National Aeronautics and
Space Administration

Flight Performance Maneuver Planning for NASA's X-57 "Maxwell" Flight Demonstrator – Part 2: Power-On Effects

Nick Borer

NASA Langley Research Center

James Reynolds, Ryan Wallace

NASA Armstrong Flight Research Center

31 July 2024

Meet "Maxwell"

- X-57 was a flight demonstrator concept for *Distributed Electric Propulsion Technology (DEP)*
- **Project Goals**: generate data and procedures and share these with academia, industry, standards organizations, and regulators to enable design and certification of DEP concepts
- **Project Approach**: spiral development through multiple design "Mods"

Mod I: Baseline performance of gasoline-powered aircraft

Mod II: High-voltage powertrain integration, impact of electric retrofit

Together: *Comprehensive impact* of electric propulsion technologies on aircraft design, performance, efficiency, acoustic signature, and operations

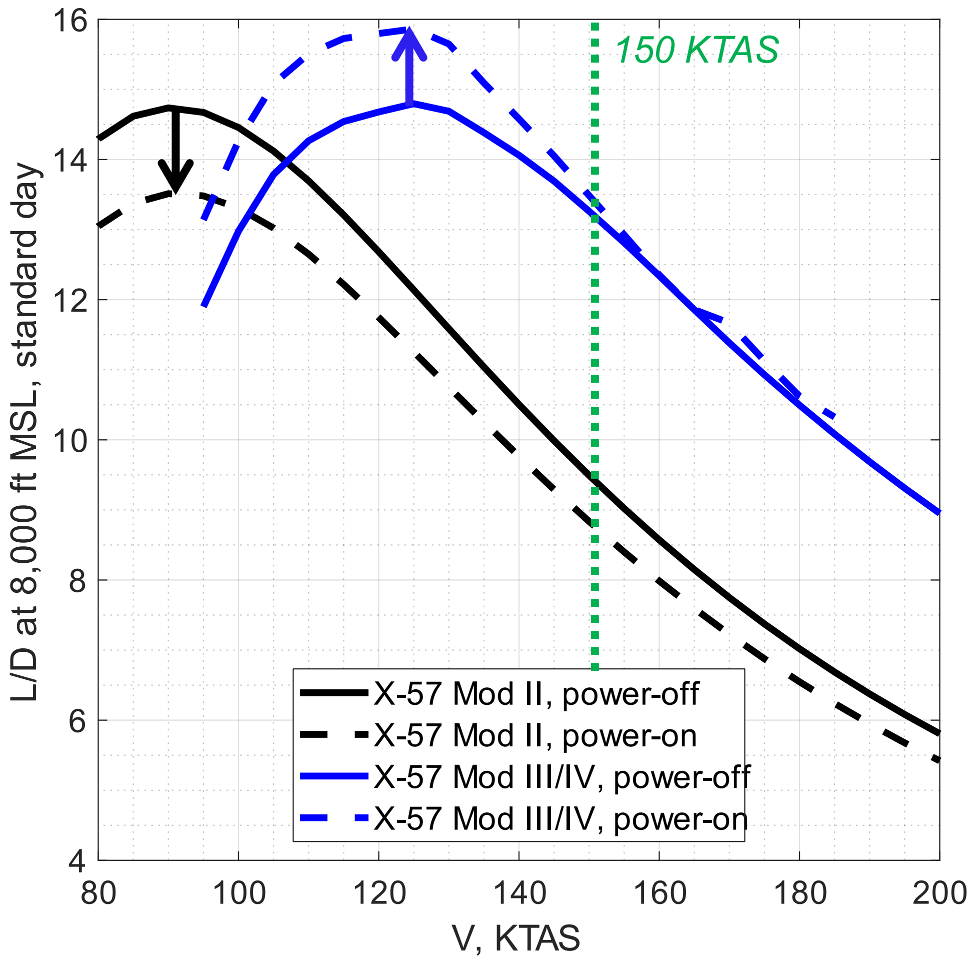
Mod IV: High-lift propeller takeoff, landing, handling qualities

Mod III: Impact of cruise-sized wing, wingtip propellers

Layered Aero-Propulsive Benefits

- High-speed aero-propulsive benefit of X-57's DEP implementation captured in Mod III/IV configuration
  - High-lift propellers (Mod IV) enables highly loaded wing (Mod III/IV)
    - Increased **power-off** performance at the cruise condition
  - Wingtip-mounted cruise propellers (Mod III & IV) for beneficial interaction of wingtip vortex and propeller swirl
    - Increased **power-on** performance throughout the flight envelope

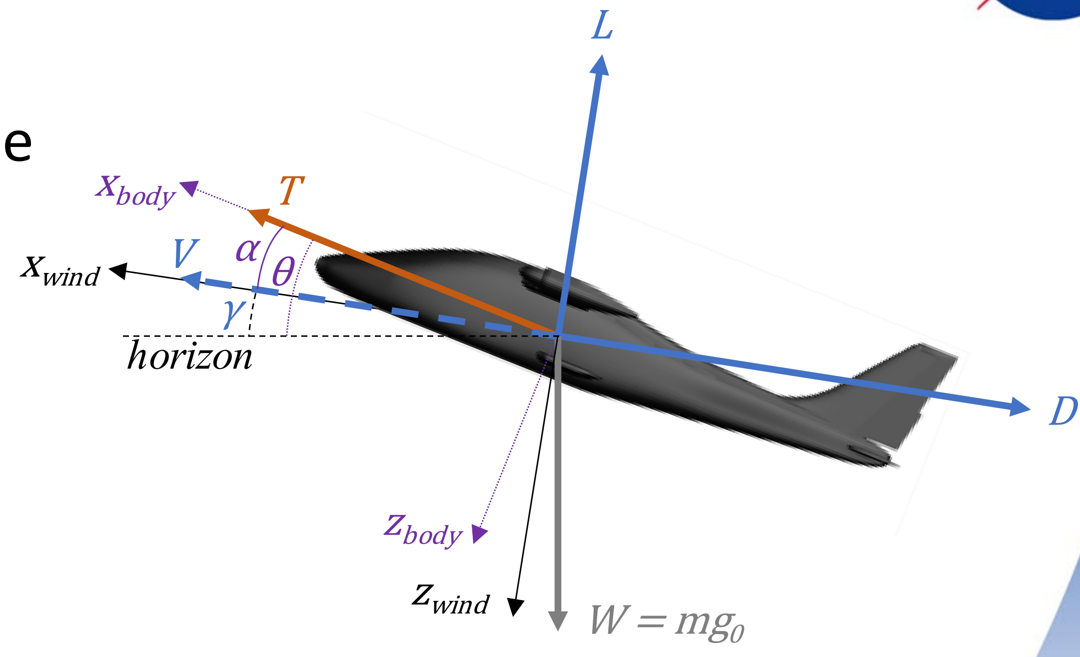
Aircraft & Power Setting	Lift-to-Drag Ratio (max | 150 KTAS)[1]	Comparison to Mod II (max | 150 KTAS)[1]
Mod II power-off	14.7 | 9.5	-- | --
Mod II power-on	13.5 | 8.8	-- | --
Mod III/IV power-off	14.8 | 13.3	1.01 | 1.40
Mod III/IV power-on	15.9 | 13.5	1.18 | 1.53



[1] Derived from N. Borer et al., "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," AIAA-2016-3920, June 2016.

In-Flight Determination of Aero Forces

- X-57 planned to estimate aero forces in flight to determine power-off and power-on performance in key areas of the flight envelope
  - Max L/D, intermediate cruise, high-speed cruise
- Aero forces estimated for steady-state glides, climbs, and cruise (level flight)
- Planned for power-off glides with propellers feathered to estimate power-off drag[2]
  - Selected six glide points for estimation of power-off drag with a mean error of 2.3% and a standard deviation of 1.5% after propagating expected errors in instrumentation and technique
- Climb and cruise points use similar measurement techniques and instrumentation
  - Downside: no generalized model (akin to a drag polar) for difference in installation losses
  - This paper propagates errors in measurements and techniques to individual climb and cruise test points



[2] N. Borer, D. Cox, R. Wallace, "Flight Performance Maneuver Planning for NASA's X-57 "Maxwell" Flight Demonstrator – Part 1: Power-Off Glides," AIAA-2019-2855, June 2019.

Error Sources from Flight Maneuvers

- Timed, steady-state maneuvers provide estimates of *installed thrust*
  - $T = \left[\left(\dot{h}W/V\right) + D\right]/\cos\alpha$
  - In smooth air, estimate $\dot{h} = \Delta h/\Delta t$
- Drag model from power-off maneuvers
  - $D = C_D qS = (K_0 + K_1 C_L + K_2 C_L^2)qS$
  - $C_L = L/qS;\ L = W\cos\gamma - T\sin\alpha$
  - Dynamic pressure: $q = 0.5\rho V^2$
  - Atmospheric density ρ estimated from altitude h
- Manufacturer data relates propeller power, speed, and advance ratio to *gross thrust*
  - Shaft power computed from product of shaft torque estimate (Q) and shaft speed (n)
  - Advance ratio: $J = V/nD_{prop}$

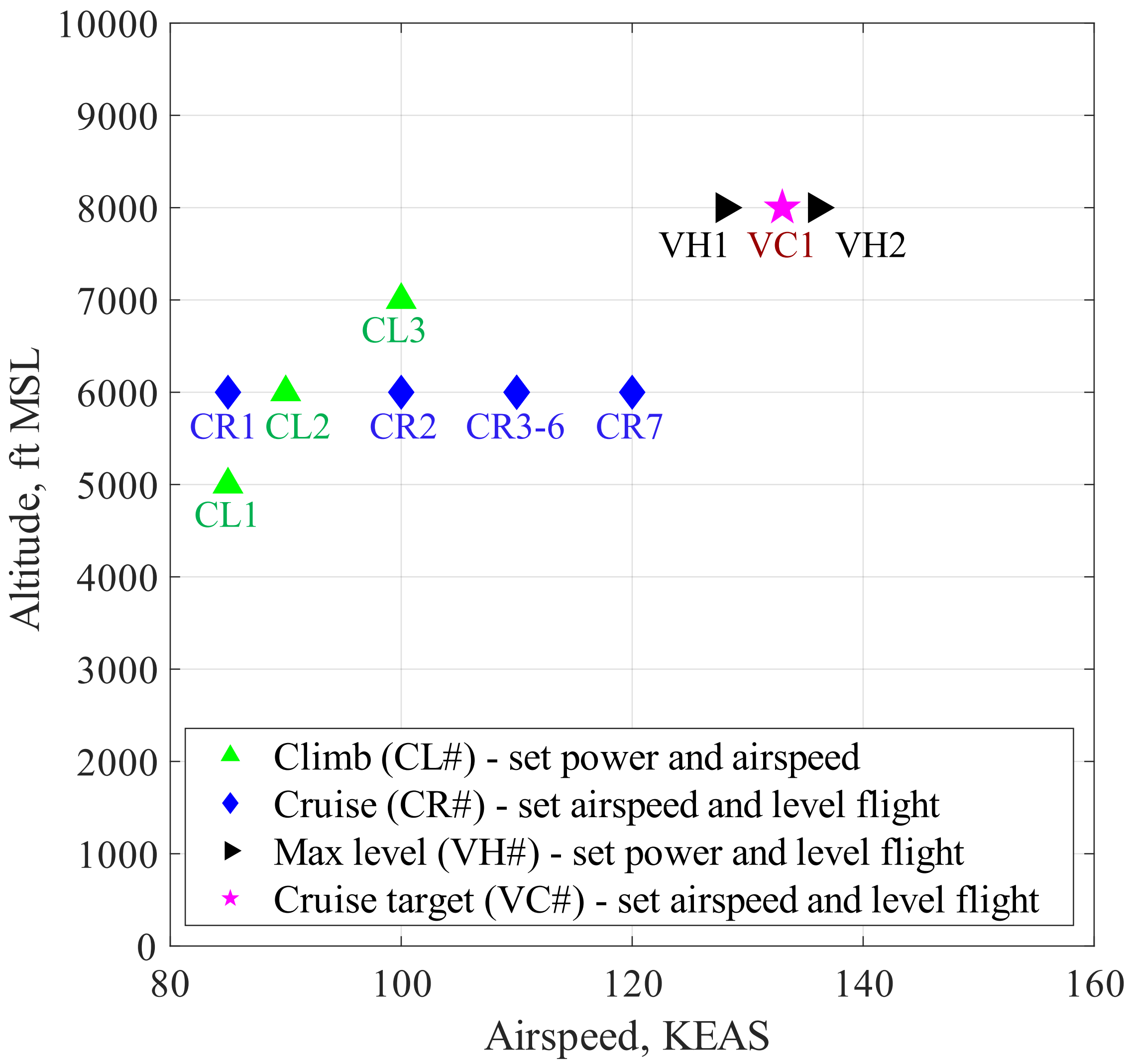
- Errors translated from measurement specifications (other than drag model)

Param.	Mean Error	Std. Dev.	Notes
α	0.0°	0.1276°	±0.25° @ 95%
V	0.0 KEAS	0.4524 KEAS	±1.0* KTAS @ 95%
W	0.0 lbf	25.0 lbf	±25 lbf @ 68%
h	0.0 ft	30.61 ft	±60 ft @ 95%
D	2.3%	1.5%	power-off maneuvers
Q	0.0 Nm	1.020 Nm	±2.0 Nm @ 95%
n	negligible	negligible	<< 1 RPM
γ	$= \alpha$	$= \alpha$	ignores error in θ
t	negligible	negligible	<< 0.1 s

*specified at 150 KTAS at 8,000 ft MSL on a standard day

Error Propagation Approach

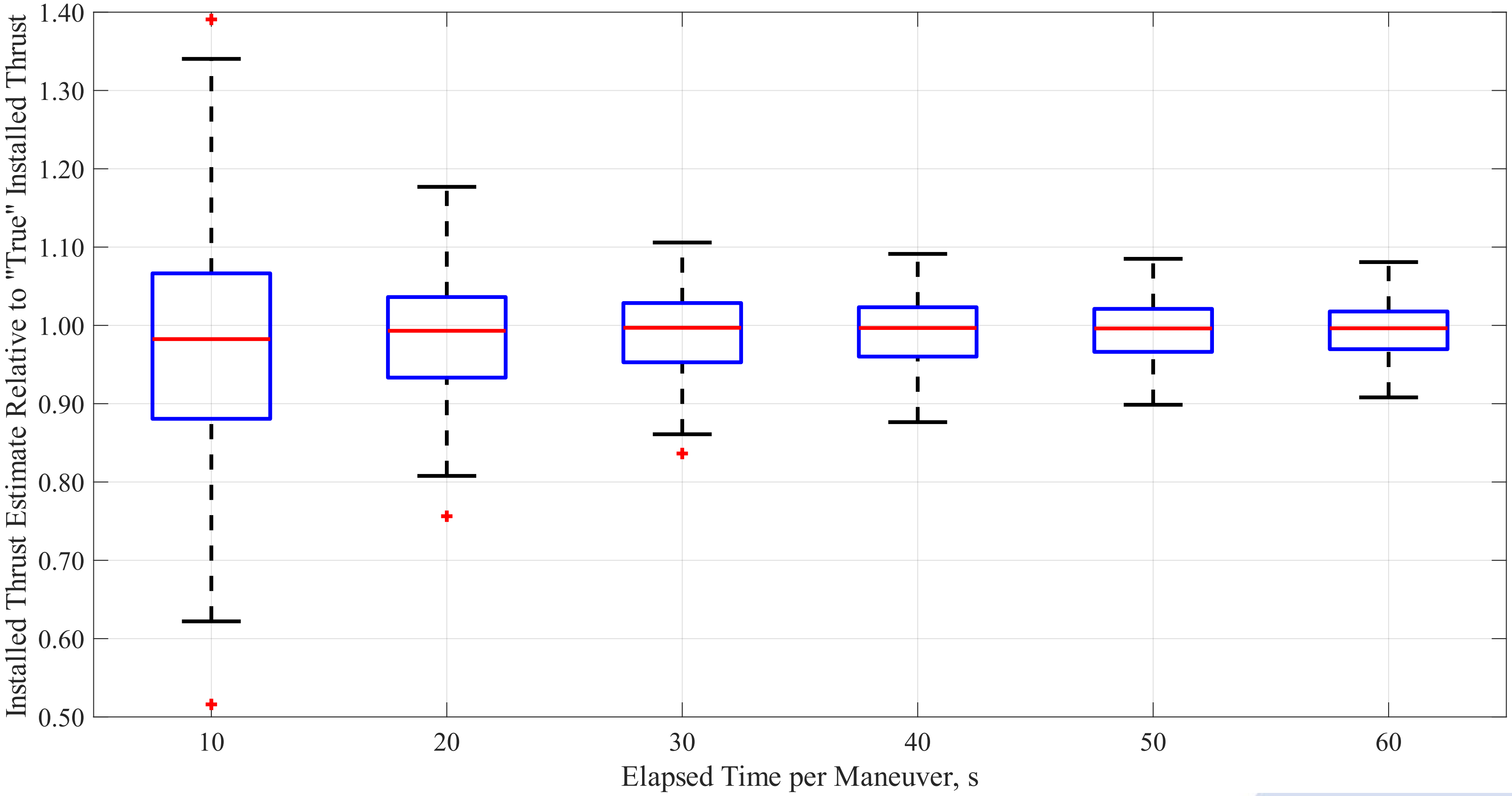
- The X-57 Mod II flight test plan included 13 test points for power-on effects
- X-57 Mod II flight simulator plant model used to generate "truth" data for each of these flight conditions[3]
- 50 independent errors sampled from pseudorandom normal distribution for each error parameter and test point
- Δt varied from 10-60 s in 10 s intervals for each maneuver suite



[3] R. Wallace et al., "Development of the Mod II X-57 Piloted Simulator and Flying Qualities Predictions," AIAA-2023-4034, June 2023.

Error Propagation: Installed Thrust (Aggregate)

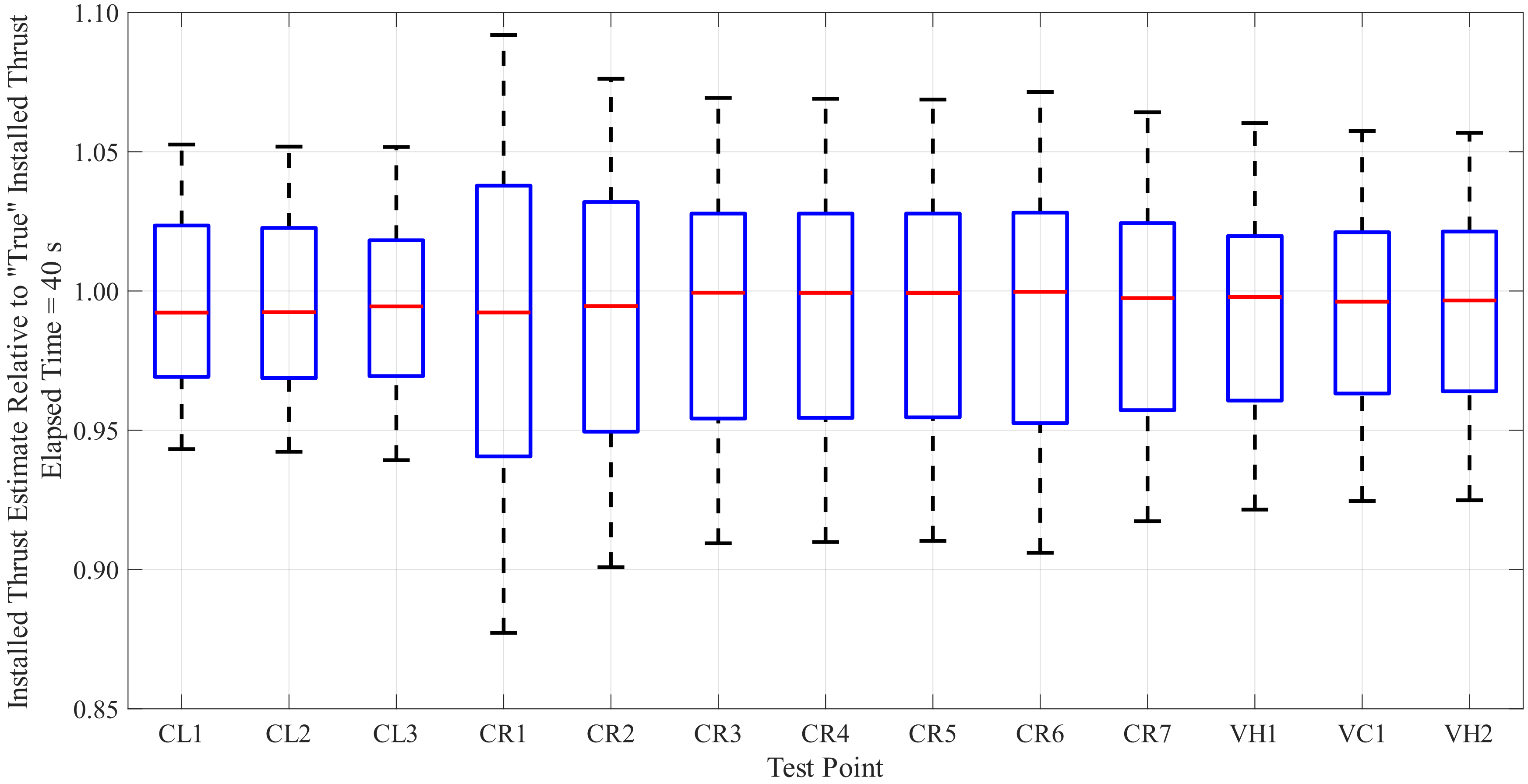
- Aggregated error across all 13 test points shows decreasing error with increasing Δt for installed thrust
  - Diminishing returns beyond Δt of 40 s
  - +2.1%/-3.4% at 50th percentile for 40 s Δt



Maneuver start to completion time of 30-40s required to keep installed thrust error within 5%

Error Propagation: Installed Thrust (Test Points)

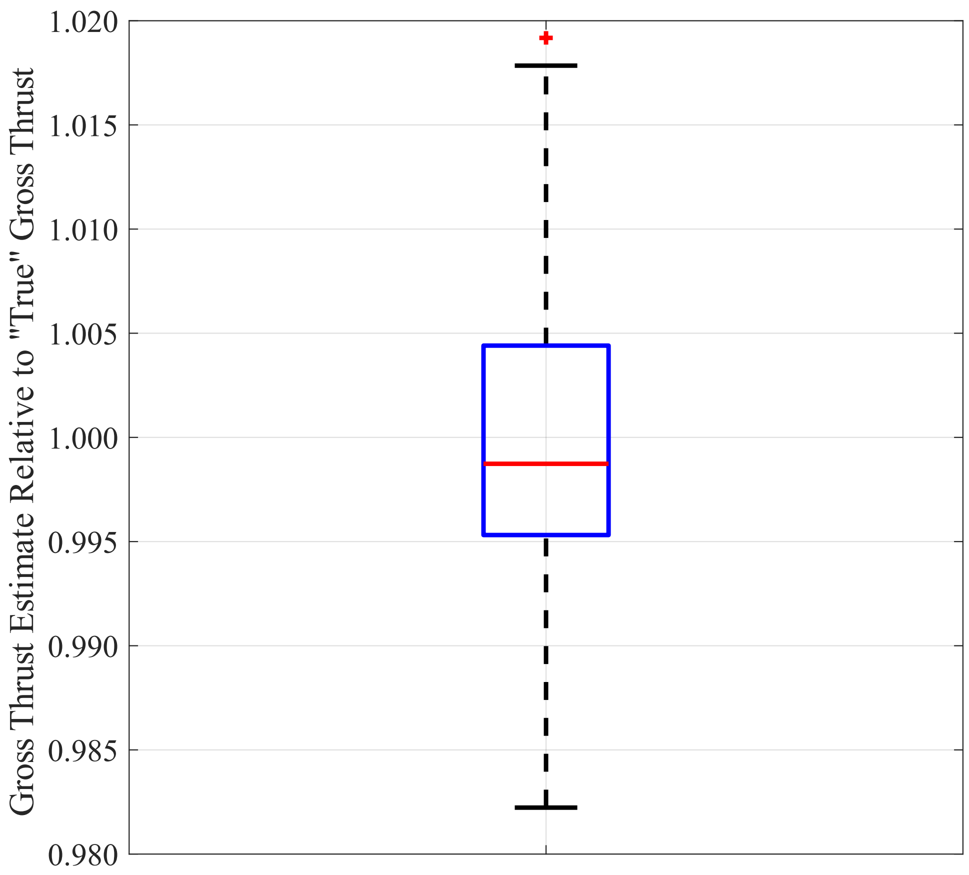
- Error propagation includes different spreads based on test points, shown here for Δt of 40 s
  - Lower airspeed + lower power setting increases error spread
  - May need to add repeat or increase Δt of low speed + lower power maneuvers



Some maneuvers may need to be repeated or time increased to reduce installed thrust error

Error Propagation: Gross Thrust (Aggregate)

- Aggregated error across all 13 test points shows low error
  - No dependence on Δt
  - +0.44%/-0.47% at 50th percentile
- Assumes no error in efficiency data provided by propeller manufacturer
  - Likely quite optimistic

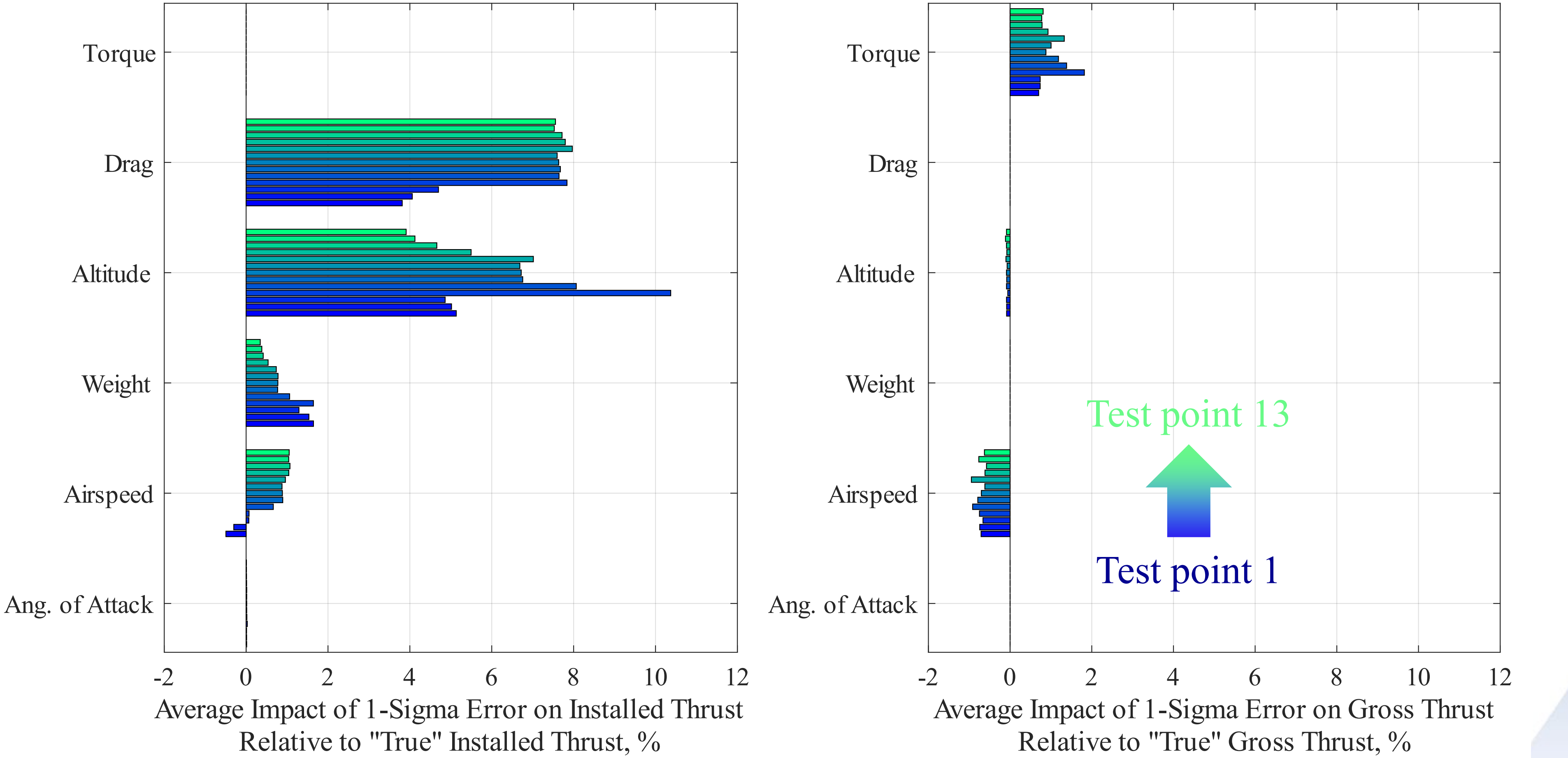


Little induced error in gross thrust but likely dominated by error in efficiency data

nicholas.k.borer@nasa.gov

Main Effects of Individual Error Sources

- Completed main effects analysis of six error parameters with full-factorial, 2-factor ($\pm 1\sigma$) design of experiments for each of the 13 test points for installed thrust and gross thrust



Installation effect dominated by errors in drag and change in altitude during maneuver

Summary

- Developed a technique to resolve the installed and gross thrust of the X-57 from flight maneuvers to identify differences in aero-propulsive effects
- Evaluated propagation of error in measurement equipment and flight test technique for all maneuvers
  - Prior work (2019) indicated six power-off test points could yield a drag model with a mean error of 2.3% and a standard deviation of 1.5% when conducting maneuvers over a time period of 30 s
  - This work indicated that the 13 proposed power-on maneuvers should use a time period of 40 s and yield an error of +2.1%/-3.4% for installed thrust at the 50th percentile
  - Lower-power, lower-airspeed maneuvers exhibited higher errors and may benefit from increased maneuver times or repeats
  - Gross thrust showed little error (within $\pm$0.5%) but did not account for errors in propeller data
- Investigated main effects of individual error sources
  - Error in installed thrust estimate dominated by error in power-off drag and altitude
  - Error may be reduced with better drag model (more power-off points) and better accounting for altitude error (bias rather than random) to reduce bounds

Acknowledgements

- Many thanks to the NASA Aeronautics Research Mission Directorate for sponsoring this project and other precursors over the past decade
  - Integrated Aviation Systems Program/Flight Demonstrations and Capabilities Project
  - Transformational Aeronautics Concepts Program/Convergent Aeronautics Solutions Project

- This research would not be possible without the efforts of our prime contractor, Empirical Systems Aerospace, Inc., or their many subcontractors that are already taking the lessons from X-57 and bringing them into practice