



AEROSPACE RECOMMENDED PRACTICE

ARP876™**REV. F**

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Superseding ARP876E

Gas Turbine Jet Exhaust Noise Prediction

RATIONALE

Revision F corrects an error in Equation 9 for the single stream shock-associated noise prediction method, and corrects an error in Table 14 for the mixed component Z4 term of the subsonic coaxial jet mixing noise prediction method.

FOREWORD

AIR876, issued on 7 October 1965, presented a summary correlation of jet engine exhaust noise data available at that time. It dealt with both static and flight modes but, by virtue of the data largely being from full scale engines, no attempt was made to subdivide the information into the relevant component noise sources. Subsequently, work on high-quality noise facilities has established that most engine exhaust systems are influenced in their noise characteristics by far more than the noise due to the external mixing process alone, and this work has provided the opportunity to develop a clearer picture of the influence of other effects.

AIR876 was also limited to jet velocities above 1000 feet/second (300 m/s), i.e., the range of exhaust velocities associated with early jet engines. The introduction of more advanced engine designs demands a prediction technique for exhaust sources over a far wider range of velocity conditions.

Therefore, it is intended that ARP876 be developed on a long-term basis as a document definitive in most aspects of the prediction of exhaust noise, consistent with the state of the art. Specific recommended procedures will be issued as sections, both for completeness and to allow for future updating. Additionally, following a decision in 1979, explanatory background material detailing the rationale behind the selection of methods will be included in separate appendices to this document.

The document will offer a method of estimating the exhaust noise from single unsuppressed engines. To be useful in estimating the noise from aircraft installations, a number of additional effects must be considered, and it is intended that these also will be covered as substantive evidence becomes available.

Areas that will not be addressed in this ARP, due to source variability with detailed engine design parameters, are aerodynamic blade noise sources; that is, noise generated by interaction effects between rotating and stationary components of the fan, compressor and turbine systems.

Each section will be dated, and will represent an approach to a particular topic as agreed by members of the SAE A-21 Propulsion Noise Subcommittee who have experience or data on that subject. Lists of members and affiliated bodies contributing experimental data or other information used in compiling any one section will be included. Correspondence should be addressed to the SAE for the attention of the A-21 Committee and appropriate distribution.

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1. SCOPE

ARP876 is intended to provide specific recommended procedures for the prediction of gas turbine jet exhaust system noise sources. Procedures are issued as separate sections, to allow for future updating as additional methods, consistent with state-of-the-art, become available.

2. SOURCES OF EXHAUST NOISE

The exhaust system noise of gas turbine engines for aircraft applications can be considered to comprise the following main sources:

- a. Pure jet mixing noise resulting from a hot core exhaust stream mixing with its surrounding environment (which may be influenced by a bypass flow)
- b. Pure jet mixing noise resulting from a cold bypass stream mixing with both the surrounding environment and the core flow
- c. Shock associated noise, where either or both hot and cold exhaust systems comprise a choked final nozzle
- d. Noise from the core engine resulting from aerodynamic disturbances upstream of or at the final nozzle, including combustion noise.
- e. Aerodynamic noise, tonal and broadband, resulting from blade interaction effects in fan, compressor or turbine systems

All the above sources combine in varying degrees to produce the overall exhaust noise characteristics. The relevance of each source is a function of both engine operating condition and aircraft speed. Because of the dependence of aerodynamic blading noise on the intimate design configuration of any given engine, this aspect is specifically excluded from subsequent consideration, and every attempt has been made to remove such phenomena from any engine data used.

3. NOTES ON USE OF PREDICTION PROCEDURES

- 3.1 Prediction methods included in this document are self-contained. To develop an estimate of the total exhaust noise signature from an engine it is necessary to integrate the individual source components.

This is effected by estimating each component spectrum and summing the energy in each one-third octave band. This is usually most conveniently carried out prior to any extrapolation to the relevant distance or corrections for atmospheric conditions and ground reflection effects. It is also necessary to incorporate any estimated turbo-machinery content (not covered herein) at the initial stage, in order to obtain a complete spectrum of engine noise. Furthermore, it is advisable that any assumed modification to the noise by virtue of suppression features or installation effects is made in the component calculation state.

- 3.2 Methods contained in this document are expressed in terms of noise levels that would be measured under free field conditions. Reflective augmentations and cancellations from real surfaces, primarily the ground surface over which measurements are made, produce peaks and troughs in the observed test spectra, and these have been corrected out of the experimental data used where they have not been obtained under anechoic conditions.

Spectra and directivity plots in this document must, therefore, be converted to non-free-field conditions to make them representative of typical measurements "in the field". SAE AIR1327 provides guidance on such conversion for an acoustically hard surface (i.e., concrete, tarmac) and advice on how to deal with other typical surfaces (e.g., grassland).

- 3.3 The prediction methods provide spectral information derived from measurements taken in the acoustic far field, but corrected for loss due to atmospheric attenuation and normalized for distance.

Since practical distances involved in aircraft noise calculations are large, apart from the normal inverse square law correction, allowance must be made for atmospheric absorption. SAE ARP866A provides a standard method of allowing for atmospheric absorption under a range of ambient temperature and humidity conditions.

- 3.4 Prediction methods are directed at producing estimates of noise levels generated during the normal take-off and approach regimes of aircraft operation. Extrapolation of the methods to higher flight speeds, or use for estimation other than in the acoustic farfield, is not recommended since experimental evidence in support of such extrapolation was not available at the time of preparation of this document.

4. SYMBOLS

a_o	Ambient speed of sound	m/s
A	Cross-sectional area of jet exhaust nozzle (with subscripts to define nozzle referred to)	m^2
C_v	Velocity coefficient for relevant discharge nozzle	
DI	Farfield directivity index	dB
D	Exhaust nozzle diameter (with subscripts)	m
EXA	(distance from fan face to fan duct exit)/(fan diameter)	
f	Frequency	Hz
g	Gravitational constant; 9.80665	m/s^2
ISA	International Standard Atmosphere	
L	Sound pressure level	dB
$m(\theta_1)$	Relative Velocity exponent used in converting static mixing noise to flight conditions	
M	Jet Mach number V_j/a_o	
M_a	Aircraft flight Mach number (V_a/a_o)	
n	Jet velocity exponent	
N	Rotational speed (with subscripts)	rpm
NPR	Nozzle pressure ratio (P_j/P_o)	
$OAPWL$	Overall sound power level (re 1 pW)	dB
$OASPL$	Overall sound pressure level (re 20 μPa)	dB
p	Sound pressure	Pa

p_o	Ambient static pressure	Pa
p_{ISA}	Static pressure under ISA, sea level conditions	Pa
p_{ref}	Acoustic reference sound pressure, 20 μ Pa	Pa
P	Total pressure	Pa
P_o	Ambient-total pressure	Pa
P_{ISA}	Total pressure under ISA, sea level conditions	PA
PWL	One-third octave-band sound power level (re 1 pW)	dB
r	Radial distance from sound source (or nozzle exit) to observer	m
R	Gas constant with value 287.05 J.kg ⁻¹ K ⁻¹ based on the universal gas constant of 8.31432 x 10 ³ J/[K(kg-mol)] and mass per kilogram-mole in dry air of 28.9644 kg/(kg-mol)	J.kg ⁻¹ K ⁻¹
Sr	Strouhal number	
S	Normalized free-field Overall Sound Pressure Level	dB
$S(f)$	Power level spectrum shape factor	dB
SPL	One-third octave-band sound pressure level (re 20 μ Pa)	dB
t	Static temperature	K
t_o	Ambient static temperature	K
T	Total temperature	K
T_o	Ambient total temperature	K
T_j	Jet total temperature	K
V_a	Forward speed of engine (i.e., airplane)	m/s
V	Fully expanded jet velocity (with subscripts)	m/s
W	Massflow rate	kg/s
x	Number of shocks in supercritical jet	
X	Noise source location downstream of primary nozzle exit	m
β	Jet pressure ratio parameter	
γ	Ratio of specific heats for propulsion medium	

θ	Angle to nozzle axis (with subscript i inlet, j jet)	degrees (except where stated)
λ	Wavelength	m
ξ	Strouhal frequency adjustment factor	
π_{ref}	Acoustic reference power, 1 pW	Watt
ρ	Density	kg/m ³
ρ_{ISA}	Atmospheric density under ISA conditions (1.225 kg/m ³ based on atmospheric pressure of 1.01325×10^5 Pa at an air temperature of 288.15 K)	kg/m ³
ρ_j	Fully expanded jet density	kg/m ³
ϕ	Angle between direction of aircraft motion and direction of sound propagation	degrees
ψ	Angle between airplane flight path and engine thrust axis	degrees
ω	Variable density index used in computing OASPL from jet mixing noise	

Subscripts:

i	intake
j	jet (general)
a or o	ambient
p	primary jet
s	secondary jet
m	mixed jet
std	standard (e.g., sea level, ISA)

NOTE: The units quoted for the physical quantities are the recommended Systeme Internationale units. Except for the logarithmic quantities, temperatures and angles, any other consistent system of units may be used since results are expressed as dimensionless ratios.

5. PREDICTION OF SINGLE STREAM JET MIXING NOISE FROM SHOCK-FREE CIRCULAR NOZZLES

DATE OF COMPILATION

Static Conditions - September 1976

Flight Conditions - November 1978

5.1 Static Conditions

Definitive model scale experimental work in the 1970s provided a firm data base for the study of mixing noise over a wide range of jet velocity and temperature conditions. That work showed that jet mixing noise level and spectral character is a function of the following principal parameters:

- a. The velocity differential between that of the jet and its environment
- b. The jet density relative to the density of the surrounding air
- c. The jet dimensions

It has been concluded that one of the most convenient ways to express jet noise characteristics is to consider first the normalized overall sound pressure level (OASPL) as a function of jet velocity (V_j) and angle of measurement (θ_i or θ_j) and to then relate the spectrum (on a one-third octave-band basis) to the overall level at any point in the field. This procedure may be adopted by using Figures 2 through 12. The information in Figures 2 through 12 is also presented in Tables 1 through 11.

The method of calculation is as follows:

Step 1—Calculate the fully expanded mean jet velocity (V_j) from a knowledge of jet temperature and pressure, where:

$$V_j = C_v \left\{ \left[(2\gamma Rg) / (\gamma - 1) \right] [T_j] \left[1 - NPR^{-(\gamma-1)/\gamma} \right] \right\}^{1/2} \quad (\text{Eq. 1})$$

or, where a knowledge of temperature and pressure is not readily available (for example, from engine test stand measurements) an alternative method of calculating V_j is from thrust and mass flow, where:

$$V_j = \text{static gross thrust divided by mass flow}$$

Step 2—Using V_j obtained from Step 1 and the ambient speed of sound (a_o) obtain the variable density index (ω) from Figure 2.

Step 3—For any desired angle and jet velocity use Figure 3 to obtain the normalized free-field overall sound pressure level (S) where:

$$S = OASPL - 10 \log_{10} \left\{ \left[(\rho_j / \rho_o)^\omega \right] (A_j / r^2) \right\} - 20 \log_{10} (P_o / P_{ISA}) \quad (\text{Eq. 2})$$

for the value of V_j at any desired angle.

Step 4—Calculate the overall sound pressure level (OASPL) from:

$$OASPL = S + 10 \log_{10} (\rho_j / \rho_o)^\omega + 10 \log_{10} (A_j / r^2) + 20 \log_{10} (P_o / P_{ISA})$$

Step 5—Calculate the one-third octave-band spectral levels from Figures 5 to 12, using jet velocity (V_j), temperature ratio (T_j/T_o), nozzle diameter (D_j) and the angle (θ_i) as follows:

Determine the Strouhal frequency adjustment factor ξ from Figure 4 and then calculate $(fD_j/\xi V_j)$ for each one-third octave-band centre frequency. Enter Figures 5 to 12 with the values of $(fD_j/\xi V_j)$, and values of (T_j/T_o) at the values of $\log_{10} (V_j/a_o)$ and θ_i to determine values of one-third octave-band relative sound pressure level (SPL - OASPL).

For values other than those specified in Figures 4 to 12, linear interpolation on angles (θ_i), and on the values for $\log_{10}(fD_j/\xi V_j)$, $\log_{10}(V_j/a_o)$ and (T_j/T_o) is recommended.

Step 6—From the values of OASPL and one-third octave-band relative sound pressure level (SPL - OASPL) as derived in steps 4 and 5, respectively, calculate values of one-third octave-band SPL.

These values represent the free-field jet noise spectrum at position (r, θ_i) in a loss free atmosphere.

NOTE 1: The spectra of Figures 4 to 12 satisfy the following condition:

$$\log_{10} \left[\sum_{i=1}^{33} 10^{0.1(SPL_i - OASPL)} \right] = 0 \quad (\text{Eq. 3})$$

over the range of one-third octave-band frequencies defined by:

$$-1.6 \leq \log_{10} (fD_j / \xi V_j) \leq 1.6 \quad (\text{Eq. 4})$$

NOTE 2: Accuracy of Prediction

The accuracy of prediction of OASPL at (r, θ_i) relative to the model data on which it is based varies between ± 2 dB at low jet velocities to ± 4 dB at very high jet velocities. The accuracy of prediction of one-third octave (SPL - OASPL) varies between ± 1 dB at frequencies near the peak of the jet-noise spectrum. However, these limits apply to the extreme cases. For all normal purposes, the majority of predictions will be accurate within ± 3 dB at all frequencies.

5.2 Flight Condition

Forward speed has the effect of reducing the shear between the jet and its environment. Work in the 1970s produced conflicting evidence on the change in jet mixing noise in going from static to flight conditions. Model scale wind tunnel testing has, in general, produced a greater reduction in level than tests carried out on ground based engine facilities and aircraft. The differences may be associated with contamination by other sources, both engine based and aircraft installation induced. The method herein is based upon data obtained on a ground based engine flight simulation facility. In general, the results of applying the prediction method fall between the extremes represented by some model tests and some aircraft flight tests.

The method relies upon a modification of the static sound pressure levels obtained in 5.1.

For a jet of given velocity V_j (corresponding to a given nozzle pressure ratio and temperature), moving at a flight speed V_a , the method of calculation is as follows:

Step 1—Calculate the free field static overall sound pressure levels (OASPL) as a function of angle to inlet axis, as outlined in steps 1 to 4 of 5.1, corresponding to the exhaust conditions.

Step 2—Calculate the OASPL in flight at any desired angle θ_i ($20 \text{ degrees} \leq \theta_i \leq 160 \text{ degrees}$):

$$[OASPL(\theta_i)]_{flight} = [OASPL(\theta_i)]_{static} - \Delta OASPL(\theta_i) \quad (\text{Eq. 5})$$

where:

$$\Delta OASPL(\theta_i) = 10 \log_{10} \left\{ \left(\frac{V_j}{V_j - V_a} \right)^{m(\theta_i)} (1 - M_a \cos \phi) \right\},$$

with:

$m(\theta_i)$ = relative velocity exponent $m(\theta_i)$, a function of angle θ_i between the engine inlet axis and the line connecting an aircraft reference point and the observer location, shown in sketch, is given in Figure 13 and Table 12

$M_a = V_a/a_o$ = aircraft flight Mach number or ratio of airspeed V_a to speed of sound a_o at the ambient temperature of the surrounding medium

ϕ = angle between direction of aircraft motion and direction of sound propagation (see Figure 1)

V_j = fully expanded jet velocity, corresponding to a given pressure ratio and total temperature of the jet and being the same in static and in flight (see Equation 1)

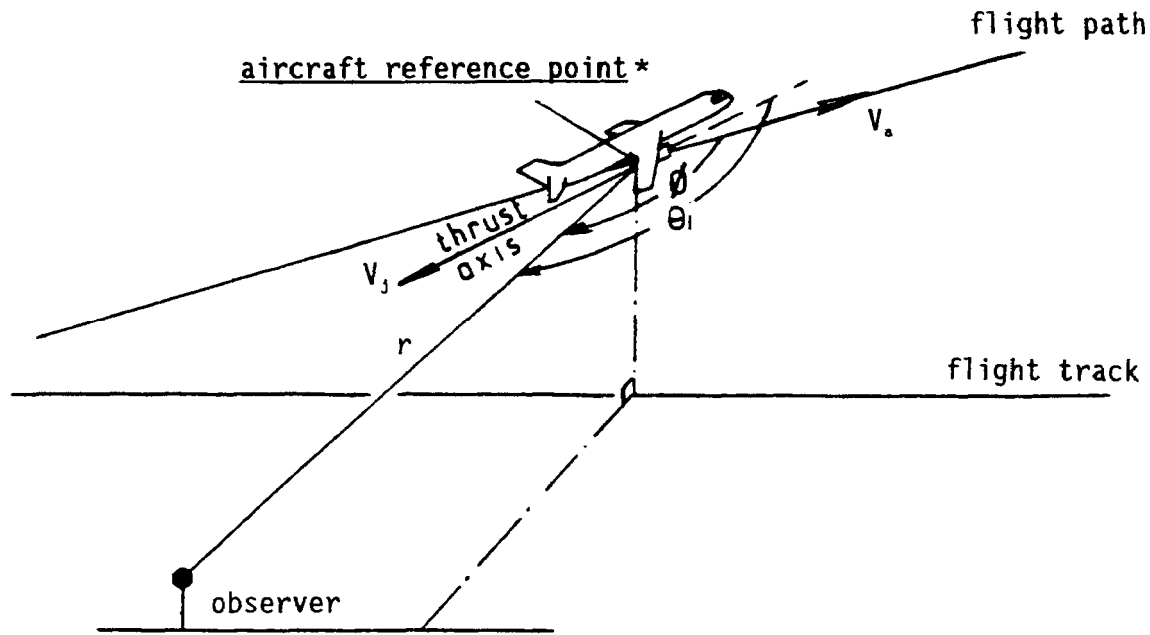


FIGURE 1

NOTE: For consistency with the prediction procedure under static conditions, the aircraft reference point * should be the center of the nozzle exit. For practical applications (aircraft noise predictions) alternative reference points may have to be selected (e.g., center of the engine nacelle, or centroid of the nozzle exits for airplanes powered by more than one engine, etc.)

Step 3—Calculate the one-third octave-band sound pressure levels in flight for any desired angle θ_i , following steps 5 and 6 of 5.1, with the exception that now the OASPL is the value in flight as derived in step 2 of this section and that the Strouhal number:

$$(fD_j / \xi V_j) \quad (\text{Eq. 6})$$

has to be replaced by one based on relative jet velocity $(V_j - V_a)$, that is:

$$[fD_j / \xi (V_j - V_a)] \quad (\text{Eq. 7})$$

The value of ξ is still obtained from Figure 4 for the corresponding value of the jet velocity V_j .

NOTE: Accuracy of Prediction

The accuracy of $\Delta OASPL(\theta_i)$ prediction, as calculated in step 2 for any angle θ_i , is a function of velocity ratio, and may be obtained from the following formula:

$$\pm \delta[\Delta OASPL(\theta_i)] = \pm [\delta m(\theta_i)] \times \left\{ 10 \log_{10} \left[V_j / (V_j - V_a) \right] \right\} \quad (\text{Eq. 8})$$

$\delta m(\theta_i)$ being the uncertainty in $m(\theta_i)$.

In the present prediction procedure, the range of uncertainty of the exponent $m(\theta_i)$ with respect to aircraft flight test data is estimated not to exceed ± 1 unit (see Figure 14). This comment does not apply to wind tunnel model data where the exponent $m(\theta_i)$ is always greater than ± 1 unit over the angular range $60 \text{ degrees} \leq \theta_i \leq 130 \text{ degrees}$, and by as much as 0 to 5 units.

5.3 References

For the derivation and substantiation of the static prediction method, references may be made to the following documents:

- 5.3.1 Boeing Document No. D6 - 42929 - 1, Empirical Jet Noise Predictions for Single and Dual Flow Jets and without Suppressor Nozzles Volume 1. Single flow Subsonic and Supersonic Jets. C. L. Jaeck, S. J. Cowan, R. P. Gerend.
- 5.3.2 SNECMA Document YKA No. 5898/76, Comparaison des spectres 1/3 d'octave de bruit de jet mesurés en chambre sourde A 17 du CEPr aux diverses propositions de révision de l'ARP876 de la SAE.
- 5.3.3 SNECMA Document YKA No. 5317/75, Révision de la méthode de prévision du bruit des jets (SAE ARP876).
- 5.3.4 For a description of the facility on which much of the basic data used herein were acquired, reference may be made to the AIAA Paper No. 76-534, July 1976, entitled, "Use of the Bertin Aerotrain for the Investigation of Flight Effects on Aircraft Engine Exhaust Noise," by R. G. Hoch and M. Berthelot.

5.4 Parties Contributing to Formulation of Section 5

Department of Transportation, USA

Douglas Aircraft Company, USA

General Electric Company, USA

Hamilton Standard, USA

Lockheed California Company, USA

Lockheed Georgia Company, USA

National Aeronautics and Space Administration, USA

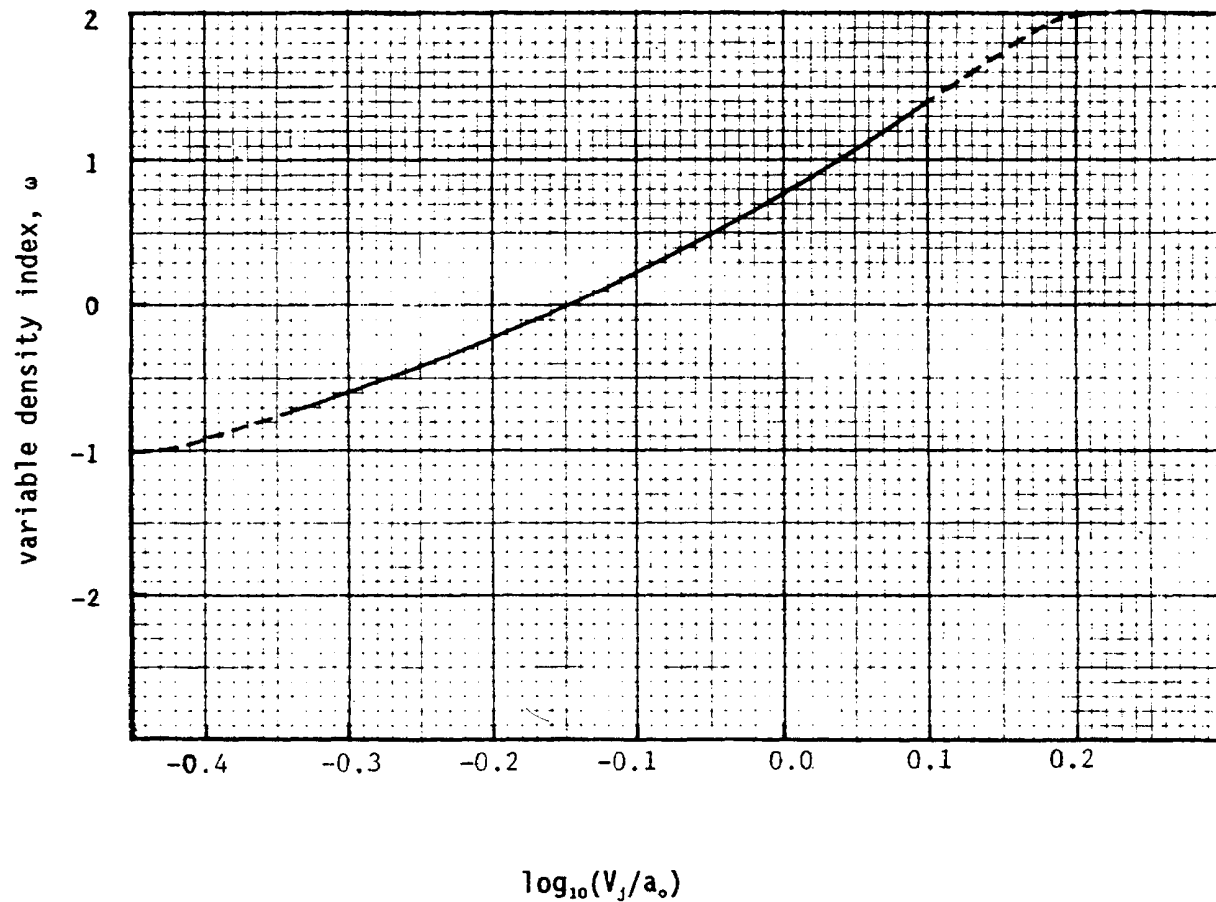
National Gas Turbine Establishment, United Kingdom

Pratt & Whitney Aircraft Company, USA

Rolls-Royce Limited, United Kingdom

SNECMA, France

The Boeing Company, USA



NOTE: Experimental evidence is represented by the solid line.

Above $\log_{10}(V_j/a_0) = 0.2$, the value of ω should be taken as 2.0

FIGURE 2 - VARIABLE DENSITY INDEX ω

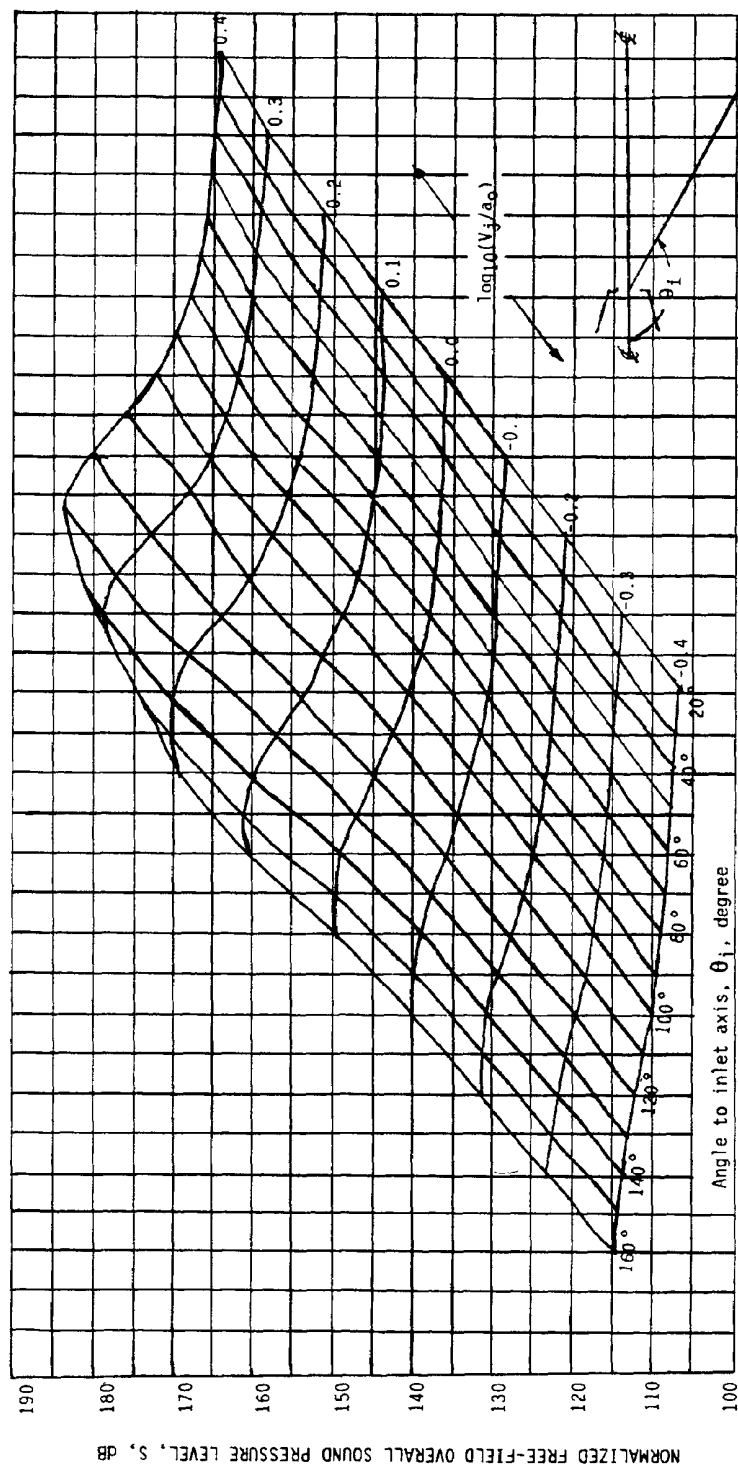


FIGURE 3 - CARPET PLOT FOR NORMALIZED OVERALL SOUND PRESSURE LEVELS OF PURE JET-MIXED NOISE

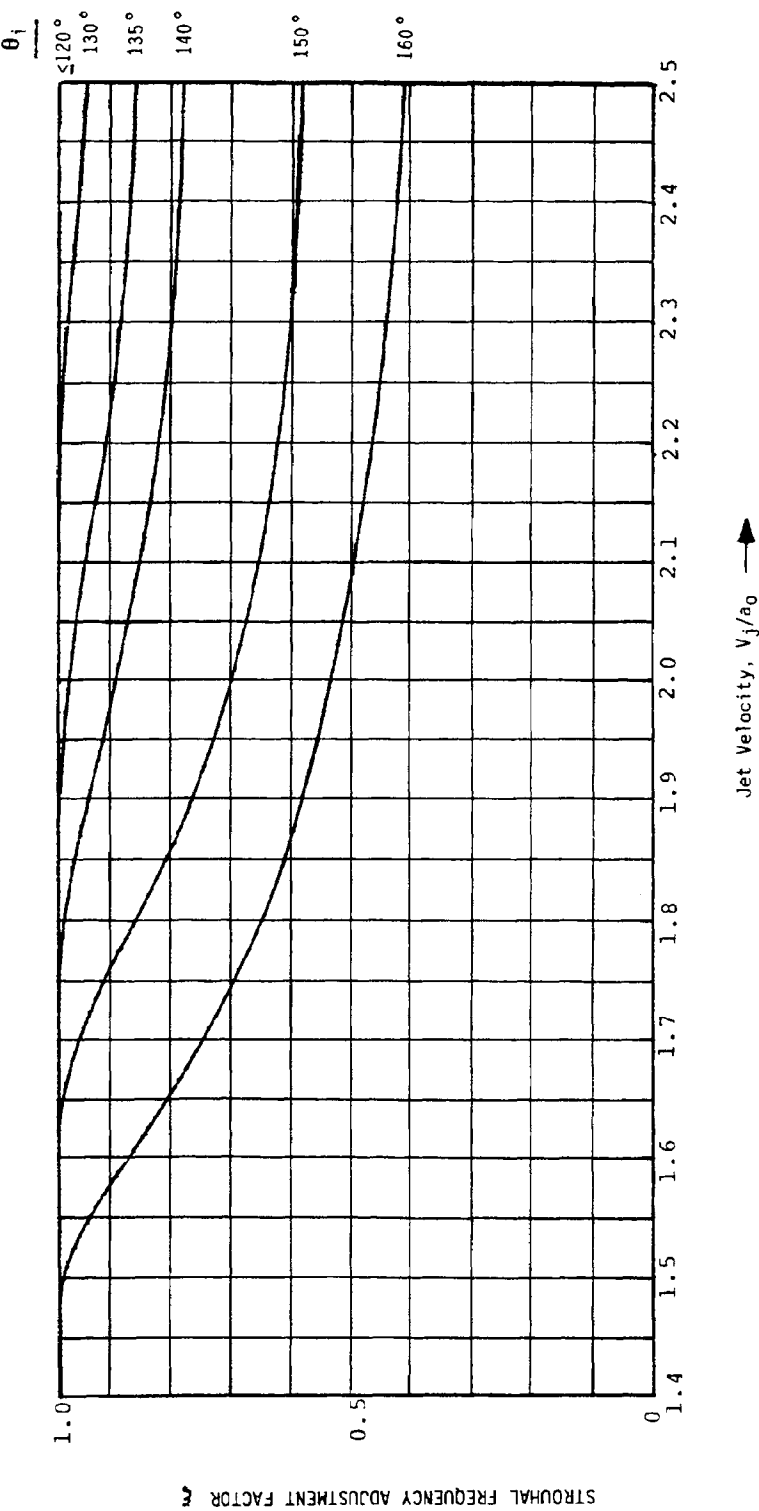
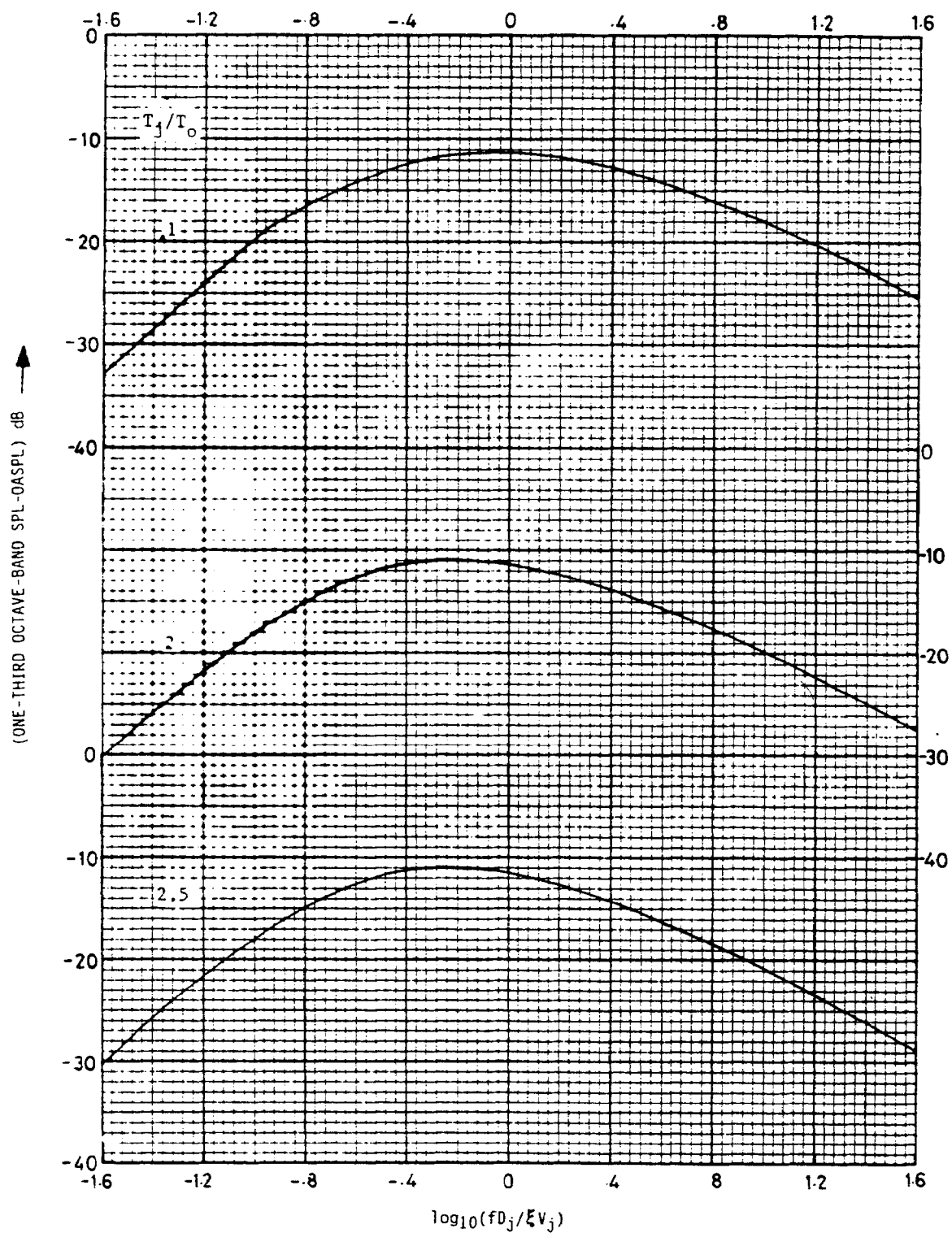


FIGURE 4 - ADJUSTMENT FACTOR FOR NORMALIZED FREQUENCY

FIGURE 5 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_i \leq 90$ DEGREES

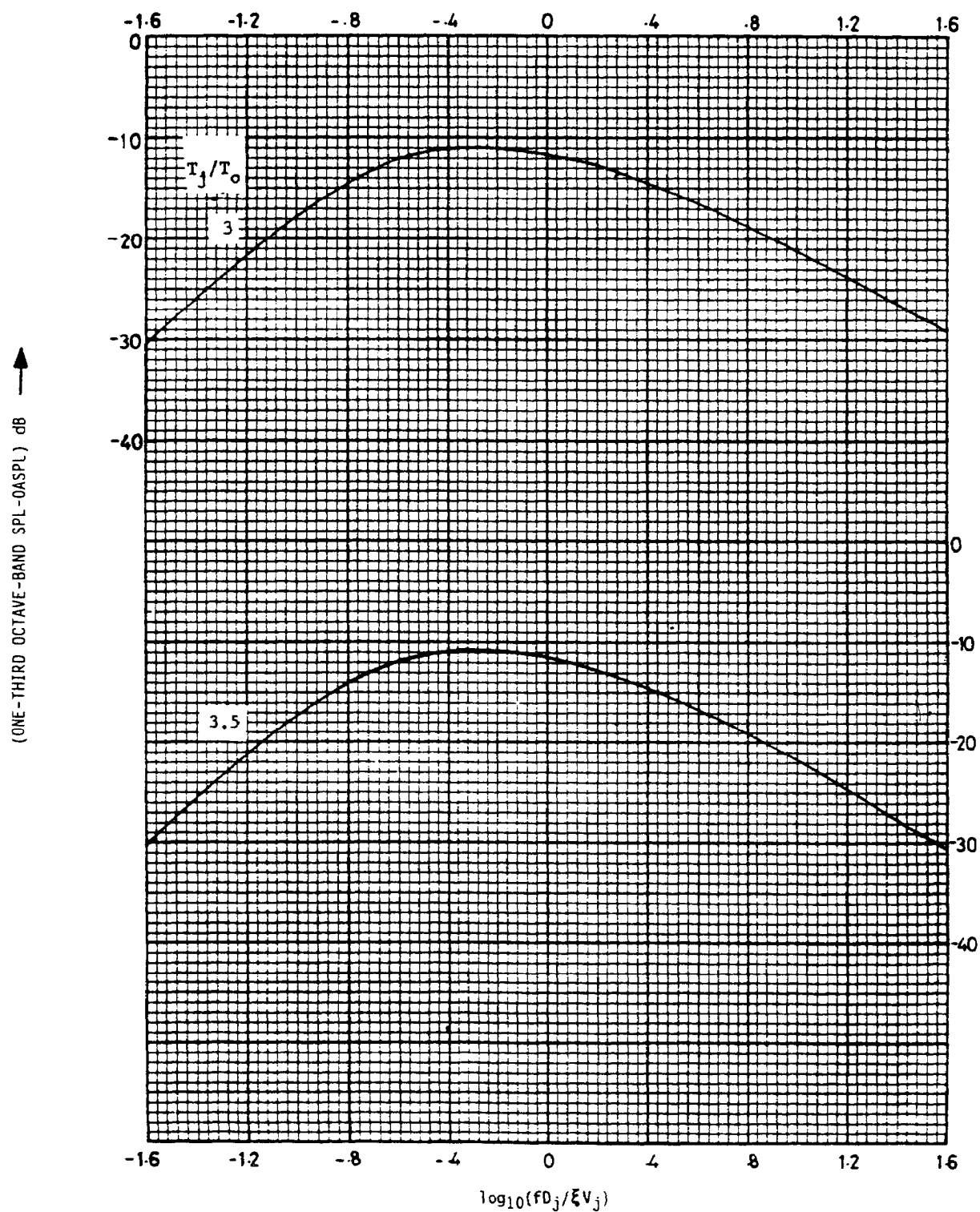
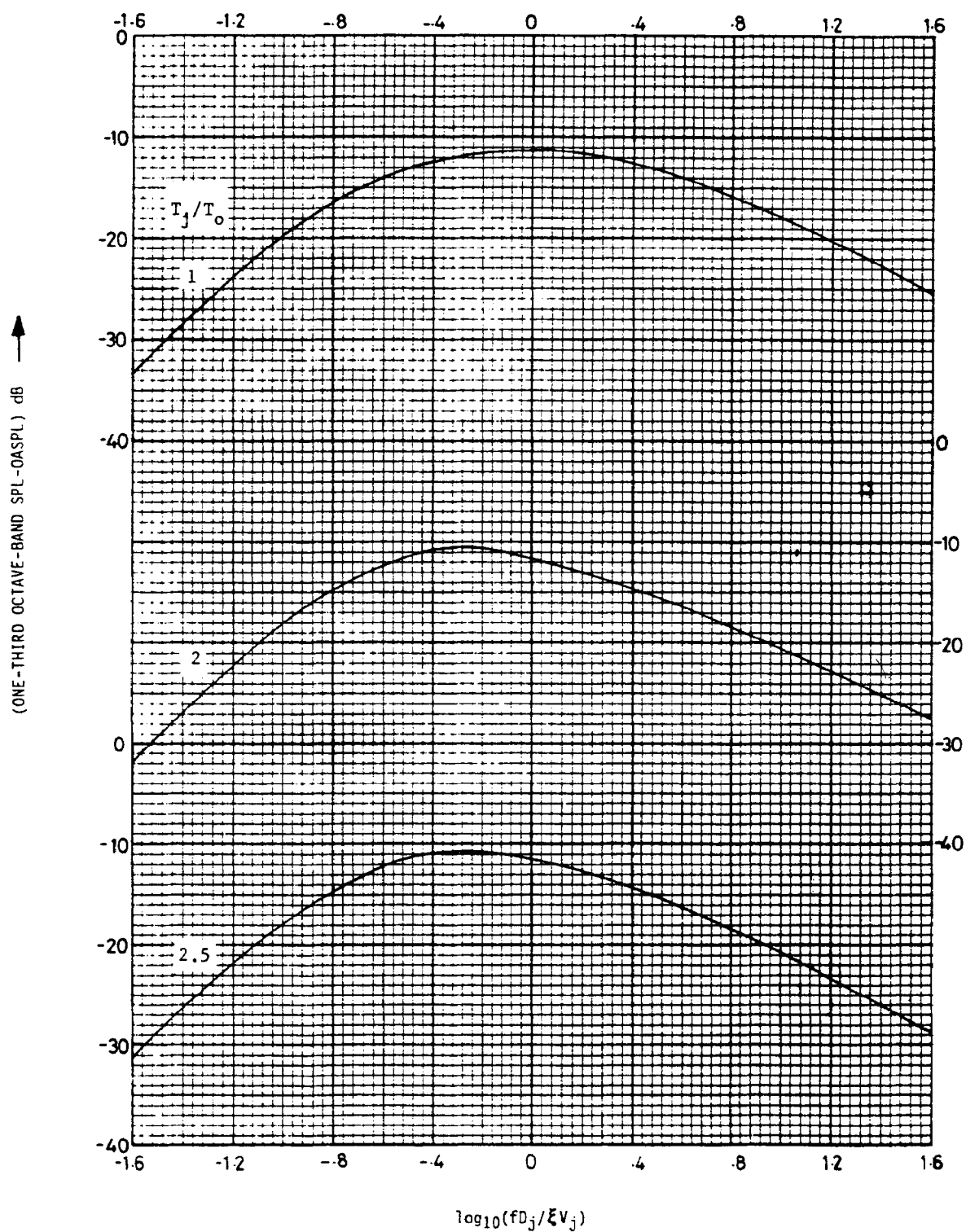


FIGURE 5 (CONTINUED)

FIGURE 6 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_i = 100$ DEGREES

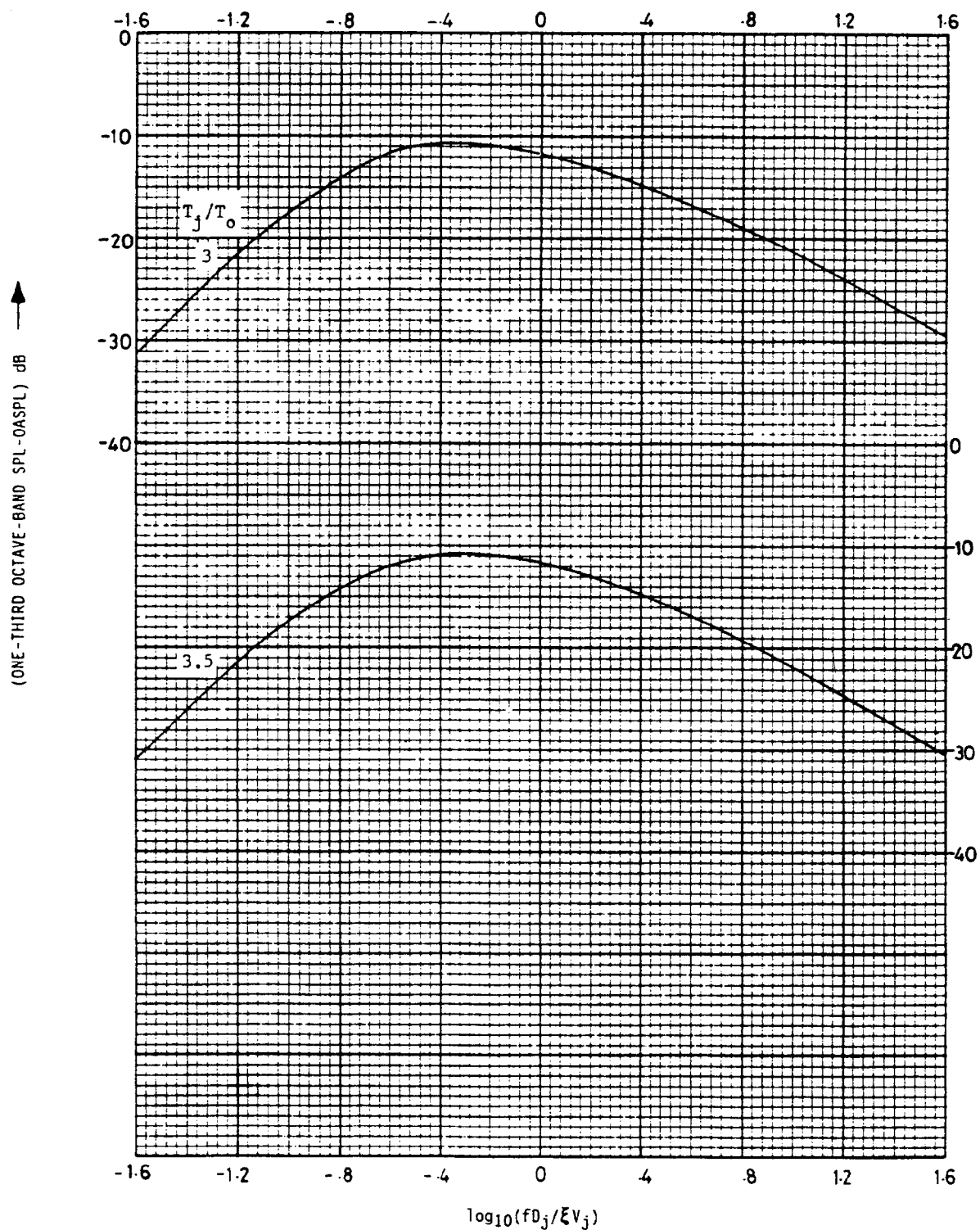
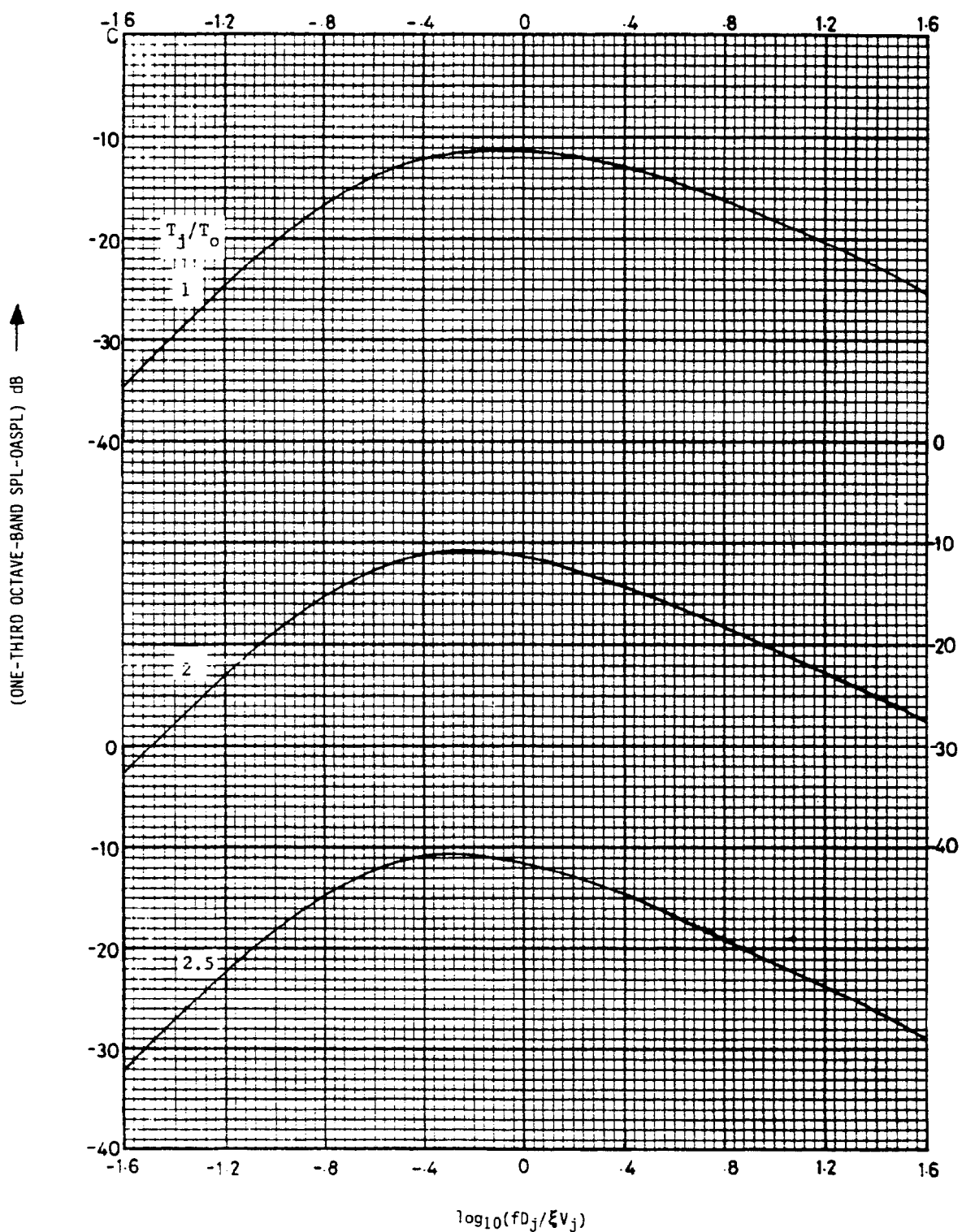


FIGURE 6 (CONTINUED)

FIGURE 7 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_l = 110$ DEGREES

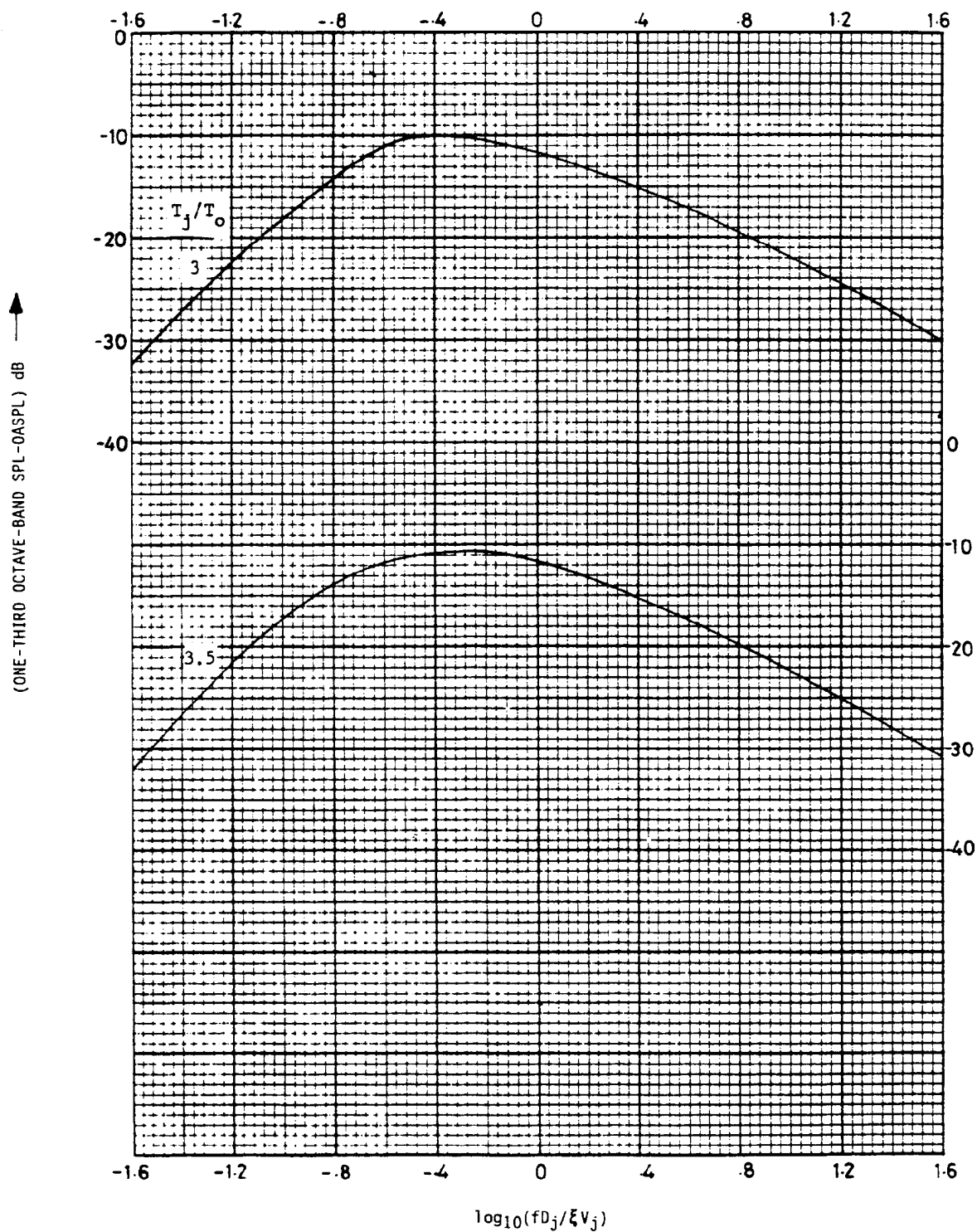
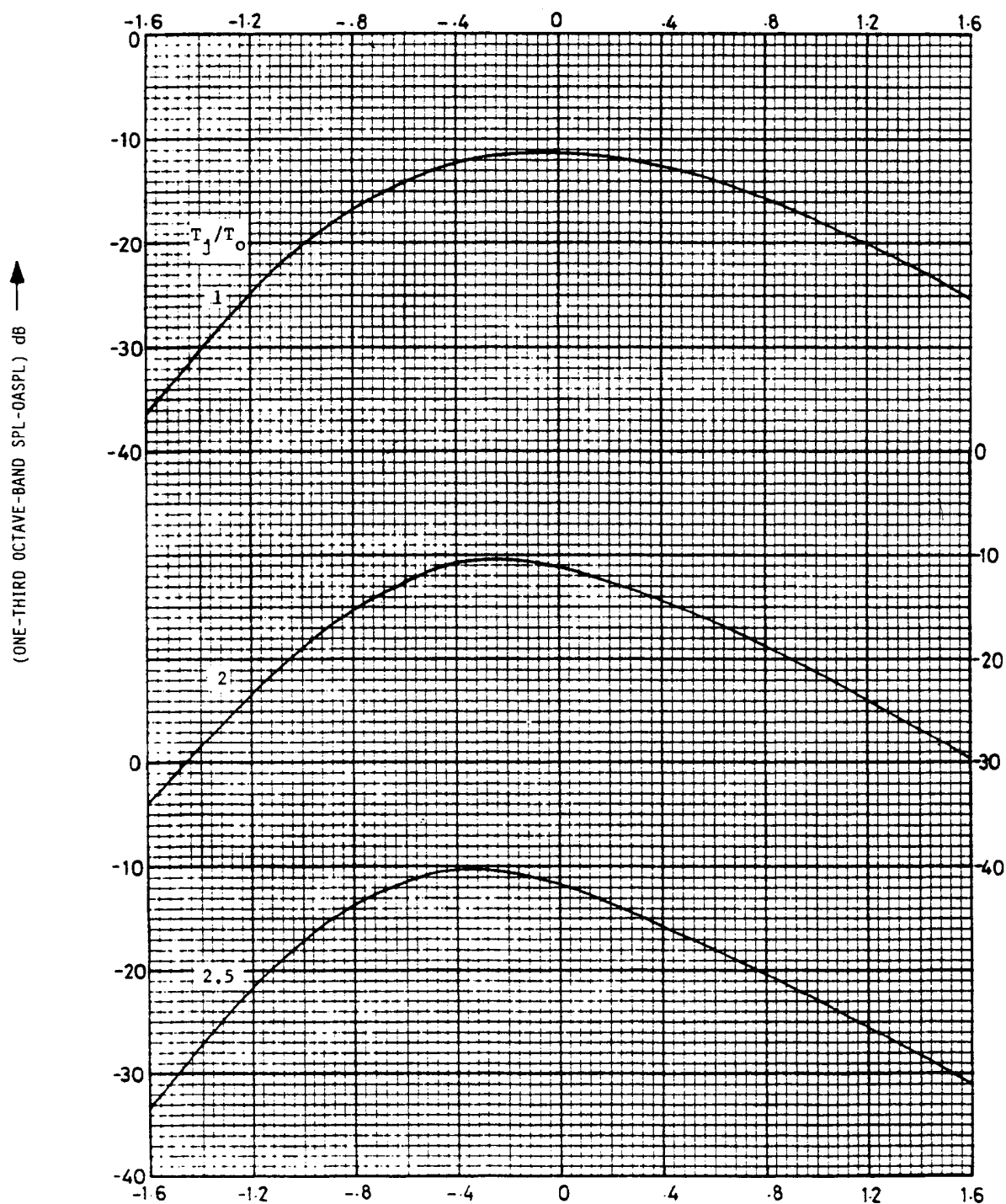


FIGURE 7 (CONTINUED)

FIGURE 8 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_1 = 120$ DEGREES

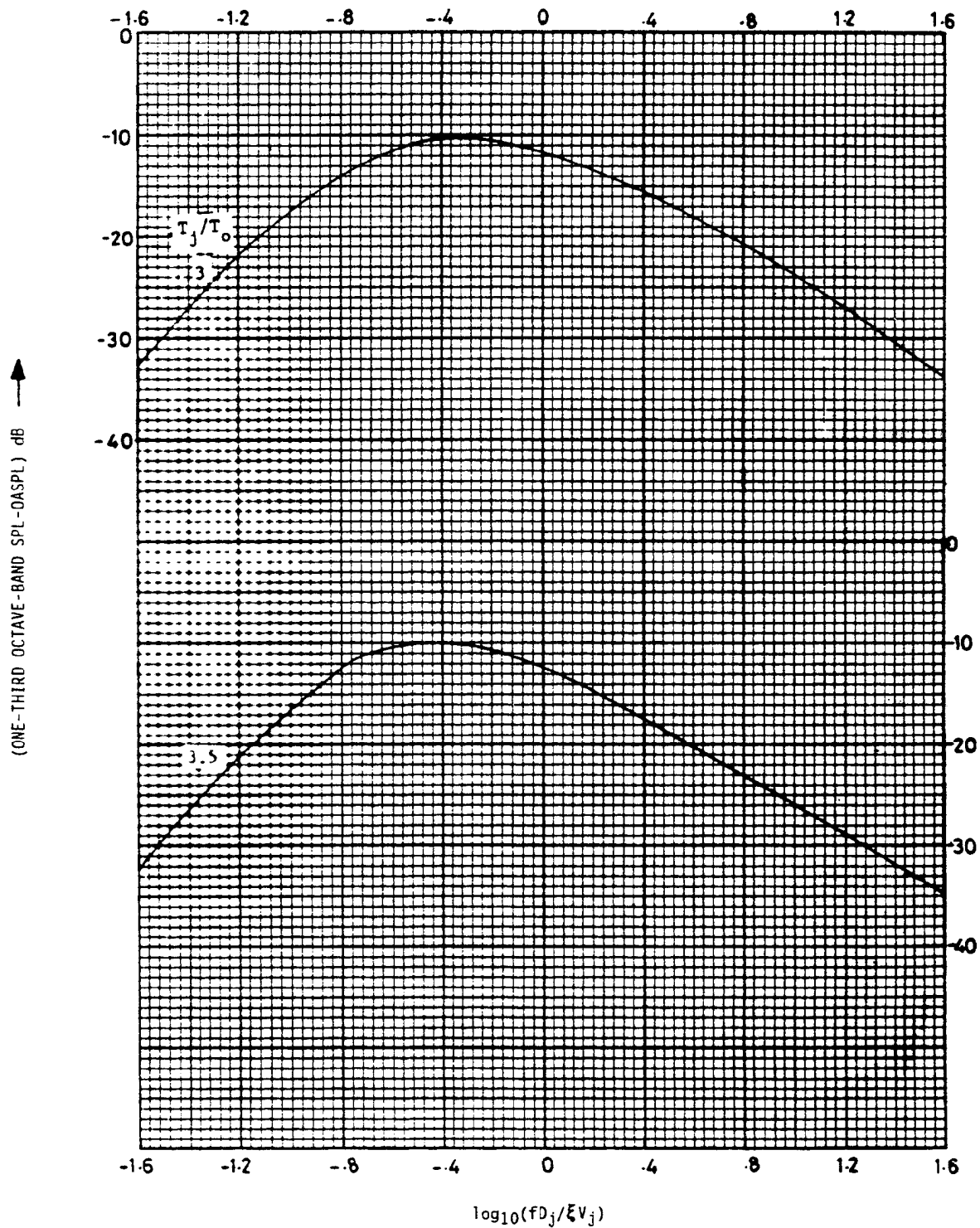
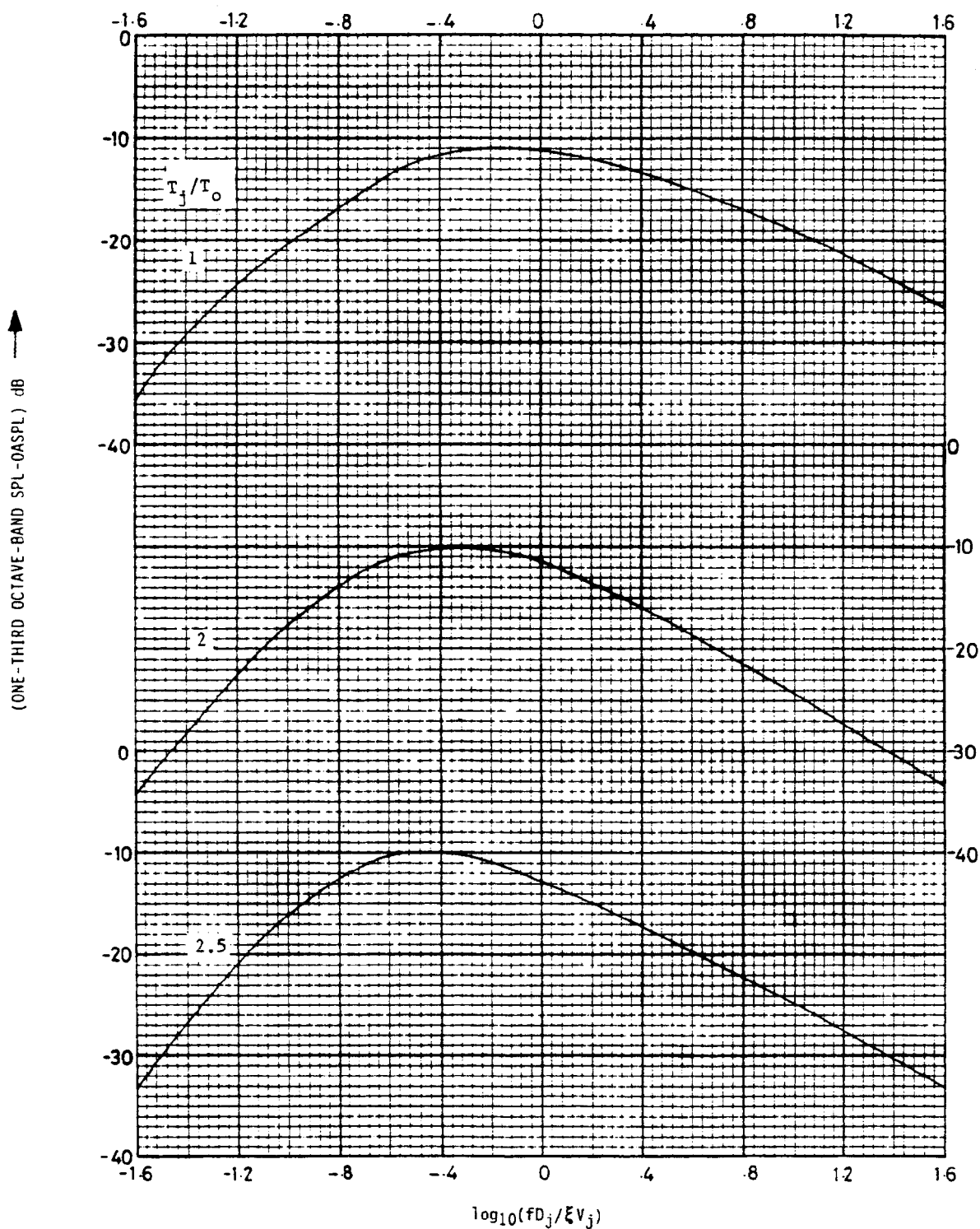


FIGURE 8 (CONTINUED)

FIGURE 9 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_l = 130$ DEGREES

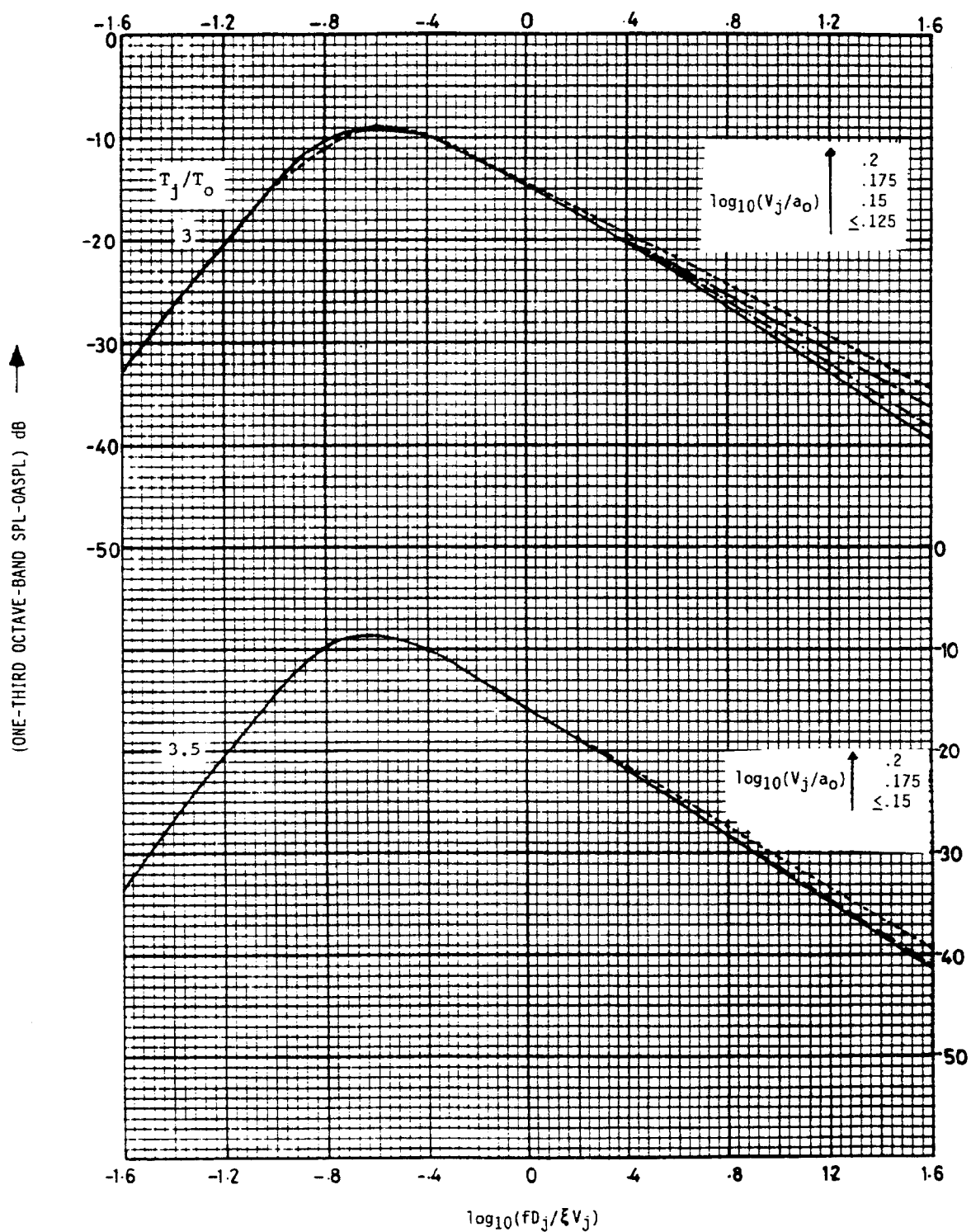
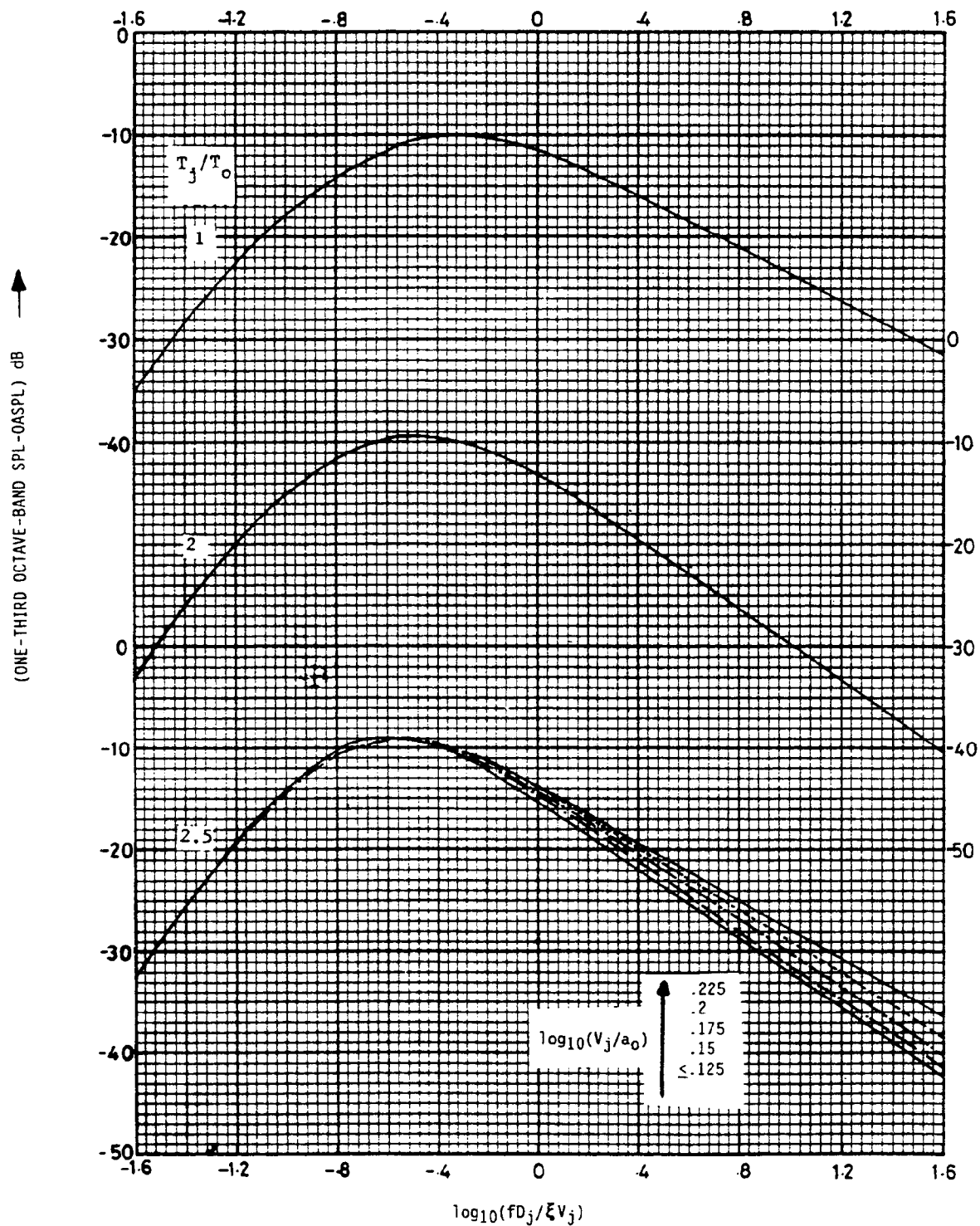


FIGURE 9 (CONTINUED)

FIGURE 10 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_i = 140$ DEGREES

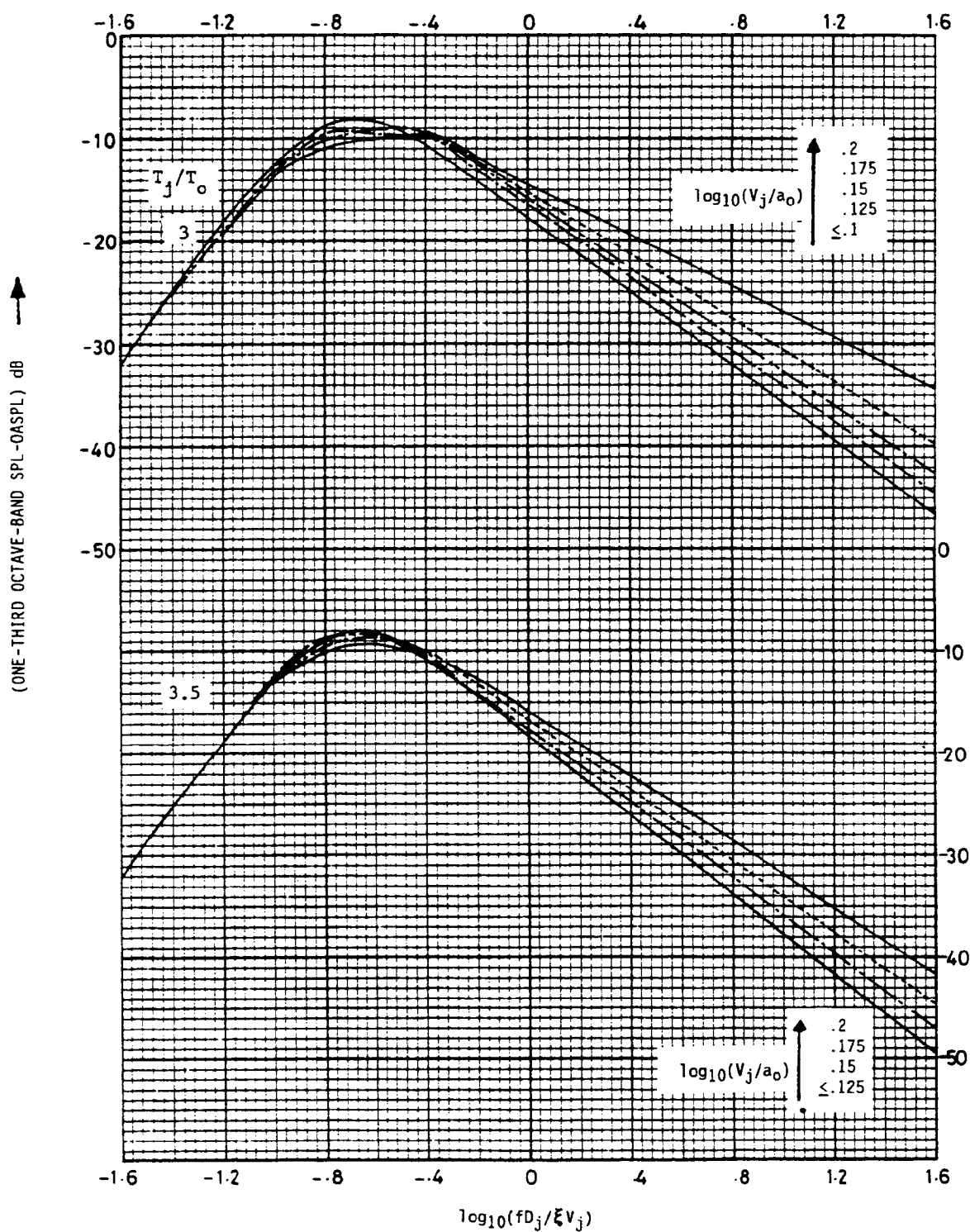
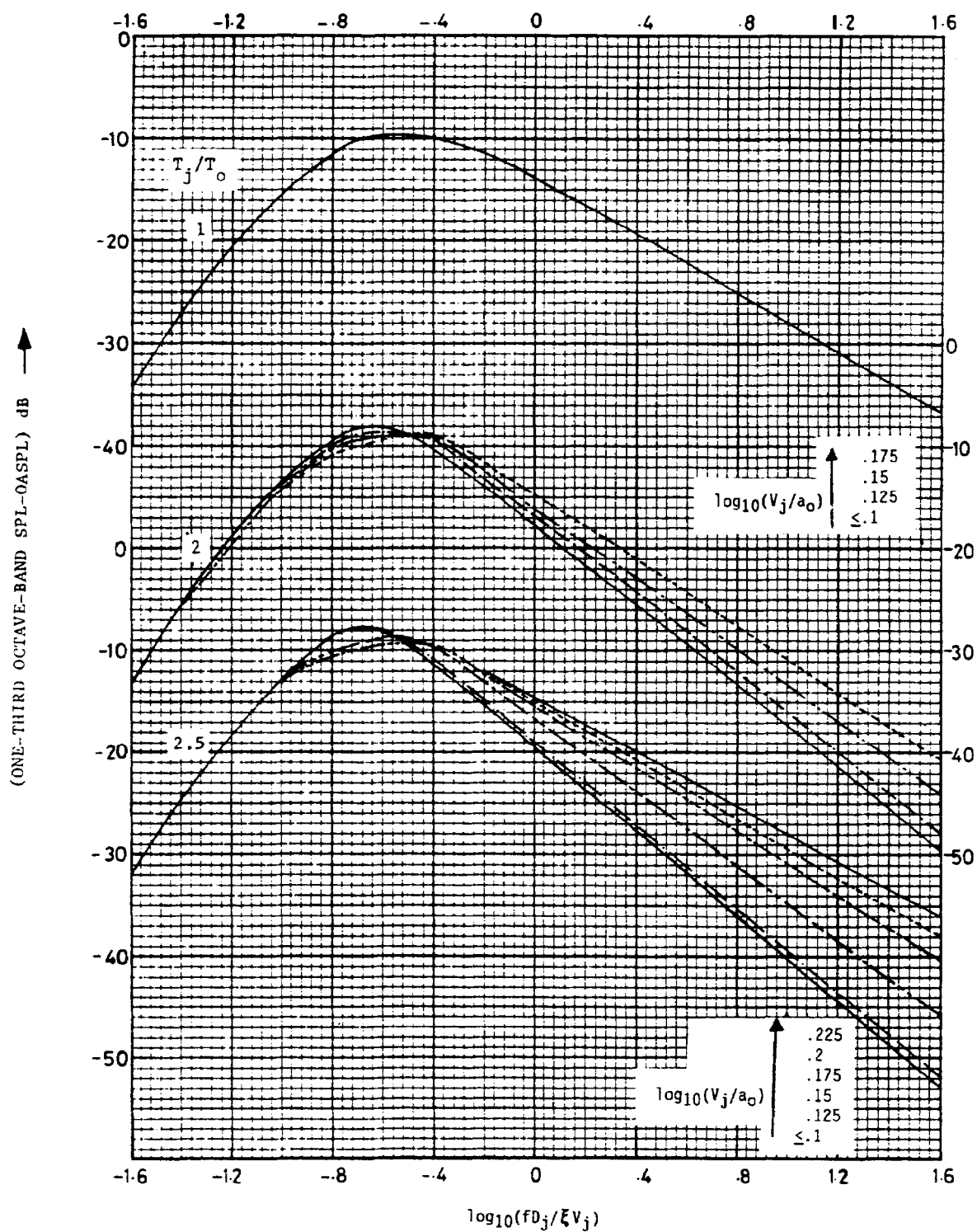


FIGURE 10 (CONTINUED)

FIGURE 11 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_i = 150$ DEGREES

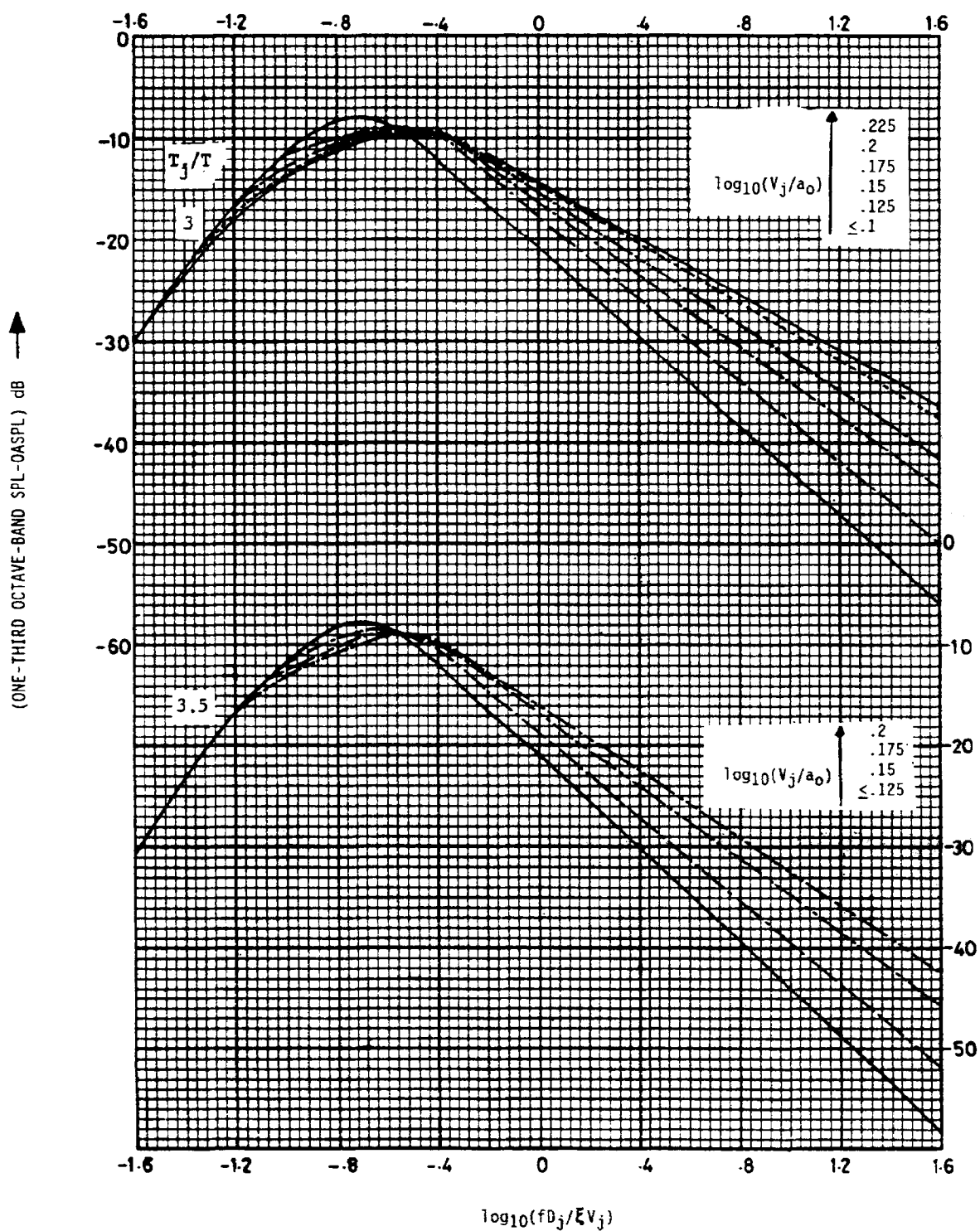
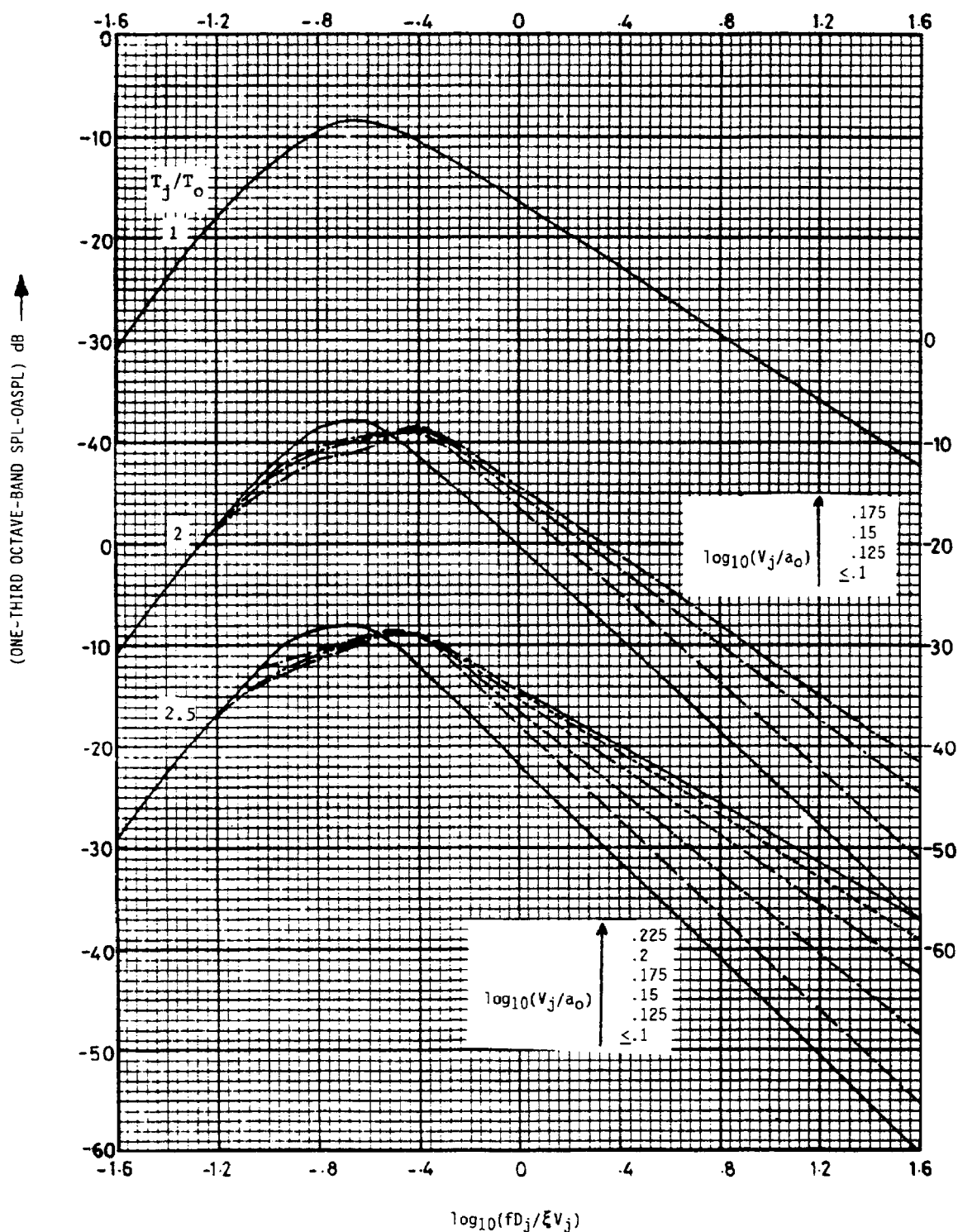


FIGURE 11 (CONTINUED)

FIGURE 12 - ONE-THIRD OCTAVE-BAND NORMALIZED SPECTRA $\theta_i = 160$ DEGREES

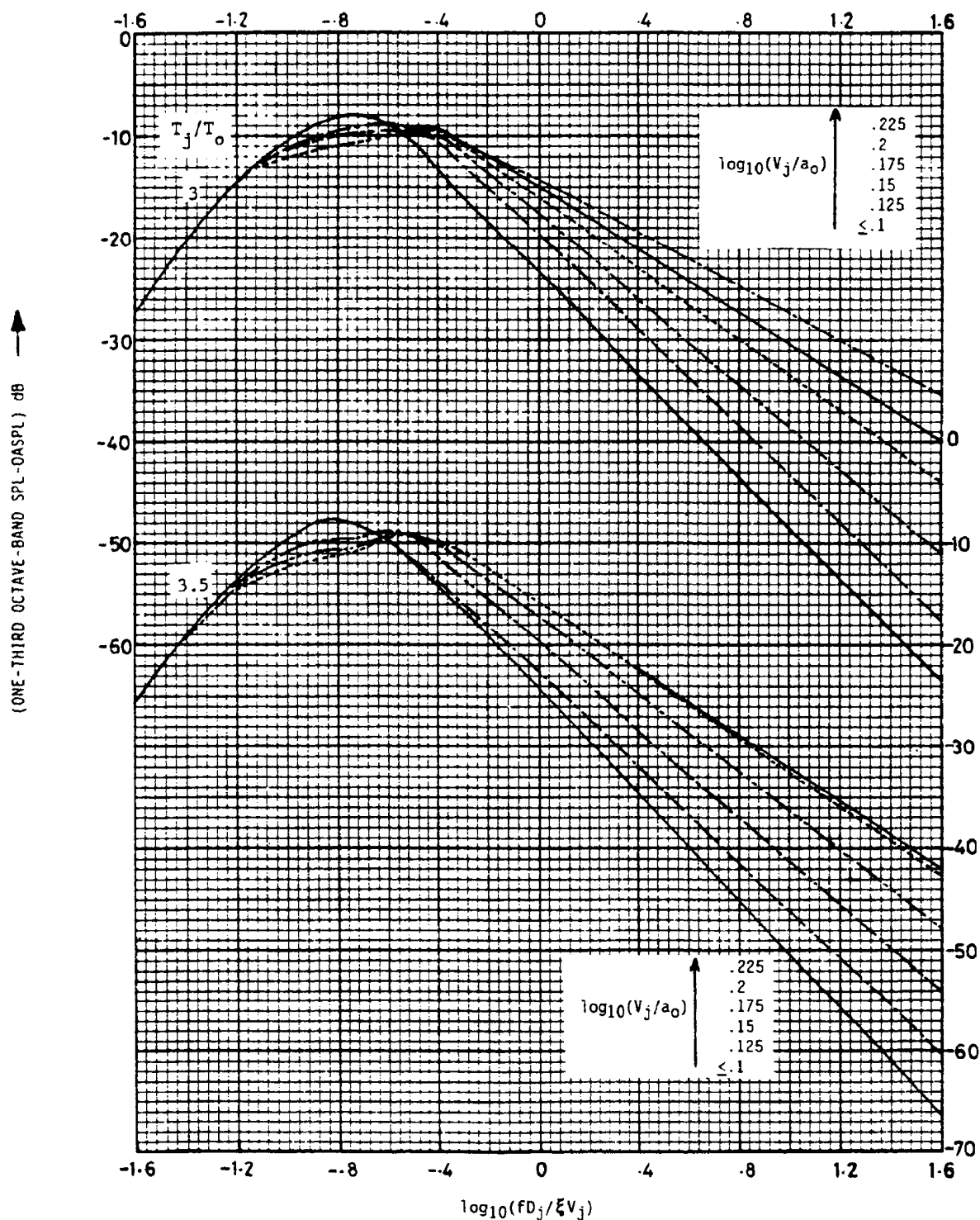


FIGURE 12 (CONTINUED)