Summary of Wind Tunnel Tests and Vehicle Analysis for Open Rotor Propulsion Systems

Presentation to ICAO's Noise
Technology Independent Expert Panel
February 1, 2012

National Aeronautics and Space Administration
U.S.A.

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Acknowledgements

General Electric/CFM International

NASA

Subsonic Fixed Wing Project

Environmentally Responsible Aviation Project

Aeronautics Test Program

Arctic Slope Research Corporation

Federal Aviation Administration

Specific NASA Contributors:

Aeropropulsion Division

Structures and Materials Division

Facilities Division

Testing Division

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Model Scale Open Rotor Wind Tunnel Tests

NASA/FAA/GE Open Rotor Collaboration

- **Objective:** Explore the design space for lower noise while maintaining the high propulsive efficiency from a counter-rotating open rotor system.
- **Approach:** A model scale, low-noise open rotor system was tested in collaboration with General Electric (GE) and CFM International. Candidate technologies for lower noise were investigated. Installation effects such as pylon integration were investigated in partnership with GE and the Federal Aviation Administration (FAA).

Gen-1 Blade Sets (NASA/GE)
- Historical Baseline
- Modern Baseline
- 4 Advanced Designs

Gen-2 Blade Sets (NASA/FAA/GE)
- 6 GE Advanced Designs
- Pylon wake mitigation

Historical Baseline
(12 x 10 Blade Count)

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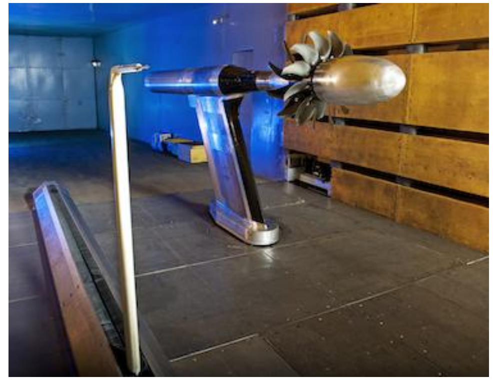
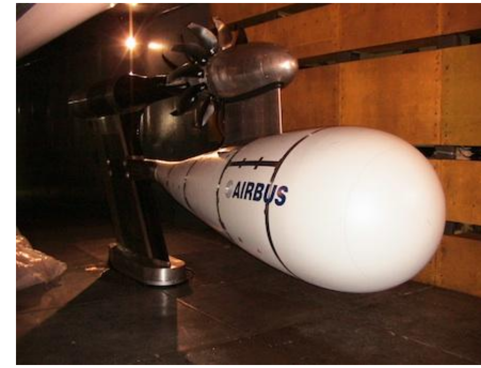
History (1/3) 2009

Drive Rig Rehab
and Installation



First Research Run
Oct 28



Influence Body Tests
Dec 14

Aug	Sep	Oct	Nov	Dec

Drive Rig Checkout
Sep 24 – Oct 27

Linear Array Checkout
Dec 7-11

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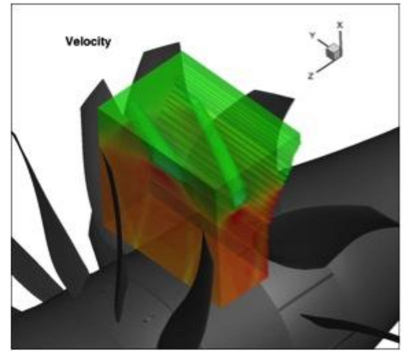
History (2/3) 2010



Flow Measurements
Jul 19 – Sep 7

Continued Influence Body Tests
Concluded – Apr 28

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Drive Rig Muffler
Implementation

NASA Glenn Annual
Facility Shutdown

Open Rotor Installed
In the 8x6 Wind Tunnel

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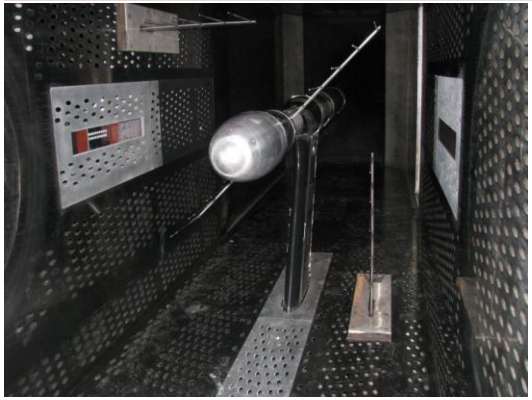
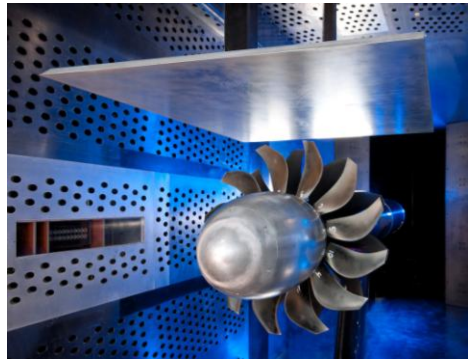
History (3/3) 2011



8x6 Tare Runs
Feb 9



Gen-1 8x6 Test
Feb 28 – Aug 25

Gen-2 8x6 Test
Aug 26 – Sep 9

Gen-2 9x15 Test
Nov 10 – Jan 18

Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**

Diagnostic Tests

Jan. 18, 2012
End of Gen-2 Test

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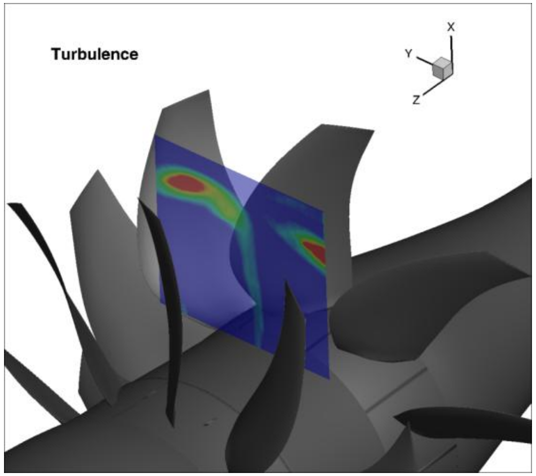
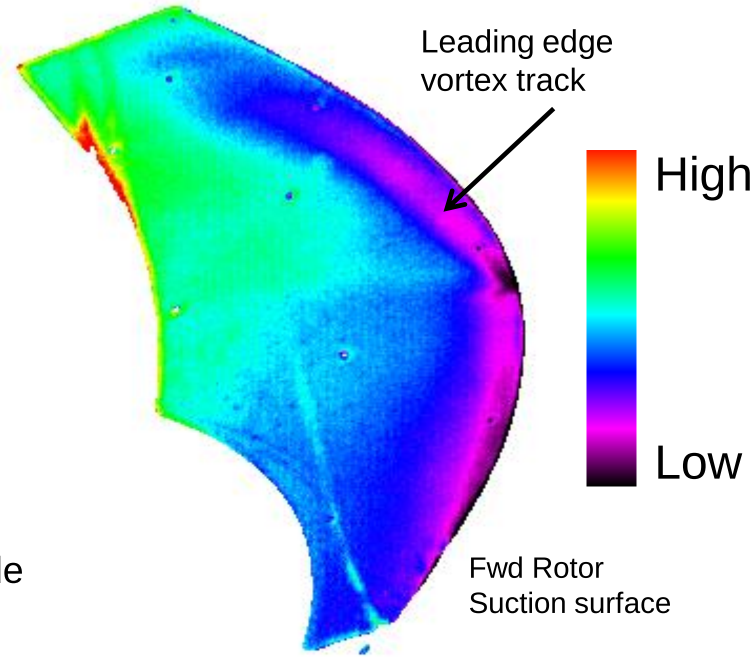
Flow Measurements & Diagnostic Tests



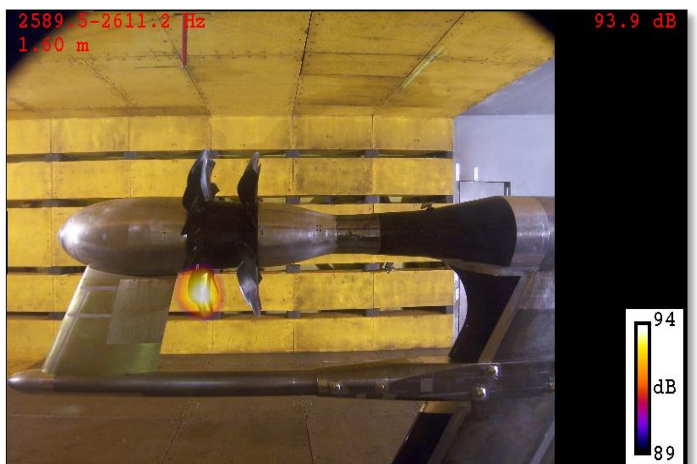
The 3D **PIV** measurements provide a wealth of information about the blade wakes and vortex track.

A canonical **Shielding** configuration provides code validation data.



The **Pressure Sensitive Paint** measurements show phase locked static pressure on the surface of the rotating blade.

The location of peak noise level in the **Phased Array** map changes in the presence of the CFMI pylon indicating a change in the relative strength of sources.



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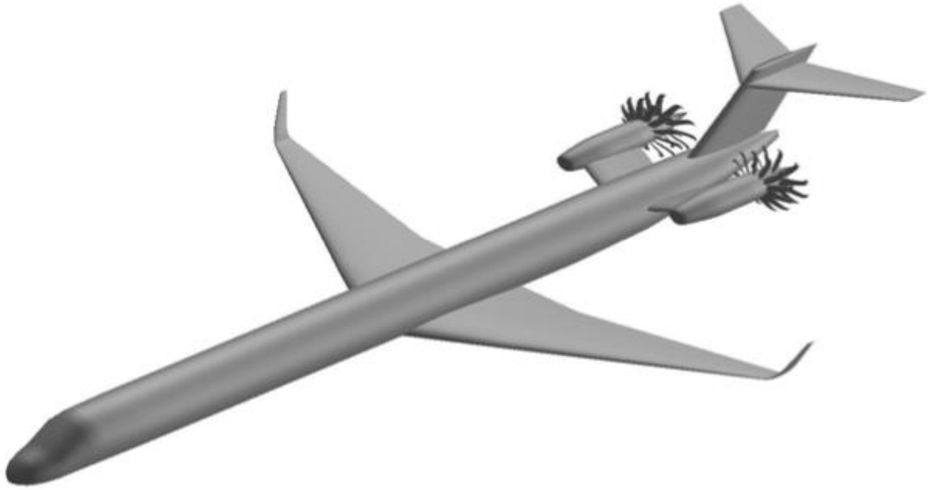
Systems Analysis Results of an Open Rotor Propulsion System on an Advanced Single Aisle Transport



Background

- NASA's systems analysis team has been investigating potential environmental benefits of advanced propulsion systems on "Advanced" Single Aisle aircraft
  - Direct Drive
  - Geared Turbofan
  - Open Rotor

- Open Rotor assessment is joint effort between NASA's Subsonic Fixed Wing (SFW) & Environmentally Responsible Aviation (ERA) projects
  - SFW had FY11 milestone to assess fuel burn/noise characteristics of an open rotor propulsion system
  - ERA measured advanced 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
  - Allowed coordination with industry on modeling approaches/technical assumptions

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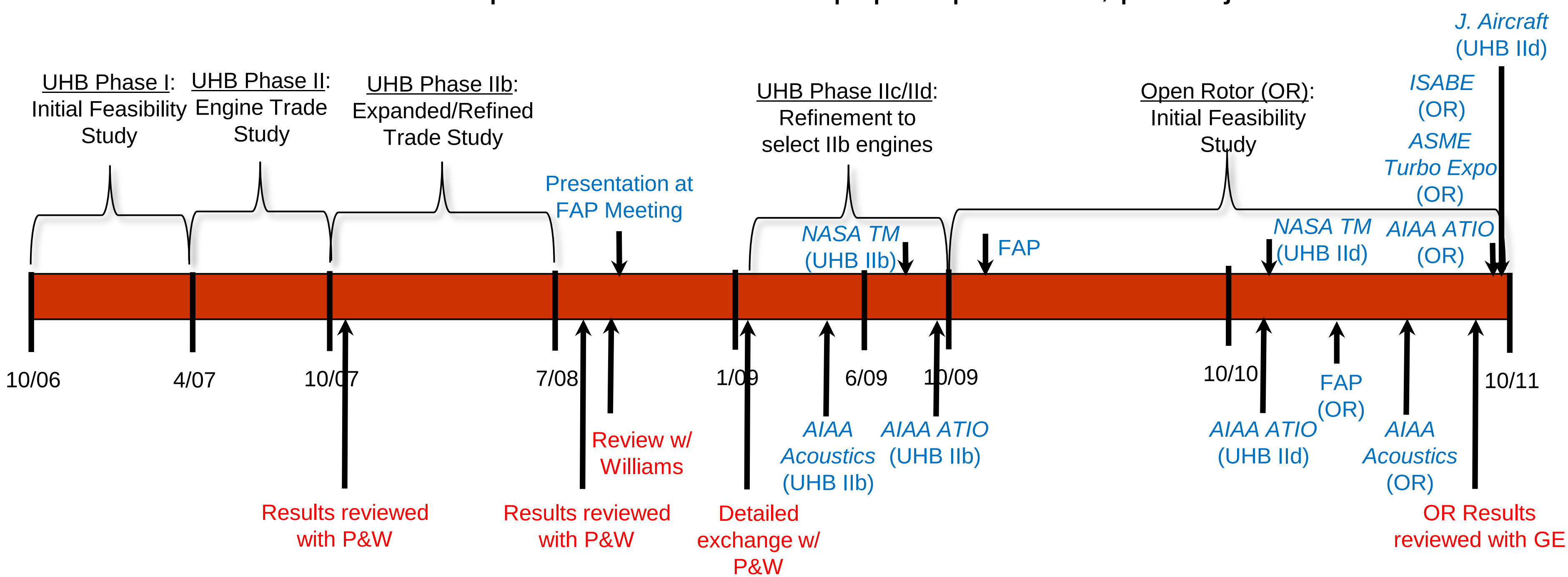
Historical Look at Propulsion Studies

- 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 over the years to obtain feedback
  - Numerous technical reports and conference papers produced, plus 1 journal article



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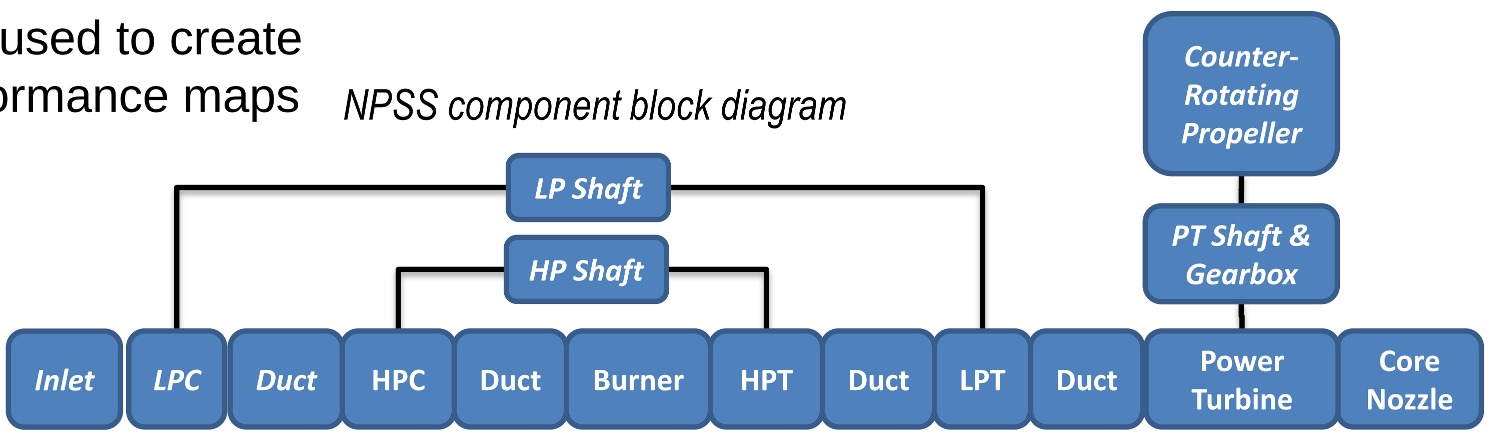
Open Rotor Cycle Model (NASA Notional Engine)

- A complete Numerical Propulsion System Simulation (NPSS) model was created for a geared, pusher open rotor engine
- Core component performance assumptions are similar to those used in a recent NASA advanced turbofan study
- Counter-rotating propeller data from a favored Gen-1 rotor set was used to create performance maps

Component	Parameter	Value
LPC	Pressure Ratio Adiabatic Efficiency (%)	4.2 89.6
HPC	Pressure Ratio Adiabatic Efficiency (%)	10.0 88.6
HPT	Adiabatic Efficiency (%)	91.9
LPT	Adiabatic Efficiency (%)	94.2
Power Turbine	Adiabatic Efficiency (%)	94.0
Counter-Rotating Propellers	Net Efficiency (%) Front Tip Speed (ft/s) Power Loading (shp/ft^2)	**Proprietary Data**

NPSS component block diagram



Open Rotor Engine Performance

Flight Condition	Engine Performance Parameter	Value
Top of Climb (M0.78, 35kft)	Net Thrust (lbf)	5000
	TSFC (lbm/hr/lbf)	0.428
	OPR	42.0
	OR Advance Ratio	Proprietary Data
	OR Power Coefficient	
	OR Thrust Coefficient	
	OR Net Efficiency (%)	
Rolling Takeoff (M0.25, 0 ft, +27F)	Net Thrust (lbf)	19,000
	TSFC (lbm/hr/lbf)	0.229
	OPR	28.5
	OR Advance Ratio	Proprietary Data
	OR Power Coefficient	
	OR Thrust Coefficient	
	OR Net Efficiency (%)	
Sea Level Static (M0.0, 0 ft, +27F)	Net Thrust (lbf)	27,300
	TSFC (lbm/hr/lbf)	0.158
	OPR	29.4
	OR Advance Ratio	Proprietary Data
	OR Power Coefficient	
	OR Thrust Coefficient	

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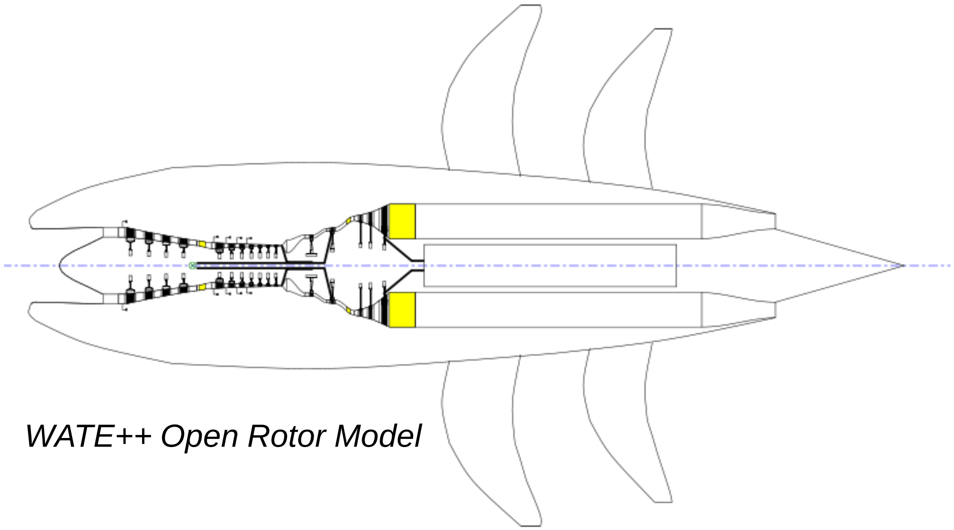
Engine Flowpath and Weight

- Key cycle parameters passed to flowpath tool (WATE++) to calculate engine core weight
- Turbomachinery aeromechanical limits and materials consistent with those of previous 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 actual gearbox weight data from over fifty rotorcraft, tiltrotors, and turboprop aircraft).



WATE++ Open Rotor Model

Weights and Dimensions	Value
Open Rotor Weight (lbm)	3244
Gearbox Weight (lbm)	1028
Total Engine Pod Weight (lbm)	9219
Propeller Diameter (ft)	13.76
Nacelle Diameter (ft)	5.6
Overall Length (ft)	23.2

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Airframe Modeling and Analysis

MD-90-30 Like Model

Calibrated to publicly available weight and performance data

↓

Improve Wing Aerodynamics

MD80 technology to 737NG-like performance

↓

Study Mission Requirements:
- Lengthen Fuselage for 162 Passengers
- ↓
- Resize for 3250 nm Mission

↓

CSAT-re

↓

Advanced Airframe Technology Assumptions

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

↓

ASAT-re → ASAT-or

MD92V Model, MD92 Model

1980s concepts with V2500 & GE36

↓

Open Rotor Airframe Impacts

↓

ASAT-or

Nomenclature
- CSAT: **C**urrent technology **S**ingle-**A**isle **T**ransport
- ASAT: **A**dvanced technology **S**ingle-**A**isle **T**ransport
- re – **r**ear **e**ngine
- or – **o**pen **r**otor

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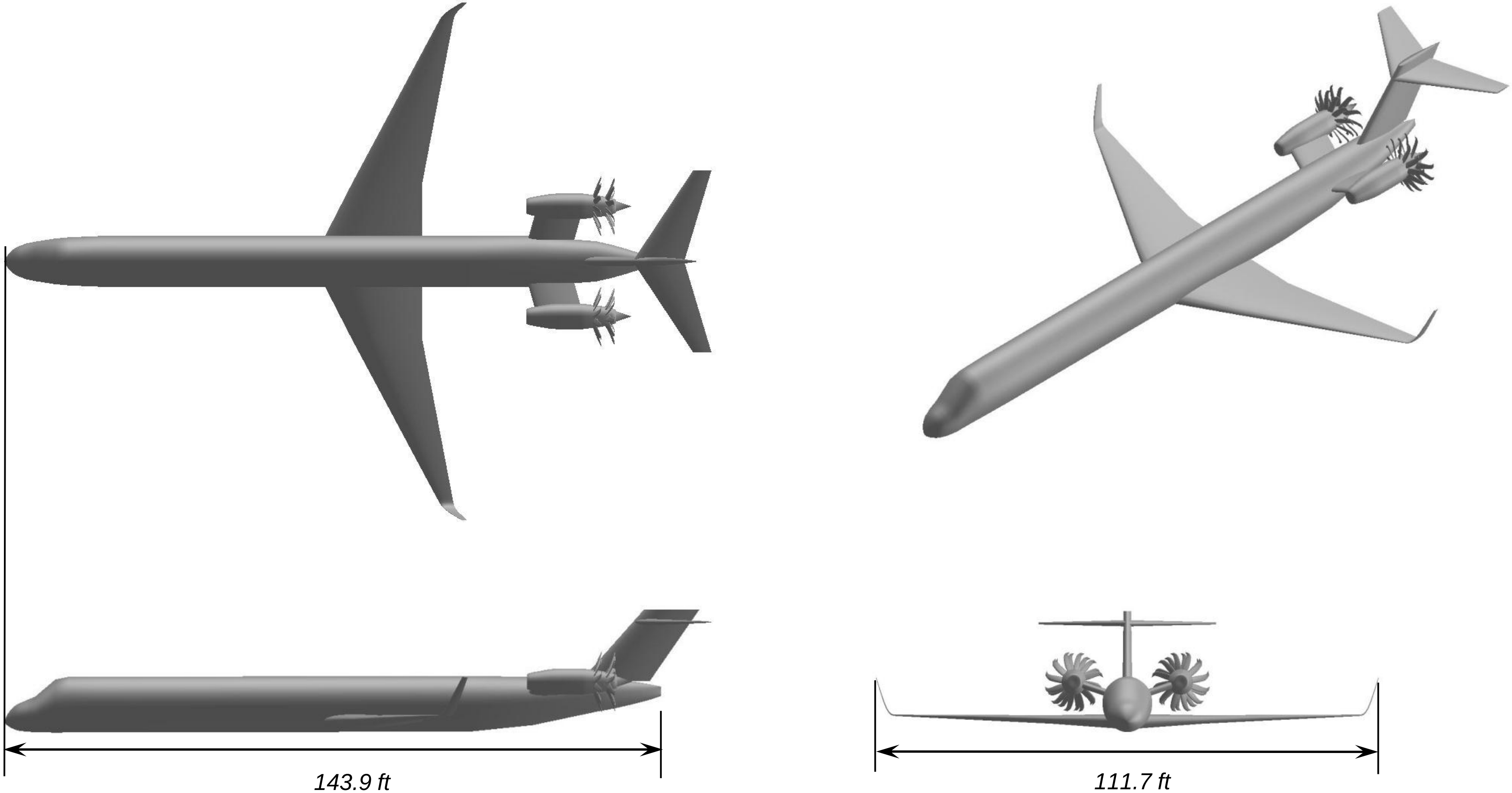
NASA Open Rotor Airplane



See AIAA-2011-7058 for airplane design details

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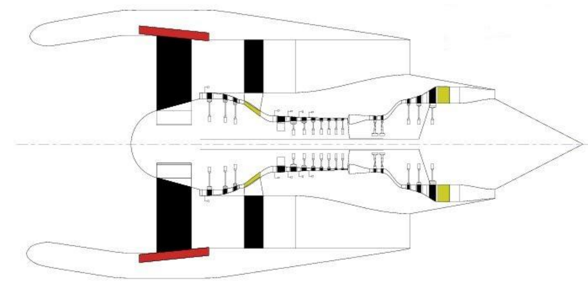
Results (System Performance)

- Engine models combined with airframe models

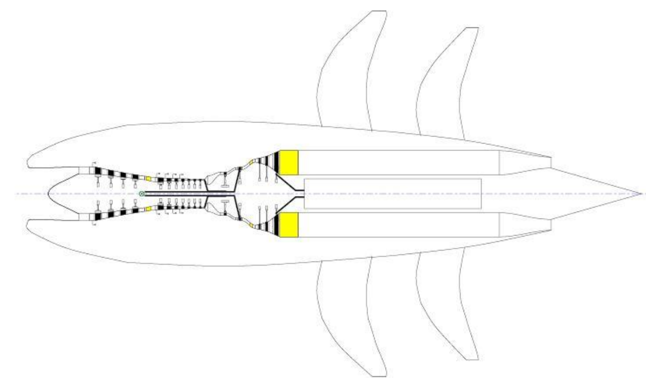
	Airframe:	MD90-30like	CSAT-re	ASAT-re	ASAT-or
	Engine:	V2525-D5	V2525-D5	Adv. GTF	Geared OR
Design Mission:					
Design Mission Range	nm	2040	3250	3250	3250
OWE	lb	88162	94450	79646	87817
Mission Fuel	lb	36825	49164	35803	31056
Passengers		158	162	162	162
Payload	lb	31000	32400	32400	32400
Ramp Weight	lb	155987	176014	147849	151273
Wing Area	ft^2	1278	1530	1240	1250
W/S	lb/ft^2	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
Economic Mission: 1000 nm,					
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-**A**isle **T**ransport
ASAT: **A**dvanced technology **S**ingle-**A**isle **T**ransport
re – **r**ear **e**ngine
or – **o**pen **r**otor



Advanced Geared Open Rotor (OR)

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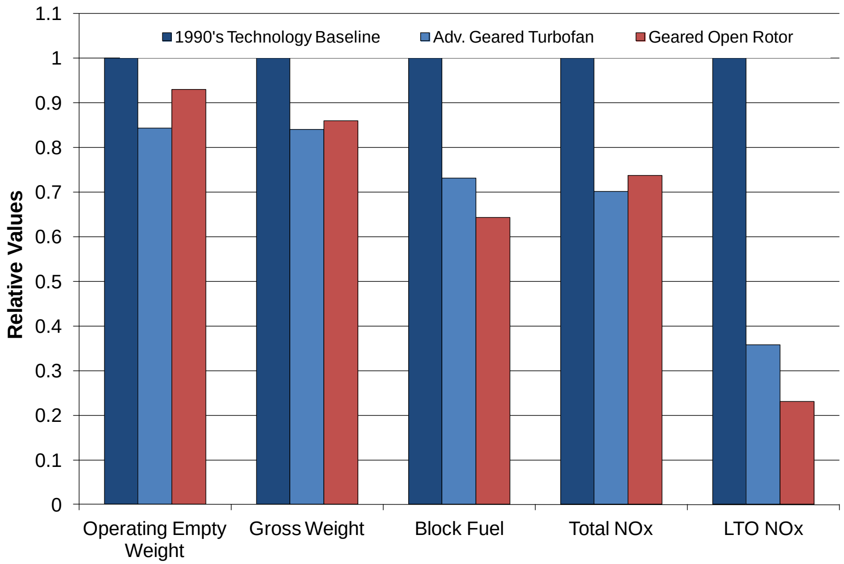
Relative Improvements



- 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_X: -30%(GTF); -26%(OR)
  - LTO NO_X: -64%(GTF); -77%(OR)

- Open rotor relative to advanced turbofan…
  - Empty Weight: +10%
  - Gross Weight: +2%
  - Block Fuel: -12%
  - Total NO_X: +5%
  - LTO NO_X: -36%

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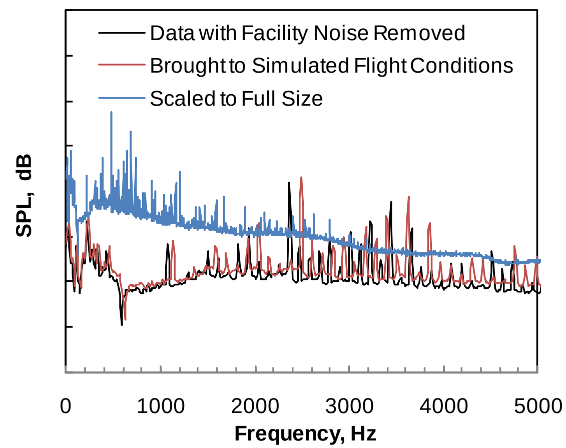
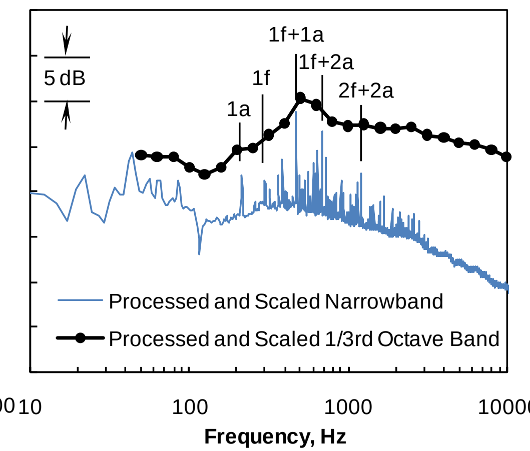
Acoustic Data Processing Steps

Measured, narrowband spectral densities → *Convert to flight conditions* → *Source strength corrections* → *Model scale to full scale*

ΔAmplitude = 10 log[Area Scale Factor]
freq shift = Linear scale factor





→ *Convert narrowband to 1/3rd octave band*

IEC 225-1966 band filter

→ *Aircraft system noise prediction (ANOPP)*

Included effects:
SAE 866 absoption
Spherical spreading
Ground reflections
Other sources

Spectral basis for Part 36 Noise Certification

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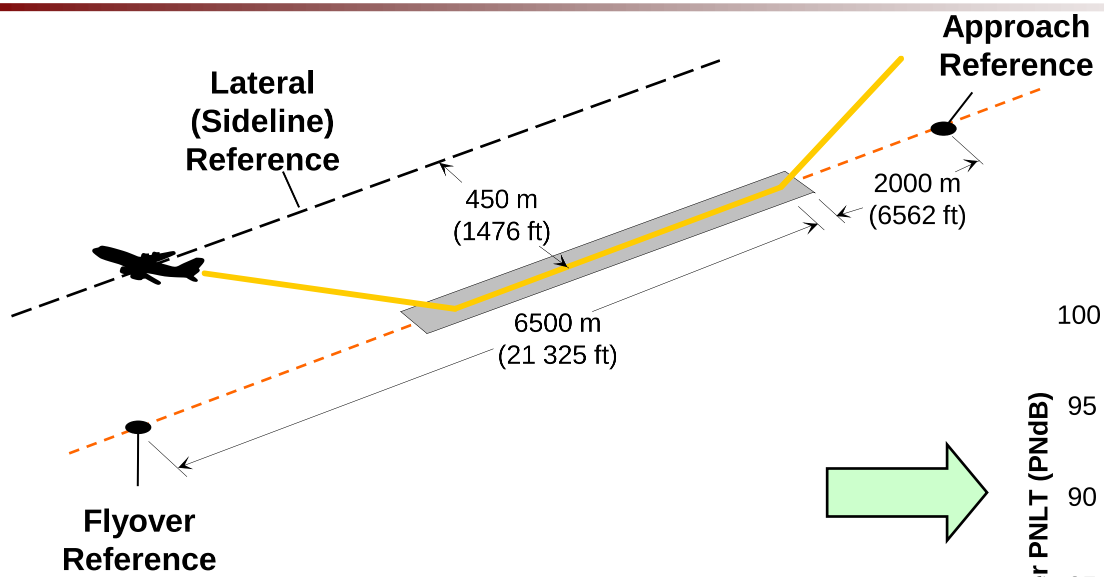
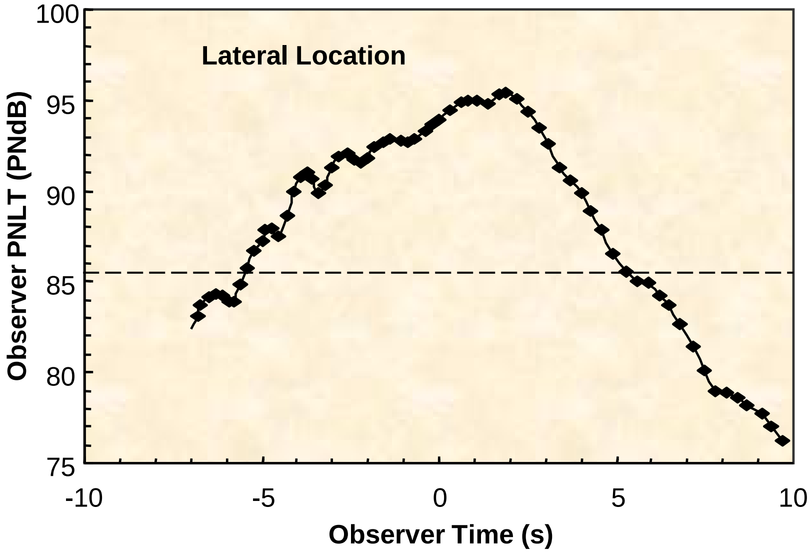
Part 36 Noise Certification



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

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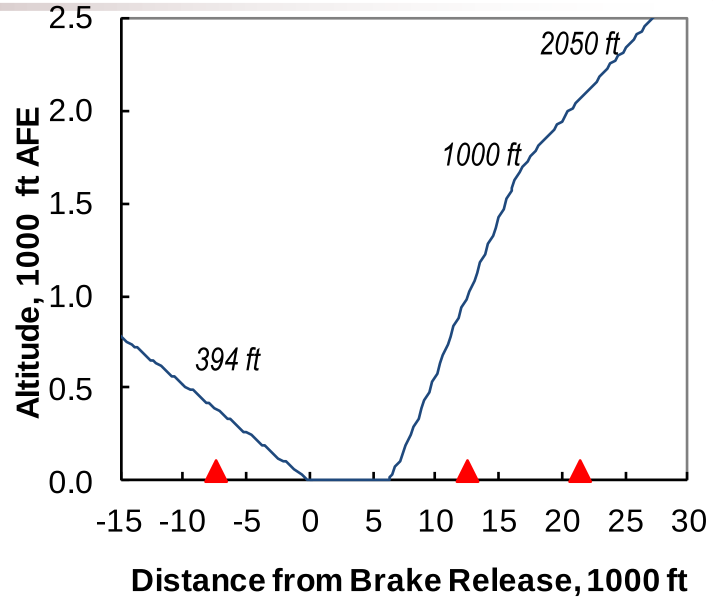
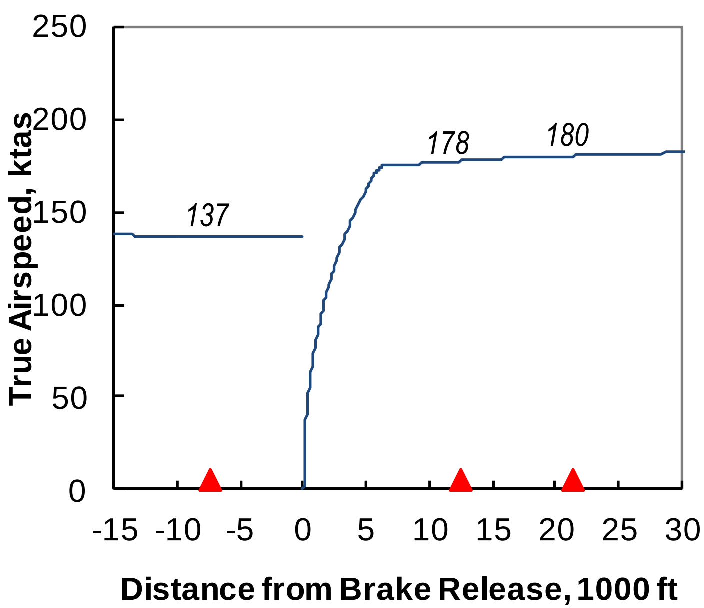
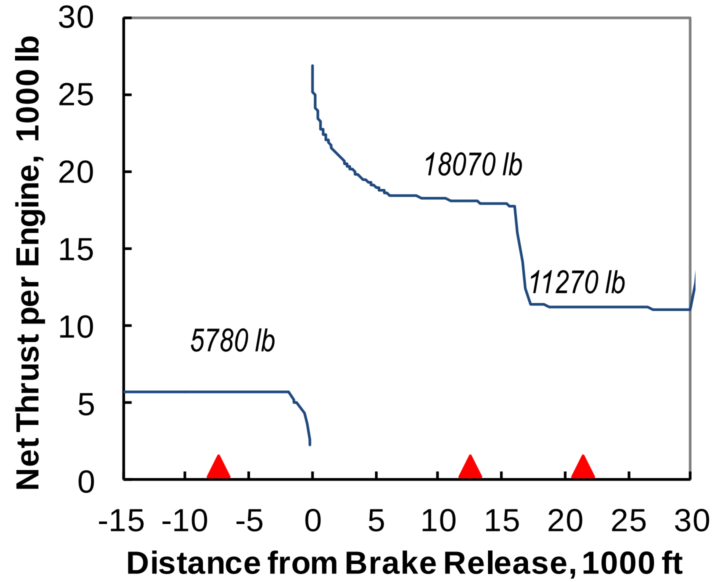
Trajectory Modeling

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







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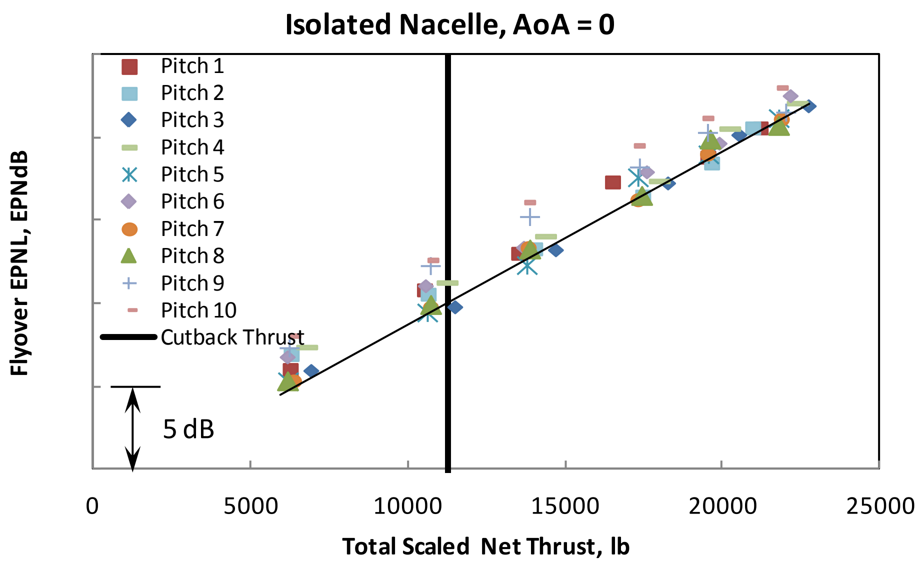
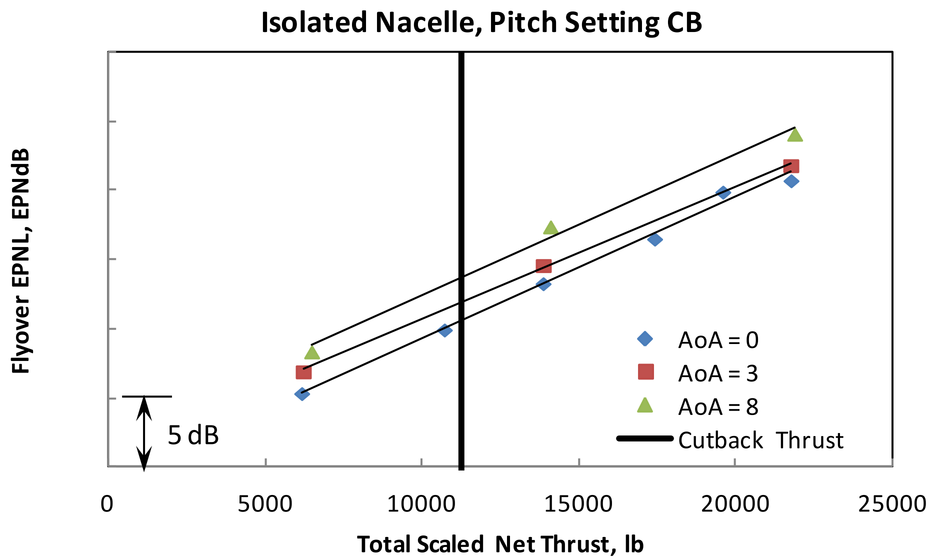
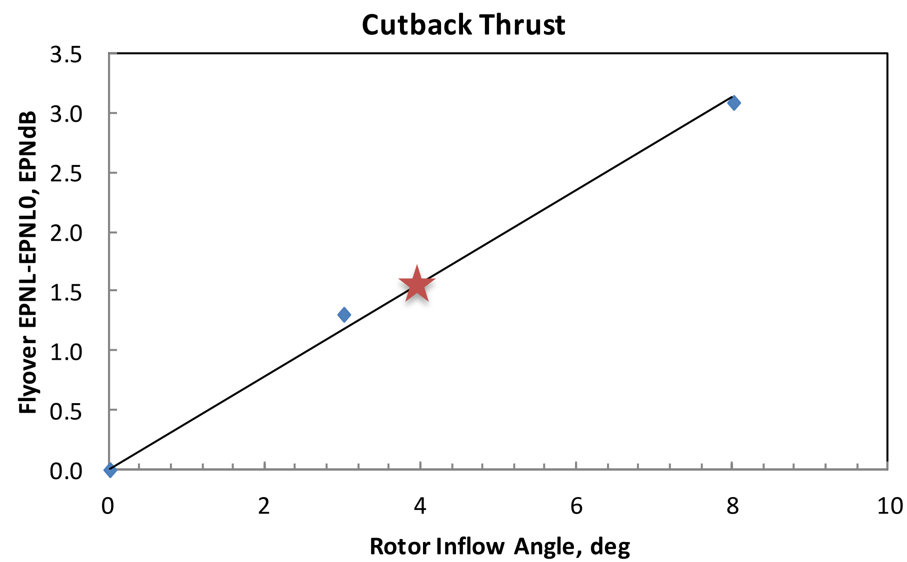
Impact of AoA and Pitch on Flyover EPNL







Sources modeled:
Open rotor, core, core jet, flaps, trailing edge

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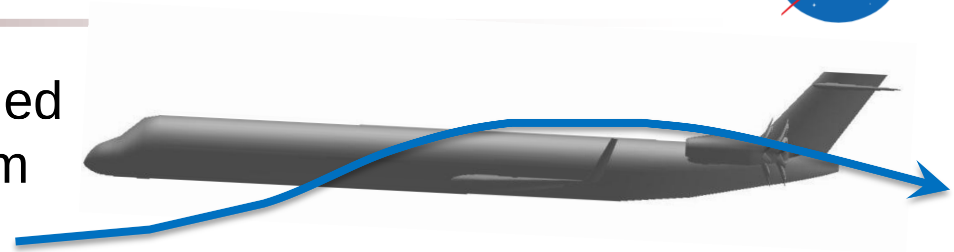
Rotor Inflow Angle and Airplane Angle of Attack

- Rotor inflow angle (α_{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 (α)
- Nose-up engine mounting angle (α_{Cant} = 2 deg, re clean airplane waterline) gives α_{Inflow} = 0 at cruise
- Downwash angle into rotor at α = 0 (ε_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:

- $d\varepsilon/d\alpha = 0.336$
- ε_0 = 2.342 deg
- $\alpha \approx$ 7 deg
- $\alpha_{\text{Inflow}} \approx$ 4 deg

Approach:

- $d\varepsilon/d\alpha = 0.349$
- ε_0 = 5.194 deg
- $\alpha \approx$ 7 deg
- $\alpha_{\text{Inflow}} \approx$ 1.5 deg

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Gen-1 Rotor Noise Estimate

13.67 foot diameter rotor

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

†Estimated from F31/A31 data

‡Assumed "70%" reduction of the pylon penalty

***Rule based on NASA's 151.3 klb airplane*

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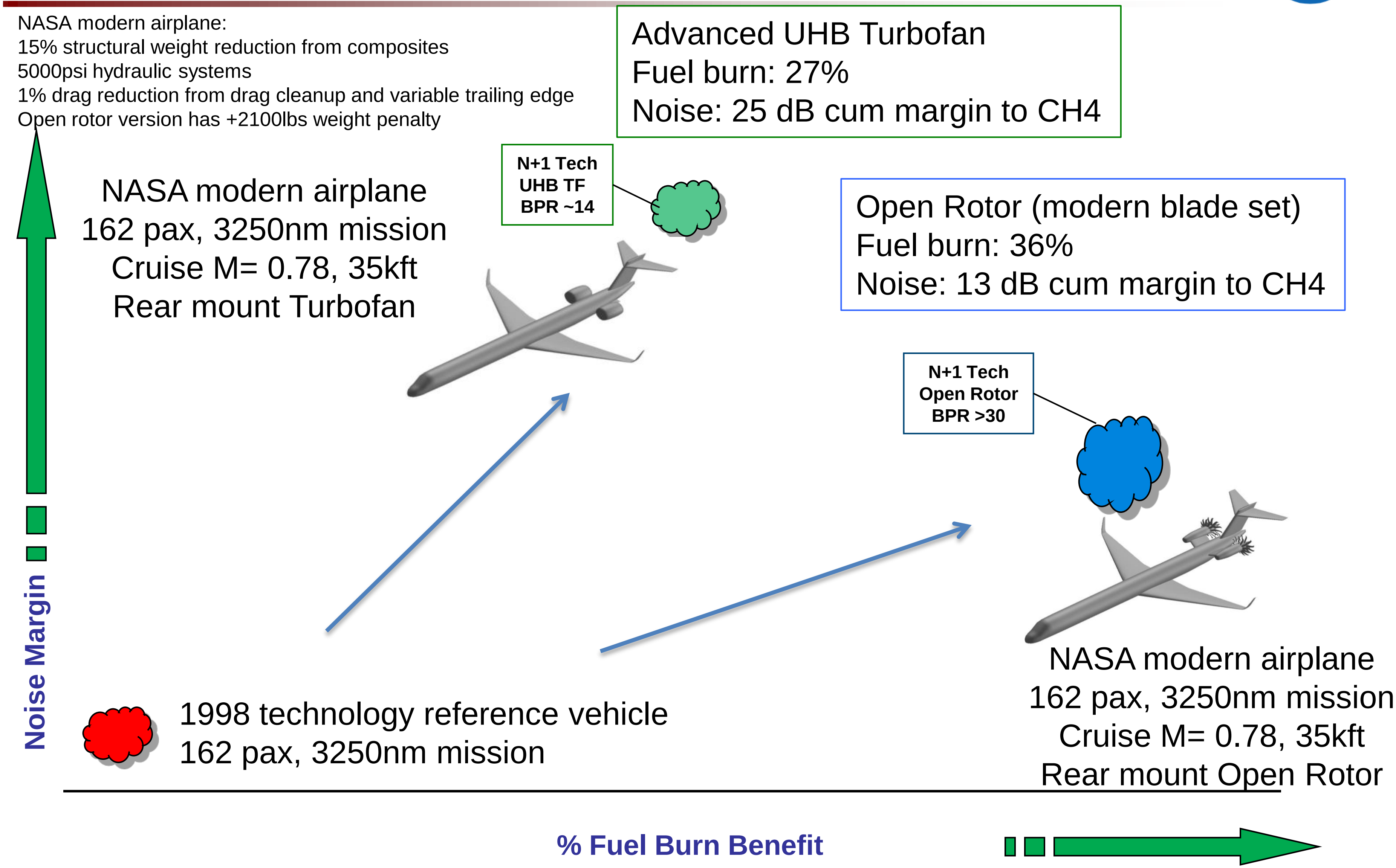
NASA Study Results – Fuel Burn vs. Noise



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Relationship to Prior 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

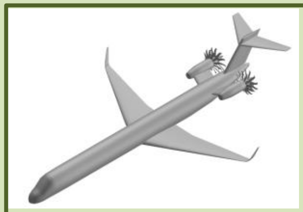
(Block Fuel = 30,420 lb)

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)

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NASA