ARMD Transformative Aeronautics Concepts Program

CONVERGENT AERONAUTICS SOLUTIONS

PROJECT

SCEPTOR

Scalable Convergent Electric Propulsion Technology and Operations Research

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SCEPTOR

(Scalable Convergent Electric Propulsion Technology and Operations Research)

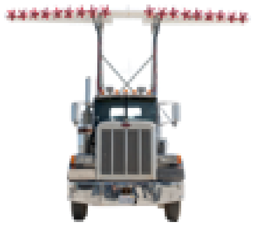
- **Lead & Partner Centers:** *Langley, Armstrong, and Glenn Research Centers*
- **External Collaborators:** *ESAero, Joby Aviation, Tecnam, Electric Power Systems, Xperimental LLC, Scaled Composites, TMC Technologies*
- **Big Question:** *Can rapid, inexpensive sub-scale technology development and testing show the ability of Distributed Electric Propulsion (DEP) to achieve ultra-high efficiency, low carbon emissions, and low operating costs at high-speed?*

- **ARMD Strategic Thrusts and Associated Outcomes Addressed:**
  - Transition to Low Carbon Propulsion
    - Near-term: Outcome for 2015-2025: Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems. Research of hybrid and fully electric propulsion systems in the general aviation sector for on-demand mobility applications.
  - Ultra Efficient Commercial Vehicles
    - Far-term: Subsonic Transport Outcome for >2035: Technology and Configuration Concepts, Including Low-carbon Propulsion, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance.
    - Far-term: Vertical Lift Outcome for >2035: Technology and Configuration Concepts, Including Low-carbon Propulsion and Autonomy, that Stretch Beyond N+3 Levels of Efficiency and Environmental Performance.

- **Idea/Concept:** Design and fabricate a DEP wing system, retrofit a Tecnam P2006T with a DEP wing, flight test to show the benefit achieved.
- **Feasibility Assessment:** Establish baseline cruise energy required, apply new technology, determine whether 5x reduction goal is achieved.
- **Feasibility Assessment Criteria:** Cruise energy required at high-speed (150 knot) cruise.

Project Approach

Mod 1

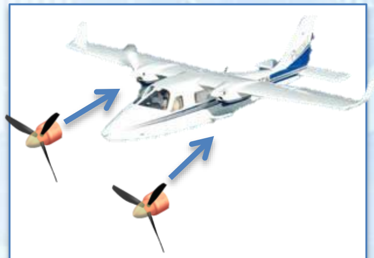


Ground validation of DEP highlift system

Flight testing of baseline Tecnam P2006T

Goals:
- Establish Baseline Tecnam Performance
- Pilot Familiarity

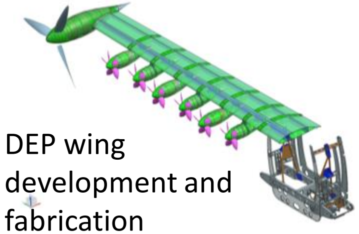
Mod 2



Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:
- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

Mod 3



DEP wing development and fabrication

Flight test electric motors relocated to wingtips on DEP wing including nacelles (but no DEP motors, controllers, or folding props).

Achieves Primary Objective of High Speed Cruise Efficiency

Spiral development process
- Build – Fly – Learn

Mod 4*

Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

Achieves Secondary Objectives
- DEP Acoustics Testing
- Low Speed Control Robustness
- Certification Basis of DEP Technologies

Mod 1

Mod 2

Mod 3

Mod 4*

** Mod 4 plan is notional; not yet funded*

Impact, Progress

- **Impact:** SCEPTOR is the first crewed DEP concept X-Plane. A fully electric General Aviation technology demonstrator with zero in-flight carbon emissions that surpasses 2035 N+3 efficiency goals with near-term application pathways.
- **Progress:** Mod I is complete, Mod II integration and Mod III design underway
  - Completed HEIST/LEAPTech DEP testing, flight test program for baseline performance and pilot training
  - PDR Complete: All actions closed. Completed design peer reviews for every discipline.
  - X-Plane designation by DoD: X-57 Maxwell is first NASA-led X-Plane in a decade
  - Graduating from CAS to IASP/FDC in FY17: To ensure success for this high risk project as a stepping stone to NAH X-planes; will have resource reserves
  - Continued significant public interest, including dozens of newspapers and magazines, Several international conference keynote speaker [illegible]
  - Significant public data sharing, including [illegible] AIAA Oral-only presentations.

New NASA Technical Challenge

AERONAUTICS STRATEGIC THRUST

Thrust 4: Transition to Low-Carbon Propulsion

AERONAUTICS OUTCOMES

Outcome (2015-2025): Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems

Outcome (2025-2035): Initial Introduction of Alternative Propulsion Systems

Outcome (>2035): Introduction of Alternative Propulsion Systems to Aircraft of All Sizes

Research Themes

Characterization and Integration of Alternative Fuels

Scalable Alternative Propulsion Systems

FDC Technical Challenges

TC: Electric Propulsion Airframe Integration (FY20): Demonstrate 5x reduction in energy usage with zero in-flight emissions through innovative electric propulsion airframe integration.

X-57 will use less than 30% of the energy used in similar IC powered aircraft

Goals and Objectives

Goal

- 5x lower energy use at high speed cruise (compared to original P2006T @ 175 mph)

Objectives

- **Primary**: Internal combustion engine vs electric propulsion efficiency changes from 28% to 92% (≥3.0x)
- **Secondary**: Synergistic integration of high aspect ratio wing combined with wing tip propulsors and DEP (≥1.2x)

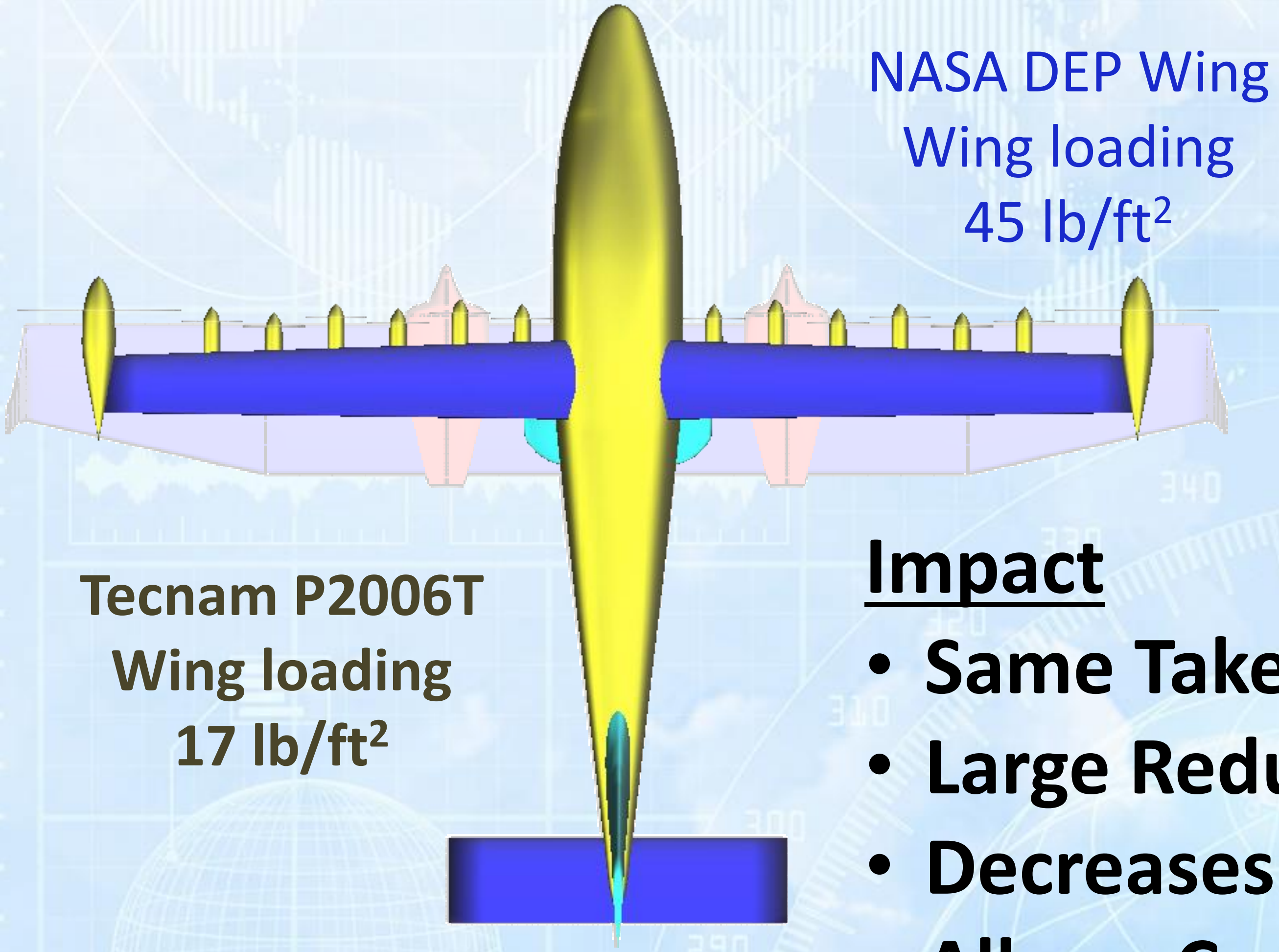
Derivative benefits

- Zero in-flight carbon emissions
- ~30% lower total operating cost

Additional Benefits (pending Mod IV extension)

- 15 dB Lower community noise
- Flight control redundancy and robustness
- Improved ride quality
- Certification basis for DEP technologies

SCEPTOR Wing Sizing Impact

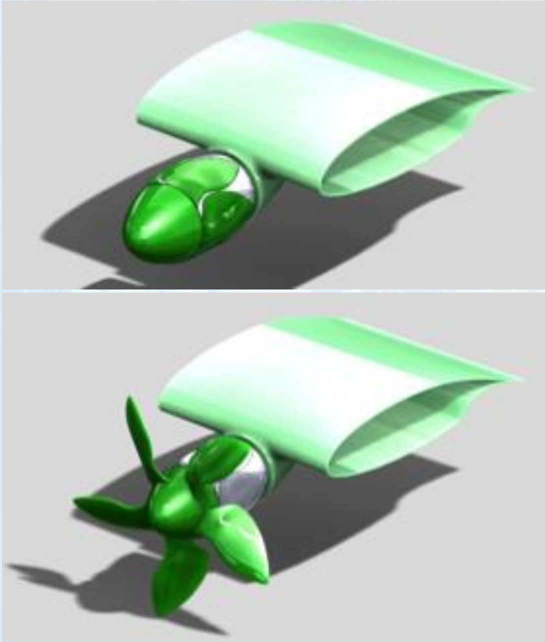


<u>Impact</u>

- **Same Takeoff/Landing Speed**
- **Large Reduction in Wing Area**
- **Decreases the Friction Drag**
- **Allows Cruise at High Lift Coefficient**
- **Less Gust/Turbulence Sensitivity**

DEP Integration Synergistic Design

Folding Inboard Propellers with Low Tip Speeds



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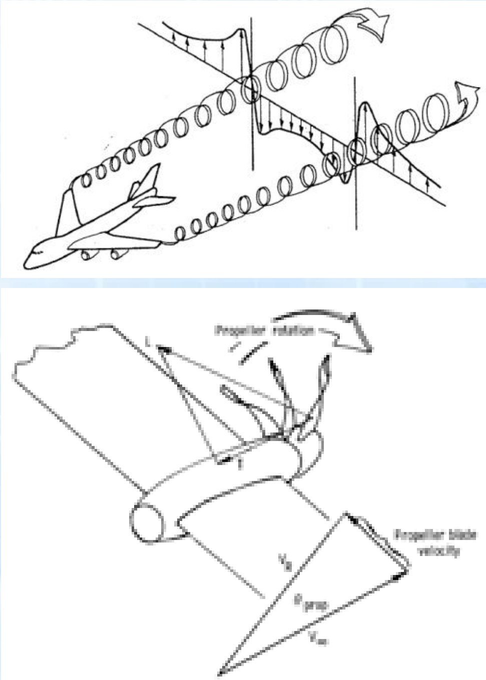
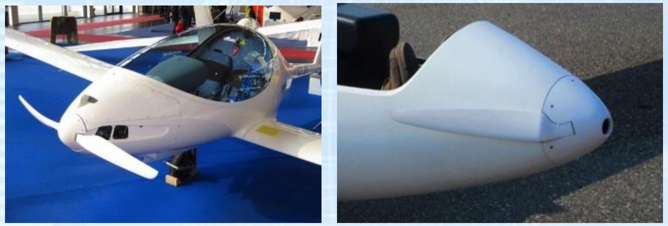
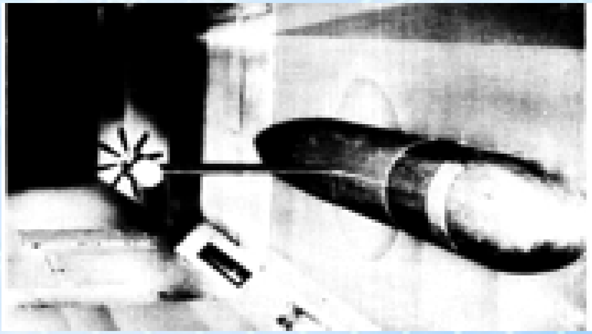
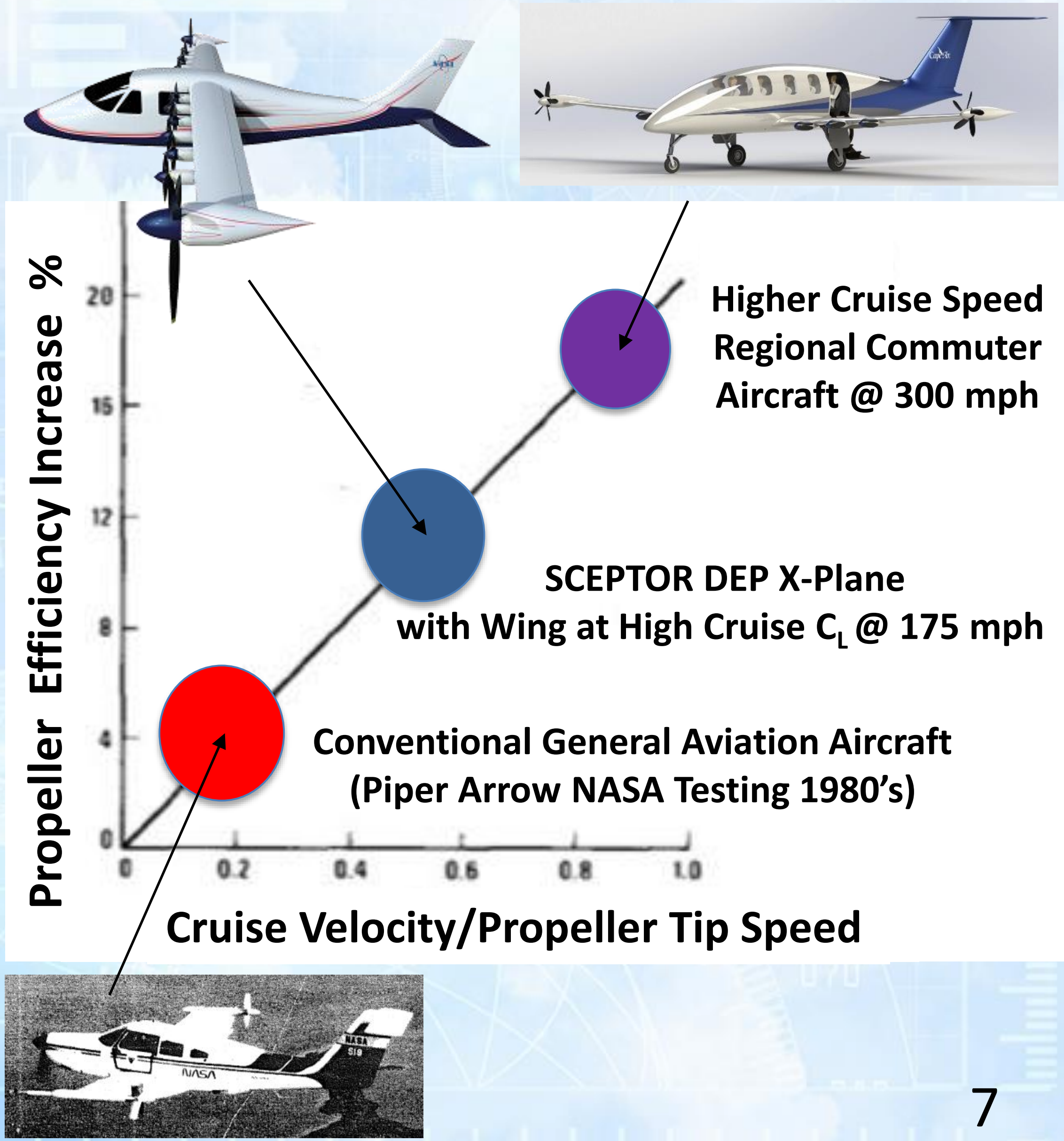
Wingtip Vortex Propeller Integration





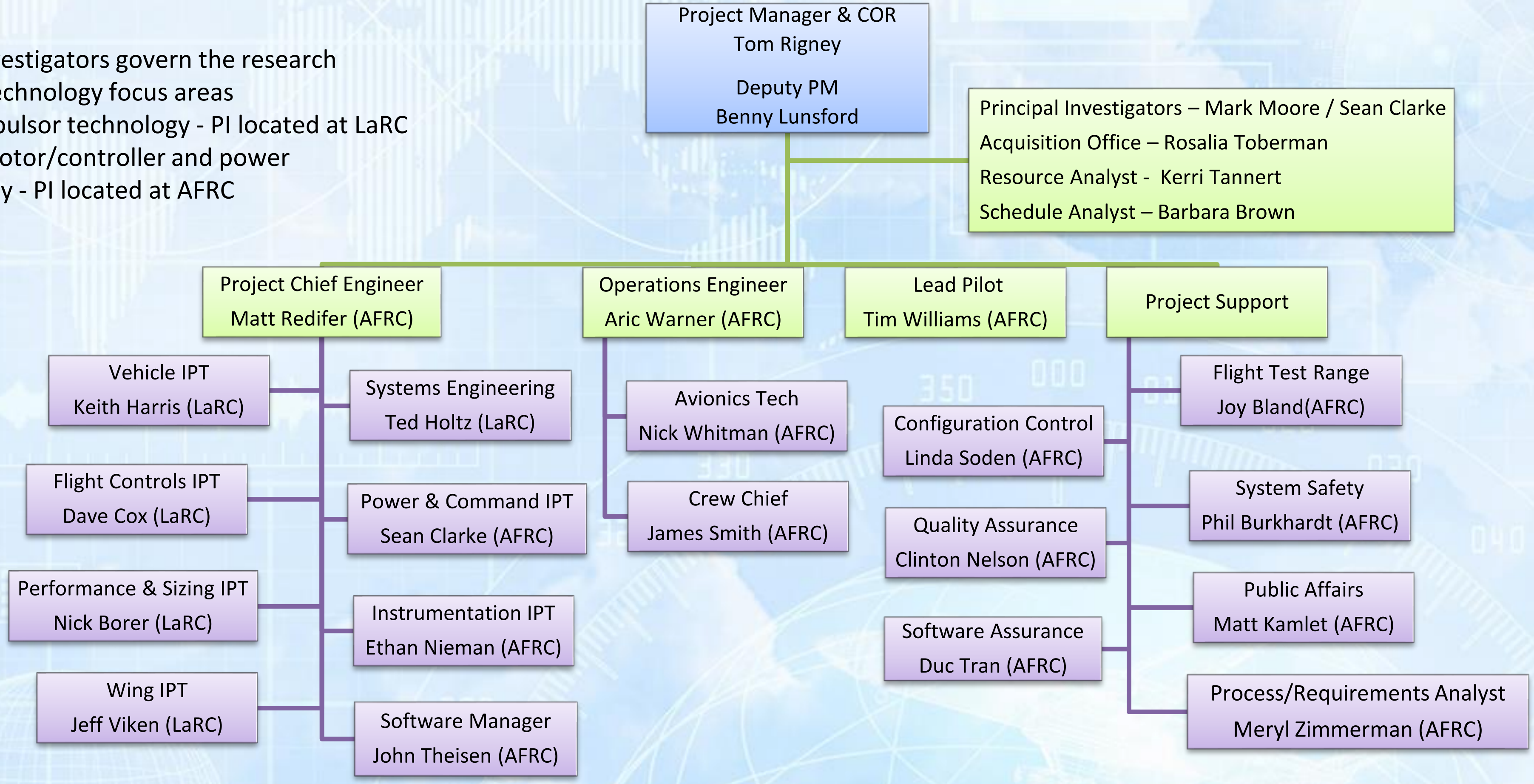
Viva and Alisport Motorgliders





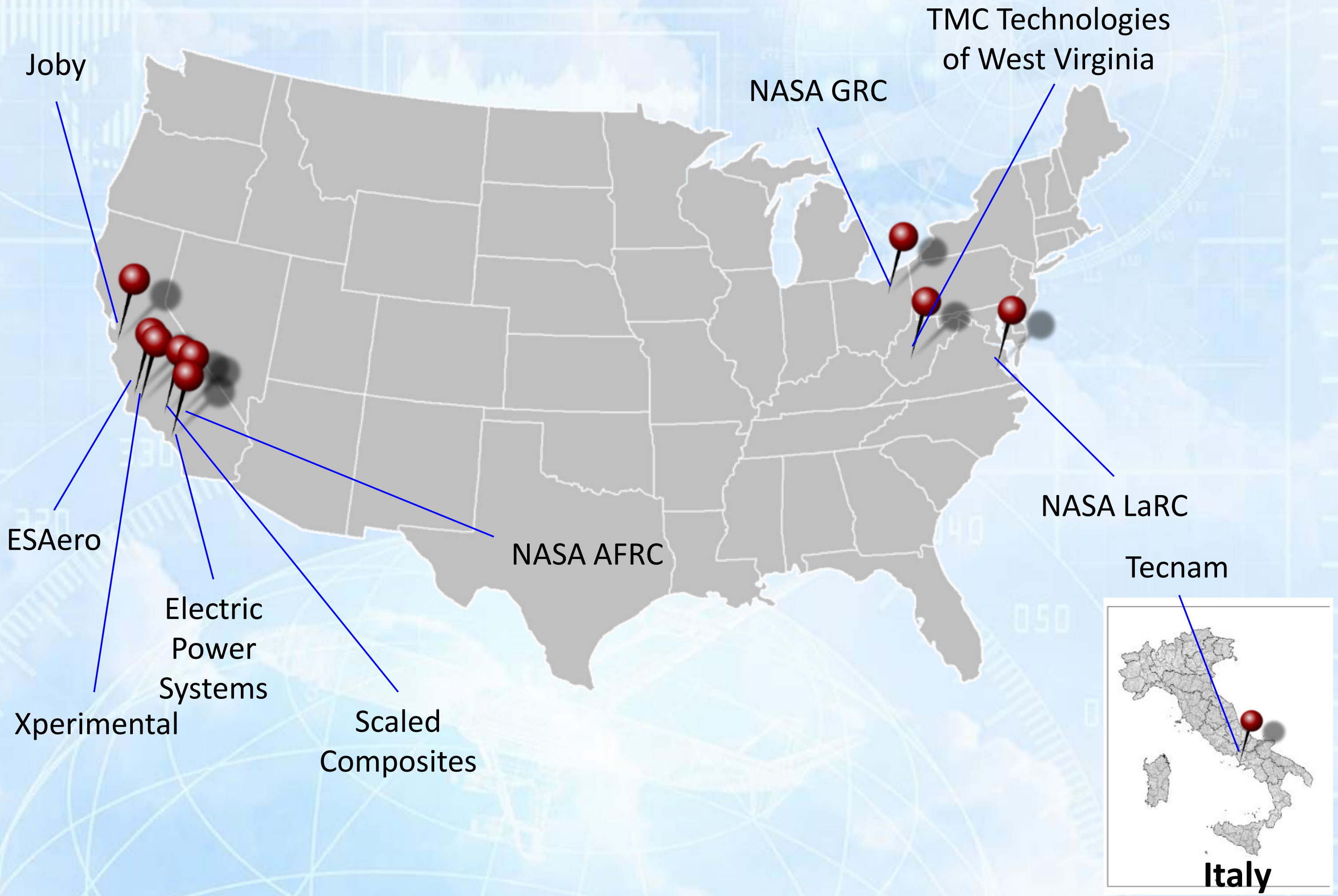
Project Organization

- Two Principle Investigators govern the research content in two technology focus areas
  - Aero/propulsor technology - PI located at LaRC
  - Electric motor/controller and power technology - PI located at AFRC



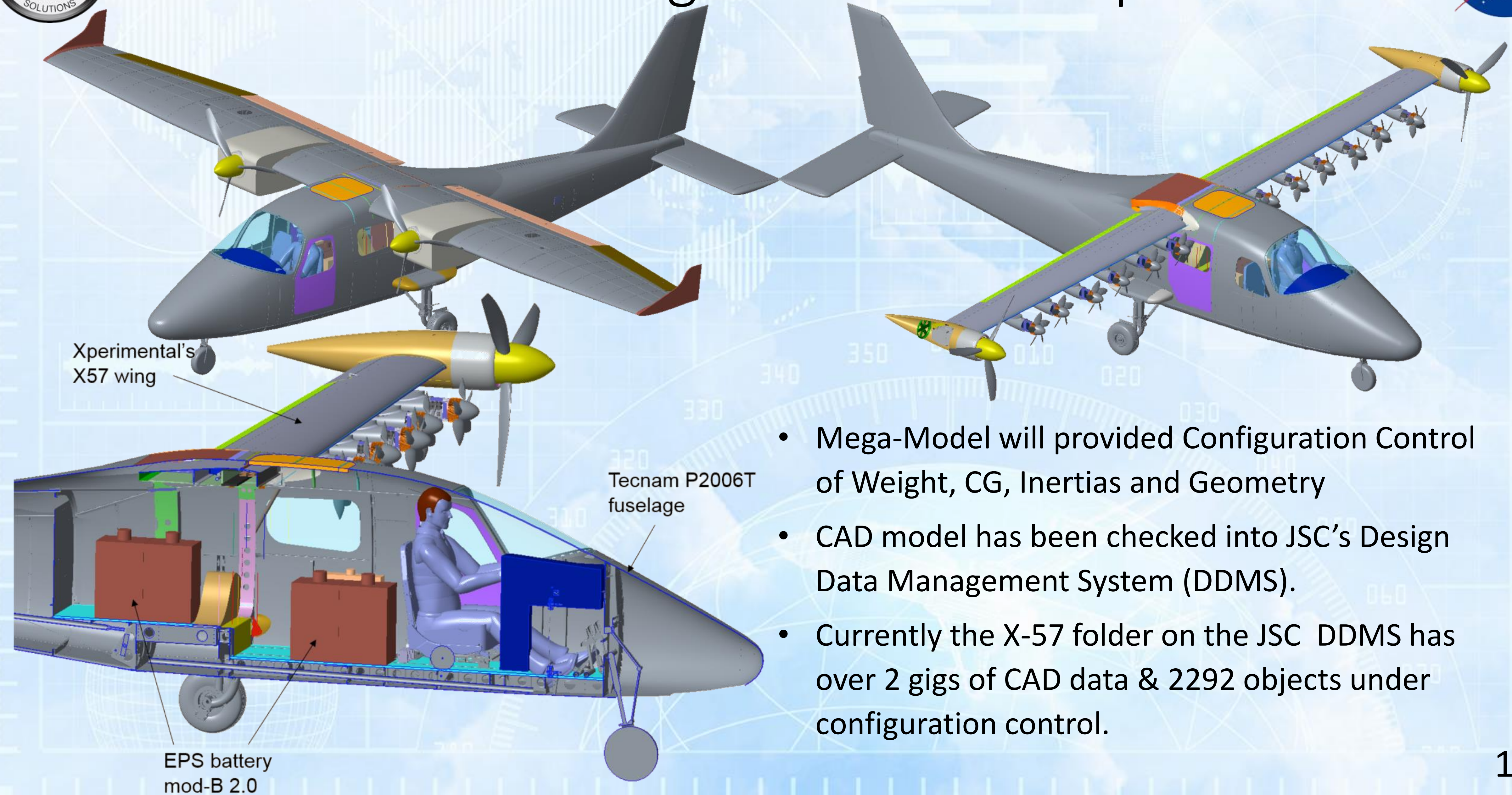
Participating Organizations

NASA Langley: Vehicle, Wing, Performance, Controls IPTs
NASA Armstrong: Power, Instrumentation IPTs, Flight Ops
NASA Glenn: Battery Testing, Thermal Analysis
Empirical Sys. Aero.: Prime contractor
Scaled Composites: Mod 2 Integration (batteries, motors, controllers, cockpit)
Joby Aviation: Motor & Controller and folding prop development
Xperimental: Wing design and manufacturing
Electric Power Sys.: Battery development
TMC Technologies: Software certification
Tecnam: Baseline COTS airframe without engines



DEVELOPMENT ACTIVITY BY INTEGRATED PRODUCT TEAM

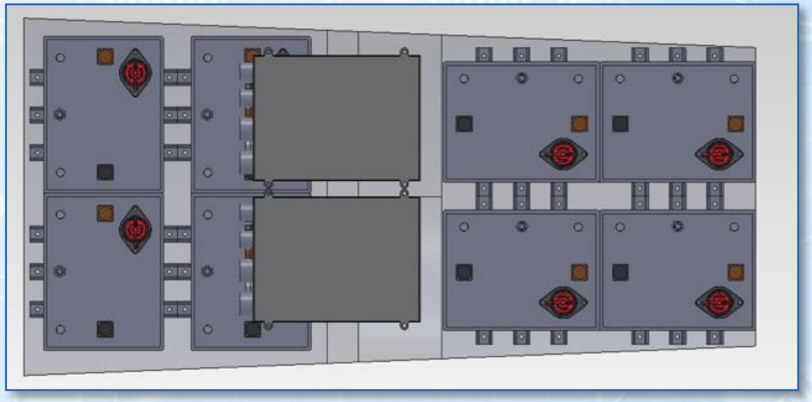
Vehicle IPT: Mega-Model Development

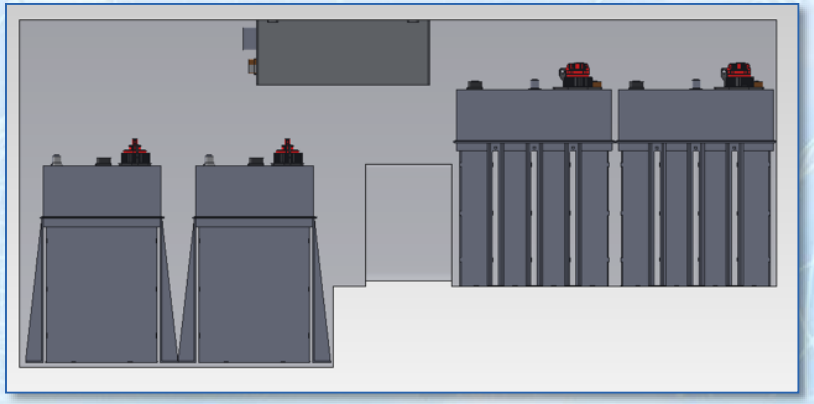


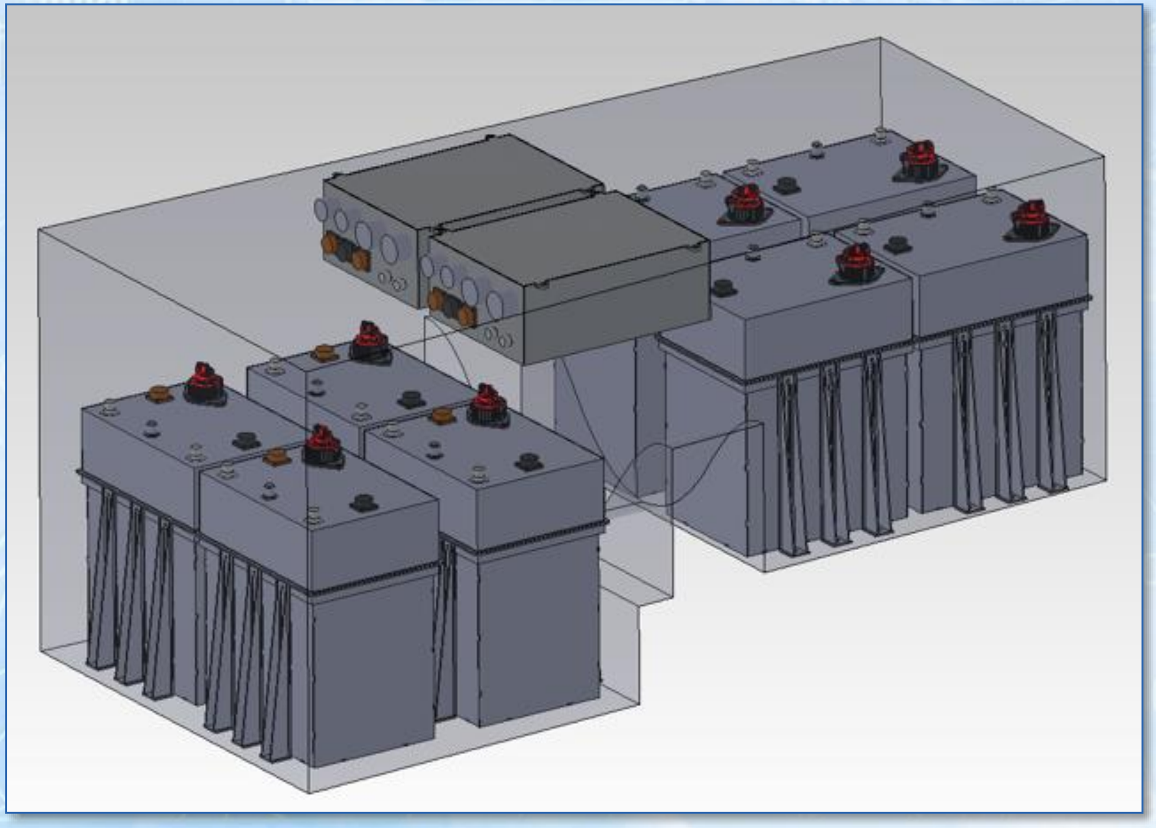
- Mega-Model will provided Configuration Control of Weight, CG, Inertias and Geometry
- CAD model has been checked into JSC's Design Data Management System (DDMS).
- Currently the X-57 folder on the JSC DDMS has over 2 gigs of CAD data & 2292 objects under configuration control.

Vehicle IPT: Battery Configuration

- A Trade Study was performed on several Battery Configurations before selecting Mod B-2.0
  - Meets CG, Volume Constant and Power Requirements



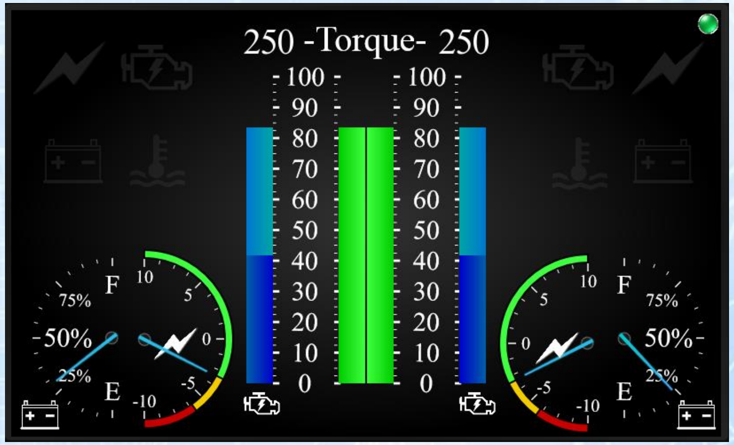




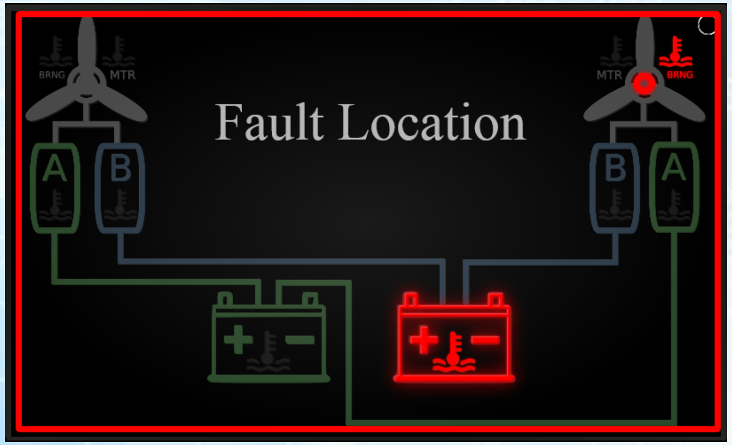
Vehicle IPT: Cockpit Displays

X-57 Cockpit

X-57 Analog Displays – Right Side

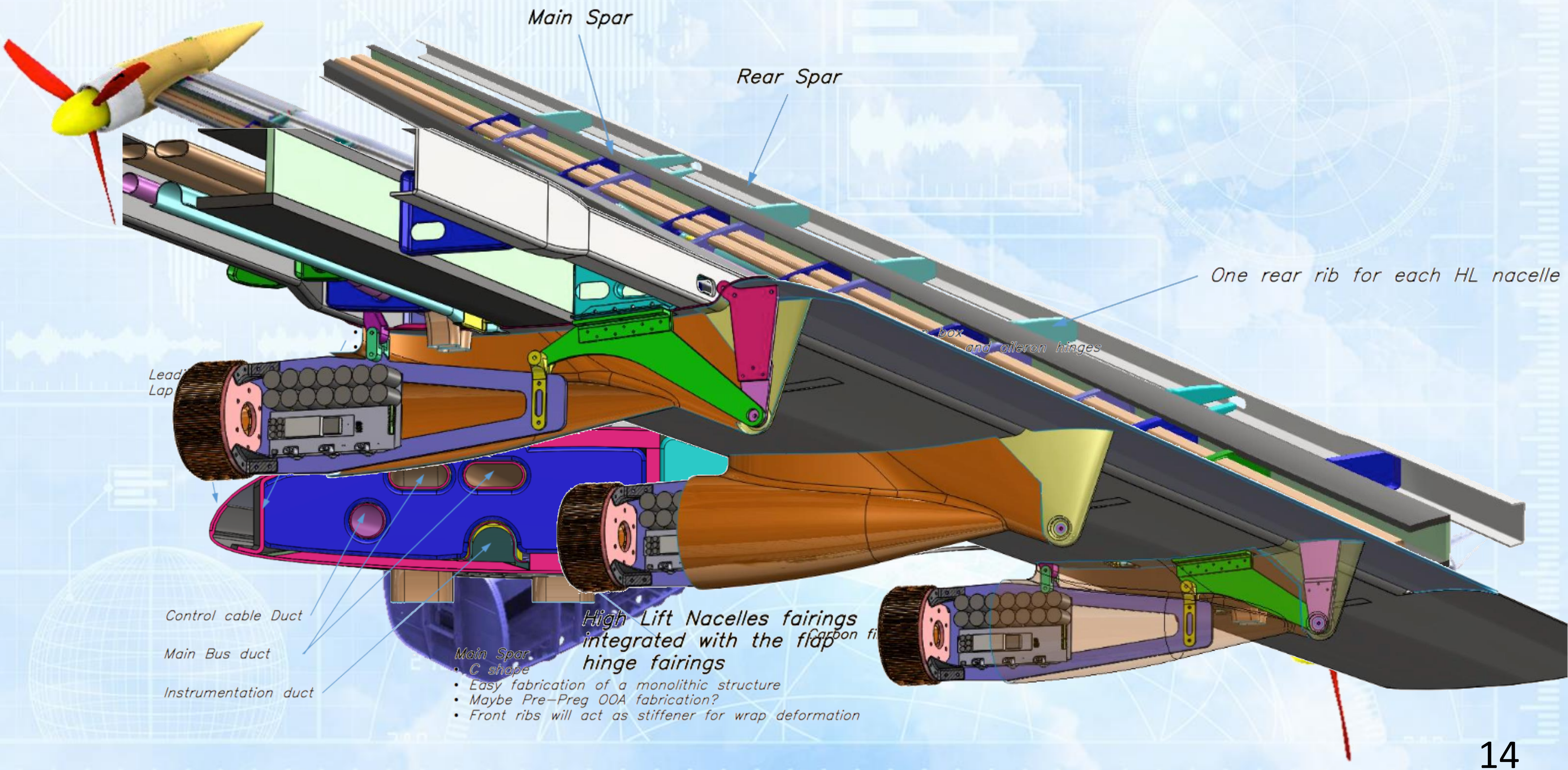


X-57 Digital Displays

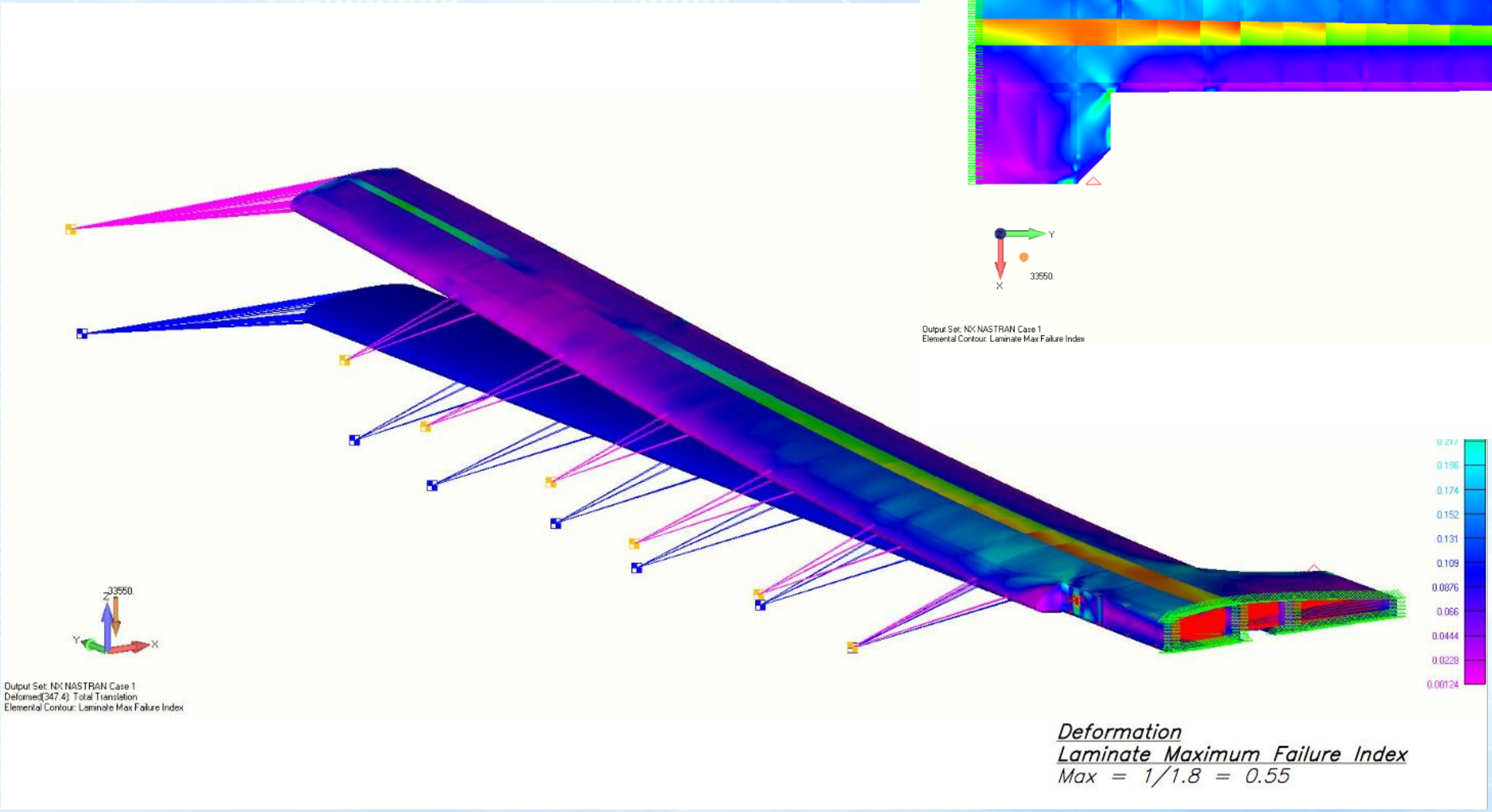


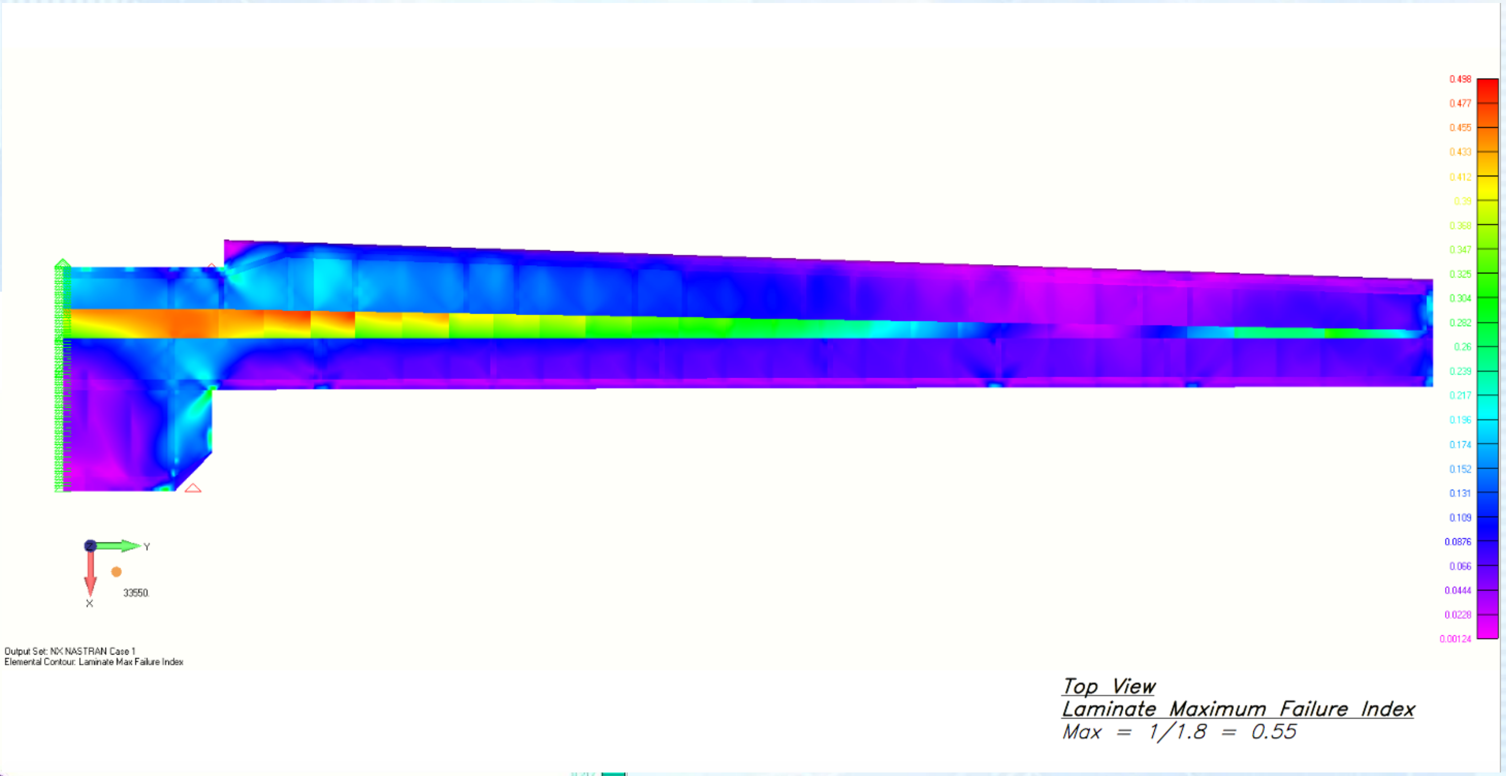
X-57 Digital Displays

WING IPT: Structural Design



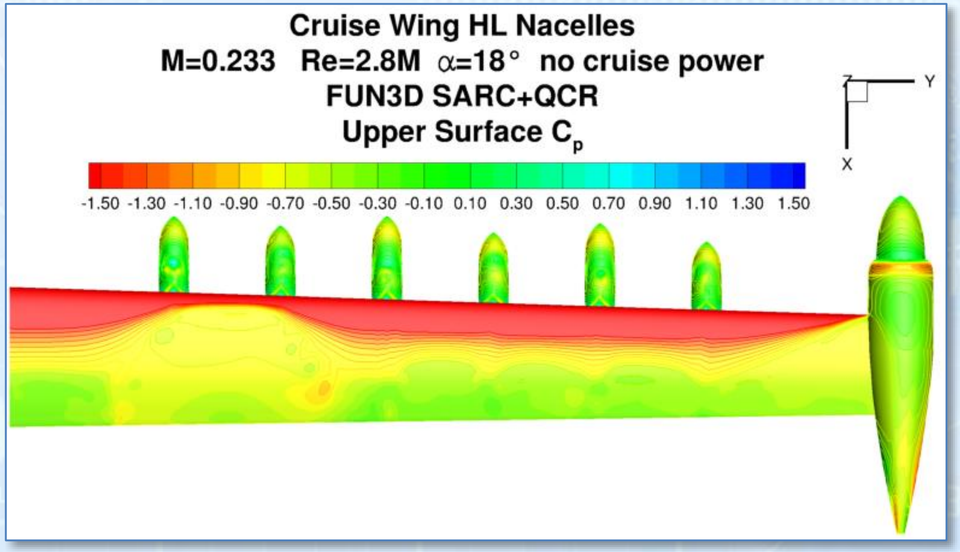
WING IPT: FEM Analysis

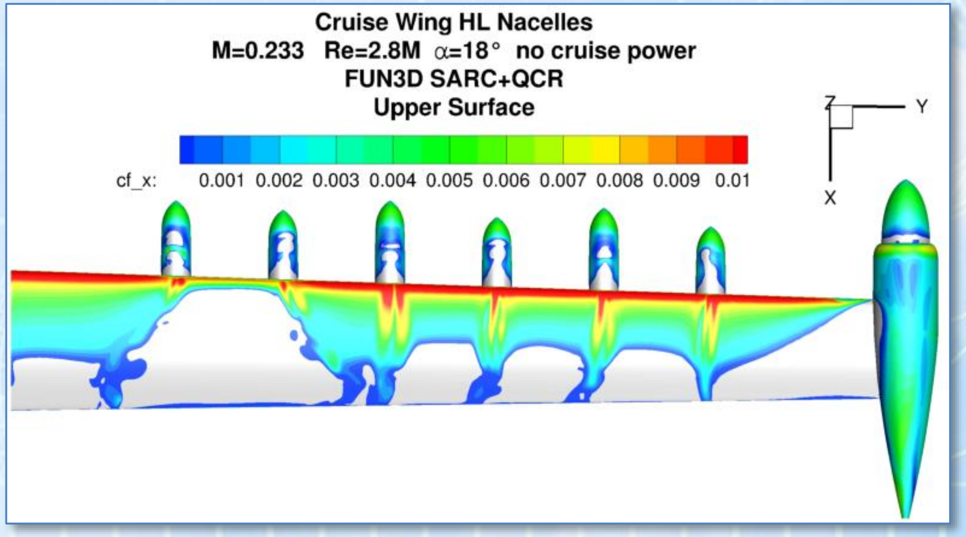


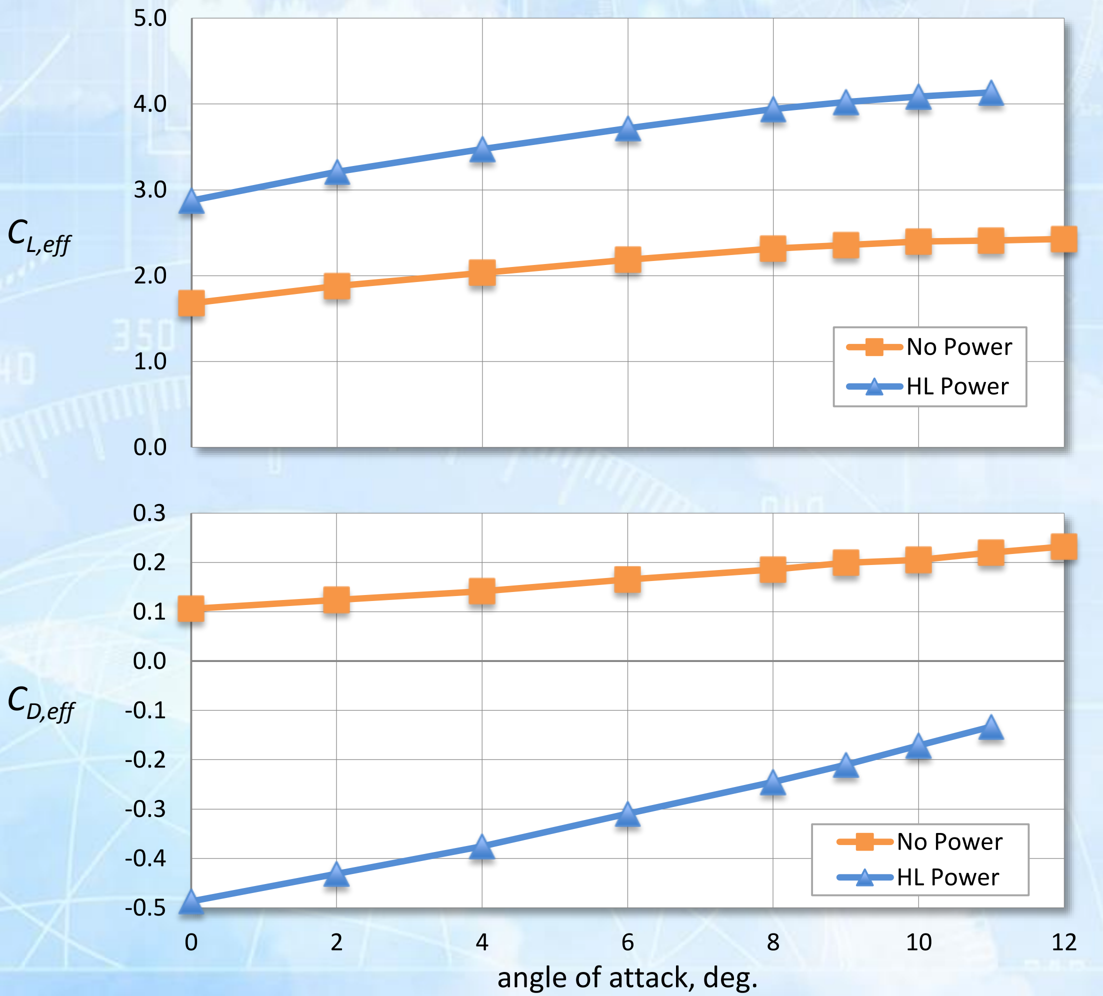


WING IPT: CFD Analysis

Effect of High Lift Power on $C_{L,eff}$ and $C_{D,eff}$



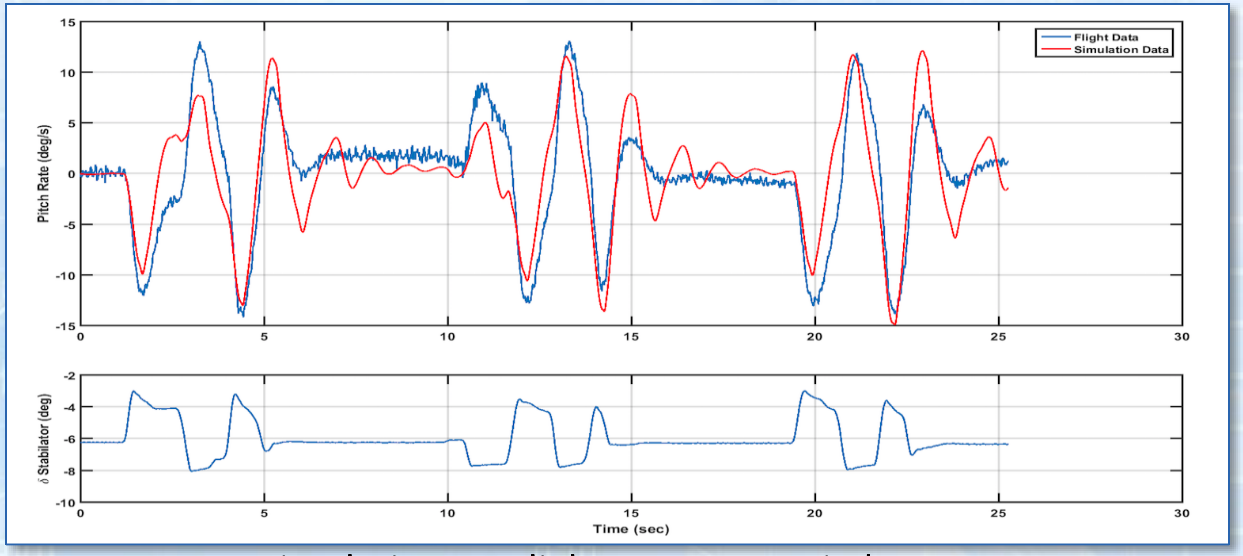




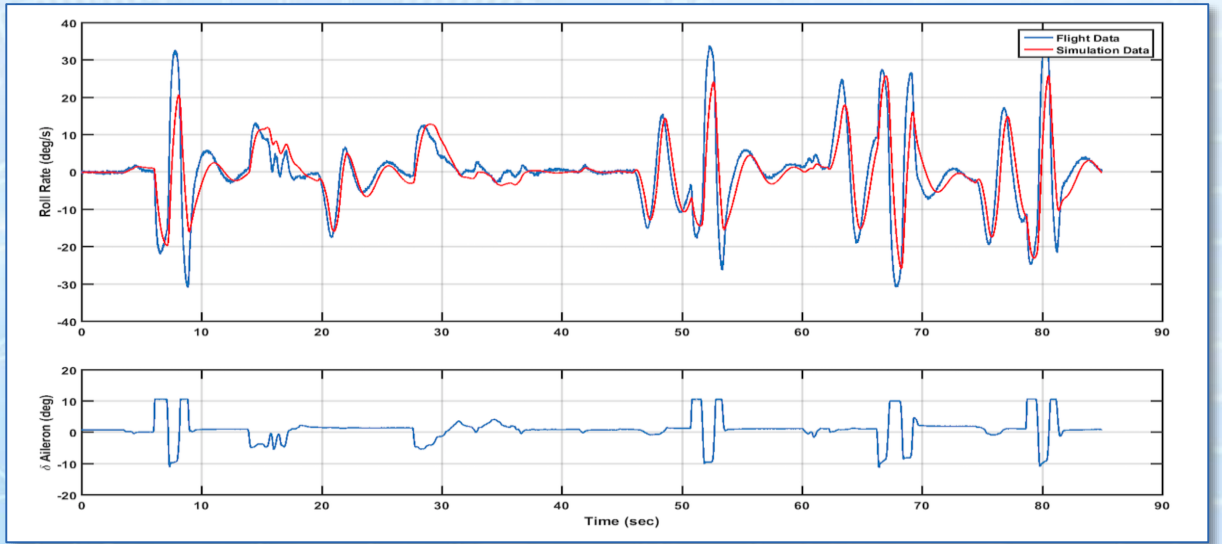
Controls IPT: Mod I Flight Test at AFRC

Test flights conducted on a commercial Tecnam P2006T

Flights supported both pilot familiarization, and a validation data-source for the Mod-II piloted simulation.



Simulation vs Flight Response, pitch rate



Simulation vs Flight Response, roll rate

Controls IPT: S&C Tunnel Test LaRC 12ft Tunnel

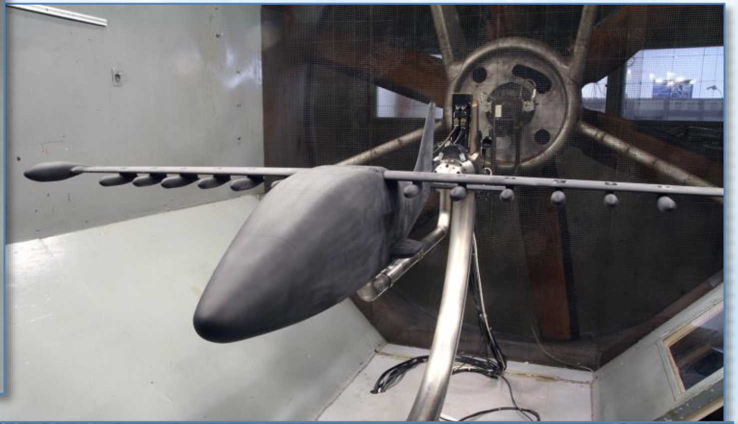
Primary Objectives:

- **Static aerodynamic database: Mod-III, unpowered**
  Alpha sweeps to and past stall (-8° to 40°)
  Beta sweeps out to 20° sideslip
- **Control Powers: ailerons, rudder, stabilator and flap**.
  Independent runs for left-right aileron
  Coupled tests for flap/stabilator and flap aileron
- **Dynamic derivatives for roll, pitch, and yaw**
  Forced oscillation testing in all 3 axes
  Several frequencies, at and below expected modes

Data Summary:

119 alpha-sweep runs, each with 16 dwell points
18 sweep runs with high-lift pods removed.
9 alpha-sweep runs with fuselage-tail only (no wing)
11 forced oscillation runs, 3 freqs each axis

Tunnel database forms the basis for analysis and piloted simulation in unpowered Mod-III configuration



Controls IPT: X57 Piloted Simulation

- Mod-II Simulation
  - Updated with data from flight test
  - Common aero-database between piloted and desktop simulations

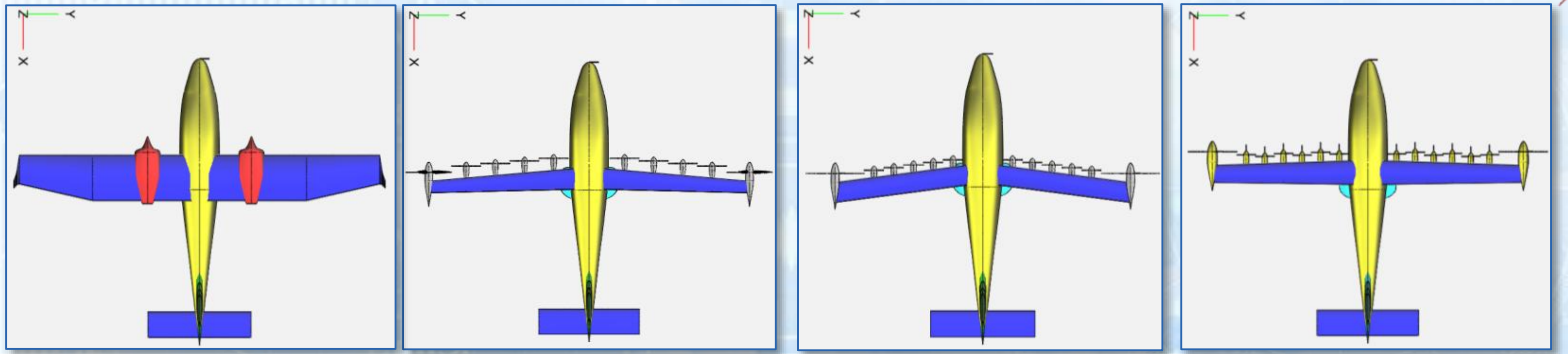
- Cockpit buildup
  - New force feedback yoke
  - Throttle/RPM Controls
  - Primary Instruments and Alarms

Piloted simulation will be used to train for test flights and verify acceptable performance and handling qualities.

Cockpit View

Tower/Chase External View, Mod-III

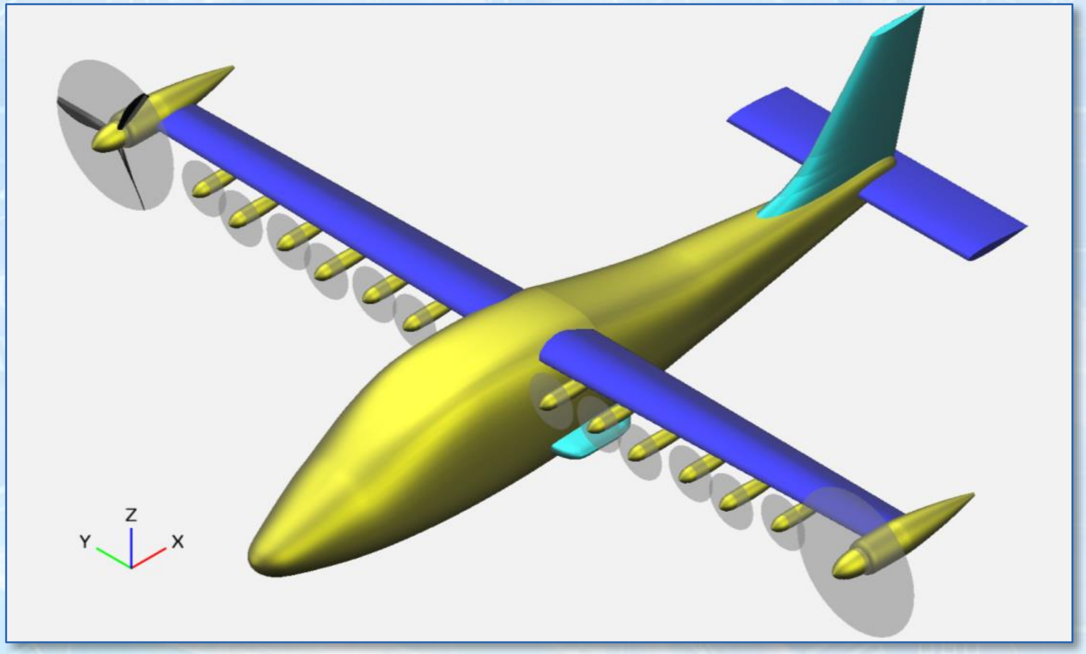
Performance IPT: Major Design Iterations



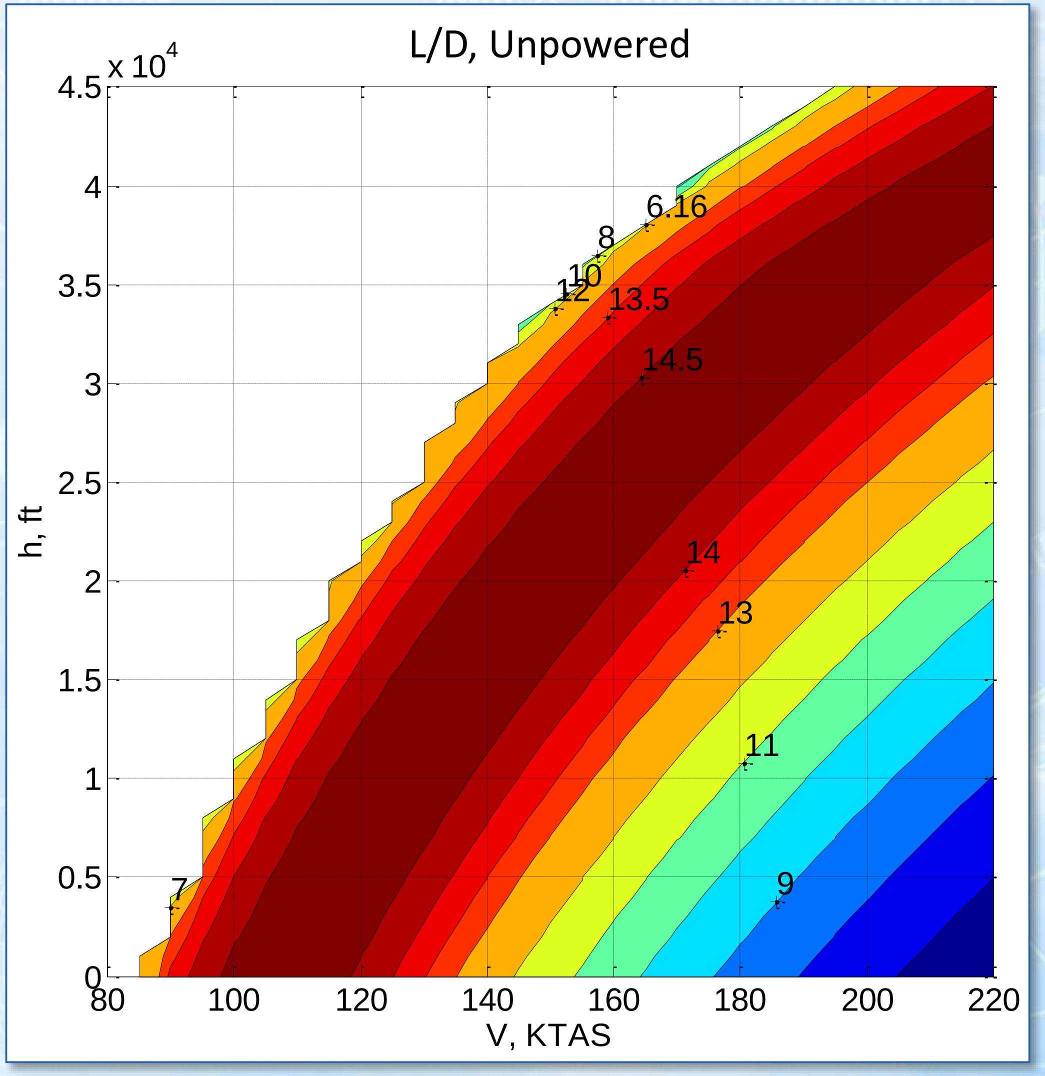
Model	P2006T (stock)	Rev 1.2	Rev 2.0	Rev 3.3 (PDR)
Span, ft	37.4	33.0	29.2	31.6
Planform area, ft^2	158.9	56.9	57.5	66.7
Wing loading, lbf/ft^2	17.1	52.7	52.2	45.0
Aspect ratio	8.8	19.1	14.8	15.0
Root chord, ft	4.57	2.25	1.97	2.48
Tip chord, ft	2.90	1.20	1.97	1.74
Leading edge sweep, deg	0.0	5.0	7.5	1.9
Cruise propeller diameter, ft	5.84	4.70	5.74	5.00
Cruise propeller RPM	2250	2470	1500	2250
High-lift propellers	-	8	10	12
C_L @ 58 KCAS, 3000 lbf	1.66	4.63	4.58	3.95

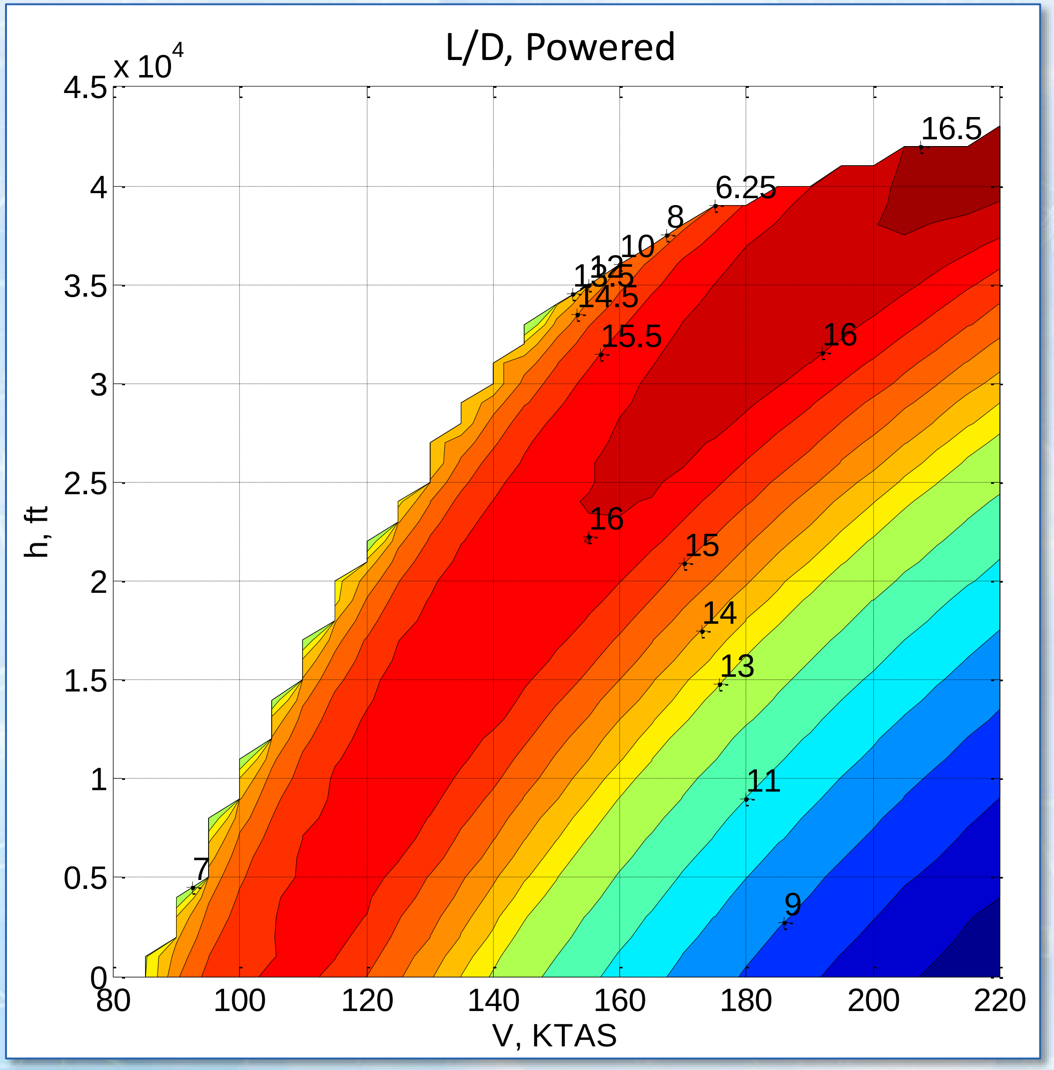
Performance IPT: Latest X-57 Design Features

- MTV-7-152/64 FAA-certified wingtip propellers
- Longer tip nacelles to house JMX57 outrunning motors, inverter cooling flowpath, and instrumentation
- Staggered high-lift nacelles to mitigate impact of blade-out failures to adjacent nacelles

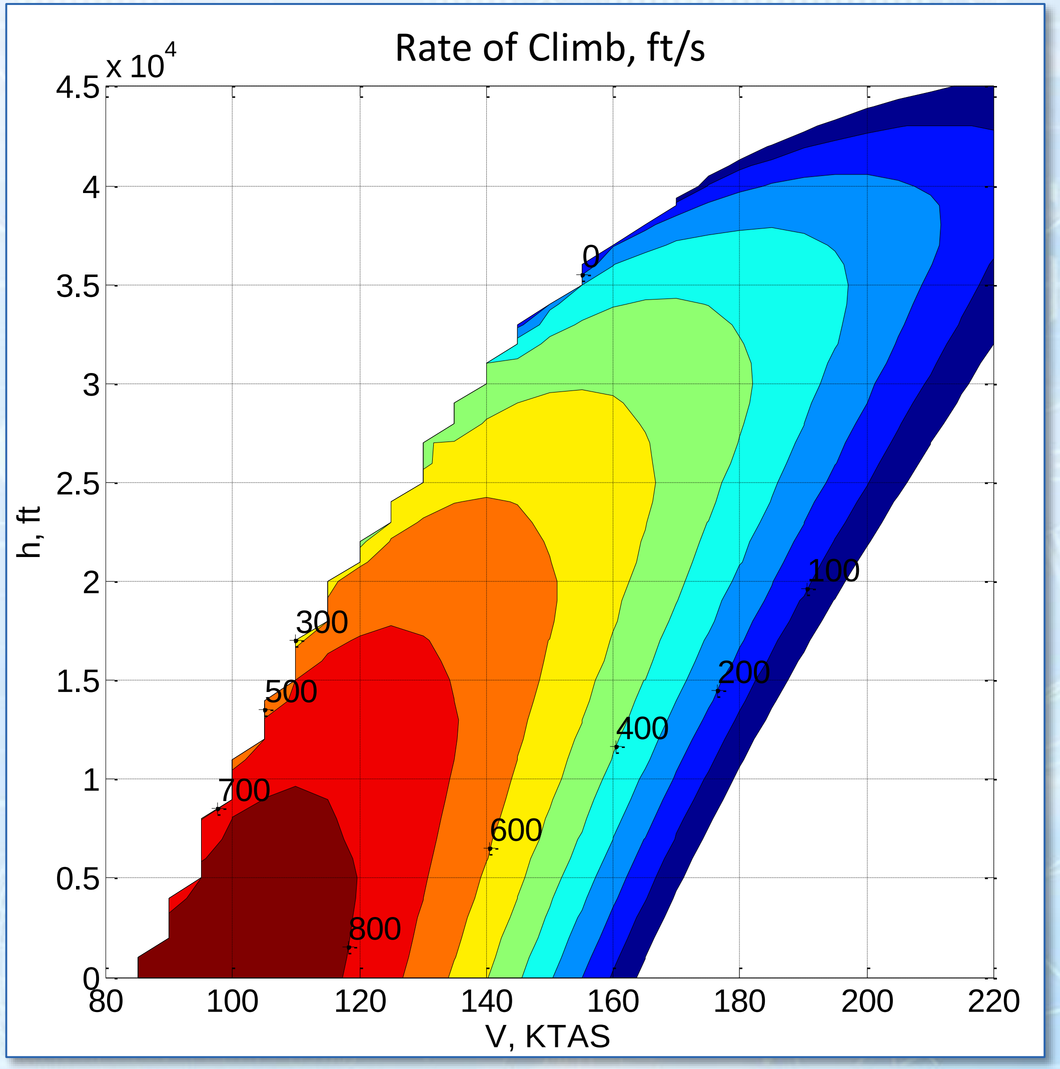


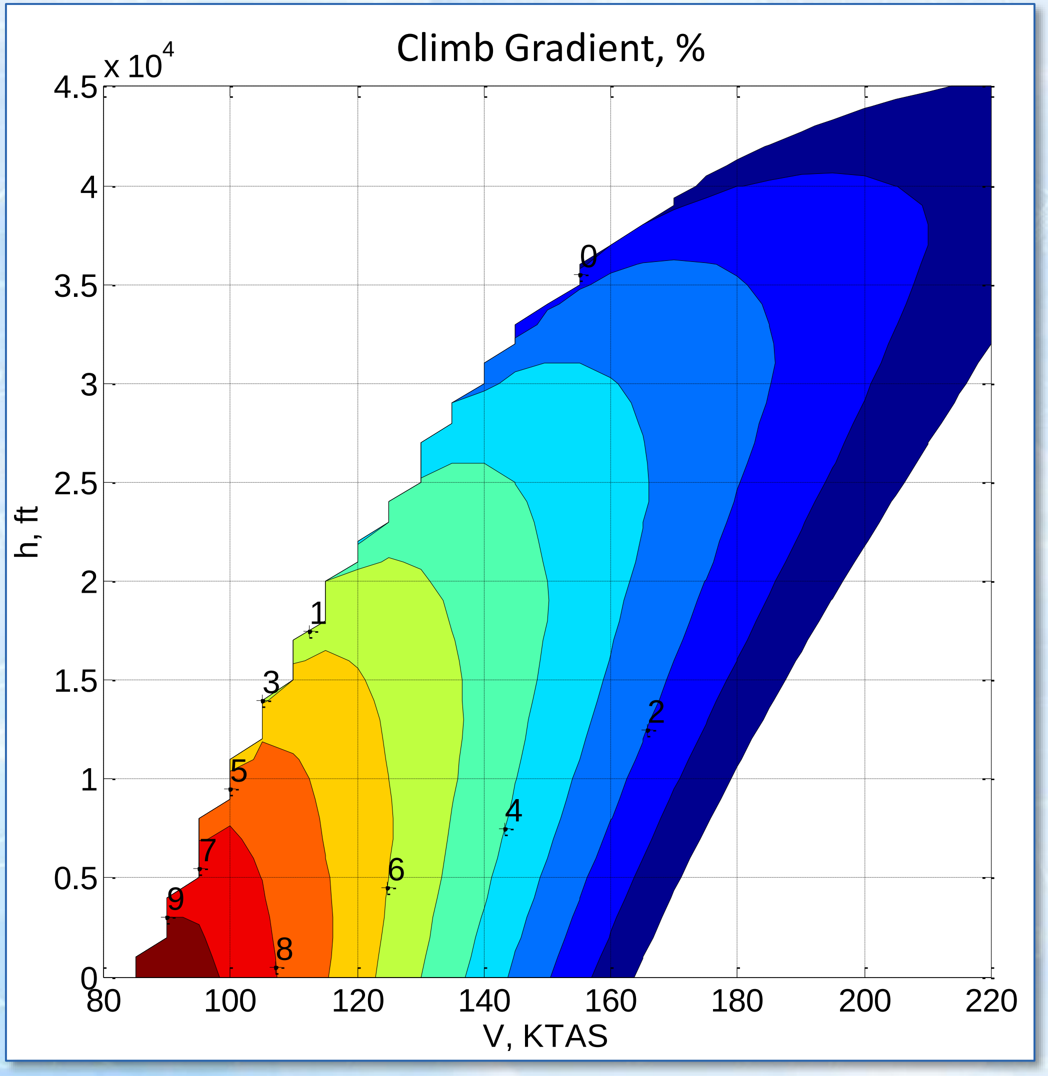
Performance IPT: Lift-to-Drag Ratio (Cruise Configuration)



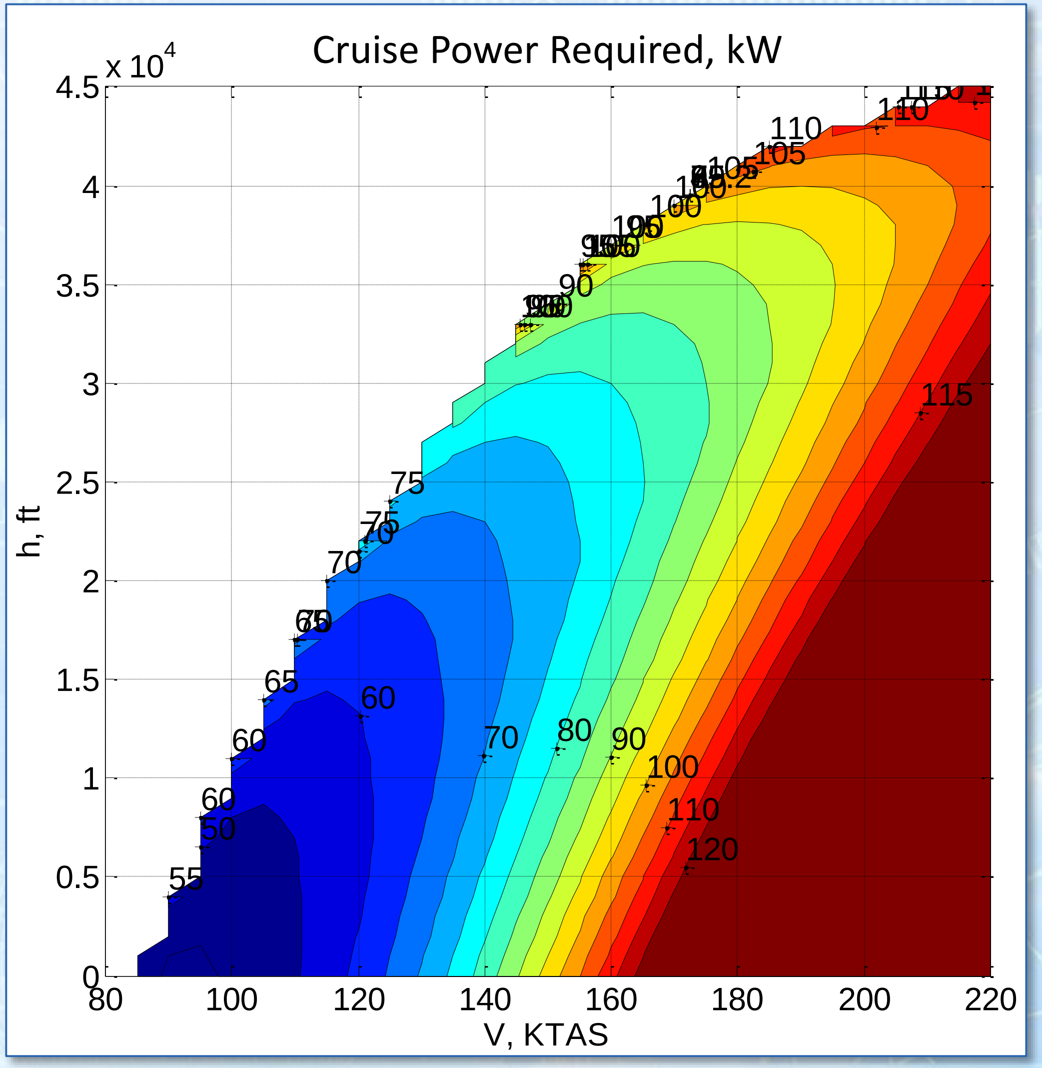


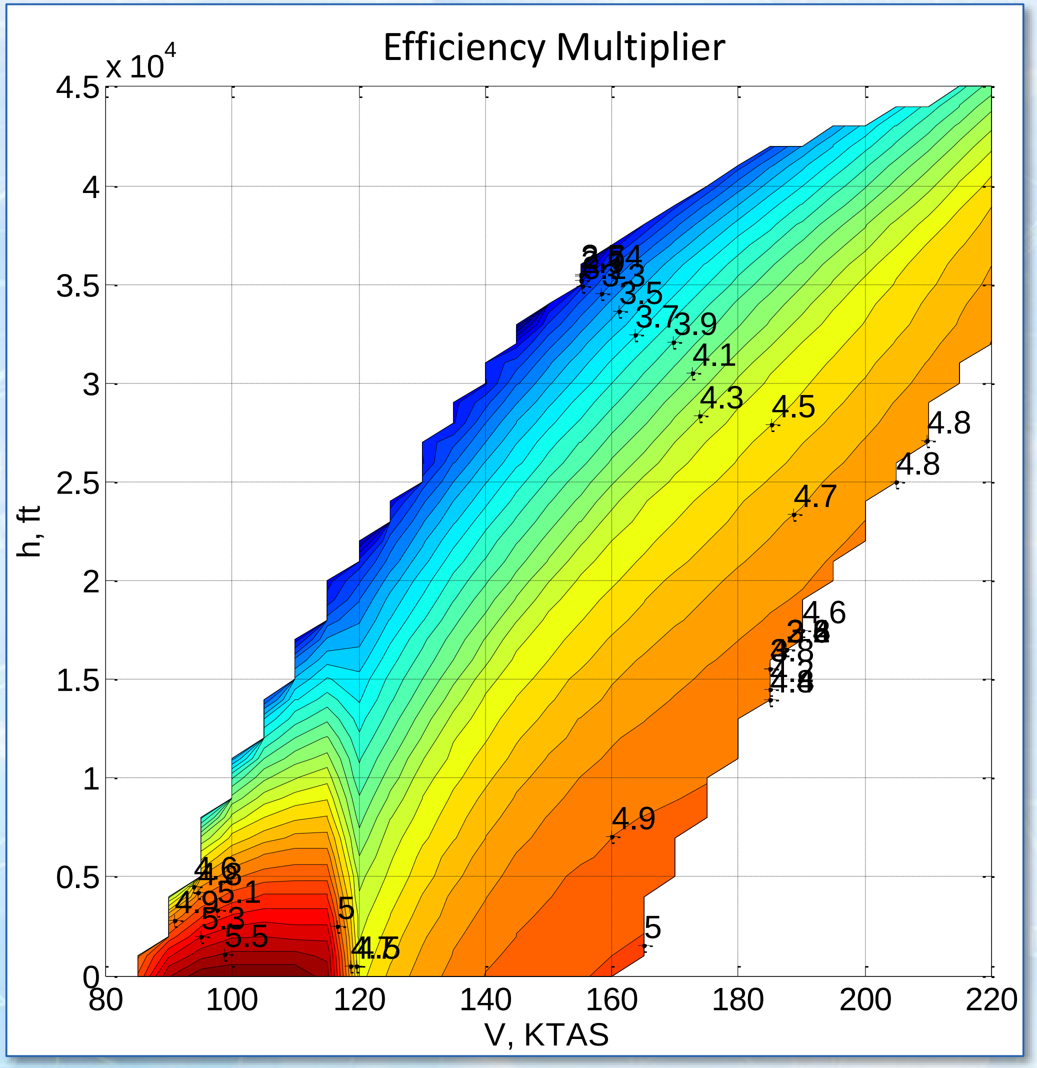
Performance IPT: Climb Performance (Cruise Configuration)





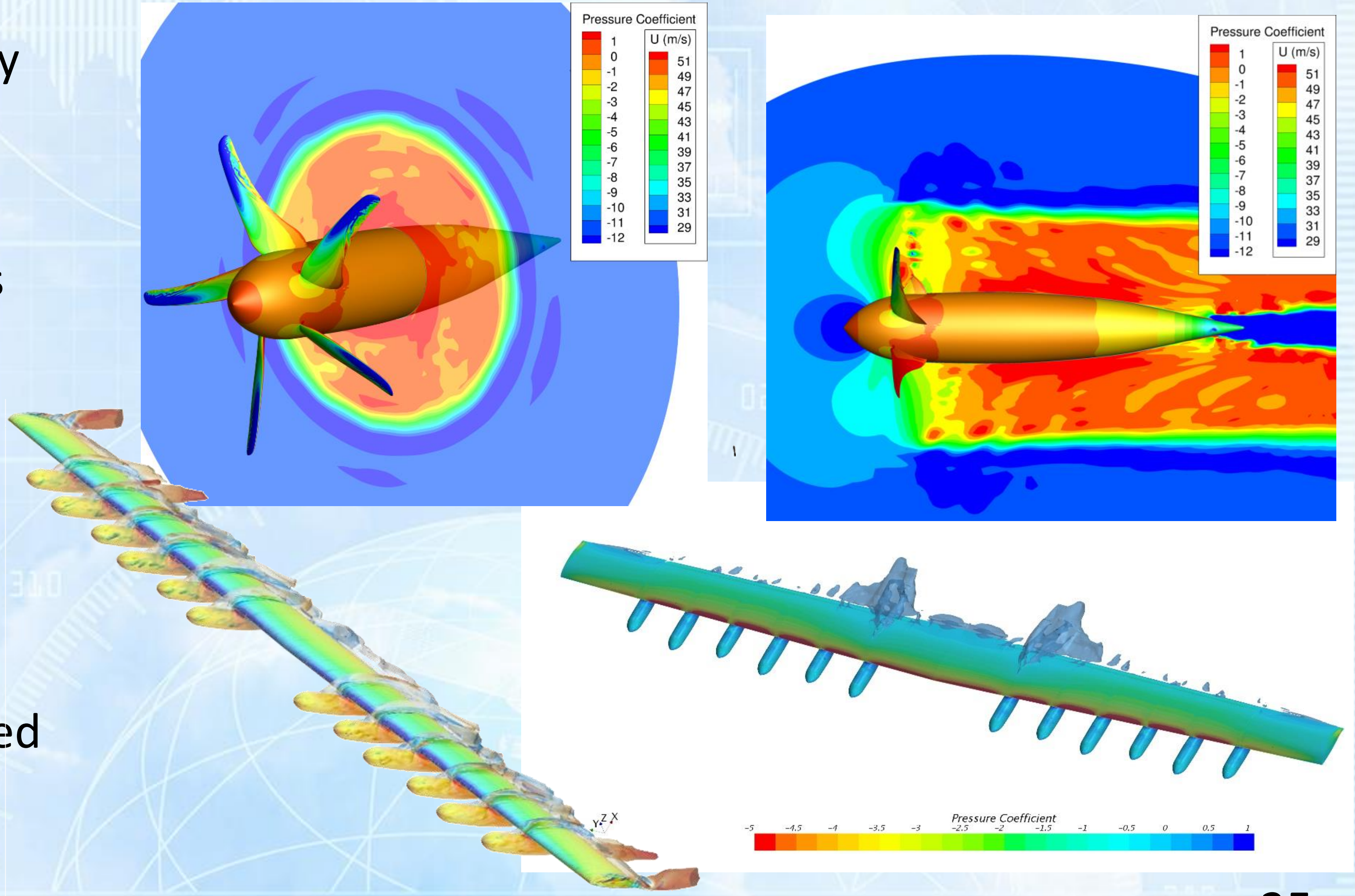
Performance IPT: Cruise Performance





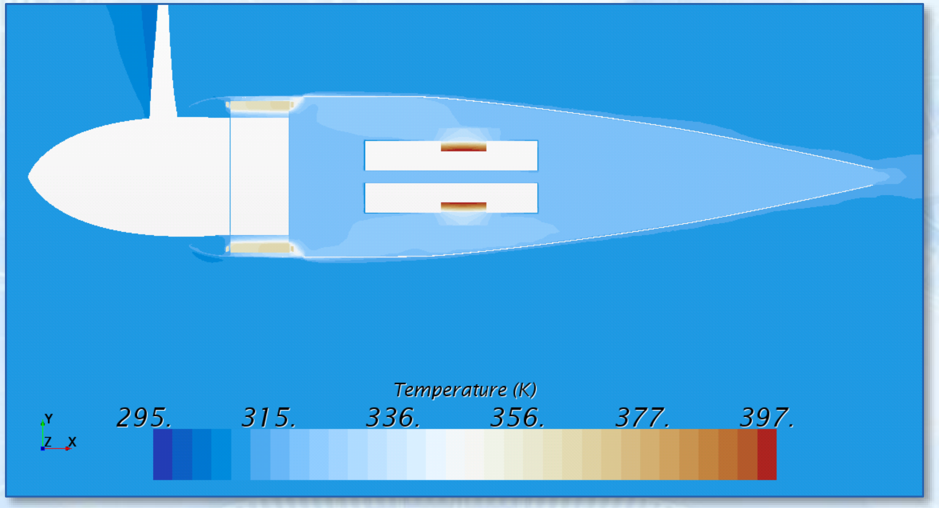
Performance IPT: High-Lift System Design and Analysis

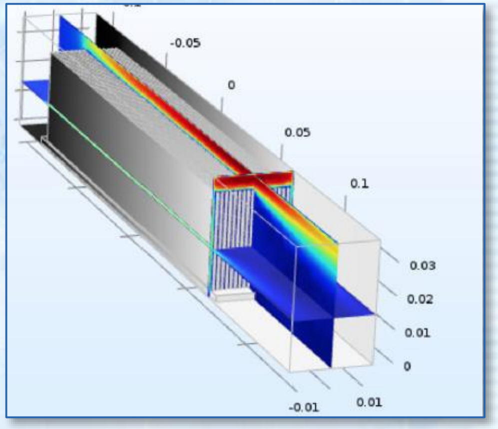
- Developed blade geometry for high-lift propeller that produces uniform axial velocity increase and folds nearly flush with high-lift nacelles in cruise
- CFD results indicate that wing and propeller design will meet or exceed requirements for stall speed

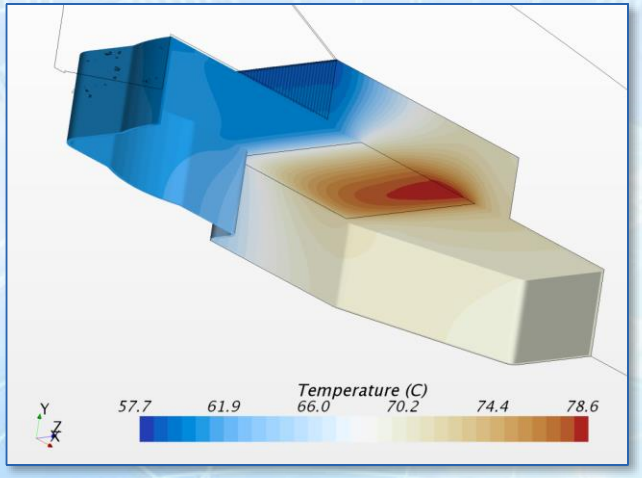


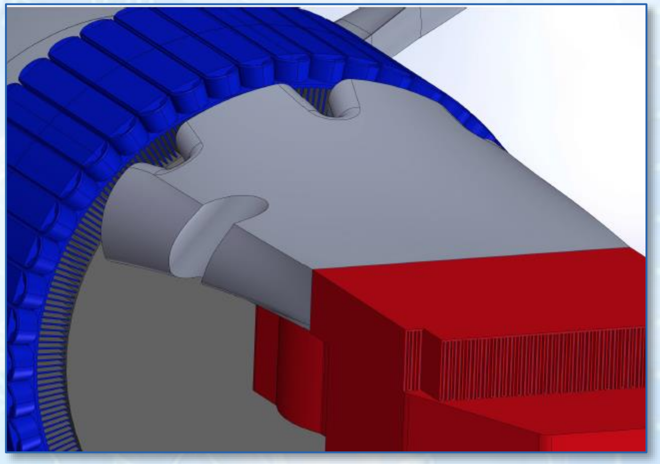
Performance IPT: Thermal System Analysis

- Developed annular cooling inlet geometry for motor and motor controller
- Inlet provides more than adequate airflow for combined motor and controller cooling
- Finalizing internal motor controller cooling flowpath and heat sink design



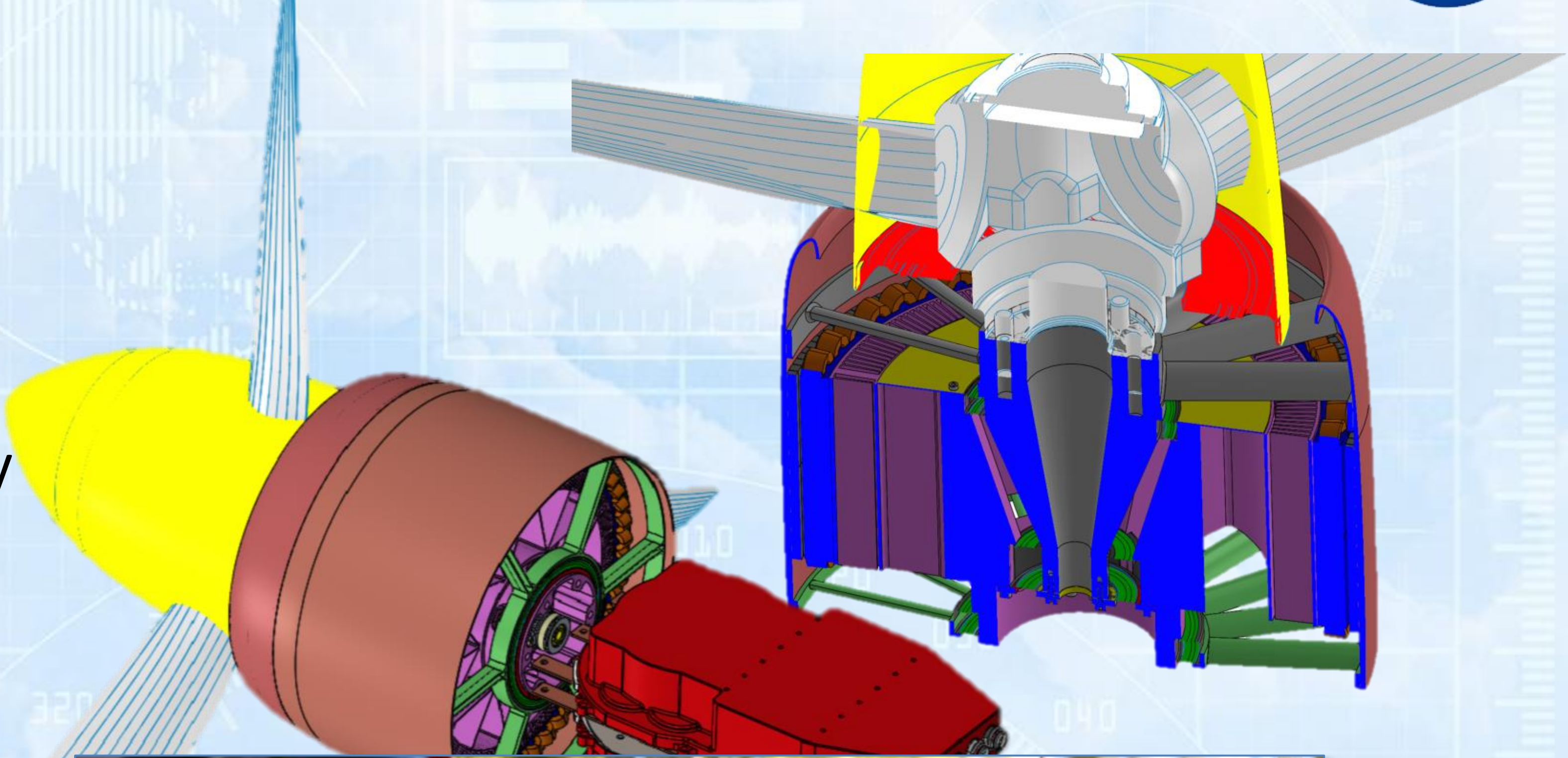






Power IPT: Cruise Motors

- Replaces 100 HP Rotax 912S engine with 60 kW Joby motor
- Air cooled, direct drive, permanent magnet outrunner
- FPGA based variable frequency switching (real time peak seeking controller)
- Redundant architecture: each battery, power bus, controller contributes half of the torque
- Wide band-gap SiC half bridges
- Prototype testing underway

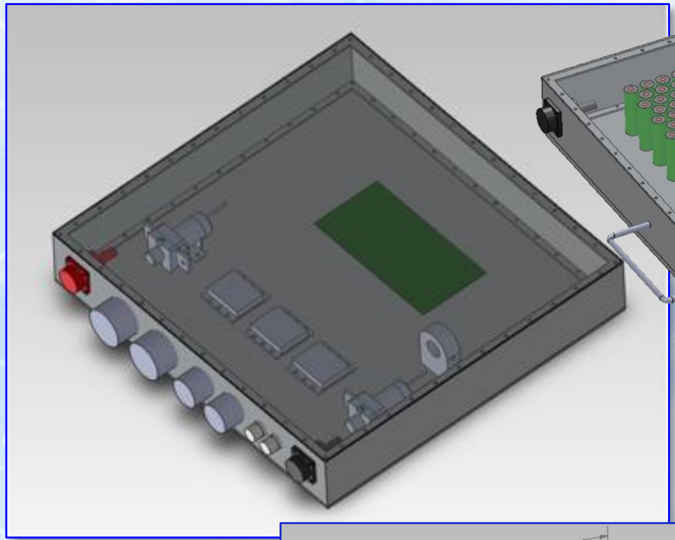


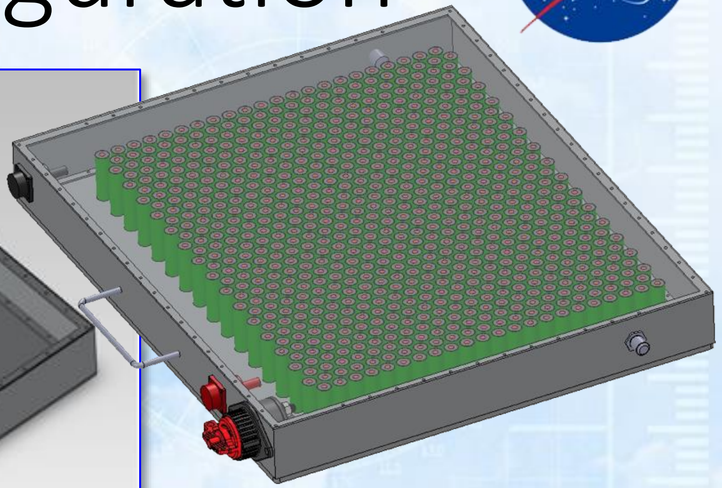
E|S|AERO

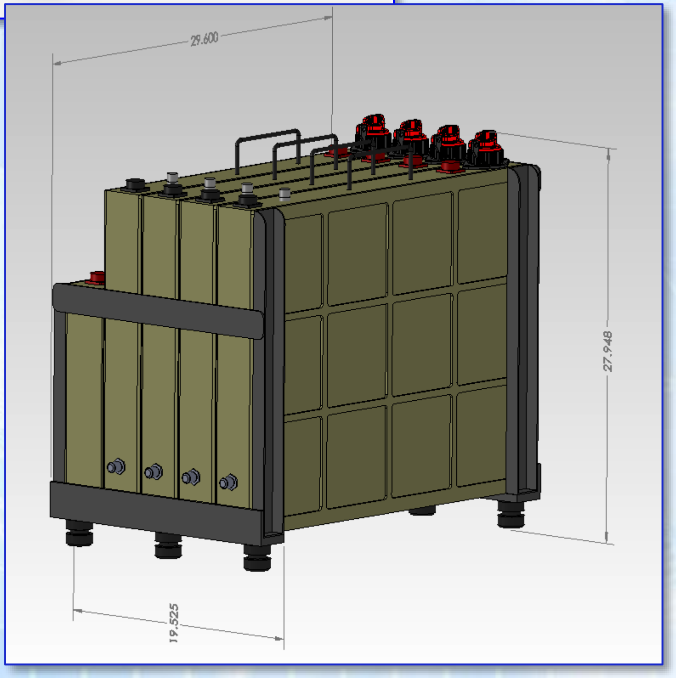
JOBY AVIATION

Power IPT: Battery Module Configuration

- Electric Power Systems design
- Two battery packs on board, each with 4 battery modules and a control module
- Nickel Cobalt Aluminum 18650 cells selected; provides sufficient energy density and discharge rate for SCEPTOR mission. Modules interconnected in series with cells arranged in 20p32s inside
- 47 kWh useful capacity, 461 VDC nominal (416 to 525 across SOC range), peak discharge of 132 kW.
- Will comply with flight environment, including 18 g crash loads, -5 to +45 °C operating environment





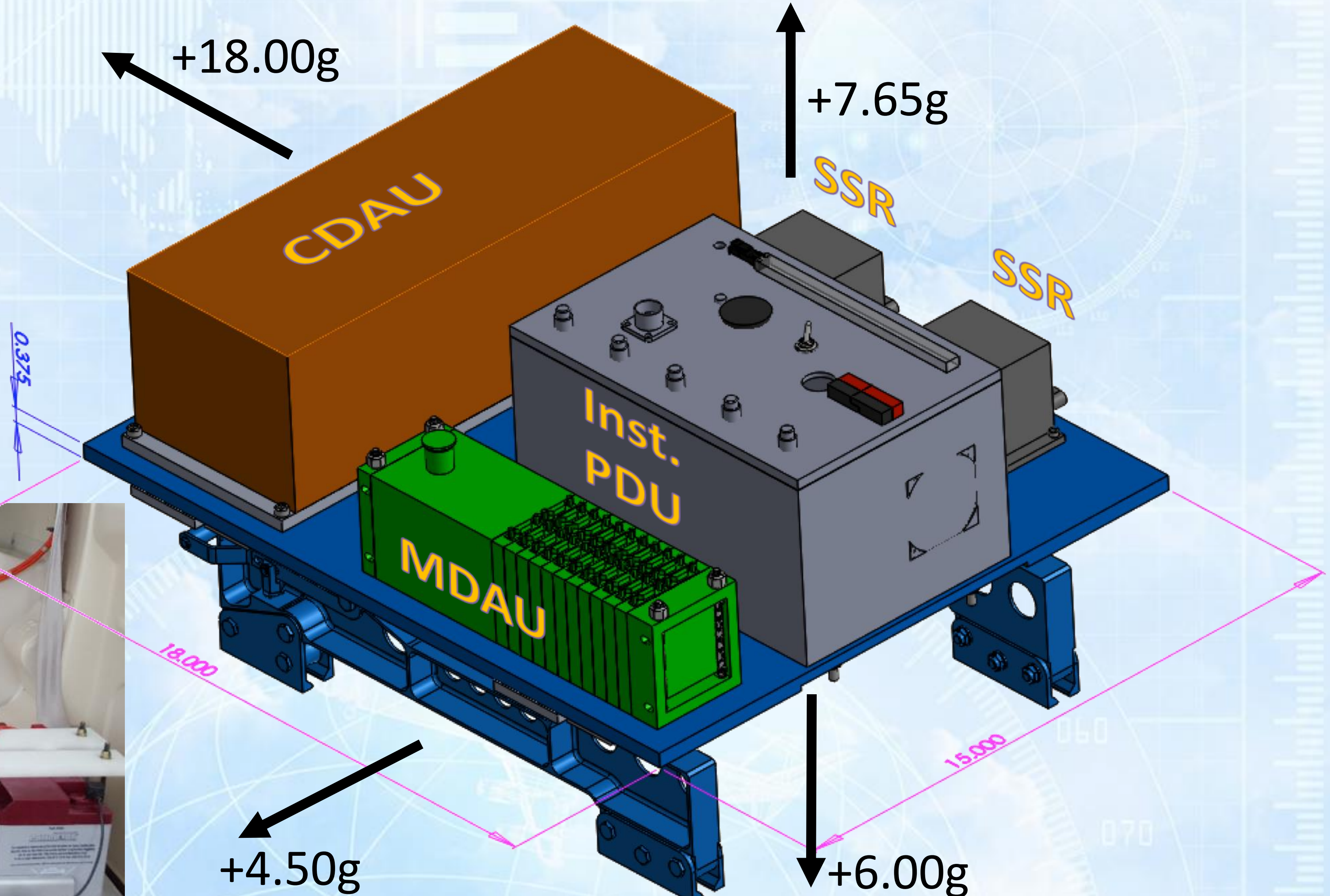


Power IPT: Command System Hardware

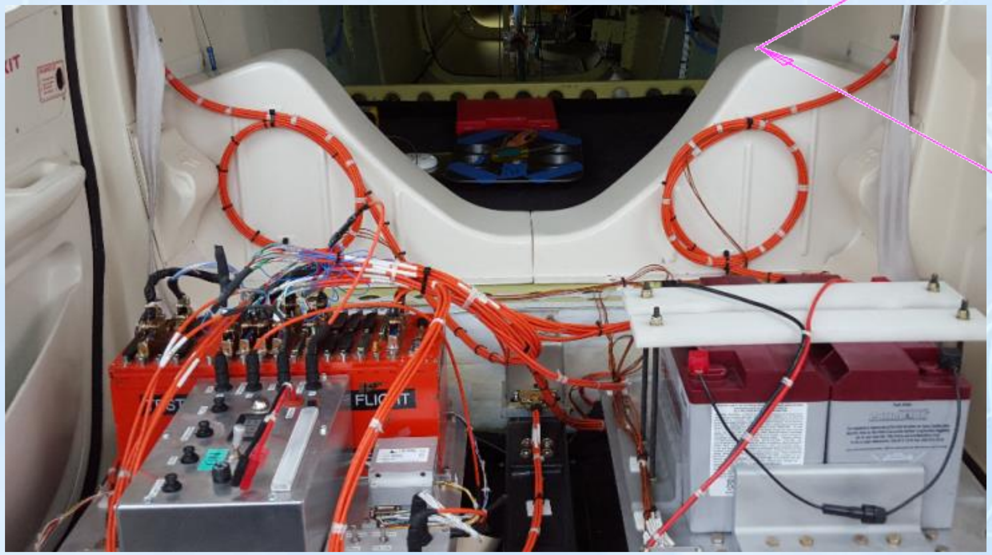
- CAN Bus used as the common command and data handling backbone
- Command system will use COTS throttle position encoders and programmable digital display units in the cockpit
- Fiber Optic Bus Extenders will tunnel C&DH bus through fiber down the length of the wing (avoid EMI)
- Additional data collection via analog-to-CAN measurement system

Instrumentation IPT: Fuselage CDAU & MDAU

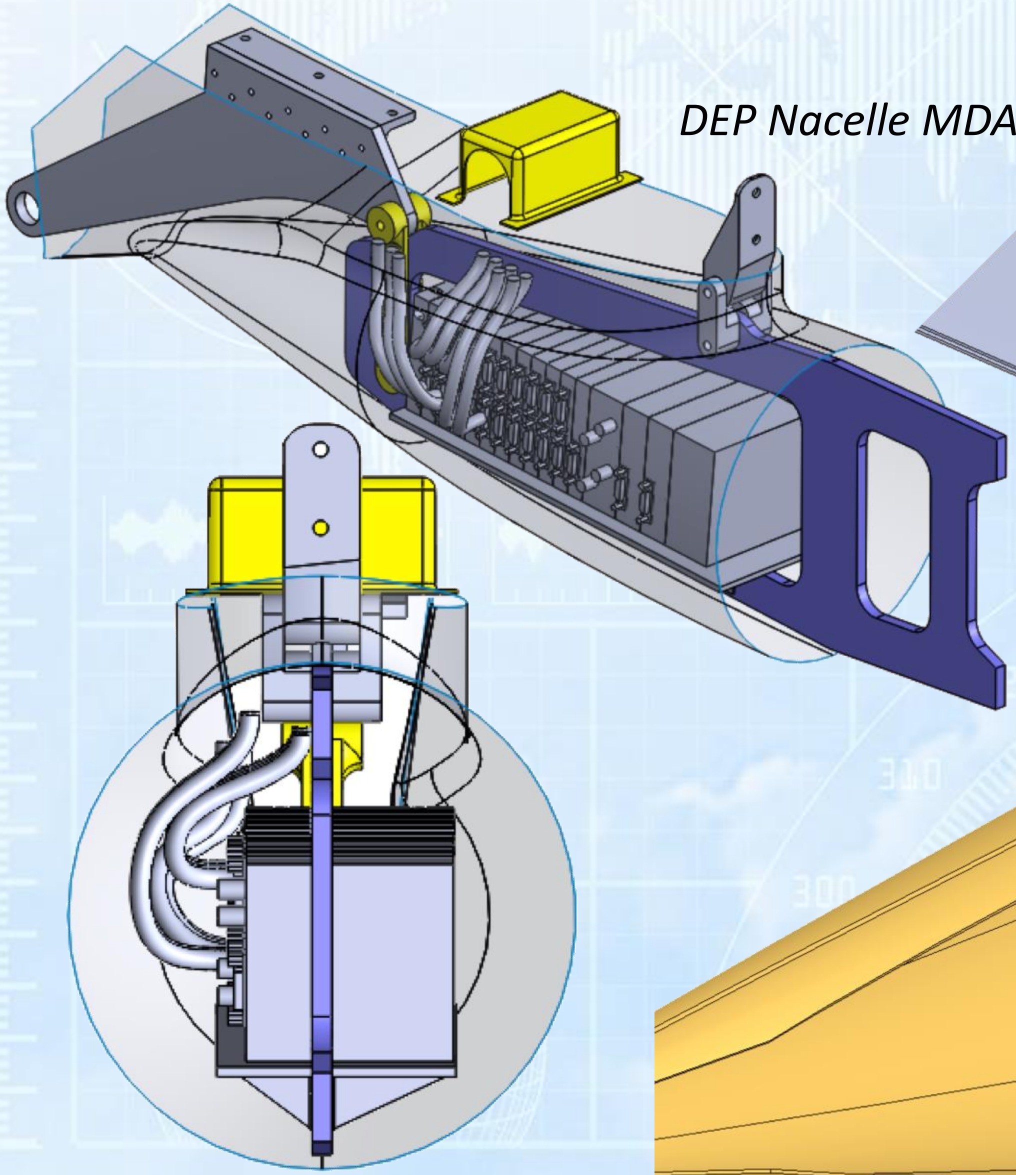
- New instrumentation pallet
  - Based on MOD 1 Design
  - FoS of 1.0x for forward, side and downward G loading
  - FoS of 2.25x for vertical loading
  - Additional MDAU added
  - Additional Recorder



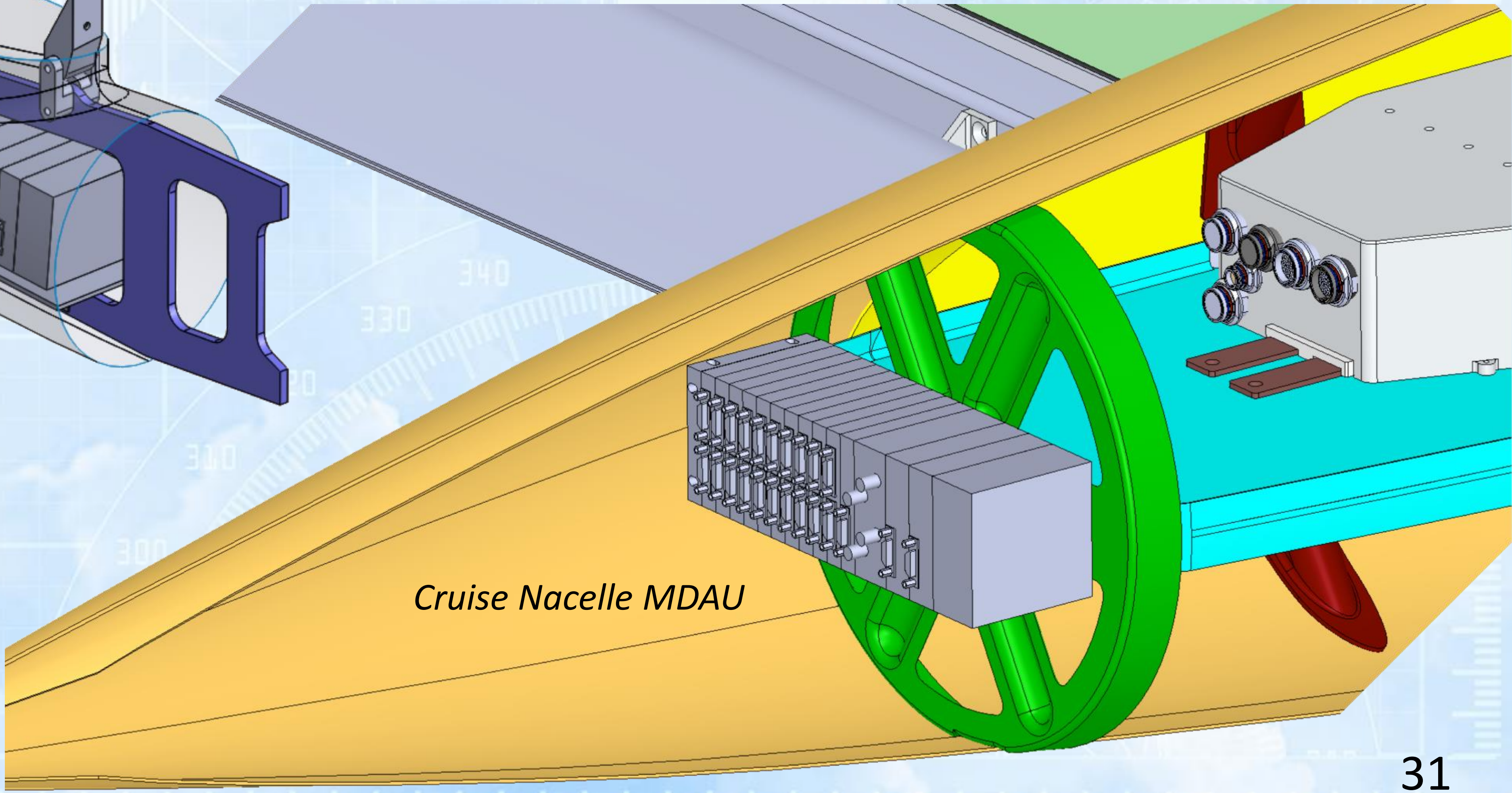
Mod I instrumentation pallet



Instrumentation IPT: Wing Mounted MDAUs



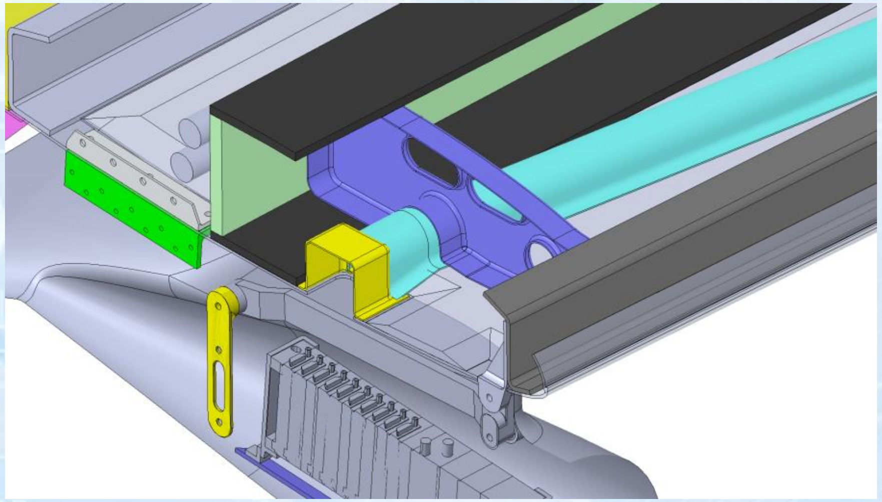
DEP Nacelle MDAU



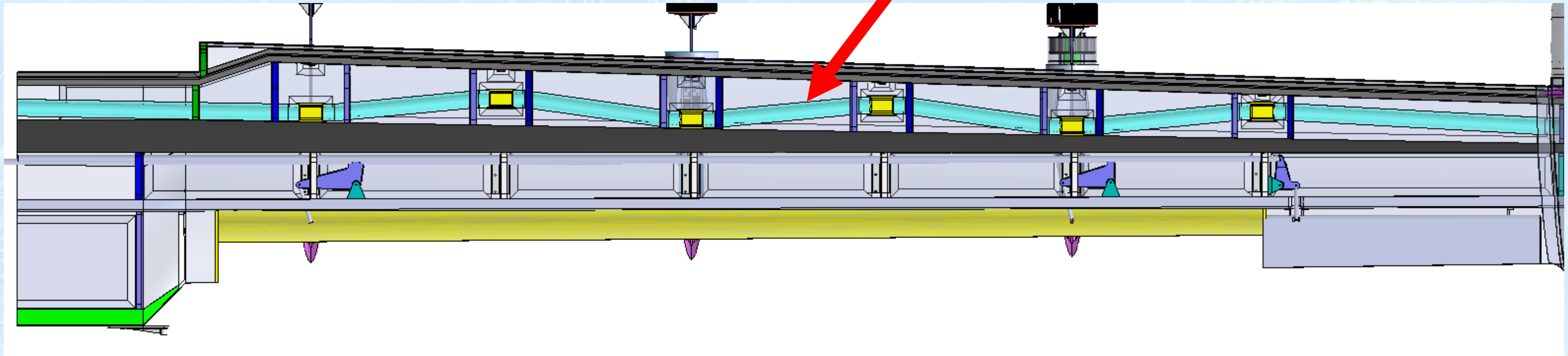
Cruise Nacelle MDAU

Instrumentation IPT: Harness Routing

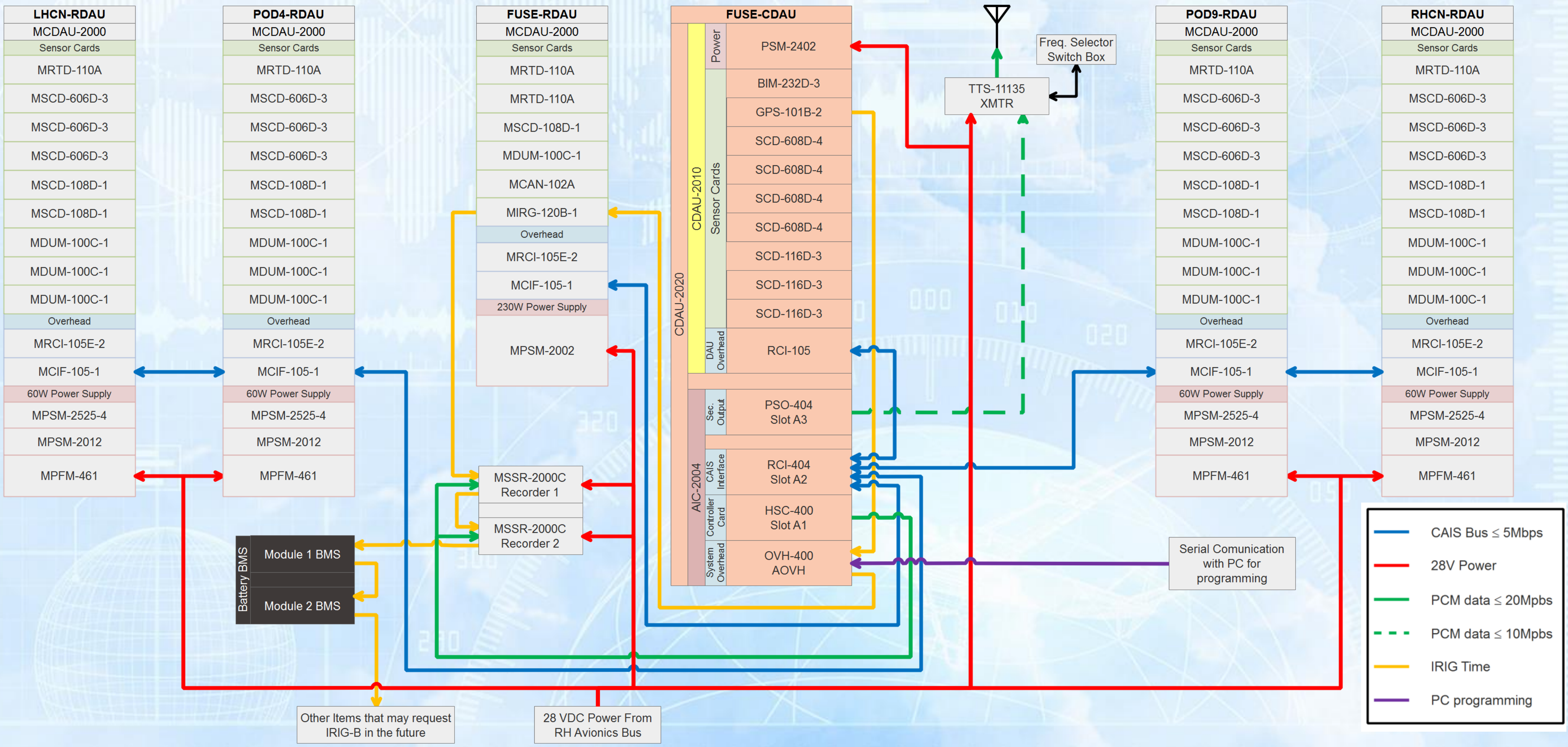
- Instrumentation Duct installed in MOD 3/4 wing
- No need for securing at intervals inside ducting
- Will secure harness in pods if needed
- Protection from elements
- Easily accessible
- Additional wires can be run easily



Instrumentation duct zig-zagged for Traction Bus drop downs



Instrumentation IPT: System Layout MOD 3/4



Upcoming Milestones

Critical Design Review	November 2016
Motor acceptance testing on AirVolt	March-April 2017
Final checkout of piloted simulation	April-May 2017
Motor qualification testing on AirVolt	May-July 2017
Mod II aircraft received at AFRC	Summer 2017
Mod III Wing fabrication complete	October 2017
Ship Mod III wing to AFRC	December 2017
Perform Mod II Taxi Test	Beginning of 2018
Mod II first flight	Spring 2018
Mod II flight tests complete	Summer 2018
Mod III aircraft complete	Fall 2018
Mod III first flight	Spring 2019
Mod III flight tests complete	Fall 2019

SCEPTOR

ELECTRIC FLIGHT

X-57

MAXWELL

It appears to me, therefore, that the study of electromagnetism in all its extent has now become of the first importance as a means of promoting the progress of science.

James Clerk Maxwell (1873)