FAA CLEEN Consortium Open Session

GE Aviation
8 Nov. 2012

Doug Shafer	Prgm Mgr.
Rick Stickles	TAPS II – Prgm Mgr.
Arif Khalid	Open Rotor – Aero
John Wojno	Open Rotor – Acoustics
Jeff Bult	FMS/ATM
Steve Nolte	FMS-Engine Integration

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GE CLEEN Technologies

1. TAPS II Combustor (Stickles)
2. Open Rotor (Khalid/Wojno)
3. FMS/ATM Integration (Bult)
4. FMS – Engine Integration (Nolte)

FAA CLEEN Program Goals

	N+1 (2015) CONVENTIONAL CONFIGURATION RELATIVE TO 1998	N+2 (2020-25) UNCONVENTIONAL CONFIGURATION RELATIVE TO 1998	N+3 (2030-35) ADVANCED CONCEPTS RELATIVE TO 2005
NOISE	-32 dB cum below Stage 4	-42 dB cum below Stage 4	-71 dB cum below Stage 4
LTO NOX EMISSIONS (BELOW CAEP 6)	-60%	-75%	better than -75%
AIRCRAFT FUEL BURN	-33%	-50%	better than -70%

Develop and demonstrate (TRL 6-7) certifiable aircraft technology

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GE CLEEN Program Goals

Timeframe: CY 2010-2015

TAPS II Combustor

- Emissions 60% below CAEP/6

Open Rotor

- 26% fuel burn reduction (relative to CFM56-7B)
- 17 EPNdB noise reduction (relative to stage 4)

FMS & ATM

- 7% fuel burn/CO_2 reduction
- 22% landing noise reduction (area of 60 EPNdB footprint)

FMS-Engine Integration

- Up to 2% fuel burn reduction

CLEEN Consortium

TAPS II Development Results
November 8, 2012

Doug Shafer Program Manager
Rick Stickles TAPS II Manager

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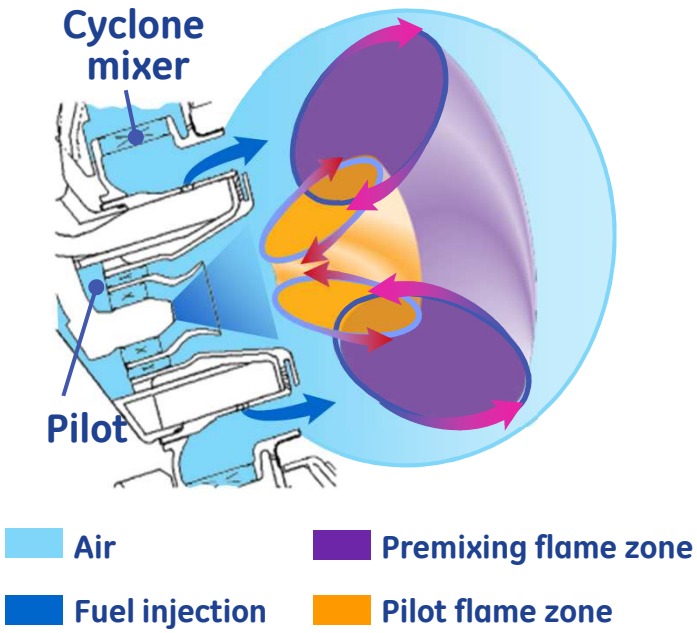
GE Aviation Approach:
TAPS (Twin annular Premixing Swirler)

Twin annular flames

- Staged combustion within mixer
- Lean-premixed fuel/air mixture in main swirler for reduced NOx at high power
- Central pilot for good operability and low CO/HC at low power
- Greater NOx Reduction at Cruise

FADEC sets optimum fuel splits

- Balance Emissions, Operability Durability, and Dynamics



Pilot Only

Pilot + Main

Nozzle sprays shown without air flow (or cyclone mixer)

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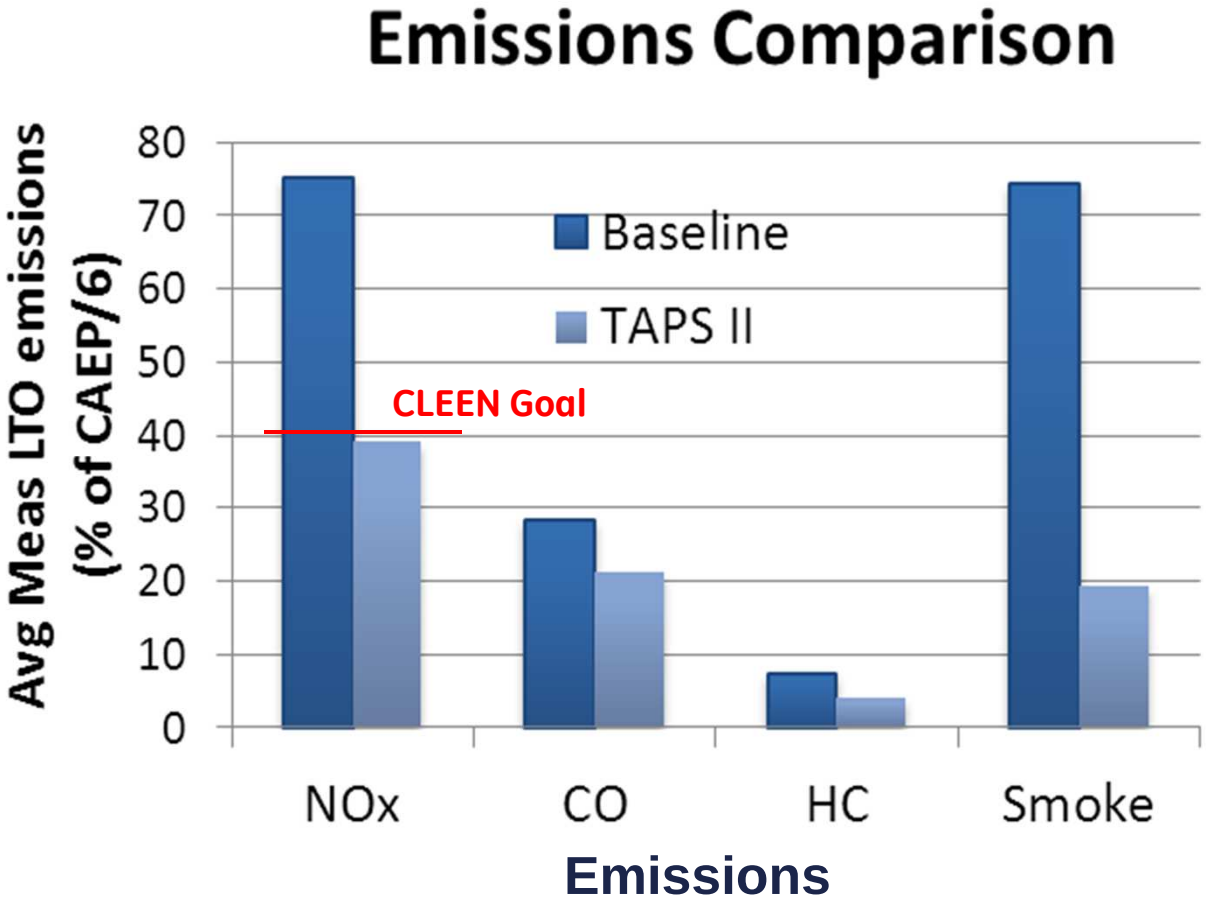
NOx Performance vs CLEEN Goal



NOx exceeds CLEEN goal… Significant improvement in all emissions vs baseline CFM56 engine data.

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CLEEN TAPS II Accomplishments

- Scaled fuel nozzle & mixer size down to narrow body application
- Developed improved main mixer concept
- Evaluated single and dual circuit pilot nozzle designs
- Completed combustor component & core engine testing
- Developed combustion dynamics rig test & modeling techniques
- Demonstrated significant emissions reduction relative to the CFM56 baseline engine
- Demonstrated average measured NOx levels that exceed the CLEEN goal of 60% margin to CAEP/6

Applications

Lean burn TAPS combustion

- TAPS I in service on 747-8 and 787 wide body aircraft
- TAPS II (FAA CLEEN) scaled technology to narrow body aircraft

Application/Engine	1st Engine To Test	Entry into Service
COMAC C919/Airbus A320 NEO		
– LEAP-1A/-1C	Sept 2013	2016
Boeing 737 Max		
– LEAP-1B	April 2014	2017

CLEEN technology in service by 2016

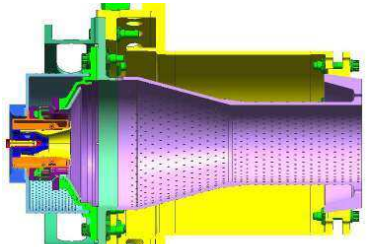
Backup

CLEEN TAPS II Development Program

2010 2011 2012 2013

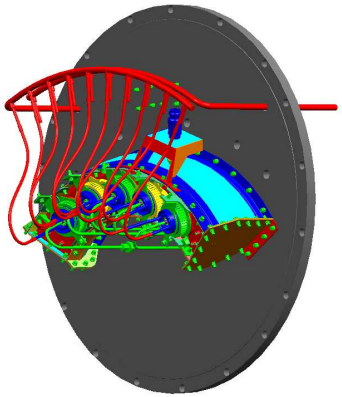
Technology Maturation

Conceptual Design
Flame tube test
Combustion Dynamics
Enabling Technology



System Engineering/Integration

5 Cup sector test #1
5 Cup sector test #2
TCA and HTP Test
Full annular Test
Test Report



Technology Demonstration

Core Engine Test
Baseline Engine Test Data
Test Report

Technology Assessment

Final Report

Program has completed all testing … team working final reports in 2012

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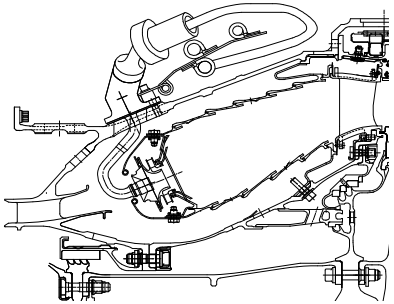
Low-NOx Combustor Evolution

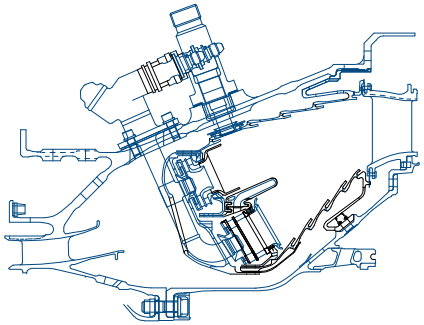
NOx

Single Annular Combustor (SAC)
- Rich burning (tech insertion)
- 25% margin to CAEP/6 NOx



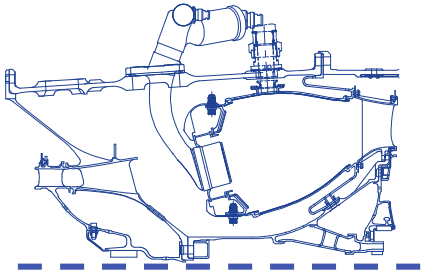
CFM56 SAC

Double Annular Combustor (DAC)
- Lean burning
- 35% margin to CAEP/6 NOx



CFM56 DAC

Twin Annular Premixing Swirler (TAPS I)
- Lean burning
- 50% margin to CAEP/6 NOx



GEnx

TAPS II (FAA CLEEN, NASA N+1)
- Lean burning
- 60% margin to CAEP/6 NOx

Improved pilot and main mixers
Scaled to smaller geometry
Evaluate simplified fuel nozzle design

NASA N+2
- Lean burning
- 75% margin to CAEP/6 NOx

Increased mixer air
Improved pilot and main mixers
CMC liners (reduced cooling)
Active dynamics control
Advanced ignition

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Open Rotor Designs for Low Noise and High Efficiency

Technology maturation in partnership with NASA and the FAA

GE Aviation:
- S. Arif Khalid
- Andy Breeze-Stringfellow
- David P. Lurie
- Trevor Goerig
- John P. Wojno

GE Global Research:
- Trevor H. Wood
- Kishore Ramakrishnan
- Umesh Paliath

November 8, 2012

NASA Glenn 8x6 High Speed Wind Tunnel (HSWT)

NASA Glenn 9x15 Low Speed Wind Tunnel (LSWT)

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Technology maturation program

Collaboration:

GE: designs, acoustic predictions, test planning/execution

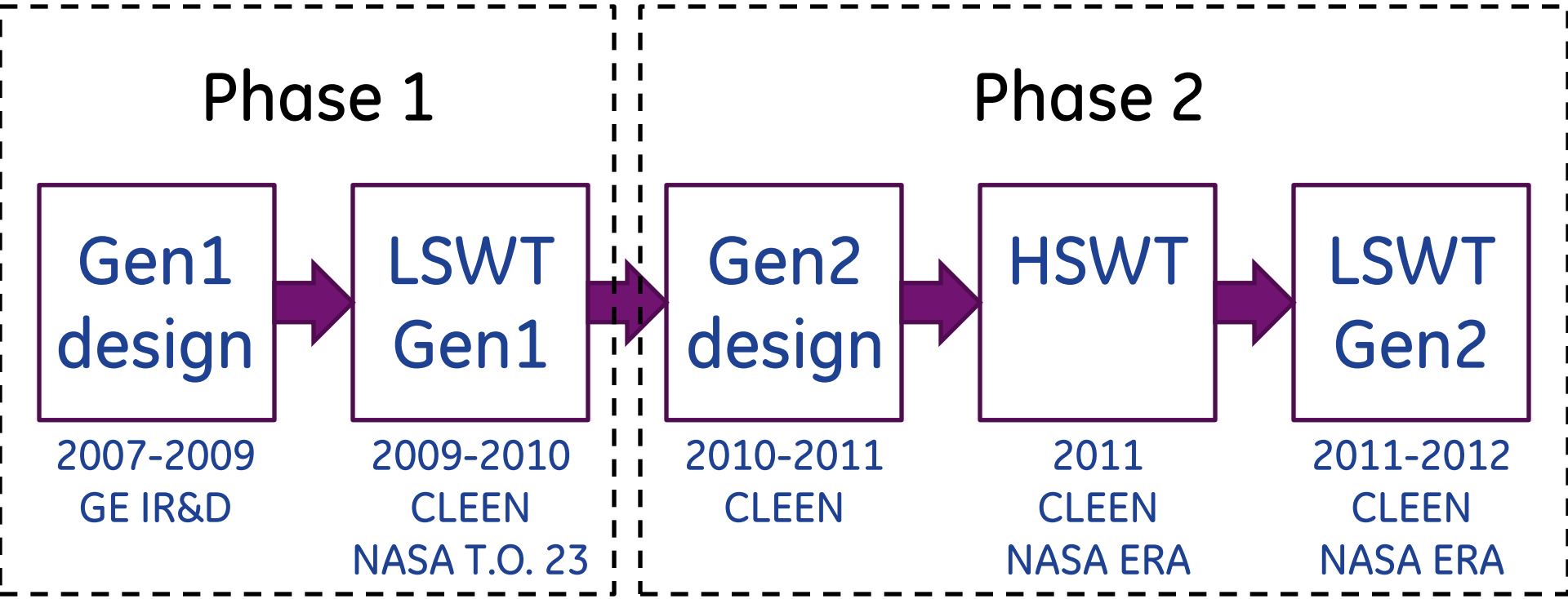
NASA: rig fabrication, facilities, data acquisition, personnel

FAA: feedback, reviews, sponsorship

Goals:

- 26% fuel burn reduction relative to CFM56-7B powered narrow body aircraft
- 15-17 EPNdB cumulative margin to Chapter 4

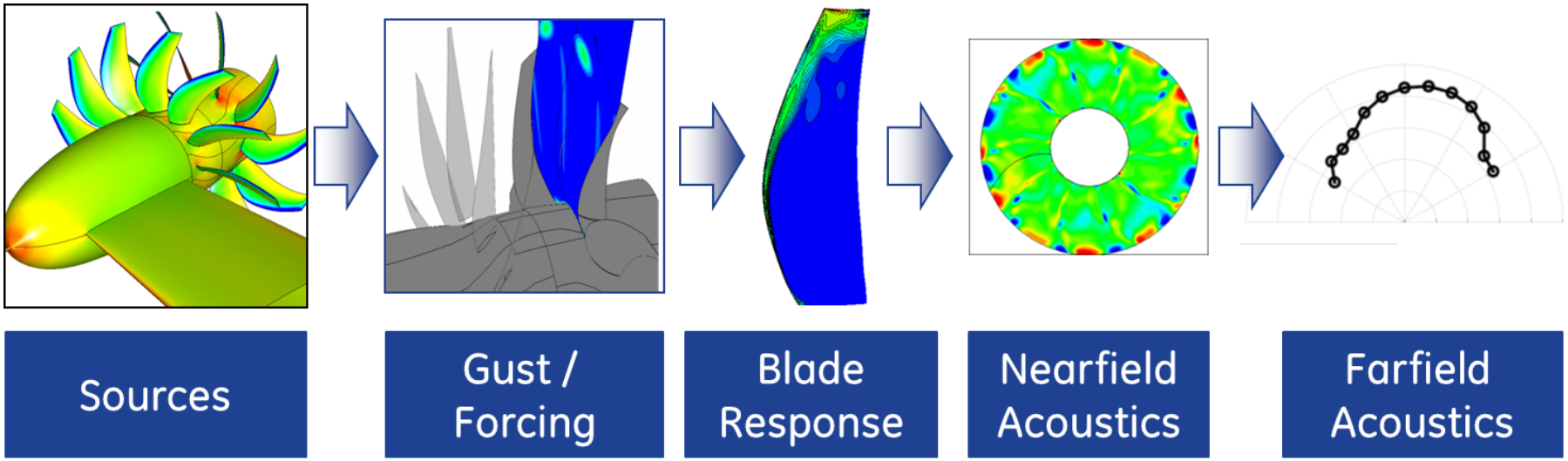
Program chronology



- Historical background & CFD/CAA → Gen1 design guidance
- Acoustic results from 9x15 Low Speed Wind Tunnel (LSWT) for Gen1 → Gen2 design guidance

Computational aero-acoustics (CAA)

Prediction process



Multi-step Acoustic Prediction Process

Wakes/Gusts → Unsteady R2 Surface Pressure → Radiated Acoustics

CFD CAA

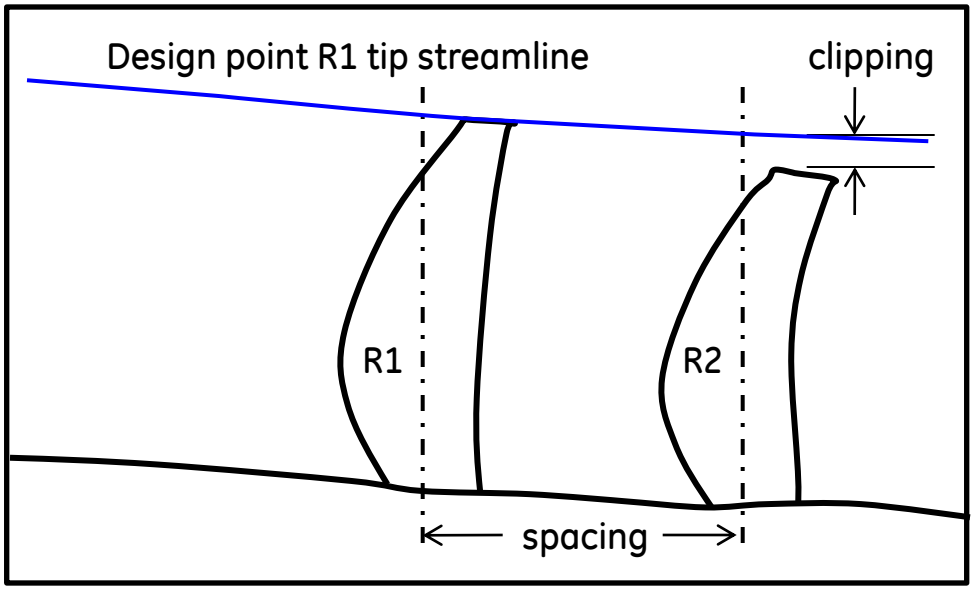
OR Analyses Demonstrated Effective Low-Noise Design Guidance

Design parameters

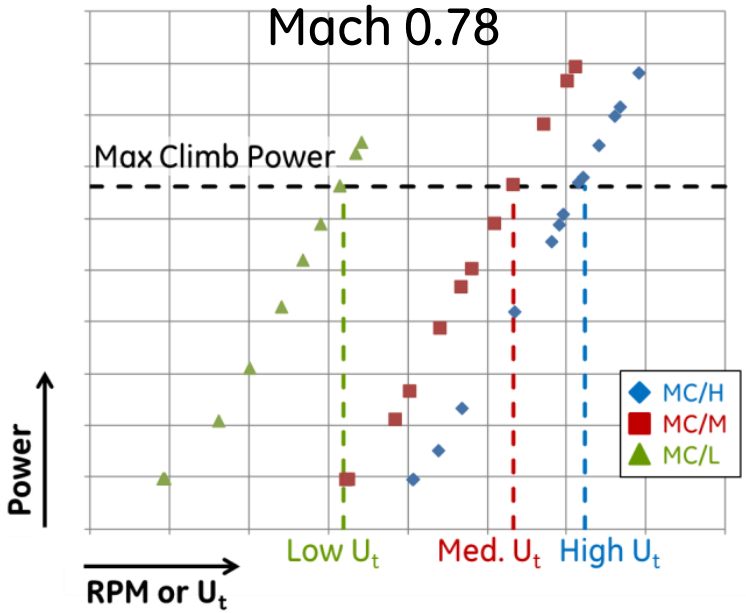
	Hist.	Now
Blade count (fwd,aft)	12x10	12x10
Diameter (ft)	11	14
Disk Loading (SHP/ft^2)	100	59
Spacing/Diameter	0.28	0.27

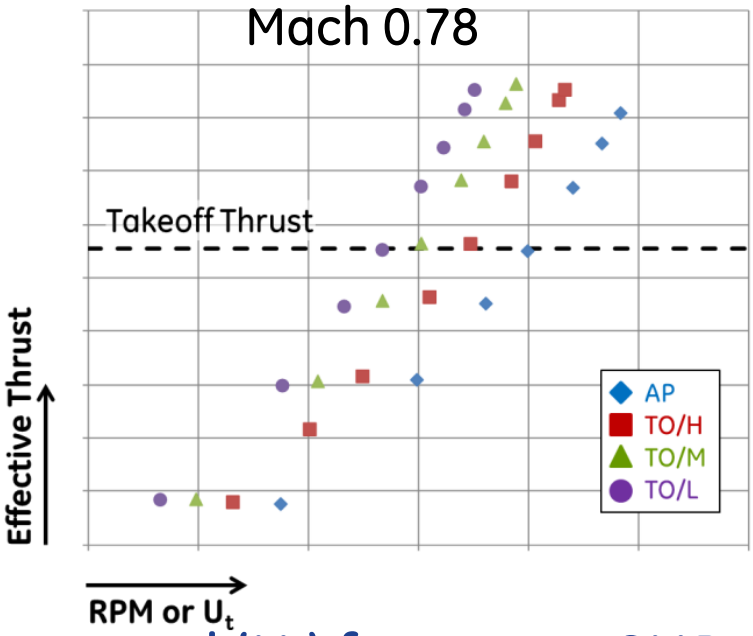
Historical "aero-only": no clipping

Development program explored baseline clipping level and 5% span additional



Tip speed/pitch setting



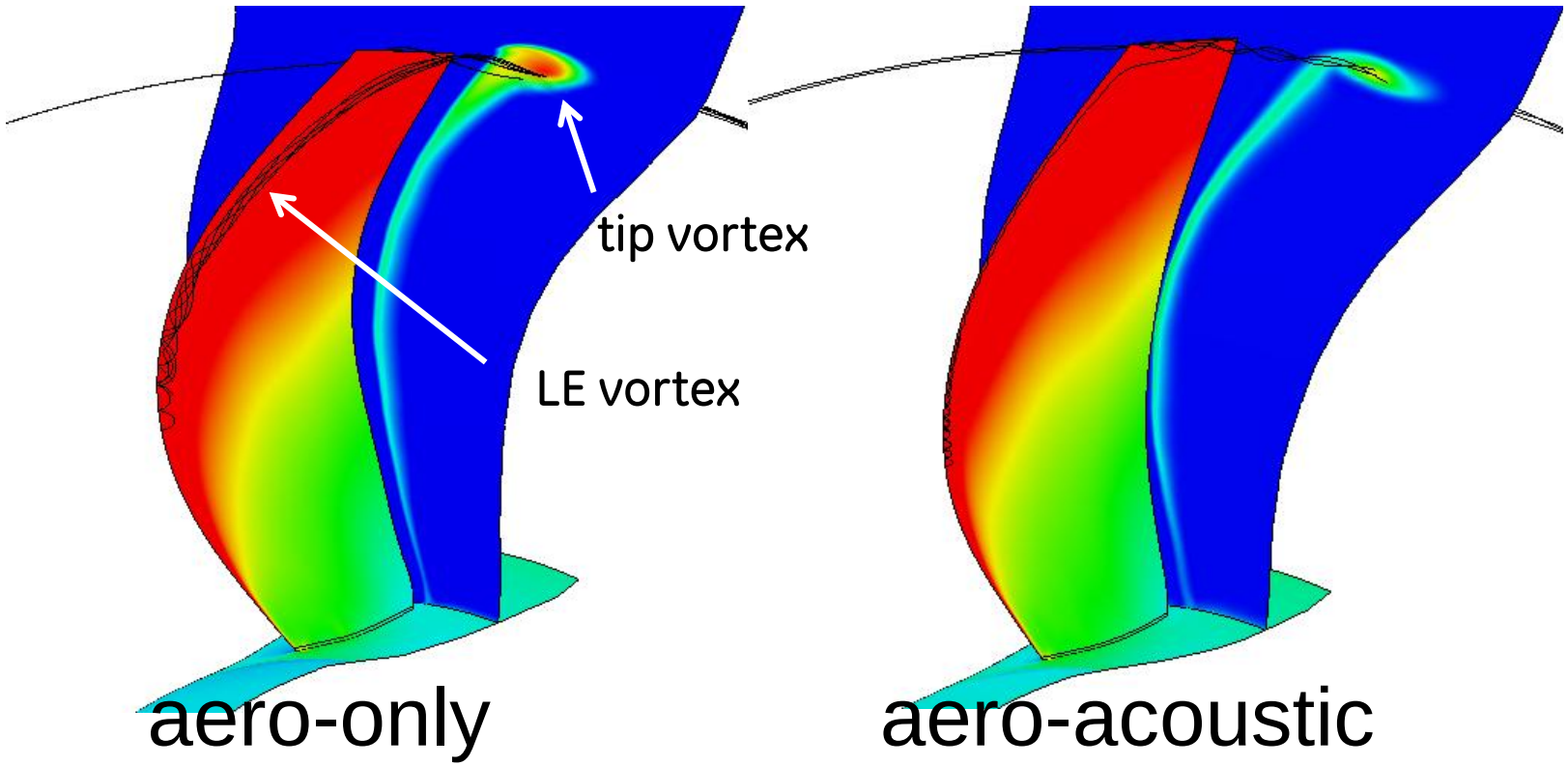


- Pitch setting can be expressed as tip speed (U_t) for target SHP or thrust and torque ratio
- Designated pitch settings by cycle point and U_t (low, medium, or high)
- Varied pitch/U_t for both high flight speed efficiency and low flight speed acoustics, regardless of "design" U_t

Designs

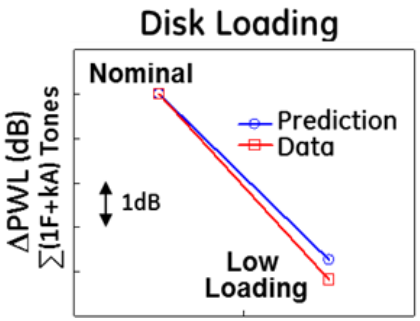
Historical	Aero-only design from 1980's UDF®
Gen1A	Lower disk loading & aero-acoustic features
Gen1A+B	Additional "+B" technology applied to Gen1A
Gen1C	Alternative design to Gen1A
Gen2A	All-new design based on lessons from LSWT and additional analysis
Gen2A+B	Analytically applied effects of "+B" technology to Gen2A results – Presented in final technology status

Results: tip vortex control

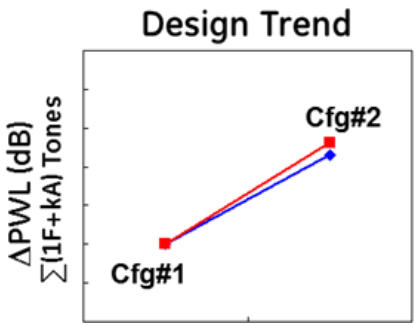


Aero-acoustic R1 design incorporated in Gen1 & 2 reduces tip vortex with estimated less than 0.5 pt efficiency penalty

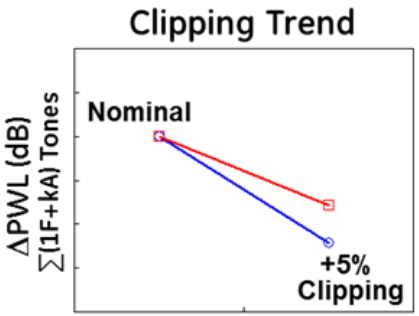
Results: acoustic trends and validation



Historical to Gen1A



Gen1A to Gen1C



Baseline to +5% Span

Summed interaction tones for R1-R2 1st R1 passing frequency

Subtract first configuration level from both prediction and data

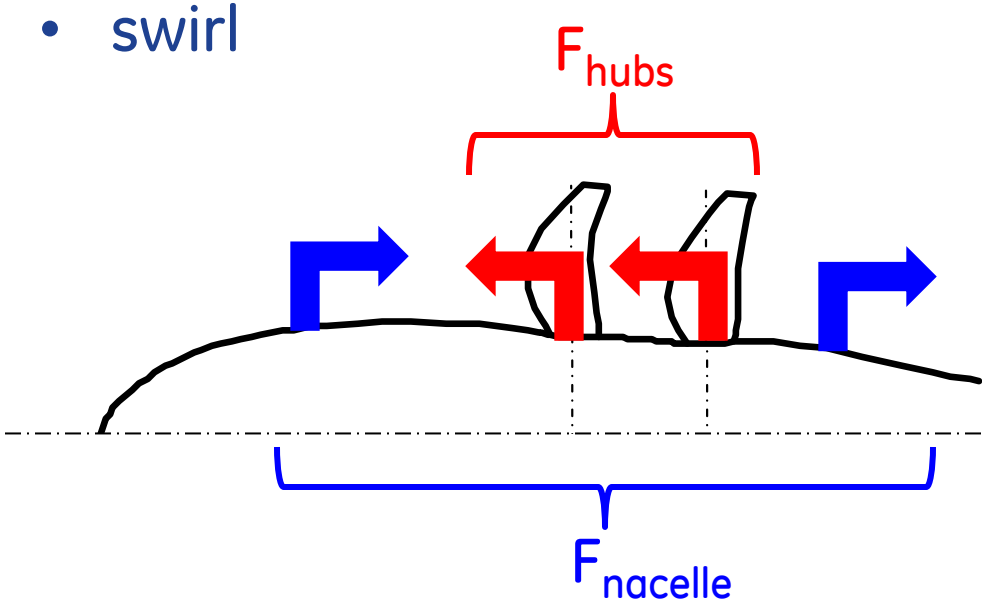
CAA captured experimental trend

Performance

$$\text{Overall Propeller Net Efficiency} = \frac{\text{(Effective Thrust) (Flight Speed)}}{\text{Shaft Power}}$$

Accounts for:

- profile & shock losses
- induced losses: axial velocity, wakes, tip vortices
- swirl



$$\frac{\Delta F_{hubs}\text{ (blades-on – blades-off)} - \Delta F_{nacelle}\text{ (blades-on – blades-off)}}{\text{Effective Thrust}}$$

Operating Conditions for Assessments

Cycle points for 26% fuel burn reduction relative to CFM56-7B

(GE internal fuel burn analysis)
-B737-800W, 162 seat
- 800 nm mission
- engine weight & drag

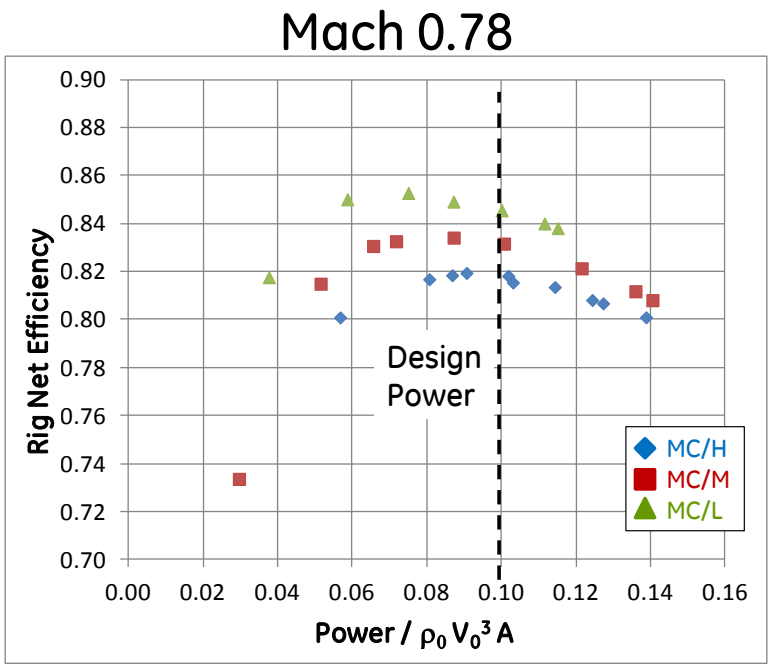
	Max Climb	Takeoff
Altitude (ft)	35,000	0
Atmosphere	ISA+18°F	ISA+27°F
Flight Mach	0.78	0.25
Net thrust	4,842	24,003
SHP	7,946	18,509
η_{net}	0.860	0.675

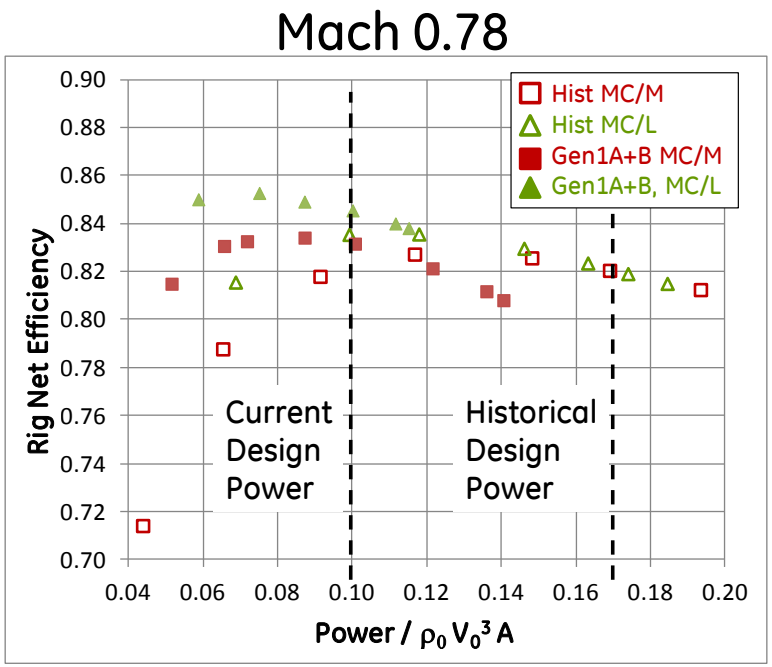
Acoustic trajectory for NASA V_2 modern open rotor aircraft

(GE/NASA RTAPS collaboration)
- Methodology similar to Guynn, Berton, Hendricks, Tong, Heller, & Thurman, 2011

	Approach	Sideline	Cutback
Altitude (ft)	389.79	979.21	2038.17
MGTOW (lbs)	140,796	151,135	151,080
TAS (kts)	136.71	177.40	180.23
Net Thrust	11,555	36,170	22,543

Performance Results
Pitch angle/tip speed





- Reducing Gen1 design point U_t (increasing pitch) → 2.7 point efficiency improvement over U_t examined in net efficiency
- Historical insensitive pitch at design point

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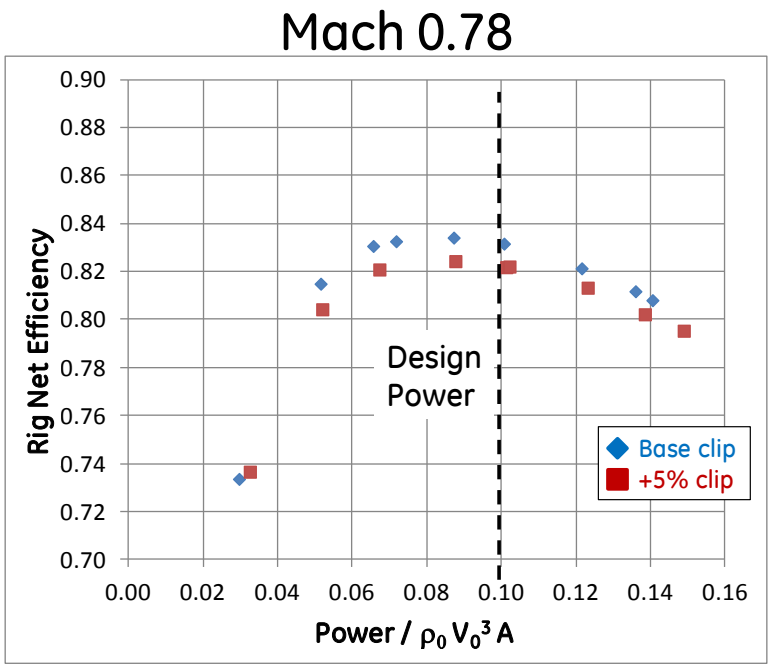
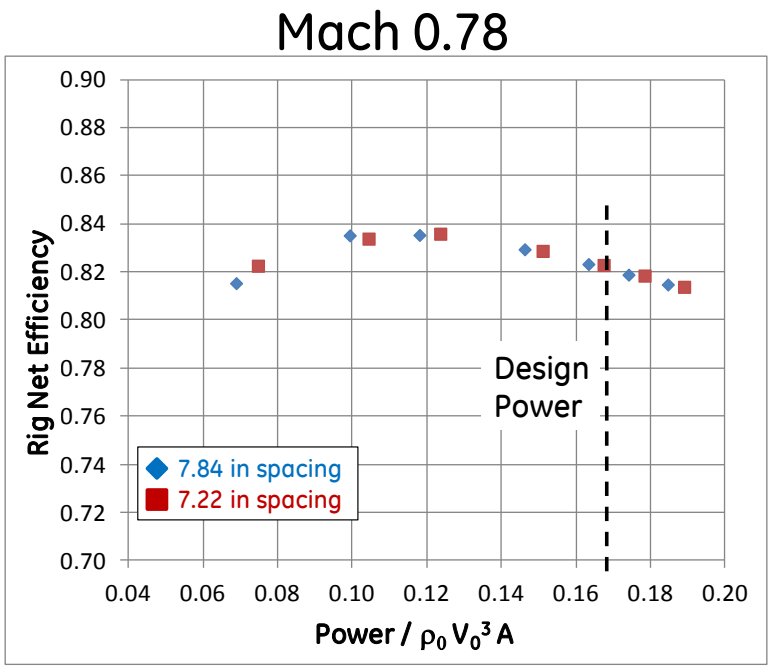
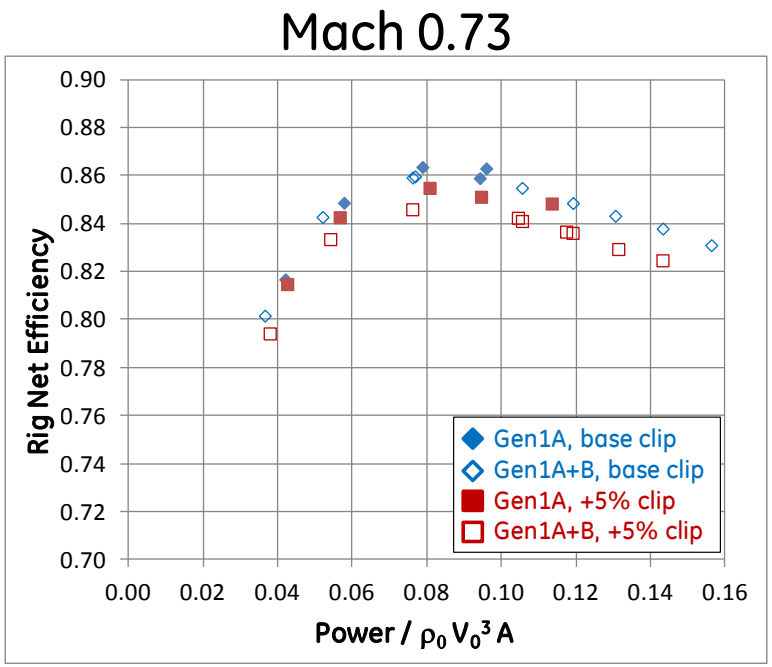
Performance Results
Clipping and spacing

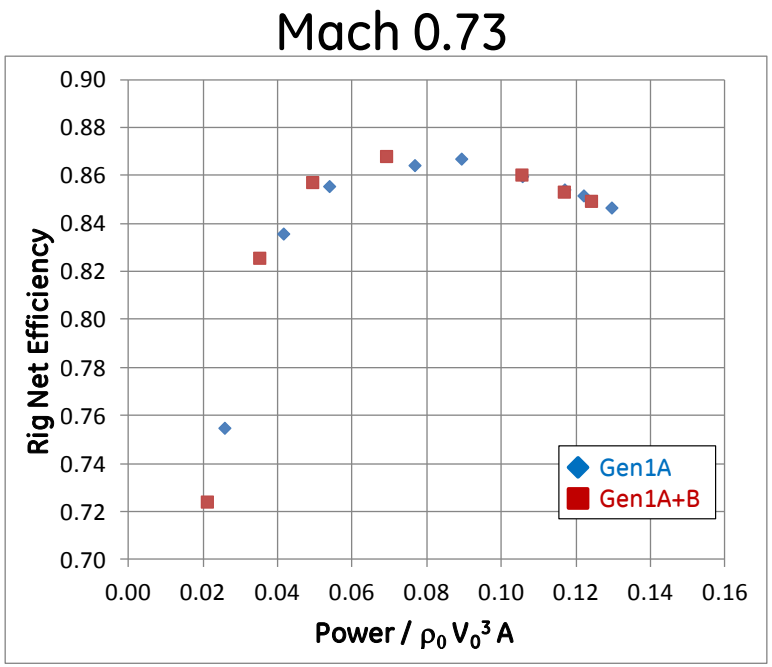




- 5% additional clipping → 1.2 point efficiency penalty at design power
- Performance insensitive over spacing/diameter 0.28 – 0.31

Performance Results
"+B" technology





"+B" technology penalty varies with pitch setting:

- ½ to 1 pt for medium U_t pitch,
- no penalty at low U_t pitch

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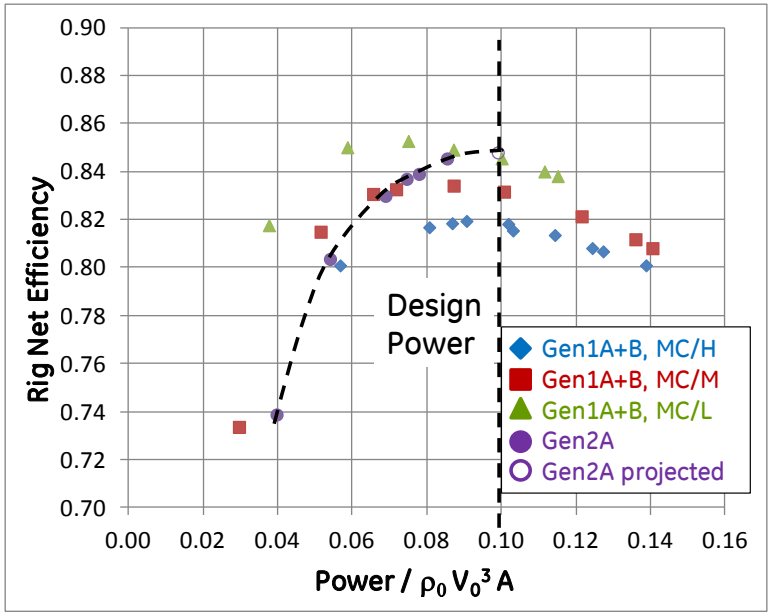
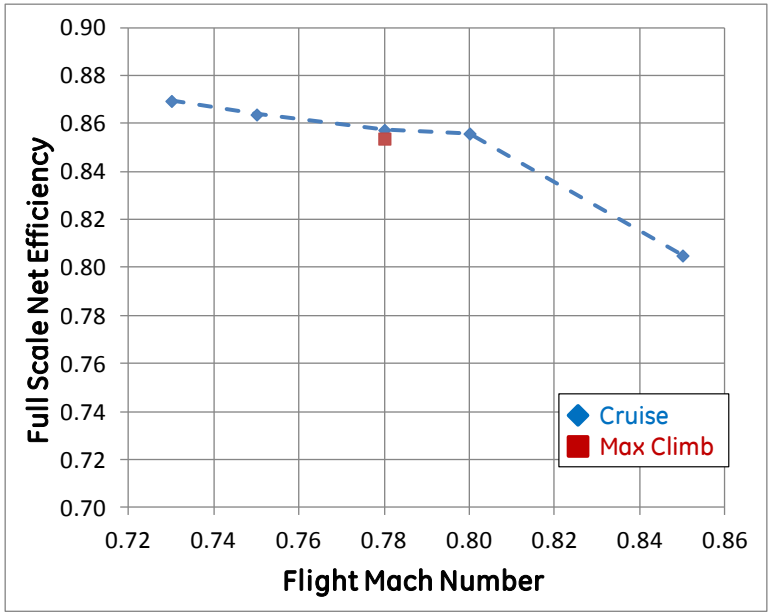
Performance Results

Gen2 and Mach number trend

Mach 0.78



Gen1A+B



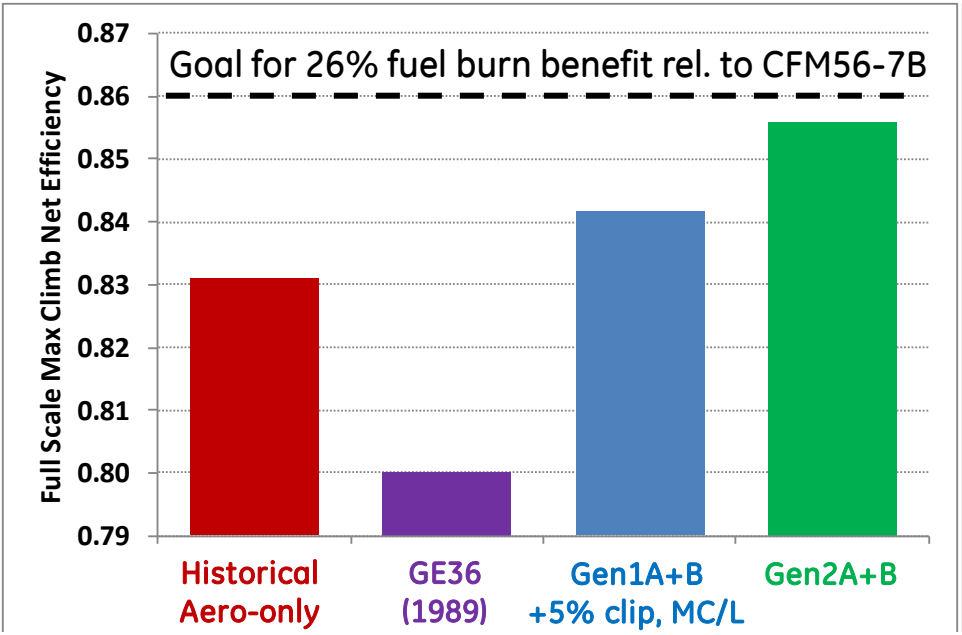
Adjusted rig efficiency by +0.8 pt for full scale Re No.

Design point net efficiency: Gen2A > Gen1A+B

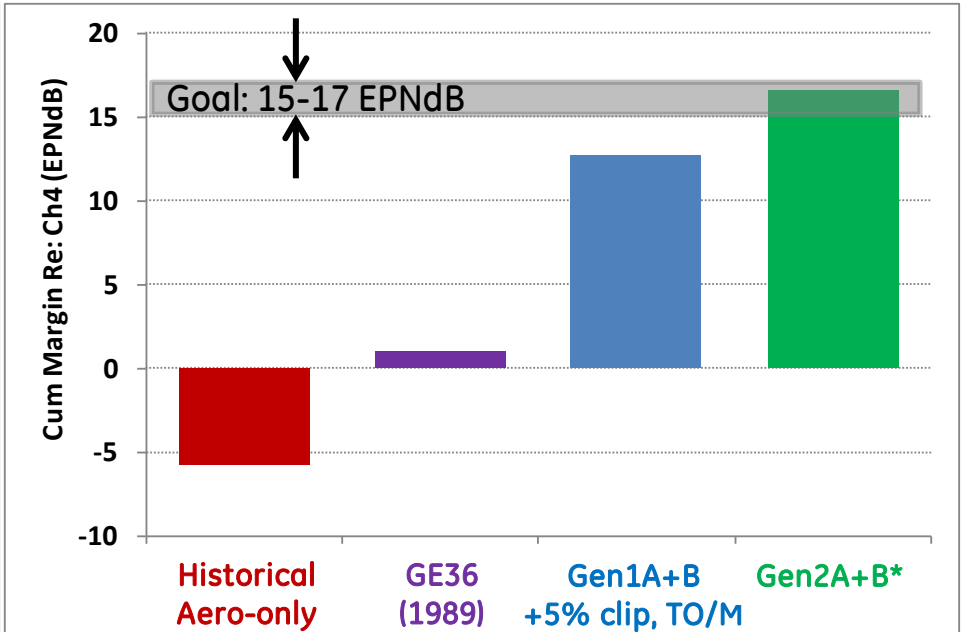
Gen1A+B net efficiency fairly constant up to Mach 0.8

Demonstrated efficiency benefits through Mach 0.8 → no need to fly slow

Open Rotor Technology Progress



- Adjusted rig efficiency by +0.8 pt for full scale Re No.



- Assessments incl. measured effects of AoA & pylon blowing
- Pitch and pylon blowing not necessarily optimized
- Gen2A+B* = measured Gen2A + assessment of "+B" tech *(based on measured Gen1A+B vs. Gen1A)*

- 1980's designs were *marginally* satisfactory for either performance or acoustics
- Demonstrated technology essentially meets CLEEN open rotor goals

Conclusions

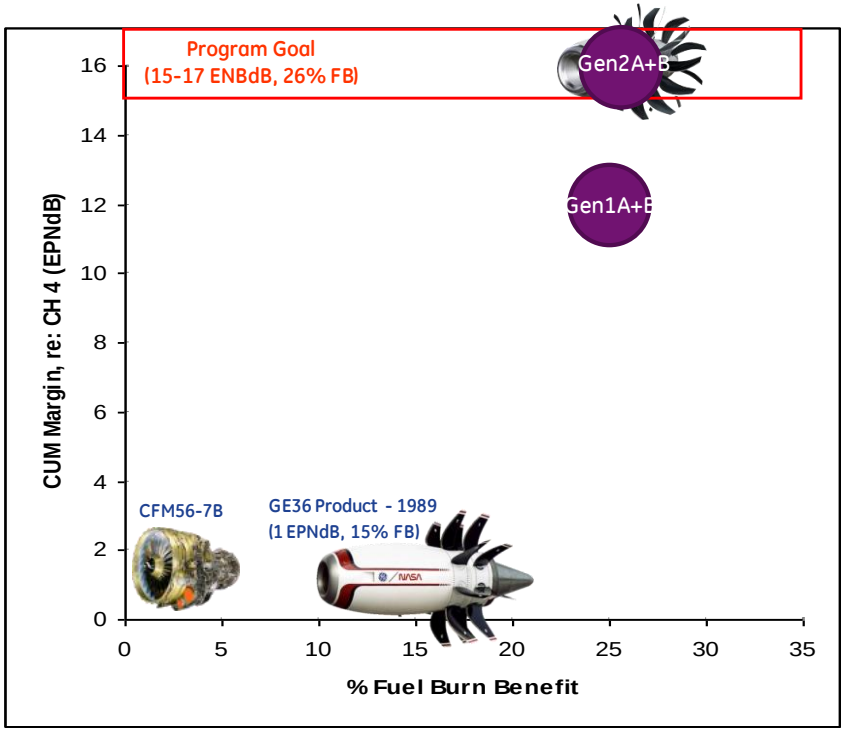
Successful GE/NASA/FAA partnership

- Achieved performance and acoustic goals for future narrow body aircraft

Open rotor technology contributions

- Validated prediction of acoustic trends
  - disk loading, design changes, clipping
- Quantified performance effects
  - clipping, operational pitch/tip speed, and "+B" interaction noise reduction technology
- Good efficiency through Mach 0.8

Identified additional optimization opportunities with demonstrated technology



Open Rotor

Quieter than what's flying today

No need to fly slow

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3. Systems Integration

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Overview

Energy, Emissions & Noise Reduction Objectives

- FMS Efficiency improvements
  - Dynamic Quiet Climb
  - FMS Wind Input Optimization
- FMS/ATM Integration
  - Trajectory Synchronization
  - Trajectory Optimization Tasks
- FMS/Engine Integration
  - Adaptive Engine Control
  - Integrated Vehicle Health Management
  - Integrated Flight-Propulsion Control

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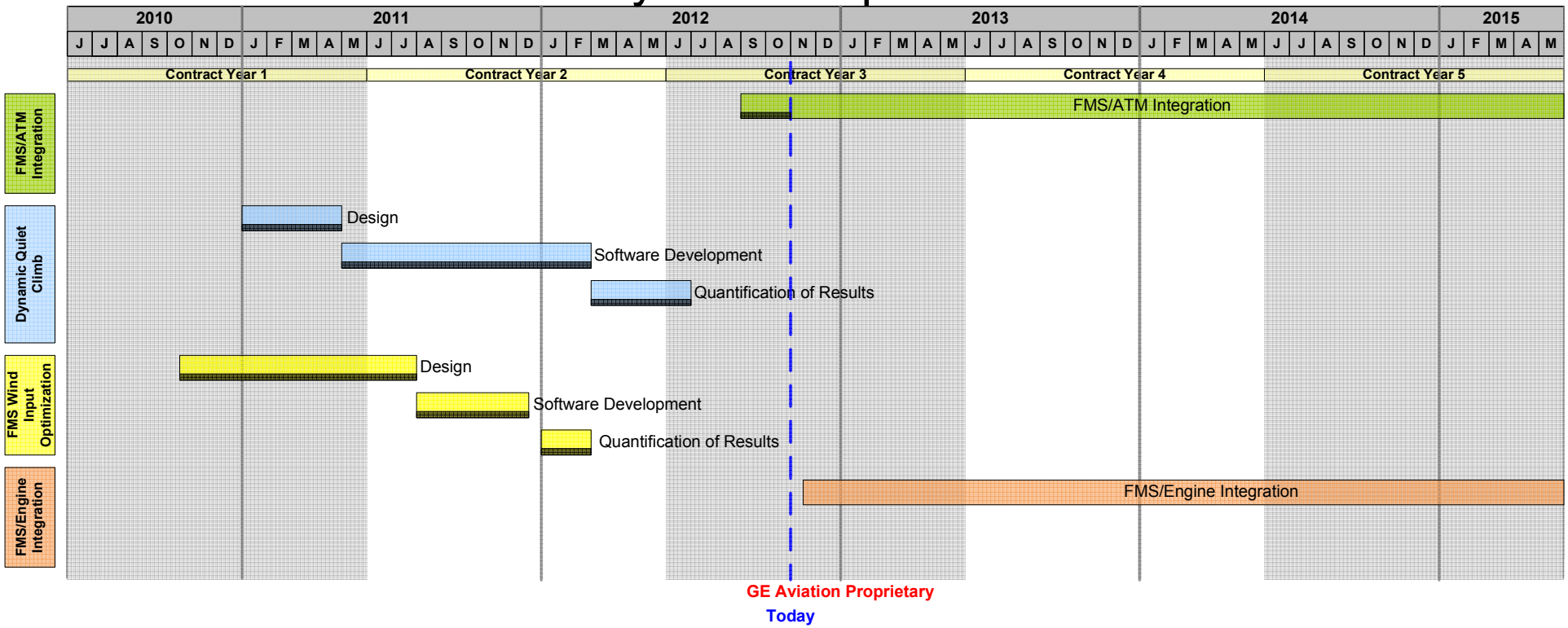
Rev 04 -04

CLEEN - Systems Top Level Schedule



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FMS efficiency improvements

Dynamic Quiet Climb

- *What*: Improved noise abatement takeoff trajectory
- *Why*: Tailored thrust profile reduces fuel burn
- *Status*: Complete

FMS Wind Input Optimization

- *What*: Wind selection tailored to trajectory
- *Why*: Reduce thrust and speed brake use in descent, and improve 4D trajectory prediction in all flight phases
- *Status*: Complete

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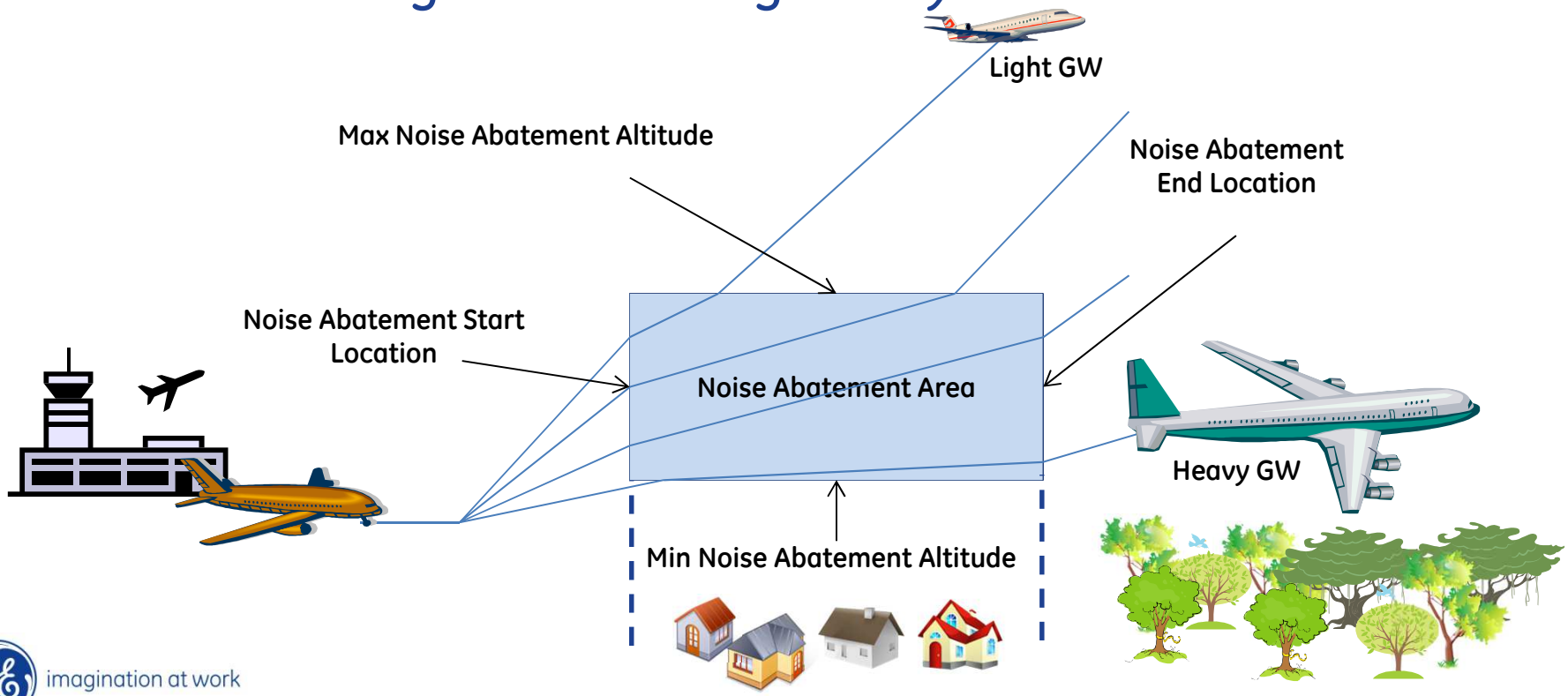
Dynamic Quiet Climb

- Adds location based cutback/restore considerations to current altitude only based procedures
- Improved trajectory predictions accuracy to determine where aircraft will cross the noise restricted volume
- Thrust and configuration changes only where needed



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Dynamic Quiet Climb

Simulation Based Benefits Analysis – B737, John Wayne Airport:

- Average fuel savings per flight using Dynamic Quiet Climb over current altitude based noise procedures:
  - 150,000 lbs Gross Weight – 42 lbs/flight
  - 90,000 lbs Gross Weight – 37 lbs/flight
- AEDT Calculated Noise at Microphones – All microphones recorded noise well under daytime limits, and very near values for altitude based procedure

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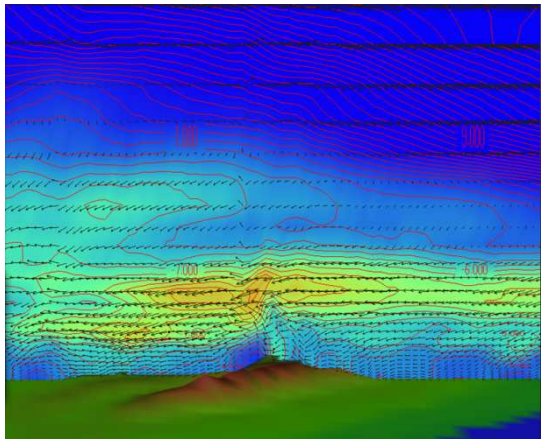
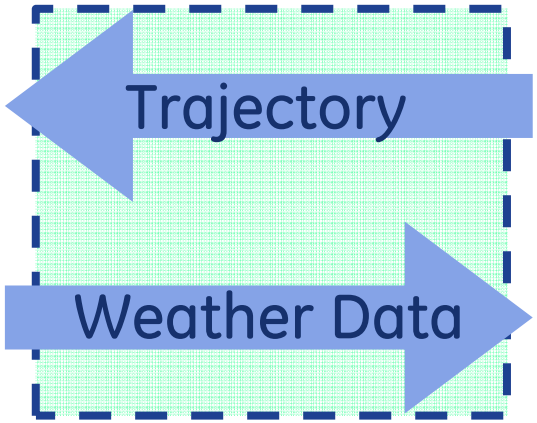
FMS Wind Input Optimization

Trajectory based wind selection

- Minimize extra fuel burn required to maintain vertical path in presence of wind errors
- Minimize use of speed brakes due to excess energy
- Improved predictions accuracy





Wind Input
Optimization Tool

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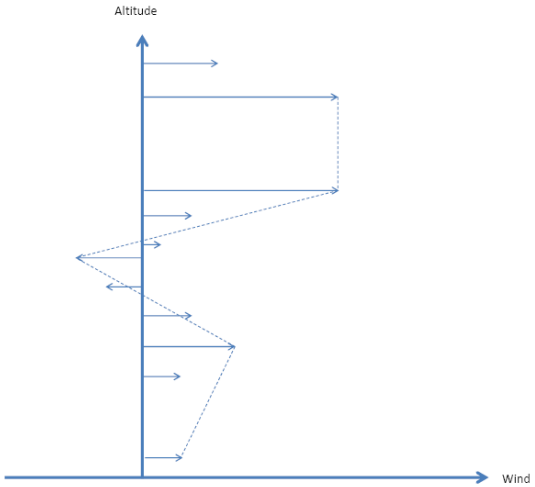
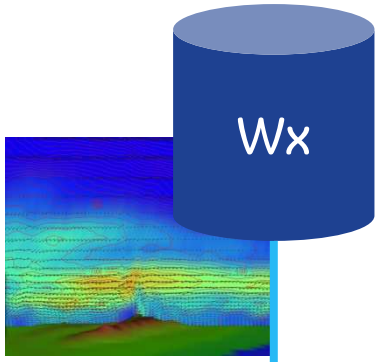
FWIO System overview

Certified weather data provider

Select wind and temperature data that minimize user-tunable cost function for the unique aircraft trajectory





Aircraft Traj

Optimization

4D Trajectory Generator

Provide wind & temp data for uplink to FMC

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FMS Wind Input Optimization

Simulation Based Benefits Analysis – B737:

- Simulation based benefits analysis suggests that ~20 lbs fuel per flight can be saved due to reduction in corrective maneuvers in descent due to inaccuracies in wind inputs
- $1.3 million annual savings in fuel for a 100 aircraft fleet*
- Tailoring winds for climb and cruise result in 2 to 5x increase in preflight predictions accuracy

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*Assumes 4 stages per day, $3/gallon of fuel

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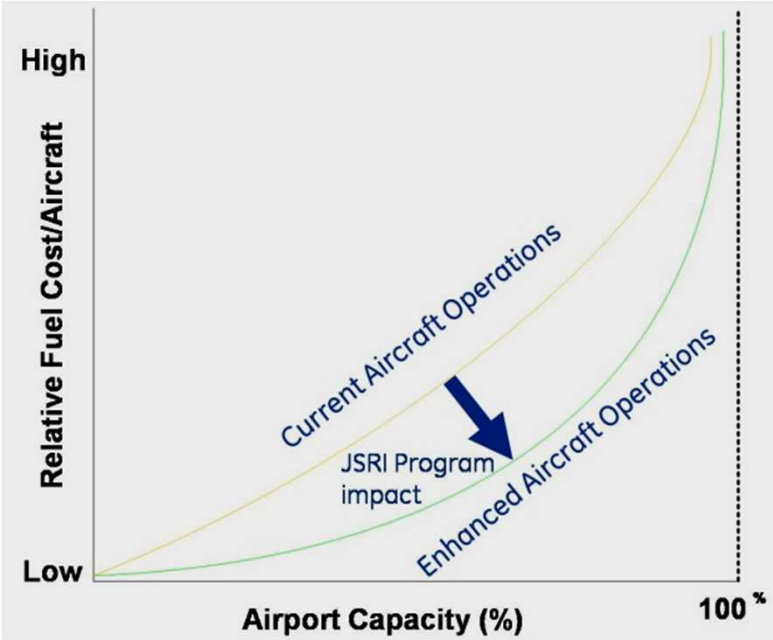
FMS/ATM Integration

Trajectory Sync:
- **What data to exchange**
- **When to exchange it**
- **Improve aircraft predictability**

Trajectory Optimization:
- **Negotiate new trajectories that consider user preferences**
- **Negotiate RTAs to enable optimized profile descent and reduced controller workload**



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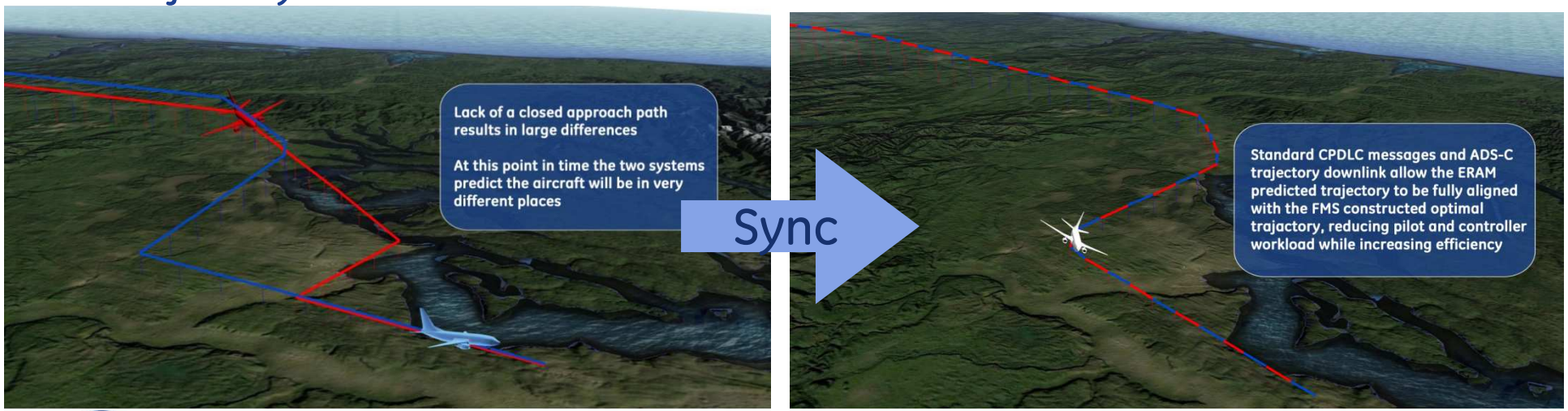
Trajectory Synchronization

Phase 1A

- **Core simulation** environment with integration and communication between aircraft and ERAM
- Incorporate **fast-time trajectory predictor** for primary aircraft
- **Single aircraft** position tracking throughout flight
- CPDLC / ADS-C EPP Implementation (Trajectory Downlink continuation)

Phase 1B

- **Expanded** CPDLC / ADS-C **messages**
- Incorporate **simulated FMS (sFMS)** for primary aircraft
- Incorporate **multiple aircraft** capability using FPPD
- Expanded interface to ERAM
- Real-world environmental benefits



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In collaboration with Lockheed Martin and Embry-Riddle Aeronautical University

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FAA CLEEN
Fuel-Burn Reduction
(Engine-FMS Integration)

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Fuel Burn Reduction Using FMS-Engine Integration

Engine - FMS Integration Offers Greater Opportunities for Environmental and Operational Benefits

- State-awareness is key aspect of technologies

Three primary focus areas of aircraft-engine integration:

- Adaptive Engine Control, FMS for computation and communication with aircraft and ground systems
- Integrated Vehicle Health Management (IVHM), uses knowledge of engine health
- Integrated Flight-Propulsion Control, synergistic optimization of engine and aircraft

Fuel-burn reduction estimated to be approximately 2%

- Thirteen technologies to be evaluated and matured to TRL6

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