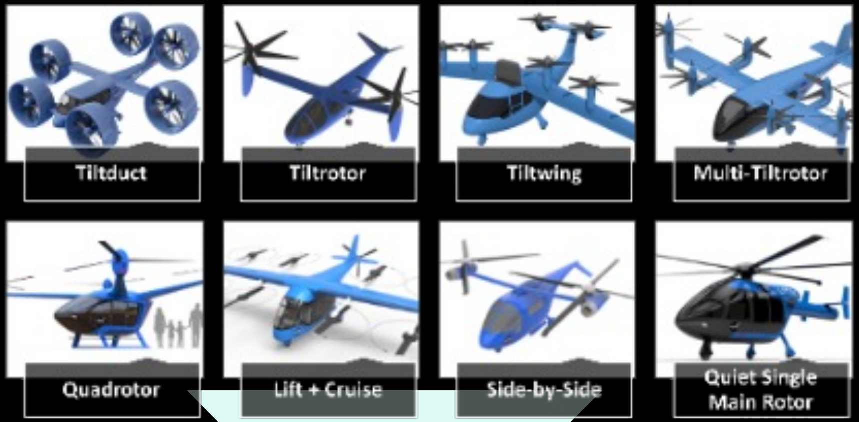
Efficiency

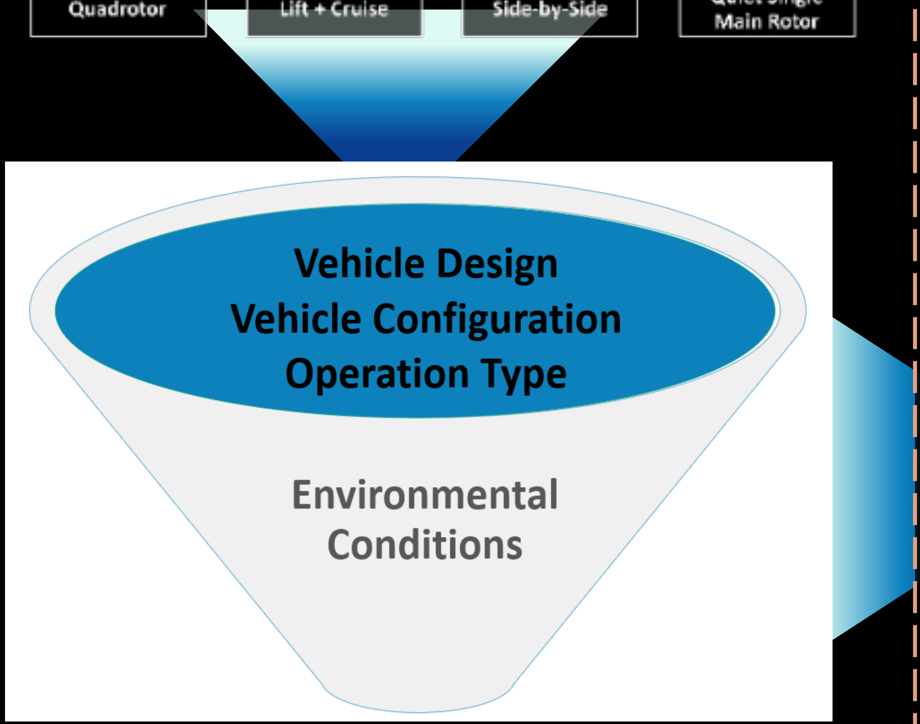
Passenger Comfort

Acoustics

Research Importance

Dynamic procedure design tailored for novel vehicles and operations





Safety

Efficiency

Passenger Comfort

Acoustics

H-60 PERFORMANCE PLANNING CARD

For use of this form, see TC 1-237; the proponent agency is TRADOC.

DEPARTURE

AIRCRAFT GWT: 20000 lb	PA: 0 ft/	0 ft	FAT: 20 °C/	20 °C
STORES WEIGHT: 4000 lb	DUAL ENGINE		SINGLE ENGINE	
FUEL WEIGHT: 1500 lb			#1	#2
ZERO FUEL WEIGHT: 18500 lb				
	ATF: .980		ETF: 1.0	ETF: .96
TORQUE RATIO	.984		1.0	.967
MAX TORQUE AVAILABLE	108 %		110 %	106 %
MAX ALLOWABLE GWT OGE/IGE	21000 lb	21500 lb		
GO/NO GO TORQUE OGE/IGE	97 %	100 %		
MAX HOVER HEIGHT IGE	OGE ft			
PREDICTED HOVER TORQUE	90 %		180 %	180 %
MIN SE AIRSPEED - IAS- WO/ W STORES			20 kts	48 kts

REMARKS:

	ΔF	DMF
ALQ-144	0.8	.08
M130	0.3	.03
LOAD	15.0	1.50
TOTAL	16.1	1.61

EMER SE IAS:

CRUISE

PA: 0 ft	FAT 20 °C	MAX ANGLE: °	Vne-IAS: kts	
	DUAL ENGINE		SINGLE ENGINE	
			#1	#2
MAX TORQUE AVAILABLE	111 %		112 %	108 %
MIN / MAX - IAS	0 kts	134 kts	47 kts	94 kts
CRUISE SPEED - IAS / TAS	100 kts	102 kts	80 kts	84 kts
CRUISE TORQUE /CONT TORQUE AVAILABLE	58 %	88 %	102 %	87 %
CRUISE FUEL FLOW	930 pph		690 pph	
MAX RANGE - IAS / TORQUE	124 kts	75 %		
MAX ENDURANCE - IAS / TORQUE	75 kts	47 %		
CRITICAL TORQUE	53 %			
MAX ALLOWABLE GWT	22000 lb		21600 lb	
OPTIMUM IAS AT MAX ALLOWABLE GWT	77 kts		77 kts	
MAX R/C - IAS / TORQUE	87 kts	100 %		
MAX ALTITUDE -MSL/MAX ENDURANCE-IAS	14000 ft	57 kts	ft	kts

DA FORM 5701-60-R, PAGE 1 OF 2

Research Importance

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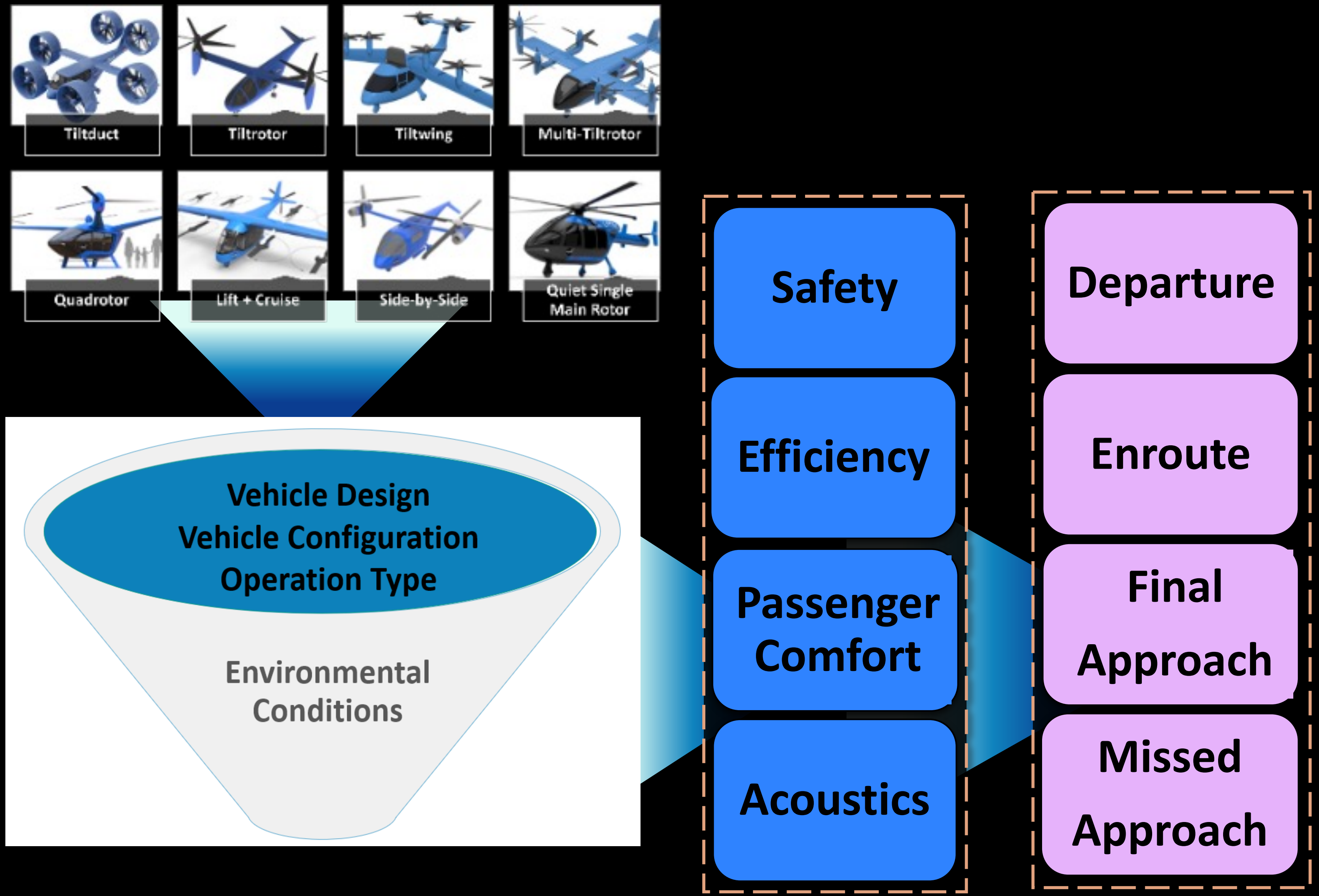

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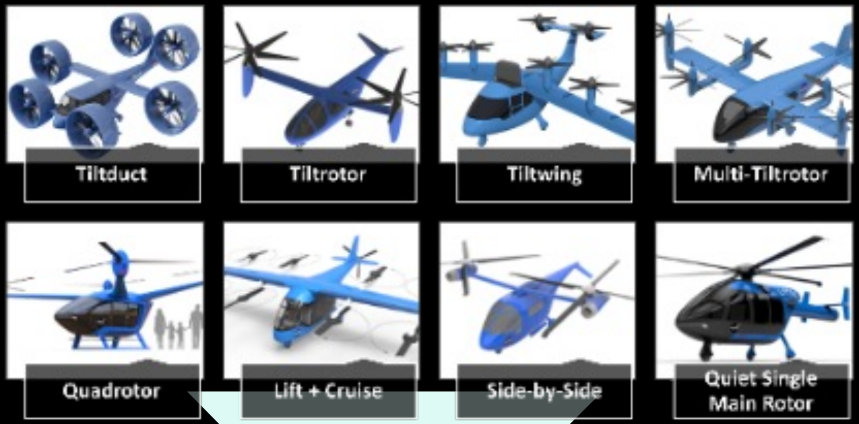
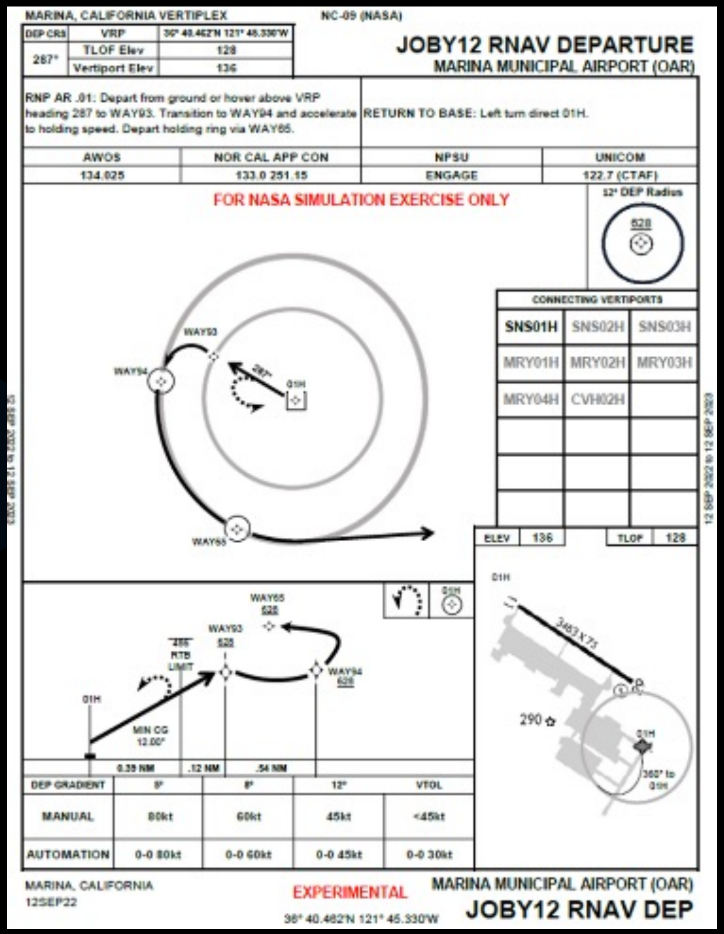


Vehicle Design
Vehicle Configuration
Operation Type

Environmental Conditions

- Safety
- Efficiency
- Passenger Comfort
- Acoustics

- Departure
- Enroute
- Final Approach
- Missed Approach



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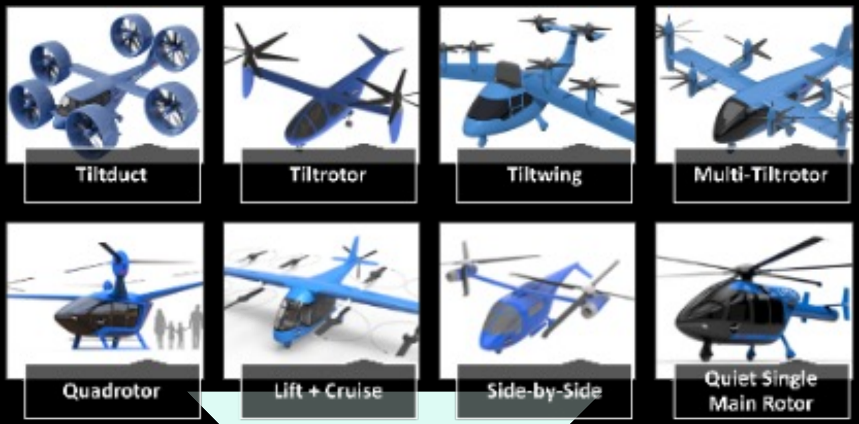
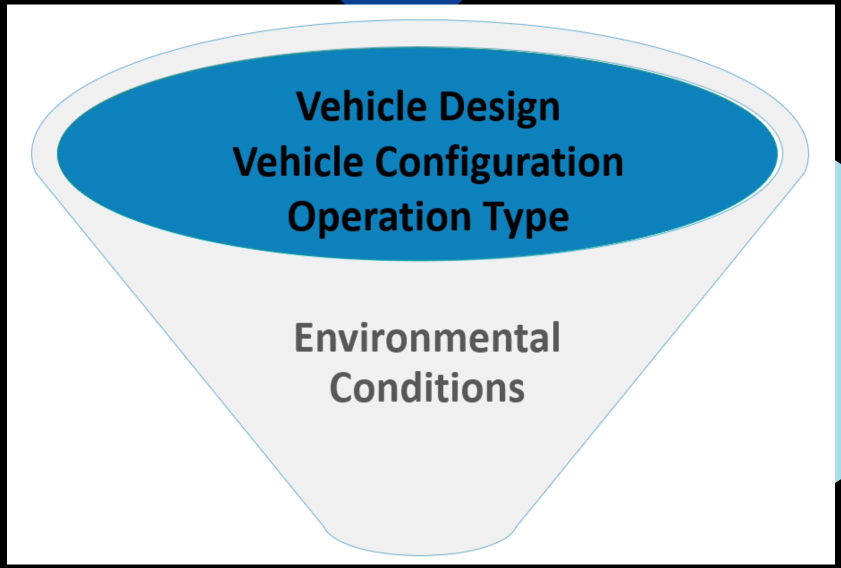
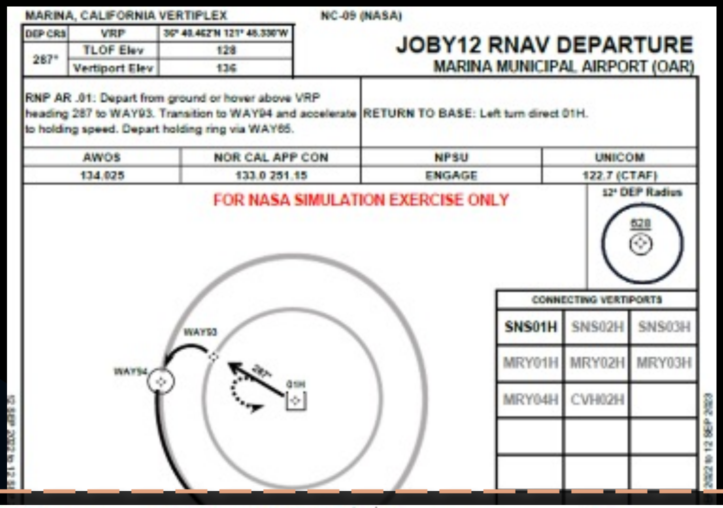
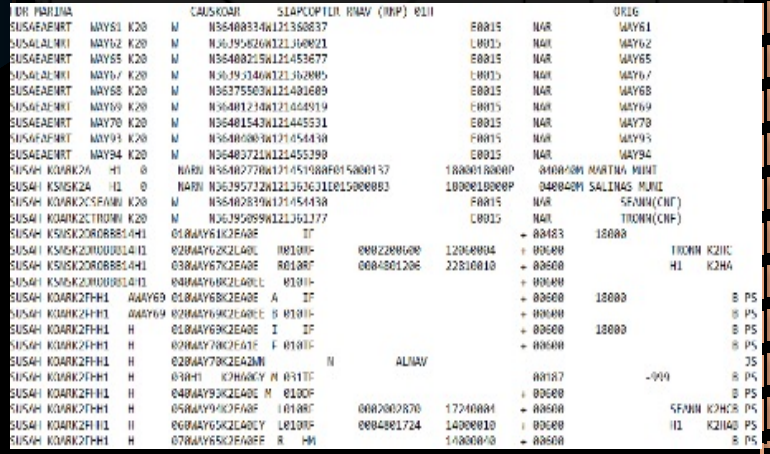




- Safety
- Efficiency
- Passenger Comfort
- Acoustics

- Departure
- Enroute
- Final Approach
- Missed Approach





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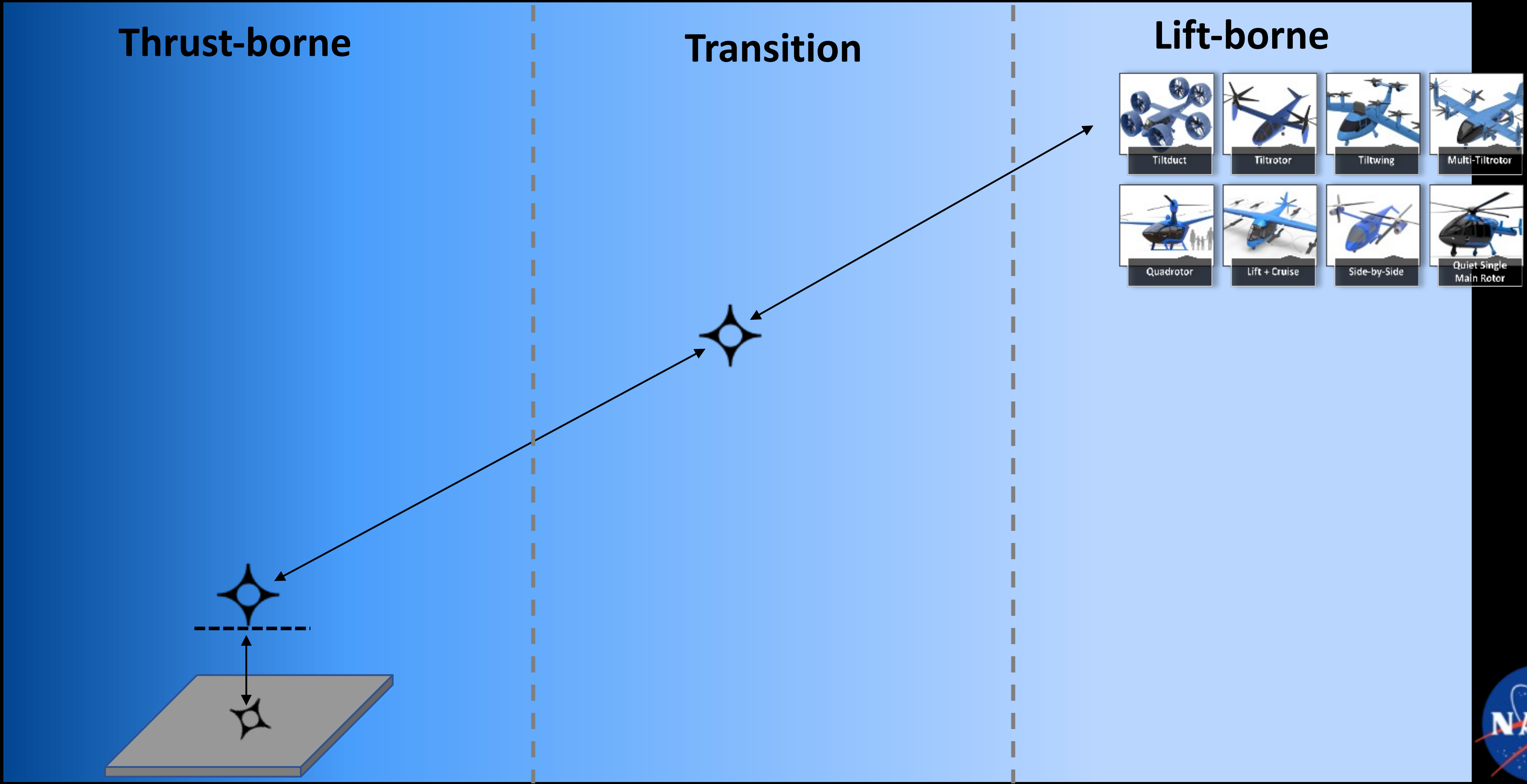

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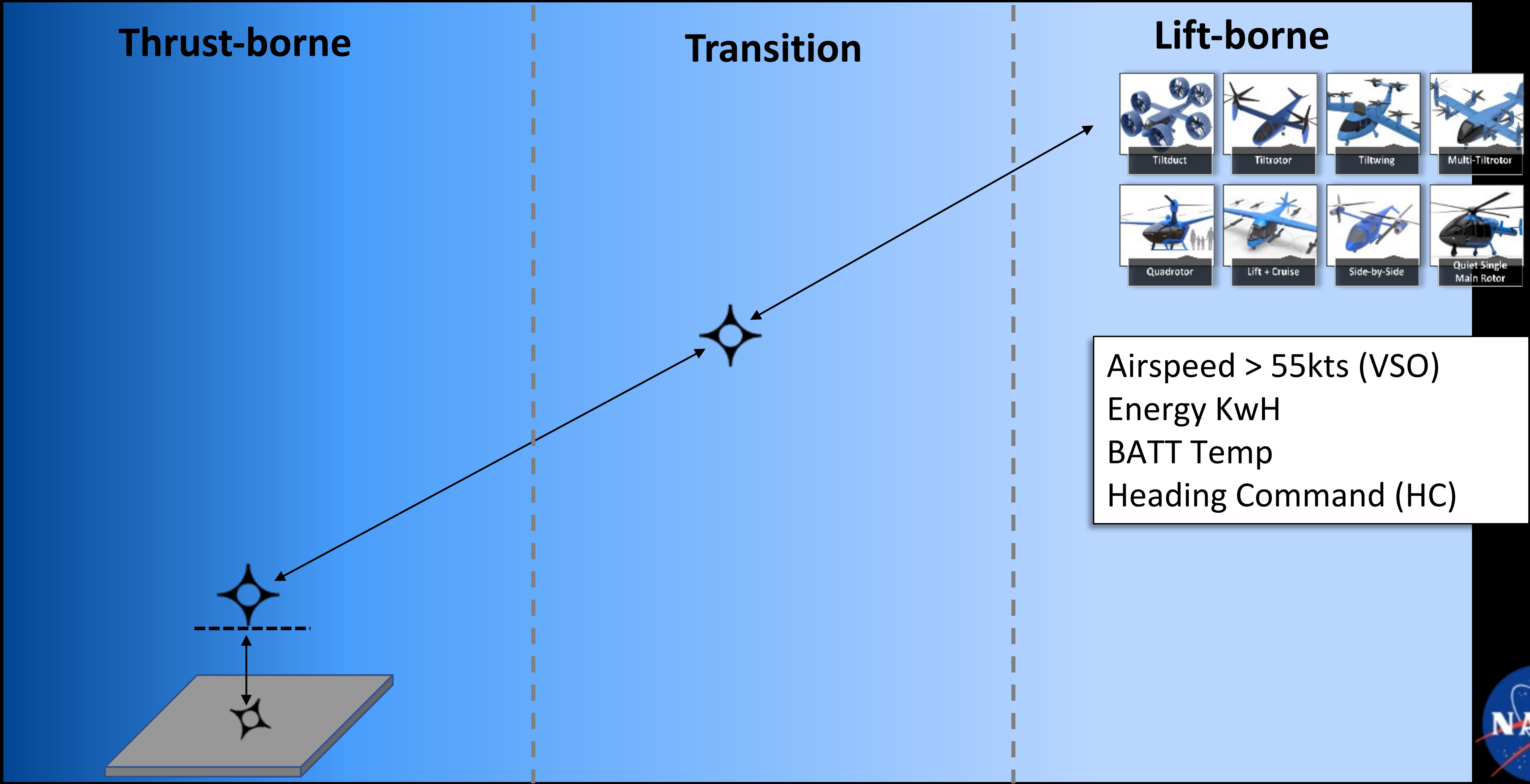

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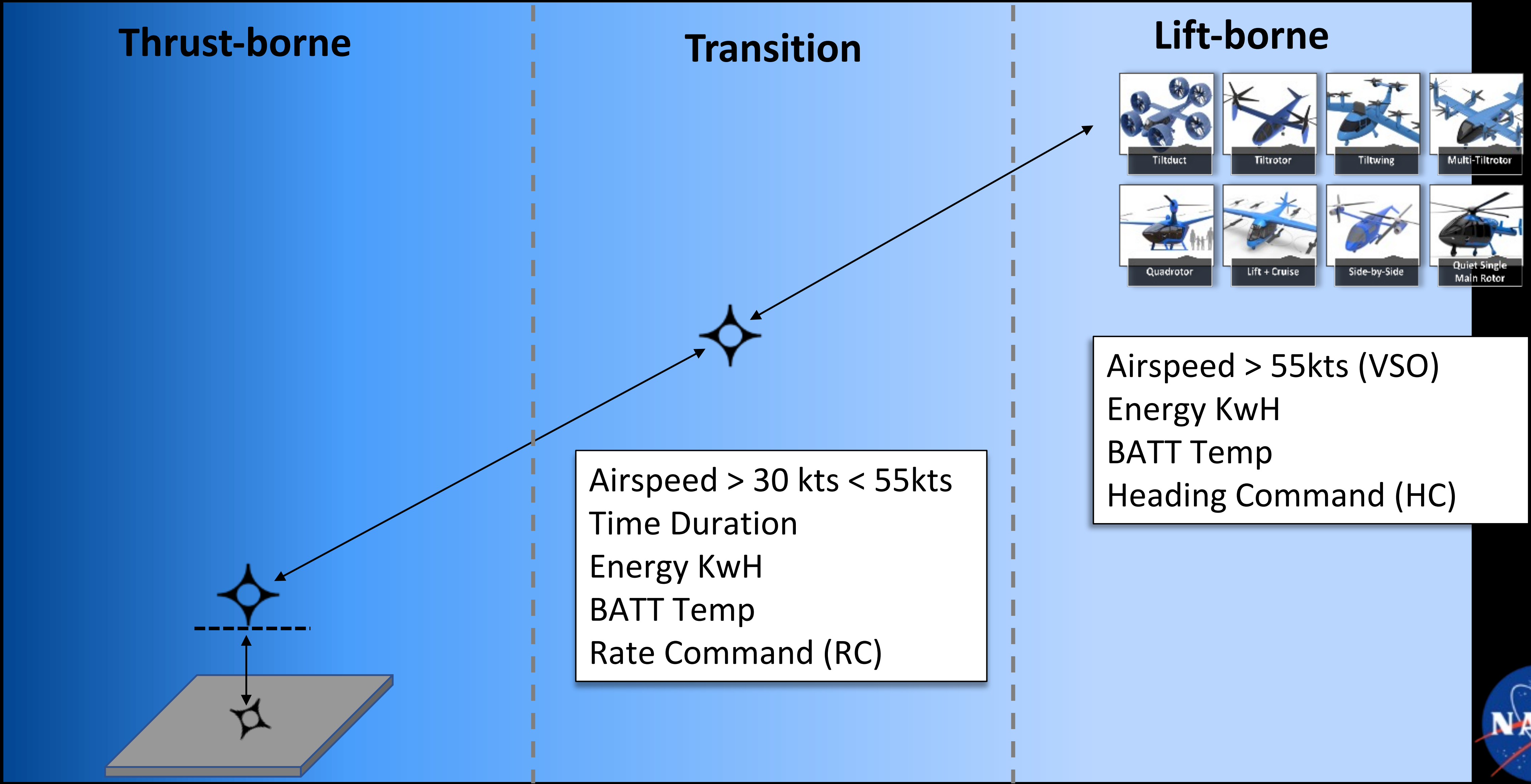
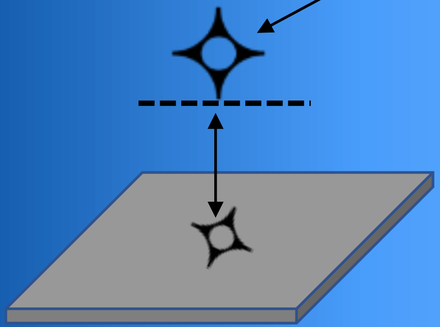


Research Importance

Dynamic procedure design tailored for novel vehicles and operations

Thrust-borne

Airspeed 0 - 30 kts
Height < 30ft
Time Duration
Energy KwH
BATT Temp
OGE/IGE
Translation Rate Command (TRC)
Vertical Speed Limitation



Transition

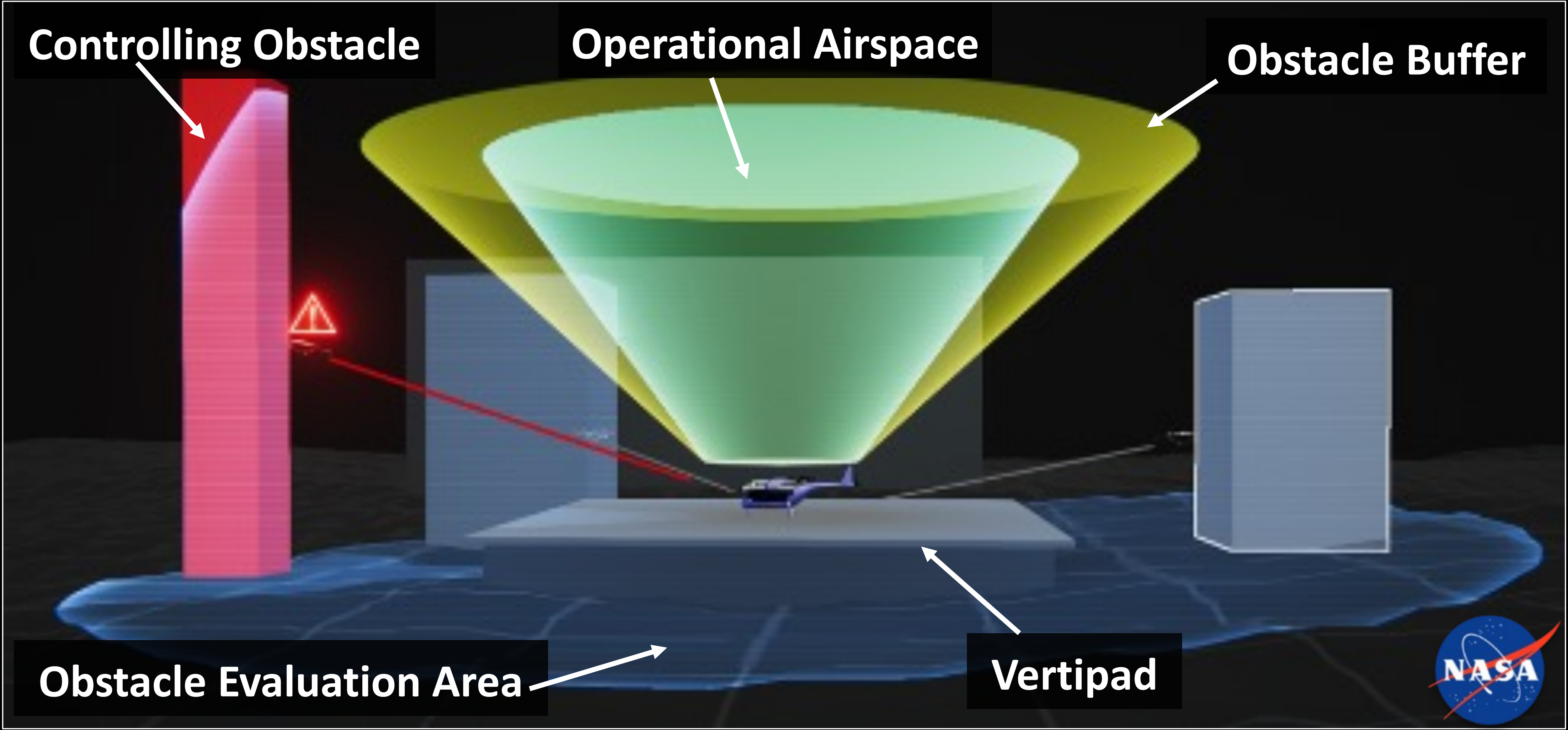
Airspeed > 30 kts < 55kts
Time Duration
Energy KwH
BATT Temp
Rate Command (RC)

Lift-borne

Airspeed > 55kts (VSO)
Energy KwH
BATT Temp
Heading Command (HC)

Technical Challenges
Airspace Construct

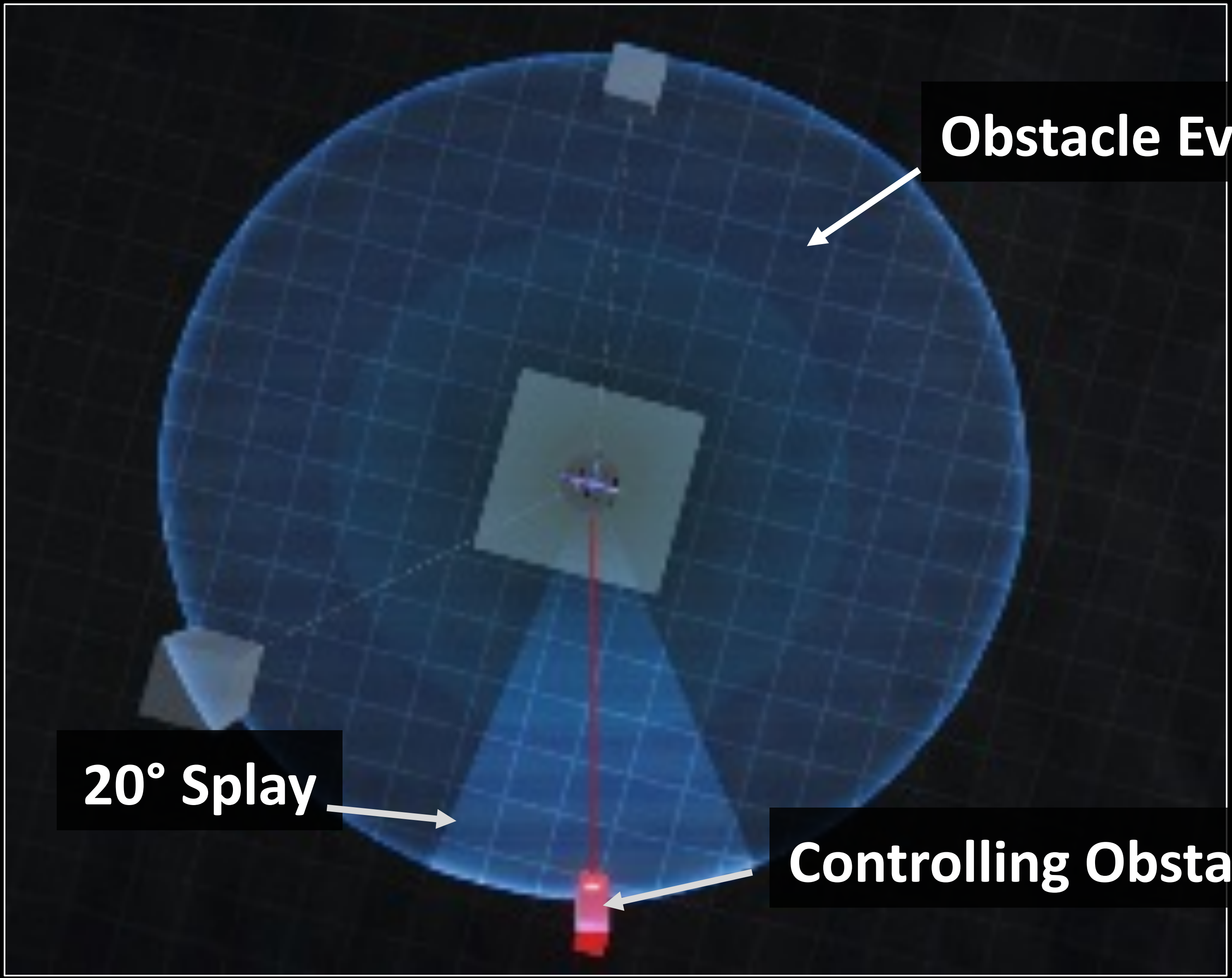
Omni-directional Terminal Airspace Architecture



Technical Challenges

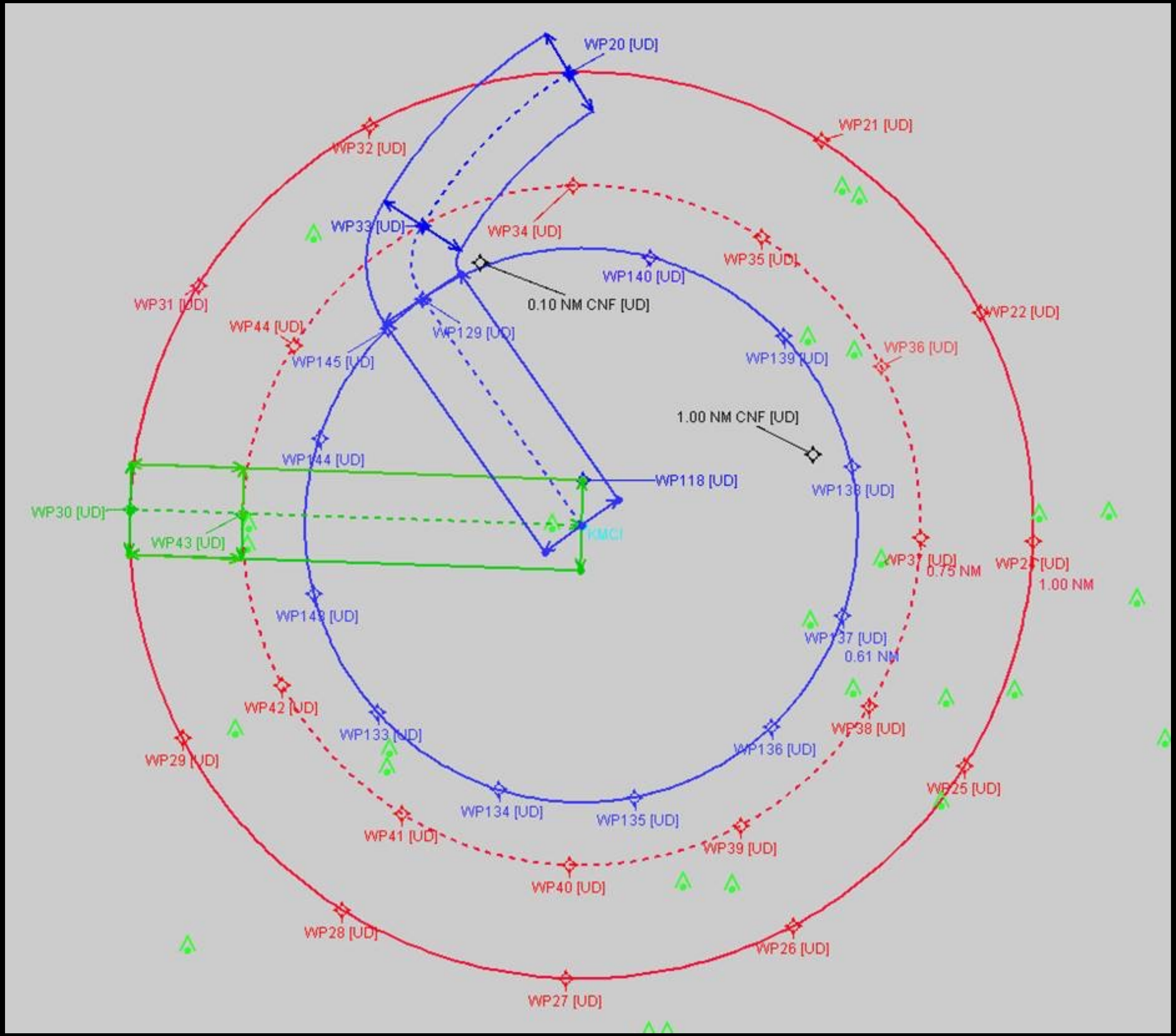
Airspace Construct

Omni-directional Terminal Airspace Architecture



Technical Challenges
Airspace Construct

Omni-directional Terminal Airspace Architecture



NASA Partnership Joby S4

UAM Instrument Flights procedures evaluated within Joby Vehicle Software Integration Lab (VSIL) high-fidelity engineering simulator

Joby S4 Engineering Simulator Marina, CA

Joby Vehicle Software Integration Lab (VSIL)

Credits: NASA & Joby Aviation

Joby Simulator
Test Points

UAM Instrument Flight Procedure Test Points and Methodology

Phase	Departure	Enroute	Final Approach	Missed Approach
Procedure	Vertical Takeoff	Turn to Final Tailwind & Headwind	Constant Speed Variable Deceleration	On-Course or Coordinated Turn
Technique	Manual vs Pilot-assist			
Angle, Max Speed	05°, 45 kts	12°, 100 kts	05°, 80 kts	05°, 80 kts
	05°, 60 kts			
	05°, 80 kts			
	08°, 45 kts		08°, 60 kts	08°, 60 kts
	08°, 60 kts			
	08°, 80 kts			
	12°, 45 kts		12°, 45 kts	12°, 45 kts
	12°, 60 kts			
	12°, 80 kts			

Joby Simulator
Metrics

UAM Instrument Flight Procedure test point and methodology

	Safety	Efficiency	Passenger Comfort	Acoustics
All phases of flight	Navigation data verification for desired path	Energy required	Linear accelerations	Acoustic signatures
	Obstacle clearance	Battery temperature increase		
	Flyability assessment			
	Vertical flight technical error	Minimization of airspace volume		
	Lateral flight technical error		Rotational accelerations	
*Missed Approach	*Glidepath decoupling point deviation			
	*Distance of height loss	Minimization of time required		
	*Flat surface length			
	*Departure intercept point			

NASA
Partnership
Joby S4

SETP Speaker V&V

Technical Challenges

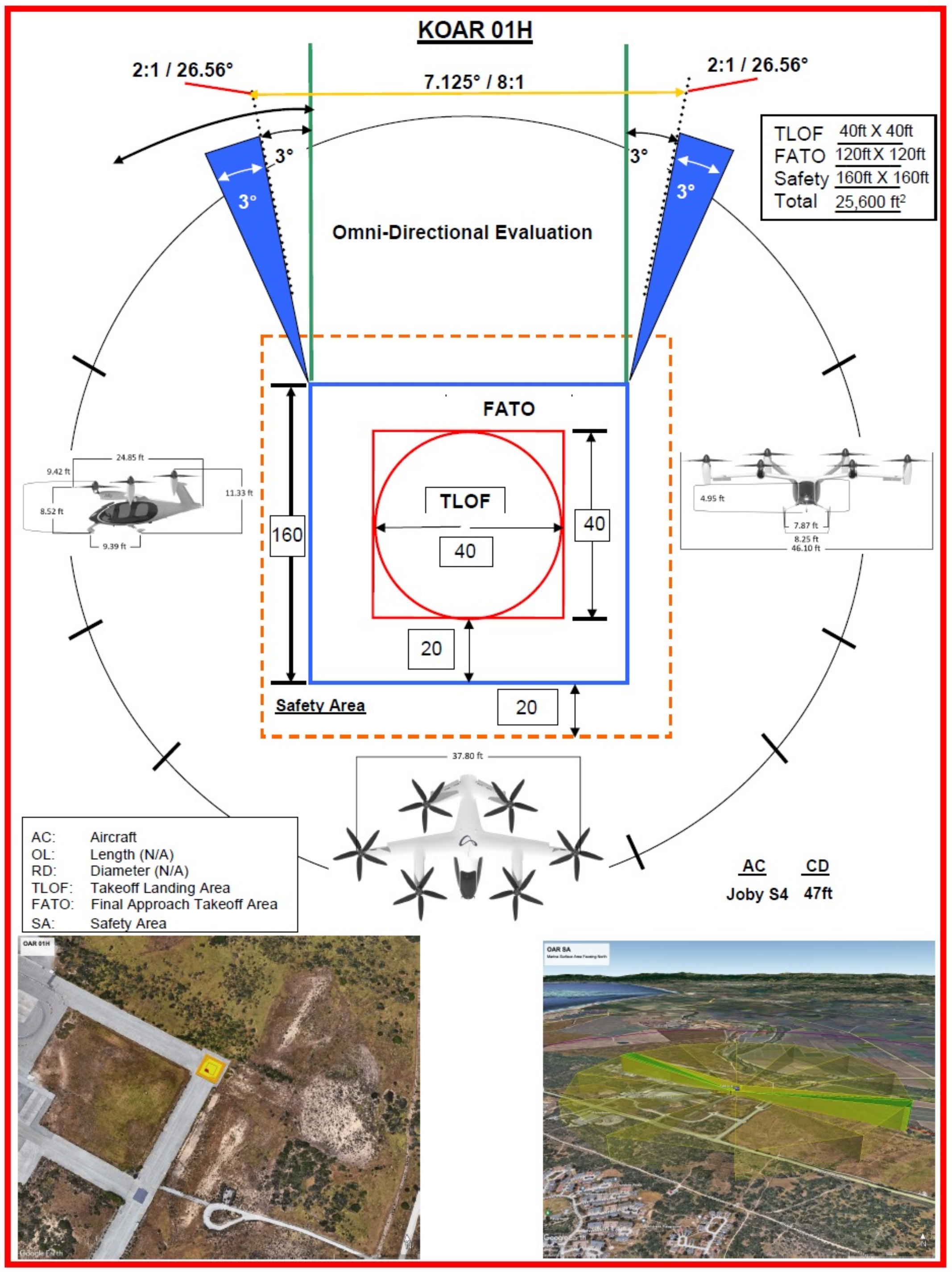
- UAM Airspace Architecture
- Tailored Terminal Procedure Design (TERPS)
- Accounting for Passenger Comfort and aircraft acoustics

Technical Challenges
Safety

Vertiport Evaluation Worksheet

Departure TF-RF Construction

RF – TF FROP Construction



Technical Challenges
Safety

Vertiport Evaluation Worksheet

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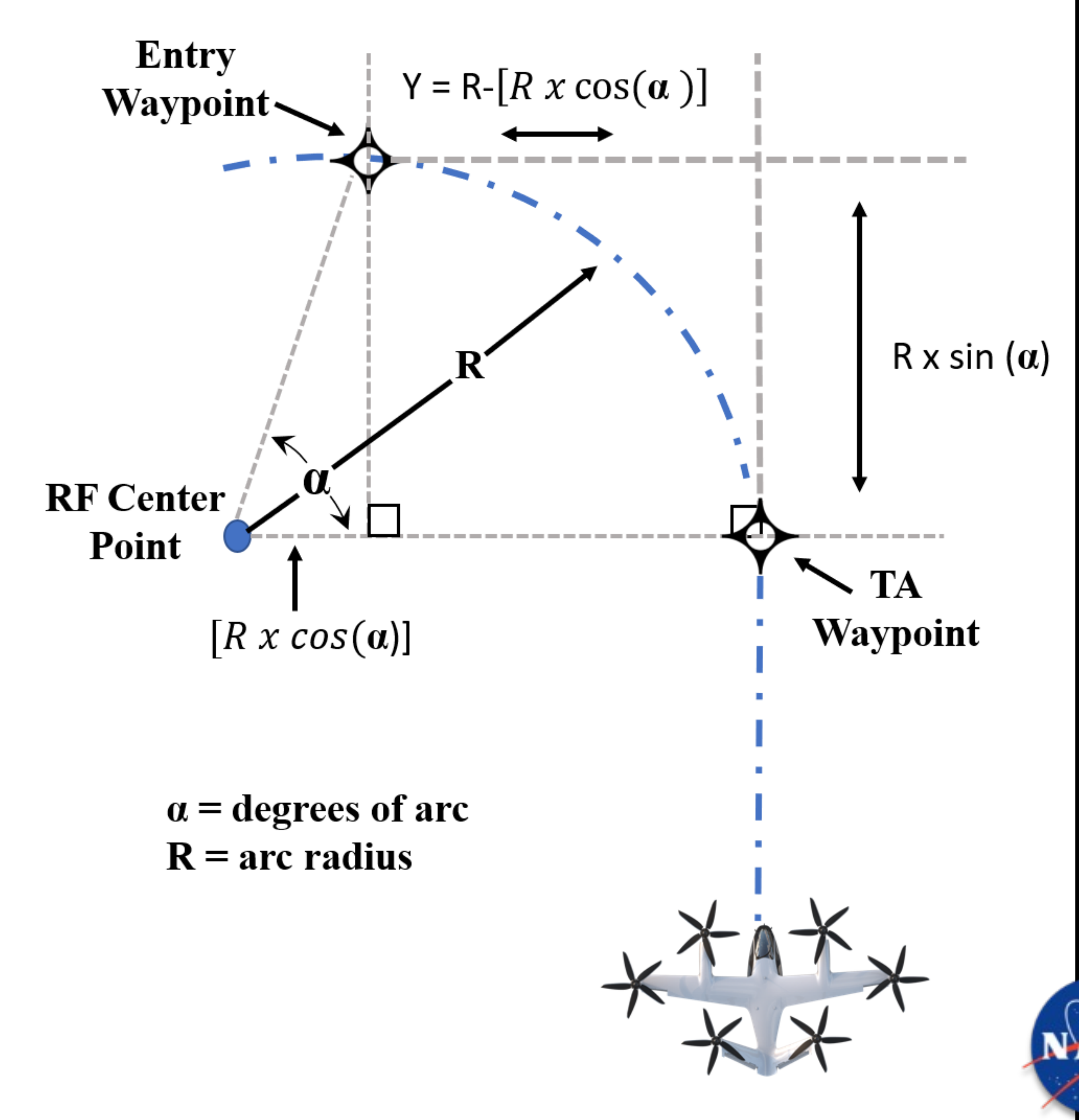
RF – TF FROP Construction



Technical Challenges
Safety

Vertiport Evaluation Worksheet

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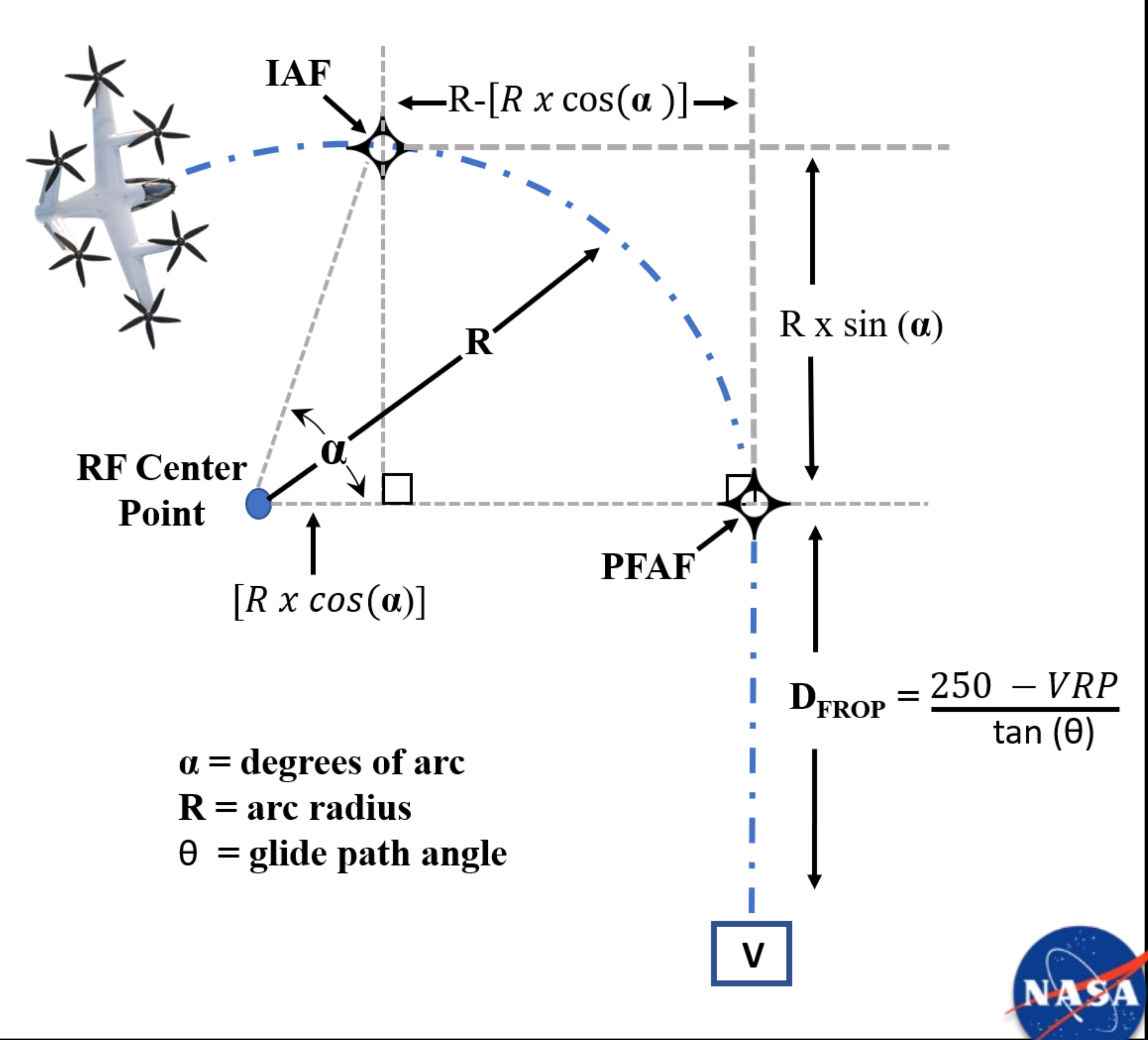
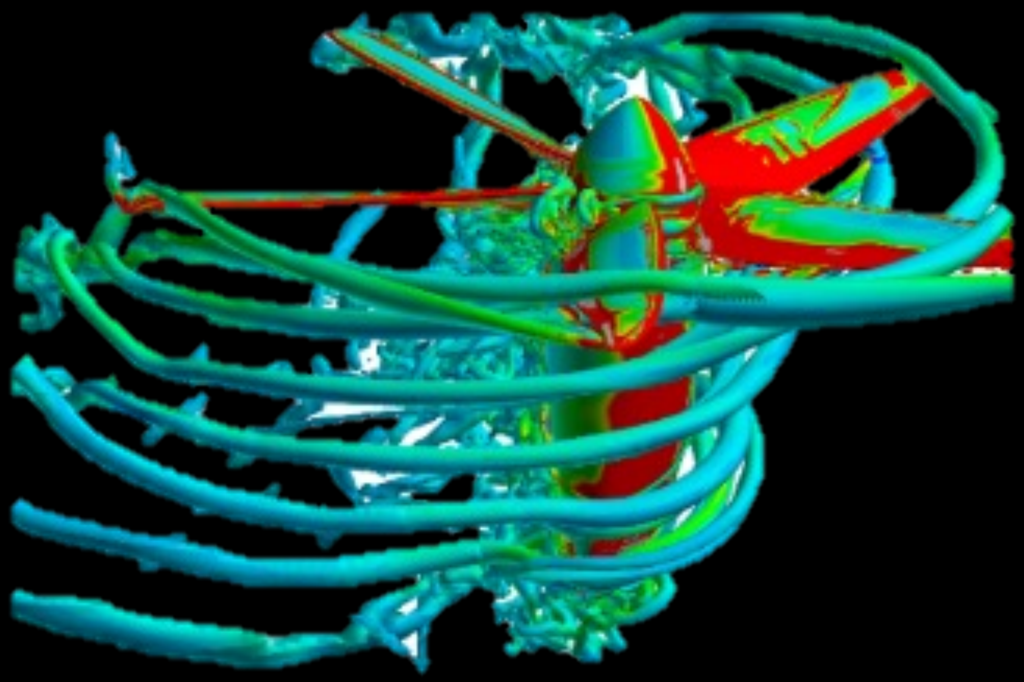
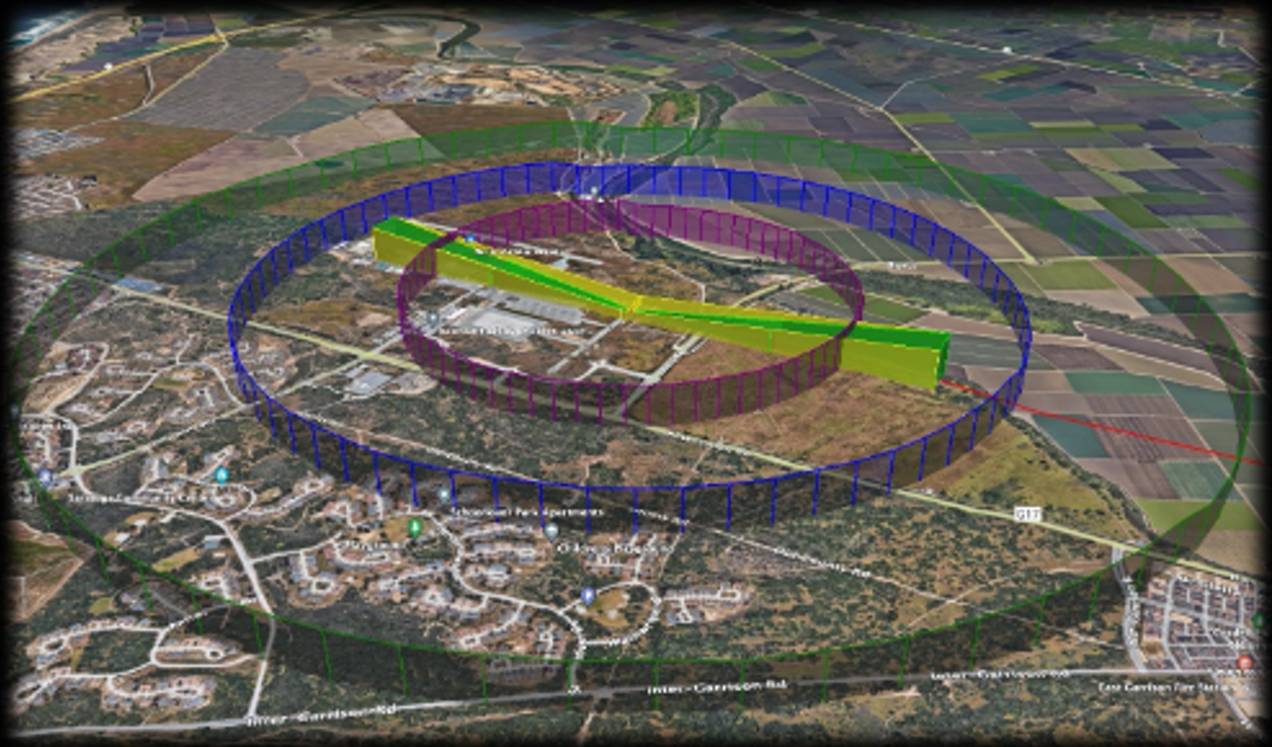


Technical Challenges
Efficiency

Define procedure efficiency in energy, thermal, time and space required baselined by high fidelity aircraft and airspace models



CFD simulation of S4 single propeller

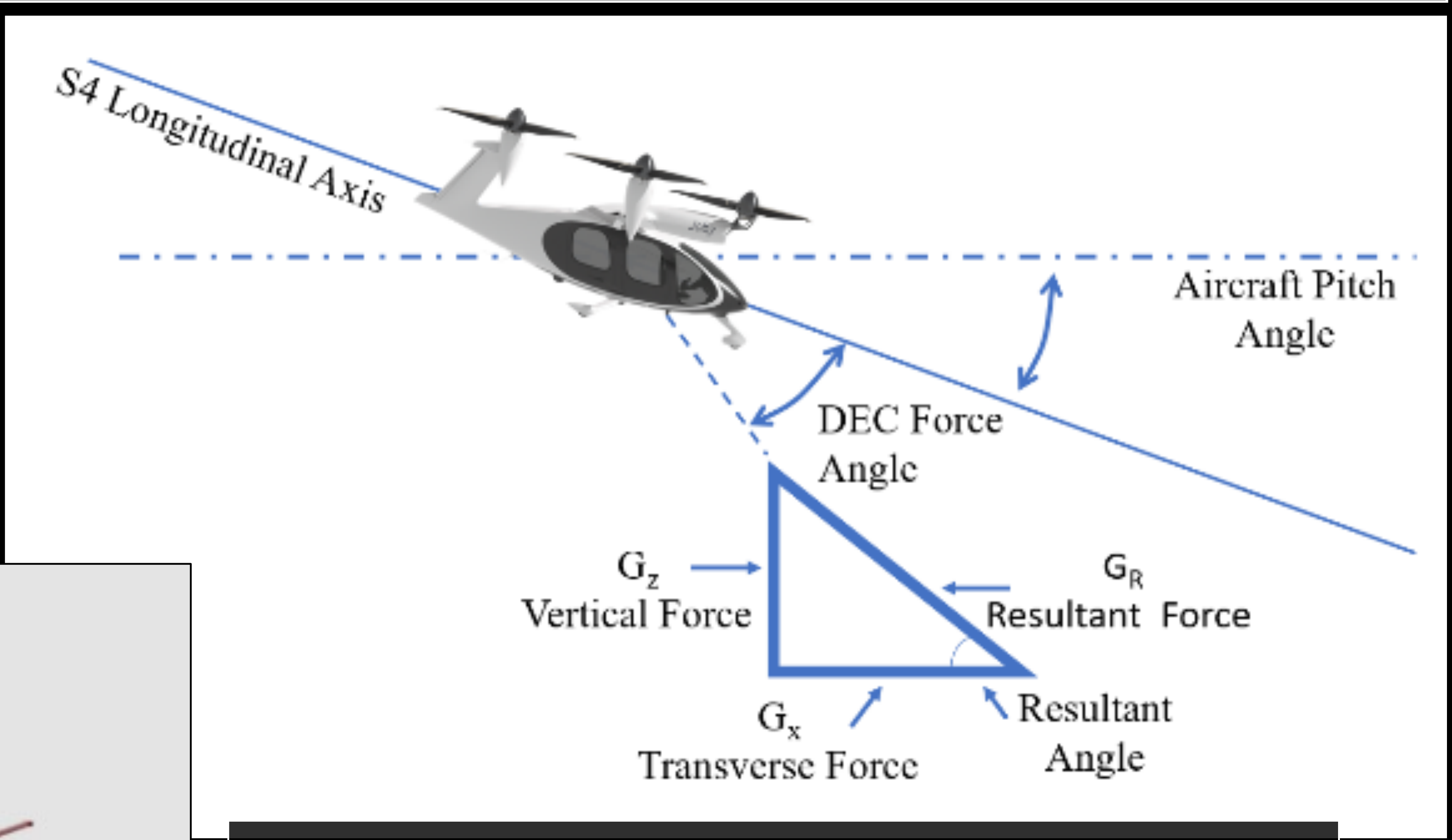


Airspace volume and terminal approach efficiency as a function of time and range

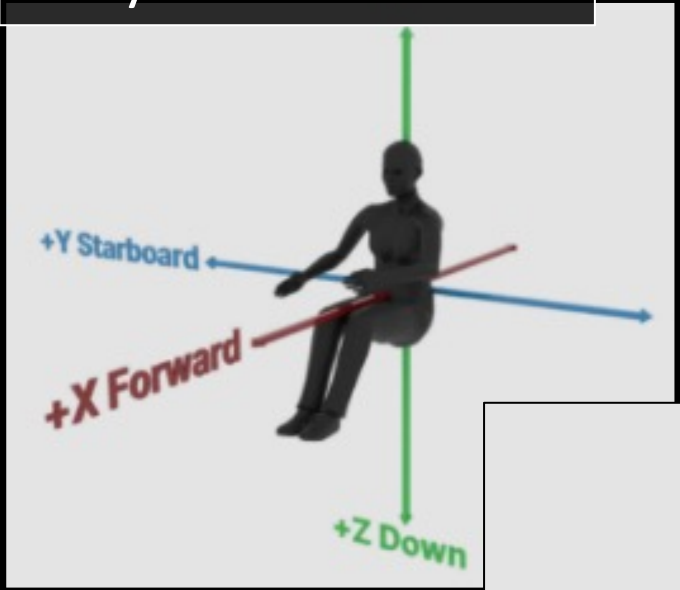
Credits: Joby Aviation

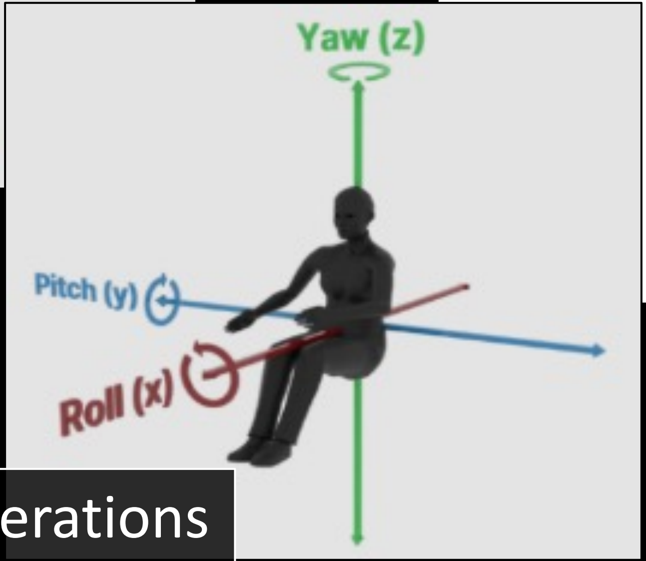
Technical Challenges
Passenger Comfort

Confirm assumed passenger comfort metrics for tailored UAM procedures development



Body axis orientation



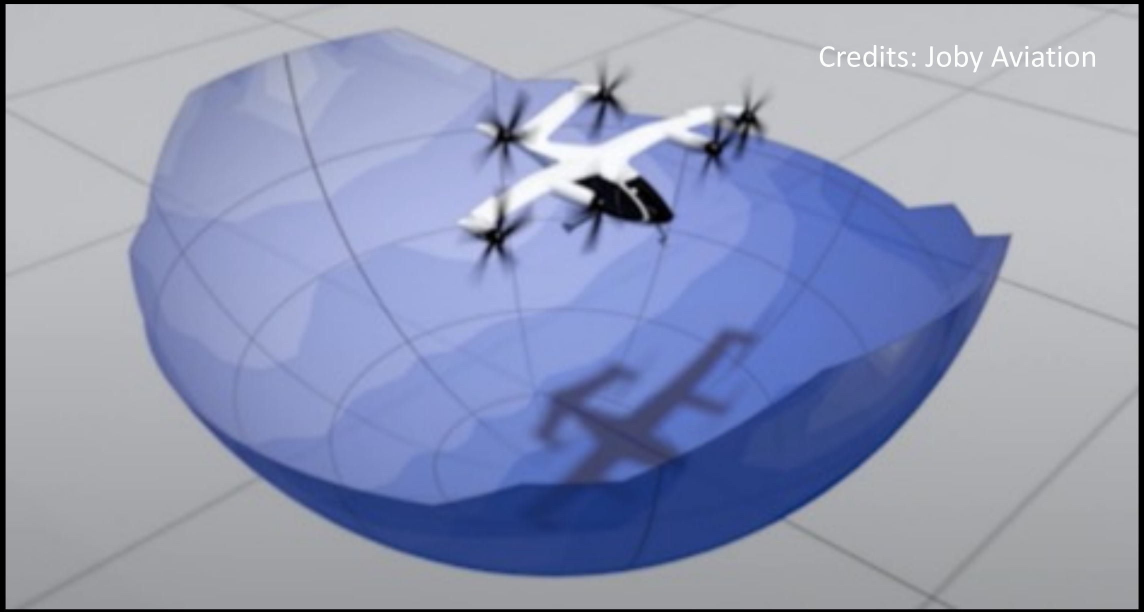


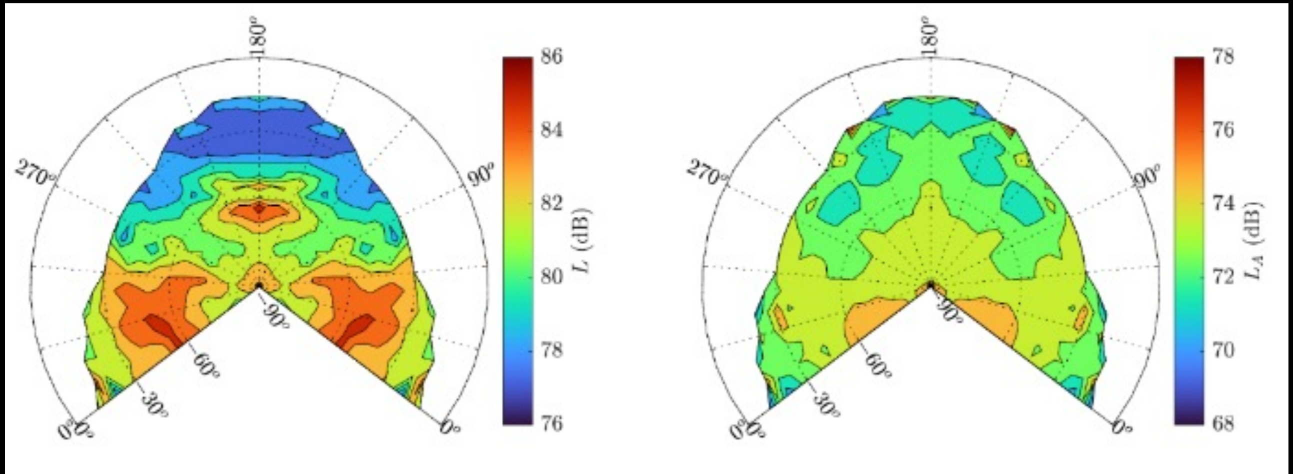
Rotational accelerations

- Linear & rotational accelerations
- Measured against industry standards in vertical, lateral axis

Technical Challenges
Acoustics

Accommodate for noise pollution specific to low-level UAM aircraft





S4 hemispheric data for 60 kt constant speed fly over

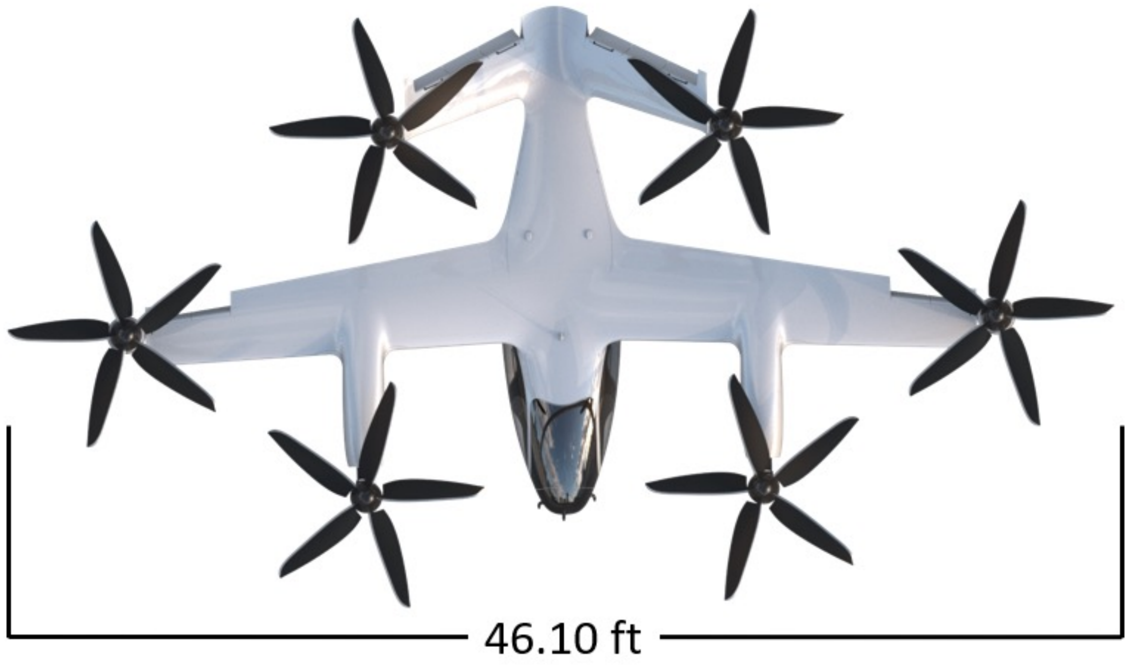
- Noise impacts that will drive UAM CATEX requirements with respect to airspeed, altitude, and transition mode profile
- Leverage flight data from NASA-Joby 2021 acoustic flight test

Results

- Airspace Architecture for PinS Approach to the ground
- Tailored Terminal Procedure Design (TERPS)
- eVTOL Missed Approach
- Acoustic signature / pollution

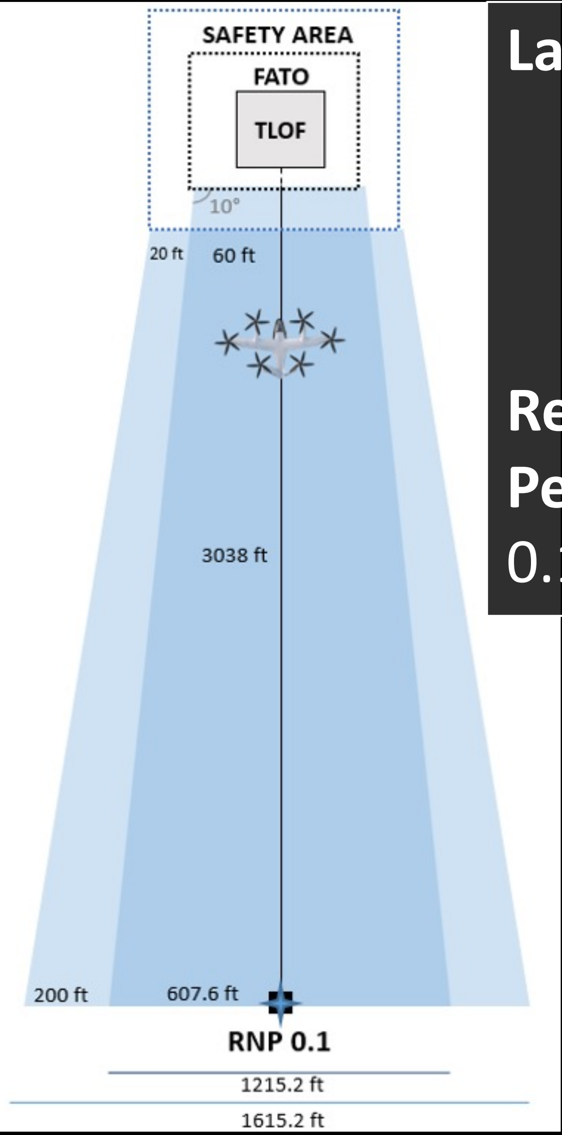
Results
Safety

Tailored Final Approach Segment (FAS) to aircraft geometry



$$BG_{S4} = \frac{46.10}{2} \text{ X } \sin(\phi)$$

Credit: Joby Aviation

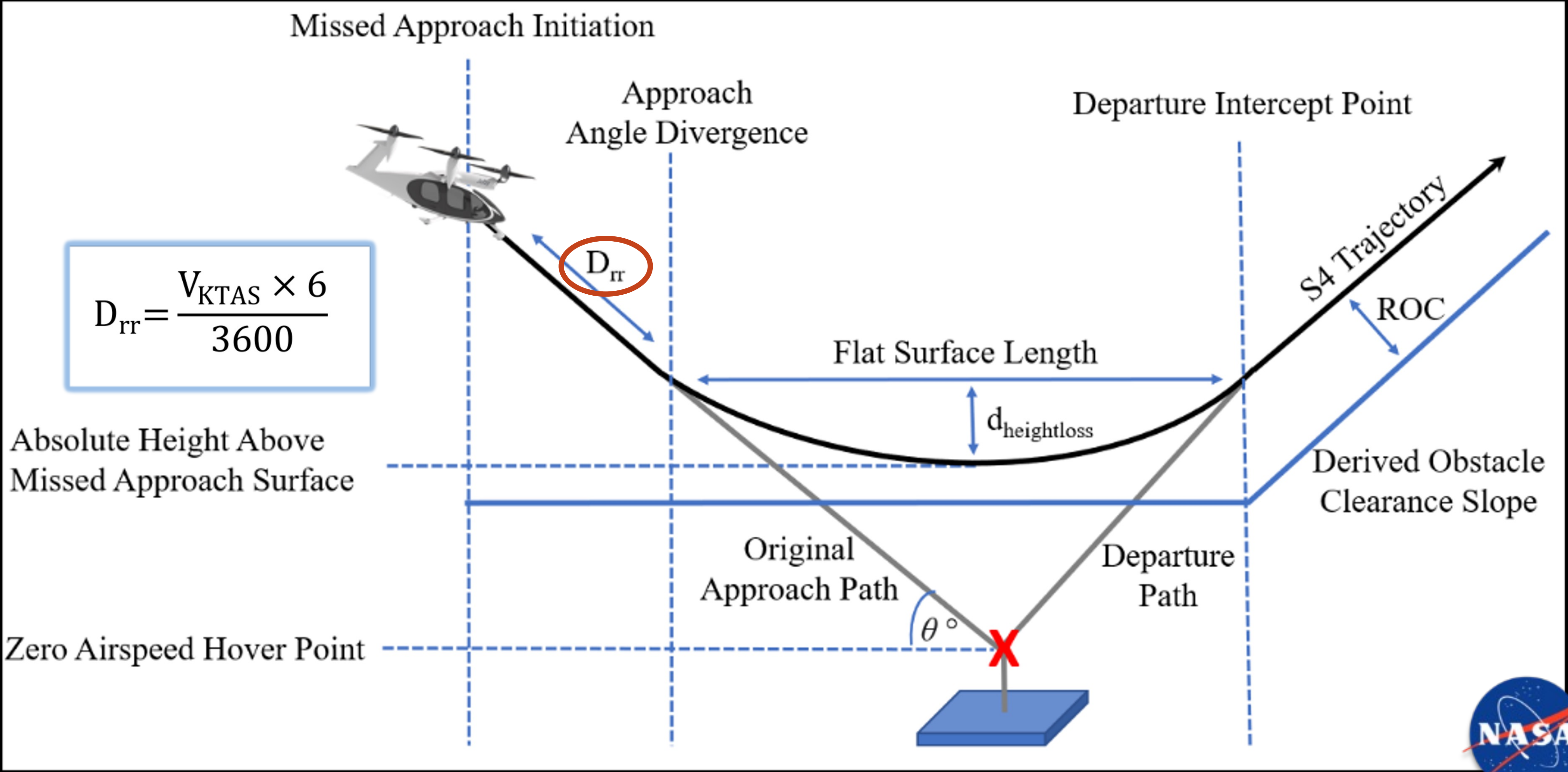


Lateral Splay Dimensions
- Final Approach/Take Off (FATO)
- Touchdown & Lift Off (TLOF)

Required Navigation Performance
0.1 NM

Results
Safety

Reimagined PinS Missed Approach with descent – decel component

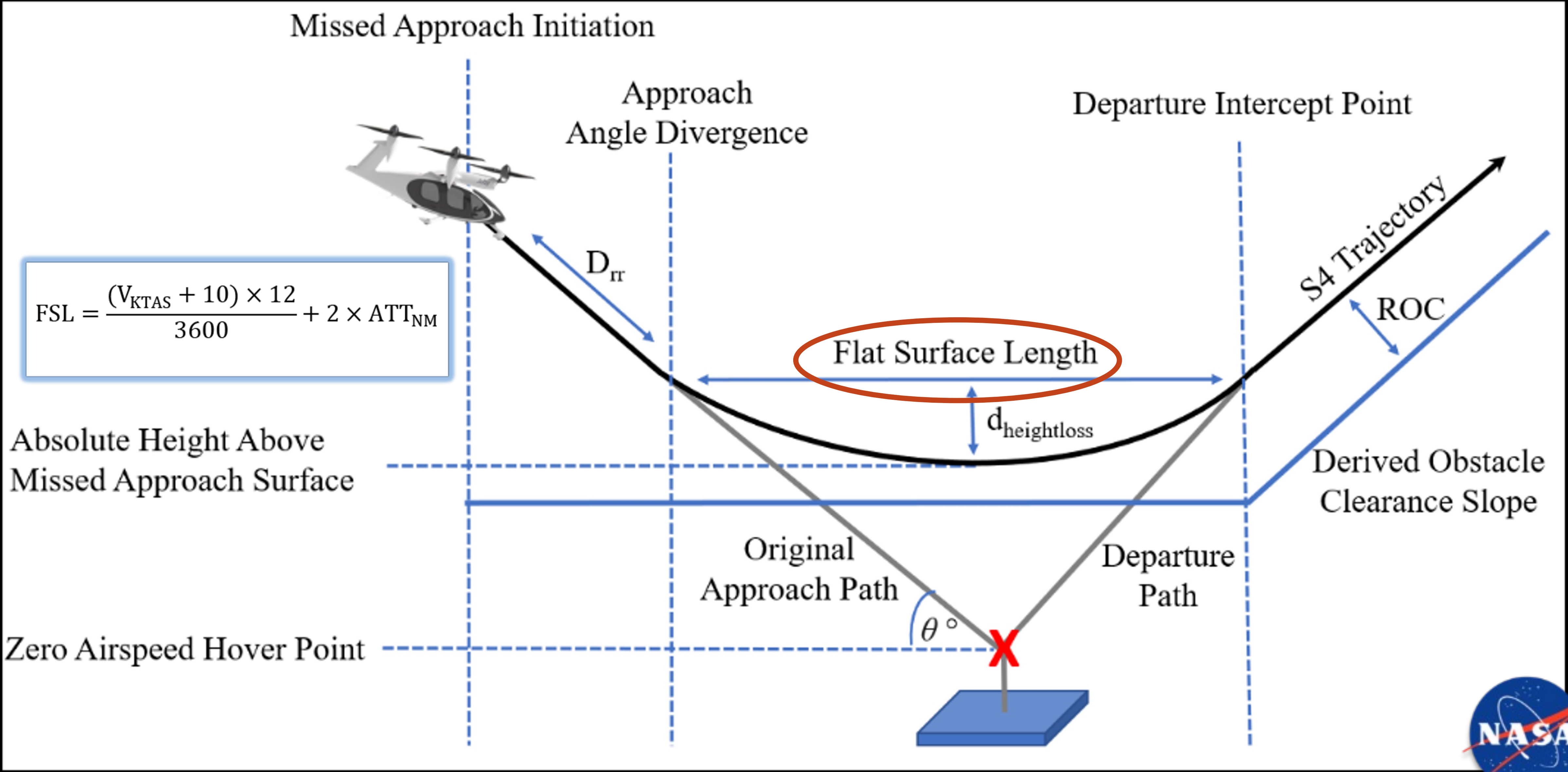


$$D_{rr} = \frac{V_{KTAS} \times 6}{3600}$$

Credit: Joby Aviation

Results
Safety

Reimagined PinS Missed Approach with descent – decel component



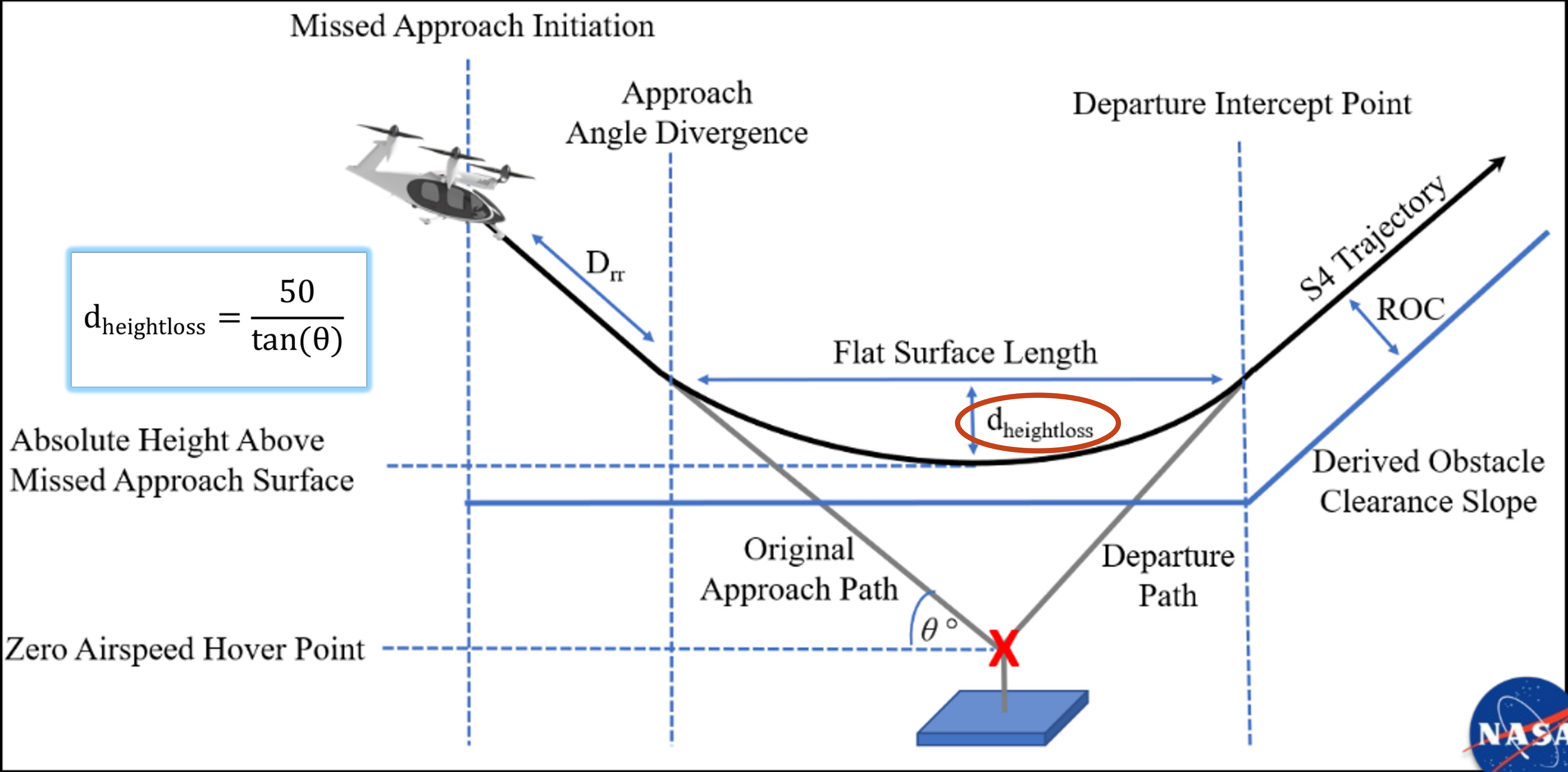
$$FSL = \frac{(V_{KTAS} + 10) \times 12}{3600} + 2 \times ATT_{NM}$$

Credit: Joby Aviation

Results
Safety

Reimagined PinS Missed Approach with descent – decel component

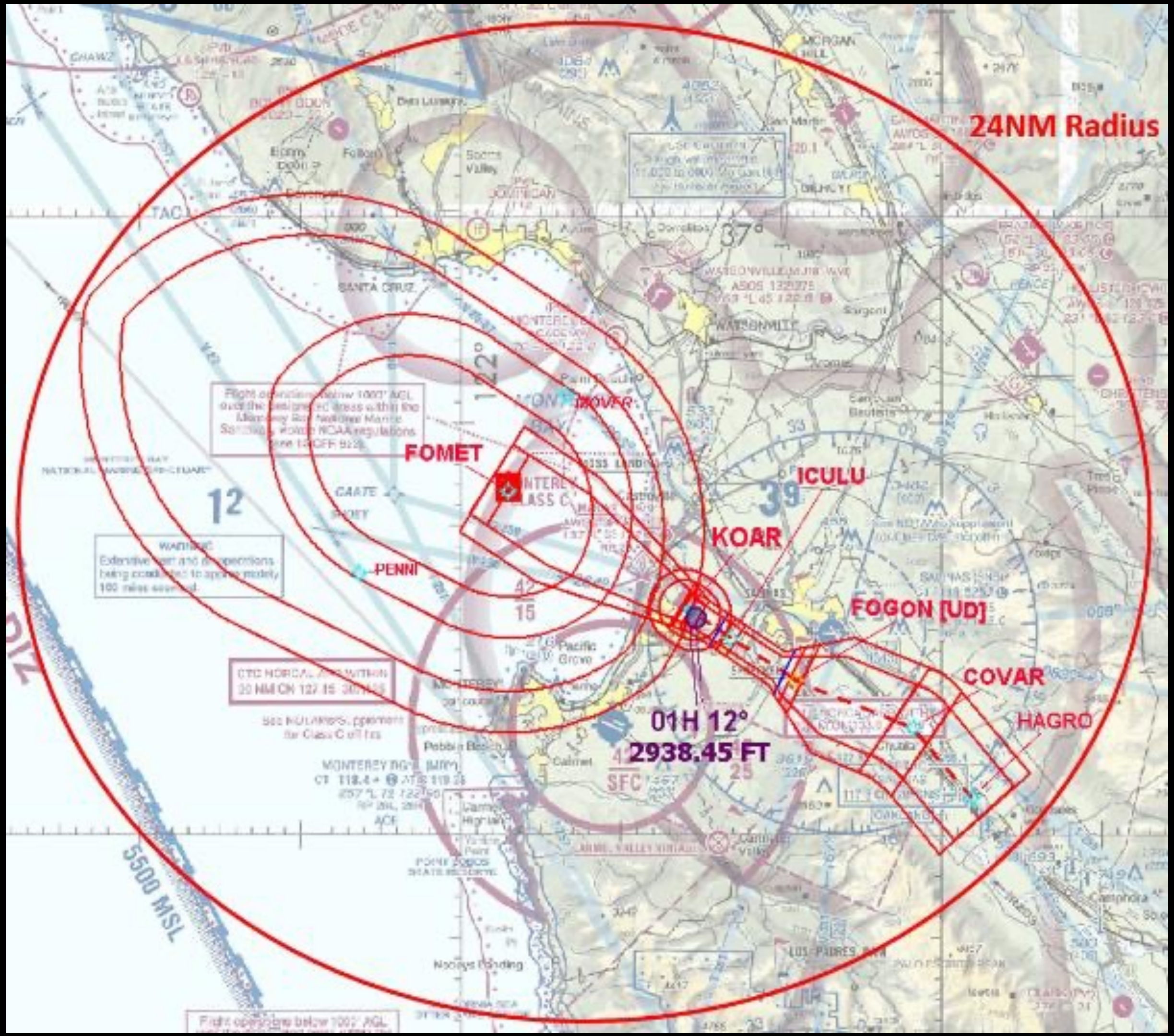
$$d_{heightloss} = \frac{50}{\tan(\theta)}$$

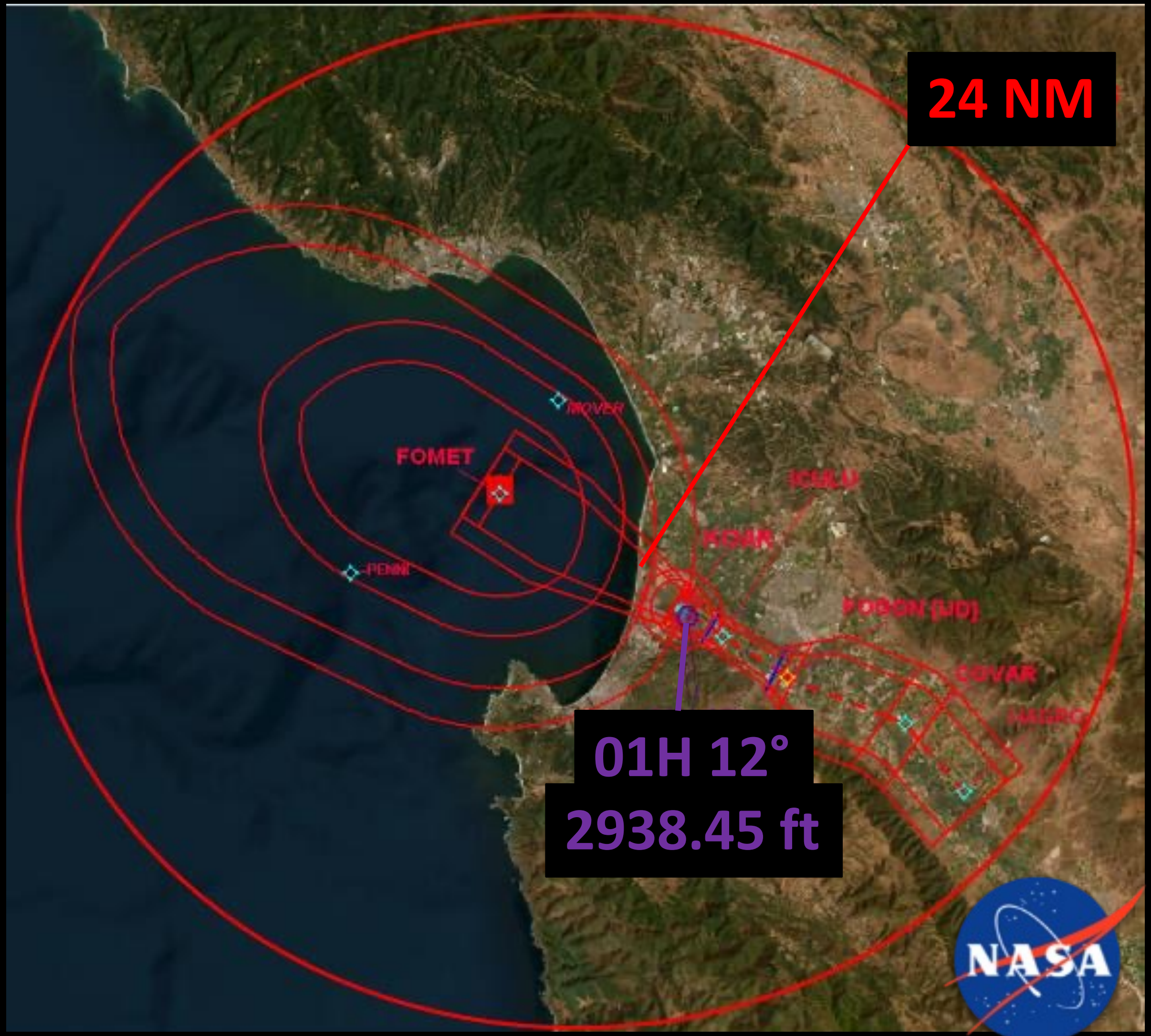


Credit: Joby Aviation

Results
Efficiency

Omni-directional terminal airspace architecture with equivalent level of safety instrument flight construct





Results
Efficiency

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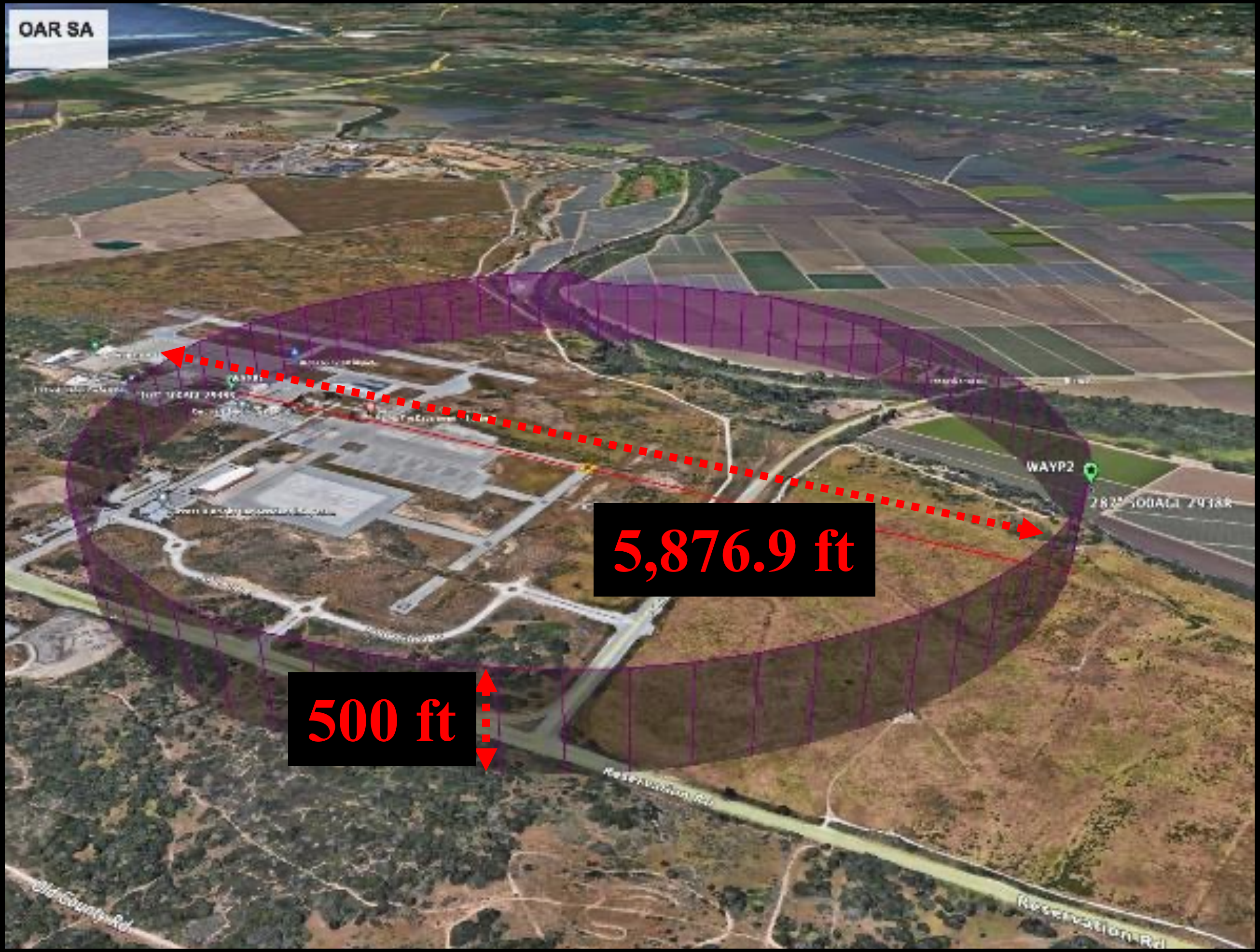
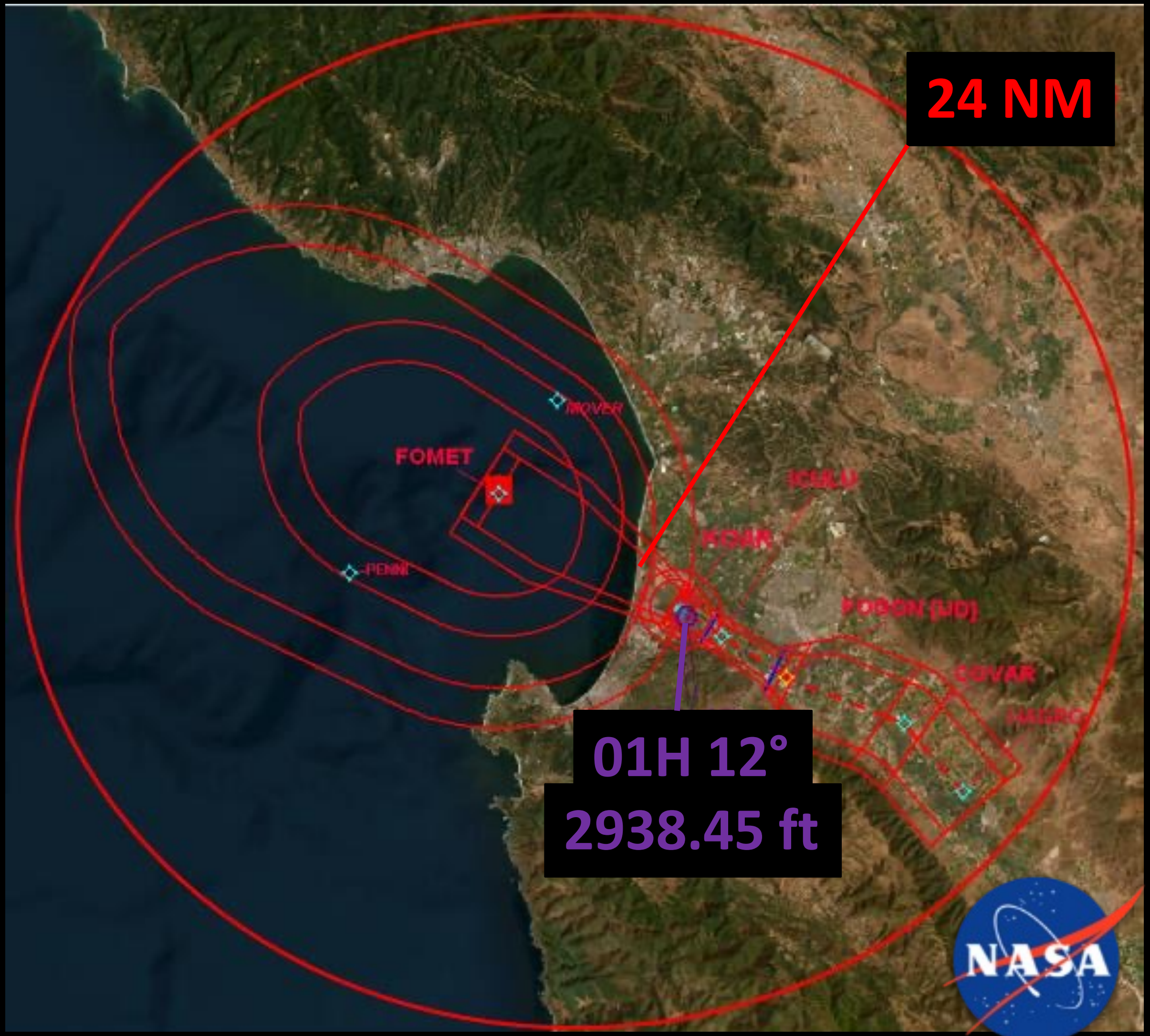
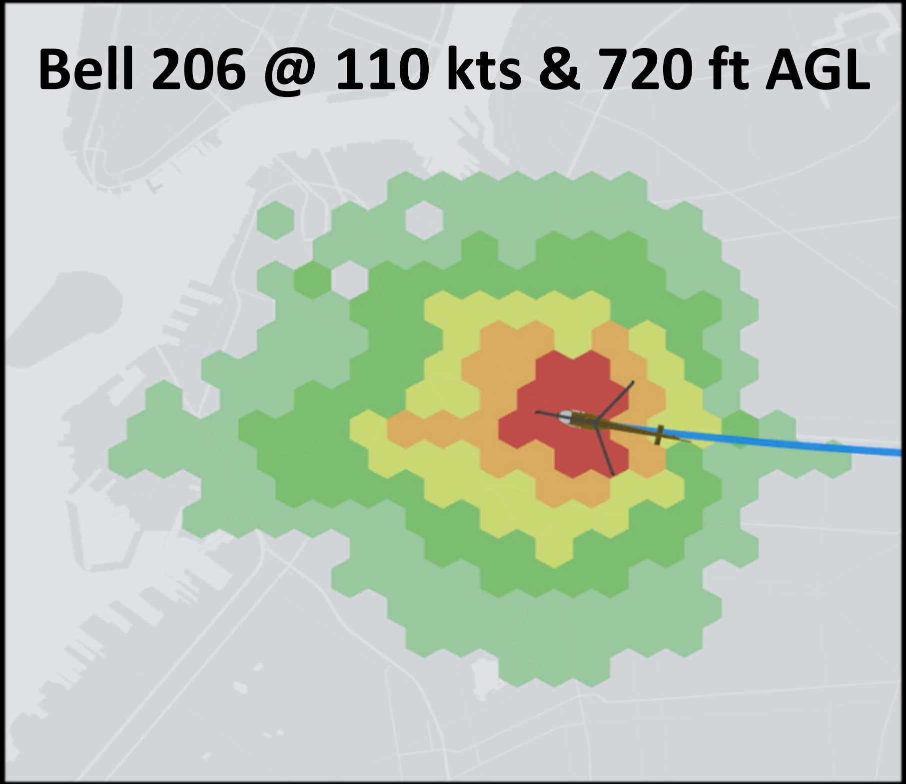




Results
Acoustics

Tailored Final Approach Segment (FAS) to aircraft geometry



An illustration of the acoustic footprint of the Joby S4 Aircraft compared to a Bell 206 at 720 Ft AGL & 110 kts.

dBA
- Less than 45
- 45-50
- 50-55
- 55-60
- 60-65
- 65 or more

Credits: Joby Aviation

Future Models & Follow-on Research

- Procedure Automation Rating Matrix (PARM)
- Dynamic approach plate human-machine Interface
- Interplanetary terminal procedure design

Future Model & Follow-on Research

Candidate UAM Instrument Approach Plate (IAP)

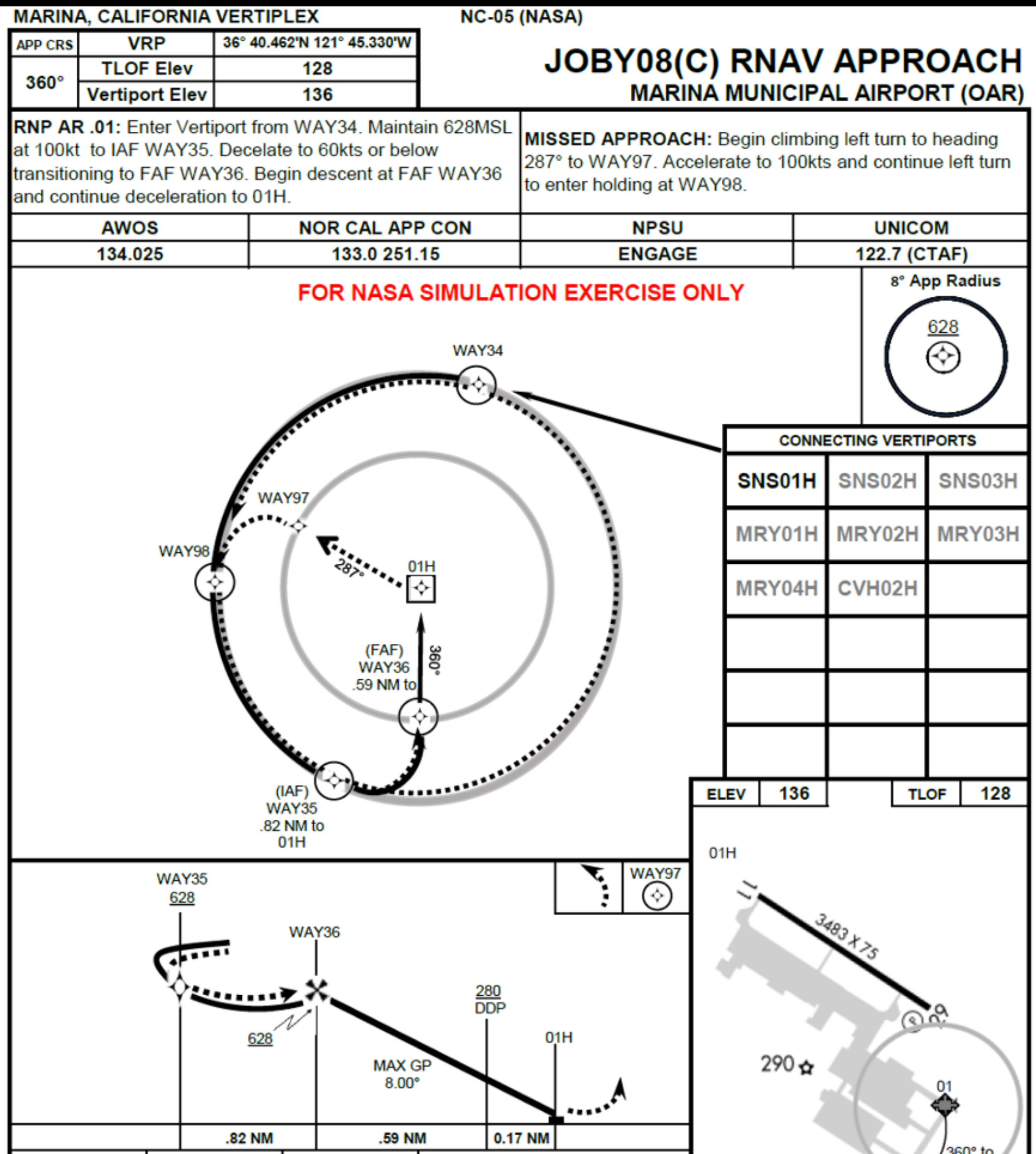
IAP reimagined for UAM operations for manual control and cross monitoring automation performance

Pilot Briefing/ Header 1

Overhead View 2

Profile View 3

Minima Section 4



APP ANGLE	5°	8°	12°	VTOL
LPV DH	328-1 80kt	428-1 60kt	528-1 45kt	628-1 30kt
AUTOMATION	0-0 80kt	0-0 60kt	0-0 45kt	0-0 30kt

MARINA, CALIFORNIA
12SEP22
EXPERIMENTAL
MARINA MUNICIPAL AIRPORT (OAR)
JOBY08(C) RNAV
36° 40.462'N 121° 45.330'W

5 Vertiport Volume/ Radius/Altitude

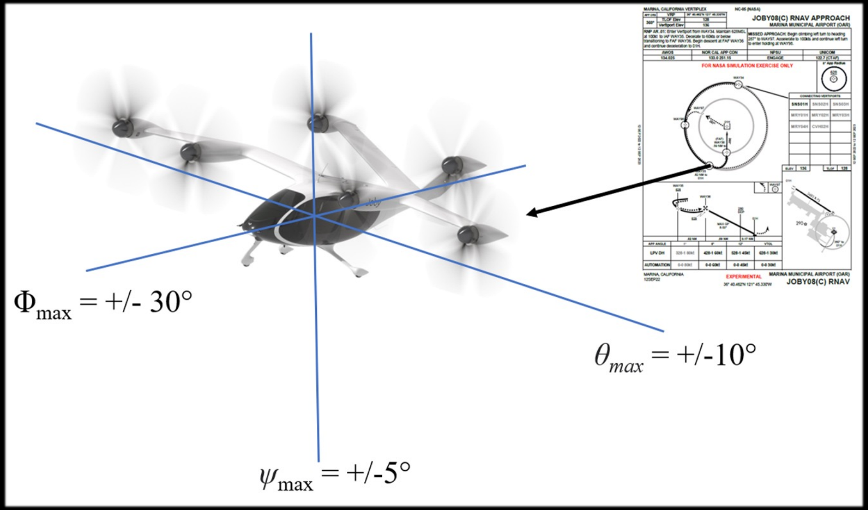
6 Vertiplex Availability and Routing

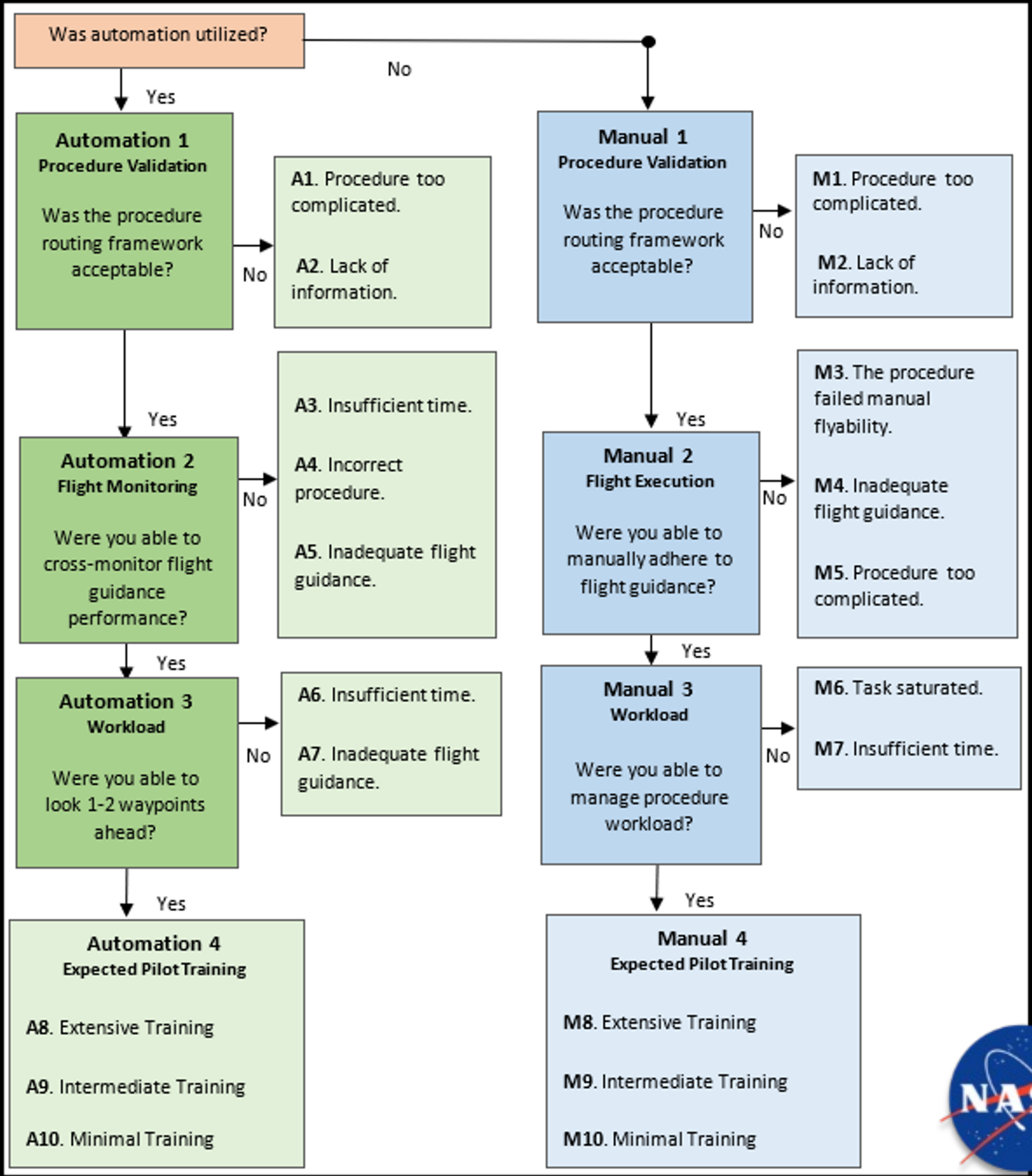
7 Airport Diagram

Future Model & Follow-on Research

Procedure Automation Rating Matrix (PARM)

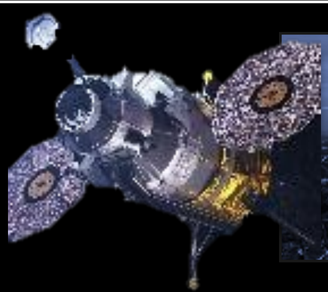
A Cooper-Harper-like rating scale for procedure flyability and pilot workload





Future Model & Follow-on Research

Dynamically generated vertically-guided approach procedures



Unknown Vehicle | Unknown Procedure
Ubiquitous Advanced Air Mobility & Interplanetary Missions

Unknown Vehicle | Known Procedure
Joby S-4

Known Vehicle | Unknown Procedure
Blackhawk & S-76 with vertical descent autoland

Known Vehicle | Known Procedure
Cessna Caravan with autopilot

Lessons Learned

Dynamic Procedure Design & Evaluation

- Spatial Data
- Speed limitations

Accounting for Electric Propulsion

- Energetics (KwH, torque)
- Battery thermal envelope
- Reserves

Human Factors

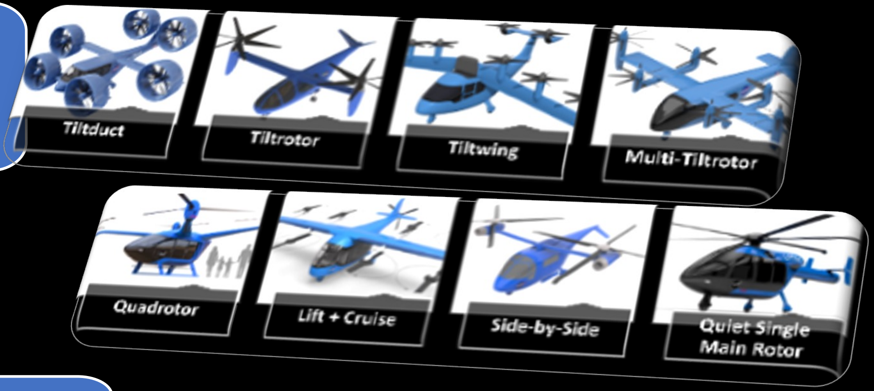
- Pilot site picture / field of view
- Acceleration and jerk rate
- Pilot rating

Partner Exchange

- Proprietary data
- Simulator fidelity
- Pilot Training

Conclusion & Recommendations

Importance of Dynamic Procedure Design & Evaluation



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- Dynamic approach plate human-machine interface
- Interplanetary terminal procedure design

Credit: NASA