



AEROSPACE RECOMMENDED PRACTICE

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GAS TURBINE JET EXHAUST NOISE PREDICTION

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1. INTRODUCTION

AIR 876, 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 sources. Work in recent years on good 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.

AIR 876 was also limited to velocities above 1,000ft/sec, 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 ARP 876 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, and specific recommended procedures will be issued as Appendices.

The document will offer a method of estimating the exhaust noise from single unsilenced 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, due to source variability with detailed engine design parameters, are aerodynamic blade noise sources; that is the noise generated by interaction effects between rotating and stationary components of the fan, compressor and turbine systems.

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

2. SOURCES OF EXHAUST NOISE

The exhaust system noise of an aero gas turbine engine 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.

2. (Continued)

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 contained 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 levels in each 1/3 octave logarithmically. 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 engine picture. Furthermore, it is advisable that any assumed modification to the noise by virtue of silencing or installation effects is made in the component calculation stage.

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 it has 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 AIR 1327 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 atmospheric attenuation and normalised.

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 ARP 866A provides a standard method of allowing for atmospheric absorption under a range of ambient temperatures and humidity conditions.

3.4 If a subjective assessment is required, Perceived Noise Levels (PNL) may be calculated using the methods in SAE ARP 865A.

4. SYMBOLS

a_o	Ambient speed of sound	m/s
A_j	Cross-sectional area of jet exhaust nozzle	m^2
C_v	Velocity coefficient for relevant discharge nozzle	
dB	Sound Pressure Level (re 20 Micro Pa.)	dB
D_j	Exhaust nozzle diameter	m

4. (Continued)

f	One-third octave centre band frequency	Hz
g	Gravitational constant	m/s ²
ISA	International Standard Atmosphere	
NPR	Nozzle pressure ratio	
OASPL	Overall Sound Pressure Level	dB
P _o	Ambient pressure	Pa
P _{ISA}	Ambient pressure under ISA conditions	Pa
r	Radial distance from nozzle exit to observer	m
R	Gas constant with value 287.05 J/kg°K based on the universal gas constant of 8,31432 J/mole°K and mass per mole in dry air of 28.9644 x 10 ⁻³ kg/mole	J/kg°K
S	Normalised Free-Field Overall Sound Pressure Level	dB
SPL	Sound Pressure Level	dB
T _j	Jet Total Temperature	°K
V _a	Forward speed of engine/airplane	m/s
V _j	Fully expanded jet velocity	m/s
γ	Ratio of specific heats for propulsive medium	
θ _i	Angle to engine inlet axis	degrees
θ _j	Angle to engine jet axis (180° - θ _i)	degrees
ρ _{ISA}	Atmospheric density under ISA conditions (1.225 kg/m ³ based on atmospheric pressure of 1.01325 x 10 ⁵ N/m ² at an air temperature of 288.15°K)	kg/m ³
ρ _j	Fully expanded jet density	kg/m ³
ω	Variable density index used in computing jet mixing noise OASPL	
ξ	Strouhal frequency correction factor	

NOTE: The units quoted above 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.

APPENDIX A

DATE OF COMPILATION

September 1976

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

5.1 Static Conditions: Definitive model scale experimental work of recent years has provided a firm data base for the study of mixing noise over a wide range of jet velocity and temperature conditions. This work has shown that jet mixing noise level and Spectral Character is a function of the following principal parameters:

- a) The velocity differential between the jet and its environment.
- b) The jet density relative to its environment.
- c) The jet dimensions.

It has been concluded that one of the most convenient ways to express jet noise characteristics is to consider firstly 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 spectral character (on one-third octave basis) to the overall level at any point in the field. This procedure may be adopted by using Figs. A. 1 through A. 11. The information of Fig. A. 1 through Fig. A. 11 is also presented in tables A. 1 through A. 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:

$$V_j = C_v \left[\left(\frac{2\gamma R}{\gamma - 1} \right) T_j \left\{ 1 - \frac{1 - \gamma}{\gamma} \right\} \right]^{1/2}$$

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:

$$V_j = \left\{ \frac{\text{Static Gross Thrust}}{\text{Mass Flow}} \right\}$$

Step 2 - Using V_j obtained from Step 1 and the Ambient Speed of Sound (a_o) obtain the Variable Density Index (ω) from Fig. A. 1.

Step 3 - For any desired angle and jet velocity use Fig. A. 2 to obtain the free-field Overall Sound Pressure Level (S) where:

$$S = \text{OASPL} - 10 \log_{10} \left\{ \left(\frac{\rho_j}{\rho_o} \right) \left(\frac{A_j}{r^2} \right) \right\} - 20 \log_{10} \left(\frac{P_o}{P_{\text{ISA}}} \right)$$

for the value of V_j at any desired angle.

5.1 (Continued)

Step 4 - Calculate the Overall Sound Pressure Level (OASPL) where:

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

Step 5 - Calculate the one third octave band spectral levels from Fig. A.3 - A.11 using jet velocity (V_j), temperature ratio $\left(\frac{T_j}{T_o} \right)$, nozzle diameter

(D_j) and the angle (θ_i) as follows:

Determine ξ from Fig. A.3 and then calculate $\left[\frac{f D_j}{V_j} \times \frac{1}{\xi} \right]$ for each 1/3 octave band centre frequency. Enter Figures A.4 to A.11 with the values of $\left[\frac{f D_j}{V_j} \times \frac{1}{\xi} \right]$, and values of $\left(\frac{T_j}{T_o} \right)$,

$\log_{10} \left(\frac{V_j}{a_o} \right)$ and θ_i to determine values of

1/3 octave band (SPL - OASPL).

For values other than specified in Figures A.3 - A.11, linear interpolation on angles (θ_i),

$$\log_{10} \left[\frac{f D_j}{V_j} \times \frac{1}{\xi} \right], \log_{10} \left(\frac{V_j}{a_o} \right) \text{ and } \left(\frac{T_j}{T_o} \right)$$

is recommended.

5.1 (Continued)

Step 6 - From value of OASPL and 1/3 octave band (SPL - OASPL) as derived in steps 4 and 5 respectively, calculate values of 1/3 octave band SPL.

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

Note 1 The spectra of Figures A. 3 - A. 11 satisfy the following condition

$$\log_{10} \left\{ \sum_{i=1}^N 10^{\frac{(SPL - OASPL)_i}{10}} \right\} = 0$$

Over the range of 1/3 octave frequencies defined by

$$-1.6 \leq \log_{10} \left[\frac{f D}{\xi v_j} \right] < 1.6$$

Note 2 Accuracy of Prediction

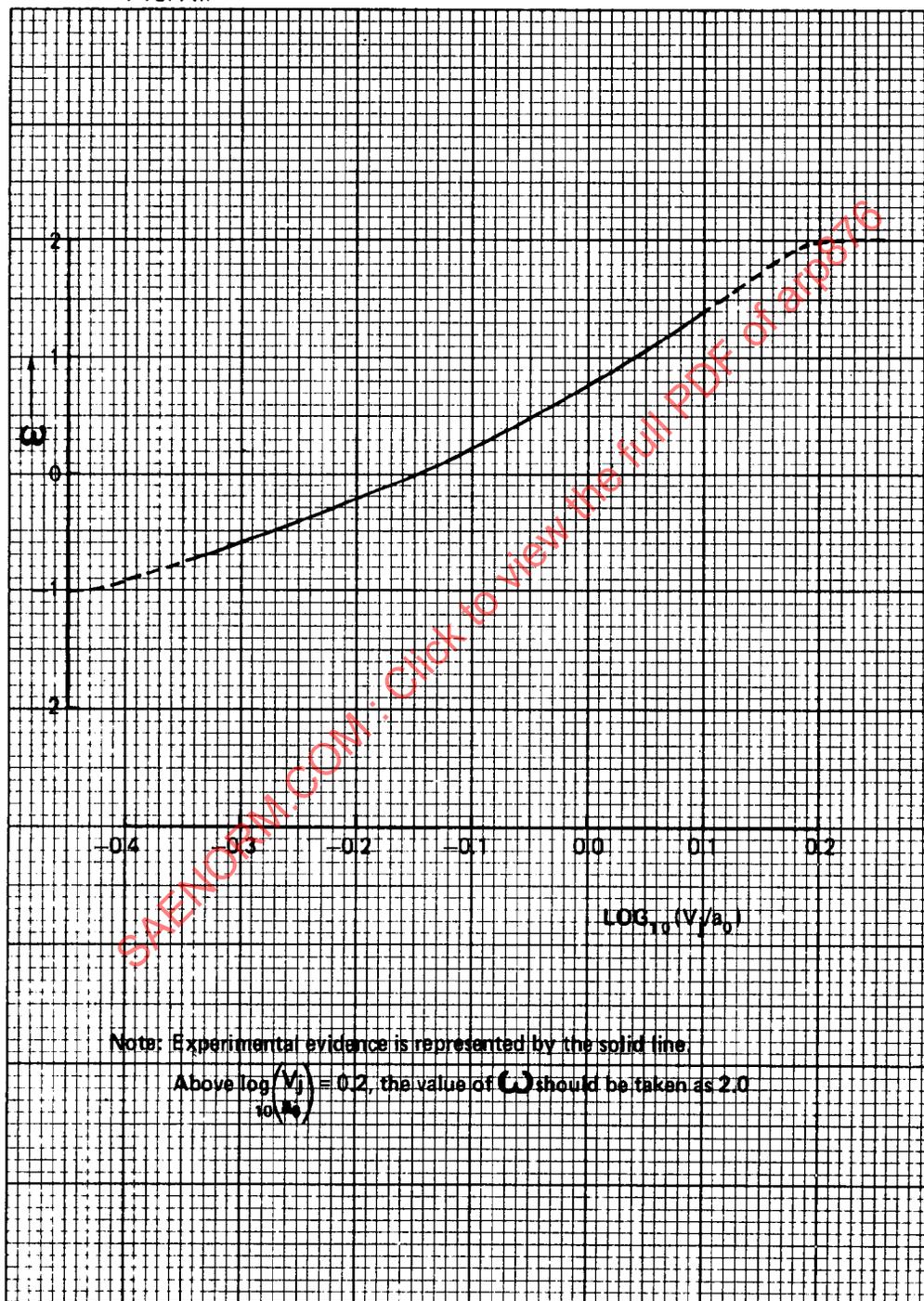
The accuracy of prediction of OASPL at (r_1, θ_1) relative to the model data on which it is based varies between ± 2 dB at low jet velocities to ± 4 dB at very high jet velocities. The accuracy of prediction of 1/3 octave (SPL - OASPL) varies between ± 1 dB at peak noise frequencies. However, these limits apply to the extreme cases. For all normal purposes, the majority of predictions will be accurate within ± 3 dB at all frequencies.

Note 3 For the derivation and substantiation of the method, reference may be made to the following documents:

- (i) 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. Jeack, S. J. Cowan, R. P. Gerend.
- (ii) SNECMA Document YKA No. 5898/76 Comparaison des spectres 1/3 d'octave de bruit de jet mesures en chambre sourde A 17 de CEPr aux diverses propositions de revision de l'ARP 876 de la SAE.
- (iii) SNECMA Document YKA No. 5317/75 Revision de la methode de prevision du bruit des jets (SAE ARP 876).

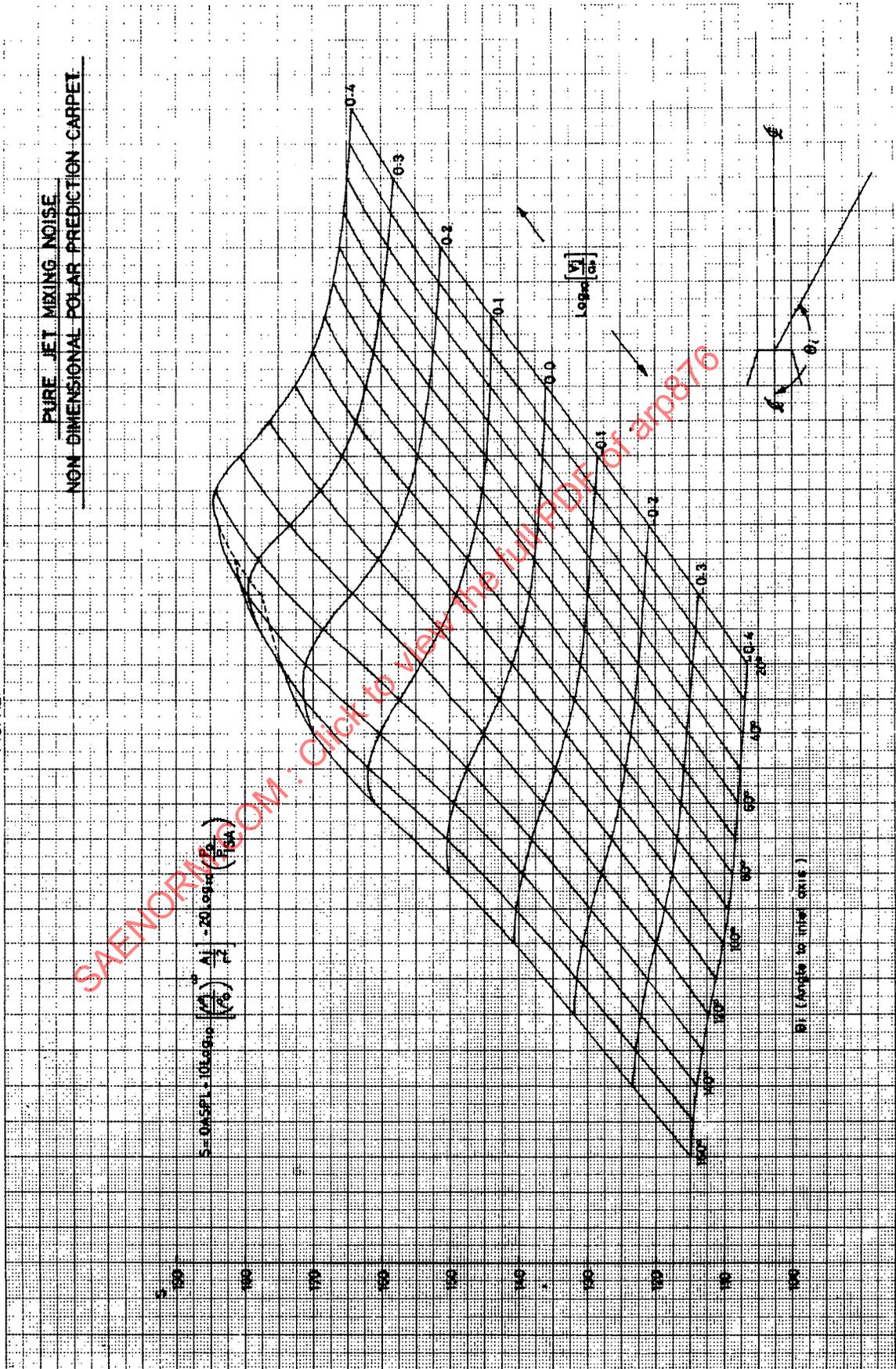
Variable density index ω

FIG. A1.



PURE JET MIXING NOISE
NON-DIMENSIONAL POLAR PREDICTION CARPET

FIG. A2



$$S = 0.45 \text{ SPL} + 10 \text{ Log}_{10} \left[\frac{M^2}{V^2} \right] - 20 \text{ Log}_{10} \left(\frac{P_0}{P_{ref}} \right)$$

B1 (Angle to travel axis)

FIG. A3

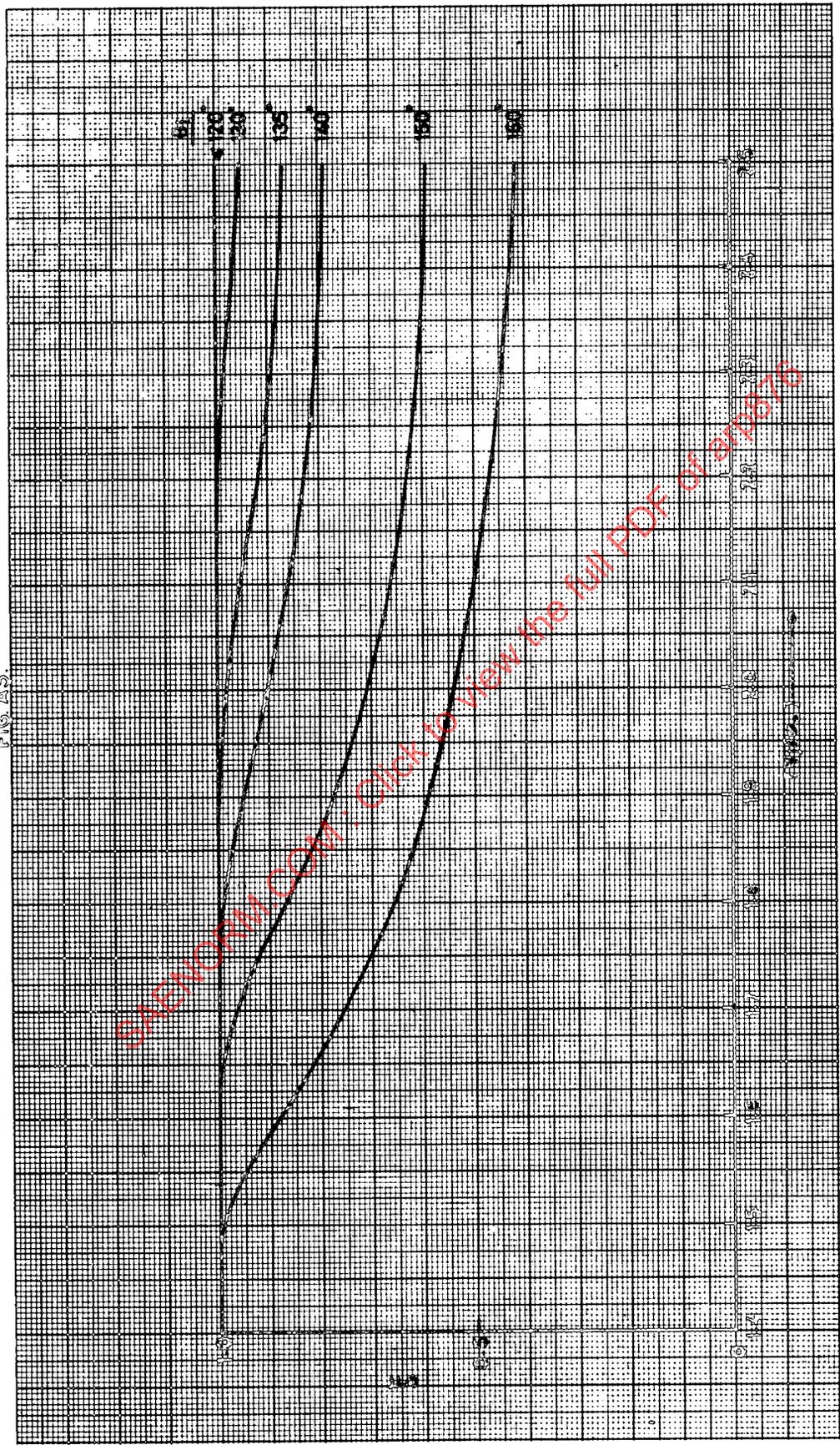


FIG. A4.
1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i \leq 90^\circ$

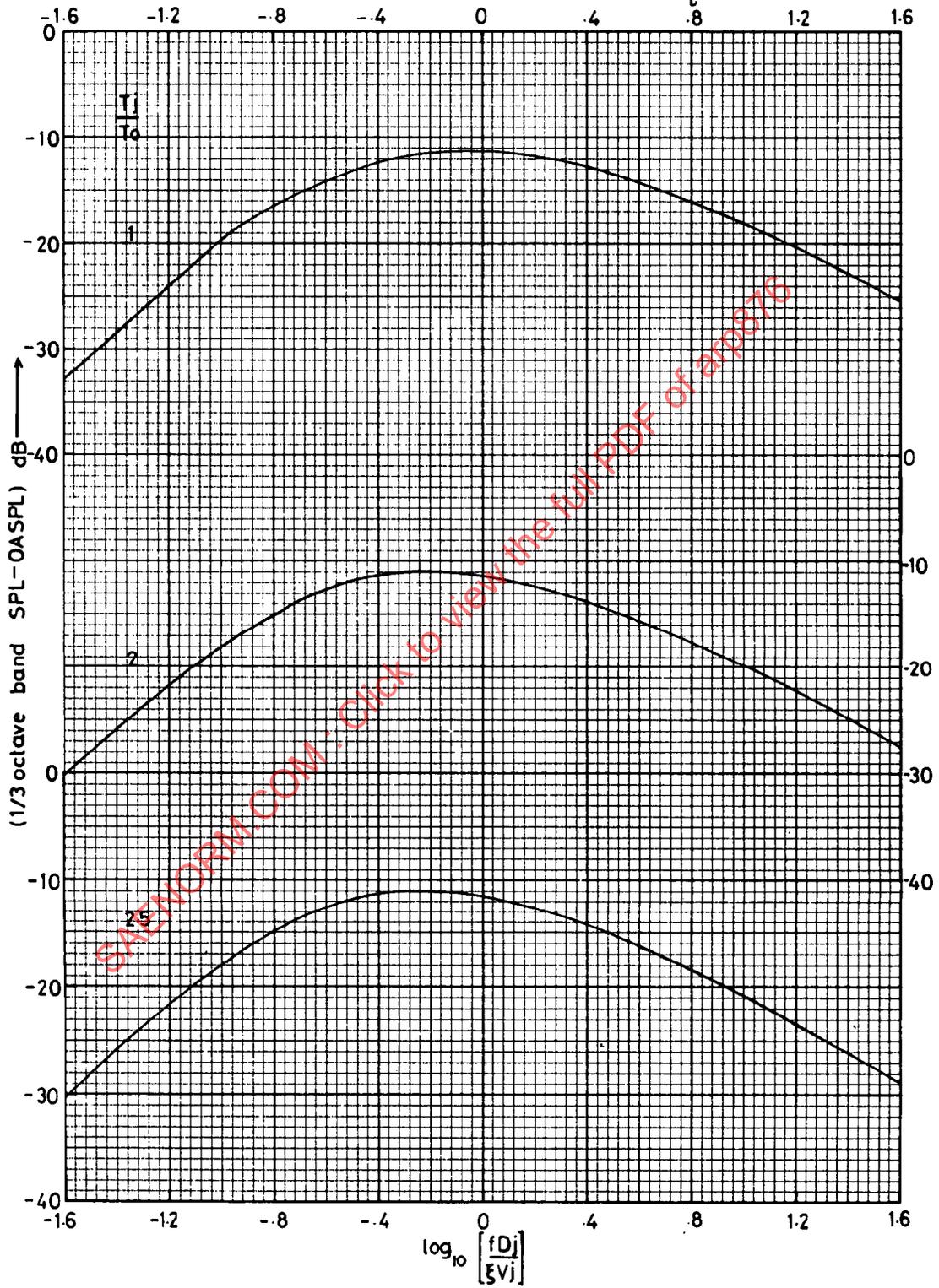


FIG. A4. (CONT'D)
 1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i \leq 90^\circ$

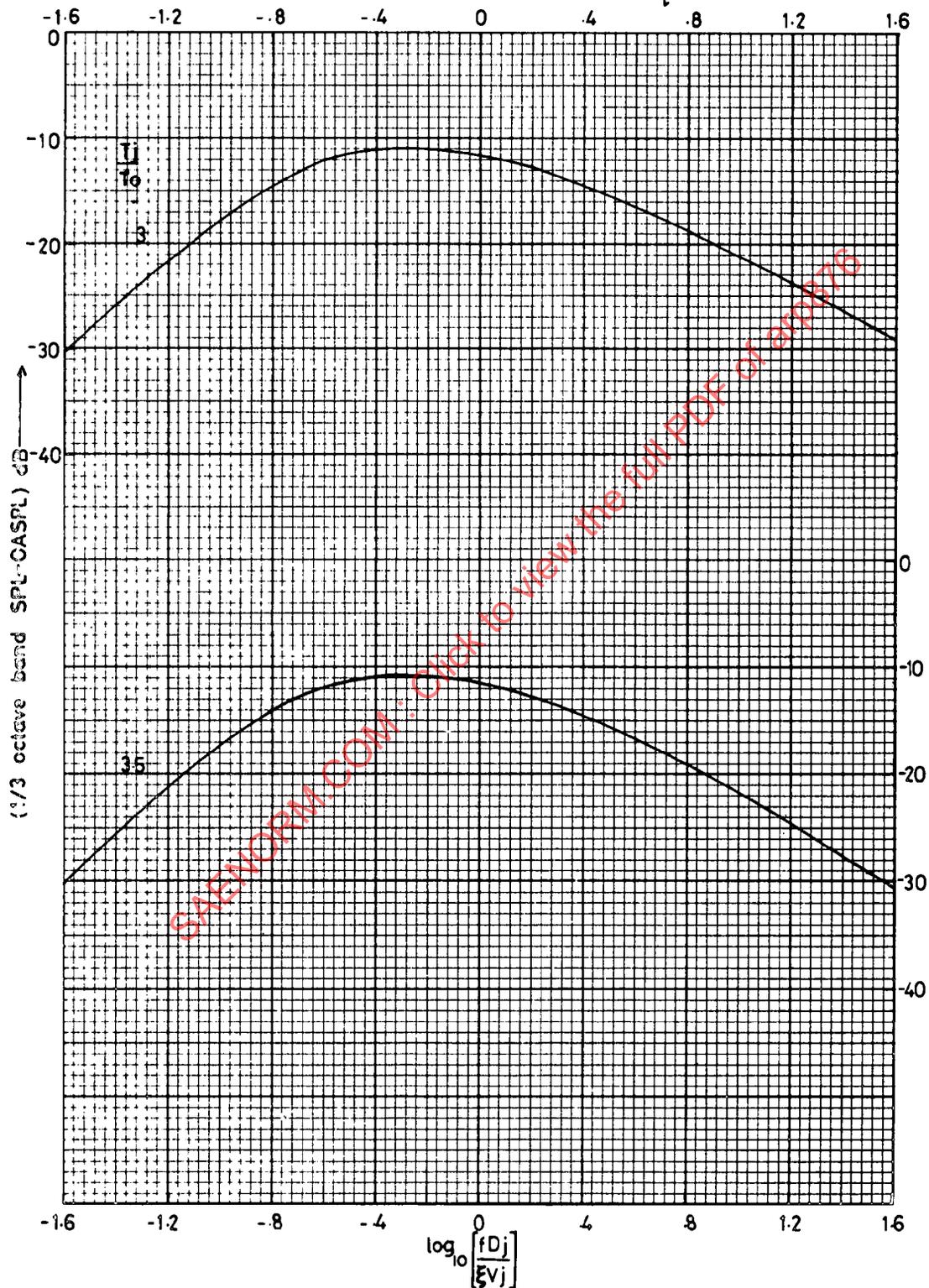


FIG. A5.
1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_s = 100^\circ$

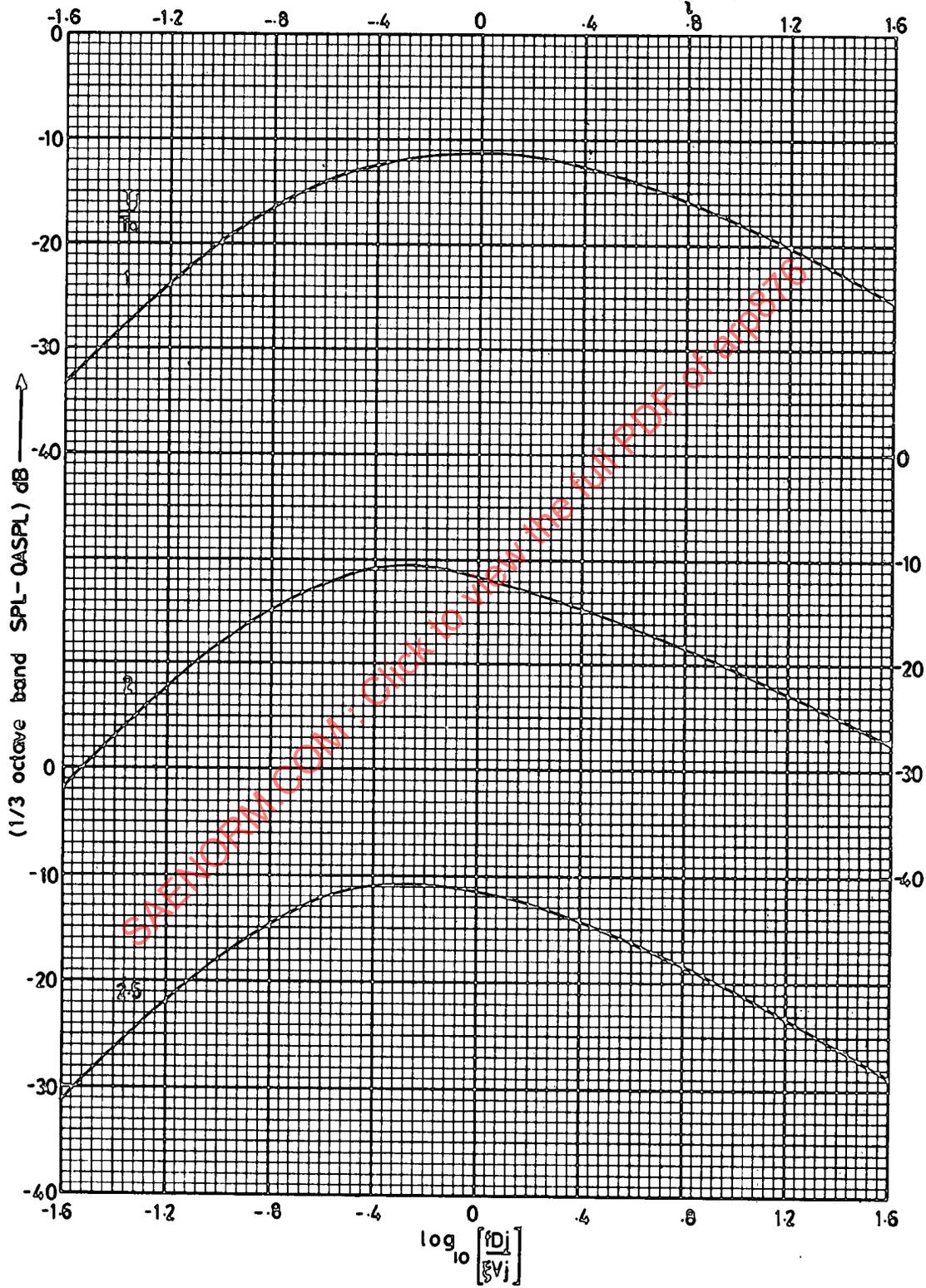


FIG A5. (CONT'D)

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 100^\circ$

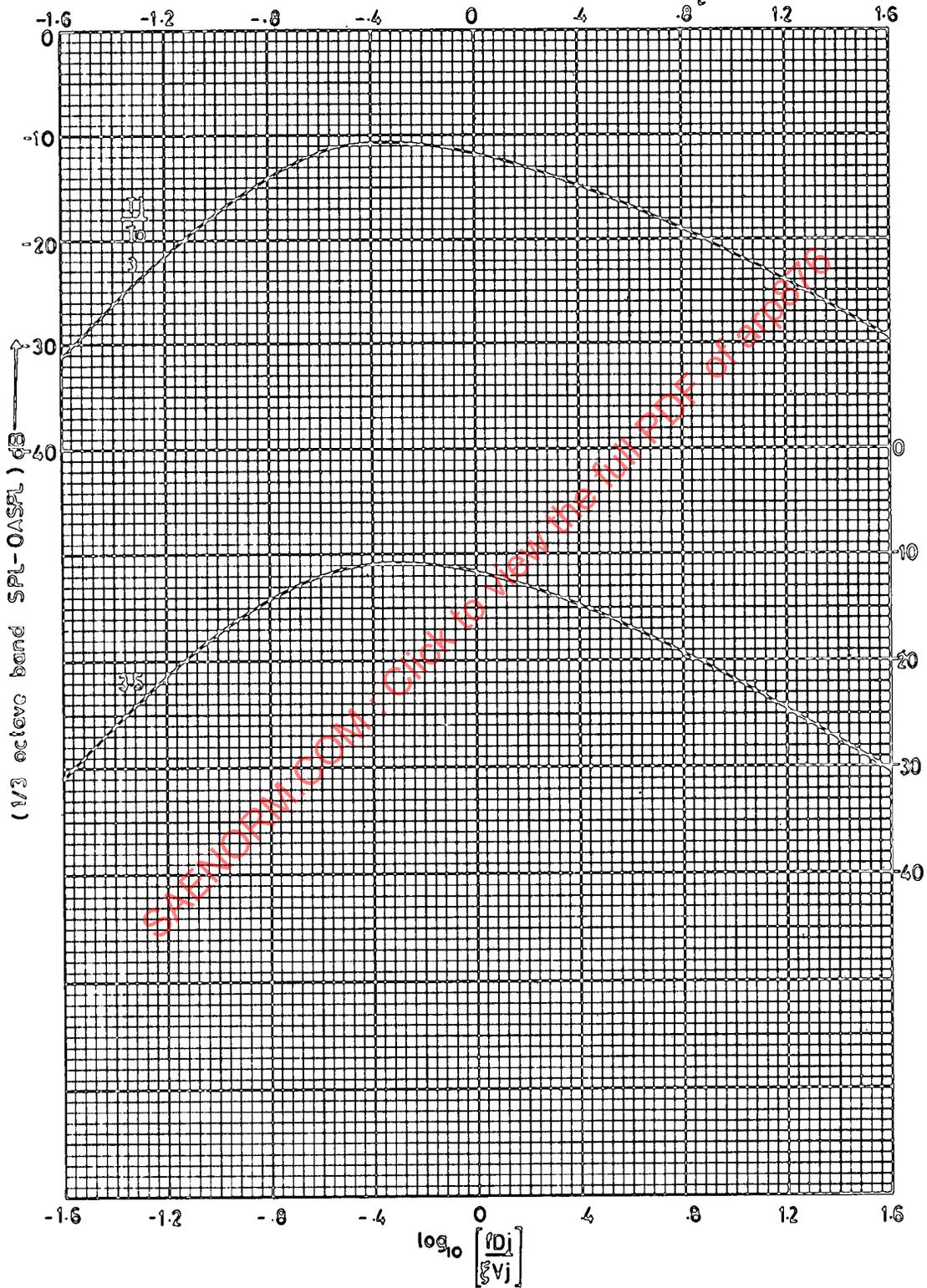


FIG A6.

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 110^\circ$

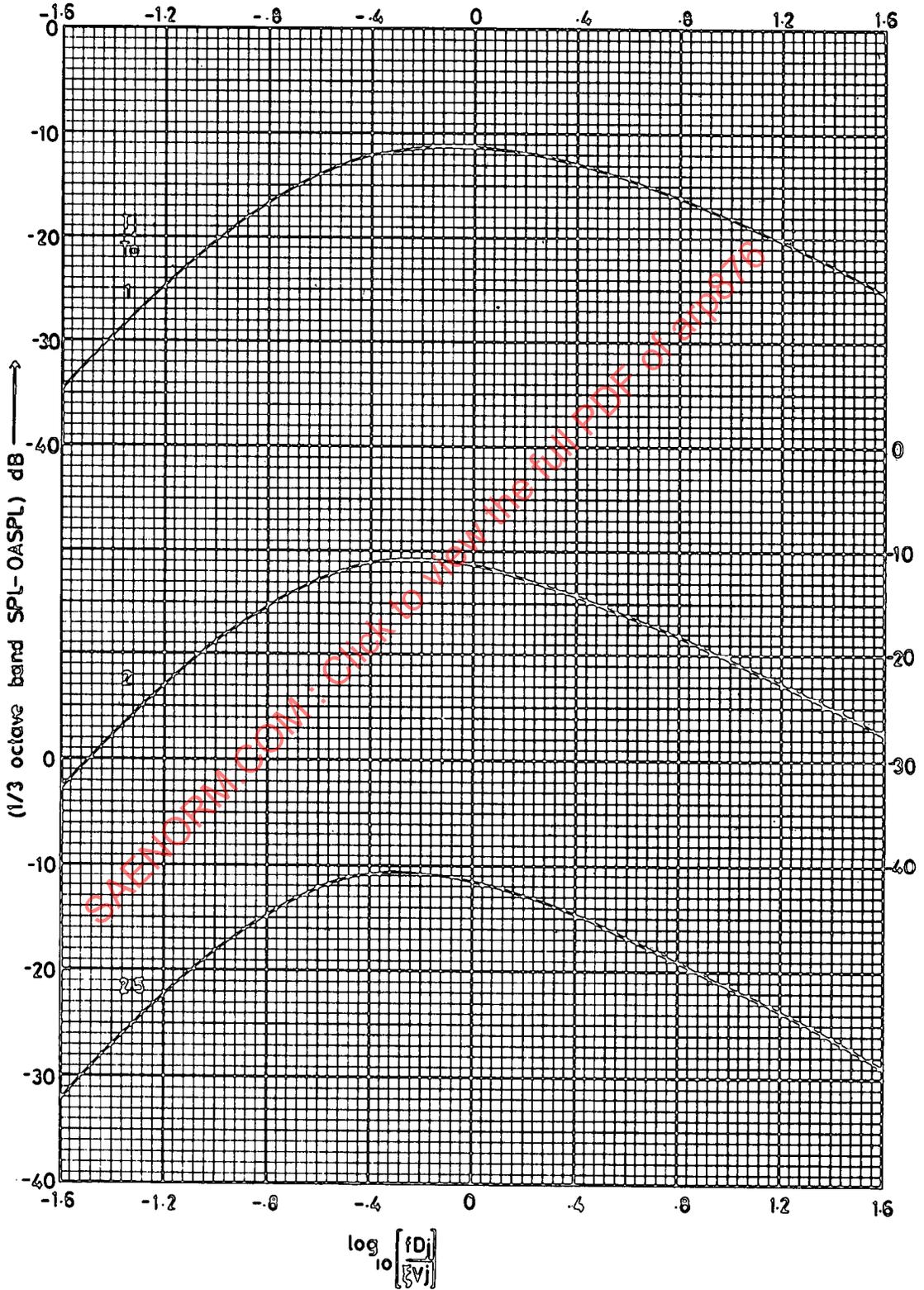


FIG. A6. (CONT'D)

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_3 = 110^\circ$

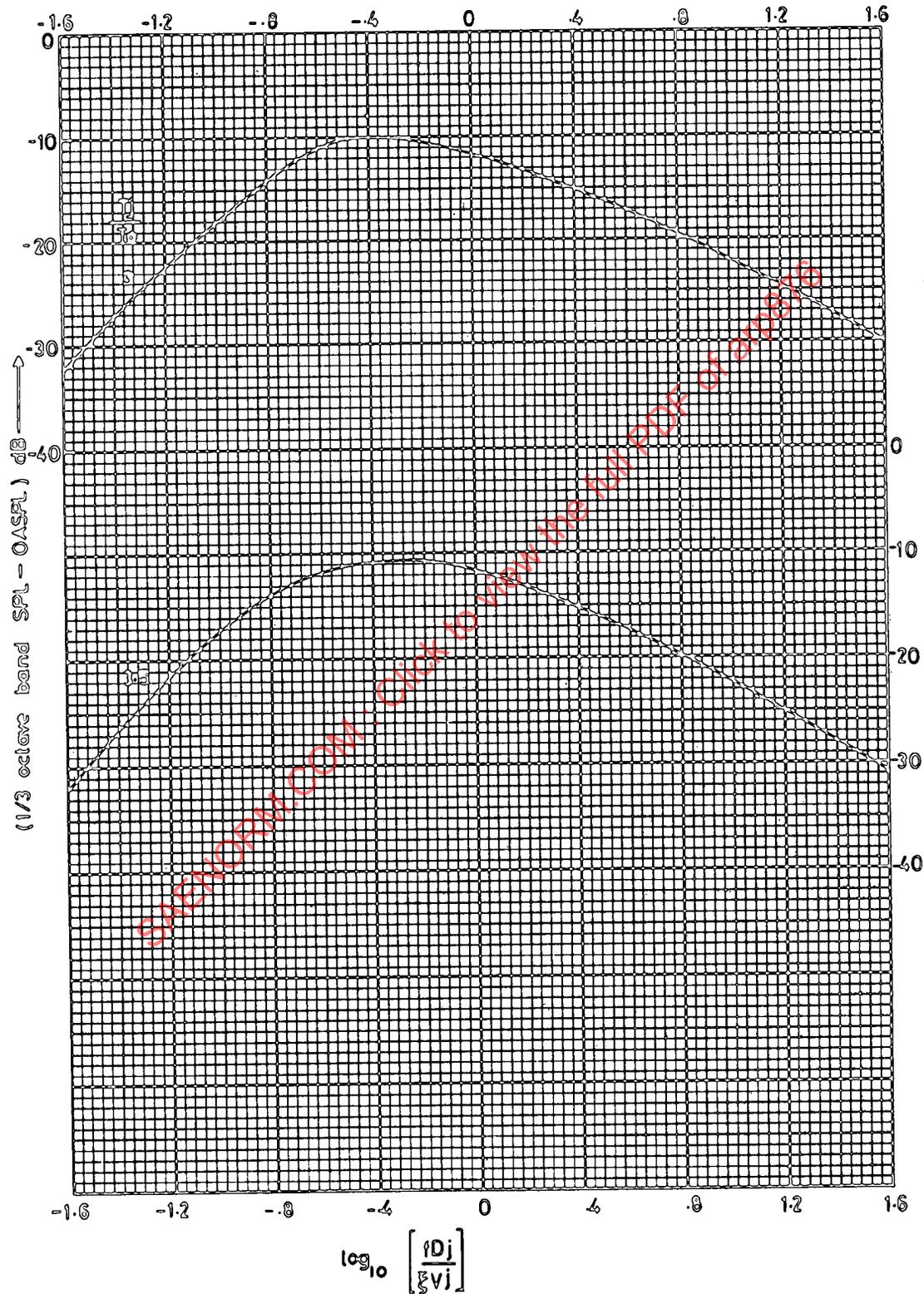


FIG. A7.

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_p = 120^\circ$

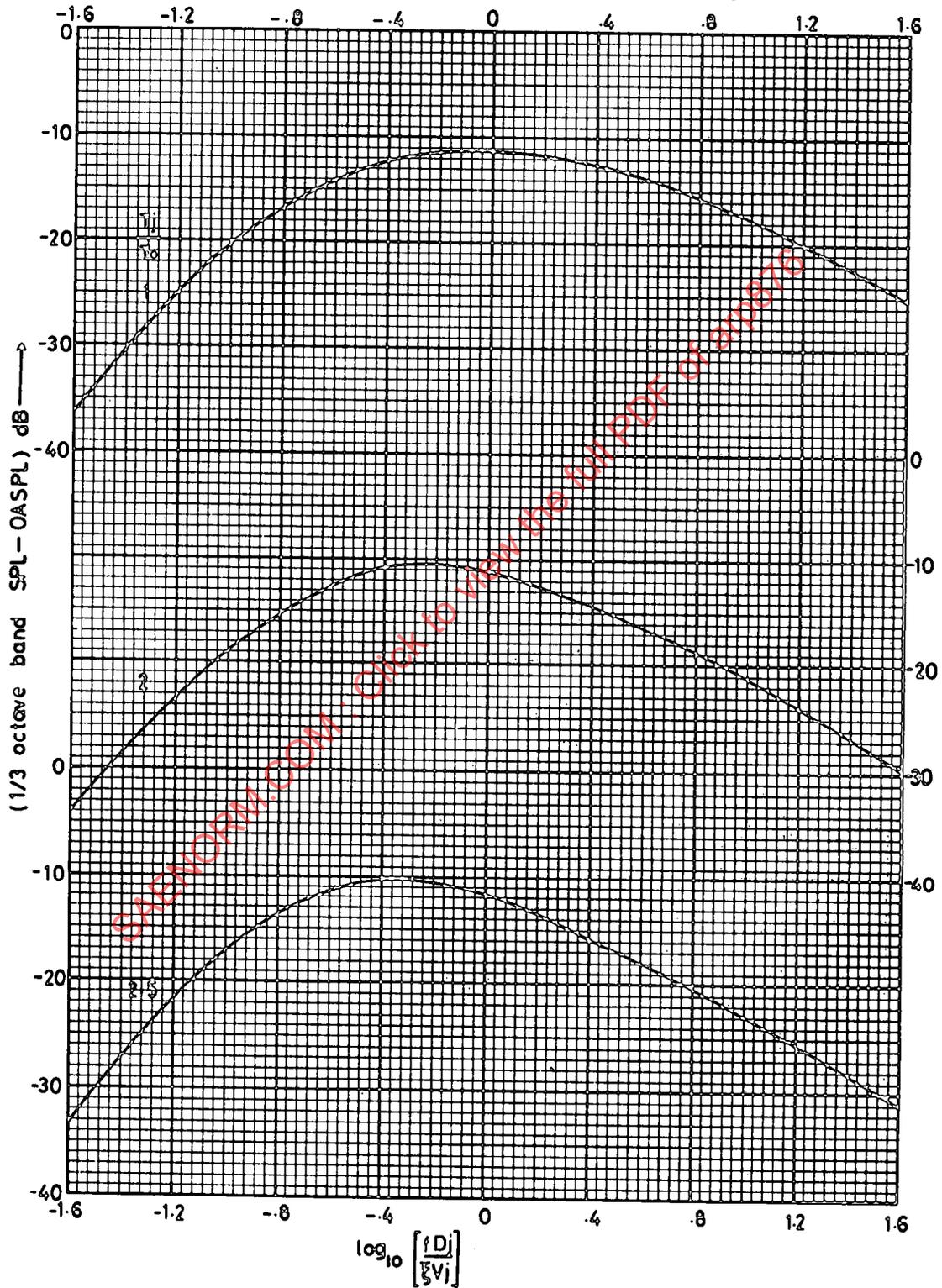


FIG. A7. (CONT'D)

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 120^\circ$

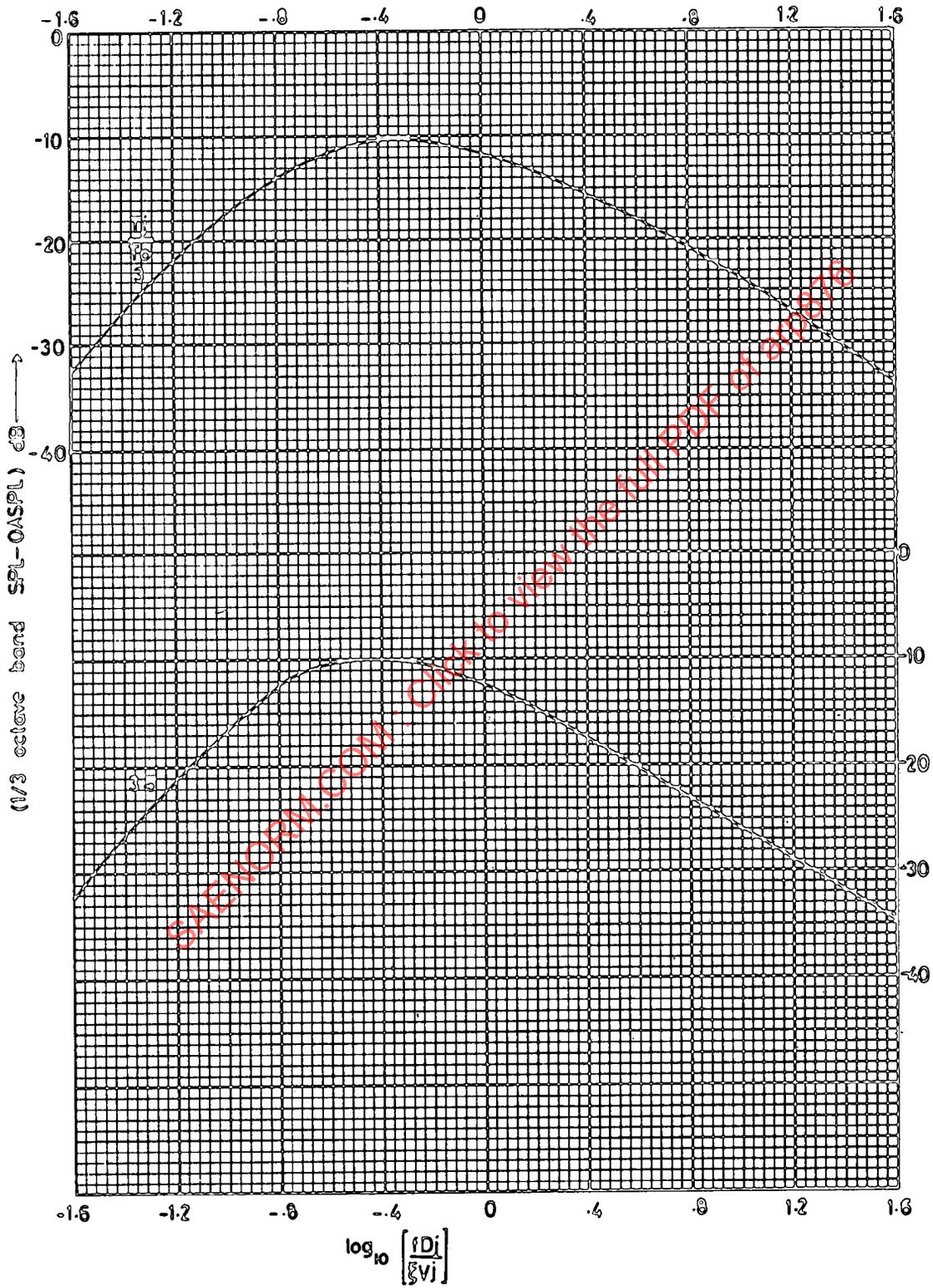


FIG. A8.

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 130^\circ$

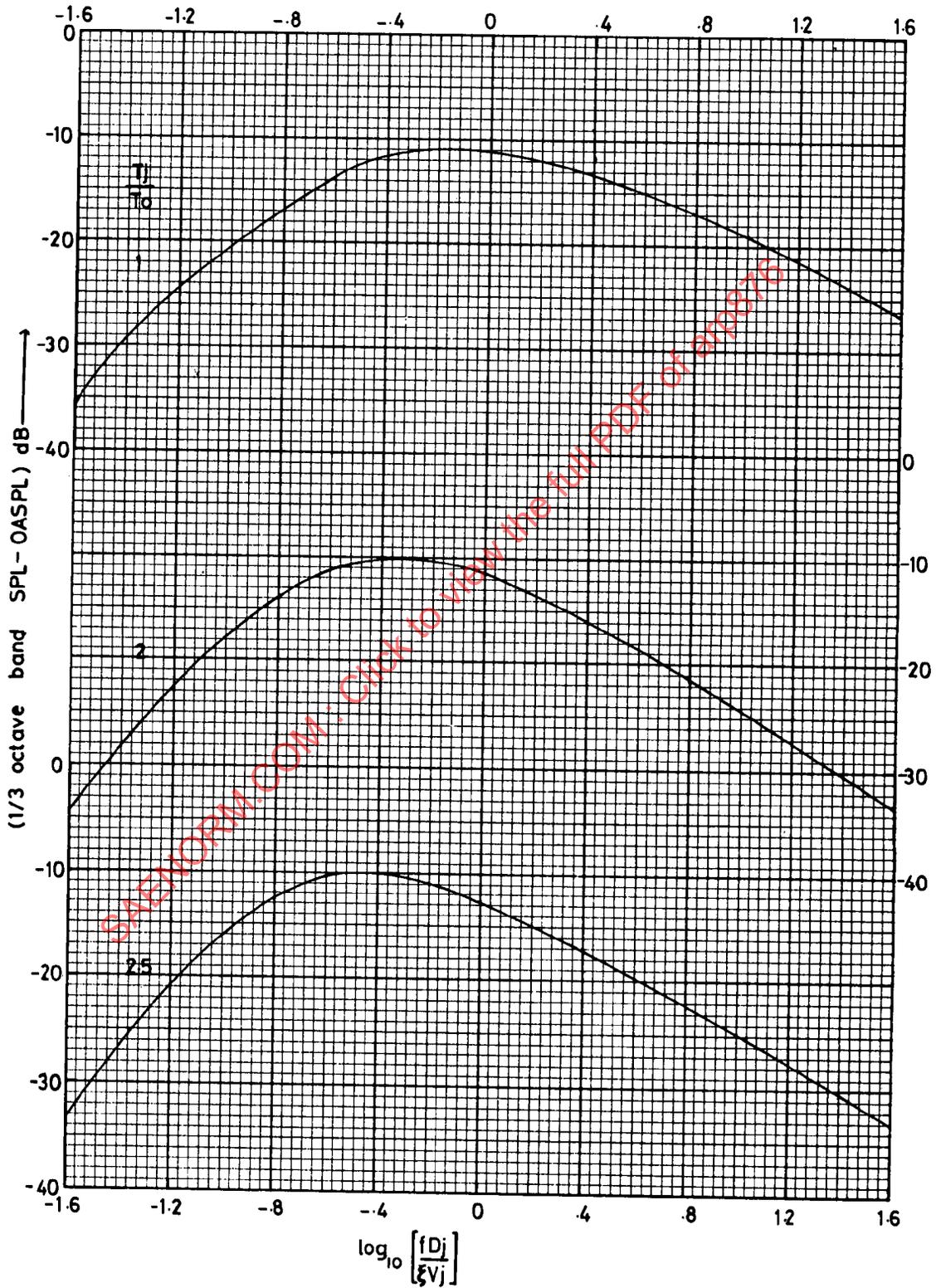


FIG. A8. (CONT'D)
 1/3 OCTAVE BAND NORMALISED SPECTRA. $O_i=130^\circ$

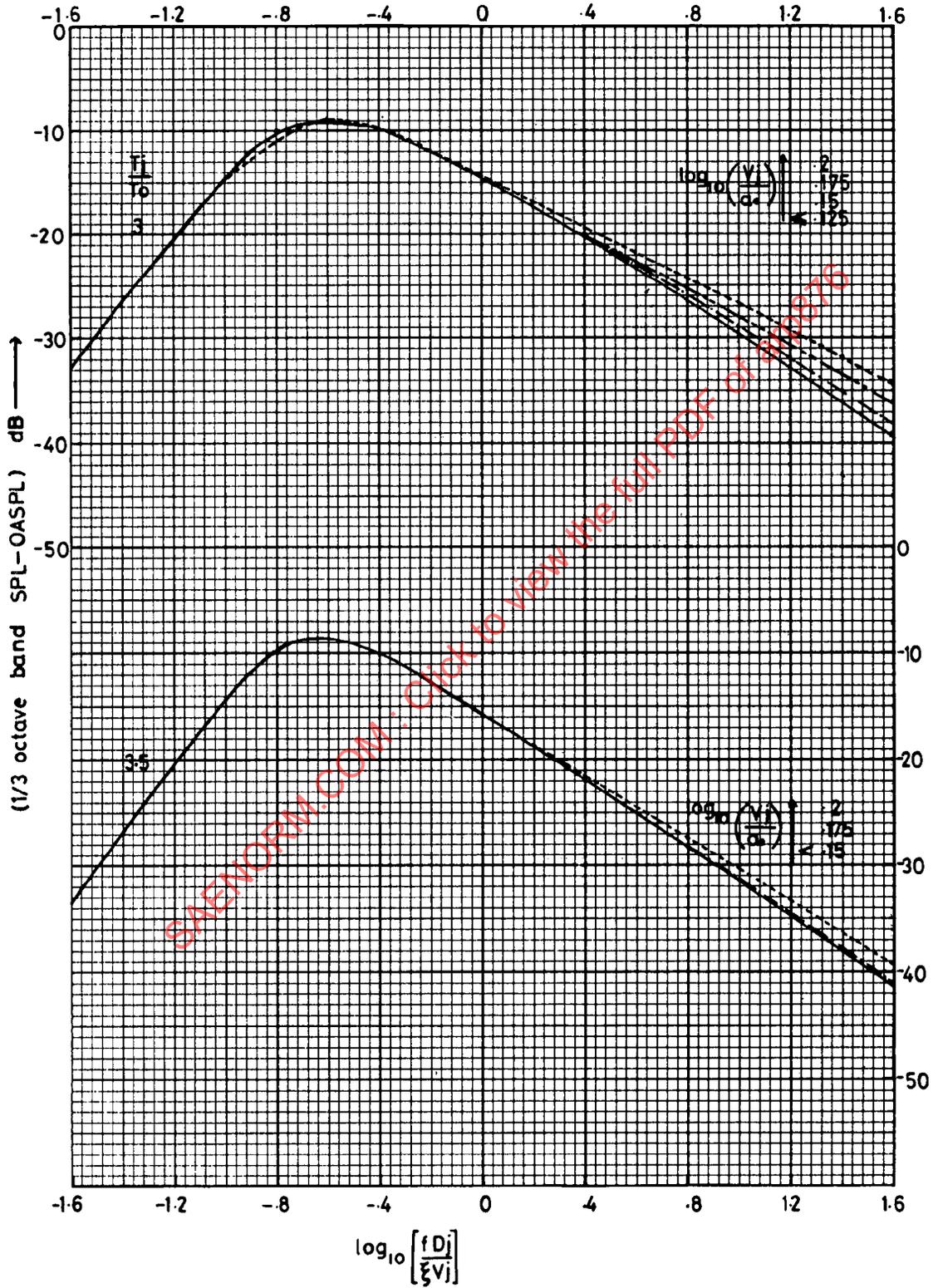


FIG. A9.
1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_1 = 140^\circ$

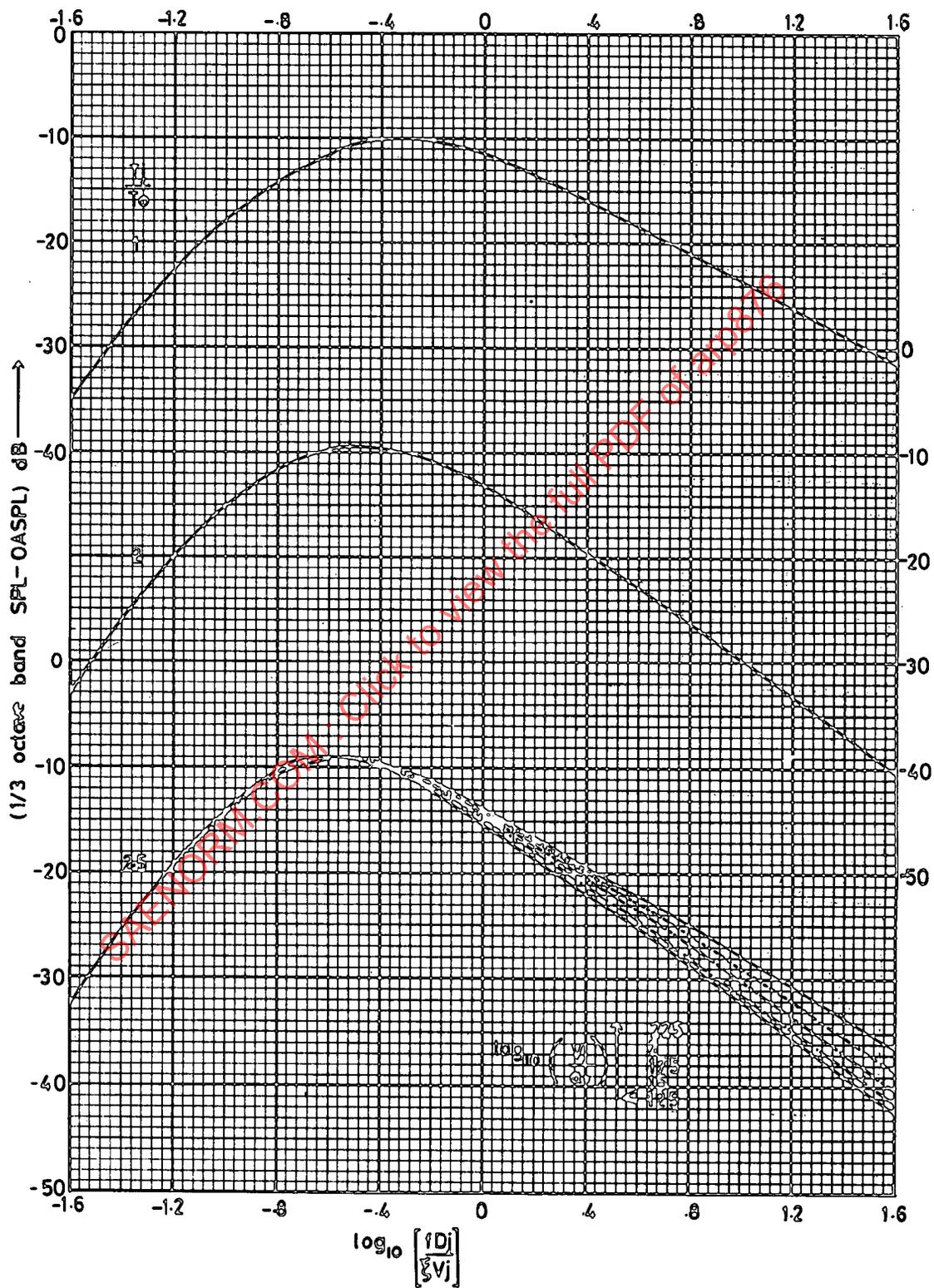


FIG. A10.
1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 150^\circ$

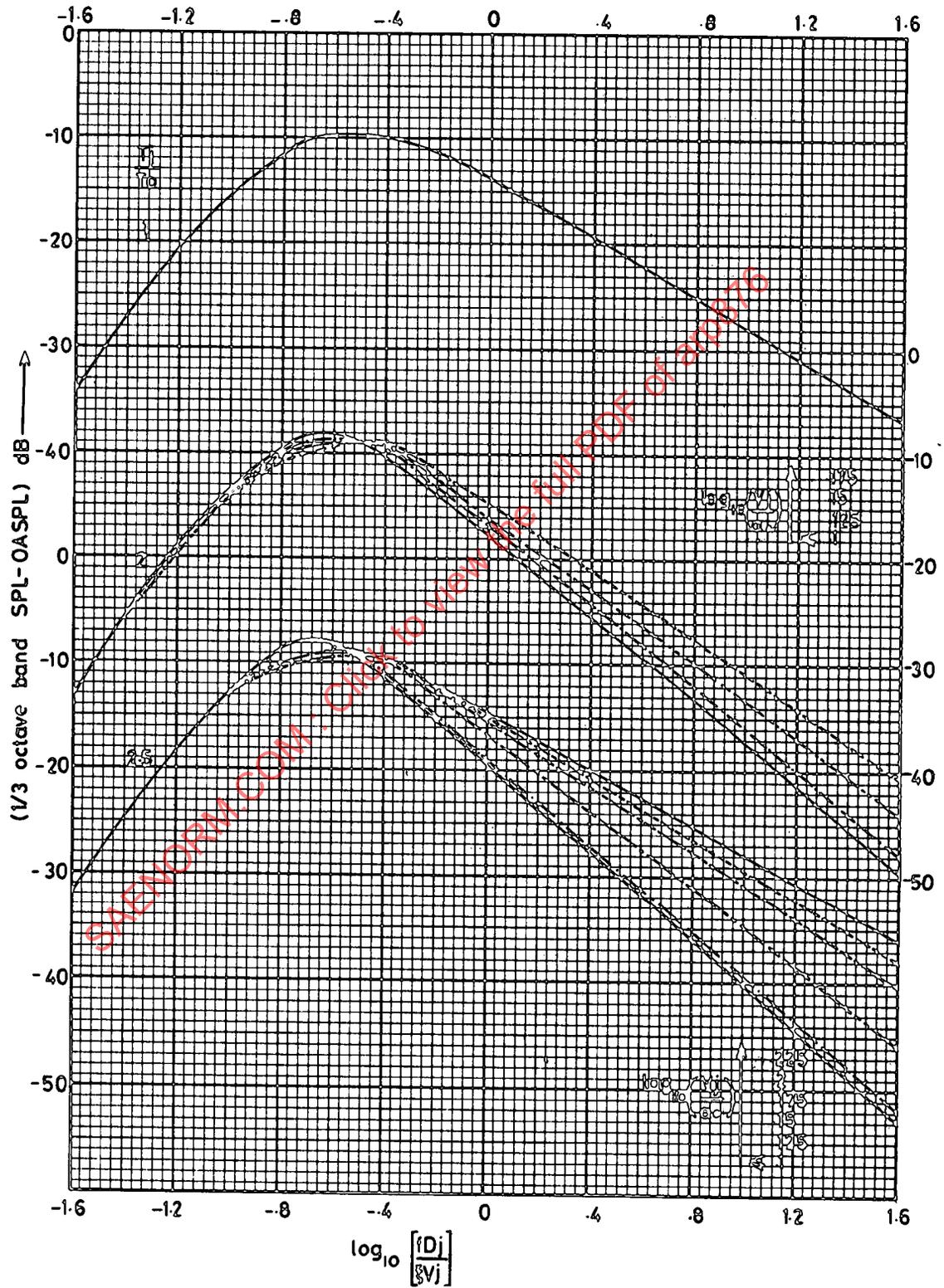


FIG. A10. (CONT'D)

1/3 OCTAVE BAND NORMALISED SPECTRA $\theta_s = 150^\circ$

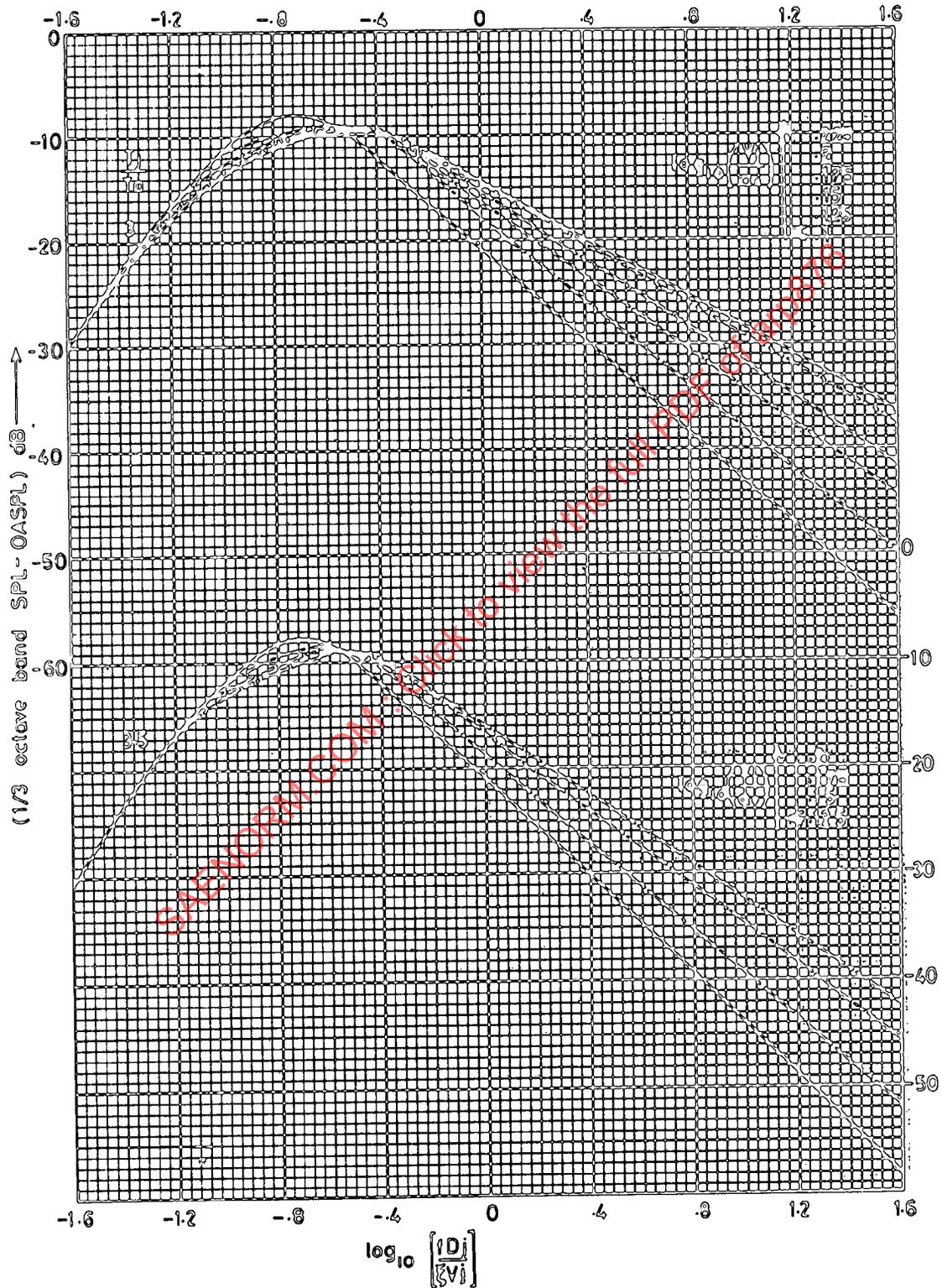


FIG. A11.

1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 160^\circ$

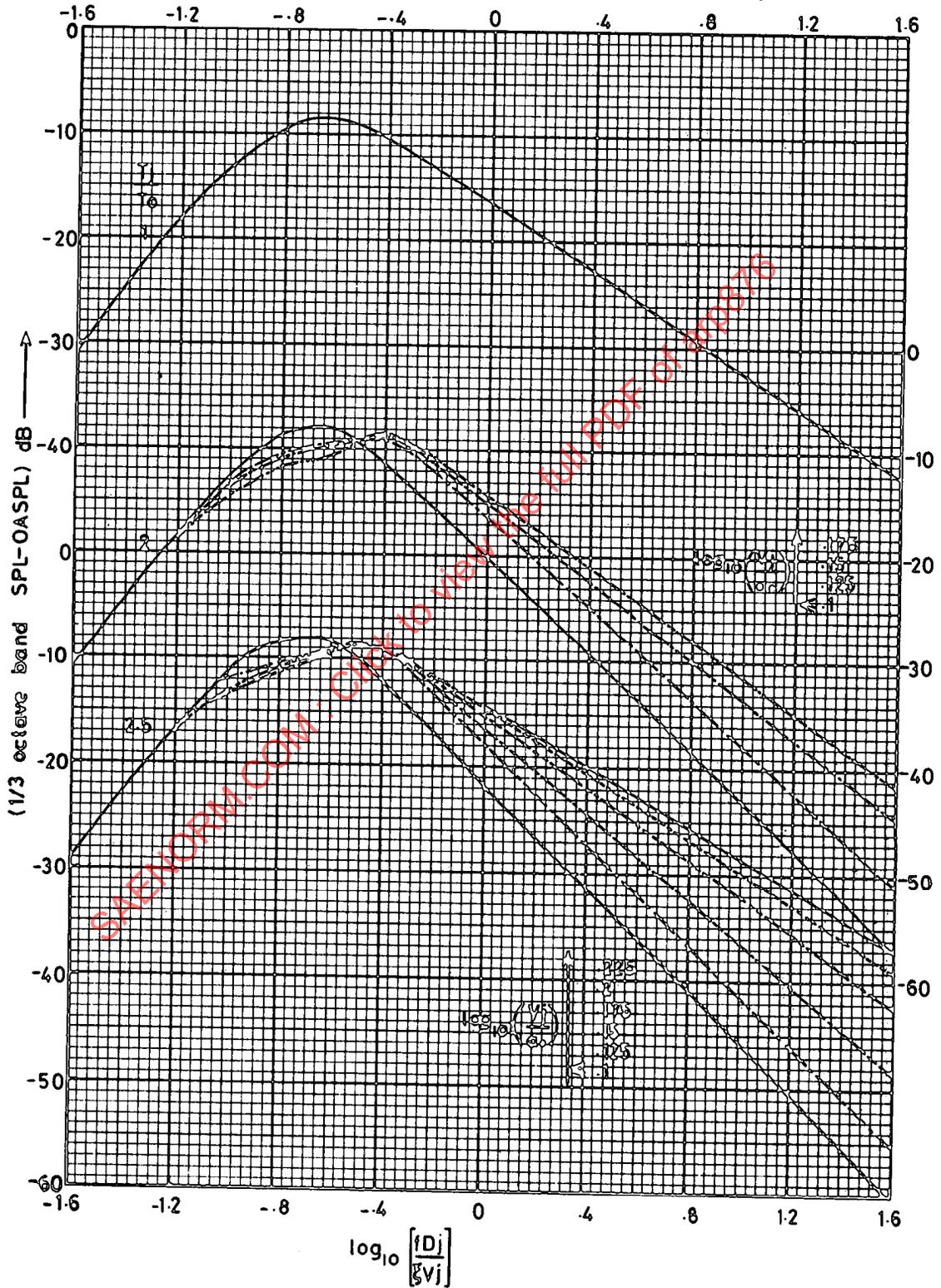


FIG. A11. (CONT'D)
1/3 OCTAVE BAND NORMALISED SPECTRA. $\theta_i = 160^\circ$

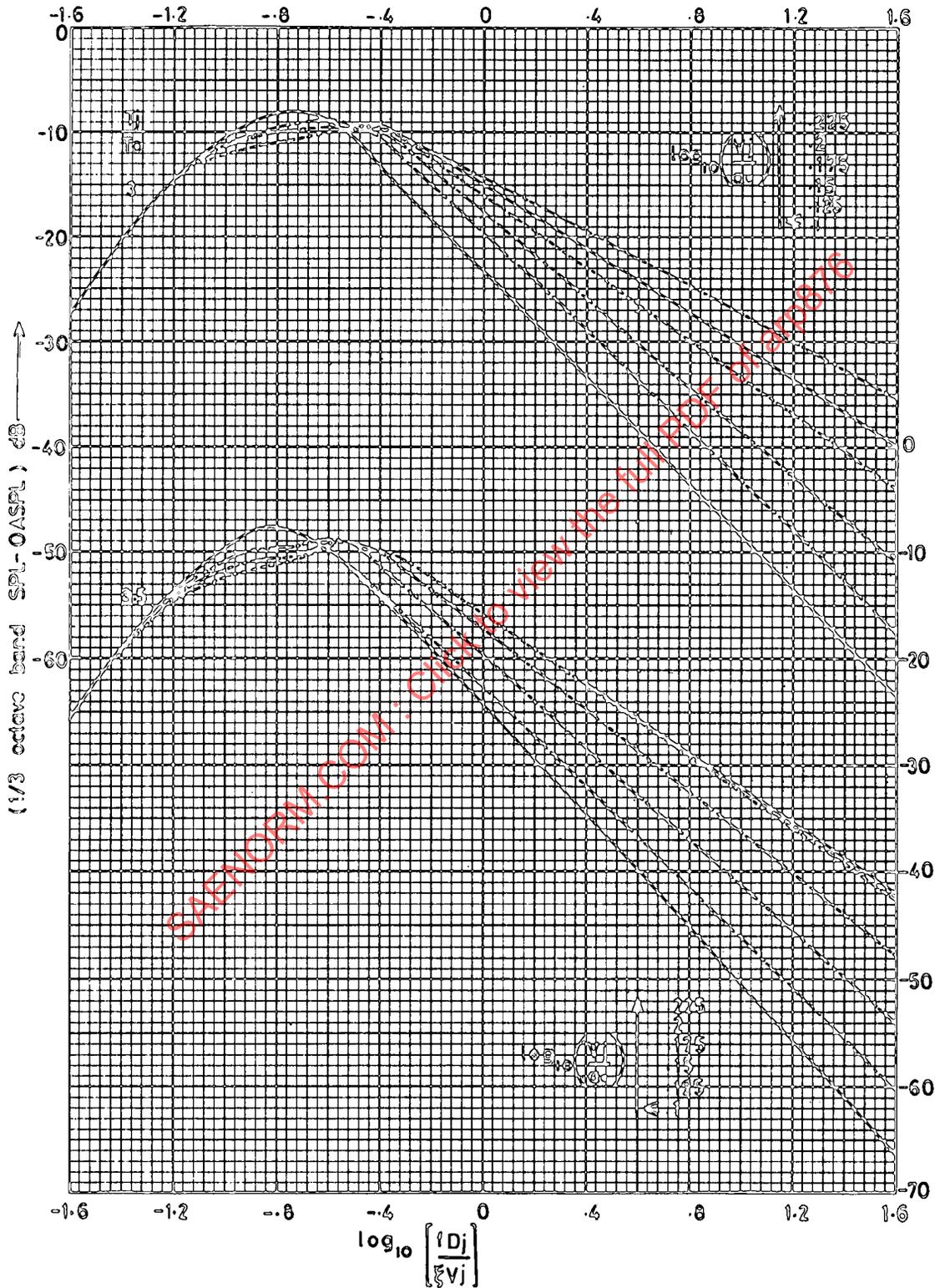


TABLE A1
 VARIABLE DENSITY INDEX ω
 (REF. FIG. A1)

$\text{Log}_{10} \left\{ \frac{V_i}{a_0} \right\}$	ω
-.4	-.90
-.35	-.76
-.3	-.58
-.25	-.41
-.20	-.22
-.15	0
-.10	+.22
-.05	+.50
0	+.77
+.05	+1.07
+.10	+1.39
+.15	+1.74
+.20	+1.95
+.25	+2.0
+.30	+2.0
+.35	+2.0
+.40	+2.0

Note:- The values of ω in this table have been derived from rig data where jet temperature T_j varies from 288°K to 1100°K.

TABLE A2

PURE JET MIXING NOISE
NON-DIMENSIONAL POLAR OASPL VALUES (REF. FIG. A2)

Log $\left\{ \frac{V_1}{a_0} \right\}$	θ_1 , Angle to Inlet														
	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
-0.4	106.6	107.0	107.2	107.5	108.0	108.4	108.8	109.5	110.2	111.2	112.3	113.2	114.0	114.6	114.9
-0.35	110.1	110.5	111.0	111.3	111.5	112.1	112.5	113.2	113.9	115.0	116.1	117.2	118.2	118.7	119.2
-0.30	113.7	114.1	114.5	115.0	115.4	115.8	116.3	116.8	117.7	118.7	120.0	121.2	122.2	122.9	123.4
-0.25	117.3	117.7	118.2	118.5	118.8	119.4	120.0	120.6	121.5	122.6	123.9	125.3	126.5	127.3	127.7
-0.20	121.0	121.3	121.7	122.0	122.5	123.0	123.6	124.3	125.3	126.5	128.0	129.5	130.6	131.5	131.9
-0.15	124.7	125.0	125.5	125.8	126.2	126.6	127.3	128.1	129.2	130.5	132.1	133.8	135.0	136.0	136.3
-0.10	128.4	128.7	129.1	129.5	130.0	130.4	131.0	131.8	133.0	134.5	136.4	138.0	139.5	140.4	140.7
-0.05	132.1	132.4	132.8	133.1	133.7	133.9	134.7	135.7	136.9	138.7	140.7	142.7	144.3	145.4	145.3
0	136.0	136.1	136.4	136.7	137.1	137.7	138.4	139.4	140.9	142.8	145.0	147.5	149.3	150.4	150.2
+0.05	139.9	140.0	140.3	140.6	141.0	141.4	142.3	143.3	145.0	147.1	149.6	152.3	154.8	156.1	155.4
+0.10	143.9	144.0	144.1	144.3	144.6	145.2	146.1	147.4	149.0	151.4	154.2	157.4	160.3	161.9	161.0
+0.15	147.5	147.8	148.0	148.3	148.8	149.3	150.3	151.5	153.3	155.8	159.0	162.8	165.8	167.0	165.8
+0.20	151.3	151.5	151.9	152.4	152.9	153.7	154.6	155.9	157.7	160.4	164.2	168.5	171.1	171.3	170.0
+0.25	154.8	155.2	155.5	156.0	156.7	157.5	158.5	159.9	161.7	164.8	168.8	173.6	175.7	174.9	172.6
+0.30	158.1	158.5	159.0	159.5	160.2	161.1	162.2	163.7	165.8	168.9	173.4	178.0	179.6	177.8	174.6
+0.35	161.3	161.6	162.1	162.7	163.3	164.3	165.5	167.1	169.3	172.7	177.2	181.5	182.5	180.1	176.2
+0.4	164.3	164.5	164.9	165.4	166.0	167.0	168.3	170.0	172.5	176.4	180.6	184.2	183.8	181.4	177.5

TABLE A3

$\left(\frac{v_i}{a_0}\right)$	Values of ξ (ref. Fig. A3)					
	$\theta_i \leq 120^\circ$	130°	135°	140°	150°	160°
1.4	1.0	1.0	1.0	1.0	1.0	1.0
1.5	1.0	1.0	1.0	1.0	1.0	.995
1.6	1.0	1.0	1.0	1.0	1.0	.885
1.7	1.0	1.0	1.0	1.0	.965	.76
1.8	1.0	1.0	1.0	.99	.87	.66
1.9	1.0	1.0	1.0	.95	.775	.59
2.0	1.0	1.0	.981	.90	.71	.54
2.1	1.0	1.0	.955	.86	.66	.5
2.2	1.0	1.0	.920	.83	.63	.47
2.3	1.0	.985	.895	.81	.61	.445
2.4	1.0	.970	.88	.795	.595	.43
2.5	1.0	.955	.87	.79	.59	.420

For $\left\{\frac{v_i}{a_0}\right\} < 1.4, \xi = 1.0$

Table A6

GAS TURBINE JET EXHAUST NOISE PREDICTION

ANGLE TO INTAKE = 110.00 DEGREES

$\log_{10} \left[\frac{fD}{VJ} \right]$	1/3RD OCTAVE BAND			SOUND PRESSURE LEVEL (SP.-OASPL) DB
	1/3RD	OCTAVE	BAND	
-1.60	-34.57	-32.82	-32.12	-32.30
-1.50	-32.12	-30.26	-29.55	-30.12
-1.40	-29.69	-27.74	-27.08	-28.14
-1.30	-27.27	-25.32	-24.72	-26.00
-1.20	-24.87	-23.10	-22.58	-23.43
-1.10	-22.40	-20.93	-20.41	-20.73
-1.00	-19.97	-18.82	-18.22	-18.10
-0.90	-18.18	-16.93	-16.26	-16.04
-0.80	-16.57	-15.24	-14.54	-14.31
-0.70	-14.98	-13.84	-13.14	-12.81
-0.60	-13.75	-12.60	-12.10	-10.80
-0.50	-12.67	-11.53	-11.22	-10.80
-0.40	-12.08	-10.93	-10.63	-10.70
-0.30	-11.57	-10.63	-10.52	-10.50
-0.20	-11.45	-10.54	-10.67	-10.52
-0.10	-11.39	-10.83	-10.92	-10.98
0.0	-11.37	-11.33	-11.32	-11.70
0.10	-11.50	-11.90	-11.96	-12.40
0.20	-11.83	-12.56	-12.79	-13.16
0.30	-12.32	-13.32	-13.73	-13.99
0.40	-12.90	-14.15	-14.74	-14.91
0.50	-13.51	-15.05	-15.76	-15.95
0.60	-14.21	-16.04	-16.81	-17.14
0.70	-15.03	-17.13	-17.93	-18.44
0.80	-15.94	-18.26	-19.08	-19.81
0.90	-16.93	-19.41	-20.25	-21.19
1.00	-17.97	-20.54	-21.42	-22.50
1.10	-19.05	-21.65	-22.59	-23.77
1.20	-20.22	-22.78	-23.77	-25.03
1.30	-21.44	-23.91	-24.97	-26.29
1.40	-22.72	-25.04	-26.17	-27.53
1.50	-24.06	-26.19	-27.39	-28.77
1.60	-25.47	-27.34	-28.62	-30.00
(TJ/T0)	1.00	2.00	2.50	3.00
LOG(VJ/A0)	≤ 0.400	≤ 0.400	≤ 0.400	≤ 0.400

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