National Aeronautics and Space Administration

System Noise Prediction of the DGEN 380 Turbofan Engine

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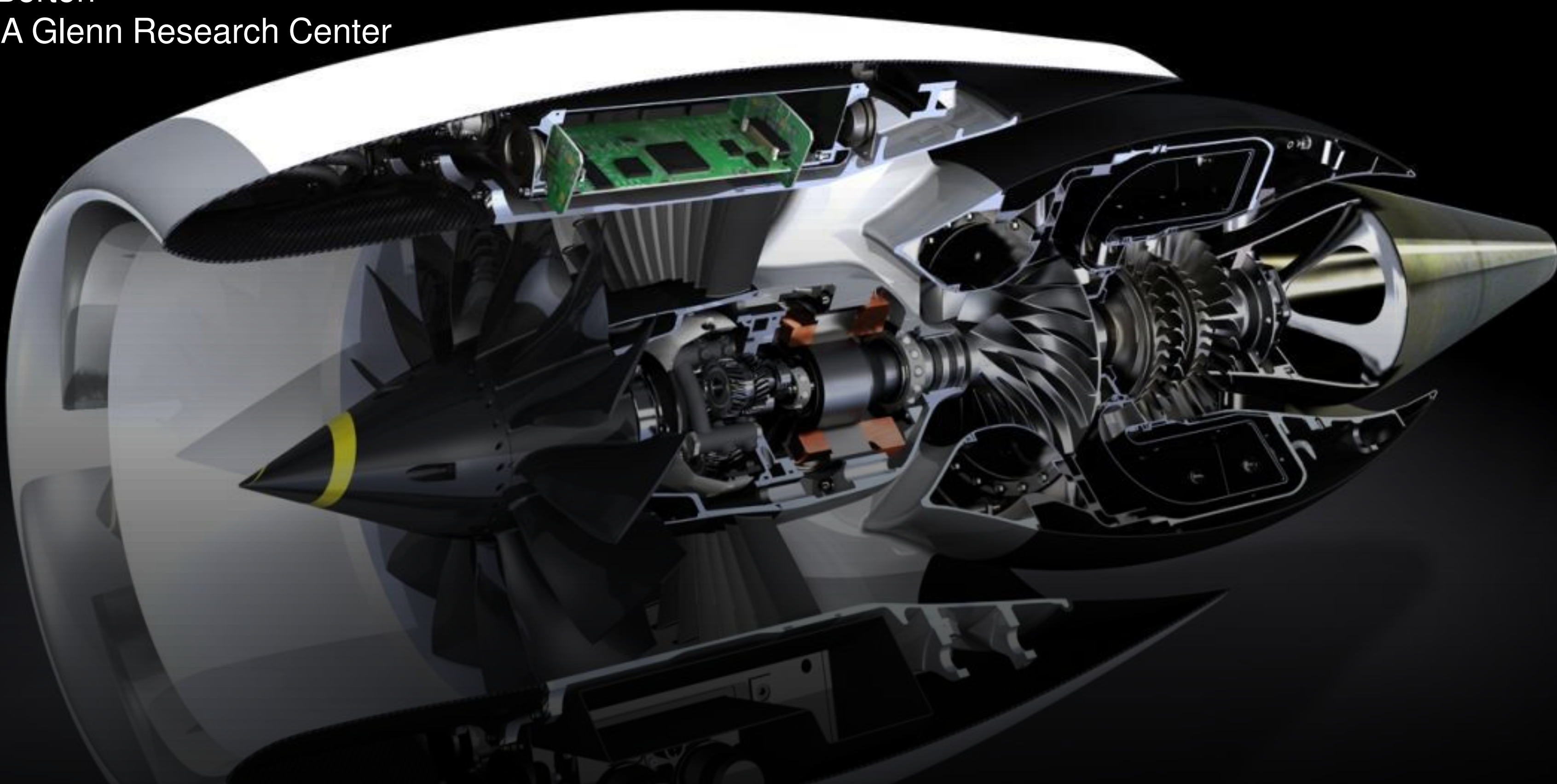

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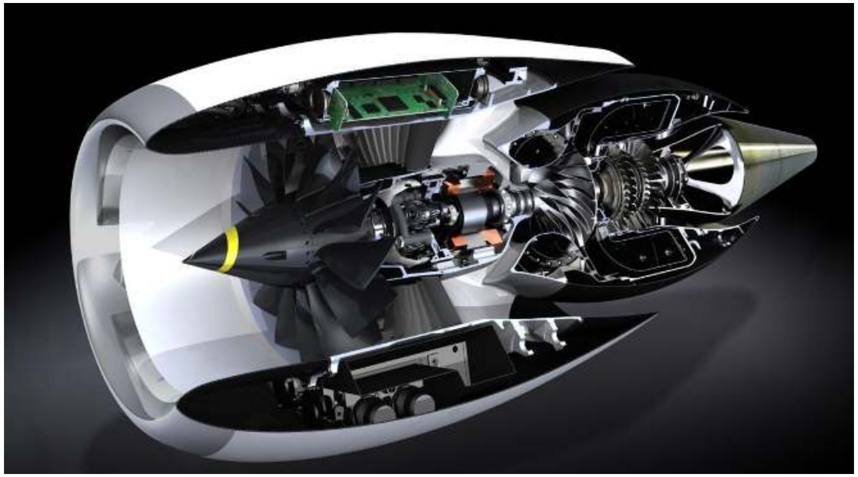
Graphics: Price Induction

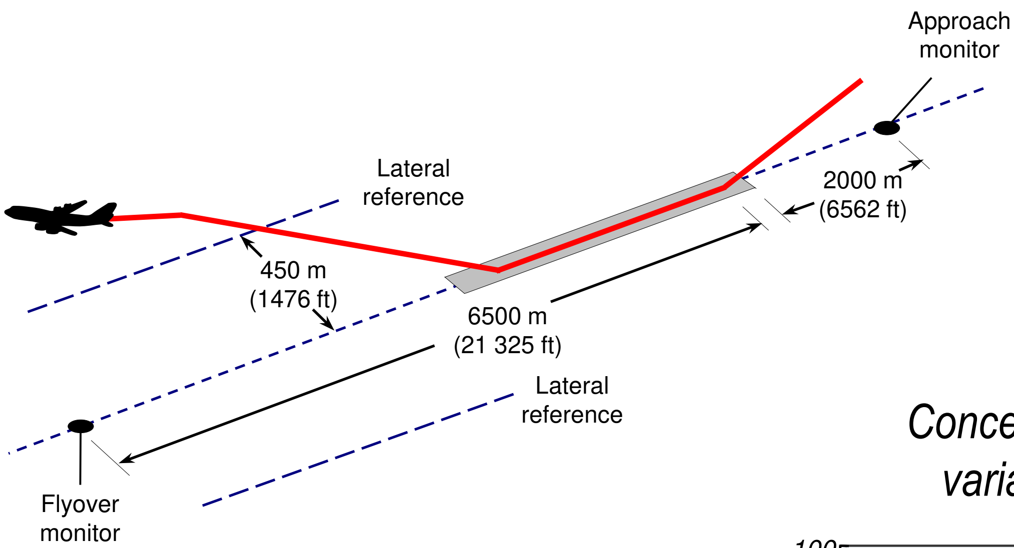
Introduction

- The DGEN 380 is a small, twin-spool, separate-flow, unboosted, geared turbofan manufactured by Price Induction
  - 570lb static thrust
  - 14in diameter fan
  - 7.6 bypass ratio



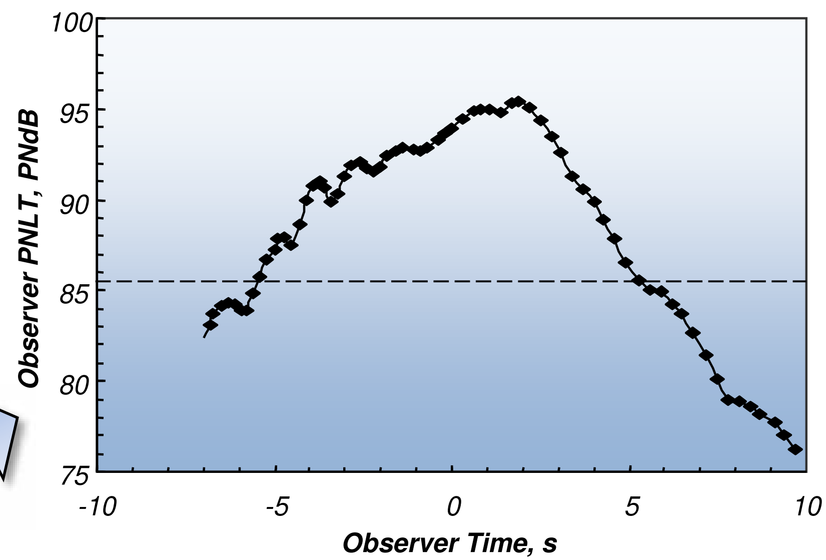
- Promoted for a small, 4- to 5-place twinjet application in the emerging personal light jet market
- Designed for aircraft operating in the regime currently dominated by propeller-driven airplanes under 25,000ft and 250ktas
- DGEN engine on promotional U.S. tour in July, 2014; arrangements made for one-day acoustic test in NASA Glenn's Aero-Acoustic Laboratory dome on July 25
- NASA has interest in purchasing a DGEN to test propulsion technologies in a relevant engine environment; thus, interest in DGEN system noise

System Noise Prediction



Concept airplane used in this study is a jet-powered variant of Cirrus Aircraft's propeller-driven SR22

- Flight conditions
- Spectra propagation
- Ground effects
- Noy-weighted frequency summation
- Tonal content penalties
- Result:
  Ground observer noise vs. time history

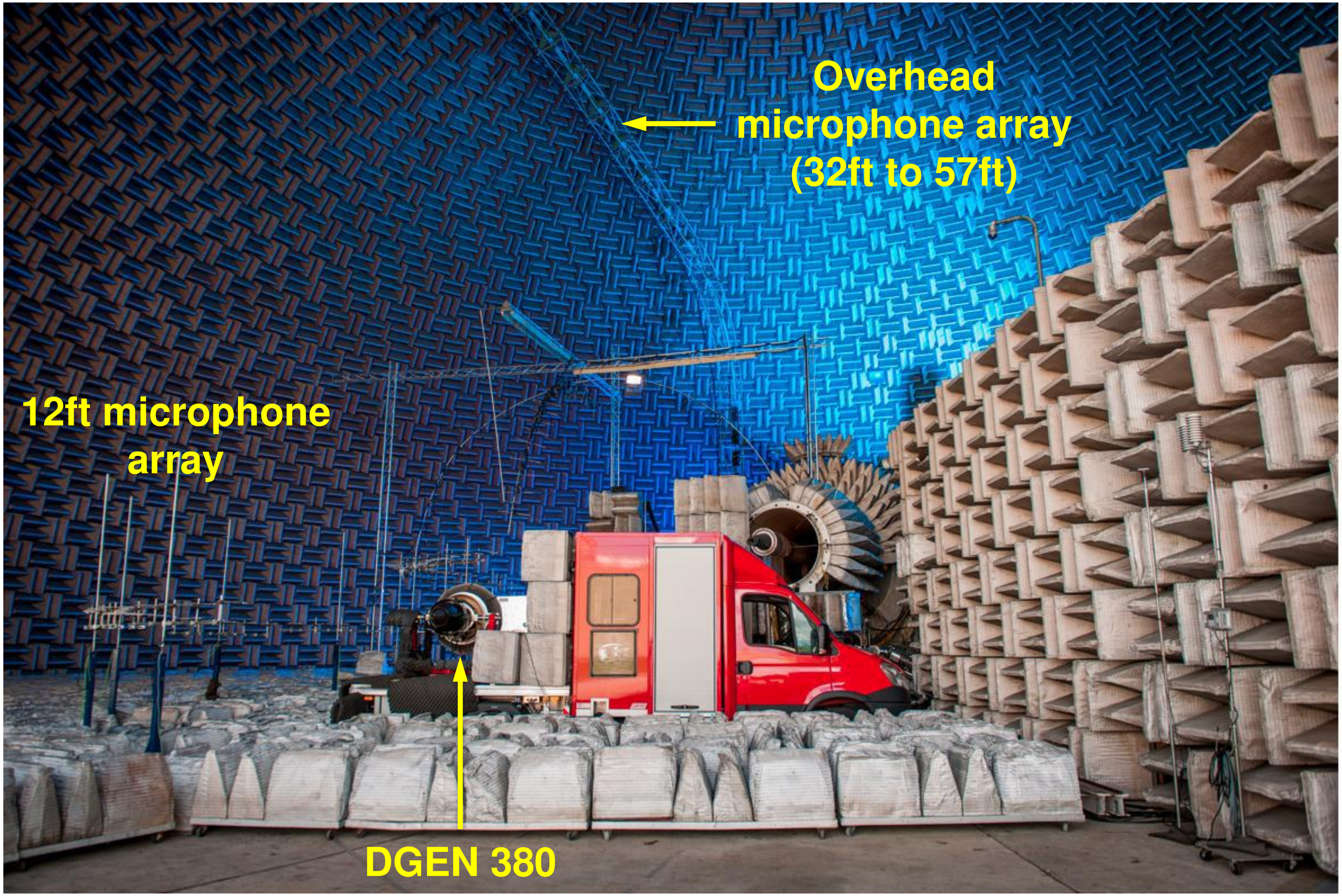


Time integration to Effective Perceived Noise Level

Method of Analysis

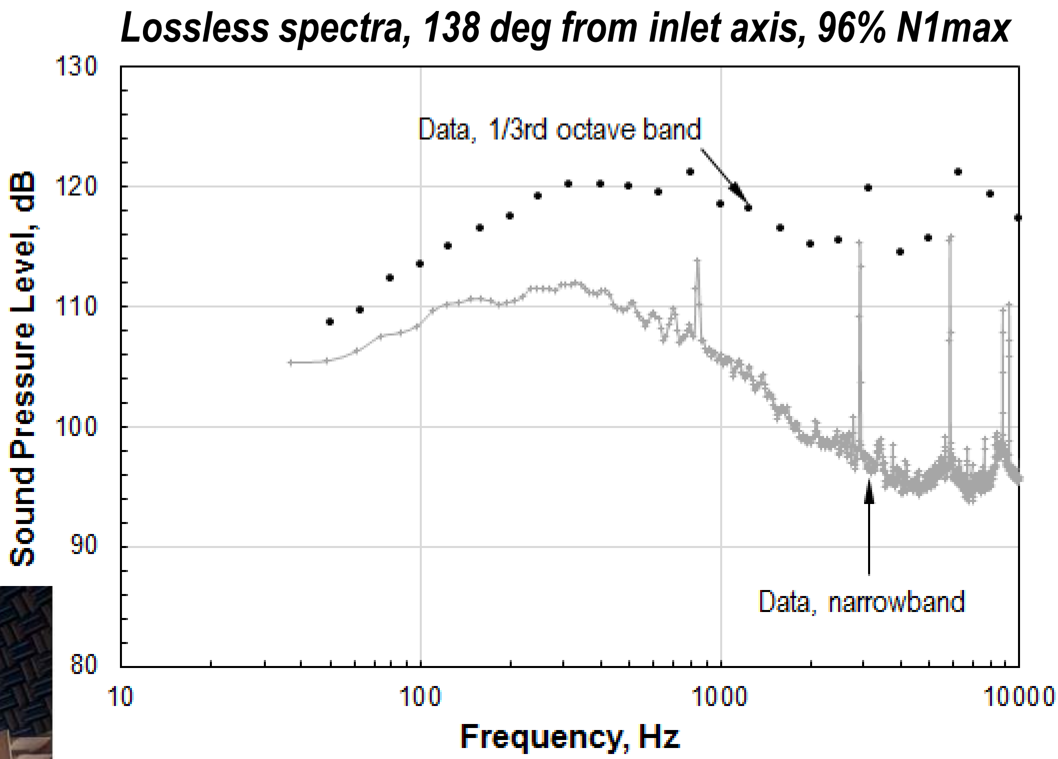
- Most expedient method for computing EPNL is to use measured engine spectra directly with a system noise analysis and propagation tool:
  - Measured spectra analytically “flown” on a trajectory past ground observers
  - Propagation and ground effects applied, EPNL computed for each observer
  - Convection and Doppler flight effects applied to improve accuracy
- Issues with this approach:
  - Engine behavior is different in flight than at ground level
  - Noise measured statically on ground not wholly representative of noise in flight
  - Jet mixing noise is a distributed source radiating along the axial plume of exhaust
- Approach used in this study:
  - Semi-empirical noise prediction methods are derived; used in place of measured noise
  - Noise surrogate models functions of engine state variables; react with flight conditions
  - Surrogate models are calibrated to static spectra measured at NASA
  - Physics-based models are relied on to project spectra to arbitrary flight conditions
  - Surrogate models in place of actual spectra allows for removal of extraneous or spurious portions of the spectra not believed to be genuine engine noise
  - Each noise source can easily be manipulated mathematically

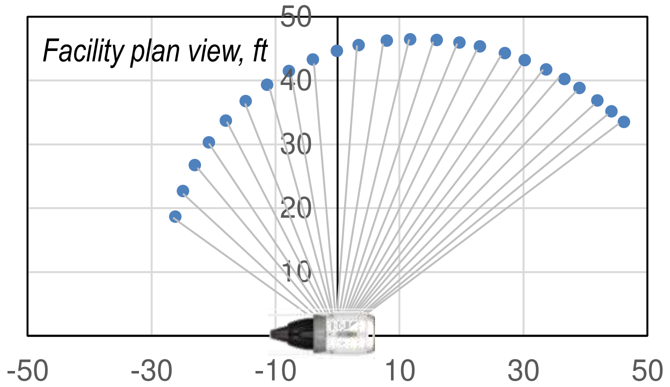
DGEN 380 Test in NASA's Aero-Acoustic Propulsion Laboratory



Engine Source Modeling and Calibration (1)

- One-day static engine test in NASA Glenn dome
- Six throttle settings (47% to 96% N1max)
- 24-microphone overhead array; 32ft to 57ft radius
- Narrowband sound pressure levels collected @12.2Hz BW



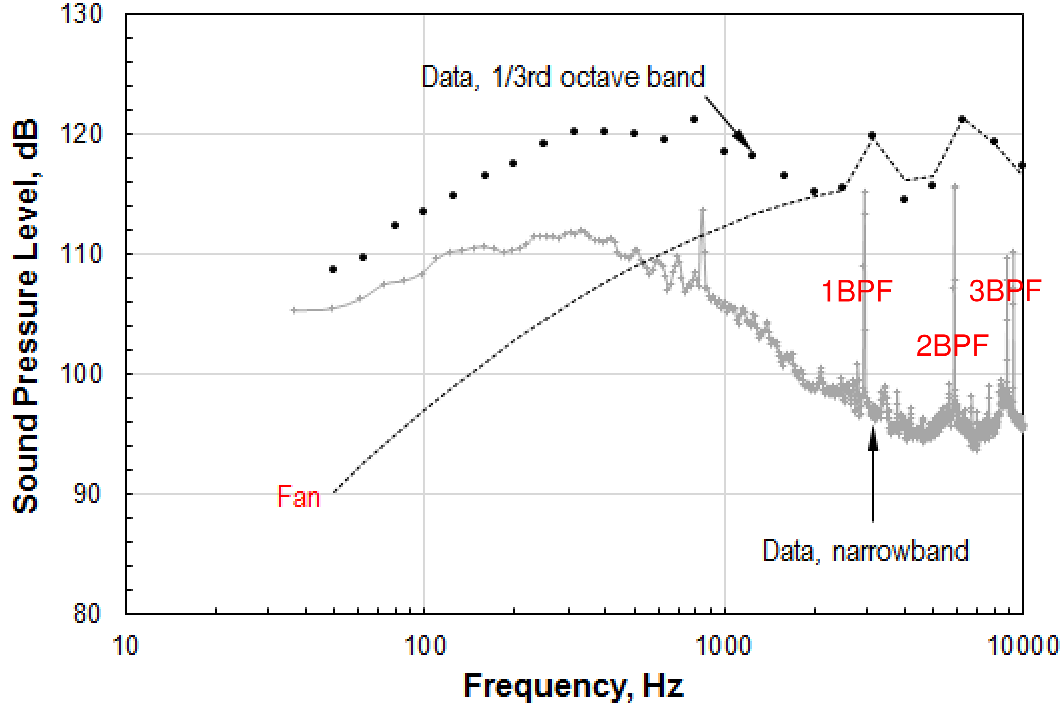


Engine Source Modeling and Calibration (2)

Fan noise:

- Based on empirical Heidmann formulation (1979), recalibrated for modern, wide-chord fans (2014)
- Acoustic power proportional to mass flow, stage temperature rise, and relative tip Mach
- Doppler and convection terms relied on to project source to flight conditions
- Calibration variables
  - x_1 amplitude
  - x_2 curvature
  - $x_3 - x_6$ discrete interaction tone levels

Lossless spectra, 138 deg from inlet axis, 96% N1max



Fan noise model (after Heidmann, et al.):

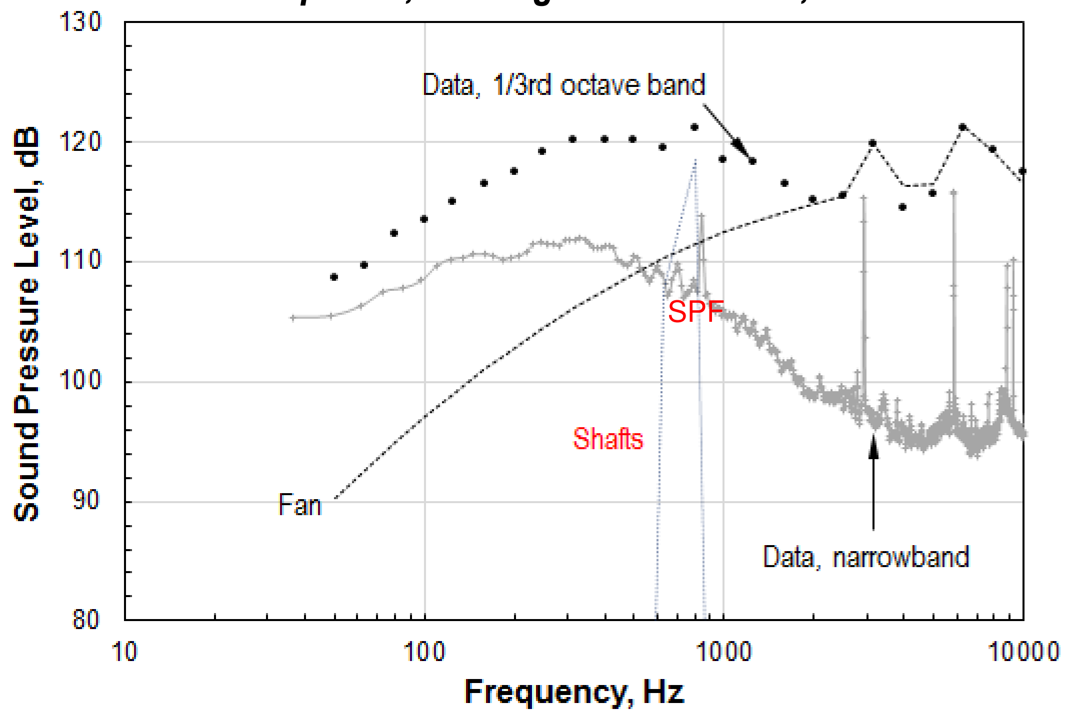
$$L_{Fan}(f,\theta) = 10\log_{10}\left\{ x_1 \frac{\dot{m}}{\dot{m}_{Ref}} \left[\frac{\Delta T_{Fan}}{T_{Ref}}\right]^2 G(M_r) \frac{D(\theta)\, S(f, x_{2-6})}{\left[1 - M_f \cos\theta\right]^k} \right\}$$

Engine Source Modeling and Calibration (3)

Shaft noise:

- Homebrew empirical function
- High- and low-pressure spool speeds used as independent variables
- Filtered at shaft passage frequencies
- Doppler and convection terms relied on to project source to flight conditions
- Calibration variables
  - x_7 low-spool tone
  - x_8 high-spool tone

Lossless spectra, 138 deg from inlet axis, 96% N1max



Shaft noise model:

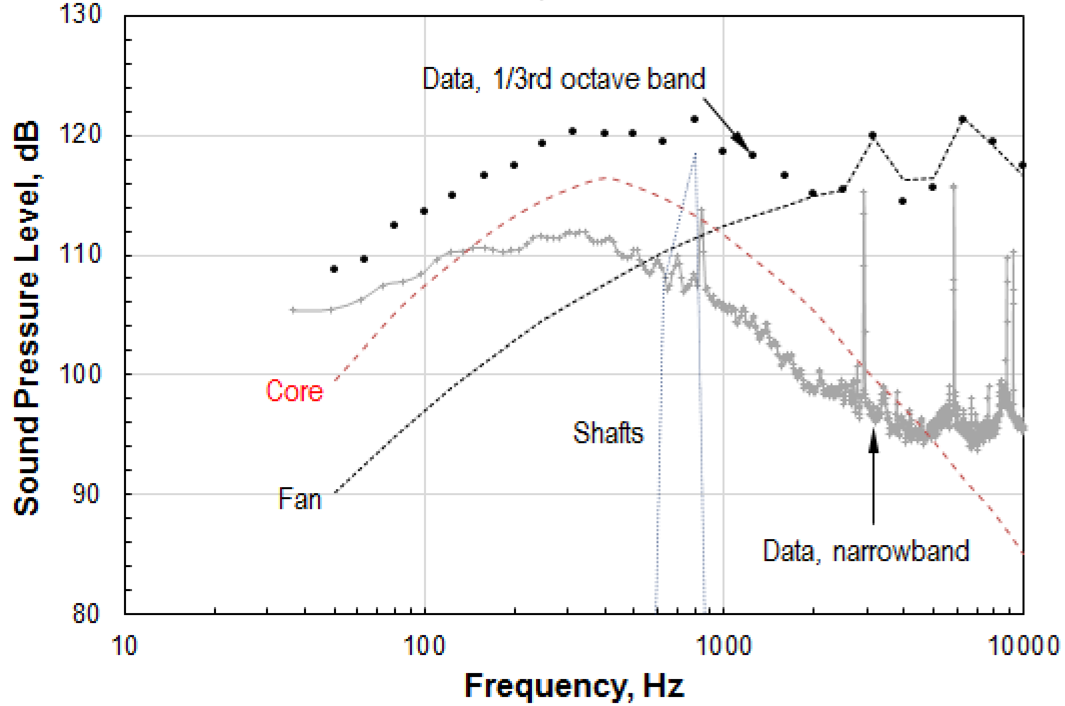
$$L_{Shafts}(f,\theta) = 10\log_{10}\left\{ x_7 x_8 H(N_L, N_H) \frac{D(\theta)\, S(f)}{\left[1 - M_f \cos\theta\right]^k} \right\}$$

Engine Source Modeling and Calibration (4)

Core noise:

- Based on 1976 SAE method
- Acoustic power proportional to burner mass flow, temperature rise, and density
- Difficult to tell when, or if, jet noise is masquerading as core noise or vice versa
- Source signal separation coherence techniques
- Use low engine power settings as a guide
- Calibration variables
  - x_9 amplitude
  - x_{10} curvature

Lossless spectra, 138 deg from inlet axis, 96% N1max



Core noise model (after Matta):

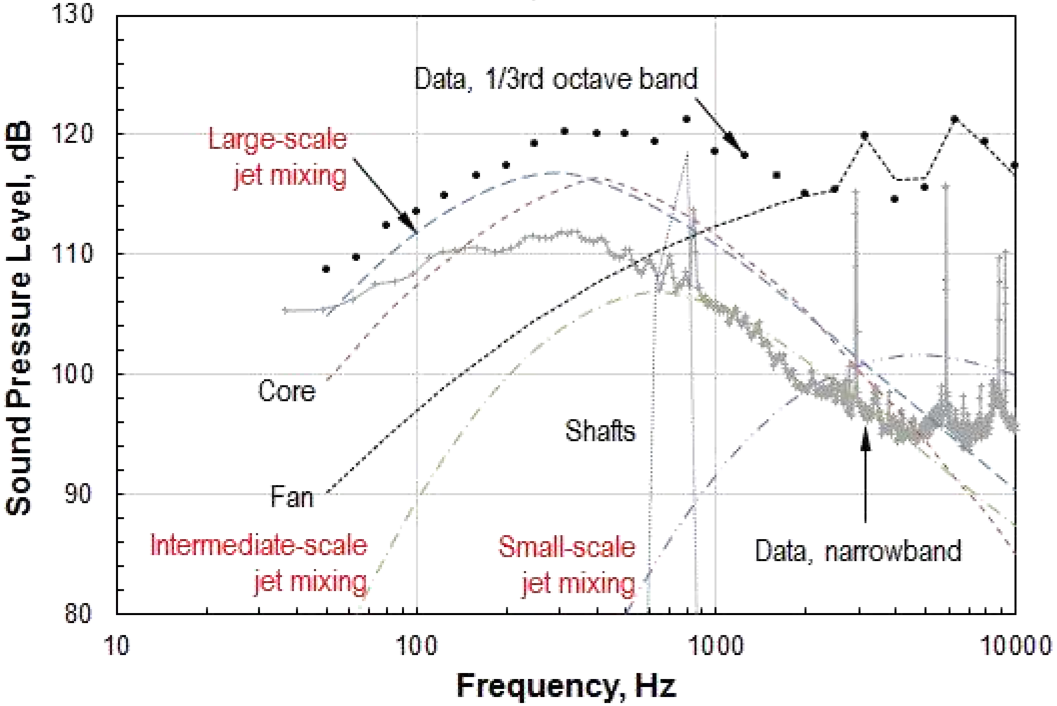
$$L_{Core}(f,\theta) = 10\log_{10}\left\{ x_9 \frac{\dot{m}}{\dot{m}_{Ref}} \left[\frac{\Delta T_{Comb}}{T_{Ref}}\right]^2 \left[\frac{\rho_{Comb}}{\rho_{Ref}}\right]^2 \frac{D(\theta)\, S(f, x_{10})}{\left[1 - M_f \cos\theta\right]^k} \right\}$$

Engine Source Modeling and Calibration (5)

Jet noise:

- Based on 2009 Stone method
- Jet mixing noise modeled as three virtual sources
- Each spectrum is adjusted to the microphone distance to exploit model's convection/refraction features
- Calibration variable: x_{11} amplitude

Lossless spectra, 138 deg from inlet axis, 96% N1max



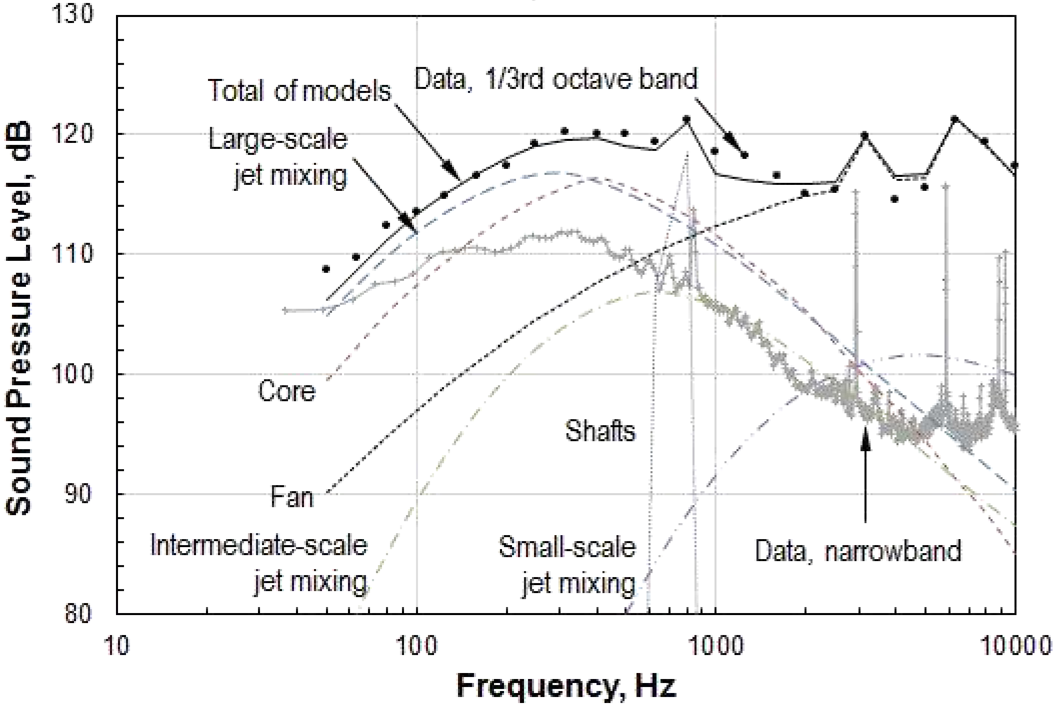
Jet noise model (after Stone):

$$L_{Jet}(f,\theta) = 10\log_{10}\left\{ x_{11}\left(V_e/c_{Ref}\right)^n \left(\rho/\rho_{Ref}\right)^{\omega} \frac{D(\theta_e)\,S(f,\theta_e)}{\left(1+M_c\cos\theta\right)^2+\alpha^2 M_c^2} \right\}$$

Engine Source Modeling and Calibration (6)

- Optimizer used to aid fitment of noise models to measurements
- Imperfect models, imperfect data… composite objective:
  - Sound pressure levels
  - Perceived noise level with tone penalty correction
- Minimum, nonzero $O(\mathbf{x})$ does not result in a unique solution
- Values of x should not stray too far from their nominal values, set limits

Lossless spectra, 138 deg from inlet axis, 96% N1max



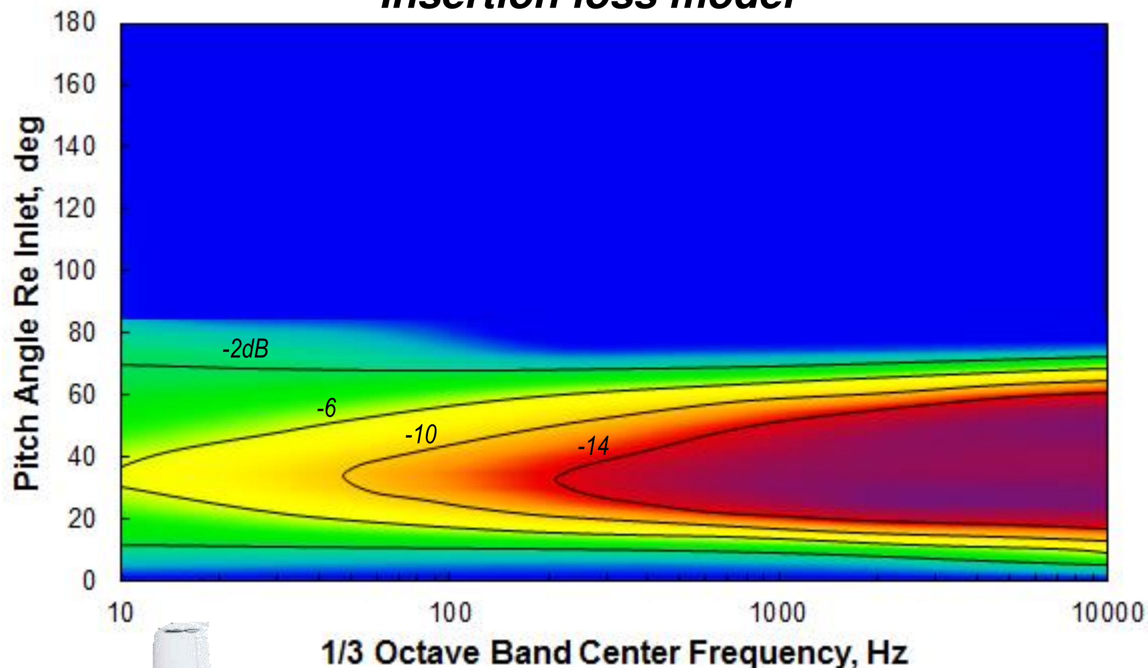
Spectral fitment objective function:

$$O(\mathbf{x}) = w_1 \frac{\sum_i \left(L_{i,data} - L_{i,model}\right)^2}{\sum_i \left(L_{i,data} - \bar{L}_{data}\right)^2} + w_2 \left(L_{TPN,data} - L_{TPN,model}\right)^2$$

Wing Planform Shielding

- Maekawa diffraction loss method
- Implemented as function of Fresnel number
- Applied to fan and core noise sources
- Not subject to shielding:
  - Airframe noise sources
  - Jet noise:
    A distributed source generated downstream throughout axial exhaust plume

Insertion loss model

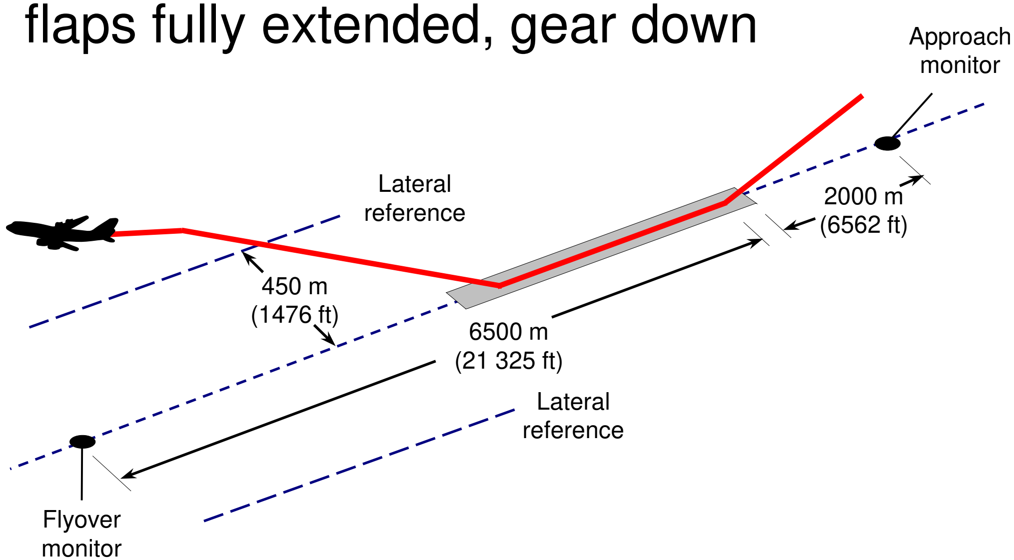


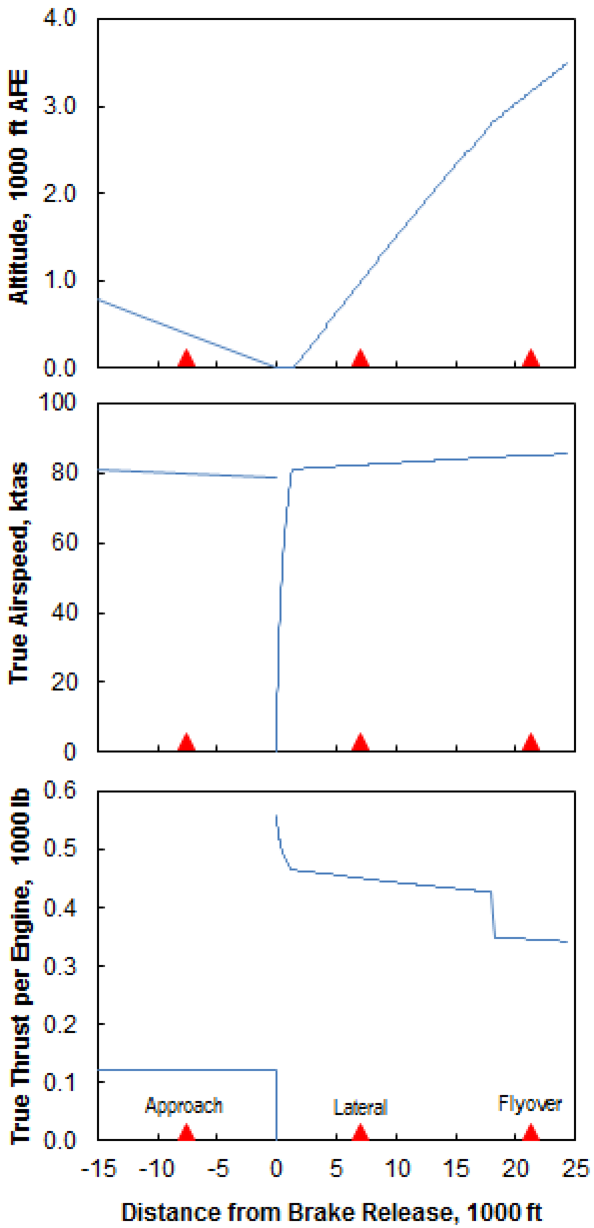
Maekawa diffraction expression:

$$L_I = 20\log_{10}\left(\sqrt{2\pi|F|}\Big/\tanh\sqrt{2\pi|F|}\right) + 5$$

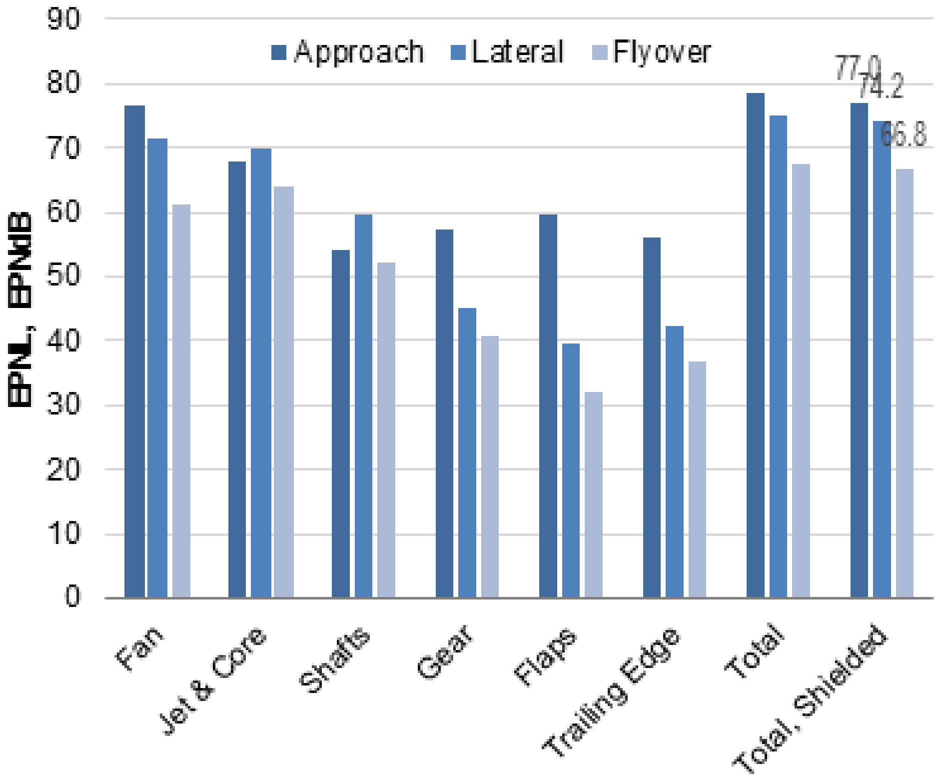
Airplane Trajectory

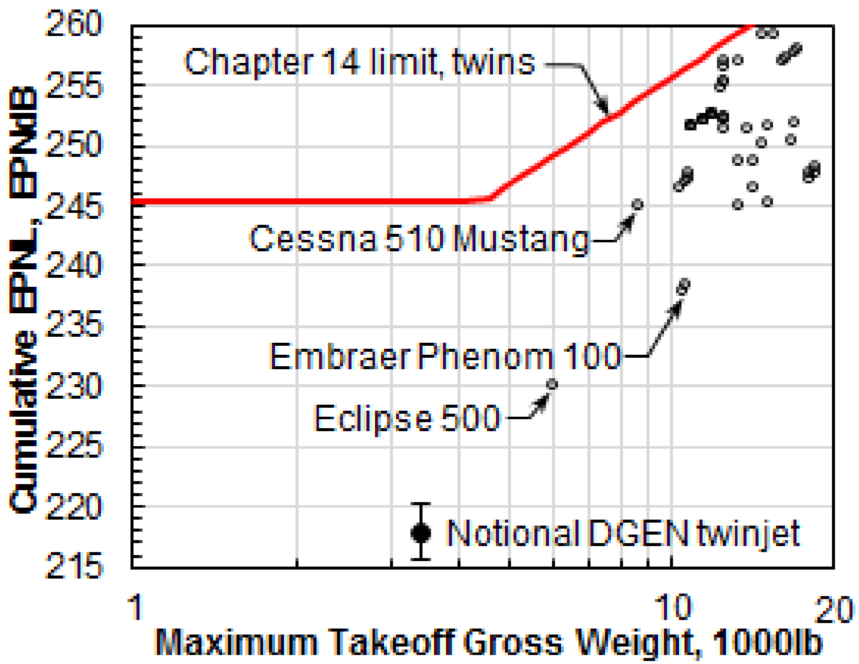
- Cirrus SR22 takeoff at 3400lb gross weight, 50% flaps
- Noise abatement power cutback; climb gradient:
  - 4%, all engines operating
  - Zero, one engine inoperative
- Approach at 2790lb
- Three-degree approach glide slope, with flaps fully extended, gear down





Noise Prediction Results



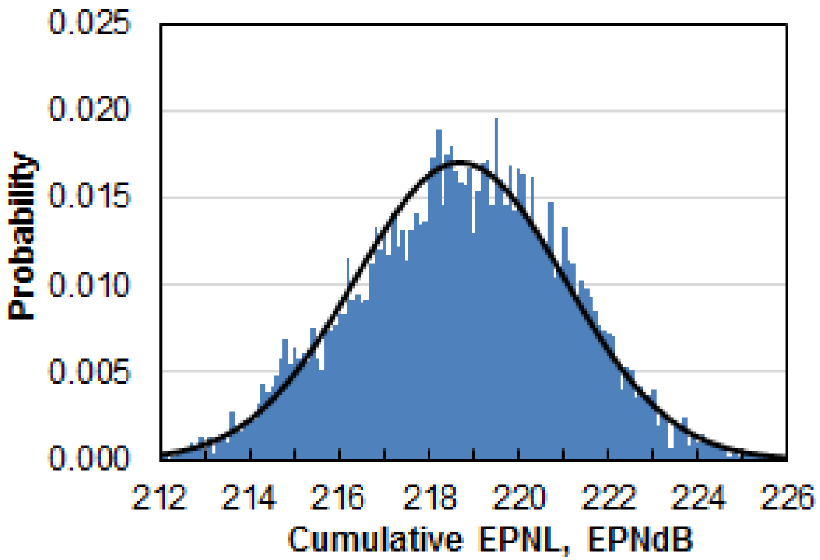


- Chapter 4 cumulative margin: 53.1 EPNdB
- Chapter 14 cumulative margin: 27.4 EPNdB

Meets NASA's "N+3" noise goal, albeit at a much smaller size!

Monte Carlo Uncertainty Analysis

- Real engine, notional airplane… Uncertainty analysis needed!
- Modeling unknowns chosen by top-down decomposition of problem
- Variables categorized into trajectory, source levels, environmental & installation classes
- Variables chosen to represent effects that would cause values to stray from benchmark during airplane development
- Benchmark noise model transformed into stochastic model
- Variables randomly permuted around benchmark case



Histogram and normal distribution generated from 8000 samples (bin span 0.1 EPNdB)

Statistic	Approach	Lateral	Flyover	Cumulative
Benchmark case	77.0	74.2	66.8	217.9
Minimum of samples	74.3	70.6	64.4	209.5
Maximum of samples	80.5	78.1	69.7	226.4
Range of samples	6.2	7.6	5.3	17.0
Mean of samples	77.3	74.6	66.8	218.7
Standard deviation	0.9	1.2	0.8	2.3

Uncertainty statistics (in EPNdB)

Summary

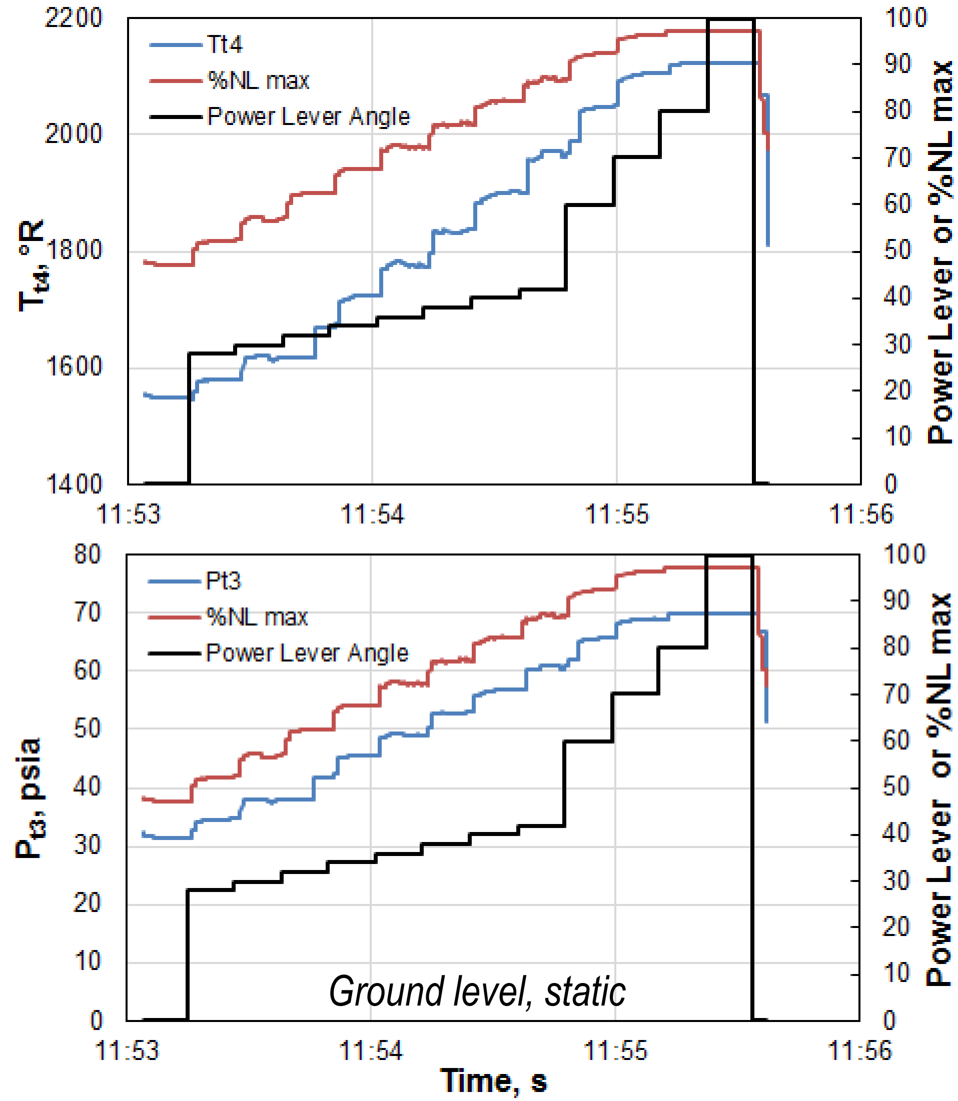
- Static noise measurements of a Price Induction DGEN 380 turbofan were collected at NASA Glenn Research Center
- Noise source models were calibrated and used to analytically project static spectra to flight conditions
- Embedded physics-based behavior allows noise source models to react properly to changing engine state and flight conditions
- The DGEN is a quiet turbofan, owing not only to its small size, but also to its design
- Cumulative margins to Chapter 14 and Chapter 4 limits are predicted to be 27.4 and 53.1 EPNdB, respectively

NASA

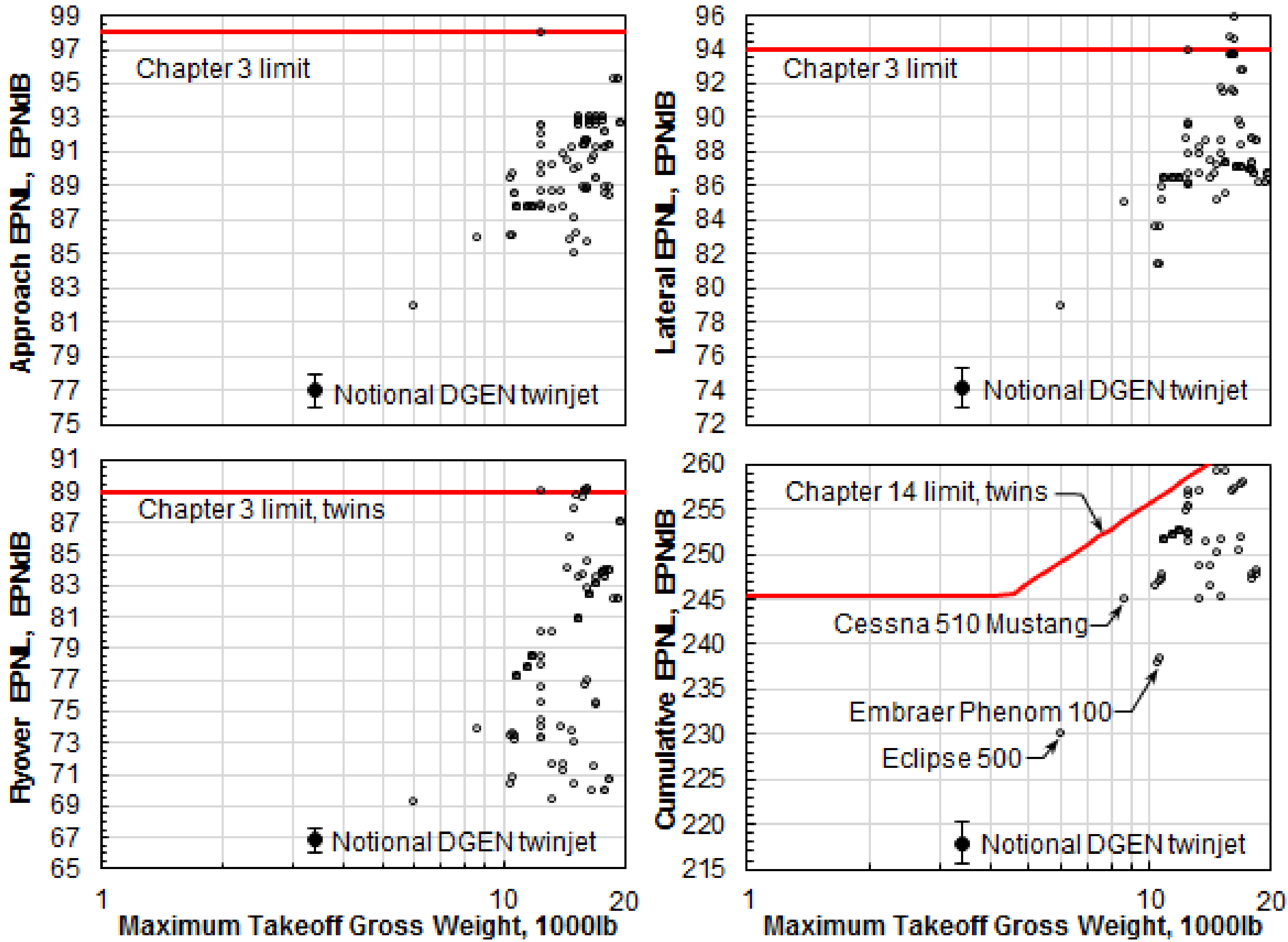
Backup Slides

Simulated Engine Cycle Data

- Empirical noise models require engine cycle data for noise level scaling
- Engine cycle data not measured during acoustic test
- Price Induction's "Virtual Engine Test Bench," a DGEN 380 digital engine control unit
- Engine data response surfaces generated for steady pressures, temperatures and airflows (ISA+18˚F) at all major engine flowstations as function of airspeed, altitude and low-spool shaft speed



Noise Prediction Results



Monte Carlo Uncertainty Analysis

Variables perturbed in Monte Carlo experiment

	Variable	Mode	Model	Min	Max	Std. Dev.
Trajectory-related effects	Approach flight Mach no.	0.119	Triangular	0.112	0.126	-
	Lateral flight Mach no.	0.123	Triangular	0.119	0.127	-
	Flyover flight Mach no.	0.128	Triangular	0.120	0.150	-
	Approach N_L setpoint	60%	Triangular	58%	62%	-
	Lateral N_L setpoint	96%	Triangular	94%	100%	-
	Flyover N_L setpoint	90%	Triangular	87%	93%	-
	Approach angle of attack	6°	Triangular	5°	7°	-
	Lateral angle of attack	6°	Triangular	5°	7°	-
	Flyover angle of attack	6°	Triangular	5°	7°	-
	Flyover altitude	3170ft	Triangular	2850ft	3490ft	-
Source levels	Fan noise adjustment	0	Normal	-	-	1.0dB
	Core noise adjustment	0	Normal	-	-	1.0dB
	Shaft noise adjustment	0	Normal	-	-	1.0dB
	Jet noise adjustment	0	Normal	-	-	1.0dB
	Landing gear noise adjustment	0	Normal	-	-	1.5dB
	Flap noise adjustment	0	Normal	-	-	1.5dB
	Trailing edge noise adjustment	0	Normal	-	-	1.5dB
Environment & installation	Ground specific flow resistance	291sl/s-ft^3	Triangular	233sl/s-ft^3	349sl/s-ft^3	-
	Lateral attenuation adjustment	0	Triangular	-2dB	2dB	-
	Wing area (shielding)	155ft^2	Uniform	0	200ft^2	-