



Advancing Sonic Boom Modeling for Space Launch Operations



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Photo Credit: NASA/Kim Schiflett



Outline



- **Background of PCBoom**
 - **NASA developed and Wyle's PCBoom**
- **PCBoom issues reported by industry users**
 - **Inaccurate carpet placement**
 - **Peak overpressure underprediction**
- **Collaboration with SpaceX**
 - **Bug fixes and fidelity improvements - PCBoom 7.5.1 Beta**
- **Interagency agreement with the Space Force**
 - **Validation of PCBoom 7.5.1**
 - **Assistance in building Space Force boom mitigation capability**
- **Efforts related to large launch vehicles**
 - **Starship**
 - **Support for KSC spaceport**

Background: NASA's PCBoom



- Maintenance and release by NASA Langley
- Origin from Wyle's PCBoom code base
- Winged-aircraft enhancements since 2017
- In-house modeling upgrades validated with F-18 data
 - Doppler effects of wind on
 - Nonlinearity
 - Atmospheric absorption
 - Computational speedup
 - Enhanced Burgers solver vs PCBurg
 - 2-3 orders of magnitude faster
- To be validated with X-59 acoustic data

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Recent Enhancements to NASA's PCBoom Sonic Boom Propagation Code

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This paper presents the recent updates the author has made to PCBoom sonic boom propagation code on its computational efficiency, predictive capability, and file operations. The updated version has recently been released and has a Burgers' equation solver, which is computationally more efficient than that in the older version by 2 to 3 orders of magnitude. The updated version also enhances the accuracy of the sonic boom propagation prediction by accounting for the full wind effects on the shock wave propagation. Predictions from the updated PCBoom are compared with predictions from the older version and with data from flight tests. Other upgrades and changes that have been made in the latest version include support for Unix-like operating systems, bug fixes, and generation of new types of output files that allow for better manipulation of PCBoom-generated data.

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PCBoom Version 7.6.0 User's Guide

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Background: Wyle's PCBoom

- **Development History** — Originally developed at Wyle by K. Plotkin et al. beginning in the 1990s
- **Funding Sources** — Supported through Air Force and NASA funding
- **NASA-released versions**
 - PCBoom 6.6 — released in 2010
 - PCBoom 6.7b — released in 2016
 - Starting version of NASA's PCBoom
- **Space Launch Capabilities** — Includes space-launch modeling features not present in NASA's PCBoom [Ref. 1]
- **Environmental Use** — Applied in an environmental assessment study performed under contract to SpaceX for compliance with FAA's regulations

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Wyle Report

WR 10-10

PCBoom Version 6.6 Technical Reference and User Manual

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Industry Partner Requests For PCBoom Support



SpaceX Boom-Related Finding

- **Falcon 9 Boom Findings** — PCBoom underpredicts Falcon 9 peak overpressure [Ref. 2]
- **SpaceX 1122 Model** — Developed by SpaceX for sonic boom prediction
— Documented in NASA TP-1122 [Ref. 3]

Initial NASA–SpaceX Engagements (Oct 2020, May 2021)

- **NASA CCSC-1** — Collaboration for Commercial Space Capabilities, Phase 1
- **Participants** — LaRC (Lonzaga), JSC (CLDP-Falcon 9 manager), SpaceX
- **PCBoom Improvement** — Joint effort to improve PCBoom sonic boom predictions
- **Launch Vehicles** — Focus on Falcon 9 and Starship
- **PCBoom Discussions** — Reviewed NASA's PCBoom code and limitations

Full NASA–SpaceX Collaboration, 2025 (CCSC-2)

- **NASA CLDP Funding** — Supported under NASA's Commercial LEO Development Program
- **LaRC–AFRC support** — Joint effort between Langley and Armstrong
- **Initial Objective** — Provide operational support for running PCBoom
- **Falcon 9 Boom Modeling** — Model Falcon 9 sonic booms from VSFB
- **Long-Term Objective** — Improve PCBoom underprediction for Falcon 9

Other Space Launch Providers

- **Additional Partners' Needs** — Requests for PCBoom support and sonic boom modeling

Adapted from an FAA Report [Ref. 2]



Federal Aviation
Administration

**Final Environmental Assessment and
Finding of No Significant Impact for
SpaceX Falcon Launches at Kennedy
Space Center and Cape Canaveral Air
Force Station**

July 2020



Ref. 2: FAA Report (2020), www.faa.gov/sites/faa.gov/files/space/environmental/nepa_docs/Falcon_Program_EA_Appendices_508.pdf

Ref. 3: Carlson (1978). "Simplified Sonic Boom Prediction," Report, NASA-TP-1122.



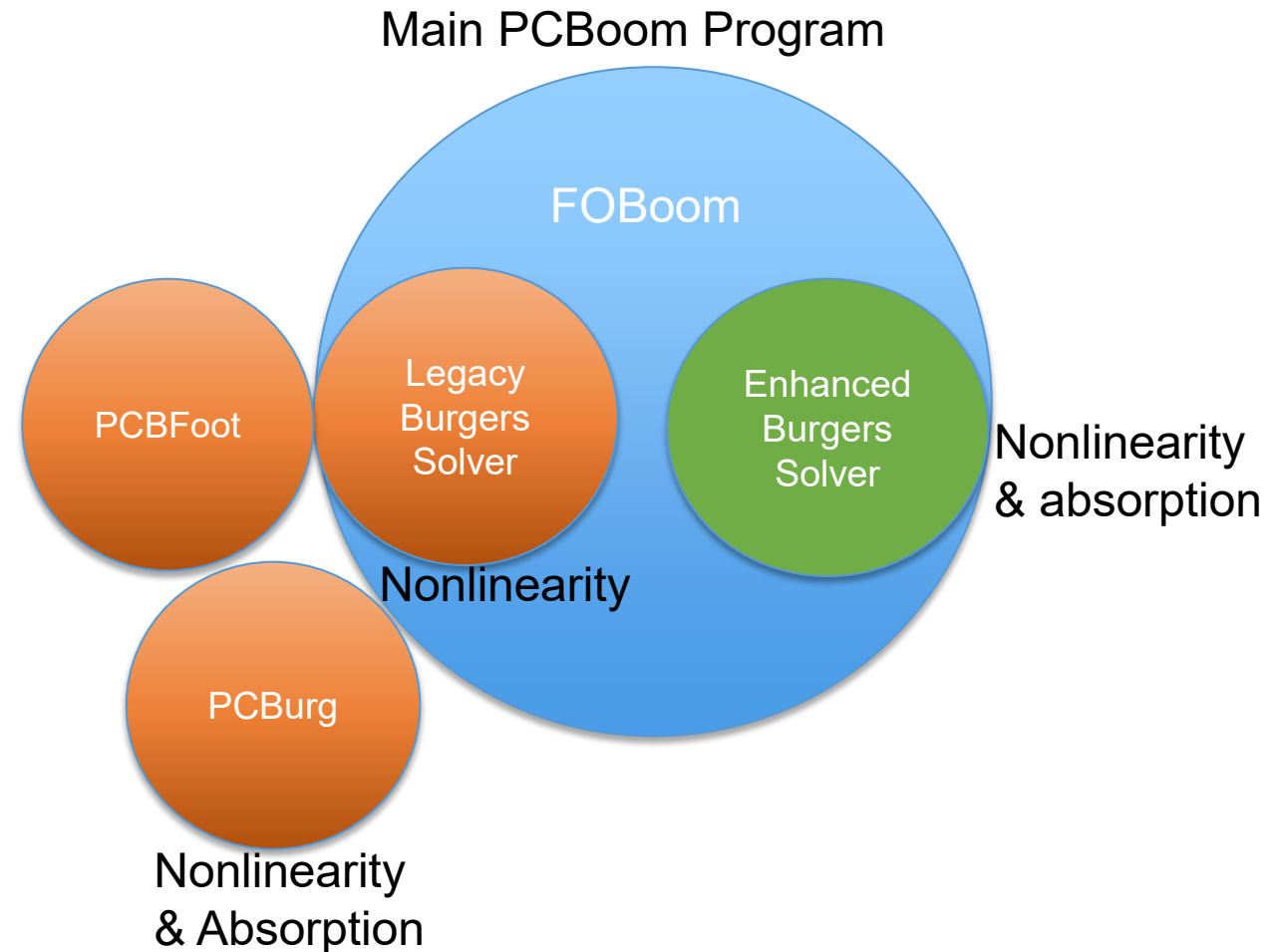
Enhanced Burgers Solver in NASA's PCBoom

NASA's PCBoom Suite

- **Main Program (FOBoom)** — Primary sonic boom propagation engine
 - Legacy Burgers Solver — lossless solver
 - Enhanced Burgers Solver — lossy solver
 - Developed in-house
- **Post-processors including**
 - PCBurg — Old lossy Burgers solver; slow
 - PCFoot — Processor of the Lossless Burgers Solver output for metric calculation
- **Lossy Burgers Solvers (Enhanced & PCBurg)**
 - Capturing: Nonlinearity and atmospheric absorption

Performance Characteristics

- Enhanced Burgers speedup — 100–1000 × faster than PCBurg
- Lossless solver tradeoff — Fast but ignores absorption



$$\text{Burgers Equation: } \frac{dU}{ds} = \frac{i\omega\tilde{\beta}}{4\pi} \int U(\omega')U(\omega - \omega')d\omega' - [\alpha_{tv} + \alpha_{vi} + \alpha_{ex}]U(s, \omega)$$

SpaceX - Identified Issues: Inaccurate Modeled Carpet

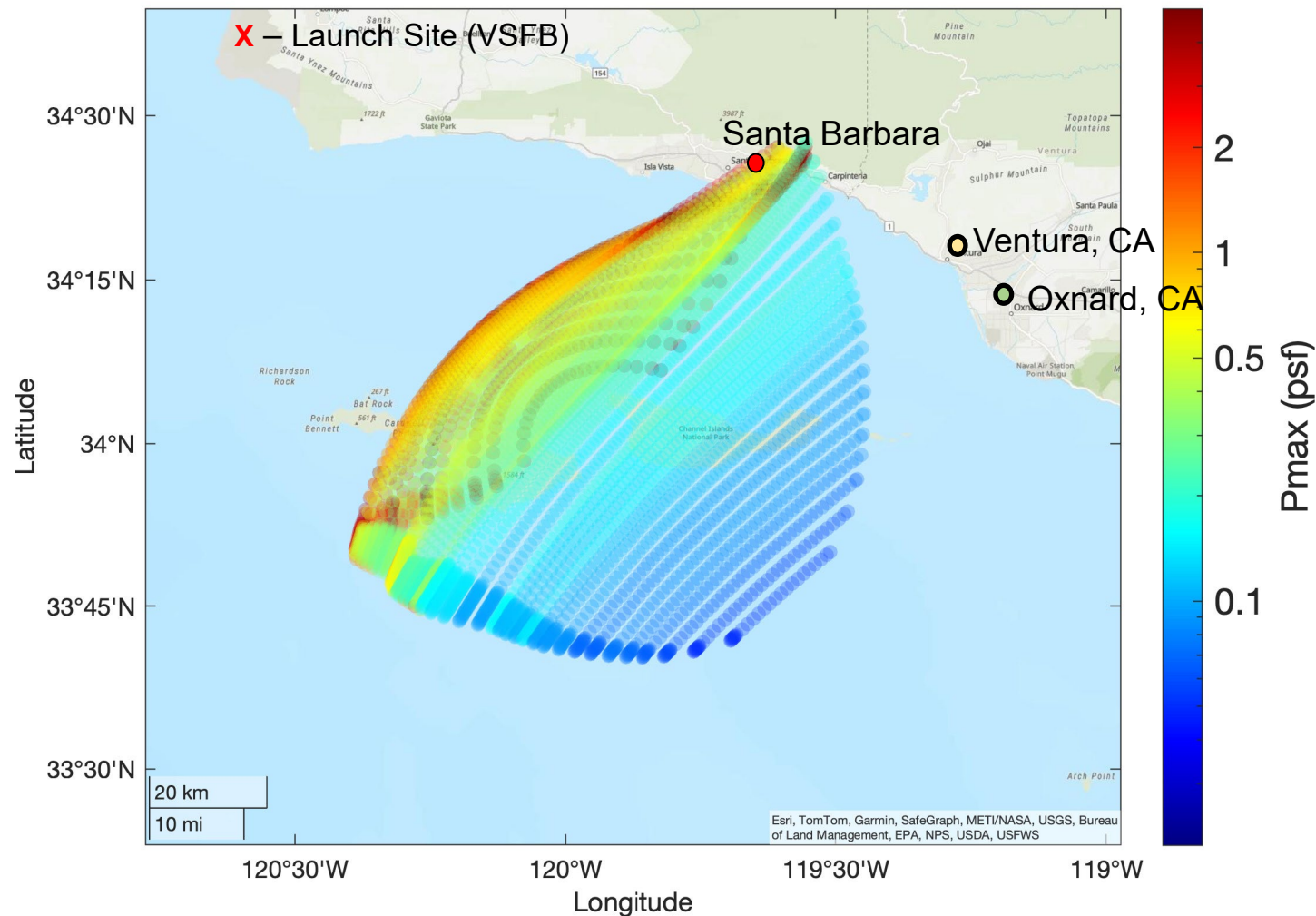


Issues in PCBoom 7.5.0

- **Ventura microphone clusters** — Microphone arrays in Ventura, CA recorded sonic-boom signatures
- **Oxnard microphone clusters** — Additional clusters in Oxnard, CA also captured boom events
- **Legacy Burgers Solver** — PCBoom modeling predicted these sensors were far outside the boom carpet
- **Enhanced Burgers Solver** — issues “segmentation fault” errors

Fix to the Legacy Burgers Solver

- Solver is sensitive to propagation time step, which is user-specified
- User-provided step was too small
- Code modification — automatic step sizing



SpaceX - Identified Issues: Model Underprediction

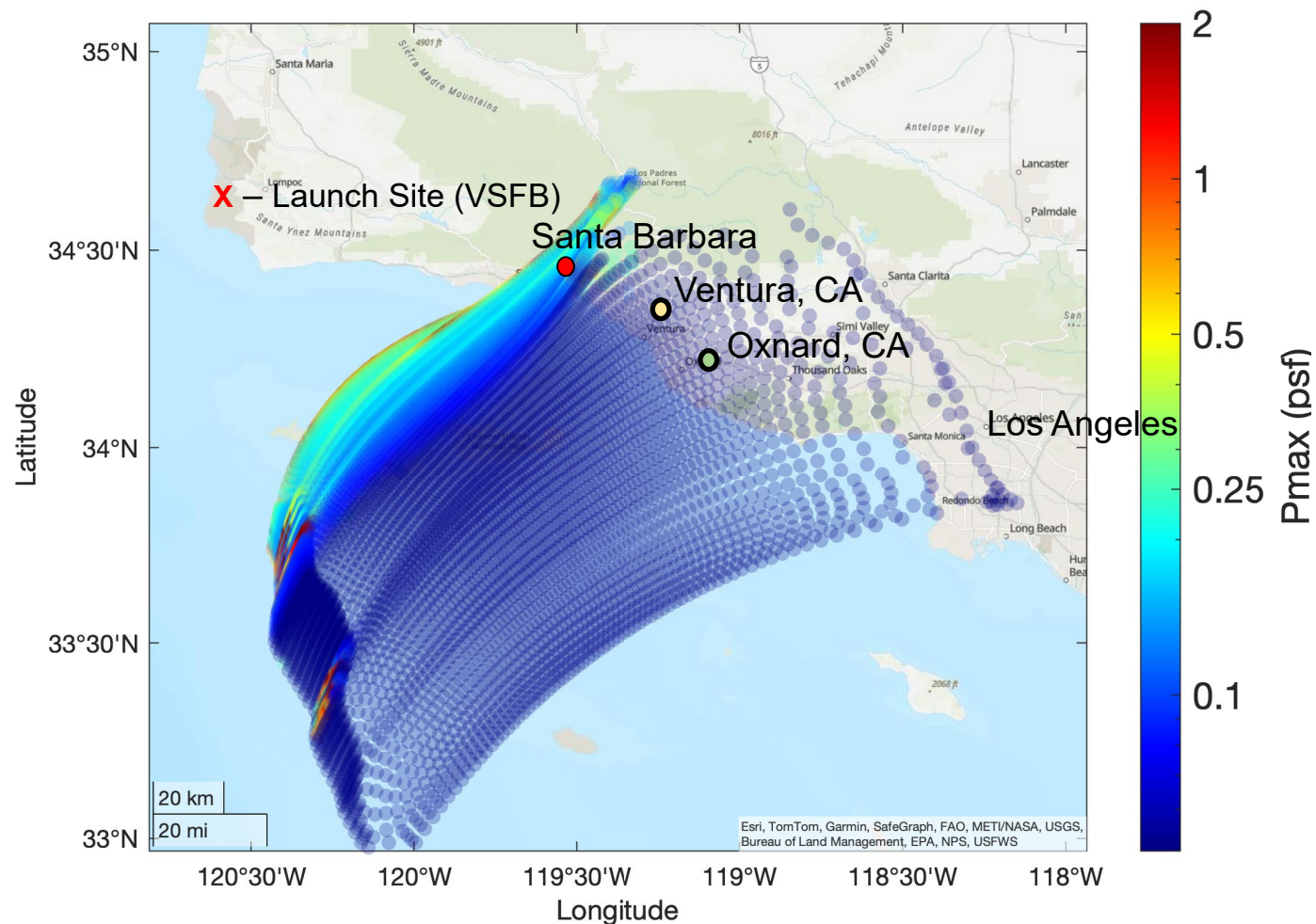


Issue

- **Santa Barbara microphone clusters** — Microphone arrays in Santa Barbara, CA recorded sonic booms with peak overpressure around 1.5 - 2 psf
- **Ventura microphone clusters** — Microphone arrays in Ventura, CA recorded around 0.5 - 1 psf peak overpressures
- **Oxnard microphone clusters** — Additional clusters in Oxnard, CA also captured booms with peak overpressure of 0.25 - 0.5 psf
- **PCBoom 7.5.0 Legacy Burgers Solver prediction** — PCBoom models indicates peak overpressures of 0.1 - 0.2 psf

Cause: Unknown (for Legacy Burgers Solver)

Fix: Enhanced Burgers Solver was fixed





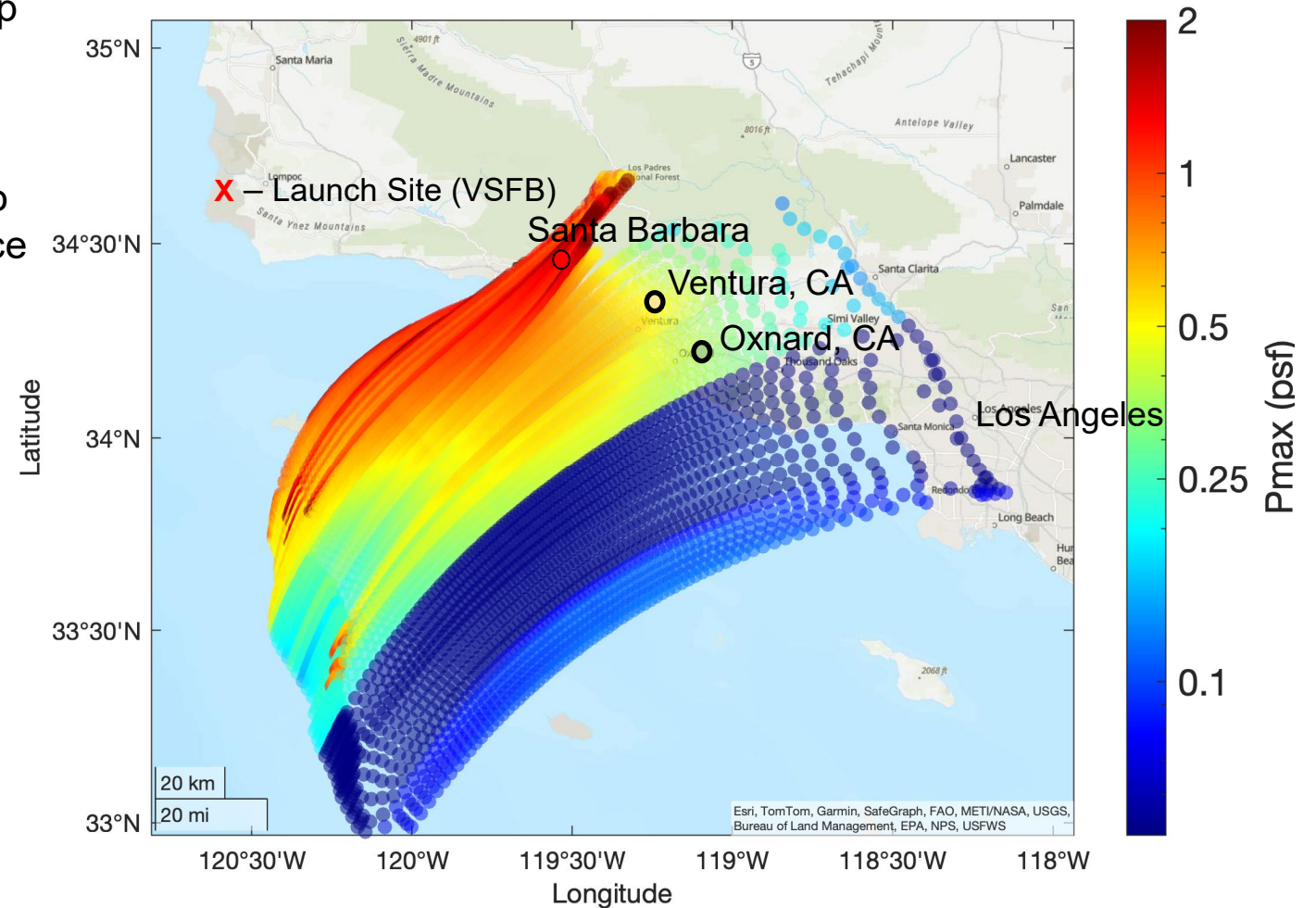
Limited Release of PCBoom 7.5.1 Beta

Solver Fixes

- **Propagation time-step automation** — Time-step handling fully automated to prevent unstable user-defined values
- **Enhanced Burgers Solver** — Updates are tied to
 - **Long-distance** propagation — Long distance leads to large cumulative nonlinear effects
 - **Strong nonlinearity at high altitude** — Large altitudes produce strongly nonlinear waveform evolution

Preliminary Results

- Outputs from the Enhanced Burgers Solver compare well with measured peak overpressures
- Discrepancy less than 50% of the measured values

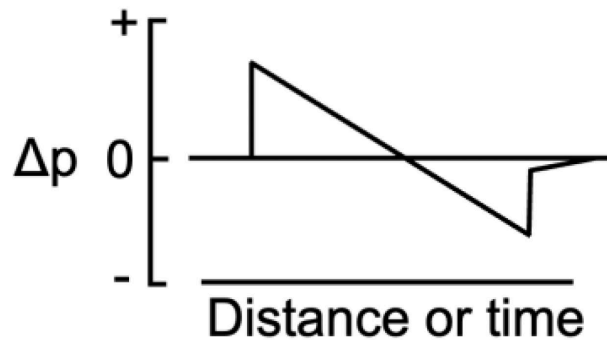


Additional Technical Difficulty For Ascent Booms



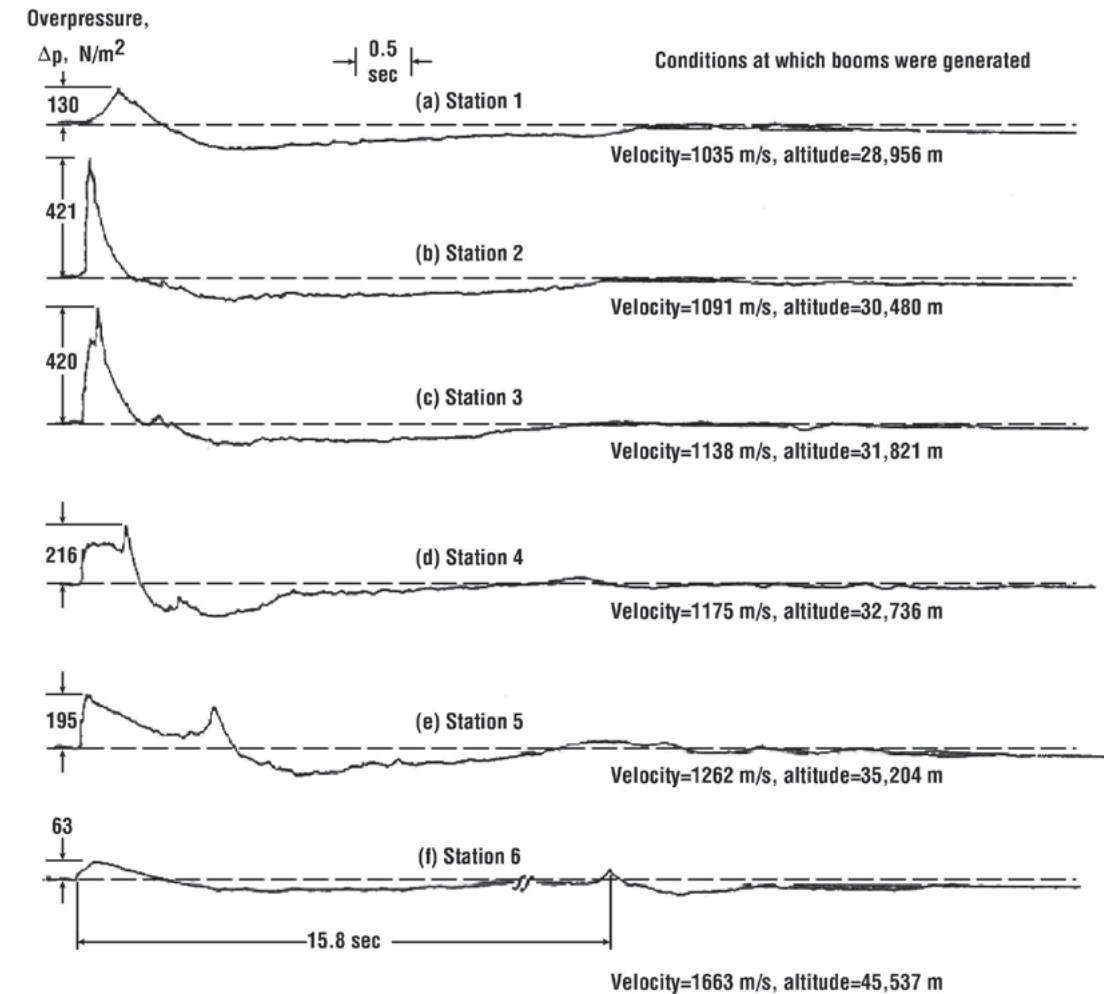
- **Improved peak-overpressure prediction** — Modeling updates predicts peak overpressures well
- **Waveform-shape mismatch** — The modeled waveform shape does not match measurements
 - **N-wave modeling behavior** — PCBoom continues to generate the boom as an N-wave
 - **Measured waveforms** — Actual recorded waveforms typically resemble a blast wave

PCBoom initial signature



Measured booms from ascending launch vehicle

- Adapted from [Ref. 4]

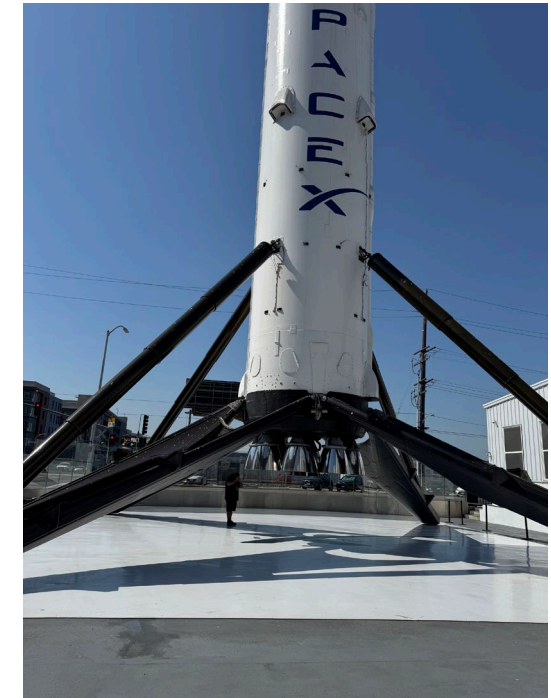




Deployment of PCBoom on SpaceX Compute Infrastructure

SpaceX HQ and VSFB Visit

- **Custom PCBoom Build** — Built a custom PCBoom executable optimized for SpaceX's supercomputing environment
- **Limited Testing** — supervised testing effort performed by a SpaceX team of engineers
- **Future Collaboration Discussion** — Discussed next-phase sonic-boom modeling and mitigation strategies
- **Vandenberg Operations Insight** — Learned about SpaceX operations at Vandenberg SFB
- **SpaceX HQ Tour** — Technical and facility tour at SpaceX Headquarters
- **VSFB Launch Site Tour** — On-site tour of SpaceX's Vandenberg launch facilities





Future Sonic Boom Prediction and Mitigation Efforts

Reimbursable Interagency Agreement with VSFB

- **Multiyear Agreement** — “Sonic Boom Launch Capacity Improvement Study”
- **Sonic Boom Capability** — NASA supporting VSFB in a sonic boom prediction and mitigation capability
- **SpaceX Model Validation** — Funding for validation of the PCBoom enhancements made for SpaceX.
- **Improved Launch Boom Accuracy** — Resources dedicated to improving prediction accuracy for space launch sonic booms



Joint Modeling with SpaceX for Starship

- **NASA CCSC-2** — Conducted under NASA’s Commercial Collaboration for Space Capabilities 2 framework
- **NASA CCP Funding** — Planned to be funded through NASA’s Commercial Crew Program

Support for KSC Spaceport Sonic Boom-Related Safety Assurance

- **Prediction & Mitigation Need** — Identified need for a sonic boom prediction and mitigation strategy
- **Funding Support**
 - Multiple conversations for boom modeling
 - Boom measurements currently underway



Summary



- NASA's PCBoom initially underpredicted peak overpressures approximately by a factor of 10 for ascent launch vehicles
- NASA's PCBoom was improved for Falcon 9 during the ascent phase
 - Collaboration with SpaceX through NASA's CCSC - 2
 - Prediction is now within 50% of measured values
- Validation will be conducted through funding from the Space Force
- Other sonic boom-related efforts include
 - Collaboration with SpaceX to characterize sonic booms from Starship
 - Support for KSC-spaceport to assess impacts of sonic booms from large launch vehicles