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A Study of Reflected Sonic Booms using Airborne Measurements

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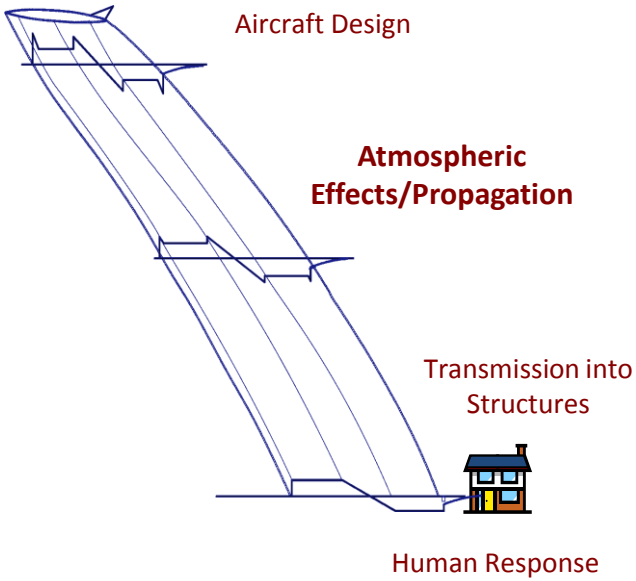
Topics of Discussion

- Background
- Research objectives
- Test architecture and execution
- Analysis and Results
  - Incident/reflected sonic boom model validation
  - Mission planning accuracy
- Conclusions and future work

Aeronautics Flight Research

- Over 60 years of flight research (NACA Muroc Flight Test Unit)
- Edwards Air Force Base (EAFB)
- Remote Location
- 350 Testable Days Per Year
- Extensive Range Airspace
- Supersonic Corridor

Sonic Booms in Atmospheric Turbulence (SonicBAT)

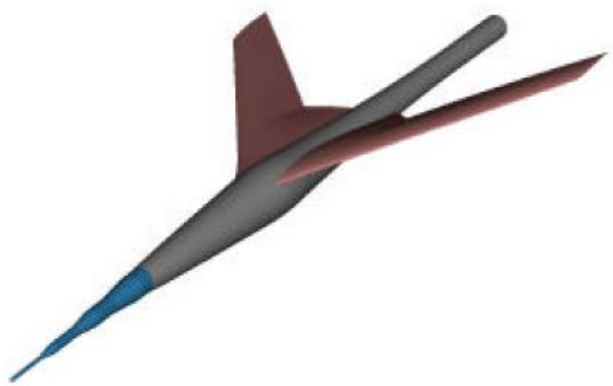


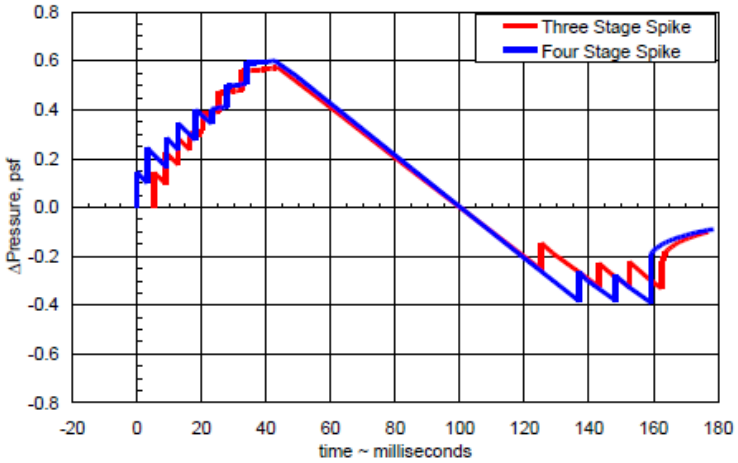
MOTIVATION & BACKGROUND

- **Need: Better understanding of sonic boom propagation**

SonicBAT Experiment Description:

The objectives of this research are to validate, via flight test measurements, models for the propagation of sonic boom signatures through atmospheric turbulence to predict the effect of turbulence on the loudness of shaped sonic booms for “low-boom” aircraft designs.





SonicBAT Overview

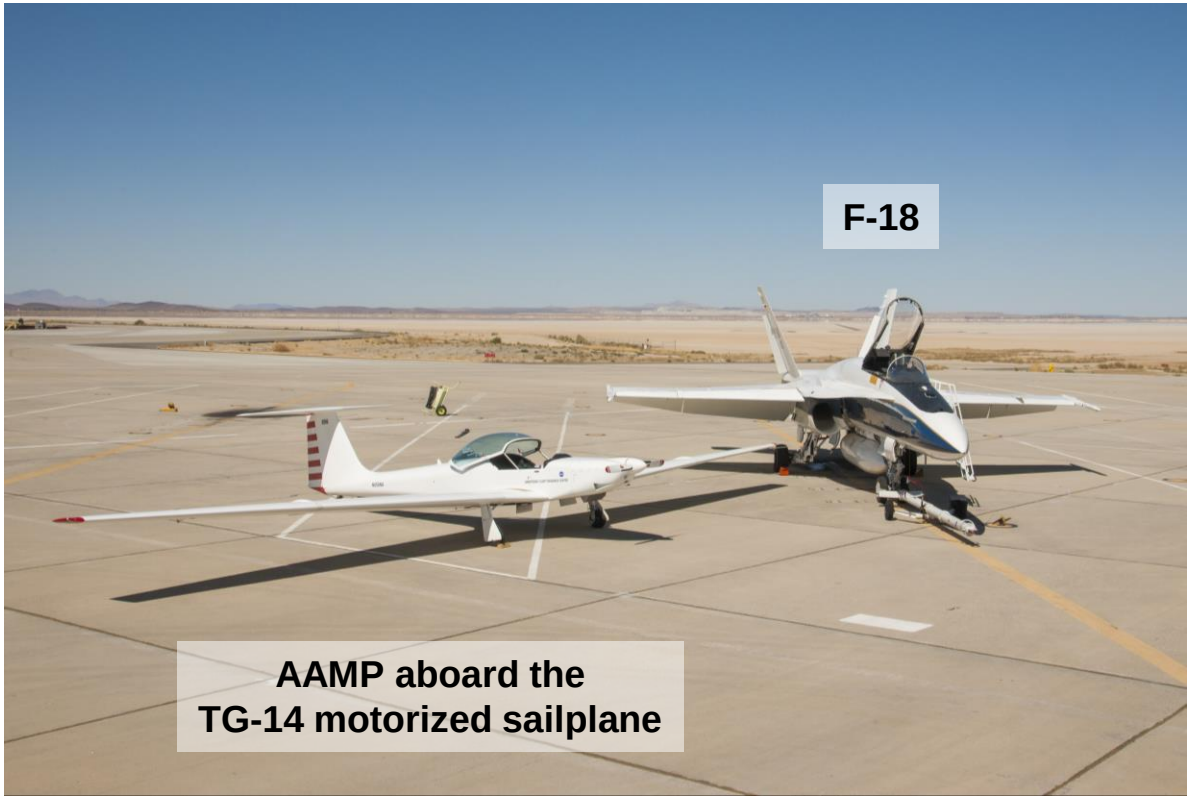
- Comprehensive dataset of sonic booms that have propagated through turbulent atmosphere at elevations anticipated by future low sonic boom aircraft to validate computer models
  - Aircraft, meteorological, acoustic data
  - Statistically significant variations can be observed

- **Ground level**
  - Instrumentation provided by NASA AFRC, Wyle, Boeing, and Gulfstream
  - Three microphone arrays
  - High-fidelity atmospheric instrumentation to measure turbulence parameters and general weather data

- **4,500 ft. to 10,000 ft. MSL**
  - Airborne Acoustic Measurement Platform (AAMP) to measure sonic boom pressure signatures just above turbulent boundary layer
  - AAMP may also measure sonic boom pressure signatures that have been reflected off of the ground, therefore heavily "turbulized" due to passing through the turbulent boundary layer twice

MOTIVATION & BACKGROUND, *CONT.*

- SonicBAT provided an unexpected dataset :
  - For most test points the Airborne Acoustic Measurement Platform (AAMP) recorded both an **incident** and **ground-reflected** sonic boom
  - This provided the unique research opportunity to analyze the propagation of sonic booms that have been reflected off of the ground



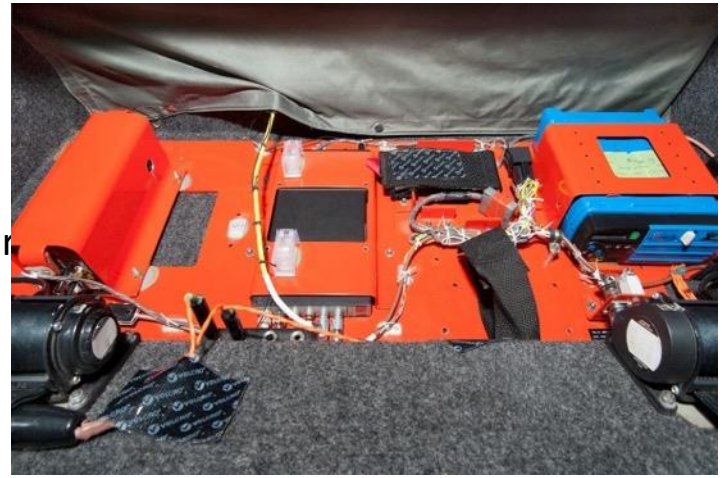
Test Setup

- Flight conditions
  - F-18B airplane
    - Mach 1.38 and 32,000 ft. pressure altitude
- Primary microphone array
  - 1,500 ft. linear array of 16 microphones
  - Brüel & Kjaer 4193 microphones
- Airborne Acoustic Measurement Platform (AAMP)
  - Capable of measuring sonic booms in flight
  - TG-14 motorglider
  - 4,000 – 12.500 ft. MSL
- PCBoom[1] used for initial flight planning

[1] PCBoom was developed by KBRwyle

AAMP System Description

- AAMP Instrumentation Pallet
  - Brüel & Kjaer LAN-XI Data Acquisition Unit
  - ITS 6155E IRIG-B GPS Timecode Generator
  - Tapped into ship's intercom with audio transformer
  - Ashtech Z-Xtreme GPS
  - UBI-2590 Ultra Life Battery
  - Accelerometer
- Microphone Boom & Microphone
  - Modified Wing-tip & Wing-tip Spacer
  - Brüel & Kjaer 4193 microphone
- Handheld Tablet PC with LAN-XI Software
- Handheld Garmin GPSMap 496



AAMP Instrumentation Pallet – Aft Baggage Compartment

Microphone & Microphone Boom – Left Wing Tip

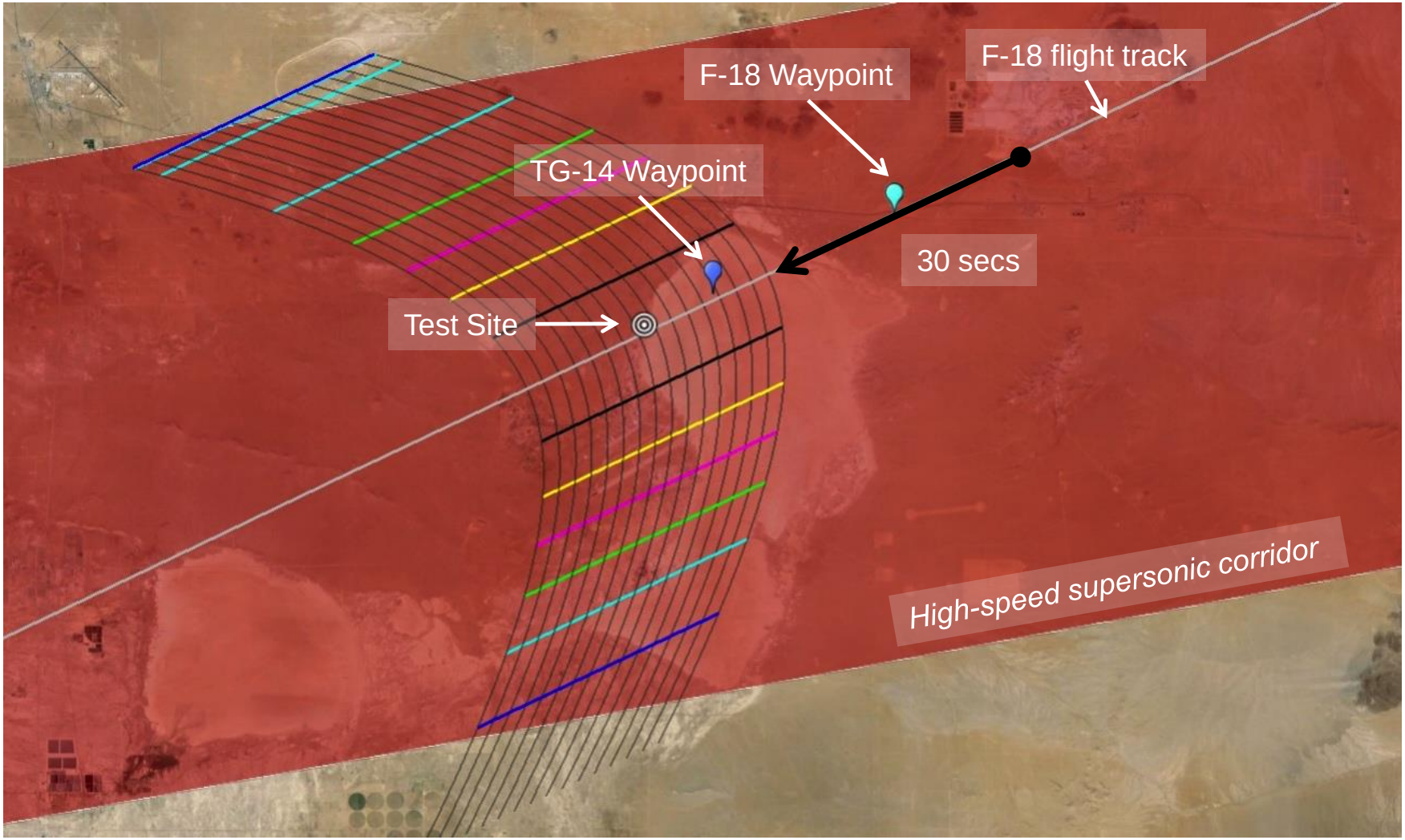
TG-14 Motorglider

Meteorological Instrumentation

- Sonic Anemometer
  - 10m tower
  - 140ft tower
  - 3 component winds, 30 sps
  - Ct^2 and Cv^2
- SODAR
  - Model 4000 Mini-SODAR (250m)
  - 3 component winds
  - Ct^2 and Cv^2
- GPSsonde
  - One for each takeoff time to 40K ft
  - Was EAFB or local launch
- 10 ft weather tower
  - Temp., Press., Humidity, Wind Speed & Dir

MICROPHONE ARRAY OVERVIEW

Primary test point: On-track, 32,000 Hp, Mach 1.40, 245-deg true course



Sonic boom Propagation software

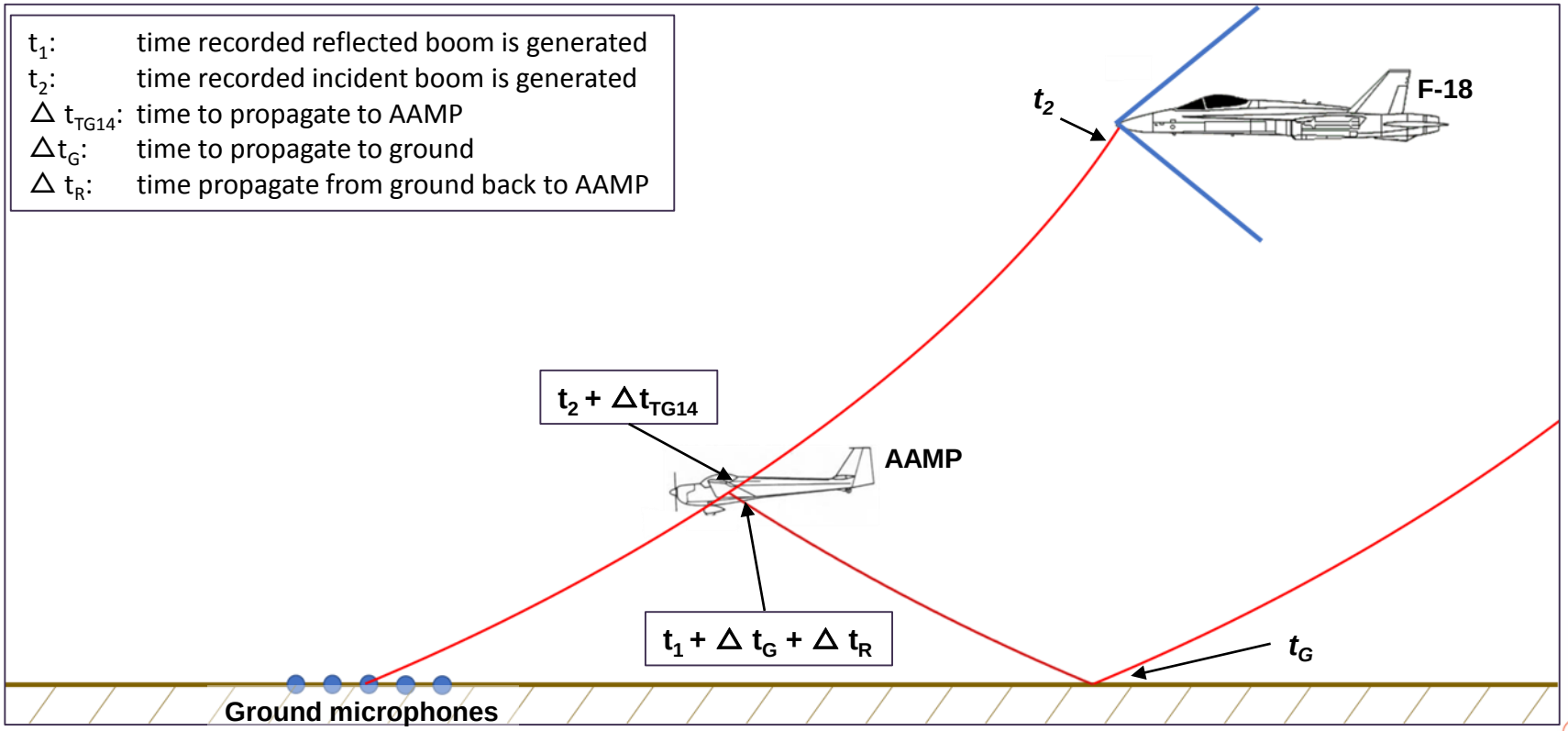
- **PCBoom** is a sonic boom propagation model developed by **KBRwyle**
- **POTRay** (Propagate Over the Top Rays) is a PCBoom module which traces ray paths in all directions and outputs raypaths and ground intercept data, including reflected booms and over the top booms.
- **FOBoom** is the Pcboom module which traces ray tubes to the ground, and outputs ground intercept and waveform data.

Research Objectives

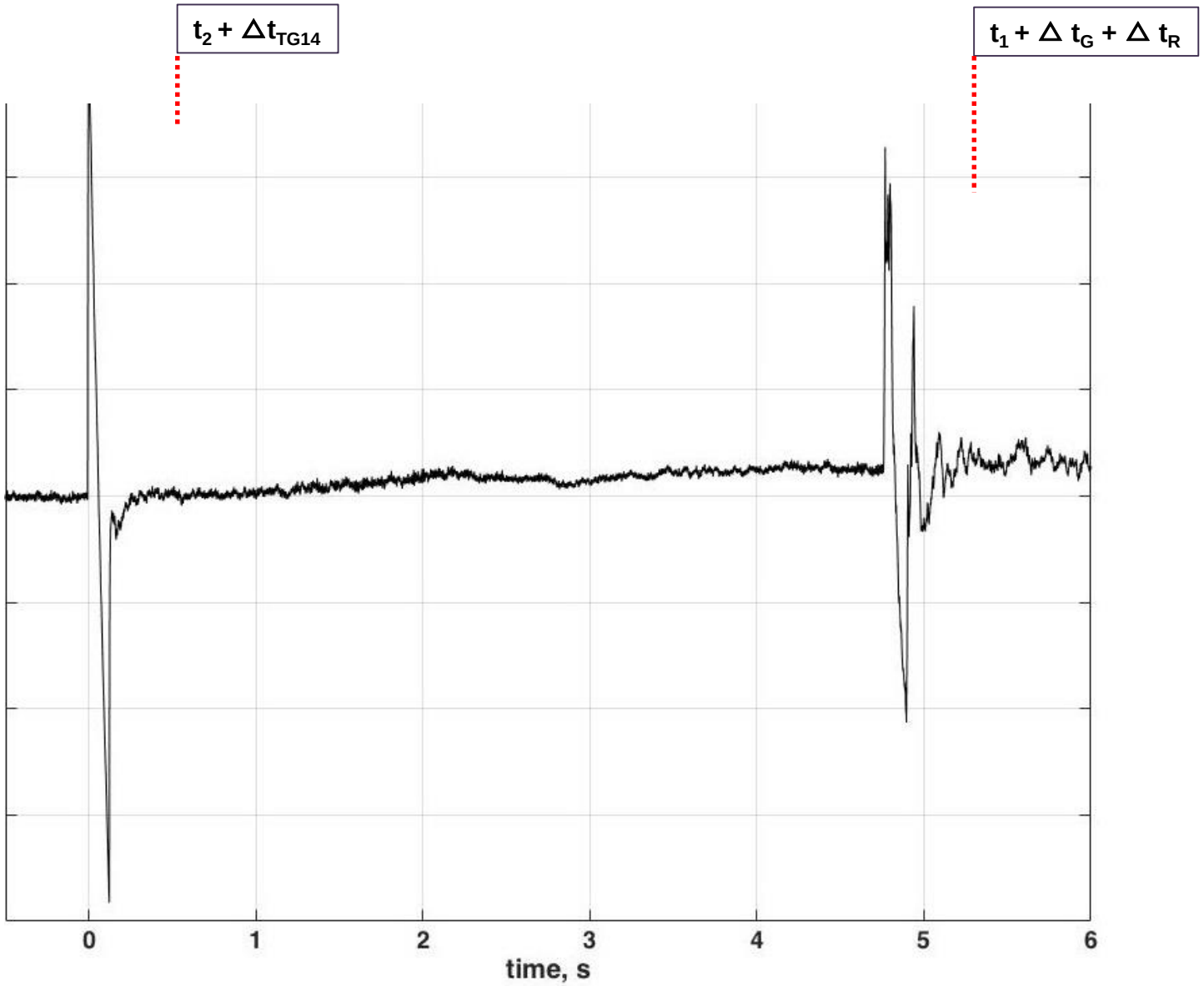
- Validate mid-field sonic boom predictions
  - Use POTRay to when an incident boom intercepted the AAMP
- Validate reflected sonic boom predictions
  - Use POTRay to predict when a reflected boom intercepted the AAMP
- Analyze the ability to record the same sonic boom ray in the mid-field and on the ground
  - Use PCBoom to predict where the ray recorded by AAMP hit the ground

AAMP Sonic Boom Intercept

- AAMP measures two N-waves:
  1. Incident boom at: $t_2 + \Delta t_{TG14}$
  2. Reflected boom generated earlier at: $\mathbf{t_1 + \Delta t_G + \Delta t_R}$
- Note: $t_{TG14} < (\Delta t_G + \Delta t_R)$
  - So the incident boom is recorded first, even though it is generated later (t1 > t2)



Incident and Reflected Measurement



Analysis and Results

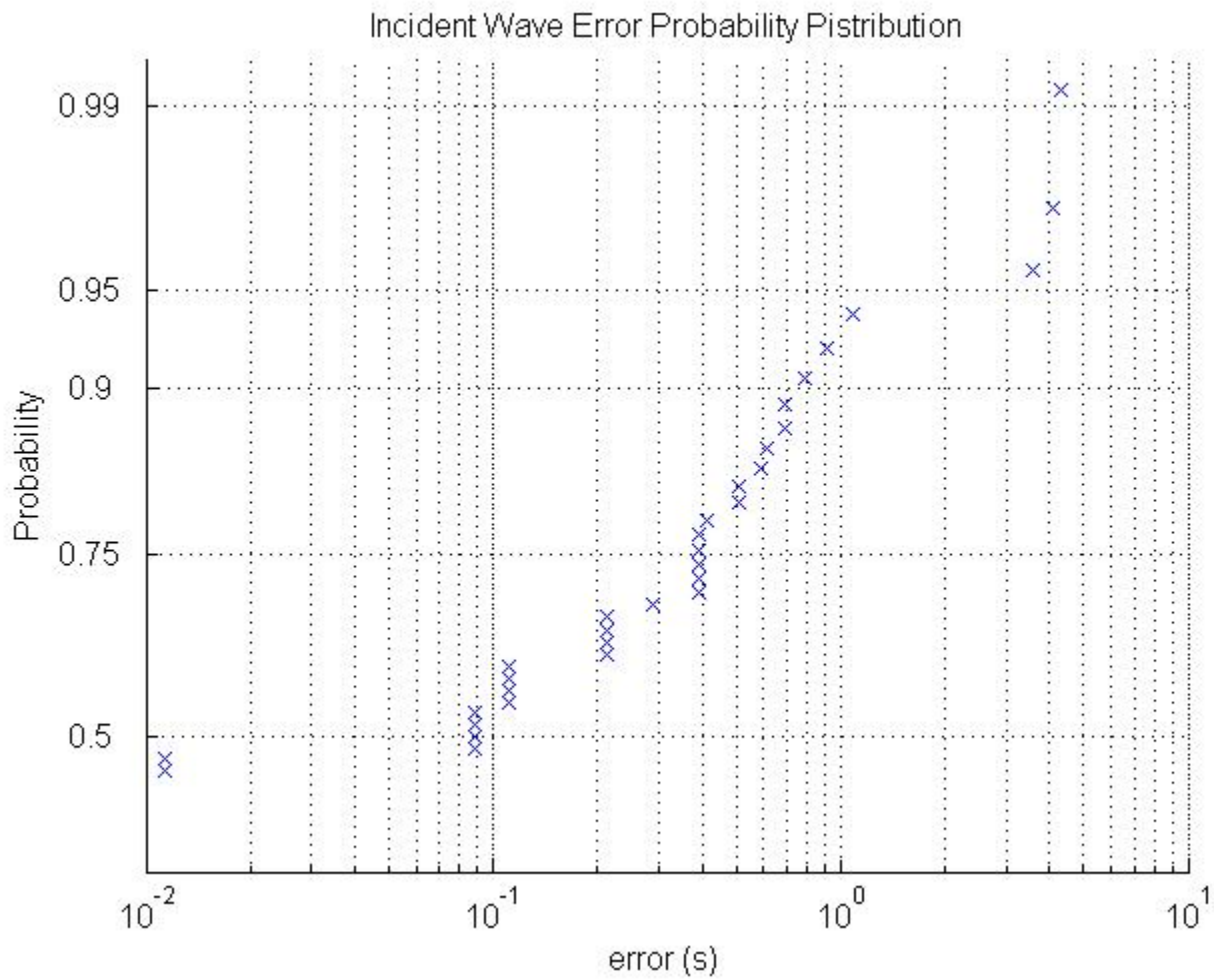
Results – Incident Sonic Booms

Analysis methods

- Ideally we would know the complete ray from the F-18 to the TG-14
- Only the location and time the wave was intercepted is known
- The key to validating the code is the time of the intercept.

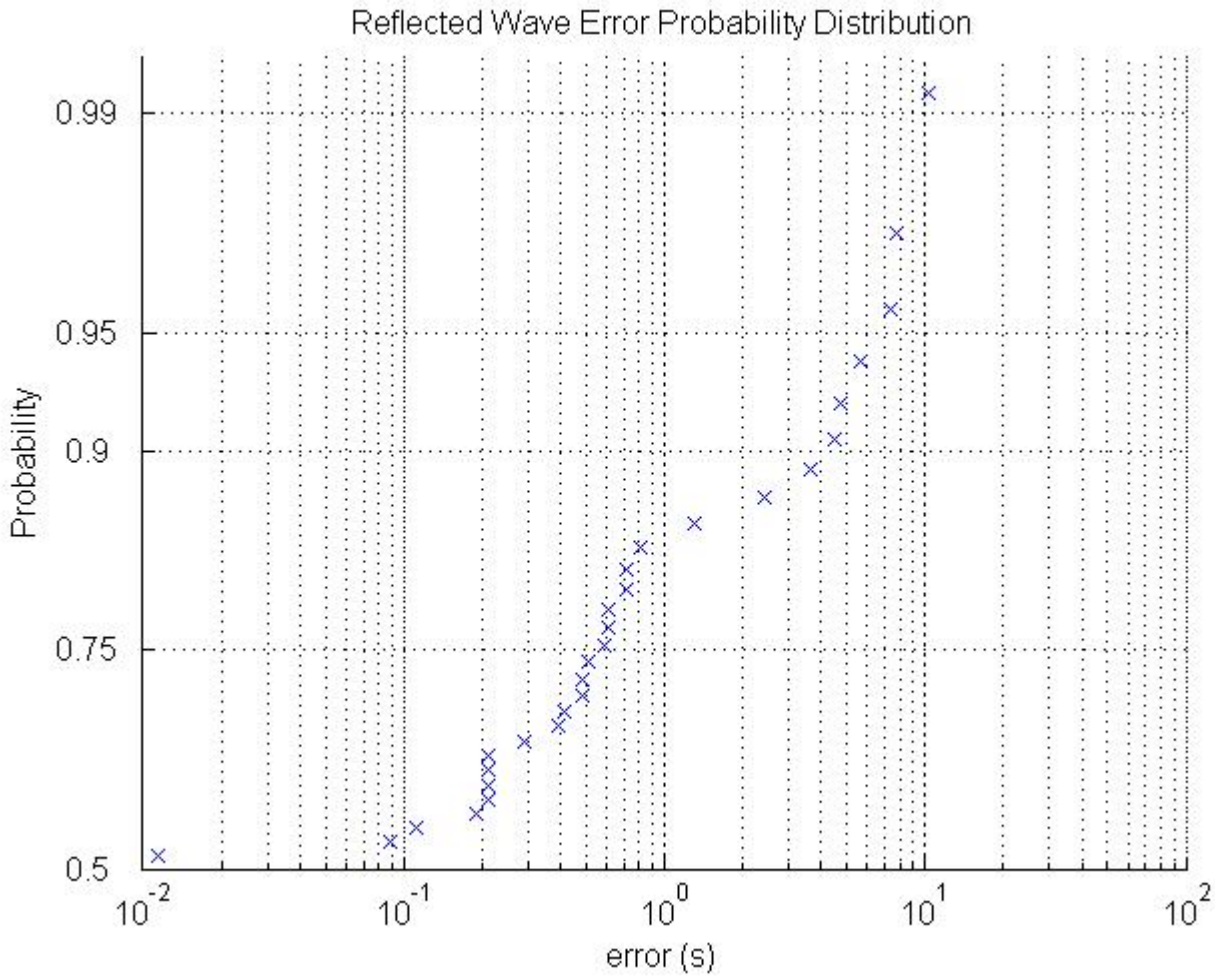
RESULTS – REFLECTED SONIC BOOMS

- 90% of error was under 0.7 seconds



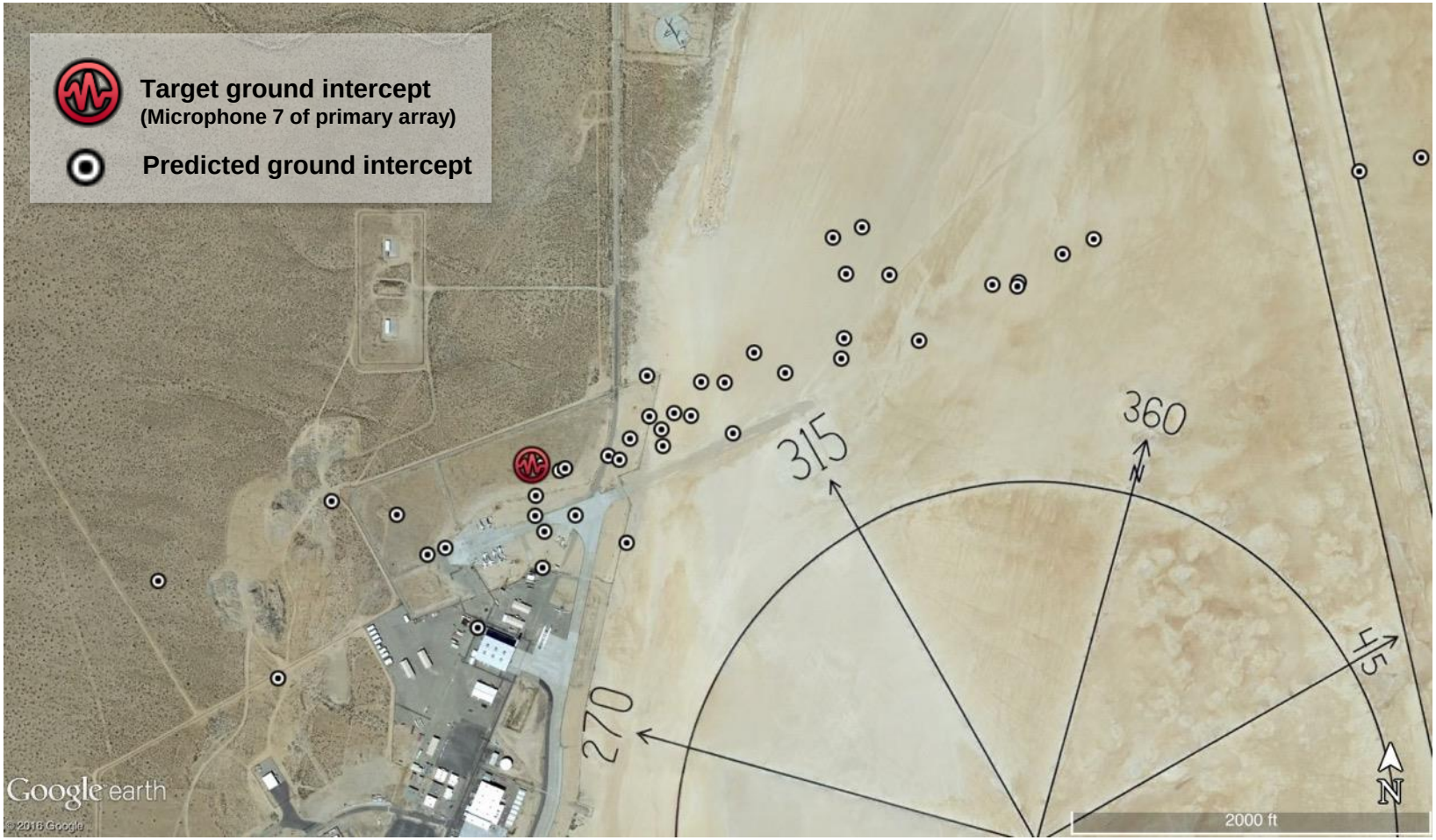
Results – Reflected Sonic Booms

- 90% of error was under 4 seconds



RESULTS – BOOM PLACEMENT ACCURACY

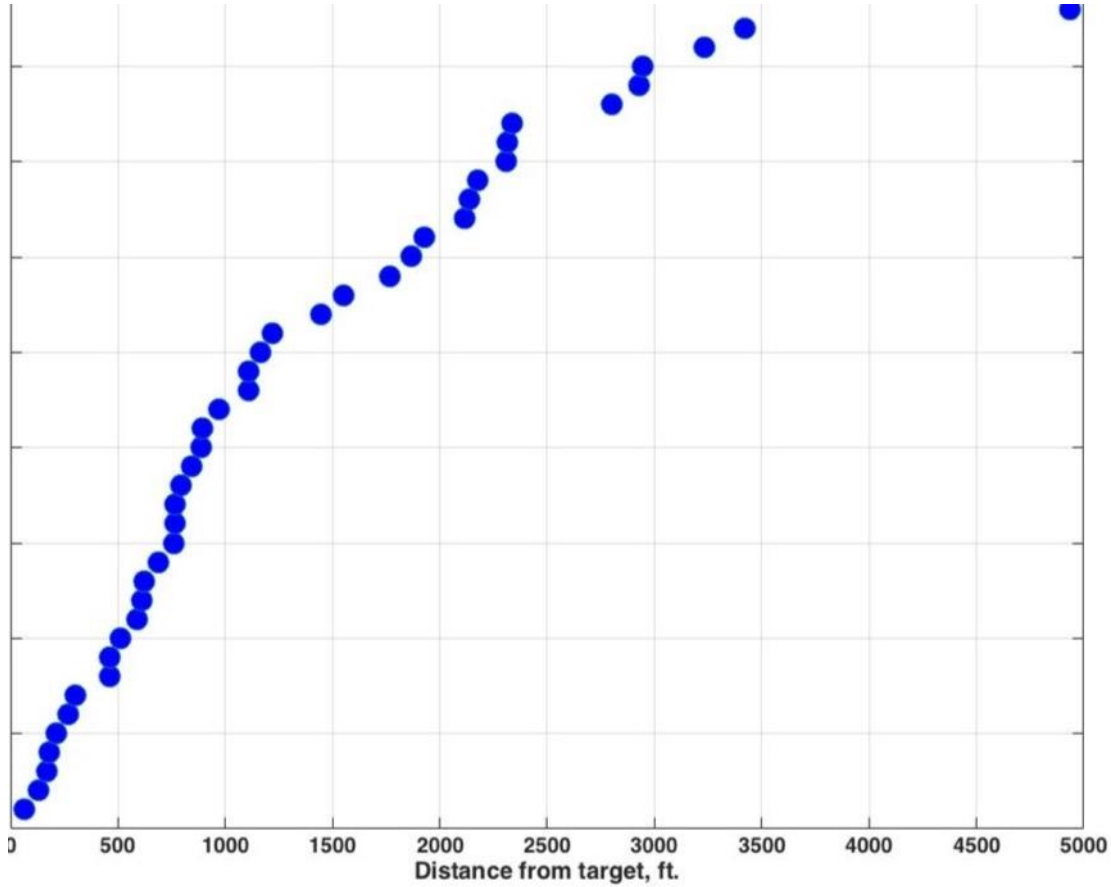
Data shows the location on the ground where the sonic boom recorded by AAMP hit the ground, compared to target/planned location (According to PCBoom predictions)



RESULTS – BOOM PLACEMENT ACCURACY

Data shows:

- **45%** of the predicted ground intercept was **within 1000 ft.** of target
- **80%** of the predicted ground intercept was **within 3000 ft.** of target



Cumulative Percentage

Conclusions and Future Work

- POTRay provides excellent accuracy for both incident rays and reflected rays
  - Test data shows that POTRay is a validated tool to use for research in sonic boom reflection, over the top booms, and other parts of the secondary boom carpet.
- FOBoom is validated as a mission planning tool even for complex missions with multiple aircraft.

Future Work

- SonicBAT II is coming to Florida this August
  - Will likely generate another database of reflected booms, this time reflected on water.
- More research can be done to quantify how much error in ground intercept is due to pilot error and how much do to error in modeling (FOBoom).

Sonic Booms in Atmospheric Turbulence
SonicBAT
NASA • WYLE • PENN STATE • BOEING • GULFSTREAM • EAGLE • LMFA

THANK YOU.