Prediction of noise levels and annoyance from aircraft run-ups at Vancouver International Airport

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Annoyance complaints resulting from engine run-ups have been increasing at Vancouver International Airport for several years. To assist the Airport in managing run-up noise levels, a prediction tool based on a Green's function parabolic equation (GFPE) model has been consolidated, evaluated, and applied. It was extended to include more realistic atmospheric and ground input parameters. Measurements were made of the noise-radiation characteristics of a CRJ200 jet aircraft. The GFPE model was validated by comparing predictions with results in the literature. A sensitivity analysis showed that predicted levels are relatively insensitive to small variations in geometry and ground impedance, but relatively sensitive to variations in wind speed, atmosphere type, and aircraft heading and power setting. Predicted noise levels were compared with levels measured at noise monitoring terminals. For the four cases for which all input information was available, agreement was within 10 dBA. For events for which some information had to be estimated, predictions were within 20 dBA. The predicted annoyance corresponding to the run-up events considered ranged from 1.8% to 9.5% of people awoken, suggesting that noise complaints can be expected. © *2007 Acoustical Society of America.* [DOI: 10.1121/1.2769988]

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I. INTRODUCTION

Vancouver International Airport Authority (YVRAA), the body that manages Vancouver International Airport, receives hundreds of noise complaints each year. A significant portion results from engine run-ups by jet or propeller aircraft. A run-up—the testing of a stationary aircraft's engines—is a routine procedure that occurs following aircraft maintenance. There are certain parameters of engine run-ups, such as the location and heading of the aircraft, that can affect community noise levels, and that the airport can manage. This could be done more effectively using a prediction tool that could predict noise levels and annoyance in communities surrounding the airport that result from aircraft run-up noise.

The propagation of noise outdoors is a complex phenomenon. As sound propagates, it can be reflected, refracted, attenuated, and amplified.[1,2] Many factors influence outdoor sound propagation, including complex atmospheric and ground conditions. The commonly assumed hemi-free-field conditions over a reflective ground are not realistic. The work reported here extends previous work, which used a Green's function parabolic equation (GFPE) model in simplified atmospheric and ground conditions.[3]

The objective of the present work was to use more realistic environmental conditions—such as realistic wind-speed and temperature profiles, and mixed ground impedance—to predict noise levels and associated community reaction, in residential areas surrounding the Vancouver International Airport, resulting from propeller- and jet-aircraft engine run-ups, to help YVR minimize community annoyance for given atmospheric conditions and airline requirements. Full details of the work described here are published elsewhere.[4]

II. RUN-UP MEASUREMENTS

Accurate noise prediction requires accurate aircraft sound-source data. Data for run-ups by two propeller aircraft—a DeHavilland Dash-8 and a Beechcraft 1900—were available from previous work.[3,5] It was of interest here to obtain data for a jet aircraft. The purpose of these measurements was to determine the energetic and directional radiation characteristics (spectra and directivities) of a jet aircraft that operates at Vancouver International Airport, and whether it is similar to or different from those for the propeller aircraft measured previously. Of course, the CRJ200 is smaller than many jet aircraft; its noise radiation does not necessarily represent that of other jet aircraft.

Noise measurements during the run-up of a CRJ200 were made in conjunction with a taxiing exercise late one evening in August 2005. The wind speed was 4 m/s and the temperature was 17 °C (at 10 and 6 m above ground level, respectively). Equivalent-continuous sound-pressure levels (L_{eq}) were measured in third-octave bands from 25 to 8000 Hz at two heights (ground level and 1.4 m above the ground), at 15 locations around the aircraft, 40 m from the center of the source, as illustrated in Fig. 1, and at three power settings (idle, 50% power, and full power). The run-up took place in a large, open area, over concrete. Measurement positions located at the rear of the aircraft were not measured, for safety reasons. Third-octave-band background-noise levels were at least 10 dB below the signal levels in all cases (except at a few positions, for some frequencies below

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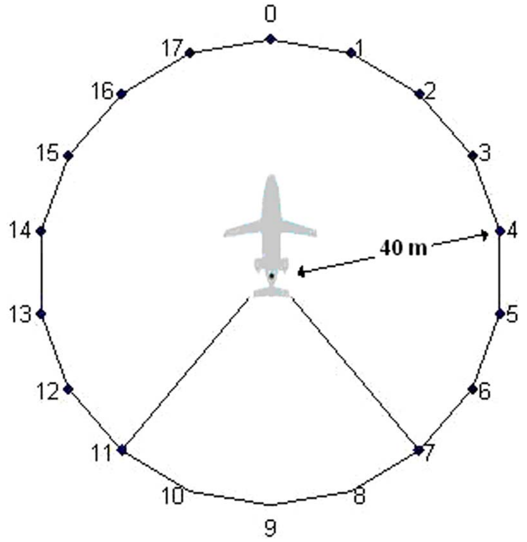

FIG. 1. (Color online) Measurement locations for the jet-aircraft noise measurements.

50 Hz, for which the difference was between 5 and 10 dB). The unweighted L_{eq} spectra at positions in front, to one side, and toward the back, of the aircraft are shown in Fig. 2. Results for Position 2 were not obtained due to equipment malfunction. The levels measured at ground level tended to be higher than those at 1.4 m above the ground, as expected, since destructive interference can result in lower sound-pressure levels at receiver positions above the ground. Two major distinctions between the CRJ200 and the propeller-aircraft noise characteristics are in the shapes of the sound-pressure-level spectra, and their magnitudes. The propeller aircraft displayed prominent tonal components at lower frequencies (e.g., at the blade-passage frequency and its harmonics), particularly at higher-power engine settings, unlike the more broadband spectra of the CRJ200. Furthermore, the levels generated by the CRJ200 tended to be higher—for example, 10–30 dB higher than the Dash-8.

Figure 3 shows the measured total, unweighted L_{eq} directivity results for the CRJ200. Results indicate that the radiation from this jet aircraft was quite axisymmetric; levels on the two sides of the aircraft were usually within a couple of decibels of one another—the average difference was around 1 dB. The directivity of the source varies by 5 dB or more at different engine-power settings. These results suggest that levels behind the aircraft, where measurements were not possible, might be fairly uniform and similar to those at the rear-most positions that were measured. Germain *et al.*[5] measured levels behind a propeller aircraft, finding variations of total, unweighted level of up to 4–7 dB.

III. GFPE MODEL

A. Model description

There are several outdoor-sound-propagation prediction models available.[6] More common models include the generalized fast field program (FFP), the parabolic equation (PE) method, and ray-tracing. Since FFP models are restricted to environments with layered atmospheres and homogeneous

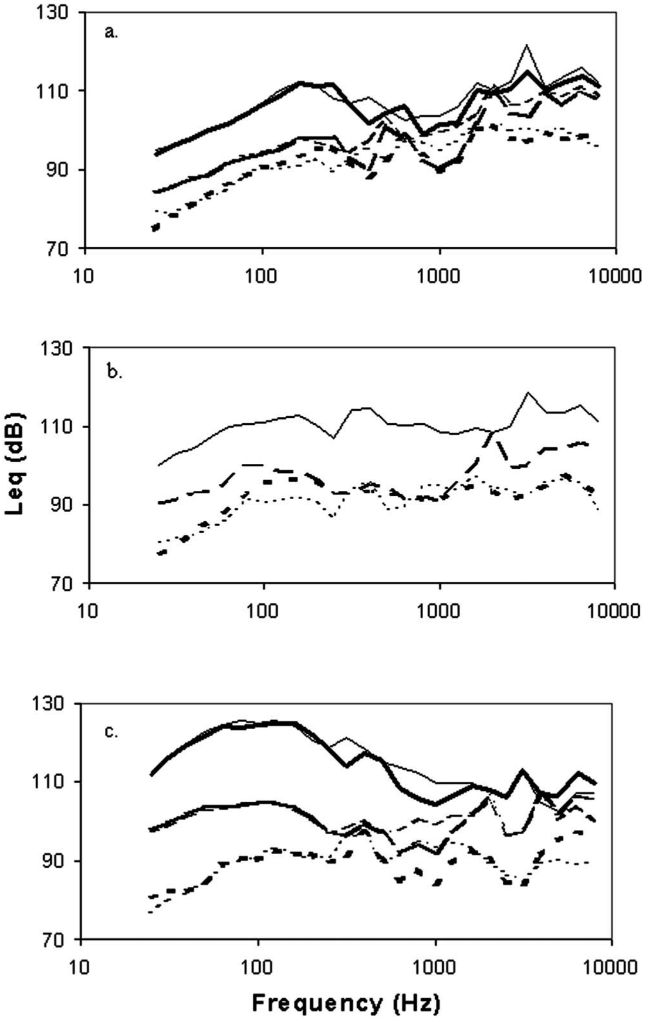

FIG. 2. Measured CRJ200 unweighted, third-octave band L_{eq} spectra at Positions (a) 0, (b) 3, and (c) 7 (see Fig. 1), at two heights, for three engine-power settings. Full power: (**—**) 1.4 m, (—) ground level; 50% power: (– – –) 1.4 m, (- - -) ground level; idle (···) 1.4 m, (···) ground level.

ground surfaces, and since ray-tracing programs become extremely computationally expensive for the long ranges involved outdoors and must deal with the appearance of “caustics,” the PE method was chosen for use here. PE models can incorporate mixed ground impedance and sound-speed profiles. There are several ways to solve the parabolic equation numerically—the Crank-Nicholson parabolic equation (CNPE) method and the GFPE method are two common methods. The horizontal and vertical step sizes for the CNPE are limited to a maximum of $\lambda/10$ (λ is wavelength). In the GFPE, the vertical step size has the same limitation, but the horizontal step size can be between 10λ and 100λ, leading to a major reduction in computation time, particularly at higher frequencies (X. Di, private communication).[7]

The theory behind the GFPE model is based on the Helmholtz equation, into which a new, simplified quantity that has cylindrical spreading removed is substituted for sound pressure. It is then assumed that the majority of sound propagates in the forward direction and that the wave number is constant across a step Δr. Integrating across the step subsequently solves the Helmholtz equation. The GFPE model solves for sound pressure on a two-dimensional (r,z)

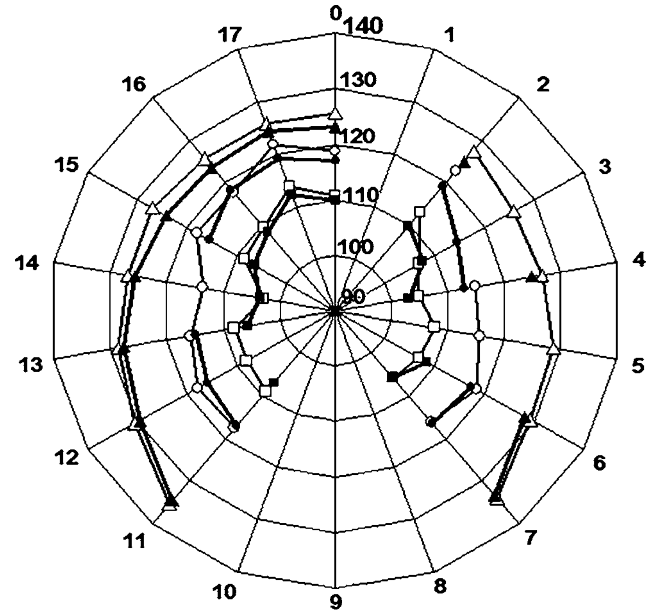

FIG. 3. Measured CRJ200 total, unweighted L_{eq} directivity at 40 m at positions shown in Fig. 1, at two heights, for three engine-power settings. Full power: (▲) 1.4 m, (△) ground level; 50% power: (●) 1.4 m, (○) ground level; idle (■) 1.4 m, (□) ground level.

grid. The horizontal dimension is the source-receiver distance, divided by steps Δr; the vertical dimension is divided into steps Δz. The domain of r is from the first step $(0+\Delta r)$ to the receiver position. The sound field at $r=0$ is represented by a Gaussian function. The domain of z is from the ground level, where the reflection coefficient determines how much sound is reflected, to an upper absorbing layer, set by the user. Rather than have the upper-atmosphere limit end abruptly, an absorbing layer that is at least 30λ thick exists above the upper limit of the atmosphere through which sound propagates, to prevent sound from reflecting unrealistically back down into the atmosphere. Unfortunately, direct integration across the steps Δr is not possible; instead, the expression is solved using Green's function, and either spectral representation or using Rayleigh's integral. This process is repeated, iteratively marching through the solution in steps of Δr, until the receiver sound-pressure level is predicted.[6,8]

B. Modifications

A two-dimensional GFPE model, originally developed by Gilbert and Di,[8] was available from previous work,[3] and was extended. The model calculates the complex sound pressure at a single frequency as a function of the distance over homogeneous ground of arbitrary acoustical impedance, with user-defined vertical sound-speed gradients.[8] Improvements implemented to achieve the objectives of the present work included accounting for nonhomogeneous ground (variations in ground type/impedance with distance), the prediction of sound-pressure levels in third-octave bands, implementing a frequency-dependent step size, accounting for air absorption, the calculation of total A-weighted levels, the automatic calculation of the sound-speed profile given the temperature and wind conditions, the estimation of sound-exposure level (SEL), and the prediction of the annoyance associated with the noise. Six predefined, finite ground impedances were programmed into the model, based on the grounds that were considered typical of the areas at and around YVR (dry grass, wet grass, dry sand, wet sand, snow, and an acoustically hard surface corresponding to concrete, water, or asphalt). The corresponding impedances were calculated according to Attenborough's two-parameter model.[9]

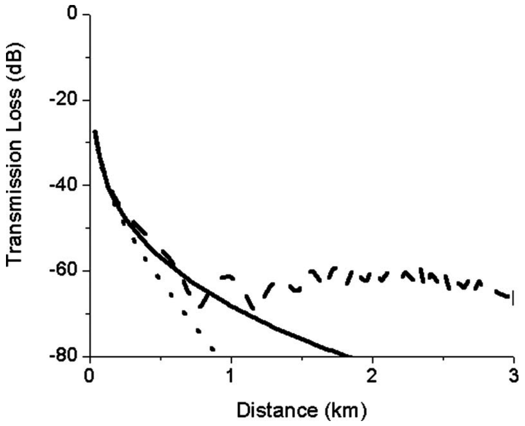

FIG. 4. GFPE predictions of the variation of transmission loss with distance at 100 Hz in (—) homogeneous, (···) upward-refracting, and (- - -) downward-refracting atmospheres (see the text).

C. Validation

The modifications made to the GFPE model were evaluated in comparison with results in the literature. Levels were predicted at various frequencies and over various distance ranges. Data from the Attenborough *et al.*[10] benchmark paper were used in the cases of homogeneous and upward- and downward-refracting atmospheres. Data from Gauvreau *et al.*[11] and Daigle *et al.*[12] were used in the case of mixed-ground impedance. Very good agreement (typically within 2 to 3 dB) was obtained in all cases (see Ref. 4).

Two representative validation results are shown in Figs. 4 and 5. First, the case of homogeneous ground impedance and different atmospheric conditions was considered. The input-parameter values were as follows: $h_{\mathrm{source}}=5.0$ m,

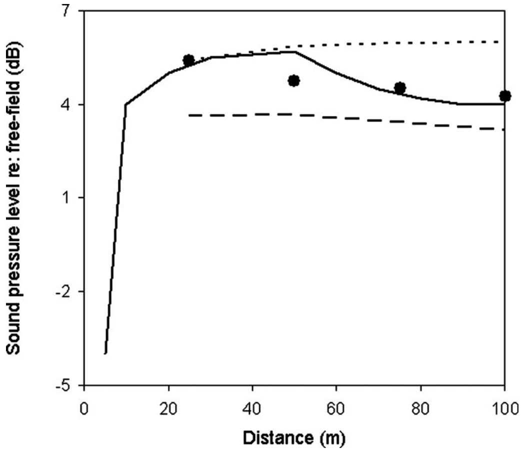

FIG. 5. Predicted variation with distance of sound-pressure level relative to free field for a mixed ground-impedance configuration (see the text): (●) GFPE; (—) CNPE (Ref. 11). Also shown for reference are the GFPE predictions for completely (···) "hard" and (- - -) "soft" grounds.

$h_{\text{receiver}}=1.0$ m, normalized ground impedance $=(12.81,11.62)$, $\Delta z=\lambda/5$, $h_{\text{vertical}}=250$ m, $c=343$ m/s, FFT length=16 384, surface-wave integration number=250. Figure 4 shows GFPE predictions of the variation of transmission loss (sound-pressure level relative to that at 1 m in a free-field) with distance up to 3 km at 100 Hz in homogeneous, upward-refracting (sound-speed gradient=+0.1 s^{-1}) and downward-refracting (sound-speed gradient=−0.1 s^{-1}) atmospheres. Levels are very similar to those presented in Ref. 10. Figure 5 compares levels predicted by the GFPE for a configuration with mixed ground impedance with CNPE values estimated from Ref. 11. There is a ground impedance discontinuity 50 m from the source; the ground nearest the source is "hard" (flow resistivity=2×10^5 kPa s m^{-2}), that farthest from the source "soft" (flow resistivity=2×10^2 kPa s m^{-2}). The other input-parameter values are as follows: frequency=160 Hz, $h_{\text{source}}=1.5$ m, $h_{\text{receiver}}=1.8$ m, $\Delta z=\lambda/10$, $h_{\text{vertical}}=100$ m, $c=340$ m/s, FFT length=16 384, surface-wave integration number=100. Also shown for reference are the GFPE predictions for uniformly hard and soft grounds. The GFPE predictions are credible and agree well with the CNPE prediction. Results were equally as good at other frequencies (see Ref. 4).

Modifications were also made to include turbulence in the GFPE model. Predictions gave results similar to those of Gilbert[13] (see Ref. 4). However, in preliminary prediction work, the effects of turbulence were not found to contribute significantly in homogeneous, downward-refracting, and in very weak upward-refracting (e.g., with a decrease of 1 m/s over 200 m), atmospheres. These conditions were typical of the run-up events considered in this work; thus, turbulence was not considered further.

IV. PREDICTION

A. Atmospheric assumptions

There are three general states that exist for a static atmosphere: stable, unstable, and neutral. In a stable atmosphere, the temperature increases with height. The shape of the temperature-profile increase is expected to be parabolic (D. Steyn, private communication). An unstable atmosphere is one for which the temperature decreases with height at a rate greater than 0.0098 °C/m (the dry adiabatic lapse rate of the atmosphere). Instability indicates that the vertical movement of air packets is not restricted. The temperature profile in a neutral atmosphere decreases at a rate of 0.0098 °C/m.

The temperatures at two heights—1.6 and 6 m—were available for the times of the run-up events considered in this work. Unstable conditions at night are uncommon (D. Steyn, private communication). Thus, if the change in temperature was positive, stable conditions were applied; if the change in temperature was negative, neutral conditions were assumed. To approximate stable profiles, the temperature at 6 m was input and a parabola was fit to this value, and to the values at 0 and 200 m, which were assumed to be 2 °C lower and 6 °C higher, respectively, than the temperature at 6 m. The temperature profile for neutral conditions was set to decrease at a rate of 0.0098 °C/m. Temperatures in the first 10 m above the ground do not follow a simple curve; this part of the profile is almost impossible to estimate without making measurements at several heights, adding an additional element of uncertainty to the assumptions made in prediction.

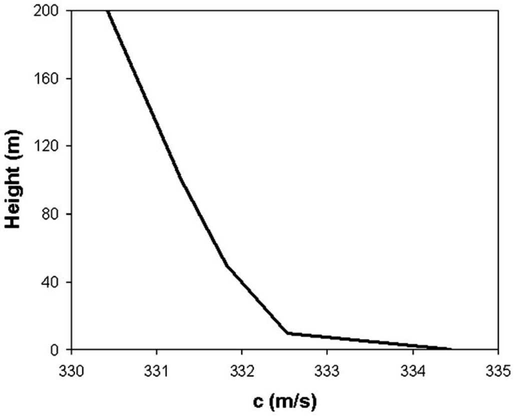

FIG. 6. Typical sound-speed profile used in GFPE predictions (details in the text).

For both atmospheric states, the wind-profile power law was used to calculate the wind-speed profile (the variation of wind speed with height):

$$\frac{u(z)}{u(10)}=\left(\frac{z}{10}\right)^{1/7}, \tag{1}$$

in which u is wind speed and z is height above the ground. The wind vector was then projected onto the source-receiver direction and added to the sound speed. It was suspected that mixing due to winds greater than 5 m/s at 10 m would prevent the above-described stable and neutral atmospheric states from forming. Run-up events that took place during such times were therefore separated from those with lower winds in the analysis in Sec. IV C.

The sound-speed profile for a "typical" night-time run-up (18 April 2005; neutral conditions, temperature of 6 °C at 6 m above the ground, wind speed of 2.5 m/s at 10 m above the ground, incident at an angle of approximately 42° to the source-receiver direction) is illustrated in Fig. 6. In this particular case, the sound would be refracted upward as it propagates from the source to the receiver. The curve is not perfectly smooth, as the GFPE model integrates the sound-speed profile from a set of points calculated by Eq. (1).

B. Sensitivity analysis

To investigate the dependence of predicted noise levels on the input parameters of the GFPE model and, therefore, the expected influence of uncertainties in the input-parameter values, a simple configuration was chosen as a reference, and predictions for other cases were compared with levels predicted for it. The prediction input parameters were varied slightly, one at a time. A-weighted levels from 25 to 2000 Hz were predicted and compared. In one variation, the frequency range was also extended, for comparison with the reference spectral range. The parameter values for the reference case were as follows:

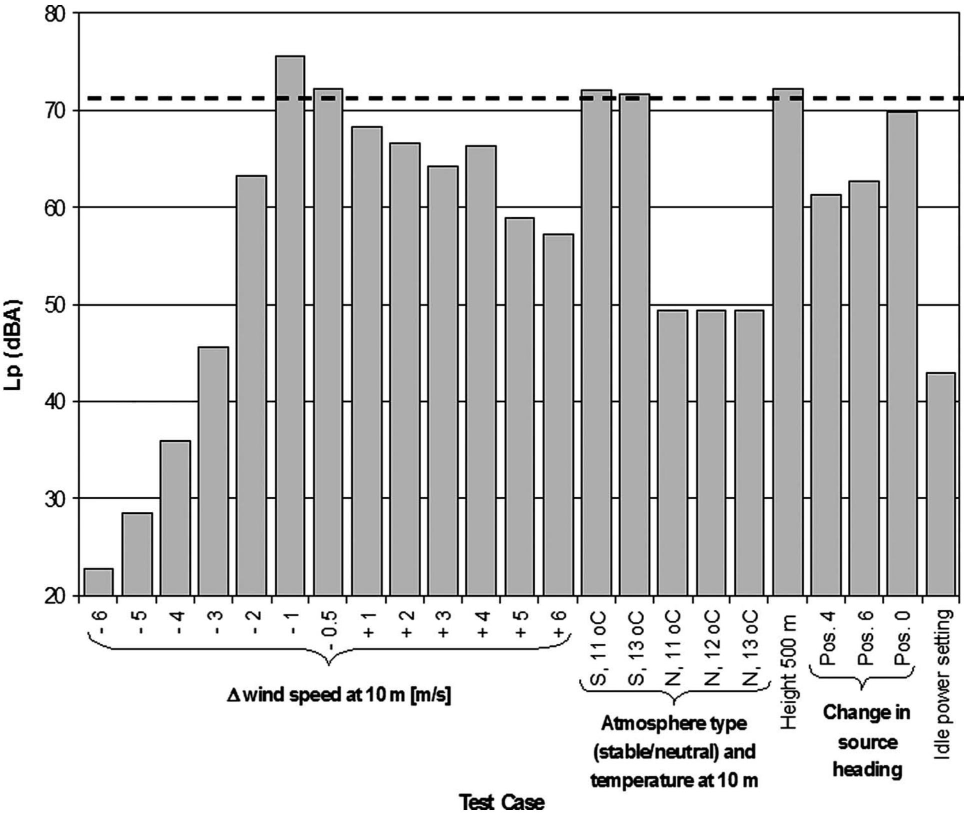

FIG. 7. Comparison of predicted total, A-weighted sound-pressure levels for the reference test case (dashed line at 71 dBA) with those for test cases with input-parameter variations in wind speed, temperature, height of propagation, and aircraft details.

(1) Source-receiver distance of 2 km;
(2) One ground-impedance transition point midway between the source and the receiver (at 1 km), separating "concrete" nearest the source from "dry, loamy grass" farthest from the source;
(3) Dash-8 propeller-aircraft source, running-up at full power; source height 3 m above the ground;
(4) Receiver height 6 m above the ground (a typical noise monitoring terminal microphone height); and
(5) Stable atmosphere, with no wind, and a temperature of 12 °C at 6 m.

Geometric variations included changes in the total source-receiver distance (calculated by adding or removing 10 m from either the grass or concrete section), shifting the transition point by 10 m, as well as changes in the source height (±1 m) and receiver height ($\pm 0.1, 0.5$ m). The magnitudes of these changes were chosen to represent the uncertainties involved in estimating the input values. All of the resulting predictions were within 2 dB of the reference case.

Variations relating to the atmosphere included changes in the wind speed used in the wind-profile power law, changes in the temperatures at the reference heights, and switching from stable to neutral conditions. Atmospheric-variation predictions, along with predictions for a doubling of the numerical-grid height for which the sound-pressure levels are calculated (as mentioned in Sec. III A), and changes in the aircraft engine-power setting and heading, are presented in Fig. 7.

By way of these predictions it was found that, in general in the current application, the sensitivity of the GFPE model with respect to variations in most input parameters is rather low: realistic variations do not yield very different results. The exceptions to this are the cases of wind speed, atmosphere type, and aircraft engine-power setting and heading. The values of the latter two factors are well known and, as long as communication between the aircraft operator and the airport is clear, this information should be readily accessible. This is, however, not the case for wind profiles, and for the state of the atmosphere: these will never be known accurately unless they are measured. Their dynamic nature makes the measurements difficult.

Temperature and wind profiles can strongly influence the sound-speed gradient, and thus the manner in which sound will be refracted as it propagates. In instances of very strong upward refraction where shadow zones are created, such as the extreme case with wind designated "-6 m/s@10 m," very large differences, such as the decrease of nearly 50 dB in Fig. 7, can occur. This is not to say that the outdoor sound-pressure level will actually be 23 dBA; background levels will invariably be higher, masking the contribution from the engine run-up. Moreover, turbulence will reduce the high attenuation at large distances.

C. Test cases

Run-ups that occurred at the Vancouver International Airport between January 2005 and June 2006 were drawn upon as the basis for comparisons between predicted and measured noise levels, to investigate prediction accuracy in realistic situations. In order for a run-up to be considered, someone in the community, whose address or approximate location was available, was required to have reported a noise complaint corresponding to the approximate time of the en-

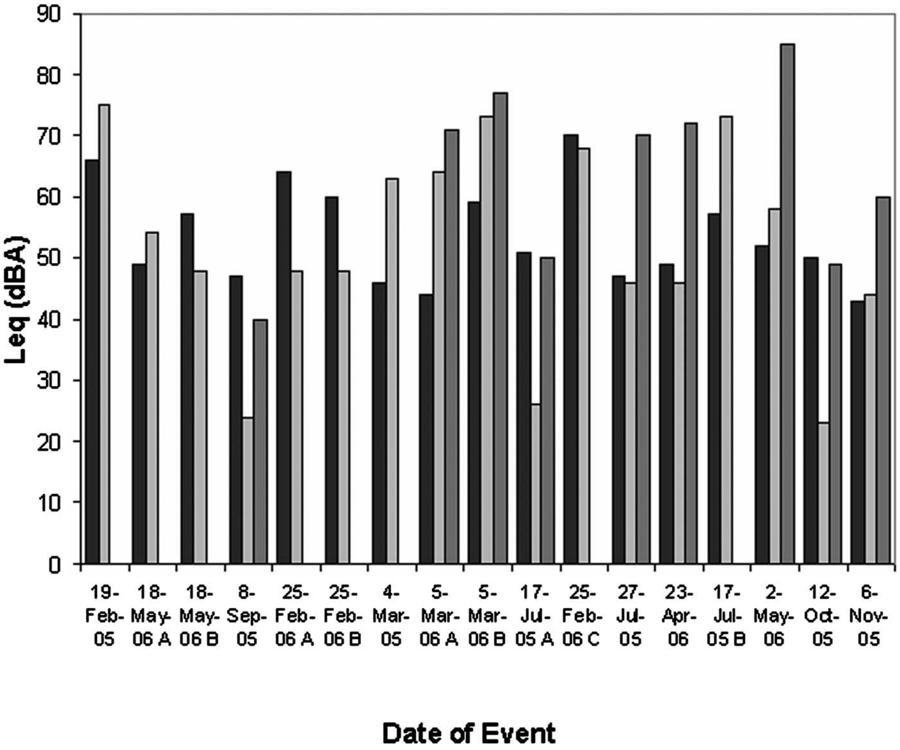

FIG. 8. Summary of GFPE-predicted total, A-weighted run-up noise levels and measured equivalent-continuous NMT levels: (closed square) measured; (gray square) "low" prediction; and (dark gray square) "high" prediction, where applicable.

gine run-up. Only night-time run-up events were considered. Seventeen such events were identified, and predicted sound-pressure levels were compared with the corresponding levels measured at noise monitoring terminals (NMTs); the annoyance corresponding to the levels was also predicted to investigate the subjective magnitude of the problem. NMTs are measurement stations located at and around the Vancouver airport, which record A-weighted, 1-s, equivalent-continuous noise levels. The GFPE model predicted levels in third-octave bands from 25 to 4000 Hz. The total A-weighted GFPE calculated levels, and the corresponding measured A-weighted, equivalent-continuous NMT levels during the run-ups, are plotted in Fig. 8.

Source-radiation characteristics were only available for the three aircraft discussed earlier; the Beechcraft-1900 and Dash-8 propeller aircraft, and the CRJ200 jet aircraft. Since, however, run-ups at YVR are not limited to these three aircraft, when predicting run-ups that involved other aircraft, the data for one of the three measured aircraft were "substituted." The aircraft noise "assigned" to it was chosen based on similarity of the aircraft type (jet/propeller) and engines (number/type). The substitutes (e.g., a Dash-8 for a D2, a CRJ200 for a Boeing 767, etc.) were not necessarily good matches. Clearly, the cases for which the source sound levels were unknown were associated with an increased prediction uncertainty. Moreover, the orientation of the aircraft (for directivity) was not always recorded in the run-up incident report. Finally, the actual power setting of the aircraft was not always as indicated on the incident report if, for instance, the operator decided to test at other power settings (see the examples in Secs. IV C 1 and IV C 4). As was shown in Sec. III B, these uncertainties can lead to large variations in predicted levels. Thus, in cases for which information was missing, GFPE predictions used estimated values of the missing inputs. One or two sets of plausible values were used, to predict levels indicative of the ranges predicted; these are shown in Fig. 8. The cases labeled "low" are either for the single level, or the lowest of two values, predicted; the cases labeled "high" are for the highest of two values predicted. The prediction that was closest to the average level was used as the basis of the discussion.

One of the run-up locations at Vancouver International Airport had a blast fence located at the southern end. Previous work had measured the insertion loss of this particular blast fence.[5] While the insertion loss varied somewhat across the frequency spectrum, for the midfrequencies of most interest here it was relatively flat, with an average value of approximately 8 dB. Thus, for cases in which the blast fence was involved, an attenuation of 8 dB was subtracted from the predicted levels.

1. Available aircraft source levels, known headings

There were three events on two nights for which atmospheric conditions were stable, the correct aircraft source levels were available, the aircraft headings were known, and the wind speeds were below 5 m/s (in fact, they were all below 4 m/s): one on 19 February 2005, and the two on 18 May 2006 (A and B). In the first two cases, GFPE predictions overestimated the measured levels by 9 and 5 dBA, respectively. However, for the run-up on 19 February 2005, the blast fence was between the aircraft and the receiver. Applying the average insertion loss, the predicted value for 19 February 2005 is within approximately 1 dB of measurement.

8 September 2005 also had a known heading and available aircraft-noise data, but took place during neutral conditions. This run-up was recorded as at "idle" engine power. In

the past, there have been problems with requests for run-ups at a lower power setting, when in fact the aircraft were run at a higher power setting. Following a suspicion that a higher power setting may have been used for this runup, GFPE predictions were made for both idle and full power. Full-power predicted levels were 7 dBA below the average measured level, compared to the idle-power level, which was 23 dBA below the average measured level. Both predicted levels are shown in Fig. 8; however, due to the likelihood that the aircraft was run at full power, the full-power level was used for further analysis.

2. Unavailable aircraft source levels, known headings

Considering now cases for which the source data were unavailable for the specific aircraft but the heading was known, two stable-atmosphere cases (with the same aircraft—the events took place one after the other during the same night) and one neutral-atmosphere case were available with wind speeds below 5 m/s: on 25 February 2006 (A and B) and on 4 March 2005, respectively. For the stable cases, the GFPE predictions were 12 and 16 dBA below the average levels. The cause of these disagreements is likely the aircraft substitution of the Beechcraft 1900 for the Beechcraft 100.

In the neutral case, on 4 March 2005, levels were overpredicted by 17 dBA relative to the average measured level. Here again, however, the blast fence was located between the source and receiver. When including the attenuation due to the blast fence, the GFPE prediction is 9 dBA above the measured values.

3. Available aircraft source levels, unknown headings

The need to estimate the aircraft heading (orientation) when it was not recorded makes accurate prediction difficult, since the data available suggest that aircraft, particularly propeller aircraft, can be directional. As discussed in Sec. II, there is considerable uncertainty associated with the noise levels behind aircraft—particularly jet aircraft—adding to the complexity of predictions in cases missing relevant information. If no information was available, a source level at the front of the aircraft, and a source level toward one of the rear sides of the aircraft were used. For the run-ups on one night (5 March 2006 A and B), levels were predicted at two NMTs for aircraft for which source levels were available, but the headings were unknown. These predictions were 20 and 14 dBA above measured levels at Position 0 (see Fig. 1—levels at Position 5 were overpredicted by even more). Taking into account the combination of the insertion loss of the blast fence, and the possibility that the true heading resulted in lower sound-pressure levels, this prediction may in fact be much closer to the measured level. 5 March 2006 was also noted to have a stable atmosphere. The positive change in temperature between heights of 1.6 and 6 m was the largest that occurred for all of the run-up events considered: 4.3 °C over 4.4 m. Wind speeds were relatively low, at 1.1 m/s at 10 m height; the difference between prediction and measurement is not believed to be caused by unknown atmospheric-parameter values in this case.

4. Unavailable aircraft source levels, unknown headings

Four run-up events had unknown aircraft source levels and unknown headings: two in stable conditions, 17 July 2005A and 25 February 2006C, and two in neutral conditions, 27 July 2005 and 23 April 2006. Surprisingly, GFPE predictions underpredicted the average levels in the four cases by only about 1, 2, 1, and 3 dBA, respectively. The event on 17 July 2005 was recorded as an idle event, but when the full-power source data were used, the best prediction accuracy was obtained. The idle power setting listed for 27 July 2005 gave good agreement—better than the full-power setting. This suggests that sometimes the aircraft being run-up was at the idle-power setting as recorded, but that at other times it was at a higher power setting. The 23 April 2006 prediction gave a level equal to the background-noise level. What is interesting here is that the decibel sum of the background-noise and predicted levels equals the measured level. The prediction for 25 February 2006C is well above the background levels, below the peak level, and only 2 dBA different from the measured level. It is surprising how well the levels in this section agree, given the uncertainties in the inputs.

5. Wind speeds above 5 m/s

Four run-ups, each of which occurred during high-wind conditions, remain to be discussed: these occurred on 17 July 2005B, 2 May 2006, 12 October 2005, and 6 November 2005. If wind speeds had been lower, the former two run-ups would have been categorized as stable, and the latter two as neutral. If those conditions are assumed, GFPE predictions are about +16, +6, −1, and +1 dBA different from the measured levels of the noise events. Wind should not affect the propagation of sound significantly in any of these cases, because the source-receiver direction was not parallel to the wind direction (the differences between the source-receiver directions and the wind directions in the four cases were around 55°, 124°, 74°, and 135°, respectively). These stronger winds are, however, expected to affect the atmosphere, preventing the "standard" temperature profiles (parabolic or linear) from existing at greater heights, or even from being established. What makes this analysis extremely difficult is that information pertaining to the aircraft source levels, and/or the aircraft heading, is missing for all four run-up events, except on 6 November 2005 (for which the measured level was overpredicted by only 1 dBA). While, in principle, strong winds should affect the atmosphere in such a way as to make predictions difficult, uncertainties associated with the aircraft source data make this difficult to isolate. The fact that more than one GFPE prediction (i.e., the high and low predictions in Fig. 8) was made for all events except 17 July 2005B increases the chance of finding one prediction result that agrees well with the measured level.

6. Summary

The prediction results, corrected for blast-fence insertion loss where applicable, have been replotted against the measured levels in Fig. 9. The many points lying near the $y=x$

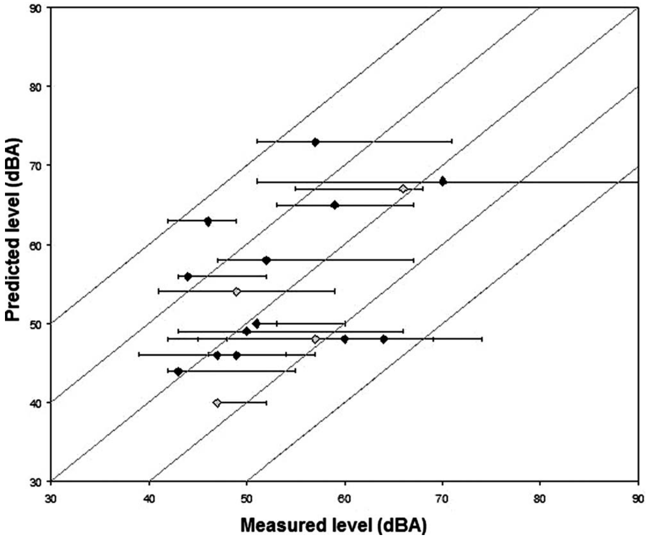

FIG. 9. Comparison of total, A-weighted GFPE predictions with NMT measurements. The central diagonal line represents $y=x$, the other lines are at 10 and 20 dBA offsets: (◇) Predictions for which all information was known. (◆) Predictions for which some information was unknown. Error bars indicate the range of measured NMT levels, from background to peak.

line suggest that the GFPE model generally predicts measured sound-pressure levels with reasonable accuracy. The fact that this sometimes occurs when the input data are not well known apparently indicates that good agreement can sometimes be a coincidence. The symmetrical distribution of the data indicates that the GFPE model does not have an inherent tendency to over-or underestimate sound levels.

While many (71%) of the event-average levels in Fig. 9—after correction for barrier insertion loss, where applicable—were predicted within 10 dBA, some events were inaccurately predicted by nearly 20 dBA; the worst prediction, which was 17 dBA higher than the average NMT level, was for a Boeing 767 on 4 March 2005.

Given this small sample size (17), and the surprisingly accurate predictions discussed in Secs. IV C 4 and IV C 5, it is hard to draw conclusions regarding what conditions are more likely to result in accurate or inaccurate predictions. It appears that, for run-up events for which the aircraft noise levels are available, it is nearly three times (58%) more likely that prediction will be within 10 dBA than if the levels were estimated with a substitute aircraft (20%). It is more difficult to draw conclusions for the cases with known/unknown headings, with wind speeds greater/less than 5 m/s, and with stable/neutral atmospheric states, as they all gave similar results. It is, of course, of interest to consider whether prediction had a tendency to be above or below the measured levels; in fact, overestimates appear to be equally as likely to occur as underestimates for predictions within 10 dBA of measured levels (42%), and for predictions within 20 dBA of measured levels (60%). Again, it is difficult to have high confidence in these overall results with this small sample size, and given the surprising prediction results of Secs. IV C 4 and IV C 5.

Though the data pool is limited, the results in Sec. IV C 4 suggest that if all information is available—particularly the noise levels of the aircraft performing the run-up—prediction can be accurate within about 10 dBA. With relevant information unknown, prediction uncertainty will increase; with reasonable choices, however, predictions can be expected to be accurate within about 20 dBA.

D. SEL and annoyance

It is of interest to investigate the annoyance associated with aircraft run-ups at Vancouver International Airport. Since night-time run-ups were of concern, annoyance was quantified in terms of the percentage of people awoken, as described in ANSI S12.9-2000/Part 6.[14] This standard relates the indoor SEL to the percentage of people awoken, as follows:

$$\%\,\text{Awakenings} = -7.02 + 0.14\ \text{SEL}. \qquad (2)$$

Using the outdoor SEL predictions, the percentage of people annoyed (awoken) due to the engine run-ups identified in the present work ranges from 1.8% to 9.5%, with the average being 5.9%. An uncertainty of ±10 dB in SEL corresponds to an uncertainty of ±1.4%, ±20 dB to ±2.8% uncertainly.

Neither the indoor SEL nor the actual percentage of people awoken was known (no measurements were taken indoors). The only information that was available was that, at the time of the events in question, people were sufficiently annoyed by the noise that they contacted the airport with their concerns.

Indoor levels are equal to outdoor levels reduced by the insertion loss of the residence. Since these are difficult to estimate accurately, no attempt has been made to do so here. If indoor levels were available and used, as they should be according to ANSI S12.9-2000/Part 6, SEL would be lower; thus, the true percentage of people awoken is likely lower than as predicted earlier.

While light sleepers may be very sensitive to noise and be awoken regardless of the SEL, to lower this percentage theoretically to zero, SEL should be below 50 dB. Exceptions will always exist. Depending on the geometry of neighborhoods and of houses, some sound focusing may take place, making some areas louder than others. Even if predictions of SEL are well below 50 dB, there is a chance that some people will be awoken.

V. CONCLUSION

The objective of this work was to consolidate, evaluate, and then apply a prediction tool that could assist the Vancouver Airport Authority in managing aircraft-engine run-ups, to minimize noise levels and disturbance for the residents of the communities living near the airport. This objective has been achieved.

Parameters that influence the propagation of sound were consolidated into a simple outdoor sound-propagation model. The original GFPE model that was available when this work began was modified to better describe the ground and the atmosphere, and to produce a more useful output. To ensure that changes made to the GFPE code were accurate, the model was evaluated. A comparison of predictions with results in the literature found very good agreement—typically within 2 to 3 dB. The agreement was considered sufficiently accurate to apply the GFPE model in realistic cases.

Availability of accurate input information was a big issue: a sensitivity analysis found that the state of the atmosphere, wind speeds, aircraft headings, and engine-power levels were the major sources of variability in predicted noise levels. Predictions were compared with noise levels measured at noise monitoring terminals near the airport. Some input parameters were difficult to obtain with accuracy, and estimates of unknown input data were required in several cases. For the four cases for which all input information was available, predicted levels were within 10 dBA. For cases where some information (i.e., the aircraft heading) was missing, the prediction error was within 20 dBA.

The sound-pressure levels predicted in the community for a sample set of 17 run-up events correspond to a predicted percentage of people awoken ranging from 1.8% to 9.5%. Identifying annoyance by percentage of people awoken is likely a better way to assess the number of people disturbed by noise than are complaints, as many members of the community do not feel inclined to report incidents, even if their sleep is disturbed.

While uncertainties of 10 dBA (and 20 dBA) are rather large, given the complexity of the problem and the small data pool, the agreement was good. Almost all prediction parameters—the ground impedance, the temperature and wind profiles, the source levels, the source and receiver positions, and the air absorption—had to be estimated or approximated in some way. The results of this study show that obtaining more accurate information—particularly relating to the aircraft noise-radiation characteristics and the atmosphere—is crucial to obtaining reliable predictions.

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