Acoustic Atmospheric Propagation Model Validation with the NRC Convair 580

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The National Research Council Canada was concurrently assessed the visibility and audibility of aircraft in the vicinity of low-traffic aerodromes. This paper discusses the efforts to numerically estimate the acoustic propagation of an aircraft's acoustic signature using the Impedance Plane Formulation and the Fast Field Program. The experimental methodology includes the estimate of low-altitude fly-by acoustic measurements as reference data and high-altitude fly-by acoustic measurements as target data for the acoustic propagation models. It is shown that the selected acoustic atmospheric propagation models are able to accurately estimate the acoustic signature of the Convair 580 aircraft. Signature aircraft tones located at 70 Hz and 140 Hz are identified by the models and accurately estimated in location and amplitude. The models' performance is evaluated to a range of 8 km in the horizontal plane and 3.66 km vertically; the models exhibited reduced performance as a function of distance.

I. Acronyms

AGL	=	Above Ground Level; altitude as referenced to the local ground level
FFP	=	Fast Field Program
FRL	=	Flight Research Laboratory
GPS	=	Global Positioning System
NRC	=	National Research Council
PE	=	Parabolic Equation
PSD	=	Power Spectral Density

II. Introduction

The National Research Council Canada was tasked to assess the visibility and audibility of aircraft in the vicinity of low-traffic aerodromes. The project required a multi-disciplinary team of acousticians, data acquisition designers, machine vision specialists and aircraft pilots. The project outcomes include, but are not limited to, the enabling of the assessment of population awareness to the presence of an aircraft. This paper describes the concurrent acoustic experimental measurement procedure and analysis.

Ungar (Ungar, March 1972), and later, Fidell et all (Fidell & Horonjeff, October 1982), performed extensive studies into aircraft audible detectability. Paraphrasing, the derived principle steps can be summarized as:

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1. Characterization of the aircraft's acoustic signature
2. Computation of the aircraft's acoustic signal at the location of a listener
3. Comparison of the aircraft's acoustic signal at the location of the listener to the ambient acoustic noise spectrum at the location of the listener

It follows that the audibility of an aircraft is simply a function of the signal-to-noise ratio of the aircraft acoustic signature and the local background noise. As the local background noise is a significant contributing factor to the assessment of aircraft audibility, it becomes necessary to assess aircraft noise as a function of aircraft distance, local traffic, time-of-day, weather conditions etc. In order to enable the assessment of aircraft audibility in circumstances infeasible for acoustic measurements, NRC developed a method of estimating the acoustic signature of a particular aircraft in the absence of acoustic recordings. This paper details the experimental methodology to validate two established acoustic atmospheric propagation models in the task of estimating the acoustic propagation of the NRC Convair 580 aircraft.

III. Atmospheric Propagation Modeling Theory

The atmospheric propagation of sound energy from source to receiver is complicated by a number of acoustic and meteorological factors inclusive of geometrical spreading, atmospheric absorption, ground impedance, ground topography, refraction and atmospheric turbulence. A number of different models have been developed to account for these propagation factors enabling the prediction of acoustic atmospheric propagation. However, models accounting for the aggregate propagation factors are complex to initialize and time consuming in their application. Fortunately, the various propagation factors depend primarily on independent parameters; thus different factors may become dominant or negligible depending on atmospheric conditions, topology and terrain characteristics.

As discussed in further literature (Sutherland & Daigle, 1997) and (Attenborough & al, 1995), accepted models currently in use include the Impedance Plane Formulation, Hybrid Ray Based Models, Fast Field Program (FFP) and the Parabolic Equation (PE).

For the application to a high-altitude aircraft, it was anticipated that refraction would be negligible due to the steep angle of incidence between the sound propagation emission angle and the ground proximity factors. Within proximity to the ground, the combination of radiation cooling or heating of the ground over the course of the day and the viscous effects of wind speed at ground, will significantly vary the speed of sound as a function of height. Only shallow angles of incidence, as depicted in Figure 1, would be significantly affected by refraction.

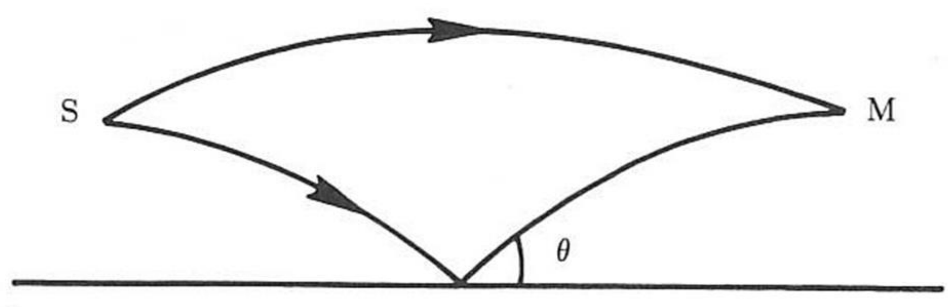

Figure 1: Depiction of Acoustic Ray Curvature Due to the Ground Proximity Speed Differential from Source, S to Receiver Microphone, M

Consequently, geometric spreading, atmospheric absorption, ground effects and turbulence would be the primary factors dominating the acoustic atmospheric propagation; the Impedance Plane Formulation can account for these factors and is thus a suitable candidate for acoustic atmospheric propagation modeling. In the interest of assessing the effects of refraction, however, the FFP was also retained for comparison. The FFP is a numerical solution wherein the computational time various from several minutes to several hours dependent upon the requested frequency and range. Please note, the FFP does not account for turbulence.

Please refer to the references for an extended discussion on the merits of the various proposed acoustic atmospheric propagation models

IV. Experimental Procedure

The validation of the Impedance Plane Formulation acoustic atmospheric propagation model, as applied to the NRC Convair 580, was enabled in three steps.

(A) The acquisition of a Convair 580 acoustic reference spectrum obtained under controlled conditions
(B) The acoustic signature of a Convair 580 in overhead flight
(C) The Impedance Plane Formulation atmospheric propagation estimation to validate against (B)

The overhead flights were completed at a local aerodrome: Smiths Falls Montague Airport, YSH. Five microphones were arranged in a kilometer sized star pattern to record acoustic data. The microphone locations are depicted in Figure 2. The locations were chosen so as to avoid the acoustically reflective surfaces of nearby buildings and additional noise produced by test personnel and ground traffic.

The NRC Convair 580, as seen in Figure 3, was outfitted with an Aircraft-Integrated Meteorological Measurement System and an in-house developed Attitude Heading and Reference System, in addition to the standard aircraft systems. These systems enabled the in-flight measurement of exterior humidity, exterior temperature, engine RPM, aircraft heading, spatial coordinates and velocity. A ground based wind sensor and estimations based on the National Oceanic and Atmospheric Administration (NOAA) were utilized for wind speed and direction.

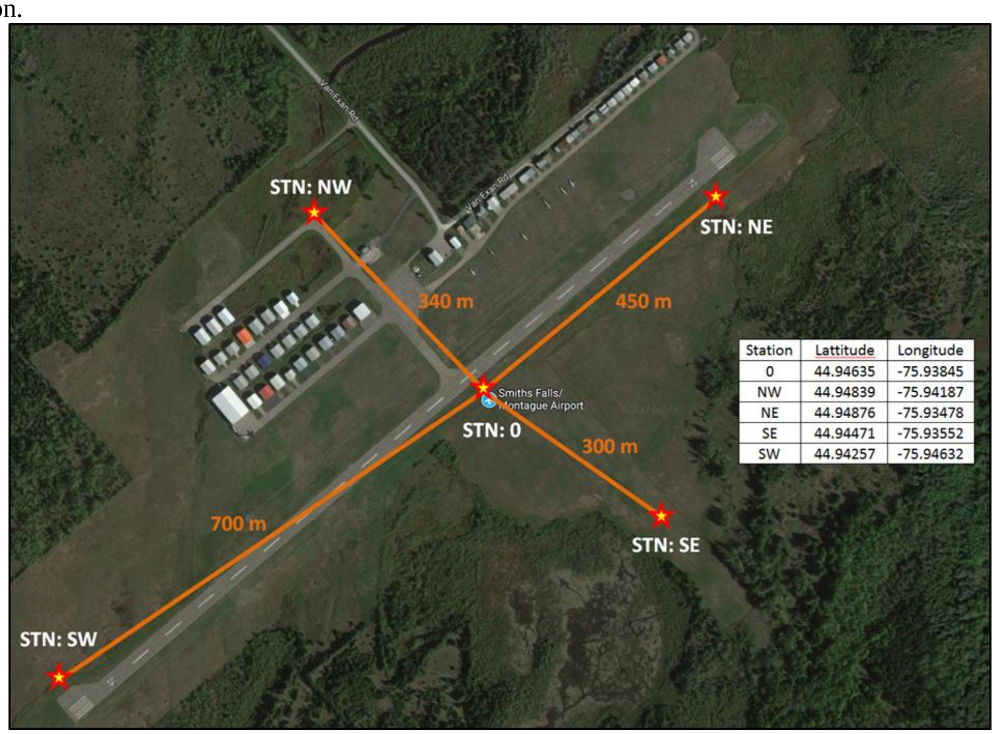

Figure 2: Smiths Falls Montague Airport Acoustic Measurement Locations

Figure 3: NRC Convair 580

A. Convair 580 Acoustic Reference Spectra

The acquisition of an operational Convair 580's acoustic signature could theoretically be obtained on the ground or during overhead flight. The advantages of a ground measurement include the ability to maintain a controlled environment and the avoidance of acoustic atmospheric propagation factors such as turbulence. The advantages of an overhead flight include operational engine settings and propeller RPM, the presence of operational aerodynamic noise sources, the ease of locating an observer microphone in the absence of acoustically reflective surfaces and the ability to measure aircraft noise emission vectors independent of the horizontal plane. The authors elected to utilize results obtained in overhead flight.

The NRC Convair 580 was flown at 1000 ft (304.8 m) and 2000 ft (609.6 m) AGL to obtain these measurements. The acoustic propagation effects of geometric spreading, atmospheric absorption and ground reflection were analytically accounted for over these short propagation distances for each height respectively. The array of microphones and the continuous measurement of the aircraft fly-by enabled the comparison of different noise emission angles.

B. Convair 580 Acoustic Signature Experimental Measurements

The aircraft was further flown at 8000 ft (2438.4 m) and 12000 ft (3657.6 m) AGL to record acoustic signature data obtained at distances representative of operational altitudes as well as operational conditions near the limit of audible detectability of a listener. To evaluate the effect of the aircraft noise emission angle as well as aircraft distance on acoustic sound pressure levels and subsequently audibility, a cloverleaf flight pattern was developed as depicted in Figure 4. Note that leg 5 is superimposed over leg 1 as the aircraft flew leg 1 and leg 5 as equal but opposing vectors. Additionally, shown in Figure 4, are the five array microphone locations as red circles. This flight pattern enabled the measurement of various aircraft noise emissions angles, distances and altitudes in a controlled and repeatable manner.

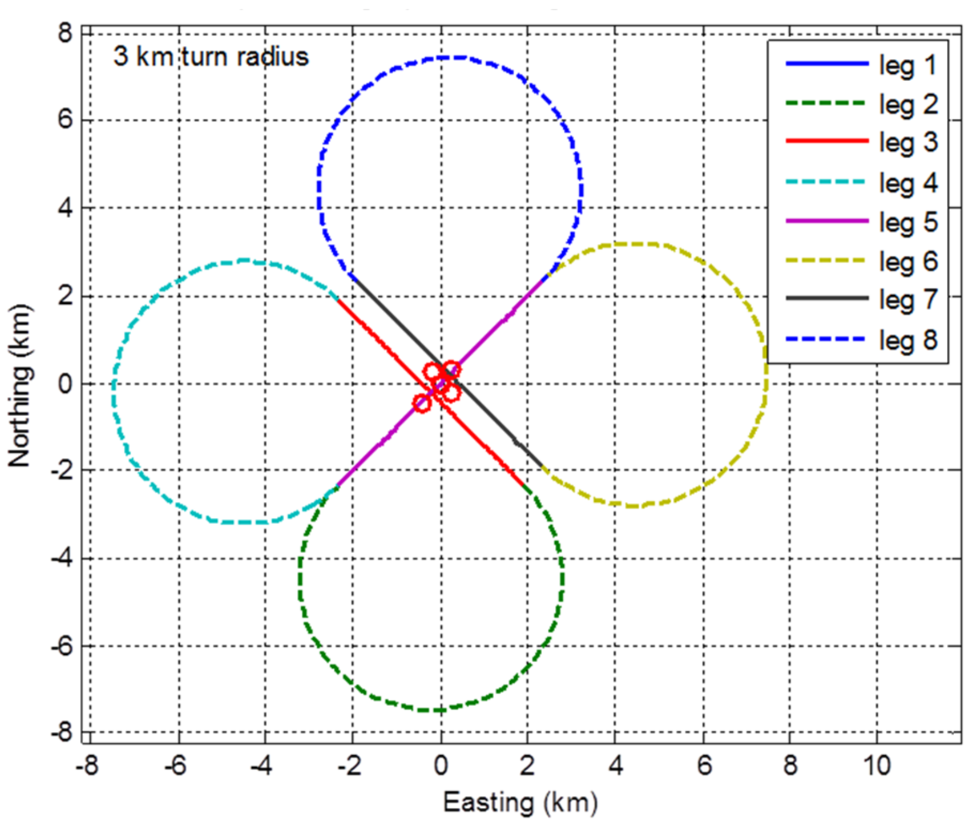

Figure 4: Overhead Flight Path of the NRC Convair 580 for AGL Flight Altitudes of 1000 ft, 2000 ft, 8000 ft and 12 000 ft

C. Atmospheric Propagation Model Validation Procedure

Once the low-altitude acoustic reference spectra and the high-altitude acoustic experimental spectra were obtained, it became possible to validate the performance of the selected Impedance Plane Formulation and FFP atmospheric propagation models.

Significant pre-processing effort was required to prepare the acoustic data for model validation by accounting for the following:

- Doppler Shift
- Aircraft Noise Emission Angle
- Propagation Time Delay
- Background Noise
- Appropriate time windowing for the aircraft's natively transient acoustic signature during a fly-by operation

The evaluated noise emission angles are shown in Figure 5 as an example of the data reduction methodology.

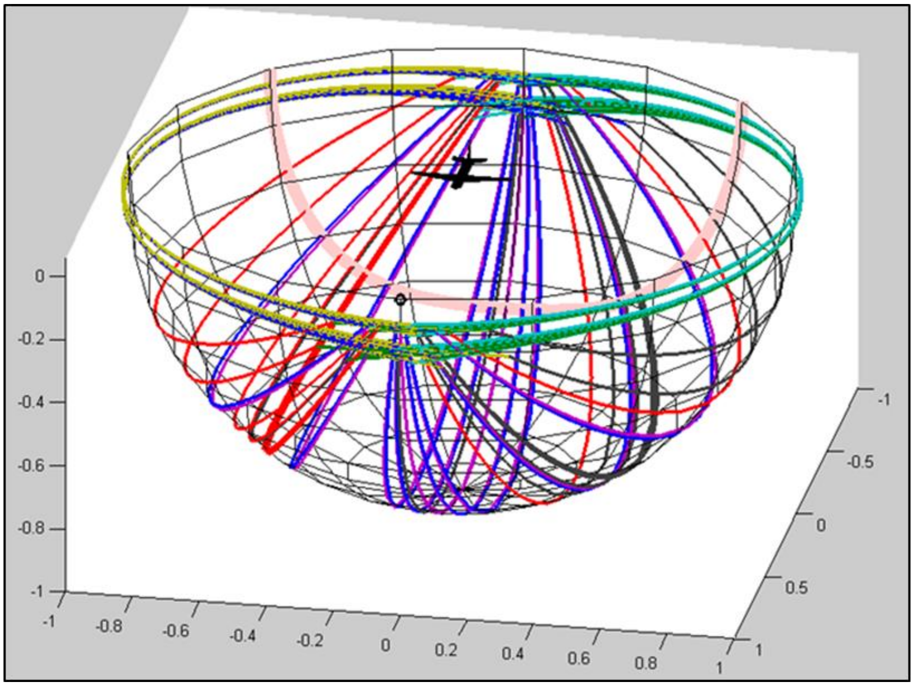

Figure 5: Noise Emission Angles at 1000 ft and 2000 ft AGL

V. Sample Results

Once the low-altitude fly-by reference spectra were corrected for geometrical spreading, atmospheric absorption and ground reflections, the spectra were utilized as a signal source in the acoustic atmospheric propagation models. The propagation models were then utilized to estimate the acoustic signature of the aircraft at high altitudes.

A. 8000 ft Acoustic Propagation Validation

A comparison of a measured acoustic spectrum and the respective estimated acoustic spectrum is shown in Figure 6. For this test point, the NRC Convair was flown overhead at 2438.4 m (8000 ft) AGL. After the data was recorded, post processing methods indicated the direction of flight and the noise emission angle. A suitable low-altitude reference acoustic spectrum was utilized to estimate the acoustic atmospheric propagation.

- The black curve depicts the Impedance Plane Formulation atmospheric propagation estimation
- The black dots depict the FFP atmospheric propagation estimation
- The red curve depicts the experimentally measured acoustic spectrum
- The blue curve is an indication of the average background levels at the local microphone measurement location

There are a number of noteworthy features contained within the plot. The NRC Convair exhibited two harmonic peaks in the vicinity of 70 Hz and 140 Hz. The locations of these two peaks are well represented in the estimation curves; this speaks well of the post processing methodology. It is indicative that a comparable low-altitude reference spectrum and high-altitude measurement spectrum with similar aircraft velocity vectors, as referenced to the local measurement microphone, were obtained; similar aircraft velocity vectors will produce repeatable Doppler shifts in the low-altitude and high-altitude spectra, as observed.

The first acoustic trough occurrence (in the vicinity of 80 Hz) was estimated by acoustic models but was not measured by the experimental recording. In an ideal noise propagation scenario, with little local background noise, acoustic troughs and peaks, independent of the signal source, are expected; the peaks and troughs are the constructive and destructive super-positions of acoustic waves and reflected acoustic waves. The Impedance Plane Formulation estimated a destructive acoustic trough, but the local background noise congested the trough. However, many troughs and peaks are observable at frequencies in excess of 200 Hz. This is indicative of a high signal to noise ratio as, despite the destructive interference, the acoustic signature remains above the local background noise levels.

Additionally one may note the excess local background noise at low frequencies (below 70 Hz) for this particular measurement.

Finally, the consistent estimations of the FFP and the Impedance Plane Formulation prediction indicate that turbulence and refraction were not dominant factors for this measurement case as the FFP does not account for turbulence while the Impedance Plane Formulation does not account for refraction.

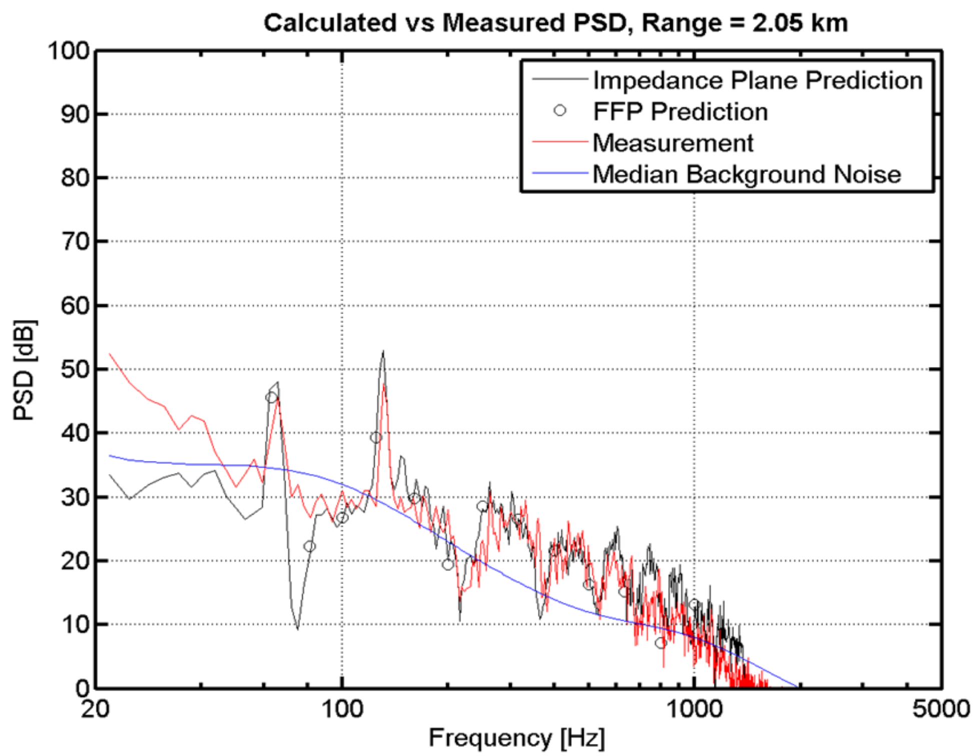

Figure 6: Measured vs Predicted Spectra of the NRC Convair; Altitude 8000 ft AGL, Range 2.21 km

B. 12000 ft Acoustic Propagation Validation

A comparison of a measured acoustic spectrum and the respective estimated acoustic spectrum at 12000 ft (3657.6 m) AGL are shown in Figure 7. Similar observations may be drawn as from Figure 6. Notably, the amplitude estimations of the acoustic propagation models begin to exhibit discrepancies from the experimental measurements. As distance increases, the indiscriminate turbulent acoustic fluctuations will correspondingly dominate.

During analysis, it was observed that identifying suitable high signal-to-noise ratio experimental data for validation against the atmospheric propagation models increased in difficulty proportionally with altitude.

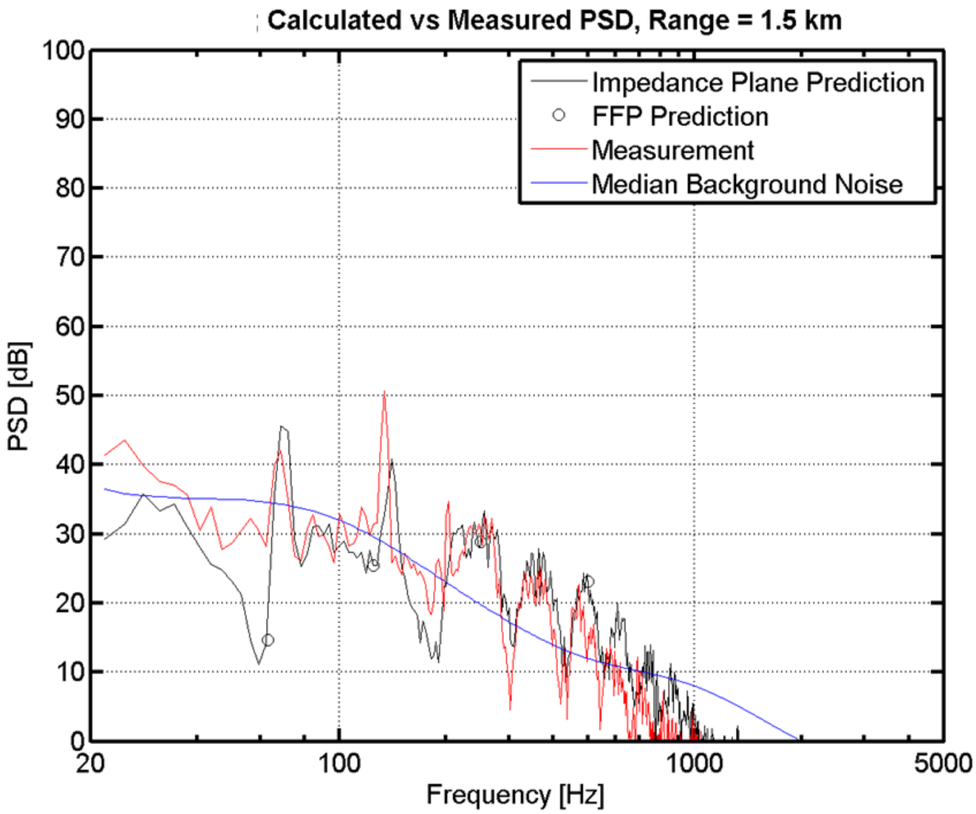

Figure 7: Measured vs Predicted Spectra of the NRC Convair; Altitude 12000 ft AGL, Range 1.5 km

VI. Conclusion

The National Research Council Canada assessed the visibility and audibility of aircraft in the vicinity of low-traffic aerodromes. The acoustic investigation included a microphone array camera located at the Smiths Falls aerodrome observing the NRC Convair 580. This paper described the specifics of the acoustic observation experiment and subsequent post processing.

Two acoustic atmospheric propagation models; the Impedance Plane Formulation and the Fast Field Program; were selected as suitable candidates for estimating the acoustic signature of the Convair at increasing altitudes. The test procedure was described including low-altitude and high-altitude acoustic measurements.

The acoustic atmospheric propagation models exhibited excellent performance, estimating the location and amplitude of signature Convair harmonic tones with excellent accuracy. Distances as far as 8 km in the horizontal plane and 3.66 km vertically were considered, with the model's estimation performance decreasing substantially as a function of distance.

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