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Washington, D.C. 20591

Effects of Filter Response on Analysis of Aircraft Noise Data

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May 1982

Final Report

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16. Abstract

This report analyzes the effects of non-ideal filter transmission characteristics upon the measurement, correction, or extrapolation of aircraft noise data. The report is based primarily upon, and represents an abbreviated summary of, two previously published, more detailed reports on this topic. (FAA-EE-80-1, Vol. 3 and FAA-EE-80-46, Vol. 1)

The basic approach used to correct aircraft spectra for analysis errors due to finite filter sidebands and signal spectrum slopes involves defining some type of approximation to the true spectrum shape of the signal at all frequencies. The closer this approximation is to the true spectrum slope, the more accurate the correction for filter effects. This report reviews several such "filter effect" correction methods of varying degrees of accuracy.

Measurements on the ground of noise from aircraft in flight can involve propagation distances of the order of 300 to 2,000 m or more. In this case, band levels at high frequencies can be substantially in error, by more than 10 dB, unless filter effects are considered. A rule of thumb is that these band errors become significant (i.e., of the order of 0.5 dB or more) under the following conditions:

- o Propagation Distance (km) x $[\text{Frequency (kHz)}]^2 > 6$
- o Propagation Distance > 6 km (at any frequency in the audio range).

However, it is also shown that while the band levels may be subject to large errors due to filter effects, errors in composite noise levels such as PNL, LA or EPNL will usually be small - less than 1 dB.

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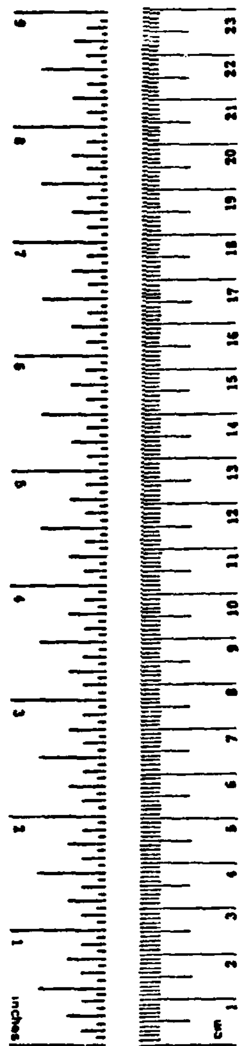
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

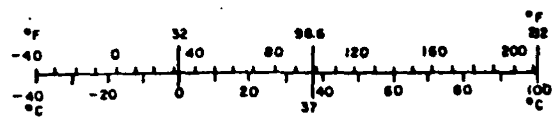
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTORY SUMMARY

This report analyzes the effects of non-ideal filter transmission characteristics upon the measurement, correction, or extrapolation of aircraft noise data. The report is based primarily upon, and represents an abbreviated summary of, two previously published, more detailed reports on this topic.[1,2]

Current engineering practice for evaluation of the spectral content of aircraft noise is well defined in FAR Part 36,[3] and in a number of related standards and documents covering the details of aircraft noise measurement and spectrum analysis.[4-7] According to the procedures cited in these references, corrections for filter sideband or spectrum slope effects are omitted when analyzing aircraft noise spectra. The basic objective of this summary is to briefly identify the potential errors involved in this omission and then evaluate alternative methods to correct for these errors. Emphasis is placed on the latter in this summary report. The reader is referred to the parent document[1,2] for a more thorough presentation of the magnitude of filter effects errors for a wide variety of cases - a level of detail that was not appropriate for this summary report.

The basic approach used to correct aircraft spectra for analysis errors due to finite filter sidebands and signal spectrum slopes involves defining some type of approximation to the true spectrum shape of the signal at all frequencies. The closer this approximation is to the true spectrum slope, the more accurate the correction for filter effects. This report addresses several such "filter effect" correction methods of varying degrees of accuracy. These methods are all applicable to specifying attenuation of a band of noise due to atmospheric absorption, given a definition of this attenuation at single frequencies. This is a fundamental problem encountered in evaluation or correction of aircraft spectra and has already been addressed in earlier studies.[8-12] However, some of these earlier studies[10-12] treated the filter associated with definition of the band levels as ideal with zero transmission loss in its nominal pass and infinite transmission loss outside this band. In this case, the reports accounted only for the difference between band attenuation values computed by integration over ideal filters and values based on attenuation at only one characteristic frequency in the band. However, as will be shown later, when this spectrum slope error becomes significant, the additional error attributable to ignoring the energy passed by the filter "skirts" outside the filter pass band may be much larger. Thus, evaluation of errors in spectrum analysis of aircraft noise due to filter effects which does not include consideration of transmission that really occurs outside the nominal filter pass band can be very misleading.

Summary of Findings

The next section of this report reviews the general nature of filter effects and shows that they are generally significant only at high frequencies and/or large distances from a source. Thus, static ground measurements of noise from full scale aircraft engines at distances of the order of 100 m or less will seldom, if ever, require any corrections for filter effects. However, measurements on the ground of noise from aircraft in flight can involve propagation distances of the order of 300 to 2,000 m or more. In this case, band levels at high frequencies may very well be substantially in error unless filter effects are considered. One rule of thumb reported in Reference 1 indicates that these band errors become significant (i.e., of the order of 0.5 dB or more) under the following conditions:

- o Propagation Distance (km) x $[\text{Frequency (kHz)}]^2 > 6$
- o Propagation Distance >6 km (at any frequency in the audio range).

However, this summary of the results from References 1 and 2 suggests that this criterion may be too optimistic (i.e., the constant 6 may need to be reduced). It is also generally true that while the band levels may be subject to large errors due to filter effects, errors in composite noise levels such as PNL, LA or EPNL will usually be small - less than 1 dB.

The principal quantitative findings of this summary report illustrate the application of the methods of Reference 1 and 2 for evaluating errors due to filter effects in the following circumstances:

- o Prediction of the excess attenuation of a band of noise due to air absorption over a given homogeneous propagation path.
- o Prediction of the change or adjustment in this attenuation if the test-day weather conditions are different from those of a standard reference day.

To illustrate the application of alternate methods for considering filter effects for these two questions, one idealized source spectrum and two representative measured aircraft spectra were considered. The idealized source spectrum was chosen to approximate an upper bound for the slope of broadband spectra measured very close to an aircraft. The aircraft spectra selected occur at the time of maximum tone-corrected Perceived Noise Level (PNLTM) and were chosen to represent a range of such spectra that might be encountered in noise certification measurements conducted according to FAR Part 36.[3] The spectra were based on actual measured data for jet aircraft[13] and were essentially free of contamination by ambient noise at all frequencies.

For each of these spectra, four alternative methods to account for filter effects when computing atmospheric attenuation of one-third octave bands have been evaluated. These methods are:

Code	Description
(S)	Single-frequency method (current practice with SAE ARP 866A).[15]
(D)	Band Integration method with real filters using two constant spectrum slopes to approximate the initial spectrum level in each band (Dytec Method).[2]
(W1)	Band Integration method with real filters using a continuously varying spectrum interpolation function to approximate the initial spectrum in each band (Wyle Method 1).[1]
(W2)	Band Integration - same as W1 but with addition of a spectrum iteration technique to match computed vs measured band levels at a receiver (Wyle Method 2).[1]

Finally, results, reported in both References 1 and 2, are also presented for filter effects on EPNL values of measured aircraft noise data.

Results for Idealized Spectrum

The idealized source spectrum with an assumed spectrum slope of -9 dB/octave for standard day conditions (i.e., 25°C and 70% relative humidity) was converted to a hypothetical spectrum that would have been measured with real filters at a receiver distance of 600 m on a test day with a temperature of 15°C and 35% relative humidity. When the above methods were applied to reconstruct the source spectrum for this "measured" receiver spectrum, by adding back the band level attenuation over the 600 m propagation path, the SAE method exhibited the largest error at frequencies below about 5,000 Hz. The error, in this case, was simply equal to the true initial source spectrum (with the -9 dB/octave slope) and the reconstructed value based on applying the computed band level attenuation to the "measured test day" receiver spectrum. Differences between predicted and true source band levels were of the order of +2 dB up to this frequency for the SAE method but decreased to less than ±0.1 dB for the Wyle Method 2, employing the spectrum iteration technique. The other band integration methods (Dytec and Wyle Method 1), which did not employ an iterative technique to improve estimates of the measured spectrum, exhibited errors between 0 and +2 dB.

For one-third octave band frequencies above 5,000 Hz, all of the methods exhibited rapidly increasing errors in reconstructing the original source levels that would have been inferred by the measured receiver levels under the test day conditions. The errors became comparable to about 50 percent of the true band level attenuation (i.e., -80 dB) at the highest frequencies. The breakdown in accuracy of the band attenuation prediction methods occurs when the slope of the measured receiver spectrum exceeds the slope of the filter sidebands. A comparable trend was found when predicting band level adjustments to correct measured receiver levels at test day conditions to receiver levels for standard day conditions.

Results for Aircraft Spectra

The aircraft data, initially measured under nearly standard day conditions, were first translated to the same more severe test day weather (15°C, 35% relative humidity) employed for the ideal spectra. Then the alternative methods for predicting band level attenuations or adjustments back to standard day conditions were applied. There was one significant difference in the results of this application to these real aircraft spectra. The methods which employed some form of band integration (all but the SAE method) no longer exhibited very large errors in predicting band level attenuation or adjustment at the highest frequency. This is attributed to the less severe shaping of these measured spectra since the true band level attenuation reached values of only about 40 dB at the highest frequency.

The maximum errors in predicting band attenuations or band adjustments for these limited samples of real aircraft noise data varied from about 25 dB for the SAE method at 10 kHz to about 2 dB or less for the other methods employing band integration. The highest accuracy in accounting for filter effects on these aircraft data was consistently exhibited by the second Wyle method which employed the spectrum iteration technique. With this method, the errors in predicted band levels were less than 0.1 dB at all frequencies in all cases except one for which the error was 0.4 dB at 10 kHz only.

While direct comparisons between true and predicted values of overall frequency-weighted (and time-integrated) aircraft noise levels, such as PNL, EPNL, or SEL were not always possible, the limited results from the two parent studies summarized herein indicate that errors due to filter effects may be very small, less than 1 dB. Maximum errors in overall aircraft noise levels, due solely to filter effects, that were found in either of the parent studies are summarized as follows:

	Maximum Error Due to Filter Effects	
Noise Metric	Wyle Method #2 (Ref. 1)	Dytec Method (Ref. 2)
PNL	0.25 dB	0.1 dB
EPNL	0.74 dB	0.1 dB
SEL	NA	0.1 dB

As outlined later in this report, the true magnitude of filter effect errors is believed to be more accurately represented by the Wyle method involving spectrum iteration. Based on these results, any of the band level attenuation prediction methods evaluated, including the currently employed SAE method, may provide a suitable means to account for filter sideband effects when analyzing aircraft noise in terms of such overall noise metrics if one is prepared to accept errors of the magnitude indicated above. However, this conclusion is necessarily based on the limited number of cases that could be evaluated in the parent studies.

2. ANOMALIES IN SPECTRAL ANALYSIS OF AIRCRAFT NOISE DUE TO FILTER EFFECTS

This summary report is concerned with filter effects on the evaluation of overall aircraft noise levels as well as individual band levels. Thus, it is helpful to start by first examining filter effects on a single band of noise before treating the problem for a complete spectrum.

There are three possible ways to define filtered band levels of a broadband noise. These three methods, illustrated in Figure 1, are:

- The white-noise band level, L_{Bo}, equal to the band level for a white noise signal which has a constant spectrum level $L_s(f_c)$ equal to that of the true spectrum at the band geometric center frequency f_c.
- The ideal filter band level, L_{BI}, of the true spectrum as measured with a perfect filter over the nominal filter bandwidth f_1 to f_2.
- The measured band level, L_B, of the true spectrum as measured with a real filter over the significant power transmission bandwidth of the filter.

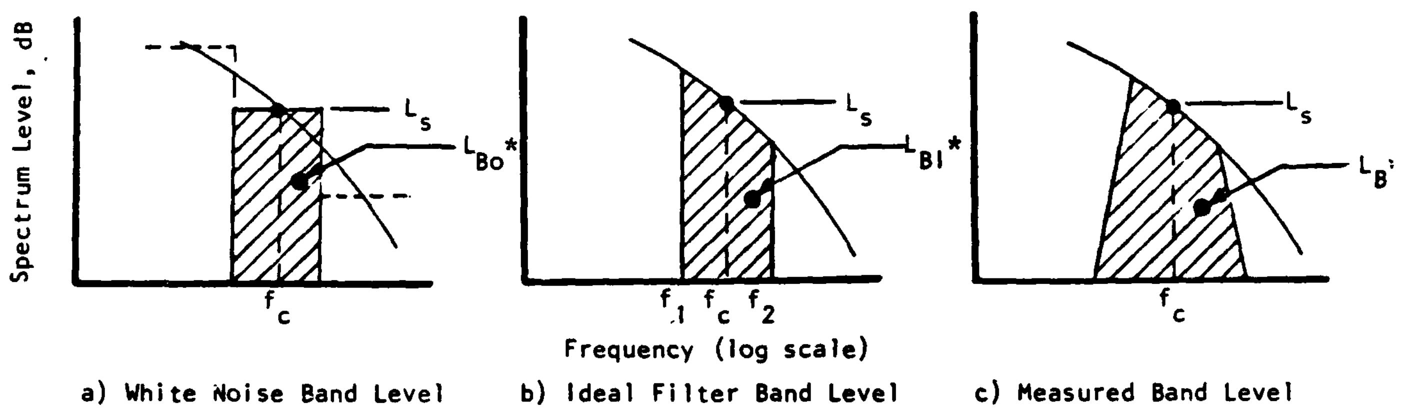


Figure 1. Conceptual Illustration of Three Alternative Ways to Interpret a Band Level Centered at Frequency f_c with a Spectrum Level L_s at this Frequency (*cross-hatched area equals indicated level).

The white noise band level is often assumed to be the effective level when one expresses the change in level of a band of noise due to attenuation processes which vary with frequency. This assumption implies that the attenuation for the entire band can be accurately defined at a single frequency, such as at the band center frequency, or at the band edge frequency. This is, effectively, the procedure employed in SAE ARP 866A.[15]

The ideal band level, L_{BI}, would be the desired form for universal application. It is, in fact, closely approximated in the analysis of aircraft noise when the spectrum slope is not large and standard spectrum analysis filters[5, 6] are employed.

The measured band level, L_B, represents, of course, the band level that is measured with real filters.

For simplicity, the following general equation can be used to express each of these forms of band levels. This general form can be expressed as:

$$\text{Band Level} = 10 \log_{10} \left[\int_{f_a}^{f_b} 10^{(L_s(f) - A(f))/10} \, df \right] , \text{dB} \qquad (1)$$

where

$L_s(f)$ = spectrum level at any frequency f between f_a and f_b. For the "white-noise" band level, this is the constant value which can be taken outside the integral, and is equal to the true spectrum level at the band center frequency f_c.

f_a and f_b = the lower and upper limits of integration equal to the lower band edge, (f_1) and upper band edge frequency (f_2) for an ideal filter or the lower and upper frequency limits of effective transmission range of a real filter. This effective range extends from $f_1/5$ to 5 f_2 in Ref. 1 and from $f_c/10$ to 10 f_c in Reference 2.

A (f) = A general attenuation function which can vary with frequency but which is 0 for the first two forms of band level and is equal to the transmission loss, in decibels, of the real filter for a measured band level.

The analytical procedures used in References 1 and 2 to carry out the integration involved in Eq.(1) are described in detail in these references and are only summarized here. While similar in concept, they differ in important detail as discussed later in Section 3.

Consider, now, the general illustrative model shown in Figure 2 for the processes involved in spectrum analysis of aircraft noise. This diagram identifies two kinds of "filter effects" correction factors.

- Error terms (Δ_S or Δ_F) associated with analysis of an individual band of noise at a source or receiver.
- Band attenuation factors (ΔL_{BI} or ΔL_B) associated with the difference in band levels between a source and receiver.

The simple mathematical operations involved in applying these two types of correction factors are portrayed diagrammatically in Figure 2 by the arrows connecting the boxes.

For now, the compounding effects or errors in spectrum analysis due to background noise are ignored.

2.1 Errors in Band Levels at a Source or a Receiver

The filter effect error terms Δ_S or Δ_F involved in receiver or source band levels are identified here to aid in understanding the rest of this summary report. The final results will be expressed more directly in terms of the band attenuation factors ΔL_{BI} or ΔL_B which do not require keeping track of these "error terms" for individual band levels explicitly. However, as will be shown later, these errors in individual band levels provide a useful basis for understanding and analyzing errors, due to filter effects, in band attenuation values between a source and a receiver. In fact, these slope and filter error terms provide a more discriminant way of examining the true significance of filter effects in band attenuation values since Δ_S and Δ_F do not contain the single frequency absorption loss term - $\alpha(f)$ x Distance - the dominate term in any band attenuation value.

2.1.1 Spectrum Slope Error Due to Finite Filter Bandwidth

This is simply equal to the difference Δ_S between the ideal and white noise band level of a given spectrum, or:

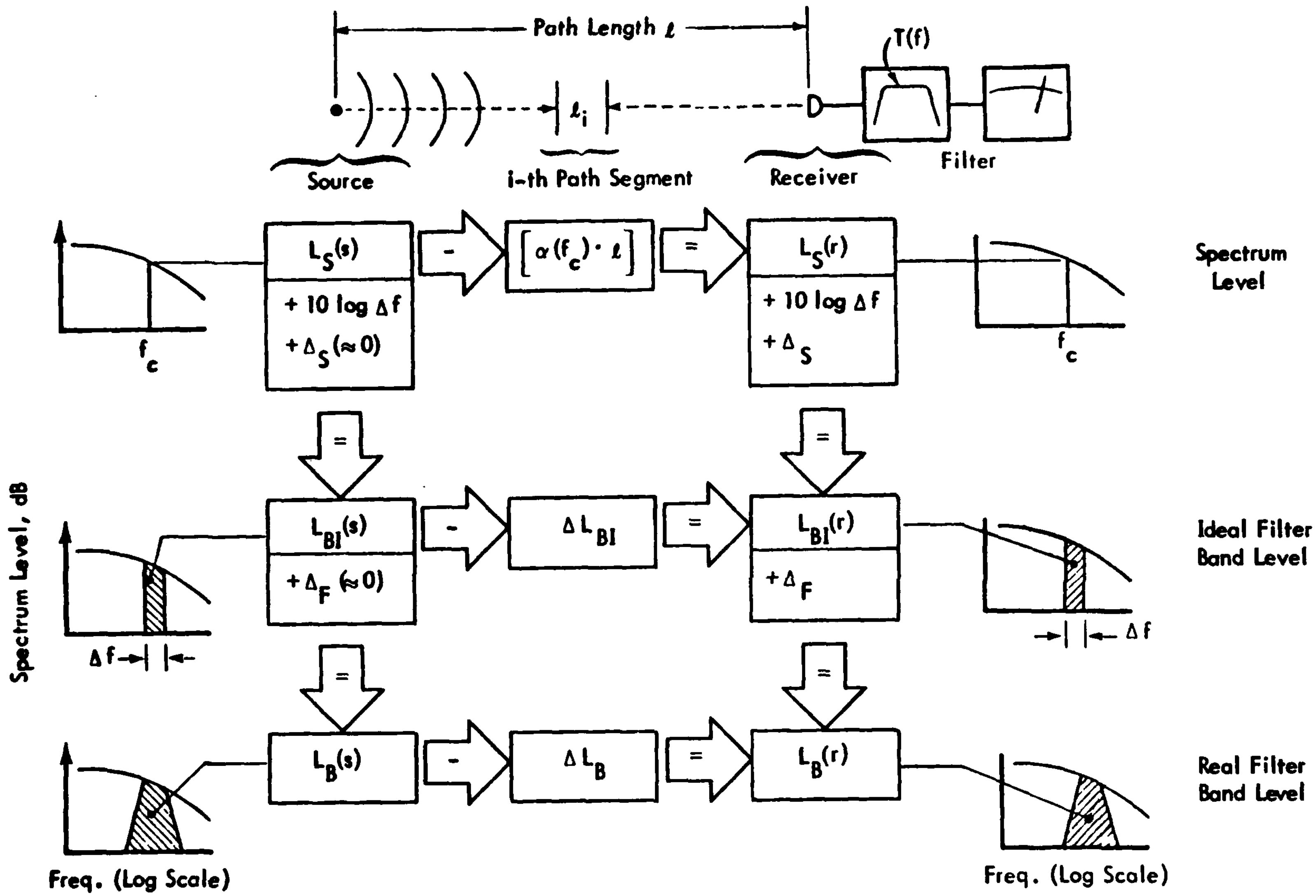


Figure 2. Illustration of the Processes and Computation Flow Involved in Accounting for "Filter Effects" Errors in Analyzing the Attenuation of Bands of Noise from a Source to a Receiver (see text for explanation of symbols)

$$\Delta_S = L_{BI} - L_{Bo} \quad (2)$$

From one viewpoint, this quantity, Δ_S, may not be considered an error in spectrum analysis but is so designated here since it does correspond to the error associated with the use of any single frequency for describing band attenuation as opposed to some form of integration over the ideal filter bandwidth.

Based on this definition, one can derive a closed form expression for Δ_S for the case of an input signal with a constant band level slope applied to an ideal filter. The derivation is developed in detail in both References 1 and 2 and is summarized in Appendix A. The resulting expression is based on applying Eq.(1) twice – once for the band level with an ideal filter, and once for the white noise band level case. The difference in the resulting band levels is equal to Δ_S.

2.1.2 Filter Error Due to Finite Filter Skirts

This real error in filtered band levels is defined as the difference between band levels measured with a real (L_B) and an ideal (L_{BI}) filter, or:

$$\Delta_F = L_B - L_{BI} \quad , \text{dB} \quad (3)$$

Thus, Δ_F is the difference between the band level measured with spectrum analyzers which have finite slopes for their filter skirts, and the ideal band level that would be measured with a perfect filter with zero transmission outside of its nominal passband. (This error is called the "bandwidth error" in Reference 6.) The filter error, Δ_F, is well known and is inherent in the fundamental process of signal spectrum analysis and has been evaluated extensively by others.[16-18] A detailed mathematical derivation of this error in filter band levels is presented in Appendix B of Reference 1. Again, the approach is based on the use of Eq.(1) for L_{BI} and L_B. For the "measured" band level, L_B, the general attenuation function A(f) in Eq.(1) is the transmission loss for the real filter. As discussed in both References 1 and 2, this filter transmission loss is simulated by a suitable mathematical expression for the filter response which closely approximates the response of real filters designed to conform to industry standards.[5, 6]

Examples of the spectrum slope and filter errors, inherent in spectral analysis, will be illustrated later with actual aircraft spectra to show that they can produce substantial errors in specific one-third octave band levels when the spectrum is rolling off rapidly at high frequencies. Any data evaluation procedure which makes it possible to account for errors directly could be very useful. Such procedures are addressed in Section 3.

2.1.3 Filter and Slope Errors for Constant Slope Source Spectra

Utilizing the concepts just defined, these two spectrum analysis error terms are examined for the case of a source signal with a known constant band level slope, before spectrum shaping by atmospheric attenuation has occurred.

The results are shown in Figure 3. Part (a) shows the slope error Δ_S for full, one-third and 1/18th octave band filters. The latter represents the effective bandwidth of the mathematical filter elements employed in the Wyle method for carrying out the numerical integration required by Eq.(1). (Note the scale change for this case.)

Part (b) shows the filter error, Δ_F for full and one-third octave band filters. Note that this error is of the order of 1/2 of the spectrum slope error Δ_S for the range of slopes considered. The small negative values of Δ_F for band level slopes near zero reflects the transmission loss at the edges of the nominal pass bands of the real filters. This is normally eliminated by proper calibration of the filter.[16-18]

For most aircraft noise signals measured close to a source within, say, 75 m (≈ 250 ft), the band level slope is usually less than 9 dB/octave unless pure tone components are present. In this case it is clear, from Figure 3, that both Δ_F and Δ_S would be very small for one-third octave band spectral analysis of aircraft noise close to a source. Under such conditions, the actual "as measured" band levels at a source can normally be considered free of filter effect errors due to the spectrum slope and the finite filter skirts so that the band levels can be closely approximated by the "white noise band level" approximation L_{Bo} cited earlier. Thus, as indicated in Figure 2, the spectrum slope error Δ_S and filter errors Δ_F can be assumed to be zero at a source (i.e., at positions close to an aircraft). This assumption may not be valid when significant tones are added to the broadband signal. However, possible solutions to this problem are addressed later.

2.2 Filter and Slope Errors at a Distant Receiver

Consider, now, the change in Δ_F and Δ_S at a receiver due to spectral shaping by atmospheric absorption. Several constant slope source spectra have been selected for this evaluation. These idealized source spectra are illustrated in Figure 4. The curves show source spectra with band level slopes from +3 dB/octave to -36 dB/octave - a range sufficient to cover normal source spectra. One special case has also been included representing the presence of a 10 dB tone superimposed at 3,150 Hz on an otherwise smooth spectrum sloping off at -9 dB/octave.

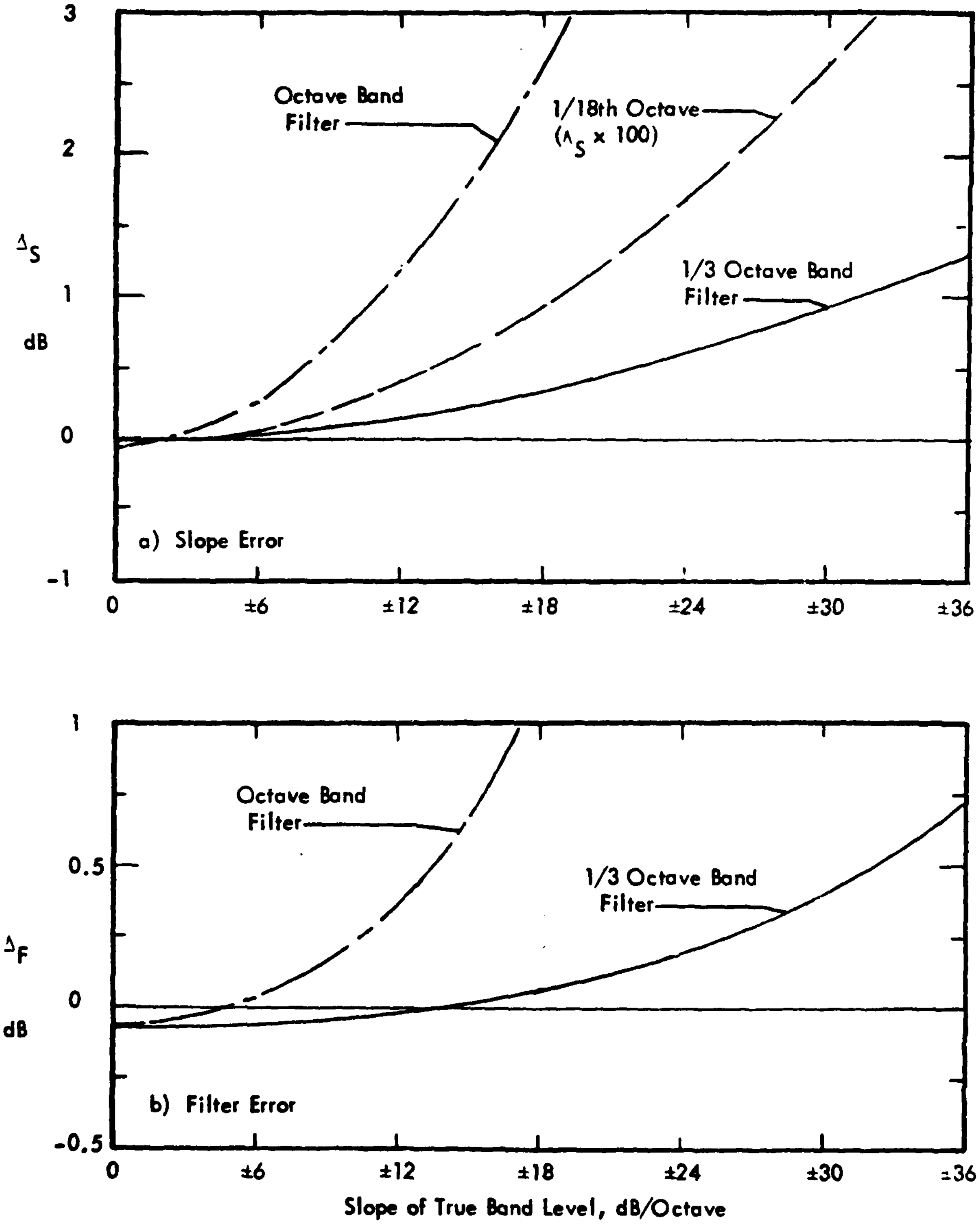


Figure 3. Slope and Filter Error for Constant Slope Signals

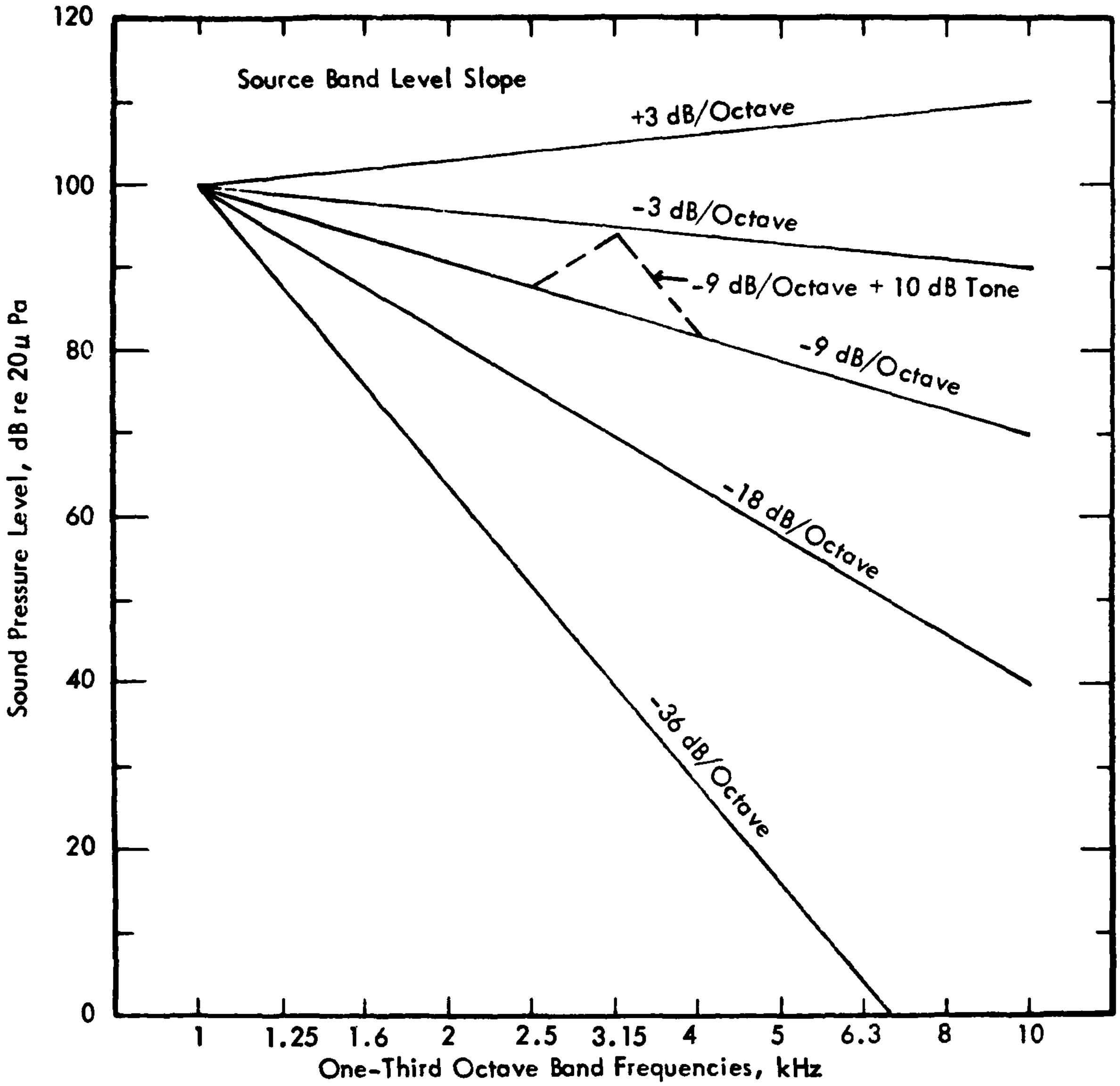


Figure 4. Idealized Source Spectra with Various Band Level Slopes, Including One with a Superimposed 10 dB Pure Tone Component, Used to Evaluate Filter and Spectrum Slope Errors

It was assumed that the source spectra were defined exactly (i.e., measured with an ideal very narrowband filter) so that the initial spectral content at the signal could be determined exactly. Then, by propagating these known spectra over a distance of 600 m, through known atmospheric absorption losses, one can redefine a new attenuated spectra at a receiver and then apply the band integration concept described at the beginning of this section to define either ideal or real filter band levels. Thus, it was possible to compute the filter error Δ_F at the receiver. Similarly, the received spectrum level can be defined exactly so the slope error Δ_S, at the receiver, can also be computed. In both cases, these new values are computed, as outlined before, with use of Eq.(1).

A portion of the results of these computations, shown more fully in Reference 1, are illustrated in Figure 5. Figure 5a) shows only Δ_F as a function of frequency for the source spectra of Figure 4 and for a standard weather condition of 25°C and 70% relative humidity. For this condition, atmospheric absorption losses are close to a minimum within the FAR Part 36 test window.[5, 16]

The general trend in Δ_F, shown in Figure 5a), can be explained by three interacting influences.

- o Δ_F increases at all frequencies, uniformly, as the source spectrum slope decreases (i.e., becomes more negative), as expected from Figure 3.
- o Δ_F increases at high frequencies due to the further increase in signal slope due to atmospheric absorption over the fixed 600 m propagation distance.
- o Δ_F is modified, in a complex way, for any bands close to or including a band with a strong tone component.

The variation in the total filter and slope error at a receiver, $\Delta_S + \Delta_F$, has been evaluated in Figure 5b), using four of the source spectra (+3 dB, -9 dB with tone, -18 dB, and -36 dB/octave), and a weather condition of 15°C and 35% relative humidity. This condition corresponds to near maximum absorption loss at high frequencies within the weather window allowable for FAR Part 36.[3] Again, the same general pattern that occurred in Figure 5a) is evident. These error terms are not shown in Figure 5 beyond an upper bound of 6 dB intentionally. When they reach such a magnitude, the total signal attenuation due to atmospheric absorption is very high normally resulting in a received signal near or below practical limits of measurement in the presence of normal background noise.[2]

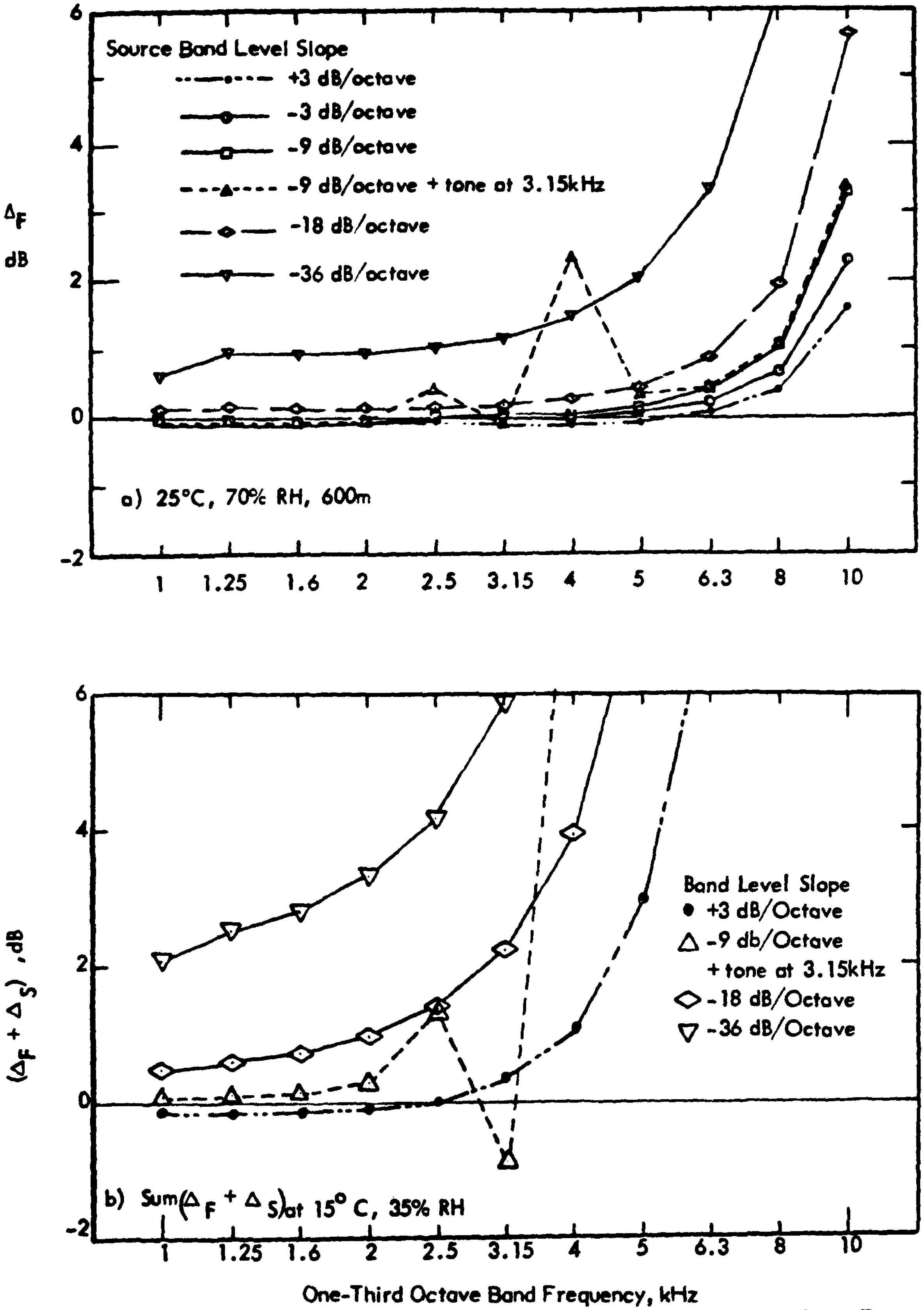


Figure 5. Variation in a) Filter Error Δ_F and b) Sum of Filter and Slope Errors ($\Delta_F + \Delta_S$) at Receiver after Propagation Over 600m with Two Different Weather Conditions.

One point should be clear by now - the filter error Δ_F and the slope error Δ_S behave in a complex manner with the measured signal spectrum characteristics. This complexity is well-recognized, of course, and is one reason why almost no attempt is made to account for these error terms when analyzing aircraft noise data. One exception is the simple procedure inherent in the aviation industry standard (SAE ARP 866A) for predicting air absorption[15] which calls for using the lower band edge frequency for evaluating all absorption losses for one-third octave frequency bands equal to or greater than 5000 Hz. This procedure is equivalent to trying to recognize the inherent slope error Δ_S term and compute atmospheric absorption losses at a frequency below the band center which should be more "representative" of changes in the band energy. In general this empirical procedure should be in the right direction to aid in minimizing filter effects errors when analyzing aircraft noise spectra. However, a more general approach to the problems of accounting for filter band and signal slope errors seems desirable. Such alternate approaches are reviewed in Section 3.

2.3 Relationship Between Spectrum Slope and Filter Errors and Band Attenuation Values

Before proceeding, however, consider just how the proceeding relates to the second category of filter effects mentioned earlier – those associated with band attenuation alues. As illustrated earlier in Figure 2, we are primarily concerned in this report with:

- The prediction of how a band level at one point, identified in Figure 2 under the "source" column, changes as the sound propagates to another point – the receiver.

- The adjustment of band levels measured at a receiver under one condition of weather (and propagation path length) to another condition with different weather (and path length). In this case, the calculation of band levels starts at the "receiver," works backward to the presumed source for atmospheric attenuation under test conditions, and then back to the receiver for attenuation under reference weather conditions.

To define these quantities, the following terminology is employed throughout the remainder of this report for clarity and, to the extent possible, for consistency with existing usage[14] and with usage in the key reference documents.[1,2]

ΔL_B The true* excess attenuation in a band level of a noise due to air absorption. If the filter band is ideal, an additional subscript I is added (i.e., ΔL_{BI}).

ΔA_B The true* adjustment in a band level due to the difference between test-day and reference day values of ΔL_B. Real filters will normally be assumed; however, one variation of this quantity will be identified. ΔA_{BRI} will signify the value of the band level adjustment if one wished to define a reference band level that would have been measured on a standard day with an ideal filter free of any filter error when the test-day band level was actually measured with a real filter.

To identify the various prediction methods to approximate the terms identified above, the code letter(s) associated with each prediction method identified in Section I is added as an argument to the terms. For example:

> $\Delta L_{BI}(D)$ is the band level attenuation (ΔL_B) for ideal filters (added subscript I) according to the Dytec method (added argument code letter D) in Reference 2.

Now then, just how do the slope and filter errors Δ_S and Δ_F relate to these parameters. By examination of the data analysis processes illustrated earlier in Figure 2, one can recognize the following simple relationships.

- o For ideal filters, the band attenuation ΔL_{BI} and the slope error Δ_S are related simply by

$$\Delta L_{BI} \simeq \alpha(f_c) \cdot D - \Delta_S, \quad \text{dB} \tag{4}$$

where it is assumed, as indicated earlier, that the slope error at the source is negligible. Thus, by subtracting the slope error Δ_S evaluated at the receiver from the single frequency attenuation $(\alpha(f_c) \cdot D)$ over the propagation path, one obtains the band attenuation ΔL_{BI} as measured at the source and receiver with ideal

*The word "true" implies no simplifying assumptions in its evaluation and represents a value as accurate as can be defined with precision numerical integration procedures.

filters. Thus, as suggested earlier, the slope error Δ_S clearly defines the actual filter effect for an ideal filter with respect to the attenuation at the band center frequency. When the former is small enough, the latter can be used to define the band attenuation.

- For real filters, the band attenuation ΔL_B and the sum of the slope and filter errors $(\Delta_S + \Delta_F)$ are related by

$$\Delta L_B \simeq (\alpha(f_c) \cdot D) - (\Delta_S + \Delta_F), \quad \text{dB} \tag{5}$$

again assuming Δ_F at the source is negligible. Thus $(\Delta_F + \Delta_S)$, at the receiver, is the difference between the total attenuation $\alpha(f_c) \cdot D$ at the band center frequency f_c and the actual band attenuation ΔL_{BI} measured with real filters at the source and receiver.

With such simple relationships between the band attenuation parameters and the slope and filter error terms, $\Delta_F + \Delta_S$, it should be possible to apply the latter as correction factors to the readily available tables (or computational algorithms) of the single frequency absorption loss $\alpha(f) \cdot D$ to define band attenuation values. Indeed one such technique, employing graphical procedures, is outlined in Reference 8 (contained in Appendix B of Reference 1 and Reference 9). To apply such an approach, it is obviously necessary to know the source spectrum slope as well as the additional slope change in the received levels introduced by atmospheric attenuation since both of these influence values of Δ_F and/or Δ_S at the receiver, as was indicated in Figure 5.

However, it does not appear to be very practical to use this approach for predicting values of slope or filter errors (Δ_S or Δ_F) when processing aircraft data. Even allowing for relatively low spectral slopes close to a source (e.g., slopes of the order of -3 to -9 dB/octave are typical for broadband jet source noise spectra), one must allow for the change in this slope due to the spectrum shaping characteristics of absorption losses over long distances. This effect is illustrated in Figure 6 for a standard day and for 15°, 35% relative humidity by the effective spectral slope, in dB/octave, as a function of frequency and distance that is introduced by air absorption losses alone. The slopes correspond to the spectrum level slopes at a receiver for a white noise source. Note that at high frequencies and large distances, the "spectrum slope" attributable to air absorption reaches

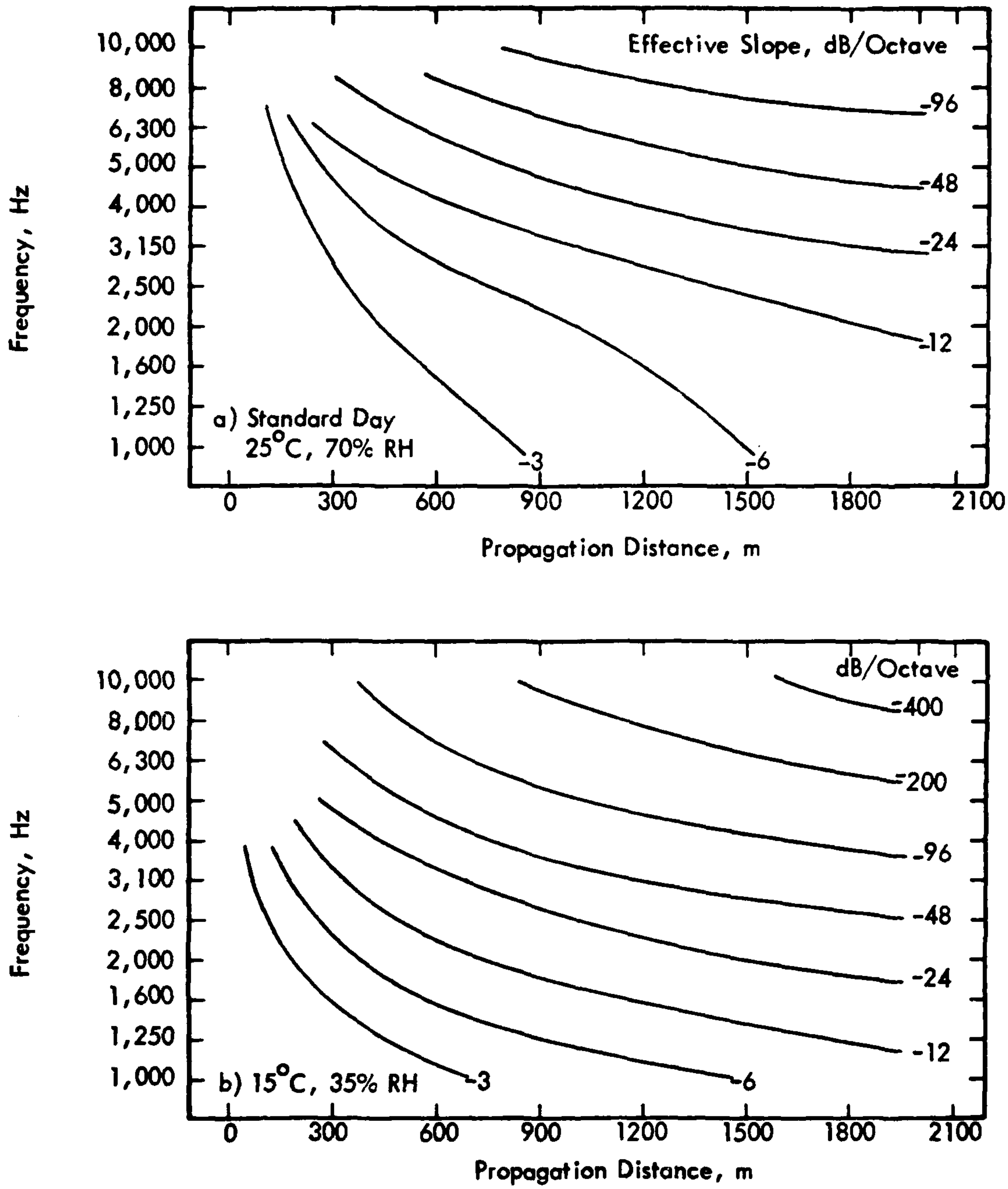


Figure 6. Effective Slope of Spectrum Level Introduced by Air Absorption as a Function of Frequency and Distance for a) a Standard Day and for b) 15°C and 35% RH.

values of as low as -100 to -400 dB/octave. Clearly, this additional change in spectral slope will dominate the true shape of high frequency portions of aircraft signatures measured at large distances. Furthermore, it would be awkward to have to first define this spectrum slope influence for any given propagation distance and weather condition before determining the appropriate values of the correction factors Δ_S or Δ_F and, from these, define effective band attenuations from an attenuation value defined at only one characteristic frequency in each band.

Thus, as addressed in the next section, practical methods to account for filter effects include the slope and filter error terms implicitly. Thus, it will normally be easier to define the band loss ΔL_B for real filters directly instead of subtracting the slope and filter error factors from the single frequency loss as indicated by Eq.(5).

3. CORRECTION METHODS FOR FILTER EFFECTS

Four basic methods are reviewed for correcting aircraft spectral data for filter effects. The methods are based on the general analytical procedures presented in References 1 and 2. These methods, identified below, are briefly summarized in the following paragraphs:

Code	Description of Method
(S)	Single-frequency method (current practice with SAE 866A).
(D)	Band Integration method using two constant spectrum slopes to approximate the spectrum level in each band (Dytec Method).[2]
(W1)	Band Integration method using a continuously varying spectrum interpolation function to approximate the spectrum in each band (Wyle Method 1).[1]
(W2)	Band Integration - same as W1 but with addition of a spectrum iteration technique to match computed vs measured band levels at a receiver (Wyle Method 2).[1]

The methods will be evaluated in Section 4 in terms of their application to two primary situations.

3.1 Single Frequency Method (SAE)

This method, as currently employed in SAE ARP 866A,[15] ignores any filter effects for all frequency bands below 5,000 HZ and defines band level attenuation (and corresponding band level adjustment) values in terms of the single frequency atmospheric attenuation ($\alpha(f_c)$. Distance) at the geometric center frequency of the bands.

For the 5,000, 6,300, 8,000 and 10,000 Hz bands, an effort is made to account, approximately, for filter effects in a very simple way by computing the attenuation for these bands, again at only one frequency, but now at the nominal lower band edge frequency of the filter, i.e., at 4,500 Hz (for the 5,000 Hz band), 5,600 Hz (for the 6,300 Hz band), 7,100 Hz (for the 8,000 Hz band) and 9,000 Hz (for the 10,000 Hz band).[15]

The method is equivalent to assuming that slope and filter errors (Δ_S and Δ_F) are negligible below 5,000 Hz and are roughly approximated by shifting the computational frequency to the lower band edge at band center frequencies equal to and higher than 5,000 Hz.

The principal advantage of this method is that band level attenuation and adjustment values are independent of the input spectrum shape. Thus, this method for evaluating atmospheric attenuation of band levels is readily adaptable to automatic data processing routines.

One disadvantage of the method, beyond its limited ability to properly account for filter effects, is its tendency to produce unrealistic tone corrections in EPNL values of aircraft noise due to the discontinuity between the 4,000 and 5,000 Hz band from the change in the frequency (band center to band edge) used for computations. For this reason, the FAA now allows the deletion of tone corrections that can be shown to result solely from the discontinuity in the SAE method.

3.2 Band Integration with Two-Slope Approximation to Spectrum (Dytec)

This method, as outlined in detail in Reference 2, employs two linear slope approximations to the spectrum level in each band, as shown in Figure 7.

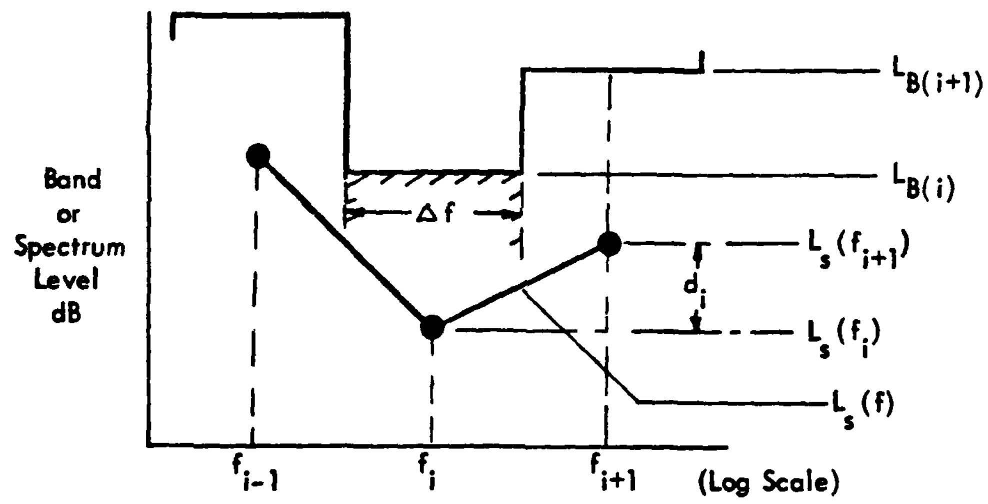


Figure 7. Illustration of Two-Slope Approximation to Spectrum Levels for i_{th} Band as Employed in Dytec Method

As illustrated, two constant-slope lines define the spectrum level over the nominal bandwidth of the i_{th} band. One line extends from the center of the next lower (i-1) band and the other line extends from the i_{th} band center to the center of the next higher (i+1) band.

In reality, then, there is only one constant slope line per band plus one more half line at each end of the full spectrum. Employing techniques similar to those outlined in more detail in Appendix A for the Wyle method, it can be shown that the spectrum level slope constant (a_i) for the upper half of the i_{th} band (and the lower half of the i+1 band) is simply equal to the difference d_i in the spectrum levels at the center of the i_{th} ($L_s(f_i)$) and i+1 ($L_s(f_{i+1})$) band. It is further assumed, for a first approximation, that the spectrum slope and filter errors described in Section 2 are negligible so that the band levels are treated as equivalent to the so-called "white noise" band levels defined earlier. Thus, the spectrum level at the center of the i_{th} band, with a bandwidth Δf, is defined by:

$$L_s(f_i) = L_{B(i)} - 10 \log \Delta f = L_{Bi} - 10 \log [f_i \text{ (constant)}] \qquad (6)$$

Over the upper half of each band and the lower half of the next higher band, the spectrum level $L_s(f)$ is then assumed to be given by the following expression where the spectrum level varies linearly (with log frequency) with a constant slope a_i:

$$L_s(f) = L_s(f_i) + 10 \log (f/f_i)^{a_i}, \quad \text{dB} \qquad (7)$$

It can be shown that for one-third octave bands, where $10 \log (f_{i+1}/f_i) = 1$, this slope constant a_i is simply equal to the difference d_i in spectrum levels between the i+1 and i_{th} band. But with Eq.(6), one can also show that

$$a_i = d_i = [L_s(f_{i+1}) - L_s(f_i)] = [L_{B(i+1)} - L_{B(i)}] - 1, \quad \text{dB} \qquad (8)$$

Since the band level slope S in dB/(one-third octave band) is equal to this difference in band levels, then

$$S = [L_{B(i+1)} - L_{B(i)}] = (a_i + 1), \quad \text{dB/one-third octave band}$$

For the Dytec method, the spectrum slope over the lower half of the lowest (i=1) band is assumed to be the same as over the upper half. Similarly, the spectrum slope over the upper half of the last (i=N) band is assumed to be the same as for the lower half of this band.

Utilizing this "two-slope" model for estimating spectrum levels at all frequencies, the spectrum is now integrated over the nominal bandwidth of the assumed <u>ideal filter</u>. The integration routine employed in the computer program defined in Reference 2 (and listed in Volume II of the latter) is a standard IBM Scientific Subroutine which accomplishes the continuous integration called for by Eq.(1) with a standard numerical integration procedure utilizing Simpson's rule and Newton's 3/8 rule.[2]

To carry out this numerical integration, each filter bandwidth is divided up into n constant bandwidth segments where n increases by 2 for each band from a value of 10 for the 1,000 Hz band to 30 for the 10,000 Hz band. In the latter case, each constant bandwidth integration segment is equivalent to approximately a 1/90th octave interval.

For the case of a known source spectrum, with spectrum slopes which can be closely approximated by constant slope linear segments between bands, the resulting integration is quite precise. If this close approximation to the source spectrum is now translated to a receiver, the receiver band levels and corresponding band level attenuation can also be accurately computed by integration over each of the many (10 to 30) segments within each band. Either ideal or real filters can be assumed.

This same two-slope method can also be applied, but with less accuracy, to approximate the measured spectrum at a receiver. The receiver spectrum levels $L_s(f)$ are again estimated within each band with the use of the two-slope model and Eqs.(6) through (8). These receiver spectrum levels are assumed, in the Dytec method, to have been measured with an ideal filter. They are corrected back to a source for test day absorption, recorrected back to the receiver for standard day conditions, and the integration process repeated to predict a receiver band level that would have been measured on a standard day.

Thus, unlike like the SAE method, the two-slope approximation method involves computing atmospheric attenuation at each integration segment within each band, but starting with the two-slope interpolation approximation of the initial (source or receiver) spectrum levels. This is the approximate procedure which is identified as the Dytec method in the next section. Clearly, when applied to prediction of attenuation from a known source spectrum, the method very accurately accounts for filter effects. A similar exact or reference method will be used in the next section for comparison of the other approximate methods to account for filter effects.

The principal advantages of this procedure are its relative simplicity in terms of automated data processing and the employment of a standard computational subroutine for numerical integration.

The principal disadvantages, not necessarily restrictive, are the potential errors inherent in the method for approximating the spectrum level at a receiver, and the use of an ideal filter model for analysis of an unknown spectrum. Thus, the method does not define the degree of error introduced by not accounting for energy outside the filter skirts when analyzing unknown spectra.

3.3 Band Integration Method with Continuously Varying Spectrum Slope (Wyle)

This method for analyzing filter effect errors, utilized in Reference 1, was described in Appendix B of that document. However, this description lacked some of the more complete details of the computational procedures, such as was provided for the Dytec method in Reference 2 (and Vol. II thereof). Such a description is now provided for the Wyle method in abbreviated form in Appendix A of this summary report. Thus, only a cursory description is provided at this point; the reader is referred to Appendix A, for a more complete description and a flowchart of the computer program.

The two versions of the Wyle method consist of:

W1 Spectrum level estimation using an algorithm allowing continuous variation with frequency in the spectrum level slope but without any iteration to improve the estimate;

W2 The same process with the addition of an iterative routine. This serves to further improve the estimate of a measured spectrum level to the point where band levels computed by integration over the full effective transmission bandwidth of analytical models for real filters agree with measured band levels. Apparent agreement to within 0.1 dB between computed and measured band levels was shown in Reference 1 for a number of different actual measured aircraft spectra.

A simplified flowchart of the overall computational method for the second version (W2) is shown on the next page in Figure 8. The first version is identical except that the iterative loop (from Step 5 through Step 6 back to Step 3) is eliminated and the receiver spectrum levels, estimated without iteration in Step 3, are used in Step 4 to compute band levels at the receiver, and in Steps 7 to 9 to compute source band levels. This simplified version of the flowchart is also applicable to the Dytec method for estimating source levels. The only significant differences lie in the methods employed in Steps 2 and 3 to estimate receiver spectrum levels. For the Wyle method, as illustrated in Figure 9, the spectrum level over the nominal bandwidth of each filter band is described by an interpolation equation which allows for a continuously varying spectrum level.

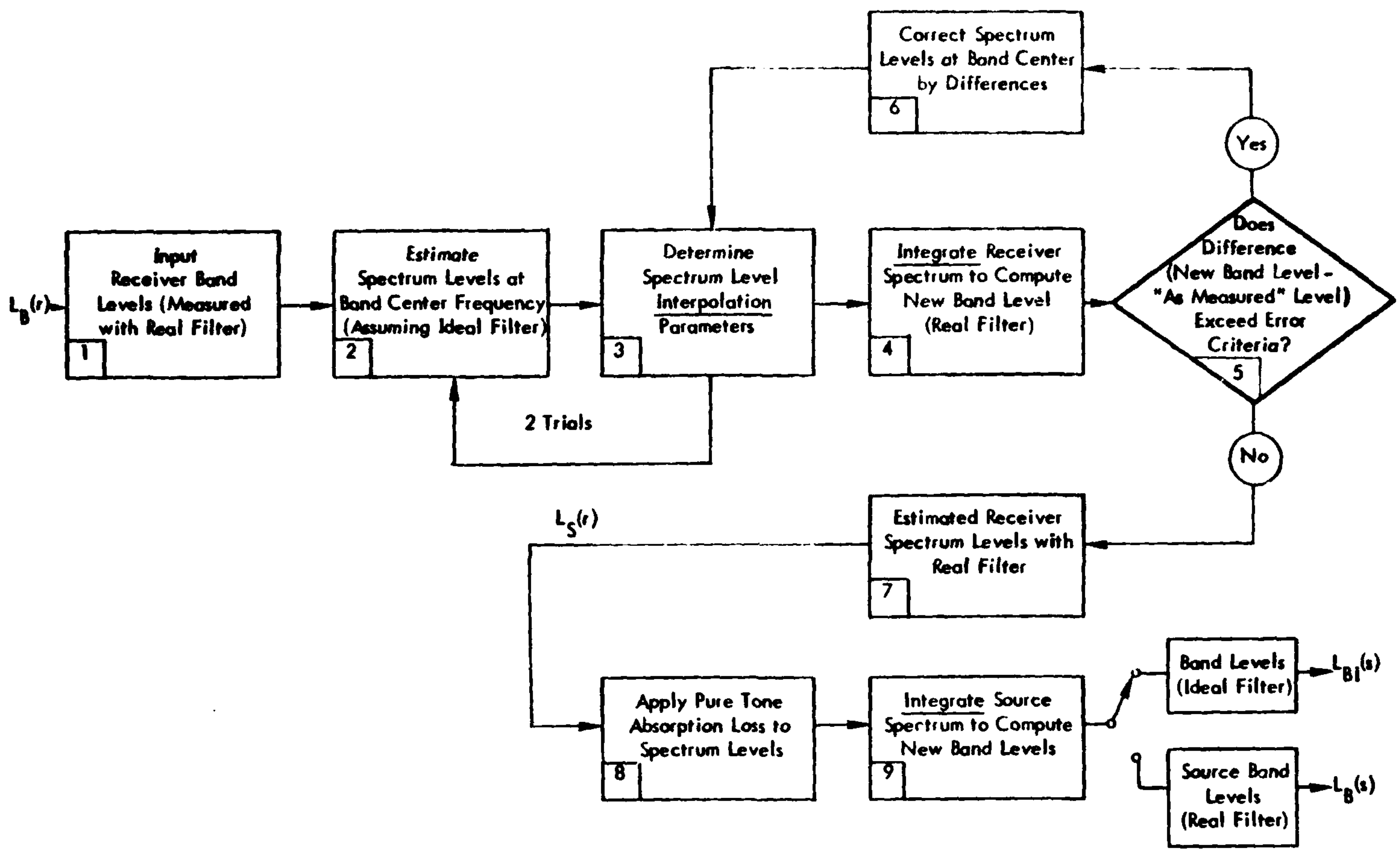


Figure 8. Spectrum Iteration Process to Estimate True Receiver Spectrum from Measured Receiver Spectrum and Thus Allow Reconstruction of Source Band Levels Free of Errors Due to Finite Filter Slopes or Spectrum Slope. Wyle Version I eliminates the iteration loop including Steps 5 and 6 and connects the output of Step 4 directly to Step 8.

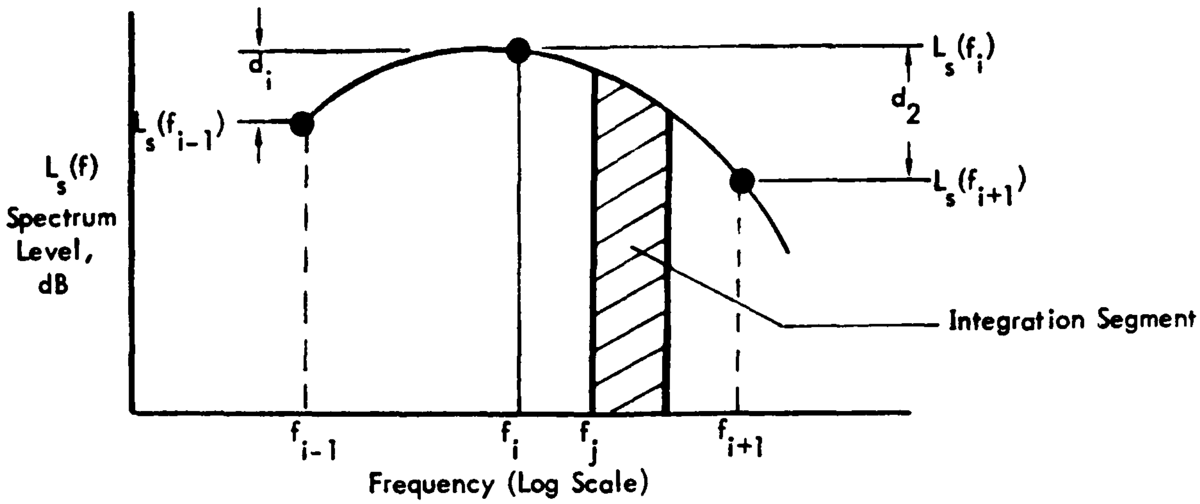


Figure 9. Illustration of Continuously Varying Spectrum Interpolation Function $L_s(f)$ used for the Wyle Spectrum Estimation Method and One of the Six 1/18th Octave Segments into Which Each Nominal Band is Divided for Integration of Band Power

This interpolation equation for the spectrum level $L_s(f)$ at any frequency within the i_{th} nominal (ideal) bandwidth is defined by

$$L_s(f) = L_s(f_i) + 10 \log (f/f_i)^{(a_i + b_i(f/f_i))} \tag{9}$$

The interpolation constants a_i and b_i are defined in terms of the two (instead of one) differences (d_1 and d_2) in spectrum levels on each side of the i_{th} filter band as identified in Figure 9. These relationships are derived in Appendix A and, for one-third octave band filters, they reduce to

$$a_i = (r^2 d_1 - d_2) / (r^2 - 1) \tag{10}$$

and $b_i = r (d_2 - d_1) / (r^2 - 1)$

where $r = 10^{1/10}$, the frequency ratio between one-third octave band filters.

Comparison of these two equations with Eqs.(7) and (8) for the Dytec method emphasizes both the similarity in, and difference between, the two spectrum interpolation methods. The initial estimates of spectrum levels at the band center frequencies $L_s(f_i)$, required to employ Eqs.(9) and 10 above, are provided by the same "white noise" band level model defined earlier for the Dytec model by Eq.(6).

The band integration method employed in the Wyle procedures differs from the more conventional numerical integration method employed in the Dytec procedure. Details are contained in Appendix B of Reference 1 (and in Reference 8). This integration method defines the band power according to the basic integration called for by Eq.(1) cited earlier. The essential features of the process, described more fully in Appendix A, may be summarized as follows:

- o Each nominal filter bandwidth is divided into six constant percentage segments 1/18th octave wide. One such segment is illustrated in Figure 9. (This contrasts with the use of 10 to 30 constant bandwidth integration segments used in the Dytec method.)
- o The spectrum interpolation function given by Eq.(9) is used to define the spectrum levels at the lower and upper band edge frequencies of these integration segments. The spectrum level between these two closely-spaced frequencies is assumed to vary linearly with a constant slope, just as for the Dytec method. Thus, between each band center frequency, six straight line segments, approximating the continuous spectrum function defined by Eq.(9) are used instead of just one straight line segment as in the Dytec method.
- o The total power passed by each filter is then determined by summing the power in the elemental segments, using the closed form algorithms described in Appendix A, over whatever total bandwidth is desired – the effective transmission bandwidth of a real filter, or the nominal bandwidth of an ideal filter.
- o The spectrum levels employed in this process are the values estimated from the initial spectrum iteration procedure indicated earlier and modified, where appropriate, by any attenuation due to propagation or by filter transmission losses. Note that atmospheric absorption values are defined at six frequencies in each band, instead of one, as for the SAE method, and 10 to 30 frequencies for the Dytec method.

The principal advantage of either of the Wyle methods is the potential for better accuracy in estimating measured band levels, and thus more accurately accounting for filter effects. This is especially true for the iteration method which was shown in Reference 1 to be capable of generating an apparent measured spectrum level which integrates to match the band levels measured with a real filter. As demonstrated in Reference 1, this match, after usually two and no more than six iterations, was shown to be within less than 0.1 dB for any band for a variety of actual aircraft spectra. It is important to note that without some form of iteration, one cannot accurately assess the filter error at receiver positions due to transmission outside the nominal filter bandwidth.

The principal disadvantage is the seemingly mathematical complexity. However, as pointed out in the next section, this is not as serious as one might think. Thus, from the standpoint of computational efficiency, the procedure may be comparable to the method of Reference 2 which employs a much simpler, and less accurate, spectrum interpolation algorithm but a very precise and conventional numerical integration routine to compute band levels.

3.4 Relative Accuracy of Band Integration Procedures

This aspect of the integration process employed in the Wyle method needs to be clarified. What is its accuracy relative to the more precise numerical integration process utilized in the Dytec method?

This was evaluated by comparing the result of integrating over a 1/18th octave segment exactly using a standard numerical integration routine with 100 intervals within the 1/18th octave bandwidth and the closed form trapezoidal approximation defined by Eq.(12) in Appendix A. The input spectrum was assumed to have the type of rapidly decreasing spectrum roll-off due to atmospheric absorption indicated earlier in Figure 6 in Section 2. An extreme case is selected corresponding to a frequency between 8,000 to 10,000 Hz, a distance of 2,000 meters and high absorption weather conditions of 15^{o}C, 35% relative humidity. Figure 6b shows that for this case, the slope of the receiver spectrum at such a distance, due solely to air absorption, would be of the order of -400 dB per octave and decreasing (becoming more negative) by over 100% per octave. Applying the spectrum iteration algorithm defined by Eq.(9) to such a case shows that the trapezoidal closed-form approximation for the elemental band power differed by less than 0.1 dB from the exact numerical integration value for the integral. For more realistic values of the spectrum slope, the difference was much less thus validating this procedure as an accurate substitute for the usual numerical integration procedure which involved 10 to 30 segments per band.

While seemingly complex, the Wyle integration process required only a few lines of computer code to define the power for each elemental segment given the spectrum interpolation factors a_i and b_i for each i_{th} band. Defining the latter for each iteration of the spectrum required only slightly more computations for each filter band than for the Dytec method. However, due to the repeated iteration process involved in the Wyle method, the net computation time for the Dytec and Wyle methods is expected to be comparable. The relative computational speed for comparable batch-processing versions of the Dytec and Wyle filter effects computer programs remains to be demonstrated.

3.5 Other Filter Effects Correction Methods

Before considering application of the preceding methods, brief mention should be made of other published methods.

Mantegani[12] has published a report which contains a detailed description of a method for accounting for filter effects in the analysis of wide band data subject to atmospheric propagation losses. The method employs the same spectrum level interpolation scheme as in the Dytec method and uses a trapezoidal integration routine over seven (1/21st octave) constant percentage segments within each one-third octave band to determine band levels. While programmed for ideal filters, the method is obviously adaptable to include filter errors for real filters for a known input spectrum.

Engineering Sciences Data Unit (ESDU)[11] has also published a procedure for accounting for filter effects in analysis of wide-band aircraft noise data for atmospheric absorption. (The report also outlines procedures, as does Reference 2, for considering attenuation through a layered, non-uniform atmosphere.)

The spectrum levels are again estimated in a similar manner as in the Dytec method except that the spectrum level slope is assumed constant over one full band. This is equivalent to shifting the spectrum level line approximations to the continuous spectrum by one-half bandwidth relative to the convention used by the Dytec method. However, this should not be a significant variation. The change in spectrum slope over a filter band due to atmospheric attenuation is predicted directly in terms of the change in atmospheric absorption loss over the frequency limits of the band. A conventional Simpson's rule integration procedure is used over the entire one-third octave band with an integration accuracy claimed of $\pm 1\%$

for spectra shaped by atmospheric absorption over a distance of 100 m. Larger errors would be expected at greater distances for this integration with only one integration segment per band.

The method assumes ideal filters and thus does not account for filter skirt errors. However, the authors claim that the filter error (Δ_F in our terminology), due to finite filter skirts, would not exceed 10% for a source spectrum slope of -15 dB/one-third octave band and an additional atmospheric attenuation of 50 dB.[11]

Finally, it should be pointed out that the computerized method reported in Reference 9 for analysis of the attenuation of bands of noise was essentially identical to the first Wyle method, (without iteration) although one of the authors (Bass) later reported successful application of a spectrum iteration routine similar to that of the second Wyle method.[19]

4. APPLICATION OF FILTER EFFECTS CORRECTION PROCEDURES

The ability of the procedures described in the proceeding section to account for filter effects errors in aircraft noise analysis is evaluated with three types of examples: 1) evaluation of band levels for an idealized known source spectrum, 2) evaluation of band levels for "unknown" receiver spectra including actual (measured) aircraft noise data, and 3) evaluation of overall frequency-weighted aircraft noise levels (i.e., PNL or EPNL) for such aircraft spectra.

4.1 Known Source Spectrum

The spectrum shown in Figure 10 was used to evaluate filter effects for the case of a known source spectrum. This source spectrum slope was chosen to approximate what is considered a reasonable bound on the minimum (most rapid fall-off) spectrum slope very near a typical jet noise source, in the absence of strong tonal components. The spectrum slope matches one of the cases considered in both Reference 1 and 2. For this source band level slope, filter effects (i.e., slope and filter errors) are negligible as indicated in Section 2 so that one can assume that the true source band levels are measurable exactly with standard filter sets. For this source spectrum, we will evaluate filter effects errors and means of correcting for them when:

- Estimating the attenuation in band levels, due only to atmospheric absorption that would be measured at a receiver 600 m away on a high absorption day ($15^{o}C$, 35% relative humidity) using an ideal (ΔL_{BI}) or real (ΔL_B) filter. The weather condition was selected to represent an approximate upper bound condition for atmospheric absorption under weather conditions within the FAR Part 36 weather window.[3] The weather condition used in Reference 2 to represent a maximum absorption condition ($25^{o}C$ and 10% relative humidity) is not uncommon for experimental aircraft measurements in hot, dry climates but it falls outside the FAR Part 36 weather window and was therefore not considered further in this review.

- Estimating the adjustment to these receiver band levels if they were measured on a standard day (25^{o}, 70% RH) at the same distance with ideal or real filters.

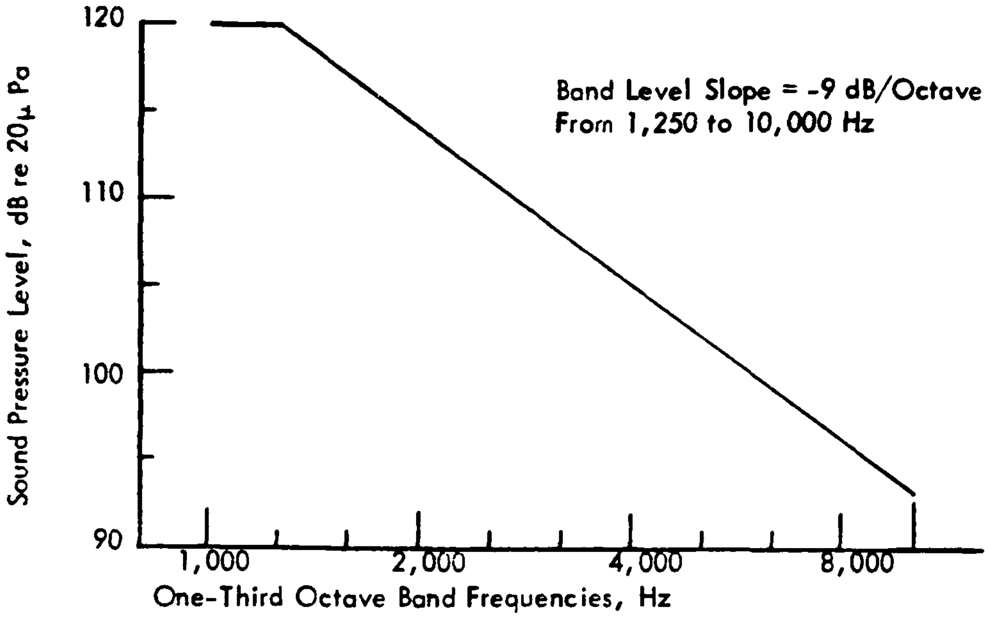


Figure 10. Idealized One-Third Octave Band Level for Case of Known Source Spectrum.

These "exact" values of band level attenuation and band level adjustment are computed by the second Wyle band integration method (with spectrum iteration) assuming an ideal filter. However, in this case, spectrum iteration is not really necessary at the source where the spectrum is known and any one of the methods, which employ band integration for a known spectrum, (i.e., the Dytec or either of the Wyle methods) would give nearly the same result. As a matter of interest, however, the iteration technique provided a computed version of the source spectrum which agreed, essentially exactly, with the values specified in Figure 10. Only the first band at 1,000 Hz differed from the specified value, but by only 0.02 dB, due to the discontinuity in the band spectrum slope at 1,250 Hz.

Thus, this exact computation of the atmospheric attenuation at a distant receiver provides a convenient reference base for evaluation of how well the various approximate methods correct for filter effects when analyzing an "unknown" spectrum. The "unknown" spectrum will be represented, then, by the levels at a receiver, 600 m away from this known source, on the assumed test day conditions as they would have been measured with a real filter.

The atmospheric absorption losses in this receiver spectrum are computed at all frequencies with the use of the new ANSI S1.26 Standard.[14] This method for computing absorption losses was chosen as a matter of convenience instead of the currently accepted industry standard (SAE ARP 866A)[15] for application to aircraft noise analysis. However, the comparison between methods to account for filter effects will not be materially changed since the two models for predicting air absorption are fairly comparable at the same single frequency in the high frequency region where filter effects are dominant.

4.1.1 True Values for Band Level Attenuation

We start with the known source spectrum shown in Figure 10 and apply the integration techniques outlined in Section 3.3 to define the attenuation in band levels for this spectrum as would be measured at 600 m on a 15°C, 35% relative humidity day. For ideal filters, the integration process is straightforward since it involves integration only over the nominal, zero-loss passband of the ideal filter. For the real filter, the mathematical model corresponding to the frequency response of real filters is included in the integral and the integration is now carried out over a wider frequency range to include the filter skirts. Figure 11, from Reference 2, illustrates how well this mathematical filter model, reported originally in Reference 14 and repeated in both References 1 and 2, describes the actual transmission loss of real filters, especially over the most critical portion of their filter skirts near the band edges.

The results of these computations are shown in Figure 12a in terms of the absolute band levels, L_{BI} and L_B, at the receiver and in Figure 12b in terms of the band level attenuations, ΔL_{BI} and ΔL_B, that would have been measured at this 600 m receiver position with ideal and real filters, respectively. The values for an ideal filter may be considered the accurate measure of the difference in the true one-third octave band levels between the source and receiver. However, the values predicted for a real filter represent what would have been actually measured with current state-of-the-art of spectrum analysis equipment. Clearly, above 5,000 Hz, the latter diverge increasingly from the true values of band level attenuation. This is, of course, the result of significant power transmission through the filter skirts outside the ideal passband. A comparison of the slopes for the "test day" spectra in Figure 12 and the slopes of the filter response curves in Figure 11 clearly indicates that the latter are not sufficiently high to reject energy outside the nominal filter passband for such high spectrum slopes (of the order of 50 dB/octave).

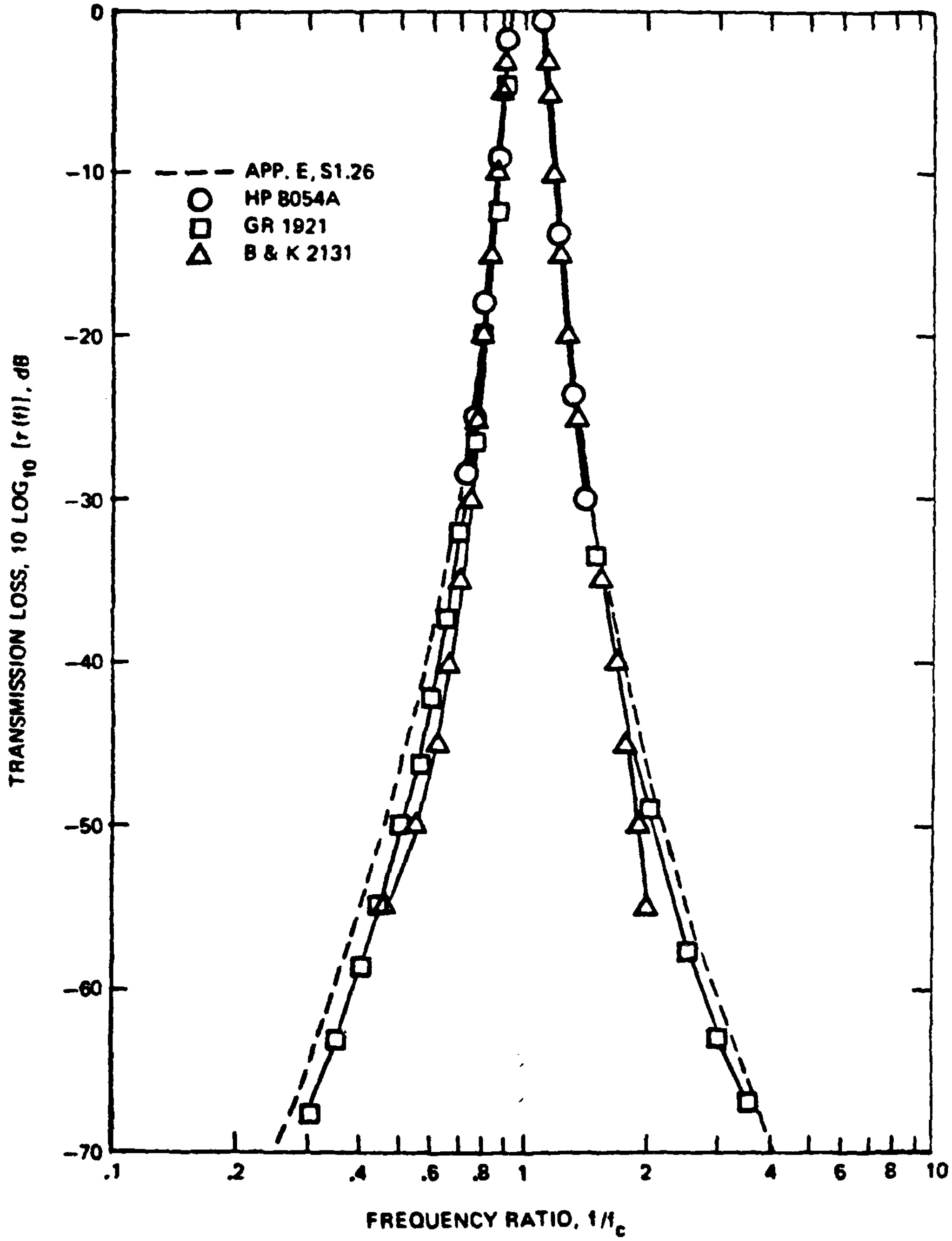


Figure 11. Transmission-loss Response Characteristics of One-Third Octave Band Filters in Real Time Analyzers Compared with Response Calculated from "Practical Filter" Transmission Response Equation; f_c is Band Center Frequency (from Reference 2).

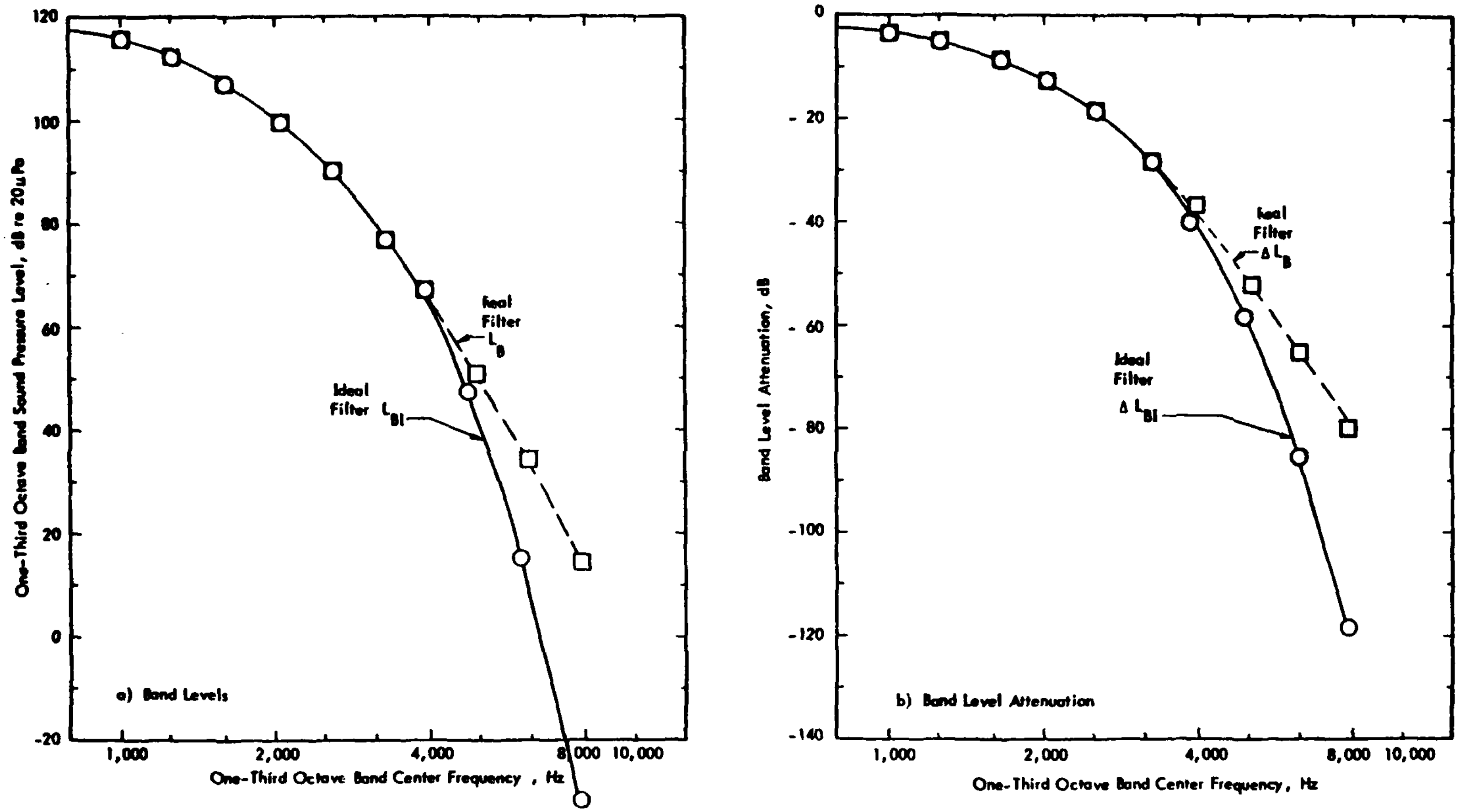


Figure 12. Band Levels and Band Level Attenuations that Would Have Been Measured at 600m from the Source Spectrum Shown in Figure 10 on a 15°C, 35% Relative Humidity Test Day

4.1.2 True Values for Band Level Adjustment

Figure 13 shows the same type of information as in Figure 12 for propagation over 600 m but for a standard day with weather conditions of 25°C and 70% relative humidity. The difference between the comparable curves in Figures 12 and 13 define the desired values for the band level adjustments from test day to standard day weather.

Thus, the data in Figures 12 and 13 provide reference (exact) values of band level attenuation and band level adjustment for one evaluation of how well one can correct for filter effects when measuring an unknown spectrum at a receiver.

4.2 Unknown "Measured" Spectrum at a Receiver Computed from Known Source Spectra

The levels computed for "measurement" with a real filter at 600 m on the assumed test day (i.e., weather of 15°C and 35% relative humidity) now become the new input levels to be evaluated with each of the correction methods described in Section 3.

To emphasize the relative accuracy of these correction methods, it is convenient to present the values of band level attenuation (ΔL_B) and band level adjustment ΔA_B predicted for these "measured" levels relative to the true values derived from Figures 12 and 13 where the source (and hence receiver) spectra were accurately known. For reference, the true absolute value of these quantities is also shown.

Thus, Figure 14 shows, on the left, the same band level attenuation values as in Figure 12b (for the same conditions – 600 m and test day weather) but now interpreted as the true band level attenuations going back from the receiver to the source. Obviously, the true attenuation values do not change with direction of propagation.

The right half of Figure 14 shows the difference between this true value and the various estimated band level attenuation values according to the following convention:

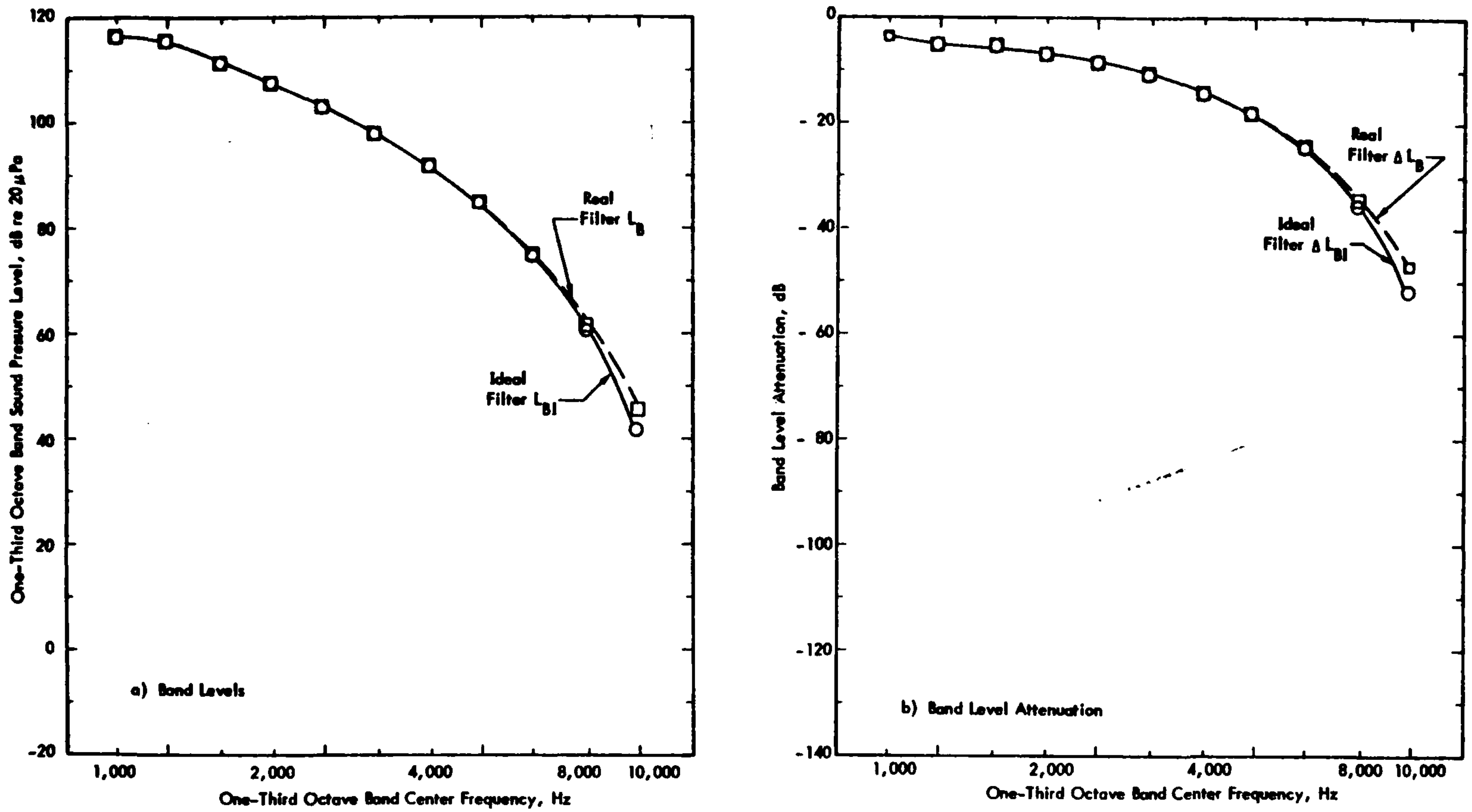


Figure 13. Band Levels a) and Band Level Attenuations b) That Would Have Been Measured at 600 m from the Source in Figure 10 on a Standard Day

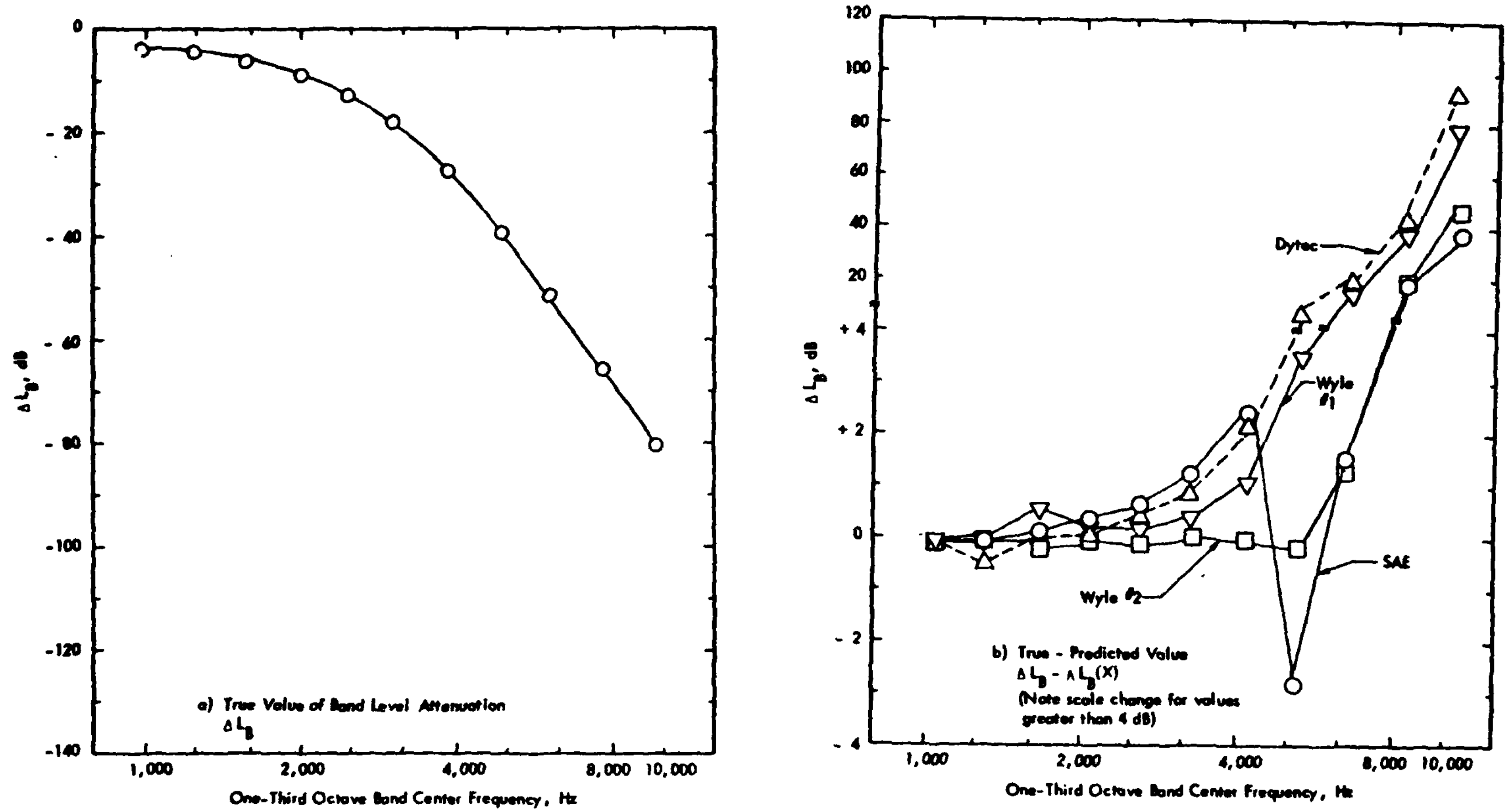


Figure 14. The True Band Level Attenuation a) for Real Filters, as Determined from Figure 12, and the Difference b) Between the True and Predicted Values, Distance = 600 m, 15°C, 35% Relative Humidity

○ Symbol designates the difference, $\Delta L_B - \Delta L_B(S)$, between the true band level attenuation ΔL_B and the value $\Delta L_B(S)$ predicted by applying the SAE prediction method. This quantity corresponds to the correction that could be applied to a predicted band level attenuation, using the SAE procedure, to obtain the true value.

△ Symbol designates the difference, $\Delta L_B - \Delta L_B(D)$, between the true and predicted value from the Dytec method. Similarly,

▽ Symbol designates the difference, $\Delta L_B - \Delta L_B(W1)$, for the Wyle #1 method (without spectrum iteration), and

□ Symbol designates the difference, $\Delta L_B - \Delta L_B(W2)$, for the Wyle #2 method (with spectrum iteration).

This same type of comparison is made in Figure 15 between the two values of the band level adjustment for a real filter ΔA_B (Figure 12b values for a real filter on a test day minus corresponding values in Figure 13b for a real filter on a standard day) and the predicted values using the various correction methods.

Again, the left part of Figure 15 shows the true value of ΔA_B and the right part shows the difference between this true reference value and the predicted values using the same notation as for Figure 14.

Finally, as suggested earlier, it may be desirable to consider correcting data measured on a test day with a real filter, to values that would have been measured on a standard day with an ideal filter. The corresponding band level adjustment is designated as ΔA_{BRI}. Figure 16 presents the comparison of the true and predicted values for this adjustment factor. Again, the same method of presentation and labeling convention is employed. In this case, however, a predicted value for the SAE method is not shown since this method was not designed to be applicable to ideal filters in the evaluation of attenuation of bands of noise.[15]

The comparisons in Figures 13 through 16 exhibit the following trends:

- o All four of the methods considered for evaluating filter effects show significant errors (>1 to 2 dB) at high frequencies when predicting band level attenuations and band level adjustments. As suggested earlier, this behavior is expected on the basis of the high slopes for the input spectra.

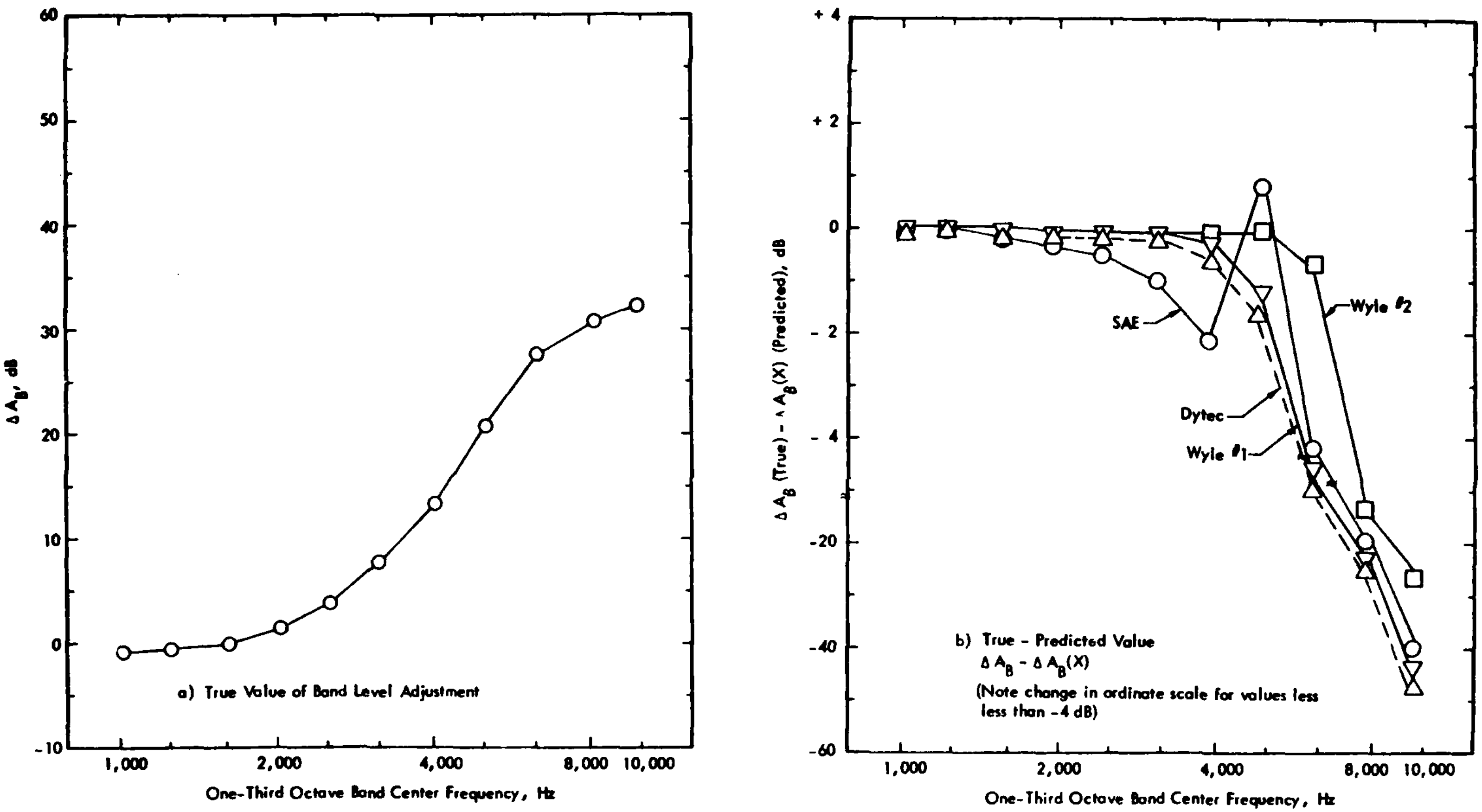


Figure 15. The True Band Level Adjustment for a) Real Filters, as Determined from Figures 12 and 13, and the Difference b) Between the True and Predicted Values, Distance = 600 m, Test Day - 15°C, 35% Relative Humidity, Standard Day - 25°C, 70% Relative Humidity

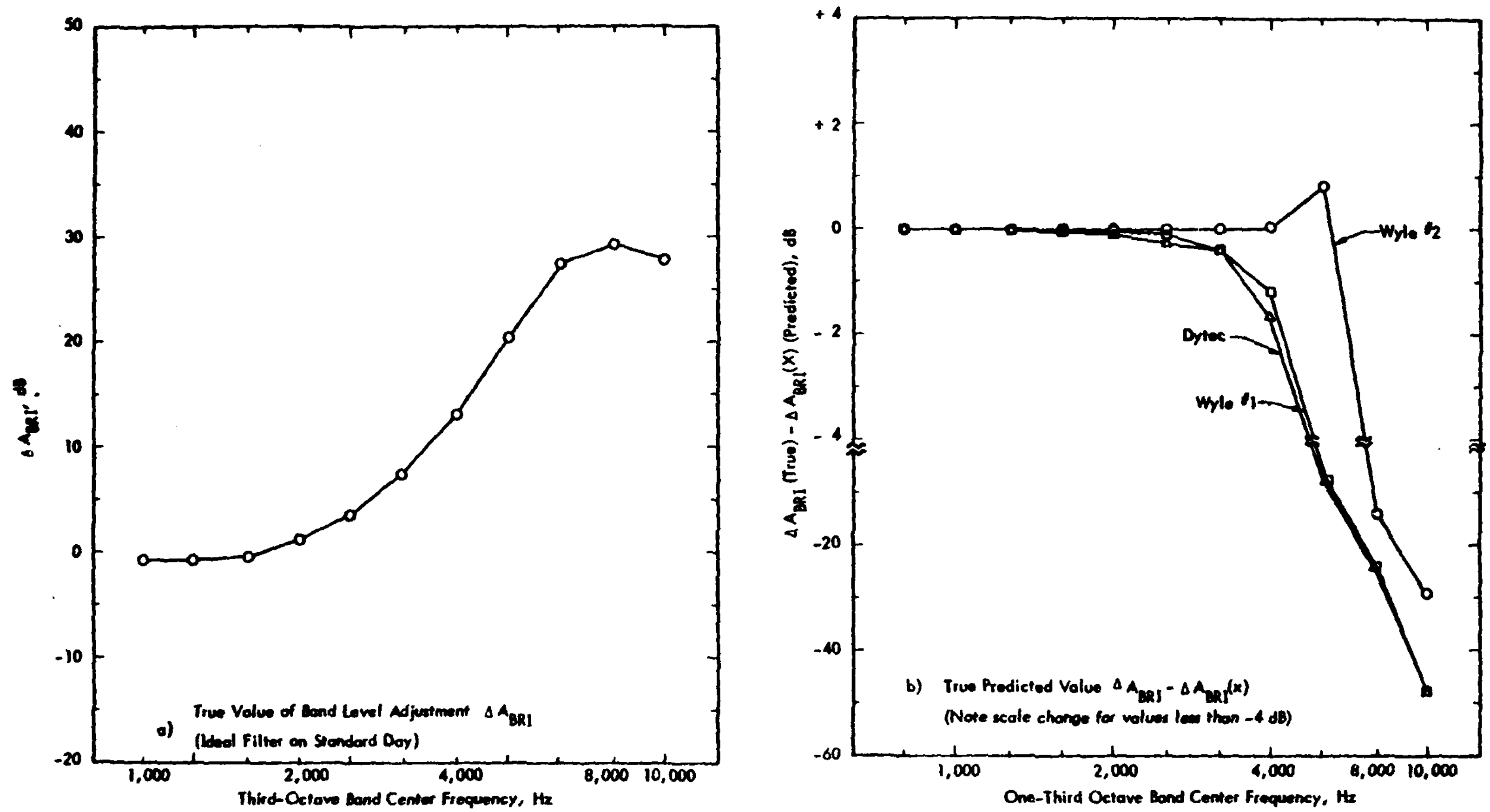


Figure 16. True Value a) of Band Level Adjustment Factor (from Figures 12 and 13 for a Real Filter on Test Day and Ideal Filter on Standard Day) and Difference b) Between the True and Predicted Values, Distance = 600 m, Test Day, 15°C, 35% Relative Humidity

- o The rapid variations in accuracy of the SAE method may be due to the discontinuity in the effective frequency above 4,000 Hz which is inherent in this method for evaluating attenuation of bands of noise.

- o The Wyle No. 2 (iteration) method generally exhibits the best accuracy but even this method fails at frequencies above 5,000 Hz when the initial spectrum slope equals or exceeds the filter skirt slope.

4.3 Unknown Spectrum From Measured Aircraft Noise Data

Consider, now, another version of the case of an unknown spectrum – a more representative case – based on evaluation of actual measured aircraft noise data. Two such examples, drawn from data utilized in Reference 1, are considered.

- o Takeoff noise at the time of PNLTM for a three engine narrow body turbofan aircraft (Data File 35 T/O)

- o Takeoff noise at the time of PNLTM for a four engine narrow body turbofan aircraft (Data File 88 T/O)

For these measured levels, the signal-to-noise ratio was never less than 5 dB in any band and was more than 20 dB in all but the highest frequency bands so that the data can be considered to be free of any significant influence from noise. What residual influence remained was essentially eliminated by applying the background noise correction procedures of Reference 20. The data were measured at propagation distances close to 300 m and for weather conditions close to a standard day. Therefore, for convenience, the data were adjusted slightly to a reference propagation distance of 300 m and standard day weather. This adjustment amounted to +0.6 dB at 4,000 Hz for the first data file (35 T/O) and +1.8 dB at 4,000 Hz for the second data file (88 T/O).

The resulting standardized one-third octave band levels for these two examples are shown in Figure 17 by the open symbols. Note that the high frequency roll-off rates for these spectra are less than -20 dB/octave. According to Section 2, with such relatively low spectrum slopes, it should be possible to obtain very good estimates of the apparent true spectrum for these measured levels without any significant influence of filter errors. The spectrum iteration method was therefore applied to these data to provide what one can assume is

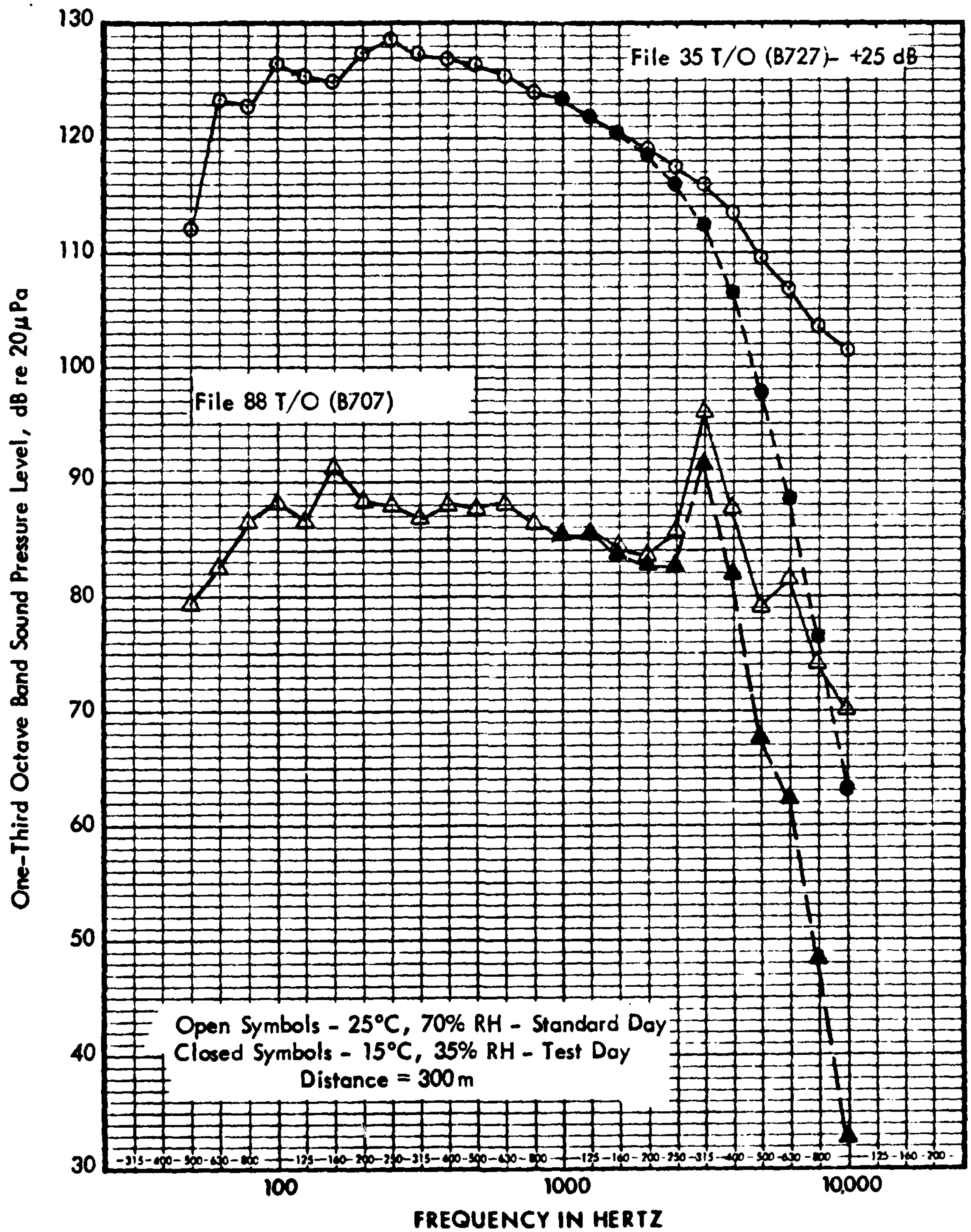


Figure 17. Aircraft Spectra, Measured at PNLTM, Used to Illustrate the Application of Filter Effects Correction Procedures. The original measured data, normalized to a propagation distance of 300 m for a standard day, have been adjusted downward to define a hypothetical test day spectra that would be measured with real filters.

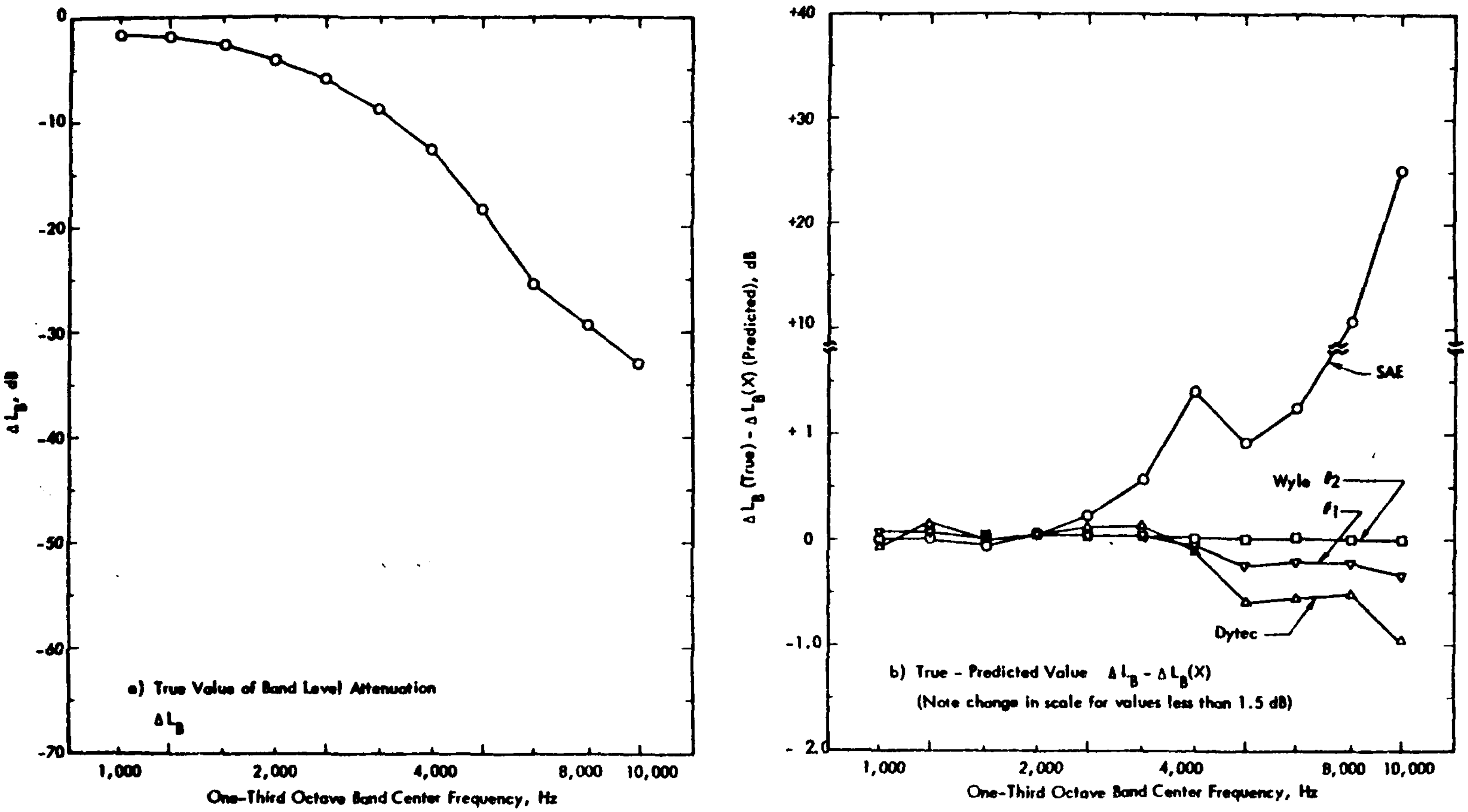
closely equivalent to known spectra, comparable to the example illustrated earlier in Figure 12. To provide the test cases comparable to that employed earlier for Figures 14 through 16, these standardized spectra were adjusted to the more severe test day conditions of 15°C and 35% relative humidity to produce the hypothetical values, "measured" with a real filter, that are identified in Figure 17 by the closed symbols. Although this adjustment in the levels was computed with the Wyle #2 (spectrum iteration) method, essentially equivalent results for these hypothetical test day levels would have been obtained with the use of the Dytec method. That is, either method can estimate the initial spectrum levels (with roughly comparable accuracy) for the standardized spectra of Figure 17. These source spectrum levels could then be accurately adjusted to test day conditions and integrated to represent levels "measured" with real filters on the test day. Thus, with these hypothetical "measured" levels as inputs to the various methods for considering filter effects, the three basic factors considered were, again:

- Band level attenuation ΔL_B for real filters at a new receiver position, 300 m further away (corresponding to a total propagation distance from the original source of 600 m);
- Band level adjustment ΔA_B from test day levels at this new position back to the original standard day values, with real filters; and
- Band level adjustment ΔA_{BRI} for correction of these measured levels back to the standard day as they would be measured with ideal filters.

Comparisons are again shown between the true values for these factors derived from Figure 17 and the predicted values using each of the filter effects correction methods under consideration.

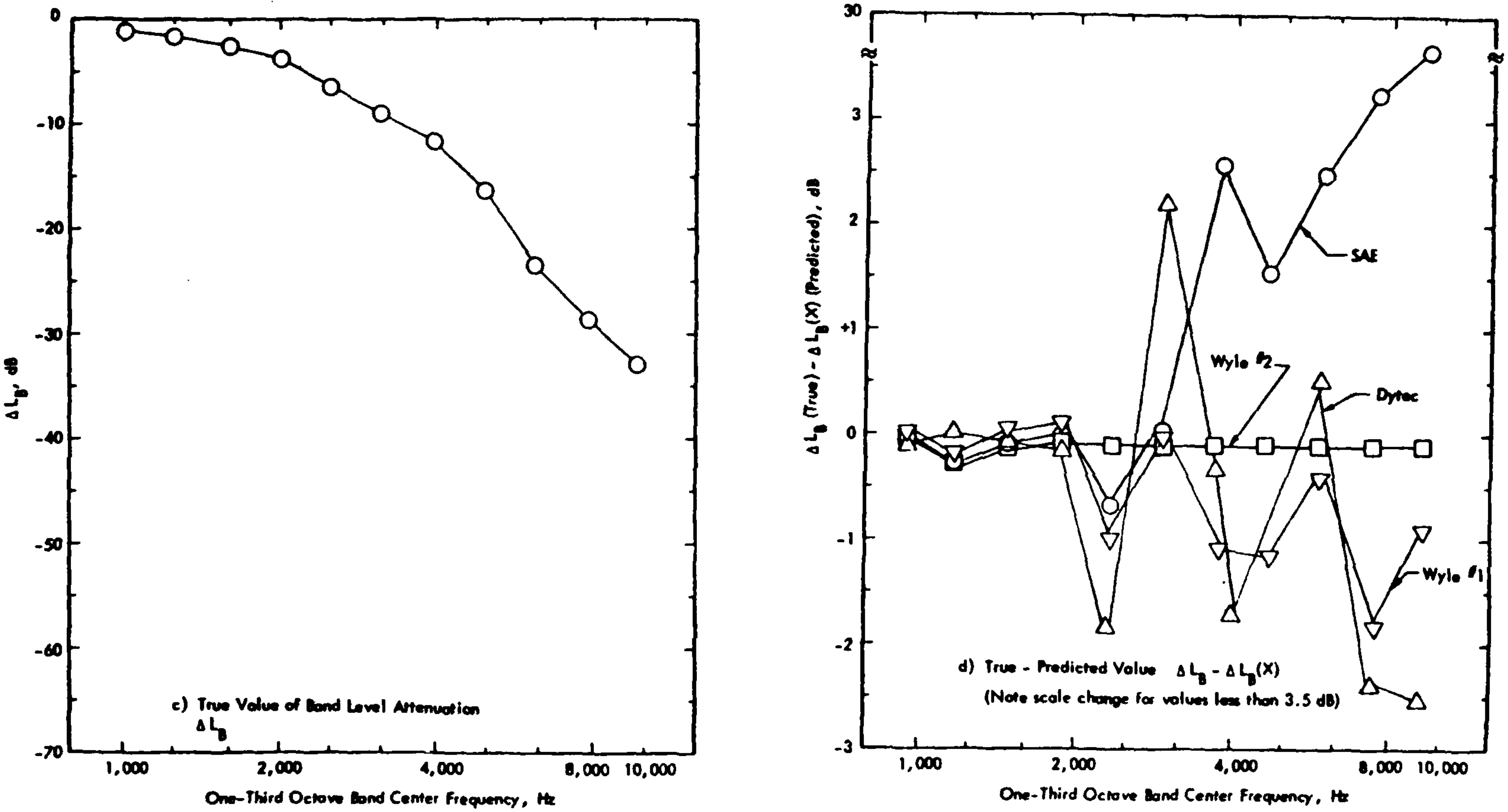
The results are shown in Figures 18 through 20 employing the same convention as before. Figure 18 presents comparisons of true and predicted values of band level attenuations, Figure 19 compares values for band level adjustments, ΔA_B, with real filters and Figure 20 compares, for a few cases, band level adjustments ΔA_{BRI} for an ideal filter assumed for the standard day.

Although the results in Figures 18 through 20 are, in some respects, similar to those in Figures 14 - 16, there are some important differences.



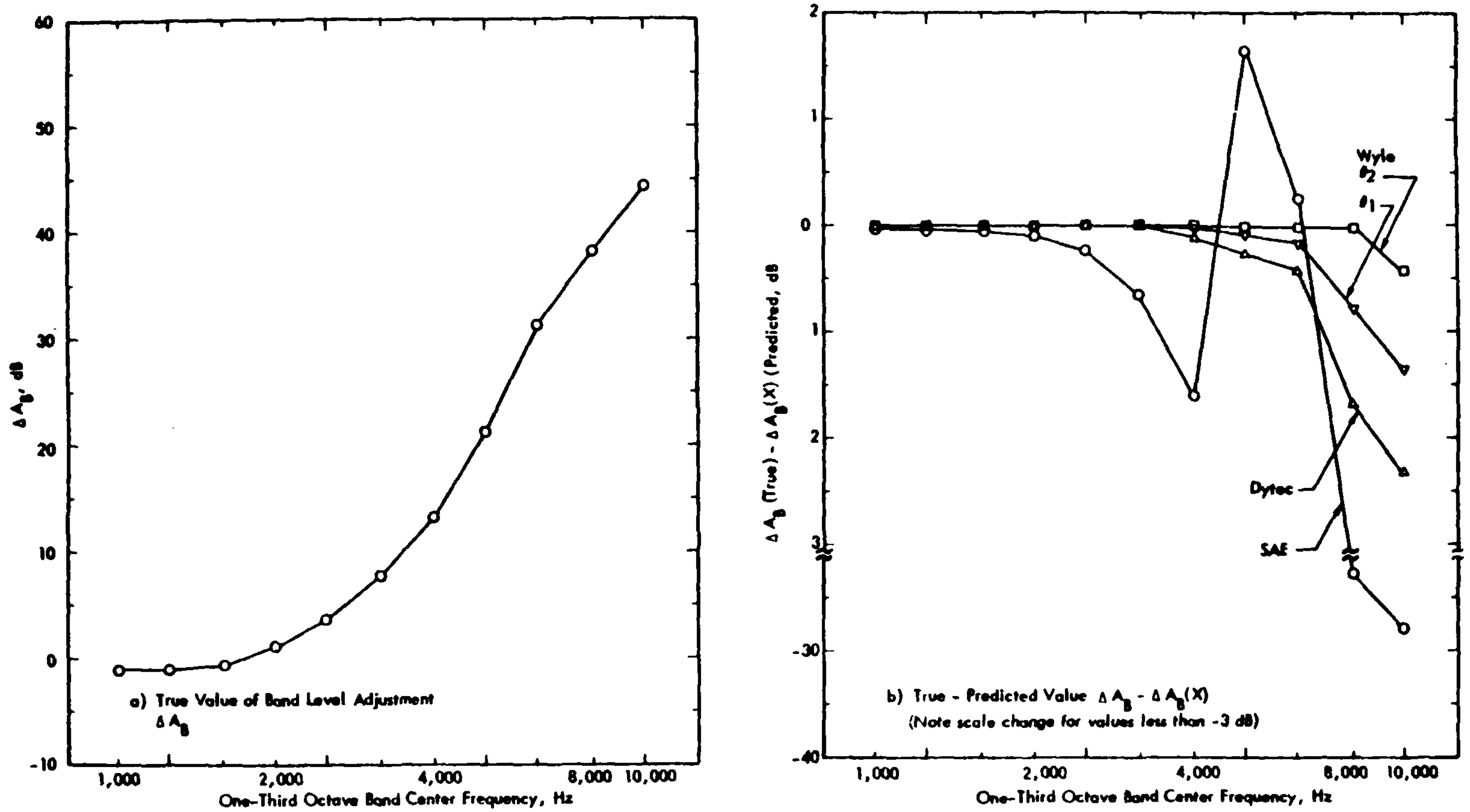
Data File 35 T/O

Figure 18. True Band Level Attenuation for the Measured Aircraft Spectra Shown in Figure 17 and Predicted Values for Propagation Over an Additional 300 m at Hypothetical Test Day Conditions of 15°C, 35% Relative Humidity



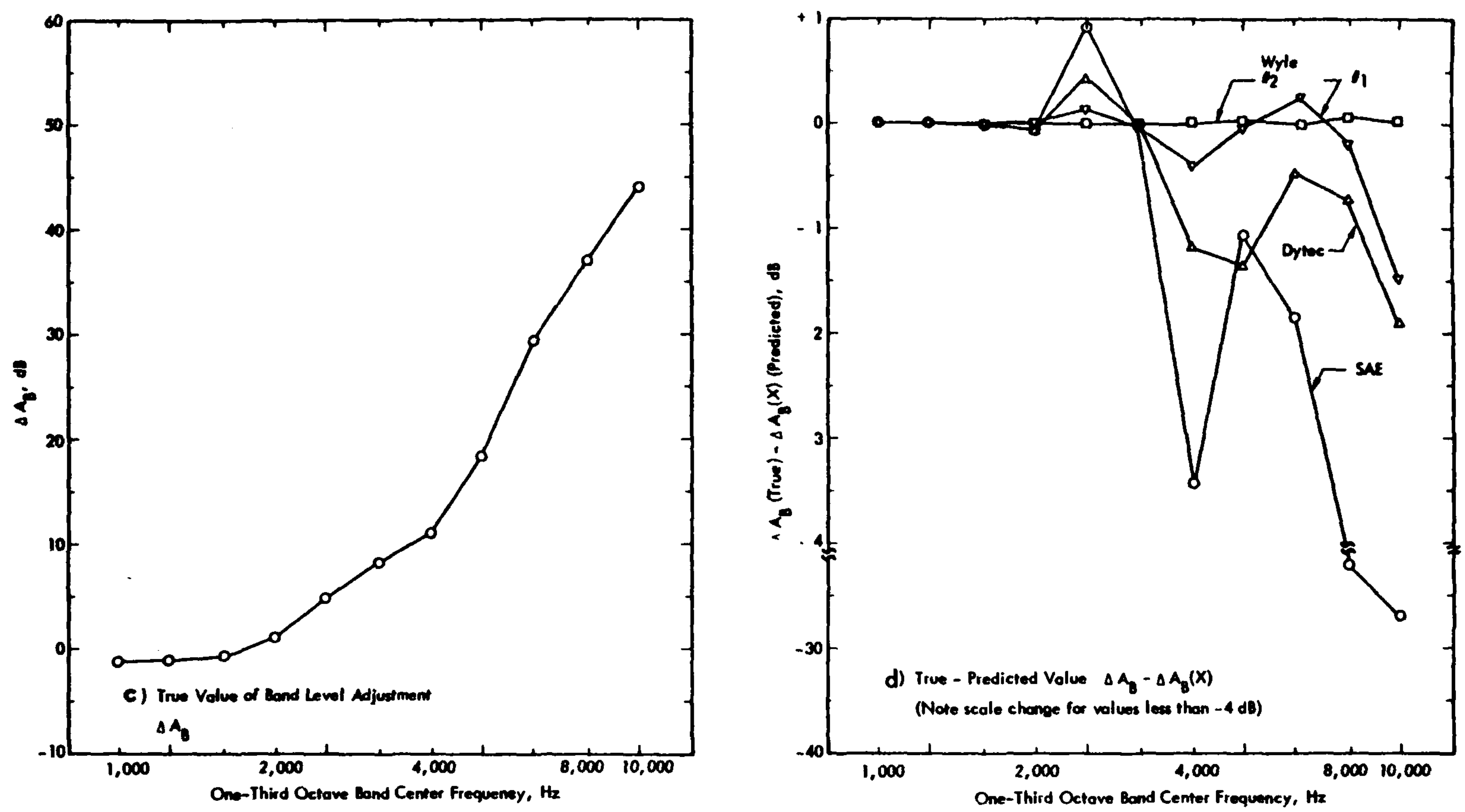
Data File 88 T/O

Figure 18 (Continued)



Data File 35 T/O

Figure 19. True Band Level Adjustments for the Measured Aircraft Spectra Shown in Figure 17 and Predicted Values for Propagation Over an Additional 300 m (Adjustment from test day conditions of 15°C, 35% Relative Humidity to standard day conditions of 25°C, 70% relative humidity - real filters assumed for each condition)



Data File 88 T/O

Figure 19 (Continued)

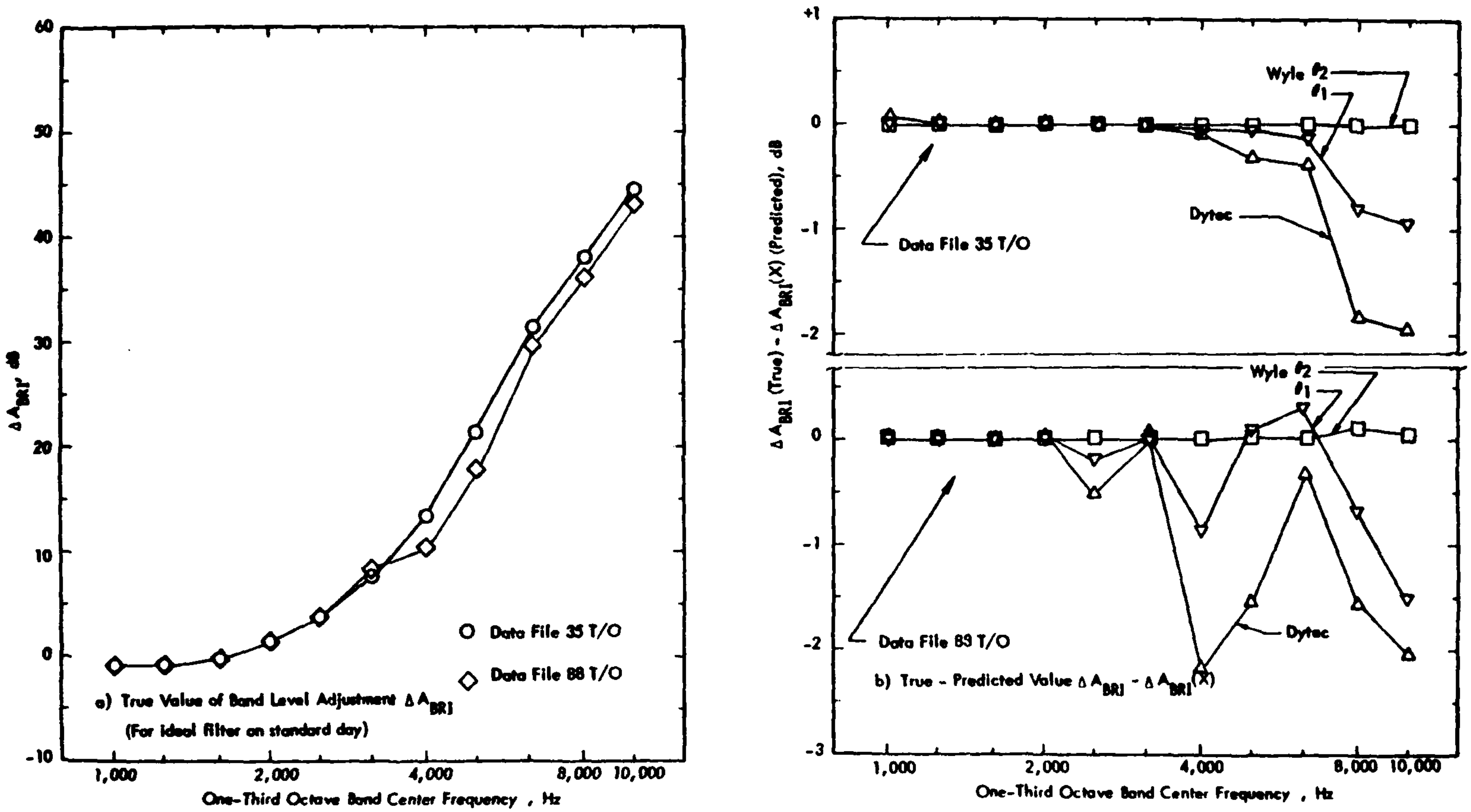


Figure 20. True Band Level Adjustments a) for the Measured Aircraft Spectra Shown in Figure 17, and Predicted Values b) for Propagation Over an Additional 300 m (Adjustment from test day measurements, with a real filter, at 15°C, 35% relative humidity, to standard day measurements, with an ideal filter, at 25°C, 70% relative humidity)

- The errors in the various correction procedures do not always consistently increase markedly at the high frequencies as was noted earlier in Figures 14 through 16.

- Only for the SAE method is there a consistent increase at high frequencies in the difference between predicted and true band level attenuations or band level adjustments. Thus, any of the band integration (Dytec or Wyle) methods appear to offer significantly greater accuracy than the SAE method for correcting for filter effects for these samples of real aircraft data.

- Furthermore, the spectral iteration (Wyle #2) method, unlike any of the other methods, seems to consistently exhibit very high accuracy in predicting the correct band attenuation or adjustment factors. This is attributed entirely to the method's ability, unique among the methods considered here, to more accurately estimate the initial spectrum levels.

- The very different behavior in the filter effects prediction methods for these real aircraft data, as compared to the idealized case analyzed in Figures 14 through 16, indicate that development of any empirical rules for evaluating filter effects should, to the extent possible, be based on evaluation with real aircraft data.

- Finally, it is desirable to see if the data presented in Figures 18 through 20 (and earlier in Figures 14 through 16) support the empirical criteria cited in Reference 1 for the occurrence of significant errors (> 0.5 dB) due to filter effects. The correct version of this criteria, which was incorrectly printed in Reference 1, is that the product of the propagation distance, in km, and the square of frequency, in kHz, should not exceed 6 km . $(kHz)^2$. Examining the examples presented here suggests that this criteria may be somewhat optimistic, i.e., perhaps the constant "6" needs to be reduced. However, additional aircraft noise data should be evaluated for filter effects before any rigid quantitative guideline or requirement involving regulatory or mandatory administrative action by the FAA can be adopted.

It is clear by now that errors in band levels due to filter effects can be quite significant under certain conditions and that methods to account for those errors differ substantially in their accuracy. Consider, finally, filter effects for overall aircraft noise levels, both with and without time integration.

4.4 Filter Effects On Overall Aircraft Noise Levels

4.4.1 Effects on Momentary Noise Metrics

As evident from the preceding review, filter effect errors can be large at high frequencies. However, in such cases, the resulting absolute levels are low so that such band level errors due to filter effects contribute little to errors in overall sound pressure levels. The latter tend to be dominated by lower frequency band levels for which filter effects are much smaller.

Representative results from the two studies[1, 2] for relative filter effects errors in perceived noise levels (PNL), maximum tone-corrected perceived noise levels (PNLTM), or maximum A-weighted noise levels (AL) are summarized as follows. True reference values for these overall levels were not available so that it was only possible to compare, against each other, the values predicted by alternate correction methods.

From Reference 1, PNL values (measured at close to 300 m at the time of PNLTM and adjusted to a standard day and a distance of 300 m) were evaluated for four cases using both the Wyle #2 method (with spectrum iteration) and the SAE method. The difference between the resulting values of PNL are listed in Table 1 for the reference distance of 300 m and for two greater propagation distances. Clearly, the difference in PNL values using the two band attenuation prediction methods is slight. Based on the preceding results, it is reasonable to consider the PNL values from the Wyle #2 method as close to representing true values (ignoring any other sources of measurement errors, such as background noise).

Table 1

Differences in PNL Values Due to Different Procedures to Account for Filter Effects (Derived from Data in Table 4 of Reference 1 for One-Third Octave Band Spectra at PNLTM, adjusted to standard day conditions)

Data File	PNL (SAE) - PNL (Wyle #2), dB[1]		
	Distance, m		
	300	600	900
35 T/O (727)	0	0.07	0.03
47 App (707)	-0.01	0.08	–
88 T/O (707)	0.01	0.09	0.08
90 T/O (DC-10)	0.05	0.25	0.22

(1) Differences between PNL values computed with the simulated SAE method and with the Wyle #2 method (with spectrum iteration) (data from Reference 1).

Thus, according to the few cases considered in Table 1, the SAE procedure for evaluating atmospheric attenuation of bands of noise seems to give very nearly the same values (within less than 0.3 dB) as the more accurate, and presumably true results, using the Wyle method. This conclusion is strongly reinforced by data from Reference 2. In Table 8 of this reference, overall momentary noise metrics for six different measured aircraft spectra were evaluated with the equivalent of the Dytec and SAE methods as defined herein. (The ANSI S1.26 procedure was actually employed in both cases, thus eliminating any secondary influences on filter effects due to differences in atmospheric absorption algorithms.)

The noise metrics evaluated were PNL, PNLTM, and AL. For five of the six spectra evaluated, there was no difference whatsoever in the noise metrics evaluated with the Dytec and SAE methods. For the sixth case, the maximum difference was only 0.1 dB – the same order of magnitude as the small differences indicated in Table 1.

4.4.2 Filter Effects for Time Integrated Noise Levels

For time integrated aircraft noise levels, the influence of background noise on the sound pressure levels measured throughout the effective (i.e., 10 dB downtime) duration of an aircraft flyby are more significant than for the momentary noise metrics at the time of PNLTM. This is especially true for high frequency bands near the beginning and end of this time integration period.

A detailed consideration of this subject is not appropriate for this summary report on filter effects. The reader is again referred to the parent documents (References 1 and 2) for more detailed considerations of the manner in which spectral time histories were corrected for ambient noise levels before applying alternative filter effects correction methods.

The point is that it is difficult to separate out, entirely, the possible influence of filter effects on time integrated aircraft noise levels from effects of background noise. Nevertheless, according to the data available in References 1 and 2, filter effects by themselves do not appear to strongly influence time integrated noise metrics. Reference 1 compares values of Effective Perceived Noise Level (EPNL), for two aircraft noise time histories, using three of the four different methods for evaluating filter effects considered here – the SAE method, the Wyle #1 (without spectrum iteration), and the Wyle #2 (with iteration) methods. The results are summarized in Table 2 in terms of the EPNL values for each of the first two methods relative to the last (Wyle #2) method.

Table 2

Differences in EPNL Values Due to Different Procedures to Account for Filter Effects (Derived from Data in Table 5 of Reference 1). Data for "As Measured" Values at Distances Close to 300 m and Near Standard Day Conditions

Data File	EPNL (SAE) - EPNL (Wyle 2)	EPNL (Wyle 1) - EPNL (Wyle 2)
	dB	
18 App (727)	-0.01	+0.01
35 T/O (727)	-0.65	-0.74

The apparent errors due to filter effects, as evidenced by the difference in EPNL values for two different band analysis methods is, again, small. However, in one of the two cases considered (Data File 35 T/O), the difference is substantially greater (about -0.7 dB) than indicated in Table 1 for corresponding differences in values of PNL.

Reference 2 reported EPNL and Sound Exposure Level (SEL) values for the same six aircraft spectra mentioned earlier in the preceding section. Again, for five of the six spectra considered, there was no difference, to within an accuracy of less than 0.1 dB, between EPNL values computed with the Dytec and the equivalent of the SAE methods, as defined herein. For a sixth case, the difference in EPNL values was only 0.1 dB.

Thus, the two studies both indicate filter effects should introduce small errors (less than 1 dB) in EPNL values. The results from Reference 2 consistently indicate nearly negligible filter effects on EPNL for six cases. While this may be more representative of the true situation than the slightly different results for the two cases from Reference 1 summarized in Table 2, it is not possible to completely discount the potential significance of filter effects on EPNL values. The Dytec and SAE methods employed in Reference 2 for evaluating filter effects are shown to be less accurate than the spectral iteration method in Reference 1. Thus, conclusions based on application of the former methods may be overly optimistic. Further data evaluation is called for with different, independently verifiable, techniques to define initial measured spectra.

4.5 Methods of Accounting for Filter Effects in the Presence of Strong Tone Components

A final issue briefly considered in this summary report concerns methods for properly evaluating filter effects for aircraft spectra which contain strong tone components.

For the most part, References 1 and 2 did not really address this issue with any distinctly separate procedures. However, two possibilities are suggested by the methods outlined in these reports:

- Use the spectrum iteration method to approximate the presence of a spectral spike or tone. One such example is, in fact, illustrated graphically in Reference 1. However, it remains to be validated by an independent, more conventional, process.

- Use some form of spectral smoothing in the initial data processing of the aircraft spectra. Tonal components could be identified and subtracted out, on an energy basis, from the total spectrum employing algorithms not unlike those currently used to identify tone penalties. Then each resulting portion – a smoothed broadband spectrum – and the tonal components, presumed to exist at the center frequency of the bands in which they fall, would be processed separately. The broadband portion could be analyzed with one of the types of band integration methods outlined here to minimize filter effects for this part of the spectrum. The "tone" components would also be processed (i.e., adjusted to standard conditions) by using simple atmospheric absorption algorithms for the presumed single frequency of the "tone." The resulting two components could then be recombined, on an energy basis, after adjustments to standard conditions.

A definitive evaluation of the need for, and if called for, the relative effectiveness and efficiency of, such procedures remains to be carried out.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This summary of two detailed studies[1,2] of potential errors in the evaluation of aircraft noise spectra due to finite energy passed by filter skirts has demonstrated the following:

5.1.1 Very substantial errors can occur in the spectrum analysis of aircraft spectrum under conditions where spectral shaping by atmospheric absorption results in steep spectrum slopes in the measured data which are comparable to slopes of filter skirts employed in the spectrum analysis.

5.1.2 These errors can be represented by two components -

- o a true filter error equal to the difference between the power transmitted by a real filter and by an ideal filter;
- o a spectrum slope "error" which is only significant when one attempts to analyze band attenuation at a single characteristic frequency in each band.

5.1.3 Methods to account for these errors vary from a simple empirical procedure involving selection of a suitable single frequency for computing band attenuations (SAE ARP 866A method) to the different forms of band integration outlined in Reference 1 and 2, which can accurately simulate the power transmission of a real filter if the input spectrum is known.

5.1.4 One unique way to effectively define an unknown, sharply sloping spectrum, is the spectrum iteration method of Reference 1. From examples involving actual measured aircraft data, this method is shown to be capable of more accurately predicting the true value of band level attenuation and band level adjustments than the other methods which do not employ any iterative correction of the initially estimated spectrum. However, when spectral shaping, caused primarily by atmospheric absorption, results in spectral slopes which far exceed the rejection rate of filter skirts, even this iterative process can be limited in its ability to recover the true input spectrum.

5.1.5 Filter errors are particularly significant when it is necessary to correct aircraft levels measured under high absorption loss test-day weather conditions to standard day weather by the use of band level adjustments. In this case, the different band integration techniques, especially the one employing a spectral iteration technique, prove to be much more accurate than the SAE procedure for accurately defining these band level adjustments.

5.1.6 It was shown in Reference 1 that, as a rough rule of thumb, filter errors become significant, calling for more accurate correction procedures than provided by the SAE method, when the following criteria are exceeded:

Propagation Distance (in km) x (Frequency, in kHz)^2 > 6

Propagation Distance >6 km at any audio frequency

Some of the limited examples presented in this review suggest that this criteria may not be strict enough - that is, the factor 6 may be too large.

5.1.7 Under conditions for which filter effects introduce large errors in measured (or adjusted) band levels, overall noise levels, such as PNL or EPNL, are unlikely to be affected by more than 1.0 dB and most likely much less than that. However, further evaluation of real aircraft data using more accurate techniques for assessing filter effects, including, among others, the spectrum iteration technique summarized herein, is needed before filter effect errors in EPNL values can be accurately defined.

5.2 Recommendations

Based on the preceding observations, the following recommendations are made:

5.2.1 A simple criteria, such as outlined in paragraph 5.1.6, should be developed or confirmed for incorporation in administrative rules for identifying when filter effects may be introducing substantial errors in aircraft noise certification data.

5.2.2 However, before restrictive procedures could be adopted in FAA regulations, a wider range of real aircraft spectral data should be evaluated with techniques designed to permit accurate assessment of the true measured spectrum and corresponding filter errors in normal spectrum analysis procedures. This should include, but not be limited to, the spectrum interation technique described herein.

5.2.3 Such evaluations should be designed to generate simple quantitative rules or algorithms for correcting EPNL values for filter effects. The spectrum iteration technique may be one such technique, but requires more complete and/or quantitatively independent validation before it can be adopted as a standard data analysis procedure.

REFERENCES

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APPENDIX A

Band Level Integration Method Employed in Wyle Method

The following method is used to compute and interpolate spectrum levels between values at the center of each of N bands analyzed. These spectrum levels, estimated from the measured band levels, are then used to compute these same band levels and the spectrum levels adjusted by an iterative process until the measured and computed band levels agree. This process requires knowledge of the spectrum level in the bands outside the nominal passband of each filter to account for energy passed by the finite filter skirts. Integration is normally carried out over ± 3 bands on either side of the i_{th} band. This is equivalent to treating the effective transmission bandwidth as extending one octave above and below the upper and lower filter band edge frequencies, respectively. Special procedures are used to handle the case of the end bands ($i=1$ or N) where there are not any identified band levels below the lowest band or above the highest band to use for interpolation. Once satisfactory estimates of "measured" spectrum levels are available, they can be translated to different ranges or to different weather conditions by accounting for changes in the absorption losses at all frequencies. The revised spectrum levels are then integrated again with the analytical model for either a real or ideal filter, as desired. The following paragraphs outline the analytical basis for a computer program summarized at the end of this appendix which allows such operations to be carried out interactively on a minicomputer terminal.

A.1 Initial Estimate of Spectrum Levels

N band levels are read into the computer program. By simple linear extrapolation of the initial and final slopes of the band spectrum, two additional band levels are estimated; one band below the lowest $L_{B(1)}$ band level measured and one above the highest band level $L_{B(N)}$ measured. The first estimate of spectrum levels $L_s(f)$, is given simply by the equation for the case of a white noise, or constant, spectrum level:

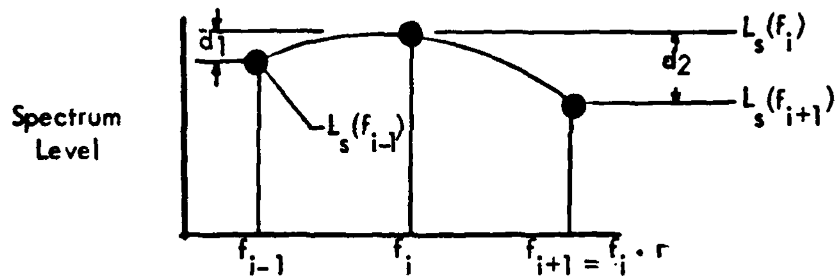
$$L_s(f_i) \simeq L_{B(i)} - 10 \log \Delta f \qquad (1)$$

where

Δf = Nominal filter bandwidth (log to the base 10 is assumed throughout this report except when otherwise noted).

A.2 Development of Refined Estimates of the Input Spectrum Levels

Referring to the sketch below, the differences d_1 and d_2 between the spectrum levels on each side of the i_{th} band are computed. For each i_{th} band, the two difference terms are then used to define an interpolation equation on the basis of the following model.



Over a frequency range $\pm$ one bandwidth either side of the i_{th} band center frequency f_i, the spectrum level is assumed to be defined by:

$$L_s(f) = L_s(f_i) + 10 \log (f/f_i)^{a_i + b_i(f/f_i)} \tag{2}$$

where

$L_s(f_i)$ = the spectrum level at f_i.

This interpolation equation simply lets the slope $(a_i + b_i(f/f_i))$ of the spectrum level curve vary linearly with the frequency ratio (f/f_i).

Thus, the constants a_i and b_i in Eq.(2) are derived by first using Eq.(2) to compute the spectrum levels at the center frequencies f_{i-1} and f_{i+1}. The latter are equal to f_i/r and $f_i \cdot r$, respectively, where *r is the ratio of the center* frequencies between adjacent bands ($=10^{0.1}$ for one-third octave bands). The difference terms d_1 and d_2, identified in the previous sketch, can then be expressed with the use of Eq.(2) as

$$d_1 = L_s(f_i) - L_s(f_{i-1}) = 10\,[a_i + b_i/r]\,\log r \tag{3a}$$

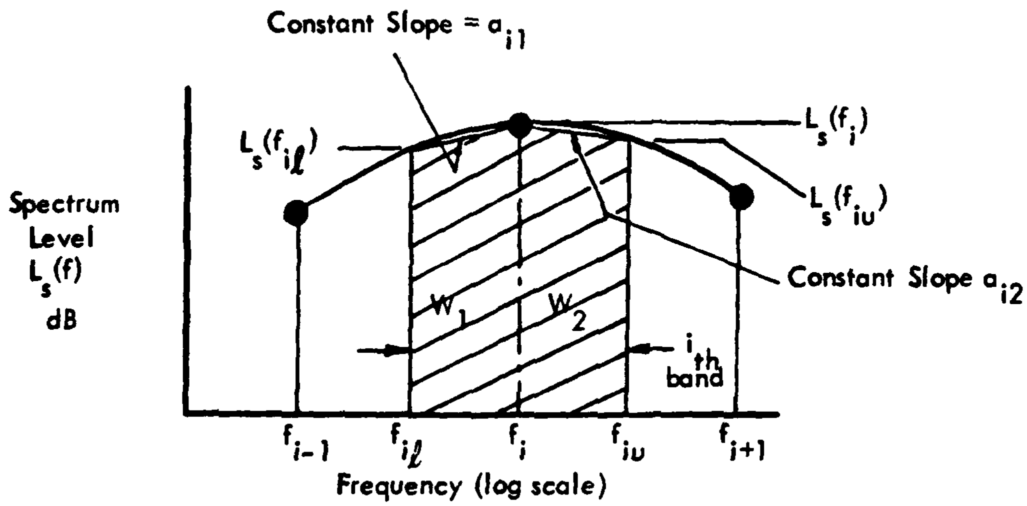
$$d_2 = L_s(f_{i+1}) - L_s(f_i) = 10\,[a_i + b_i \cdot r]\,\log r \tag{3b}$$

Solving these two equations for a_i and b_i, one obtains

$$a_i = (r^2 d_1 - d_2) / 10 (r^2 - 1) \log r \qquad (4a)$$

$$b_i = r (d_2 - d_1) / 10 (r^2 - 1) \log r \qquad (4b)$$

These interpolation constants are now used to obtain a first order improvement in the spectrum level $L_s(f_i)$ at the band center frequency. First, these constants are used again with Eq.(2) to define the spectrum levels at the lower and upper band edge frequencies of the i_{th} band (i.e., at the frequencies $f_{i\ell} = f_i/r^{1/2}$ and $f_{iu} = f_i r^{1/2}$, respectively) (see sketch).



The interpolation constants (a_1, b_1, and a_N, b_N) for the first and last measured bands (i=1 and N) are used to extrapolate the spectrum levels for the bands added at each end of the spectrum (i=0 and N+1). However, for the N+1 band, the constant b for the rate of change of spectrum slope is not allowed to be positive to prevent any turning up of the spectrum due to extrapolation from the N_{th} band with Eq.(2).

This first order improvement in estimated spectrum levels still assumes an ideal filter. It would be possible at this point to proceed directly to an integration of the power transmitted by a real filter over its full response bandwidth, including the filter skirts. However, this final refinement in the spectrum levels is reserved until later to take advantage of the large increase in estimation accuracy provided by the simpler procedure employed here which utilizes closed form solutions for the integrated band power.

Referring to the preceding sketch, the continuously varying spectrum level over the nominal filter bandwidth is now approximated by just two straight line segments, each with a constant slope, to define the spectrum level over only each half of the ideal filter bandwidth. (This differs from the two-slope procedure of Reference 2 which also defines the spectrum by two constant slope lines which, as described in Section 3.2 of the main body of the text, extend over twice this frequency range (i.e., between the band center frequencies instead of from only the band edges to the band center frequency).)

The corresponding spectrum level over each of these straight line segments is now defined by a simplified form of Eq.(2) obtained by setting b=0 to give

$$L_s(f) = L_s(f_i) + 10 \log (f/f_i)^{a_{ij}} \tag{5}$$

where j = 1 or 2, and a_{i1} and a_{i2} are the exponents which define the slopes of the two straight line segments.

From Eq.(3), setting 10 log r = 1 for $r = 10^{0.1}$, these two slope constants can be defined by:

$$\begin{aligned} a_{i1} &= a_i + b_i/r^{1/2} \\ a_{i2} &= a_i + b_i \cdot r^{1/2} \end{aligned} \tag{6}$$

Using each of these in Eq.(5), one at a time, and integrating over each half of the nominal bandwidth (i.e., from $f_{i\ell}$ to f_i with the slope a_{i1} and from f_i to $f_{i\ell\ell}$ with the slope a_{i2}), an estimate is obtained of the total power passed by the nominal ideal filter as

$$L_{BI} = 10 \log \left[W_1 + W_2 \right], \text{ dB} \tag{7}$$

W_1 and W_2 are the powers in each part of the i_{th} band given by

$$W_j = 10^{L_s(f_i)/10} f_i(-1)^j \left[r^{(-1)^j (a_{ij}+1)/2} - 1 \right] \Big/ (a_{ij}+1) \tag{8a}$$

and j = 1 or 2 for the two halves of the nominal filter bandwidth.

For the case of $a_{ij} = -1$, the expression for W_j is

$$W_j = 10^{L_s(f_i)/10} f_i \ln_e r^{1/2} \tag{8b}$$

Reviewing Eqs.(7), (6), and (4), it is now clear that one can estimate the total power passed by the i_{th} ideal filter band $L_{BI(i)}$ in terms of just three quantities, the spectral density $L_s(f_i)$ at the center of the i_{th} band and the differences d_1 and d_2 *in the spectrum levels between the adjacent bands*. But this process can obviously be reversed to solve not for the band levels (which are already known), but for the spectrum levels.

The resulting expression for this refined estimate of the spectrum level $L_s(f_i)$ at the center of the i_{th} band is

$$L_s(f_i) = L_{B(i)} - 10 \log (\Delta f_i) - \Delta_S \tag{9}$$

where

Δf_i = the nominal bandwidth of the ideal filter, and

Δ_S = the spectrum slope error - the difference between the band power assuming a *white noise (constant) spectrum* level over the ideal filter bandwidth and the band power based on the refined two-slope estimate described by Eq.(7).

Combining Eqs.(4), (6) and (7), it can be shown that Δ_S, in this case, is equal to

$$\Delta_S = 10 \log \left[(0_1 + 0_2)\, r^{1/2}/(r-1) \right] \tag{10}$$

where

$$0_1 = \left[1 - r^{-(a_{i1}+1)/2} \right] \Big/ (a_{i1}+1) , \qquad a_{i1} \neq -1$$

$$0_2 = \left[r^{(a_{i2}+1)/2} - 1 \right] \Big/ (a_{i2}+1) , \qquad a_{i2} \neq -1$$

0_1 or 0_2 = $\ln_e r^{1/2}$ if a_{i1} or $a_{i2} = -1$

and a_{i1} and a_{i2} can be determined with the use of Eq.(6) and Eq.(4).

Thus, Eqs.(9) and (10) provide a good first-order refinement to an estimate of the spectrum level $L_s(f_i)$ at the center of each i_{th} band.

A second order refinement has also been found to be useful. This is carried out simply by returning to Eq.(3) to define a new set of spectrum level difference terms d_1 and d_2 based on the first refinement in estimated spectrum levels. That is, the combination of processes from Eq.(3) through Eq.(9) is repeated a second time to define a new set of estimated spectrum levels over all bands based on Eq.(2).

A.3 Iteration Process

For the second Wyle method (W2), a final refinement to the estimated spectrum levels is now carried out. The spectrum levels are integrated over the effective response bandwidth of each filter to provide a computed value for the measured band levels. This process now recognizes the potential transmission outside the nominal filter passband. The computed and measured band levels at the i_{th} band are compared and the preceding estimates of the spectrum levels $L_s(f_i)$ at the band center frequency adjusted as necessary by any resulting difference in the computed and measured band levels. In other words, the new estimated spectrum levels $L'_s(f_i)$ at the band center frequency are defined by

$$L'_s(f_i) = L_s(f_i) - c\left[(L_{B(i)}(\text{computed}) - L_{B(i)}(\text{measured})\right] \qquad (11)$$

where

$L_s(f_i)$ = the spectrum levels previously estimated according to Section A.2, and

c = a computational stability "damping" constant (a value of c from 0.8 to 1.6 has been found to be satisfactory).

The interpolation process defined in Section A.2 is then repeated with these new spectrum levels at the band center frequencies and new estimates of the measured band levels are obtained. The process is repeated until satisfactory agreement is obtained between the measured and computed band levels. Subsequent iterations after the first no longer assume an ideal filter unless specified in the input. Satisfactory agreement in this case has been taken as no difference greater than 0.05 dB in any band. From one to six iterations were found to be necessary and sufficient for a wide range of real aircraft spectra as reported in Reference 1.

This final set of spectrum levels at the band center frequencies and the corresponding set of interpolation constants a_i and b_i for each i_{th} band provide the basis for predicting the effect of changes in band levels with changes in propagation distance and/or air absorption (i.e., different weather). The corresponding adjusted spectrum levels can then be integrated to predict new adjusted band levels using either real or ideal filters as desired for the new conditions. Filter effects are thus implicitly accounted for throughout the process to the extent that the filter response approximations and spectrum interpolation functions are accurate.

These final estimates of spectrum level are now used to carry out the basic integration process for band levels. The details of this band integration process, briefly summarized in Section 3.3 of the main body of this report, are defined more thoroughly as follows:

- o Each nominal filter bandwidth is first divided into six constant percentage segments 1/18th octave wide.
- o The spectrum interpolation function given by Eq.(2) is used to define the spectrum levels at the lower and upper band edge frequencies of these integration segments. The spectrum level between these two closely-spaced frequencies is assumed to vary linearly with a constant slope.
- o The power δW contained within this trapezoidal element can be defined in closed form by

$$\delta W = 10^{L_s(f_j)/10} \cdot f_j \left[k^{(a_j+1)} - 1 \right] \Big/ (a_j+1) \qquad (12)$$

where

$L_s(f_j)$ is the spectrum level at the lower band edge frequency f_j of this j_{th} segment (within the i_{th} filter band).

k = $10^{1/60}$, the frequency ratio of the segment's 1/18th octave-wide frequency limits,

and a_j = the constant spectrum slope derived from the difference d_j in spectrum level between these segment frequency limits. This difference is derived, in turn, from the spectrum interpolation Eq.(2), first for $f = f_j$ and then for $f = f_j \cdot k$.

- The total power passed by each filter is then determined by summing the power in the elemental segments over whatever total bandwidth is desired – the effective transmission bandwidth of a real filter, or the nominal bandwidth of an ideal filter.

- For real filters, the following special rules were required to provide practical limits for the frequency range of integration:

  - Only one band was included above each nominal band to accurately account for energy passed by the filter skirts above the upper nominal cutoff frequency for normal aircraft spectra.

  - Normally the integration is carried out over three additional bands (i.e., one octave) below the lower nominal cutoff frequency. (Band levels above 5,000 Hz were 2 to 13 dB lower when only two bands were added below the lower band edge.) In contrast, the Dytec method extends integration down to one-tenth of the band center frequency for real filters.

  - For the lowest two measured bands (i=1 and 2), the integration over the full filter response is necessarily truncated at the bottom edge of the one additional band level (i=0) added to the measured band level by slope extrapolation, at the beginning of the spectrum iteration scheme.

  - This process involves a series of logical selections of which set of interpolation constants (a_i, b_i) to use for the integration of spectrum levels for each band. The details of this complex process are implicit in the computer program described at the end of this appendix.

- The spectrum levels employed throughout the rest of the computations for one set of measured band levels are the values estimated from this spectrum iteration procedure and modified, where appropriate, by any change due to different propagation conditions (i.e., weather or distance) or by filter transmission losses. The net result is that filter effects are inherently accounted for in the data processing.

A.4 Computer Program

A simplified flowchart describing the principal computational steps in this spectrum interpolation and iteration program is contained in Figure A-1. An example input data listing, interactive input instructions and pertinent system responses, and corresponding output tables computed by the program are provided in Table A.1. The program is designed to allow convenient analytical evaluation of filter effects using the second (iteration) version of the Wyle method and provides tables of band levels in the following sequence, if requested.

1. Receiver Band Levels for test day weather conditions up to seven distances plus an echo of the "measured" input band levels. If the measurement distance is also included in the output as one of the receiver distances, the computed values of these measured input levels are also provided. The "measurement" filter may be selected as real or ideal.

2. The same data but with receiver levels computed according to the SAE procedure. (Simulated using ANSI S1.26 algorithms for absorption at each frequency.)

3. The same data as in 2. but for standard day conditions as requested.

4. The same data as in 1. but for standard day conditions and, if desired, a different model for the "measurement" filter.

A summary of other pertinent input data is also listed at the bottom of each table as appropriate.

Clearly, many variations of this type of program are possible. However, this program has proven to be a robust and useful procedure able to provide insight into filter effects in the analysis of aircraft noise levels. While the interactive program described here was designed for experimental rather than production evaluation of filter effects, a streamlined production program version has also been developed for analysis of full aircraft spectra.

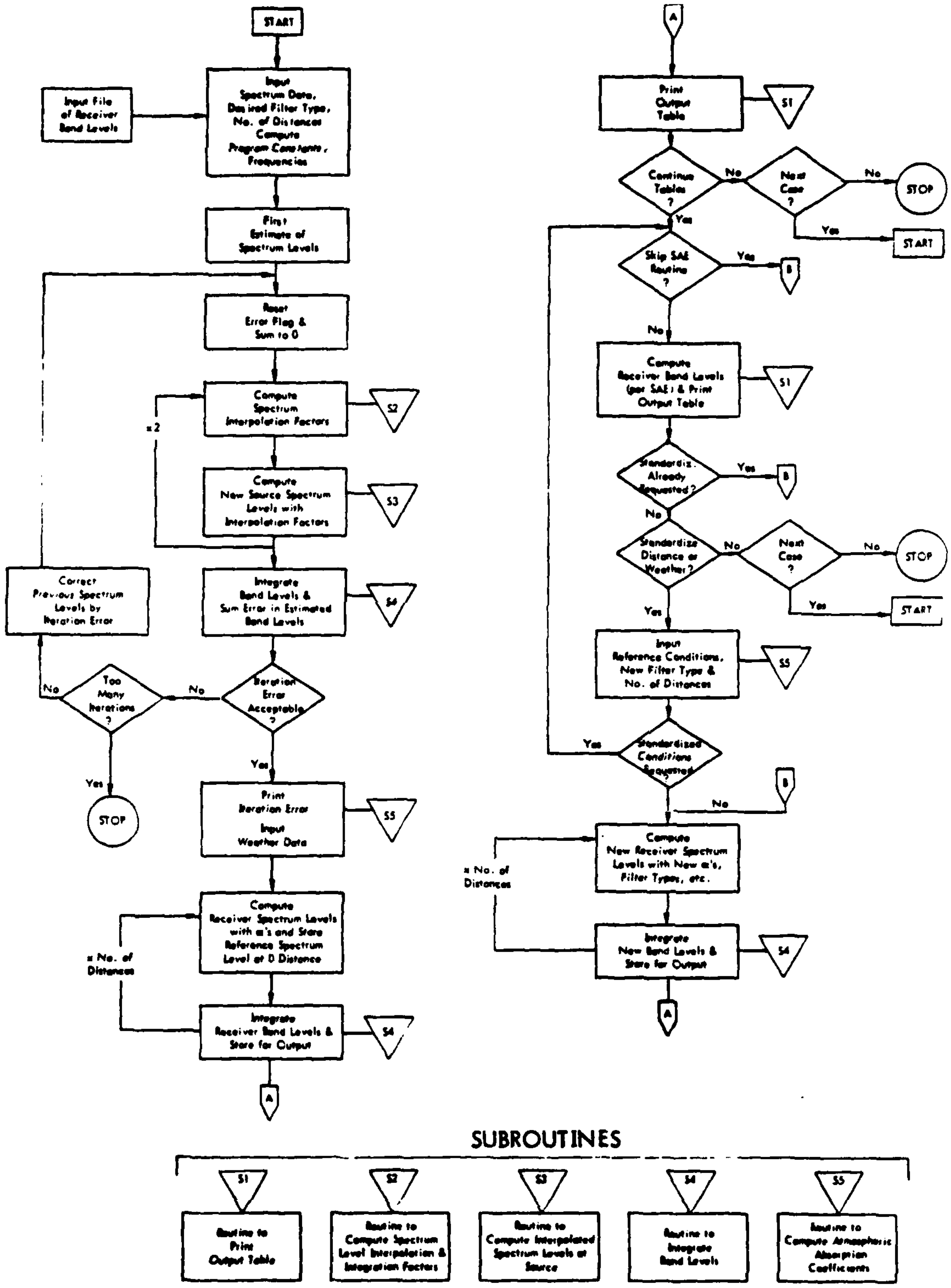


Figure A-1. Simplified Flow Diagram of Program "BAND8" for Evaluation of One-Third Octave Band Levels at a Receiver and Correcting These Levels to Standard Day Conditions with Filter Effects Inherently Accounted For

a) Data File

```
TYPE SY1:88TEST.DAT
300,11,85.95,85.83,84.35,82.78,82.9,91.68,81.33,67.47,62.21,48.35,32.72
```

b) Program Operation

```
READY
RUN


BAND8    28-NOV-81  17:15:25

FILE? SY1:88TEST.DAT
NO. OF DISTANCES? 7
NO. OF BANDS INTEGRATED (ODD NO)? 7
NO OF SEGMENTS/BAND (MULTIPLE OF 6)? 6
LAST CASE NO? 0
 5  ITERATIONS FOR SOURCE BAND LEVELS,  RMS ERROR =  0.0200 dB

 TEMP-DEG C, REL. HUMID-%? 15,35
                                    ---> Table (Case 1) Printed

PRINT BAND LVLS BASED ON ATTEN @ CNTR FREQ? Y
                                    ---> Table (Case 2) Printed

STANDARD WEATHER AND SOURCE DISTANCE ? Y
NEW SOURCE DIST. & NO. OF BANDS INTEGRATED? 300,7
HOW MANY NEW RECEIVER DISTANCES? 7
NEW TEMP.(DEG C) AND HUMIDITY(%)? 25,70
PRINT BAND LVLS BASED ON ATTEN @ CNTR FREQ? Y
                                    ---> Table (Case 3) Printed
                                    ---> Table (Case 4) Printed
TYPE 0 FOR STOP,1 FOR NEW FILE OR 2 FOR NEW REF. COND? 0

STOP at line 2420
```

Table A-1. Sample of Input Instructions for BAND 8 Program to Produce the Data on the Following Tables

c) Case 1

1/3RD OCTAVE BAND LEVELS - DB
(ANSI CLASS III ONE THIRD OCTAVE BAND FILTER)

FREQ	A(F)*	DISTANCE, M							
HZ	-	300	0	300(1)	600	900	1200	1500	1800
1000	0.48	85.95	87.32	85.88	84.44	83.01	81.58	80.16	78.74
1250	0.66	85.83	87.80	85.82	83.86	81.91	79.96	78.03	76.11
1600	0.94	84.35	87.15	84.34	81.57	78.82	76.10	73.40	70.73
2000	1.37	82.78	86.89	82.78	78.74	74.76	70.84	66.97	63.16
2500	2.06	82.90	90.09	82.93	76.10	69.60	63.40	57.49	51.86
3150	3.13	91.68	101.24	91.71	82.38	73.26	64.32	55.55	46.98
4000	4.77	81.33	93.69	81.36	69.69	58.54	47.87	37.67	28.05
5000	7.24	67.47	88.14	67.49	51.43	39.48	29.38	20.04	11.22
6300	10.90	62.21	94.16	62.25	38.60	27.33	17.71	8.41	-0.65
8000	16.11	48.35	92.25	48.34	19.73	5.76	-6.87	-19.24	-31.45
10000	23.17	32.72	99.78	32.73	-0.17	-21.61	-41.00	-59.80	-78.33

28-NOV-81 17:26:27 Case No. 1

SY1:88TEST.DAT FILE, 15 DEG C, 35 % RH, 1 ATM, 6 SEG/BAND OVER 7 BANDS
RO= 300 ,C1= 1.6 ,D5= .05 dB,F3= 1 dB/OCT., 5 ITERATIONS,RMS ERROR= 0.020 dB
* SINGLE FREQ. ATTEN. COEFFICIENT - DB/100M

(1) This column represents the computed band levels based on iteration of the input spectrum levels, to achieve a match, within an error (D5) of less than 0.05 dB, with the actual input levels given in column 3. The exception is the first band at 1,000 Hz where the error was 0.07 dB. For this band, iteration was omitted since the band level slope was less than the criteria (F3) of 1 dB per octave.

d) Case 2

PRINT BAND LVLS BASED ON ATTEN @ CNTR FREQ? Y

1/3RD OCTAVE BAND LEVELS - DB
(BASED ON SIMULATION OF SAE 866A PROCEDURE)

FREQ	A(F)*		DISTANCE, M						
HZ	-	300	0	300	600	900	1200	1500	1800
1000	0.48	85.95	87.38	85.95	84.52	83.09	81.67	80.24	78.81
1250	0.66	85.83	87.80	85.83	83.86	81.90	79.93	77.97	76.00
1600	0.94	84.35	87.16	84.35	81.54	78.74	75.93	73.12	70.32
2000	1.37	82.78	86.90	82.78	78.66	74.53	70.41	66.29	62.16
2500	2.06	82.90	89.08	82.90	76.72	70.54	64.35	58.17	51.99
3150	3.13	91.68	101.06	91.68	82.30	72.92	63.54	54.16	44.78
4000	4.77	81.33	95.63	81.33	67.03	52.73	38.44	24.14	9.84
5000	5.88	67.47	85.11	67.47	49.83	32.19	14.54	-3.10	-20.74
6300	8.90	62.21	88.92	62.21	35.50	8.79	-17.91	-44.62	-71.33
8000	13.29	48.35	88.22	48.35	8.48	-31.39	-71.26	-111.13	-151.00
10000	19.40	32.72	90.91	32.72	-25.47	-83.66	-141.84	-200.03	-258.22

28-NOV-81 17:27:01 Case No. 2

SY1:88TEST.DAT FILE, 15 DEG C, 35 % RH, 1 ATM

-

e) Case 3

BAND LEVELS CORRECTED TO STANDARD CONDITIONS
1/3RD OCTAVE BAND LEVELS - DB
(BASED ON SIMULATION OF SAE 866A PROCEDURE)

FREQ	A(F)*	DISTANCE, M							
HZ	-	300	0	300	600	900	1200	1500	1800
1000	0.65	85.42	87.38	85.42	83.46	81.50	79.54	77.58	75.62
1250	0.80	85.40	87.80	85.40	83.01	80.61	78.22	75.83	73.43
1600	0.96	84.29	87.16	84.29	81.43	78.56	75.69	72.83	69.96
2000	1.14	83.48	86.90	83.48	80.06	76.64	73.22	69.80	66.38
2500	1.38	84.94	89.08	84.94	80.79	76.64	72.50	68.35	64.20
3150	1.73	95.88	101.06	95.88	90.70	85.52	80.33	75.15	69.97
4000	2.25	88.89	95.63	88.89	82.15	75.41	68.67	61.93	55.19
5000	2.60	77.30	85.11	77.30	69.49	61.68	53.86	46.05	38.24
6300	3.61	78.09	88.92	78.09	67.27	56.44	45.61	34.79	23.96
8000	5.19	72.66	88.22	72.66	57.10	41.55	25.99	10.43	-5.12
10000	7.67	67.91	90.91	67.91	44.92	21.92	-1.08	-24.07	-47.07

28-NOV-81 17:28:21 Case No. 3

SY1:88TEST.DAT FILE, 25 DEG C, 70 % RH, 1 ATM

f) Case 4

BAND LEVELS CORRECTED TO STANDARD CONDITIONS
1/3RD OCTAVE BAND LEVELS - DB
(ANSI CLASS III ONE THIRD OCTAVE BAND FILTER)

FREQ	A(F)*				DISTANCE, M				
HZ	-	300	0	300	600	900	1200	1500	1800
1000	0.65	85.36	87.32	85.36	83.40	81.44	79.49	77.54	75.60
1250	0.80	85.41	87.80	85.41	83.02	80.64	78.26	75.89	73.52
1600	0.96	84.29	87.15	84.29	81.44	78.59	75.75	72.92	70.09
2000	1.14	83.47	86.89	83.47	80.07	76.67	73.28	69.90	66.54
2500	1.38	85.59	90.09	85.59	81.12	76.69	72.30	67.95	63.63
3150	1.73	95.99	101.24	95.99	90.76	85.55	80.36	75.19	70.05
4000	2.25	87.49	93.69	87.49	81.37	75.32	69.34	63.42	57.56
5000	3.05	78.89	88.14	78.89	70.06	61.68	53.77	46.37	39.48
6300	4.31	81.12	94.16	81.12	68.47	56.26	44.74	34.59	26.51
8000	6.29	73.86	92.25	73.86	57.05	41.53	27.58	16.26	7.75
10000	9.39	69.87	99.78	69.87	43.99	23.76	9.77	-1.62	-11.82

28-NOV-81 17:32:43 Case No. 4

SY1:88TEST.DAT FILE, 25 DEG C, 70 % RH, 1 ATM, 6 SEG/BAND OVER 7 BANDS

ATE

LME