National Aeronautics and Space Administration

Learjet Update

Flight and Scale-Model-Nozzle Acoustics Test

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NASA Advanced Air Vehicles Program
Commercial Supersonic Technology Project

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INTRODUCTION

Motivation

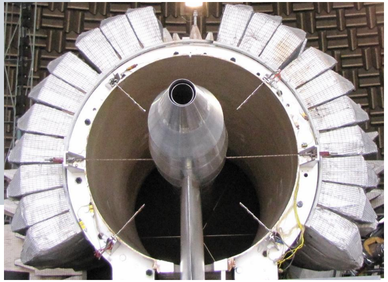
- Improve ability to predict takeoff noise of future supersonic aircraft

Objective

- Validate/Improve application of semi-empirical jet-noise prediction to flight noise
- Establish uncertainty in rig-to-flight transformation

Approach

- Learjet25/CJ610 flyover acoustic data
- AAPL/NATR scale-model acoustic data
- Compare flight and facility acoustic data



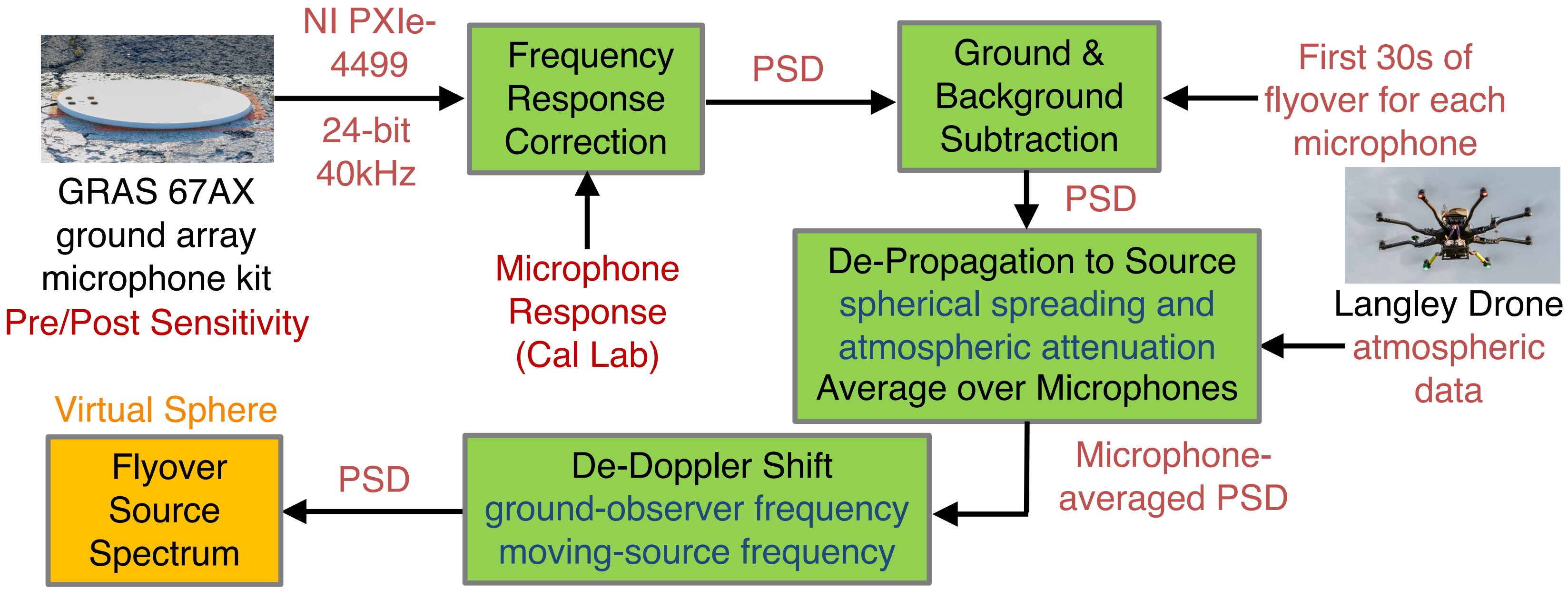
Significance

- Enable improved noise-prediction methods for use in system studies of future commercial supersonic transport aircraft

FLIGHT TEST – KIAG, September 1 & 8, 2022

- Learjet 25/CJ610 aircraft selected to ensure jet-noise dominated source
- Aircraft owned and operated by Calspan Corporation (under NASA Contract)
- Research instrumentation on aircraft for continuous recording of position (NASA) and select engine/aircraft data (Calspan; EPR, EGT, RPM, static & dynamic P_{pitot})
- 9-microphone linear array on the ground
- LiDAR for wind measurements
- Langley drone for atmospheric measurements
- 4 sorties over 2 days – total of 73 flyovers
- Aircraft flown at constant climb angles
- No flaps or landing gear deployed
- One engine at idle
- All data timestamped based on GPS

ACOUSTIC DATA PROCESSING – NASA GLENN



- Spectra computed using 0.512s interval centered about reception time (each θ_e)
- $N_{FFT} = 4096$ & pwelch (MATLAB) => 9 averages per microphone & $\Delta f = 9.77$Hz
- Each flyover spectrum is an average of 81 instantaneous spectra

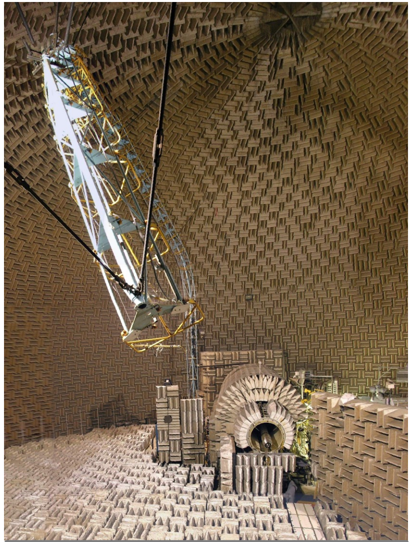
NASA GRC AAPL/NATR — Completed October 6, 2022

- Complementary Learjet scale-model test in the Aero-Acoustic Propulsion Laboratory carried out immediately after flight test
- Conditions representing those of the flight data

GRAS 46BE free-field microphones (20 s) → NI PXIe-4499, 24-bit, 200kHz → Frequency Response Correction → PSD → De-Propagation to Source: shear layer refraction, spherical spreading, atmospheric attenuation, Interpolate Microphones → PSD → Scaled-Up Source Data

- 20 s acquisition time
- N_{FFT} = 16,384, 50% overlap, Δf = 12.21Hz
- Each source spectrum is an average of 488 instantaneous spectra
- Scale frequencies and spectra to full scale
- $f_{fs} = f_{sm} / SF$ & $PSD_{fs} = (SF)^3 PSD_{sm}$

AAPL/NATR
$SF = 3.21$



NASA AAPL/NATR Facility with overhead geometric farfield 24-microphone array

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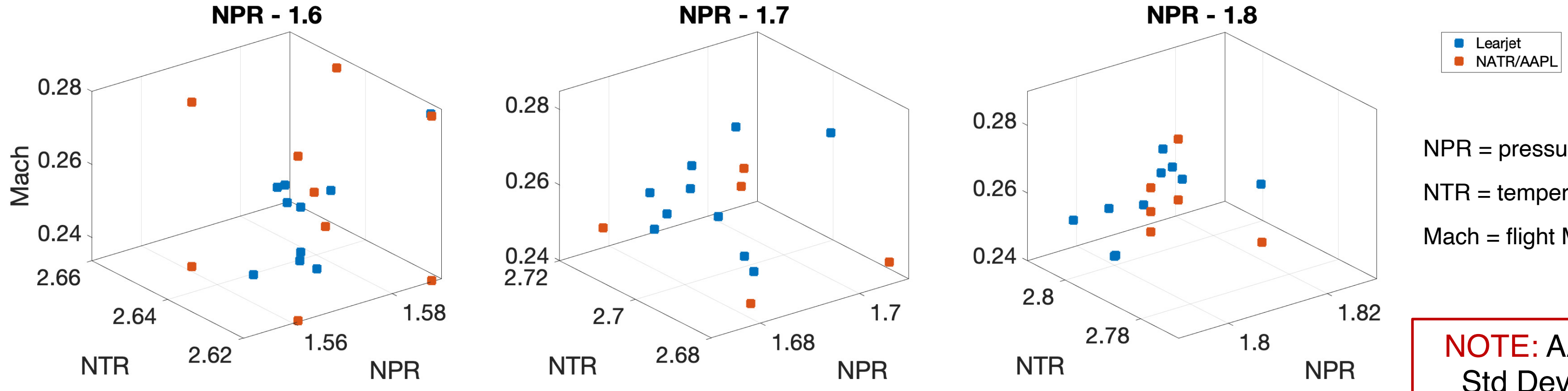
NOMINAL NOZZLE PRESSURE RATIOS ANALYZED

- NPR_{nom} = 1.6, 1.7, and 1.8 analyzed so far — data also available for 1.9 – 2.1



NPR = pressure ratio

NTR = temperature ratio

Mach = flight Mach number

NOTE: AAPL/NATR Std Dev does not reflect condition dial-in and hold capability — rather our strategy

NPR_{nom} – 1.6

	Average	Std Dev	Average	Std Dev
NPR	1.575	0.007	1.575	0.013
NTR	2.636	0.009	2.634	0.013
Mach	0.249	0.014	0.256	0.021

NPR_{nom} – 1.7

	Average	Std Dev	Average	Std Dev
NPR	1.689	0.007	1.691	0.012
NTR	2.704	0.014	2.698	0.016
Mach	0.257	0.011	0.253	0.010

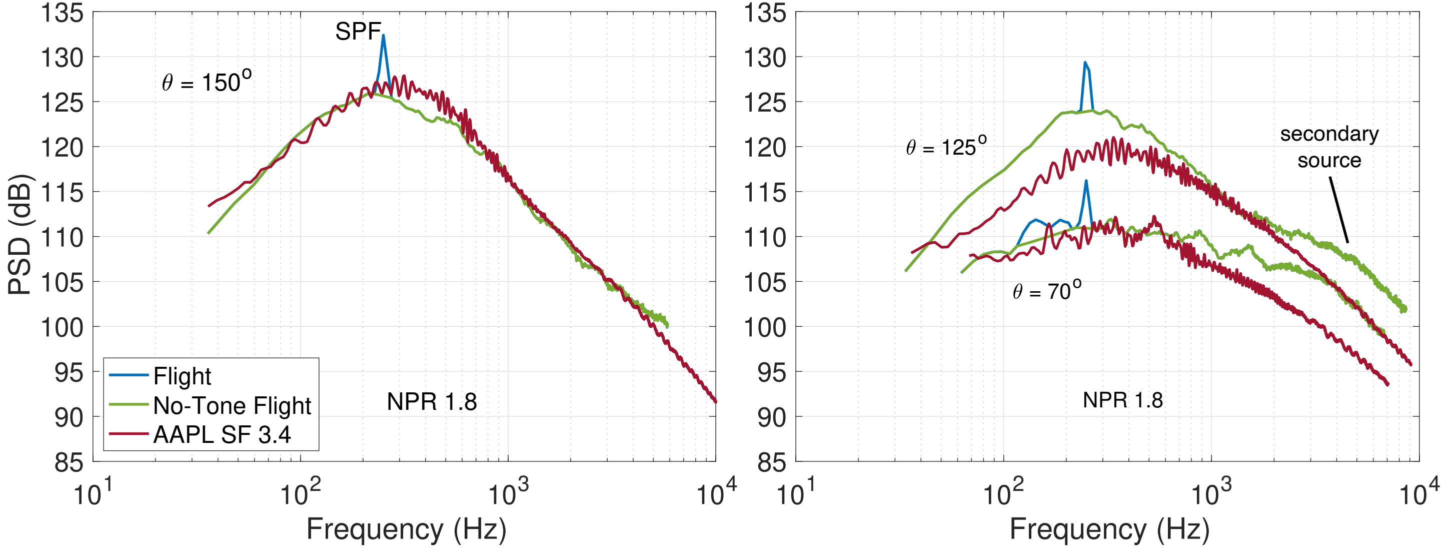
NPR_{nom} – 1.8

	Average	Std Dev	Average	Std Dev
NPR	1.804	0.008	1.806	0.007
NTR	2.796	0.007	2.794	0.006
Mach	0.260	0.007	0.258	0.006

- AAPL/NATR ‘fill-in’ data to be acquired 2023

SOURCE SPECTRA EXAMPLES — NPR = 1.8

- Narrowband spectra in source frame of reference — source frequencies



Scaling

$f_{s2f} \propto 1/SF$

$level_{s2f} \propto (SF)^{\alpha}$

PSD – α = 3

SPL – α = 2

- Physical scale factor (= 3.21) increased by 6% to *SF* = 3.4
- Good agreement for both level and frequency at peak jet-noise emission angles

NOTE
First-shaft-order tone (SPF) and a secondary broadband noise source are present in the flight data

CENTRAL LIMIT THEOREM AND UNCERTAINTY

Basic Statistics Concepts: Population and Sample

Population: Infinitely many instantaneous power spectra PS_k, $k = 1, 2, \ldots, +\infty$

- Probability distribution P with mean μ and variance σ^2
- P, μ, and σ^2 all depend on frequency, but are same for all instantaneous spectra

Sample: Average power spectrum using M independent instantaneous spectra

- $X = (PS_1 + PS_2 + PS_3 \ldots + PS_M) / M$ — sample spectrum

Central Limit Theorem

- Sample probability distribution ~ $N(\mu_X, s^2)$ — normal distribution for any P
- Mean $\mu_X \rightarrow \mu$ and $s^2 \rightarrow \sigma^2/M$ for sufficiently large M ($M \gtrsim 30$)

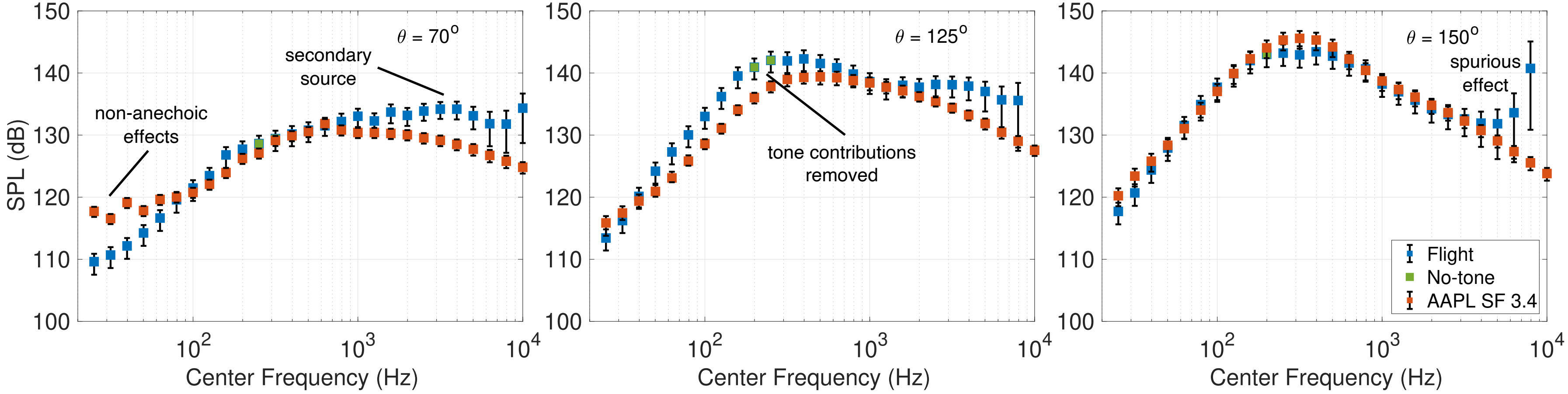
95%-Confidence Interval

- $-2\, s \leq \mu_X - \mu \leq 2\, s$
- Uncertainty is ± two standard deviations

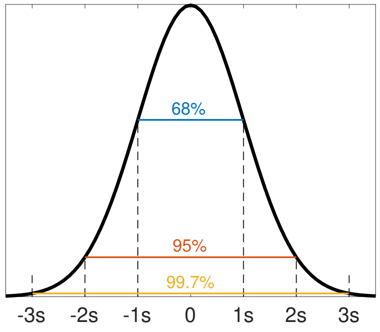
Number of Instantaneous Spectra in Each Sample Spectrum			
Test	50% Overlap	Effective (9/11)	Conservative
Flight	81	66	36
AAPL	488	399	244

1/3-OCTAVE SOURCE SPECTRA — OBSERVER

- 1/3-octave source spectra —Doppler-shifted (observer) frequencies — NPR 1.8

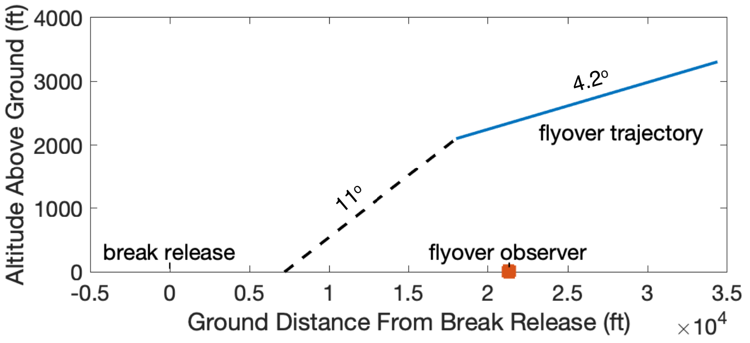


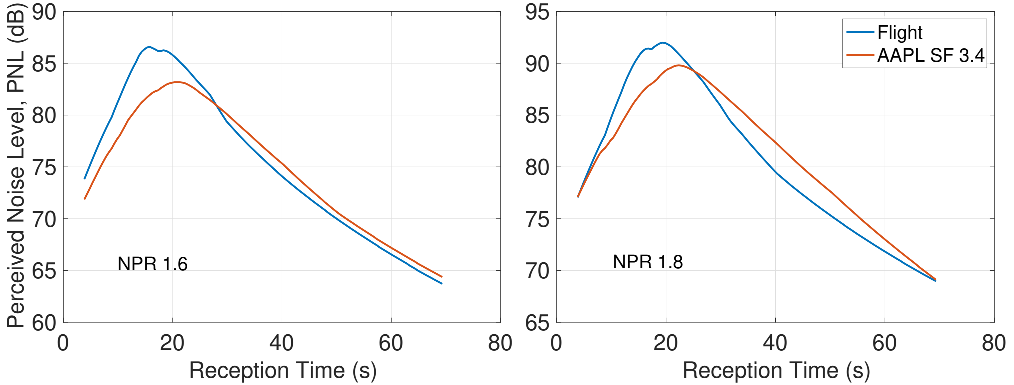
- Tone contributions to flight-data spectra have been removed
- 95%-confidence-level uncertainty (physical variables)
- Secondary noise source present in flight data
- High-frequency “kick-up” in 150° flight data due to lossless-conversion weakness (long-distance atmospheric attenuation)



EFFECTIVE PERCEIVED NOISE LEVEL — EPNL

- NASA Aircraft Noise Prediction Program (ANOPP) to fly source — ACD SFO …
- Flyover portion of a 55t-STCA flight trajectory used for calculation





	Learjet			AAPL			Lear-AAPL	AAPL
NPR	EPNL	EPNL-	EPNL+	EPNL	EPNL-	EPNL+	ΔEPNL	dEPNL/dSF
1.6	88.0	85.3	89.6	86.0	84.4	87.1	2.0	2.73
1.7	90.8	88.6	92.3	89.3	88.0	90.4	1.5	2.61
1.8	93.3	91.1	94.8	92.3	91.0	93.4	1.0	2.65

SF = 3.21 reduces AAPL EPNL by 0.5 EPNdB

- Scale-model EPNL is within the 95%-confidence-level uncertainty of flight EPNL
- Increasing NPR reduces ΔEPNL between flight and scale-model data

SUMMARY – FLIGHT AND SCALE-MODEL ANALYSIS

Obtained and compared data from:

- Well-instrumented flight test – acoustics, aircraft position/conditions, atmosphere, wind limits ✓
- AAPL/NATR scale-model acoustic data ✓

Results:

- AAPL EPNL is within uncertainty of flight EPNL
- ΔEPNL decreases with increasing NPR
- Secondary-source (flight) impact ⇘ as NPR ⇗

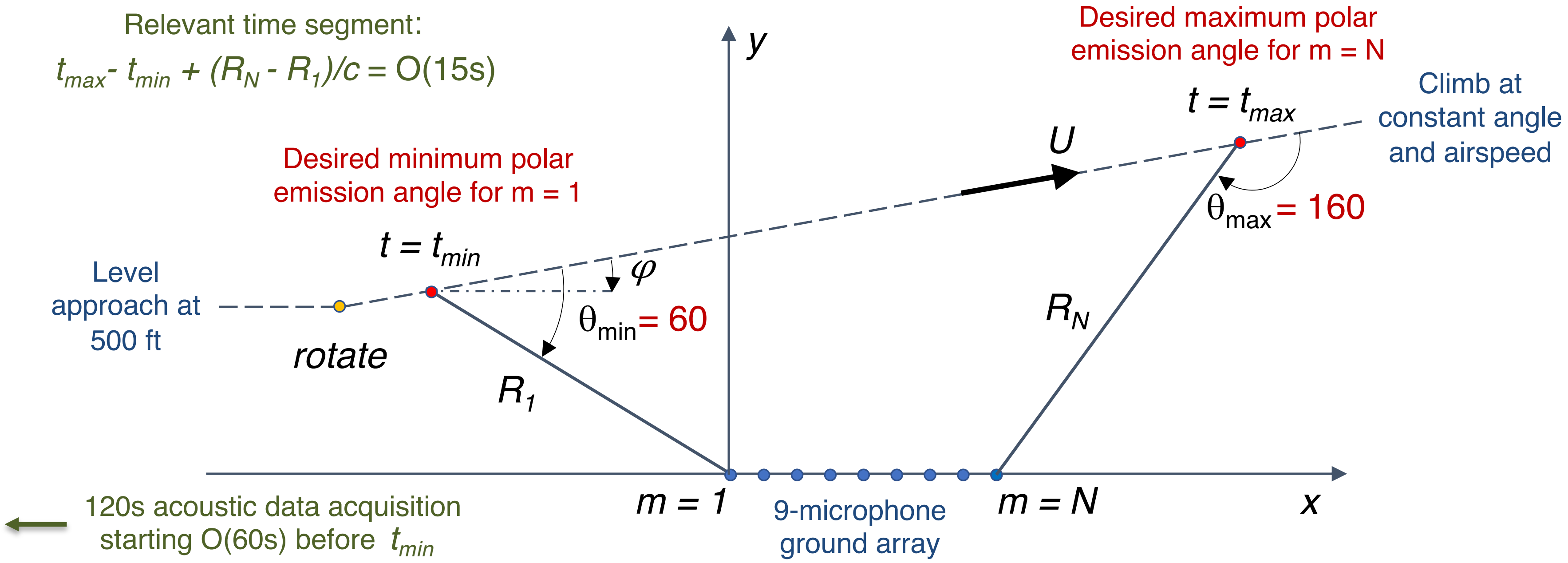
Future improvements:

- Additional data using AAPL/NATR Fall of 2023
- Impact of external nozzle boundary layer?
- Elimination/modeling of secondary source?

Significance: Improved system studies of future commercial supersonic aircraft

NASA

LEARJET-25 FLIGHT PROFILE



- Level-flight approach, one engine idle -> then rotate
- Climb at constant angle to keep airspeed constant for flyover throttle setting

AIRCRAFT POSITION PROCESSING – NASA GLENN

NASA GNSS/IMU
Unit on Learjet

Satellite Data

RTKLIB
Post-Processing
O(10 mm) accuracy

NYLP Base Station Data

LLA Position

Coordinate Transformation
LLA -> ENU -> RPY

Microphone 1 LLA Position (High Accuracy)

Source-to-microphone distance and travel time

Langley Drone
atmospheric data

- Post-processing => high-precision Latitude, Longitude, Altitude data (WGS84)
- LLA turned into local coordinates (East, North, Up), with origin at microphone 1
- ENU turned into aircraft-based spherical coordinates, with zenith direction = roll axis and reference plane defined by pitch and yaw axes
- Microphone 1–9 : distance and reception time for each emission polar angle

NASA TEAM

Flight Test: Learjet 25 at Niagara Falls International Airport (KIAG)

NASA Glenn – Acoustics, GPS Positioning, Instrument Review & LiDAR (Langley)

Brenda Henderson (PI), Lennart Hultgren (co-PI), Devin Boyle, Jordan Cluts, Alexander Svetgoff

NASA Glenn – Airworthiness (CDR/FRR), GPS Trial Flights (T-34C)

Jeff Polack, Matt Fakler, Kurt Blankenship, Mark Russel, Stephen Plaskon

NASA Langley – Drone Weather Measurements

Jacob Revesz, Jennifer Fowler, Mark Motter, Mark Frye, Scott Sims

Scale-Model Test Data, Overall Data Processing & Analysis

NASA Glenn AAPL/NATR

Brenda Henderson

NASA Glenn Data Processing and Analysis

Brenda Henderson, Lennart Hultgren

NASA