Predicting Launch Vehicle and Plume Sonic Boom using PCBoom3

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Traditional Sonic Boom Analysis

Slender vehicles, linear flow F-function
Fixed (or nearly fixed) vehicle geometry
Ray tracing in horizontally stratified atmosphere
Flat Earth geometry; Cartesian coordinates
Aircraft perspective
PCBoom3 Software

Traditional ray tracing; originated from Thomas program
Developed under NASA, USAF sponsorship
Variety of aircraft inputs
Computes complete footprints
Computes focal zones
Available from USAF AL/OEBN
Launch Vehicles: Boost Phase

Vertical launch, pitch over to horizontal
Expect acceleration focal zone
Do not expect pure N-wave booms, but:
  Do expect N-waves if no plume
  Expect forward half to be N-like, even with plume
Rocket plume is a variable geometry body
Large distances: geocoded trajectories
Obtaining F-Functions   Vehicle Alone

Expect N-wave booms at ground
Use Carlson's simple N-wave F-function:

\[ 3.46K_s^2 \sqrt{L} \]
Sources of Shape Factor $K_S$

Carlson: Charts for aircraft and Shuttle Orbiter

Simple, slender bodies: Area distribution

Complex bodies:

- CFD solutions at various $M$, angle of attack
- Project CFD to effective source distribution
- $K_S$ related to integral of F-fn positive phase:

$$K_S = \frac{2^{1/4} \gamma}{\sqrt{\gamma + 1}} \frac{1}{L^{3/4}} \left[ \int_{0}^{x_0} F(x) dx \right]^{1/2}$$
Vehicle-Plume Combination

Predict F-function separately for vehicle and plume
Assemble the two parts one after the other
Vehicle: ordinary N-wave
Plume – forward part estimated as partial N, rear part not yet satisfactorily modeled in PCBoom3.
Combined Vehicle and Plume
Jarvinen-Hill Plume Model

- Outer shock
- Slip line
- Barrel shock
- Normal shock
Shape Factor for Forward Part of Plume

Jarvinen-Hill Universal Plume Model:
Size and shape depend on Thrust, Plume Drag, and dynamic pressure. Hypersonic blunt bow.

Tiegermann hypersonic boom model:
Hypersonic blunt body: $p$ depends on $D$
Developed effective far-field N-wave

Match Tiegermann theory to J-H plume model and Carlson theory:

$$K_S = .6079 \left[ \frac{D}{2\pi p_\infty} \right]^{3/8} L^{3/4} \beta^{-1/4}$$
Rear Part of Plume

Expedient: finish off N-wave
- OK if all we want is bow shock strength
- Used for early analysis, including 1995 Titan

At source: use J-H universal plume shape
- Area distribution, linearized flow
- Current implementation, used for EELV

At ground: match measured plume booms
- Objective of current project
Boom at Ground  Current Method

$T_a = 80.250$ sec, $\Phi = 0.00$ deg, Carpet boom

$\rho_{max}, \rho_{min} = 3.92, -2.74$ psf, $T_g = 214.057$ sec, $X_g, Y_g = 174.71, -7.98$ kf

$L_{pk} = 139.5$ dB, $L_{flt} = 129.6$ dB, $CSEL = 113.4$ dB, $ASEL = 98.9$ dB

$NPTS = 200$  Loud = 113.4 PLdB

Ray unit vector: $0.89770, -0.05036, -0.43773$  Sound speed: 1118.2 ft/sec

Phase Vel = 1244. ft/sec;  $V_{px}, V_{py} = 1242. -70.$
Other Additions for Launch and Reentry Vehicles

Near-vertical flight paths watch out for singular behavior

- TRAJ2TRJ utility to convert geocoded trajectories to local flat Earth
- MAPCON utility to convert local flat Earth PCBoom3 output to geocoded

Vehicle $K_S$ from area rule or CFD near field solutions

Plume $K_S$ from J-H model, Tiegerman hypersonic theory
Typical Ascent Boom Footprint

Footprint generated around 85 kft, M=3

Launch Point

Trajectory Ground Track

Focal Zone

- 0.00 psf
- 1.40 psf
- 2.80 psf
- 4.20 psf
- 5.60 psf
- 7.00 psf

20 nm
Effect of Plume on Boom

Overpressure, psf

Distance Downtrack, nm

Max, plume

Max, no plume

With Plume

Without Plume
Summary

PCBoom3 is being used for launch vehicle sonic boom analysis

Ascent booms have narrow footprints, focal zones

Plume important for ascent

Plume modeling:
- Good results for bow shock, peak pressures
- Rear part of plume boom at ground needs work