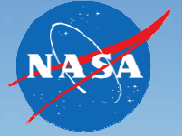


National Aeronautics and Space Administration

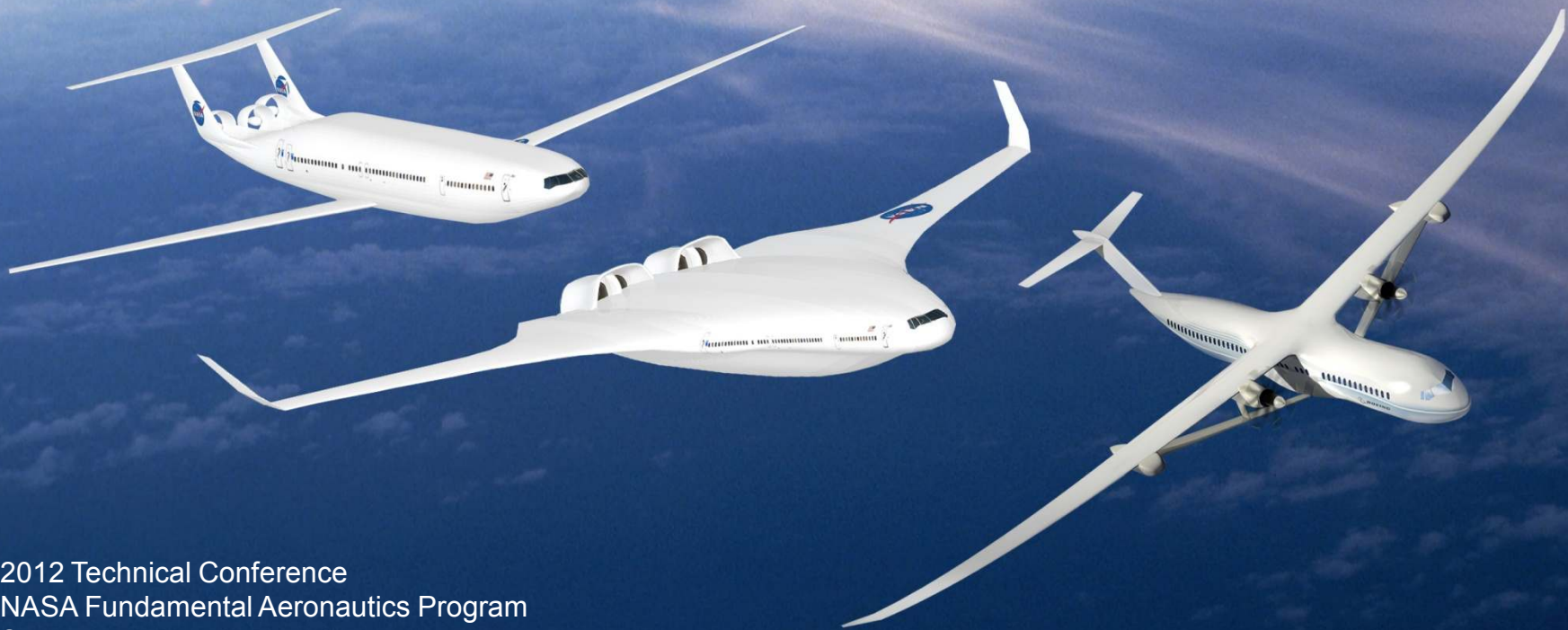


# Open Rotor Propulsion Assessment for Advanced Single-Aisle Aircraft

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NASA Langley Research Center**



2012 Technical Conference  
NASA Fundamental Aeronautics Program  
Subsonic Fixed Wing Project  
Cleveland, OH, March 13-15, 2012

[www.nasa.gov](http://www.nasa.gov)

# Contributors

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- Jeff Berton (NASA Glenn)
- Eric Hendricks (NASA Glenn)
- Mike Tong (NASA Glenn)
- Bill Haller (NASA Glenn)

# Background

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- NASA's systems analysis team has been investigating potential environmental benefits of advanced propulsion systems on “advanced” single-aisle aircraft
  - Direct Drive Turbofan
  - Geared Turbofan
  - Open Rotor
- Open Rotor assessment is a joint effort between SFW & Environmentally Responsible Aviation (ERA) projects
  - FY11 SFW milestone to assess fuel burn/noise characteristics of an open rotor propulsion system
  - ERA acquired modern open rotor blade performance/acoustic data
- ERA funded task with General Electric was conduit to NASA/industry partnership
  - Enabled NASA access to data for use in system assessment
  - Coordination with industry on modeling approaches & assumptions

# NASA Subsonic Transport System Level Metrics

.... technology for dramatically improving noise, emissions, & performance



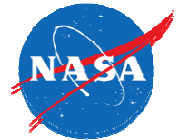
| TECHNOLOGY<br>BENEFITS*                                           | TECHNOLOGY GENERATIONS<br>(Technology Readiness Level = 4-6) |              |            |
|-------------------------------------------------------------------|--------------------------------------------------------------|--------------|------------|
|                                                                   | N+1 (2015)                                                   | N+2 (2020**) | N+3 (2025) |
| Noise<br>(cum margin rel. to Stage 4)                             | -32 dB                                                       | -42 dB       | -71 dB     |
| LTO NOx Emissions<br>(rel. to CAEP 6)                             | -60%                                                         | -75%         | -80%       |
| Cruise NOx Emissions<br>(rel. to 2005 best in class)              | -55%                                                         | -70%         | -80%       |
| Aircraft Fuel/Energy Consumption†<br>(rel. to 2005 best in class) | -33%                                                         | -50%         | -60%       |

\* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

\*\* ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

† CO<sub>2</sub> emission benefits dependent on life-cycle CO<sub>2e</sub> per MJ for fuel and/or energy source used

# SFW Strategic Thrusts & Technical Challenges



## Energy Efficiency Thrust (with emphasis on N+3)

Develop economically practical approaches to improve aircraft efficiency

## Environmental Compatibility Thrust (with emphasis on N+3)

Develop economically practical approaches to minimize environmental impact

## Cross-Cutting Challenge (pervasive across generations)

**TC1 - Reduce aircraft drag** with minimal impact on weight (aerodynamic efficiency)

Drag

**TC2 - Reduce aircraft operating empty weight** with minimal impact on drag (structural efficiency)

Weight

**TC3 - Reduce thrust-specific energy consumption** while minimizing cross-disciplinary impacts (propulsion efficiency)

TSEC

**TC4 - Reduce harmful emissions** attributable to aircraft energy consumption

Clean

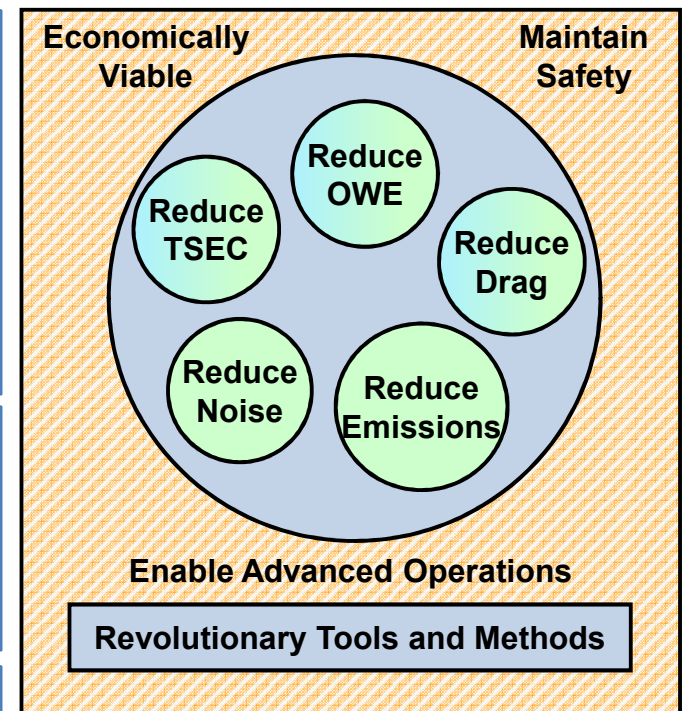
**TC5 - Reduce perceived community noise** attributable to aircraft with minimal impact on weight and performance

Noise

**TC6 - Revolutionary tools and methods** enabling practical design, analysis, optimization, & validation of technology solutions for vehicle system energy efficiency & environmental compatibility

Tools

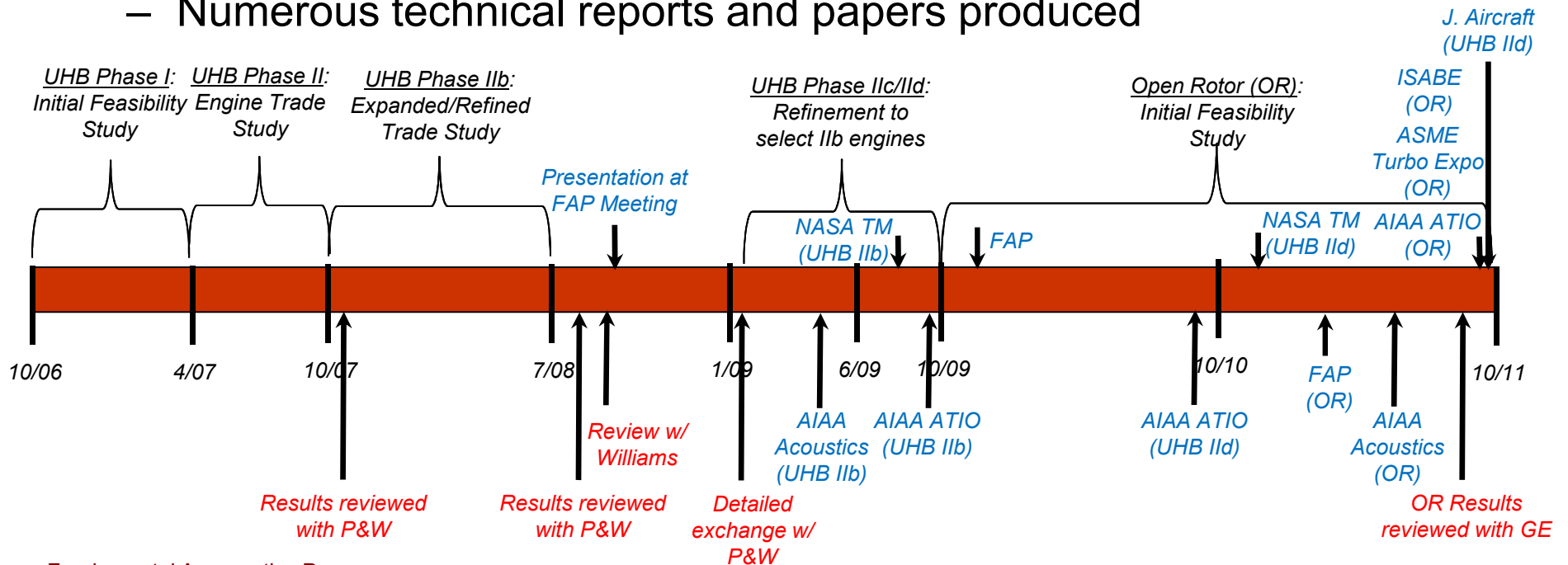
## Energy & Environment



# Historical Look At SFW Propulsion Studies



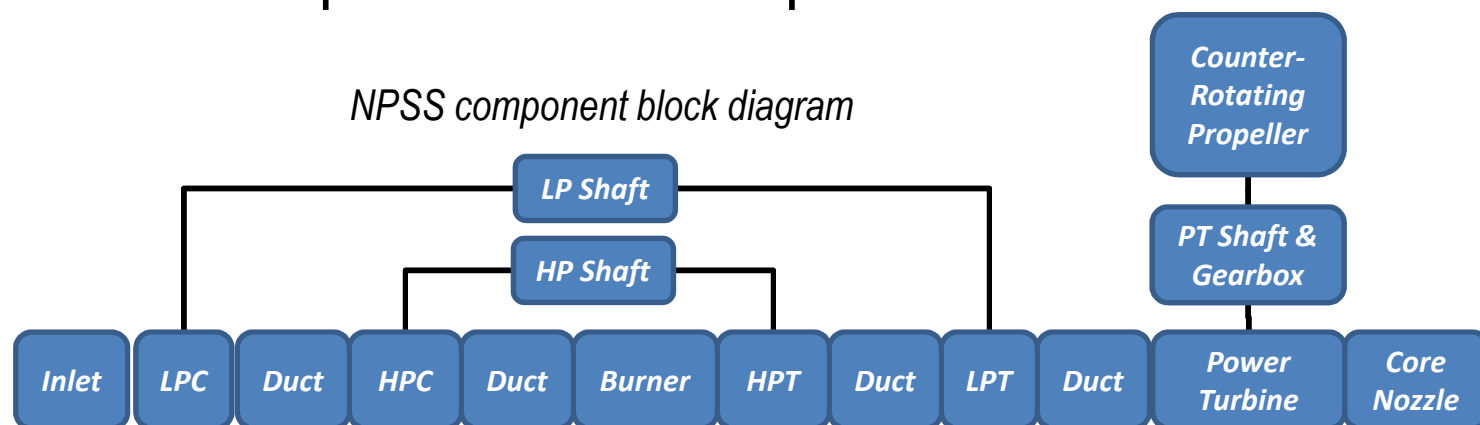
- NASA has been conducting an on-going engine trade study to assess propulsion options for advanced single-aisle (B737/A320 class) aircraft
  - Multi-year, Multi-phase effort
  - Initial focus on ultra-high bypass ratio (UHB) turbofan concepts, followed by investigation of open-rotor engine architectures
  - Multiple interactions with industry to obtain feedback
  - Numerous technical reports and papers produced



# Open Rotor Engine Modeling and Analysis



- A complete Numerical Propulsion System Simulation (NPSS) model was created for a geared, pusher open rotor engine
- A new counter-rotating propeller performance element was developed for NPSS
- Core component performance assumptions were similar to those used in earlier SFW N+1 turbofan study
- Counter-rotating propeller data for a modern rotor set was used to create performance maps



# Open Rotor Performance (NASA Notional Engine)



## Turbomachinery Parameters (Aero Design Point)

| Component     | Parameter                | Value |
|---------------|--------------------------|-------|
| LPC           | Pressure Ratio           | 4.2   |
|               | Adiabatic Efficiency (%) | 89.6  |
| HPC           | Pressure Ratio           | 10.0  |
|               | Adiabatic Efficiency (%) | 88.6  |
| HPT           | Adiabatic Efficiency (%) | 91.9  |
| LPT           | Adiabatic Efficiency (%) | 94.2  |
| Power Turbine | Adiabatic Efficiency (%) | 94.0  |

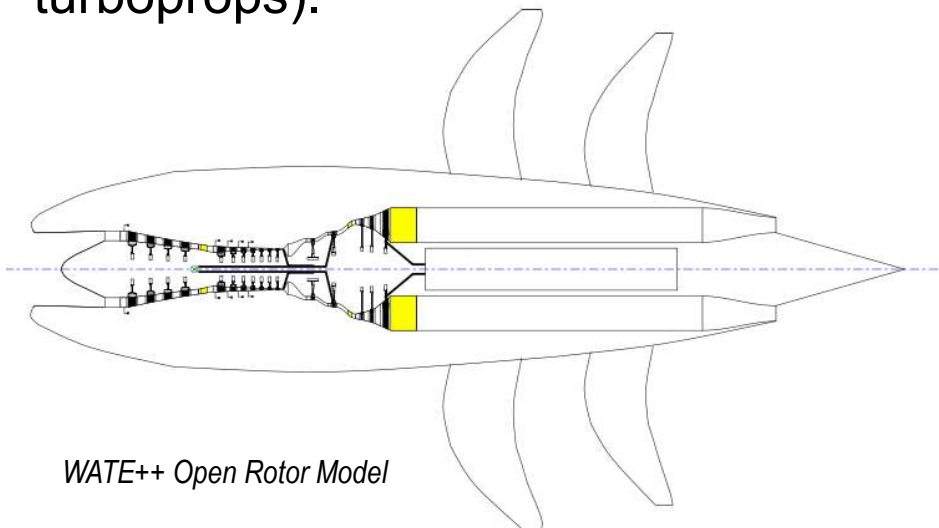
## Performance @ Key Conditions

| Flight Condition                       | Engine Performance Parameter | Value  |
|----------------------------------------|------------------------------|--------|
| Top of Climb<br>(M0.78, 35kft)         | Net Thrust (lbf)             | 5000   |
|                                        | TSFC (lbm/hr/lbf)            | 0.428  |
|                                        | OPR                          | 42.0   |
| Rolling Takeoff<br>(M0.25, 0 ft, +27F) | Net Thrust (lbf)             | 19,000 |
|                                        | TSFC (lbm/hr/lbf)            | 0.229  |
|                                        | OPR                          | 28.5   |
| Sea Level Static<br>(M0.0, 0 ft, +27F) | Net Thrust (lbf)             | 27,300 |
|                                        | TSFC (lbm/hr/lbf)            | 0.158  |
|                                        | OPR                          | 29.4   |



# Engine Flowpath and Weight

- Key cycle parameters passed to flowpath tool (WATE++) to calculate engine core weight
- Turbomachinery aeromechanical limits and materials consistent with those of previous SFW N+1 turbofan studies
- Propeller weight estimates derived from data developed during the Advanced Turboprop Project in the 1980's
- Gearbox (6:1 gear ratio) weight derived from NASA gearbox weight model (based on gearbox weight data from >50 rotorcraft, tiltrotors, and turboprops).

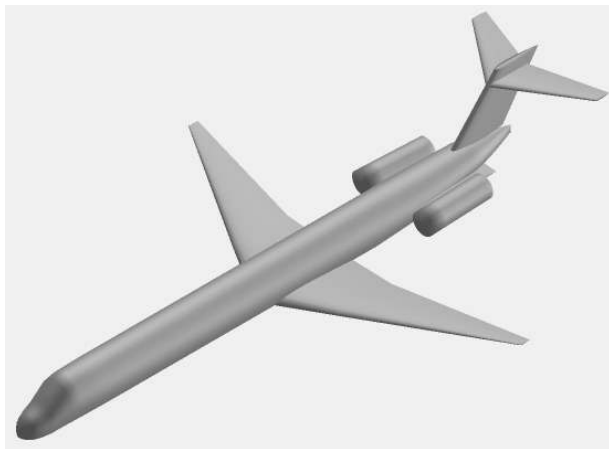


| Weights and Dimensions        | Value |
|-------------------------------|-------|
| Open Rotor Weight (lbm)       | 3240  |
| Gearbox Weight (lbm)          | 1030  |
| Total Engine Pod Weight (lbm) | 9220  |
| Propeller Diameter (ft)       | 13.8  |
| Nacelle Diameter (ft)         | 5.6   |
| Overall Length (ft)           | 23.2  |

# Airframe Modeling and Analysis



- Rear-mounted pusher configuration chosen for initial modeling due to popularity of this approach in 1980s and availability of relevant data
- Airframe model based on MD-90-30 with modifications for open rotor propulsion
- Technology advances applied to be consistent with next generation single aisle
- FLOPS (Flight Optimization System) used to build airframe analytical model and conduct performance and mission analysis



# Airframe Modeling and Analysis (2)



MD-90-30 Like Model

*Calibrated to publicly available weight and performance data*

Improve Wing Aerodynamics

*MD80 technology to 737NG-like performance*

Lengthen Fuselage for 162 Passengers

Resize for 3250 nm Mission

*Study Mission Requirements*

## Nomenclature

**CSAT: Current technology Single-Aisle Transport**

**ASAT: Advanced technology Single-Aisle Transport**  
*re – rear engine*  
*or – open rotor*

CSAT-re

Advanced Airframe Technology Assumptions

ASAT-re

MD92V Model

MD92 Model

*1980s concepts with V2500 & GE36*

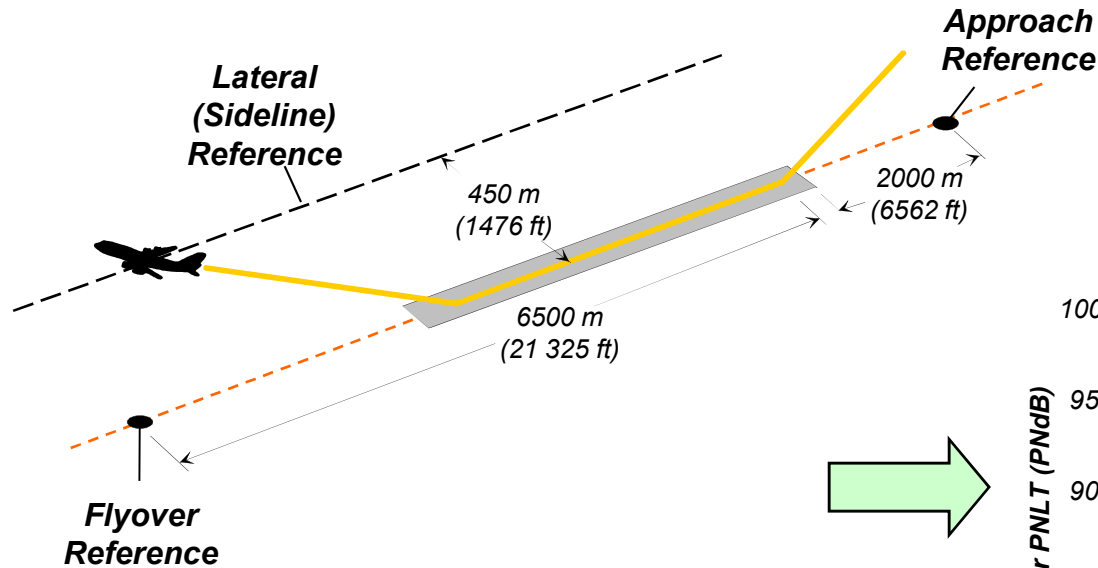
Open Rotor Airframe Impacts

ASAT-or

- *Composite structures*
- *Variable camber TE*
- *5000 psi hydraulics*



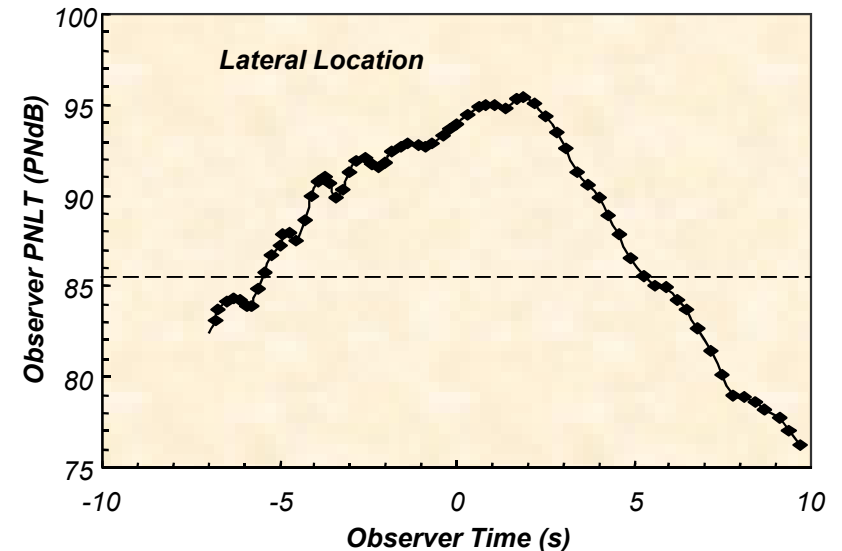
# Noise Modeling and Analysis



Part 36 Noise certification points:

- Lateral (sideline)
- Flyover (with cutback)
- Approach

- Aircraft Noise Prediction Program (ANOPP)
- Source noise modeling: User-supplied
- Trajectory simulation
- Spectra propagation (spreading, atmospheric and lateral attenuation, ground effects, reflections)
- Frequency and Noy-scale integration
- Tonal content penalties
- Ground observer noise-time history



*Time integration to Effective Perceived Noise Level*

# Acoustic Data Processing Steps



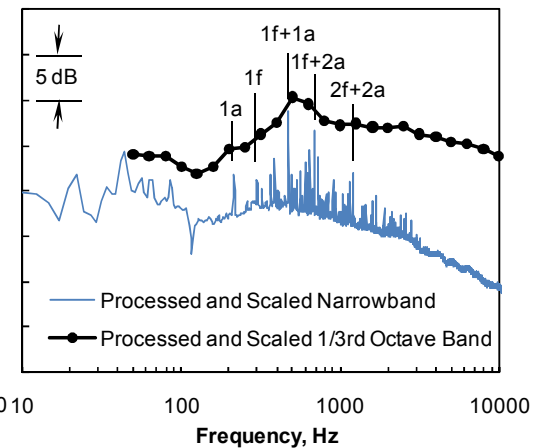
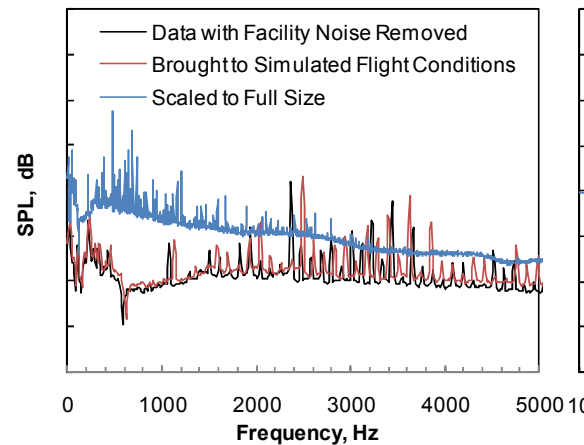
*Measured,  
narrowband  
spectral densities*

*Convert to flight  
conditions*

*Source strength  
corrections*

*Model scale to  
full scale*

$\Delta \text{Amplitude} = 10 \log[\text{Area Scale Factor}]$   
freq shift = Linear scale factor



*Convert narrowband  
to 1/3<sup>rd</sup> octave band*

*IEC 225-1966 band filter*

*Aircraft system  
noise prediction  
(ANOPP)*

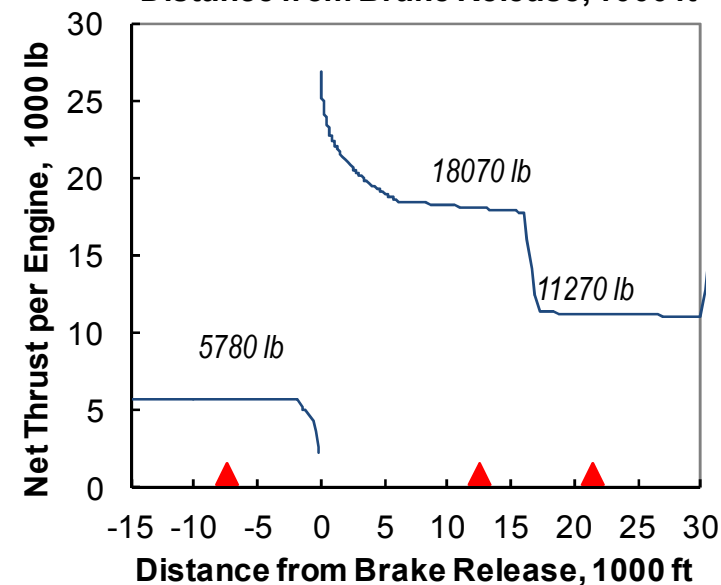
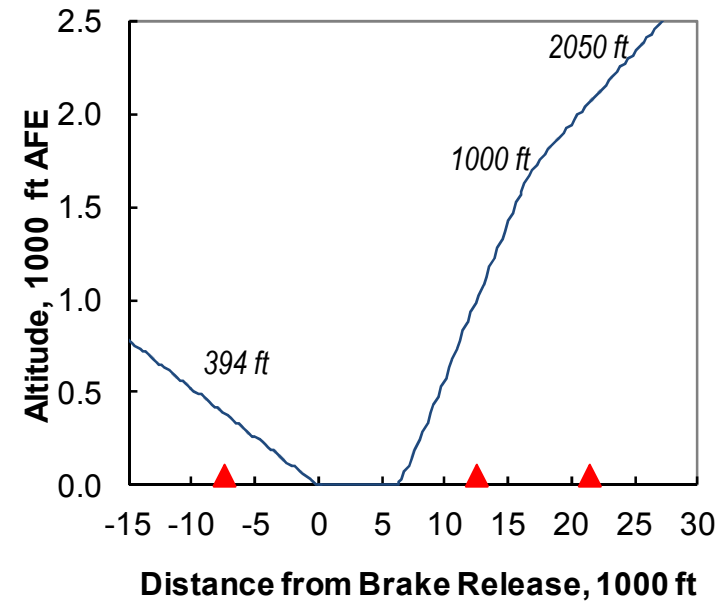
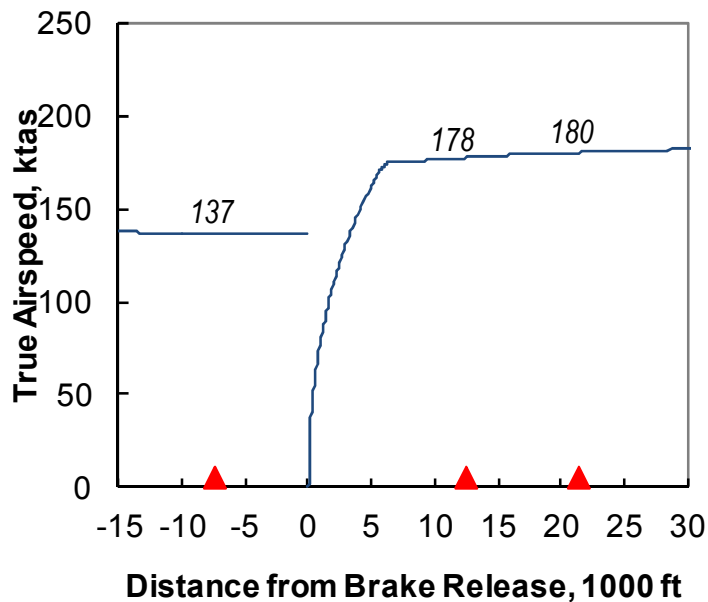
*Included effects:  
SAE 866 absorption  
Spherical spreading  
Ground reflections  
Other sources*

*Spectral basis for Part 36  
Noise Certification*

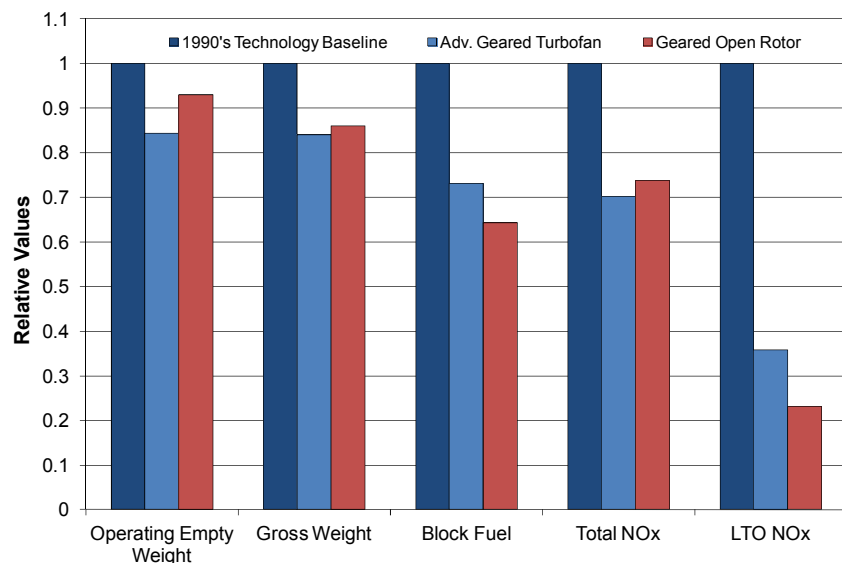
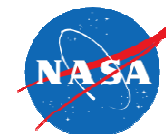
# Trajectory Modeling



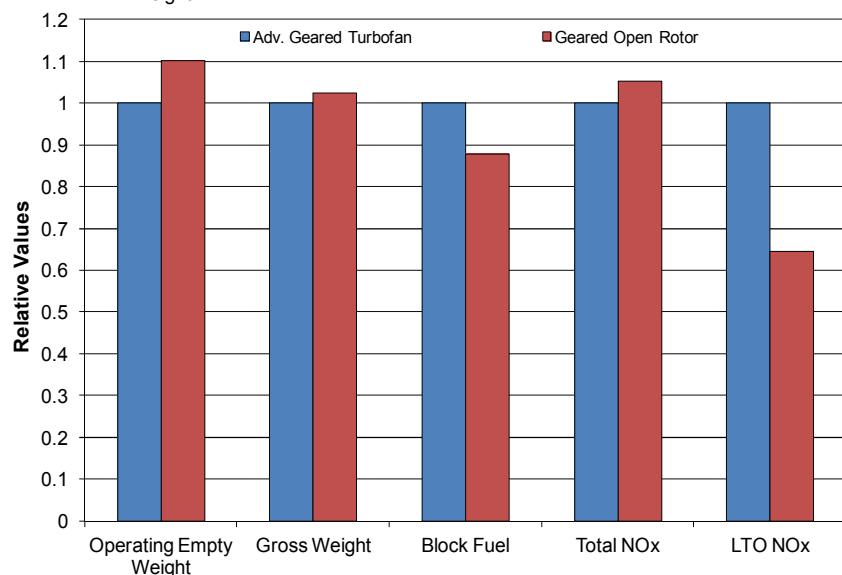
- Open rotor propulsion system and airplane performance modeled
- Detailed takeoff and landing trajectory analysis using FLOPS performance code



# Performance and Sizing Results

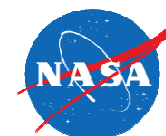


- ASAT relative to 1990s technology
  - Empty Weight: -16%(GTF); -7%(OR)
  - Gross Weight: -16%(GTF); -14%(OR)
  - Block Fuel: -27%(GTF); -36%(OR)
  - Total NO<sub>x</sub>: -30%(GTF); -26%(OR)
  - LTO NO<sub>x</sub>: -64%(GTF); -77%(OR)



- Open rotor relative to advanced turbofan
  - Empty Weight: +10%
  - Gross Weight: +2%
  - Block Fuel: -12%
  - Total NO<sub>x</sub>: +5%
  - LTO NO<sub>x</sub>: -36%

# ASAT-or Noise Estimate



|                            | Approach | Lateral | Flyover | Cumulative |
|----------------------------|----------|---------|---------|------------|
| Isolated                   | 88.8     | 88.2    | 80.1    | 257.1      |
| Inflow Angle Effects       | 0.5      | 1.5     | 1.5     | 3.5        |
| Flight Mach Effects        | 0.1      | 1.2     | 1.3     | 2.6        |
| Pylon Effects <sup>†</sup> | 2.0      | 1.0     | 2.0     | 5.0        |
| Mitigation <sup>‡</sup>    | -1.4     | -0.7    | -1.4    | -3.5       |
| Overall                    | 90.0     | 91.2    | 83.5    | 264.7      |
|                            |          |         |         |            |
| Stage 3 Rule <sup>**</sup> | 100.3    | 96.5    | 91.0    | 287.8      |
| Stage 3 Margin             | -10.3    | -5.3    | -7.6    | -23.1      |
| Stage 4 Margin             |          |         |         | -13.1      |

<sup>†</sup>Estimated from data for older rotor design (F31/A31)

<sup>‡</sup>Assumed "70%" reduction of the pylon penalty

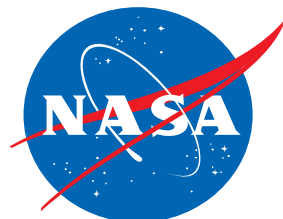
<sup>\*\*</sup>Rule based on NASA's 151.3 klb airplane

# Summary

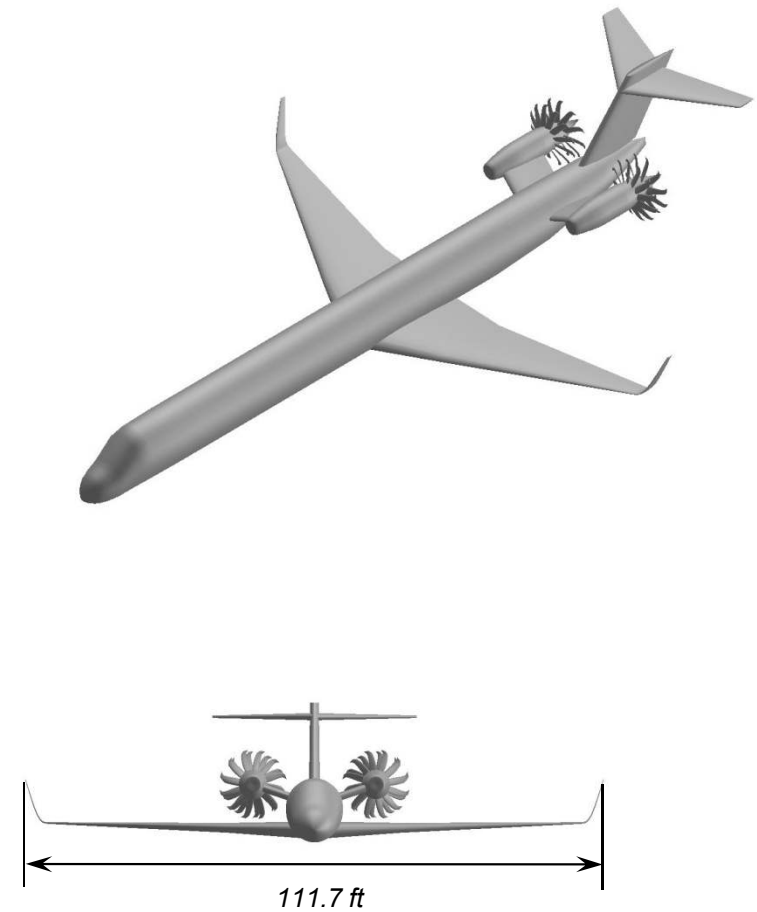
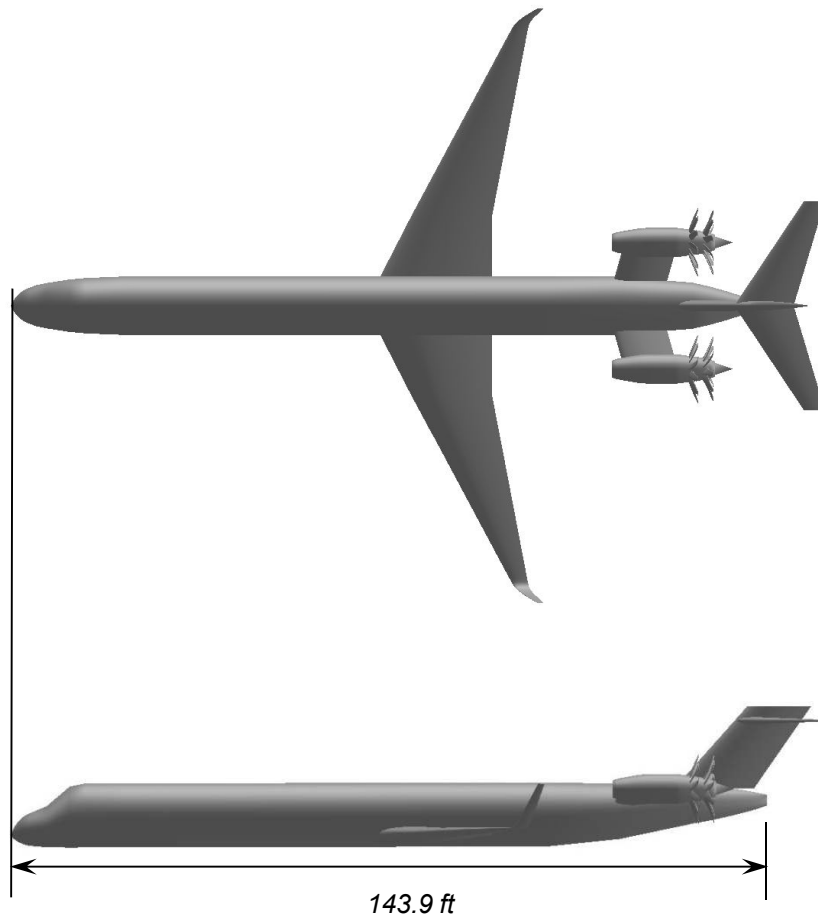
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- SFW has expanded its study of N+1 advanced propulsion options to include open rotor engines
- An initial capability to evaluate aircraft configurations with open rotor propulsion has been re-established at NASA
  - Current capability relies heavily on experimental data for existing rotor designs
- Increase in propulsive efficiency provided by open rotor designs more than offsets the engine and airframe weight penalties
  - 12% block fuel reduction relative to equivalent technology geared turbofan
- Significantly lower fuel flow at LTO conditions also leads to greatly reduced LTO NO<sub>x</sub> emissions
- Noise estimates indicate Stage 4 regulations can be met with a 13 EPNdB cumulative margin

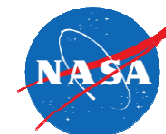


# NASA Open Rotor Airplane



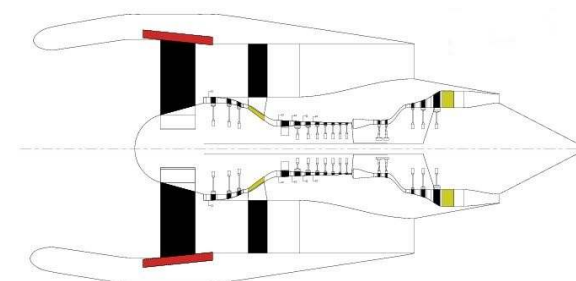
*See AIAA-2011-7058 for airplane design details*

# Results (System Performance)



- Engine models combined with airframe models

|                                   |                    |                     |                     |                           |           |
|-----------------------------------|--------------------|---------------------|---------------------|---------------------------|-----------|
|                                   | Airframe:          | MD90-30like         | CSAT-re             | ASAT-re                   | ASAT-or   |
|                                   | Engine:            | V2525-D5            | V2525-D5            | Adv. GTF                  | Geared OR |
| <i>Design Mission:</i>            |                    |                     |                     |                           |           |
| Design Mission Range              | nm                 | 2040                | 3250                | 3250                      | 3250      |
| OWE                               | lb                 | 88162               | 94450               | 79646                     | 87817     |
| Mission Fuel                      | lb                 | 36825               | 49164               | 35803                     | 31056     |
| Passengers                        |                    | 158                 | 162                 | 162                       | 162       |
| Payload                           | lb                 | 31000               | 32400               | 32400                     | 32400     |
| Ramp Weight                       | lb                 | 155987              | 176014              | 147849                    | 151273    |
| Wing Area                         | ft <sup>2</sup>    | 1278                | 1530                | 1240                      | 1250      |
| W/S                               | lb/ft <sup>2</sup> | 122                 | 115                 | 119                       | 121       |
| Thrust(SLS)                       | lb                 | 25033               | 25195               | 23075                     | 26914     |
| Engine scale factor               |                    | 1.00                | 1.01                | 0.99                      | 0.99      |
| T/W                               |                    | 0.321               | 0.286               | 0.312                     | 0.356     |
| Cruise Mach                       |                    | 0.760               | 0.780               | 0.780                     | 0.780     |
| ~Cruise L/D                       |                    | 14.0                | 17.0                | 16.2                      | 16.6      |
| ~Cruise SFC                       | lb/(lb-h)          | 0.601               | 0.603               | 0.494                     | 0.432     |
| Land field length                 | ft                 | 5527                | 5802                | 5944                      | 6006      |
| T.O. field length                 | ft                 | 7000                | 7000                | 6996                      | 6262      |
| Block Fuel                        | lb                 | 29410               | 41550               | 30396                     | 26710     |
| Block NOX                         | lb                 | 217.18              | 292.38              | 205.16                    | 215.73    |
| LTO NOX                           | lb/cycle           | 27.59               | 27.77               | 9.96                      | 6.41      |
| Active Sizing Constraint          |                    | Takeoff Performance | Takeoff Performance | Takeoff Performance, ICAC | ICAC      |
| <i>Economic Mission: 1000 nm,</i> |                    |                     |                     |                           |           |
| Ramp Weight                       | lb                 | 140543              | 146252              | 126064                    | 131868    |
| Block Fuel                        | lb                 | 14711               | 13205               | 9648                      | 8229      |
| Block NOX                         | lb                 | 120.17              | 114.86              | 90.52                     | 75.95     |



*Advanced Geared Turbofan (GTF)*  
(fan pressure ratio = 1.5)

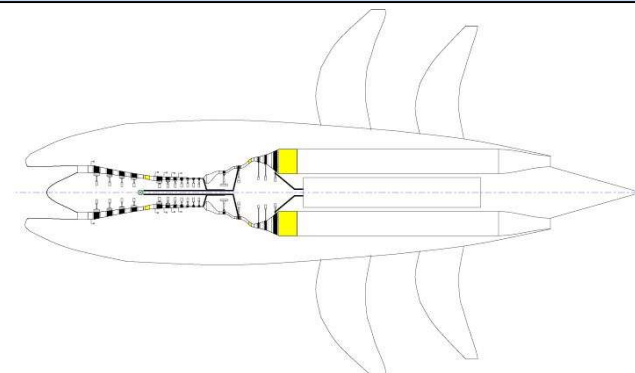
## Nomenclature

CSAT: **C**urrent technology **S**ingle-Aisle Transport

ASAT: **A**dvanced technology **S**ingle-Aisle Transport

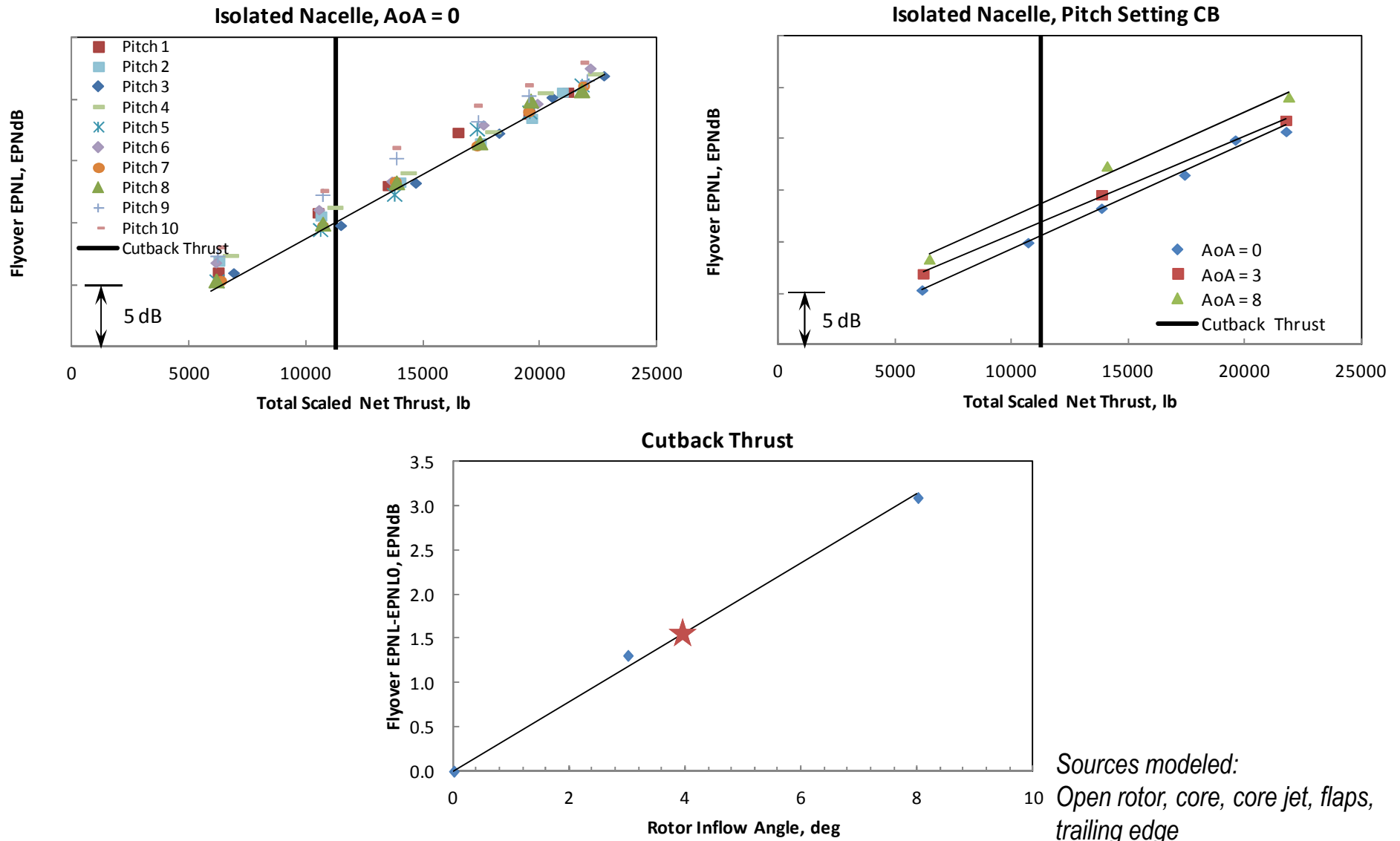
re – rear engine

or – open rotor



*Advanced Geared Open Rotor (OR)*

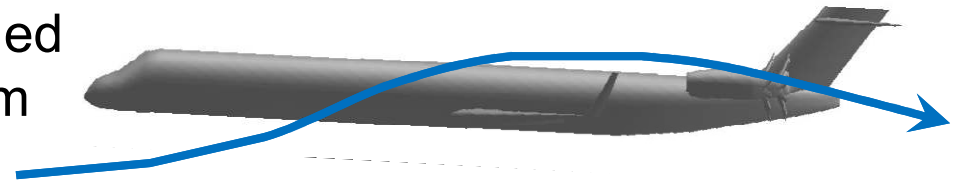
# Impact of AoA and Pitch on Flyover EPNL





# Rotor Inflow Angle

- Rotor inflow angle ( $\alpha_{\text{Inflow}}$ ) is needed to infer the correct rotor noise from wind tunnel data
- Vortex-lattice code analysis used to determine relationship of open rotor inflow angle to airplane angle of attack ( $\alpha$ )
- Nose-up engine mounting angle ( $\alpha_{\text{Cant}} = 2$  deg, re clean airplane waterline) gives  $\alpha_{\text{Inflow}} = 0$  at cruise
- Downwash angle into rotor at  $\alpha = 0$  ( $\varepsilon_0$ ) and  $d\varepsilon/d\alpha$  are functions of airplane configuration (i.e.,  $C_L$  with flaps/slats degree of extension)
- $\alpha_{\text{Inflow}} = \alpha_{\text{Cant}} - \varepsilon_0 + \alpha [1 - d\varepsilon/d\alpha]$



## Departure:

- $d\varepsilon/d\alpha = 0.336$
- $\varepsilon_0 = 2.342$  deg
- $\alpha \approx 7$  deg
- $\alpha_{\text{Inflow}} \approx 4$  deg

## Approach:

- $d\varepsilon/d\alpha = 0.349$
- $\varepsilon_0 = 5.194$  deg
- $\alpha \approx 7$  deg
- $\alpha_{\text{Inflow}} \approx 1.5$  deg

# Relationship to Prior SFW UHB Study



## Calibration Model



### 737-800 Like Model

calibrated to publicly available weight and performance data, **and proprietary aerodynamic data**;  $M=0.785$ , 3060 nm



### MD90-30 Like Model

calibrated to publicly available weight and performance data;  $M=0.76$ , 2040 nm

## Baseline Model



### CSAT (CFM56-7B-Like)

resized for 3250 nm;  $M=0.80$  cruise

(Block Fuel = 42,605 lb)



### CSAT-re (V2525-D5-Like)

**approx. updated wing aero**, stretch fuselage, resized for 3250 nm;  $M=0.78$  cruise

(Block Fuel = 41,550 lb)

## Adv. GTF Model



### ASAT (PIIdS2;Hi-g-1.5)

advanced airframe; advanced  $FPR=1.5$  GTF;  $M=0.80$

(Block Fuel = 30,420 lb)



### ASAT-re (PIIdS2;Hi-g-1.5)

advanced airframe; advanced  $FPR=1.5$  GTF;  $M=0.78$

(Block Fuel = 30,396 lb)

## Adv. OR Model



### ASAT-or

advanced airframe; advanced open rotor engine;  $M=0.78$

(Block Fuel = 26,709 lb)