Bolt Beranek and Newman Inc.

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AN EVALUATION OF SPACE SHUTTLE STS-3 PAYLOAD BAY ACOUSTIC DATA AND COMPARISON WITH PREDICTIONS

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Goddard Space Flight Center
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TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	MICROPHONE LOCATIONS	2
	2.1 Payload Bay Microphones	2
	2.2 Exterior Microphones	4
3.	GENERAL ASSESSMENT OF ACOUSTIC DATA	8
	3.1 Forward Bulkhead Measurements	8
	3.2 Data Analysis Procedures	9
	3.3 Noise Floor Corrections	9
	3.4 Data Frequency Range	10
4.	EVALUATION OF INTERIOR ACOUSTIC DATA	11
	4.1 Planned Evaluation of STS-3 Data	11
	4.2 Alternate Evaluation of STS-3 Data	16
	4.3 Comparisons to STS-1 and STS-2 Data	17
	4.4 Final Estimate of Space-Average Levels	20
	4.5 Tolerance Limits on Spatial Variability	27
5.	EVALUATION OF EXTERIOR ACOUSTIC DATA	30
	5.1 Summary of STS-3 Data	30
	5.2 Comparisons to STS-1 and STS-2 Data	30
	5.3 Estimation of Space-Average Sound Levels	35
	5.4 Data Input for PACES	45
6.	PACES CALCULATIONS	54
	6.1 Interior Space-Average Sound Levels	54
	6.2 Empty Bay Representation	54
	6.3 Representation with a Single Payload	56
	6.4 Representation with Two Subvolumes	59
	6.5 Comparison with Measured Data	61
	6.6 Influence of Vents	67
7.	CONCLUSIONS	68
	REFERENCES	70
	APPENDIX A	

LIST OF FIGURES

Page

1. Payload Bay Configuration for STS-3. 3
2. Microphone Locations on DFI Payload for STS-3. . . 5
3. Microphone Locations on OSS-1 Payload for STS-3. . 6
4. Locations of Microphones Which Provided Data on Exterior Sound Field for STS-3. 7
5. Estimate of Space-Average Sound Pressure Levels in Payload Bay for STS-3 Lift-Off. 15
6. Alternate Estimate of Space-Average Sound Pressure Levels in Payload Bay for STS-3 Lift-Off 19
7. Comparison of Space-Average Sound Pressure Levels in Payload Bay for STS-1, STS-2 and STS-3 Lift-Off 21
8. Estimated Space-Average Sound Pressure Levels in Payload Bay at Lift-Off (Based on STS-1, STS-2 and STS-3 Launches). 26
9. Limits on Spatial Variation of Sound Pressure Levels in Payload Bay at Lift-Off (Based on STS-1, STS-2 and STS-3 Launches) 28
10. Comparison of Sound Pressure Levels at Exterior Locations for STS-1, STS-2 and STS-3 Lift-Off. . . 32
11. Sound Levels on Payload Bay Door for STS-3 Lift-Off 37
12. Comparison of Space-Average Sound Levels on Payload Bay Door for STS-1, STS-2 and STS-3 Lift-Off. 39
13. Sound Levels on Mid-Fuselage Sidewall for STS-3 Lift-Off 40
14. Comparison of Space-Average Sound Levels on Forward Region of Mid-Fuselage Sidewall for STS-1, STS-2 and STS-3 Lift-Off. 42
15. Comparison of Space-Average Sound Levels on Aft Region of Mid-Fuselage Sidewall for STS-1, STS-2 and STS-3 Lift-Off 43

LIST OF FIGURES
(Continued)

	Page
16. Sound Levels on Mid-Fuselage Bottom Structure for STS-3 Lift-Off	44
17. Comparison of Space-Average Sound Levels on Forward Region of Mid-Fuselage Bottom Structure for STS-1, STS-2 and STS-3 Lift-Off.	46
18. Comparison of Space-Average Sound Levels on Aft Region of Mid-Fuselage Bottom Structure for STS-1, STS-2 and STS-3 Lift-Off.	47
19. Comparison of Sound Levels on Payload Bay Aft Bulkhead for STS-1, STS-2 and STS-3 Lift-Off . .	48
20. Space-Average Sound Levels for Exterior of Payload Bay Estimated from STS-3 Lift-Off Data .	49
21. Space-Average Sound Levels for Exterior of Payload Bay Estimated from STS-1 Data.	52
22. Space-Average Sound Levels for Exterior of Payload Bay Estimated from STS-2 Data.	53
23. Space-Average Sound Pressure Levels Predicted by PACES for Empty Payload Bay at Lift-Off (STS-1 through STS-3).	57
24. Space-Average Sound Pressure Levels Predicted by PACES for Payload Bay with Single Volume-Displacing Payload (STS-1 through STS-3)	60
25. Payload Bay Sound Pressure Levels Predicted by PACES for Single Volume and Two-Subvolume Payload Bay Representations with Volume-Displacing Payloads (STS-3)	62
26. Comparison of Predicted (Single Volume with Payload) and Measured (Bias Error Correction Method) Payload Bay Space-Average Sound Pressure Levels for STS-3	63
27. Comparison of Predicted (Single Volume with Payload) and Measured (Four-Volume Average) Payload Bay Space-Average Sound Pressure Levels for STS-3. .	64
28. Comparison of Predicted (Two-Volume Model) and Measured (Four-Volume Average) Payload Bay Space-Average Sound Pressure Levels for STS-3.	66

LIST OF TABLES

Page

1. Summary of Microphone Locations for STS-3. . . . 2
2. Measured Sound Pressure Levels in Payload Bay During STS-3 Lift-Off. 12
3. Space Average Sound Pressure Levels in Payload Bay during STS-3 Lift-Off, Estimated using Bias Corrections on Energy Average 13
4. Microphone Locations in Various Regions of the Payload Bay for STS-3. 17
5. Space Average Sound Pressure Levels in Payload Bay during STS-3 Lift-Off, Estimated using Energy Averages of Subdivided Bay. 18
6. Microphone Locations in Various Regions of the Payload Bay for STS-1 through STS-3. 22
7. Space-Average Sound Pressure Levels in Payload Bay during Space Shuttle Lift-Off, Estimated Using all Data from STS-1 through STS-3. 25
8. One-Third Octave Band Sound Levels Exterior to the Payload Bay during STS-3 Lift-Off 31
9. Exterior Space-Average Sound Pressure Levels for STS-3 Lift-Off (dB re 20 μPa). 50
10. Estimated Absorption Coefficients for Payload Bay. 55
11. Assumed Absorption Coefficients for Payload Surfaces 58

1. INTRODUCTION

During the Flight Readiness Firing (FRF) and the first two launches (STS-1 and STS-2) of the Space Shuttle, sound pressure levels were measured at various locations inside the payload bay as well as on the exterior of the orbiter structure. Among other applications, these data have been used to evaluate the "Payload Acoustic Environment for Shuttle (PACES)" computer program developed by Bolt Beranek and Newman Inc. (BBN) [1]. The preliminary evaluations of PACES using the FRF, STS-1, and STS-2 acoustic data are presented in [2-4]. Additional acoustic data inside the payload bay and over the exterior of the orbiter were collected during the third launch (STS-3). This report summarizes the analysis and evaluations of the STS-3 data for similar purposes.

The data used for the evaluations reported herein were provided by the NASA "30-Day Report" [5] and by additional data reduction performed by NASA at the request of BBN. The general approach followed in the analysis is as detailed in [6] with the modifications introduced in [2-4]. In particular, an additional data evaluation procedure is carried out whereby the bay is divided into four regions and the average sound pressure levels are determined for each region separately. This additional procedure, first introduced in the STS-2 data evaluations [4], is motivated by the apparent increase in payload bay sound pressure levels as the measurement location moves forward.

2. MICROPHONE LOCATIONS

During the STS-3 launch, sound pressure levels were measured inside the payload bay of the orbiter vehicle, on the exterior of the vehicle and in the aft fuselage.

2.1 Payload Bay Microphones

A total of 12 microphones were installed in the bay, but two microphones malfunctioned and a third could not provide representative data because it was located inside a payload component. Of the nine microphones in the bay providing good measurements, three each were mounted on the payload bay structure, the DFI payload and the OSS-1 payload, as detailed in Table 1. The three microphones mounted on the orbiter structure (I1 through I3) are shown in Figure 1, the three installed on the DFI payload (I4, I5 and I7) are illustrated

Table 1. Summary of Microphone Locations for STS-3

General Location	BBN Code	NASA Code	Station Number X	Station Number Y	Station Number Z	Frequency Range*
Bay Structure	I1	VO8Y9405A	576	+4	423	A
	I2	VO8Y9219A	863	-100	381	A
	I3	VO8Y9403A	1306	+12	400	A
DFI Payload	I4	VO8Y9220A	1159	0	427	A
	I5	VO8Y9275A	1139	-68	432	B
	I7	VO8Y9281A	1219	-68	384	A
OSS-1 Payload	I19	VO8Y9232A	1060	-35	419	B
	I20	VO8Y9234A	976	11	409	A
	I22	VO8Y9231A	1032	-10	471	B

* A - 20 Hz to 8 kHz; B - 5 Hz to 2 kHz

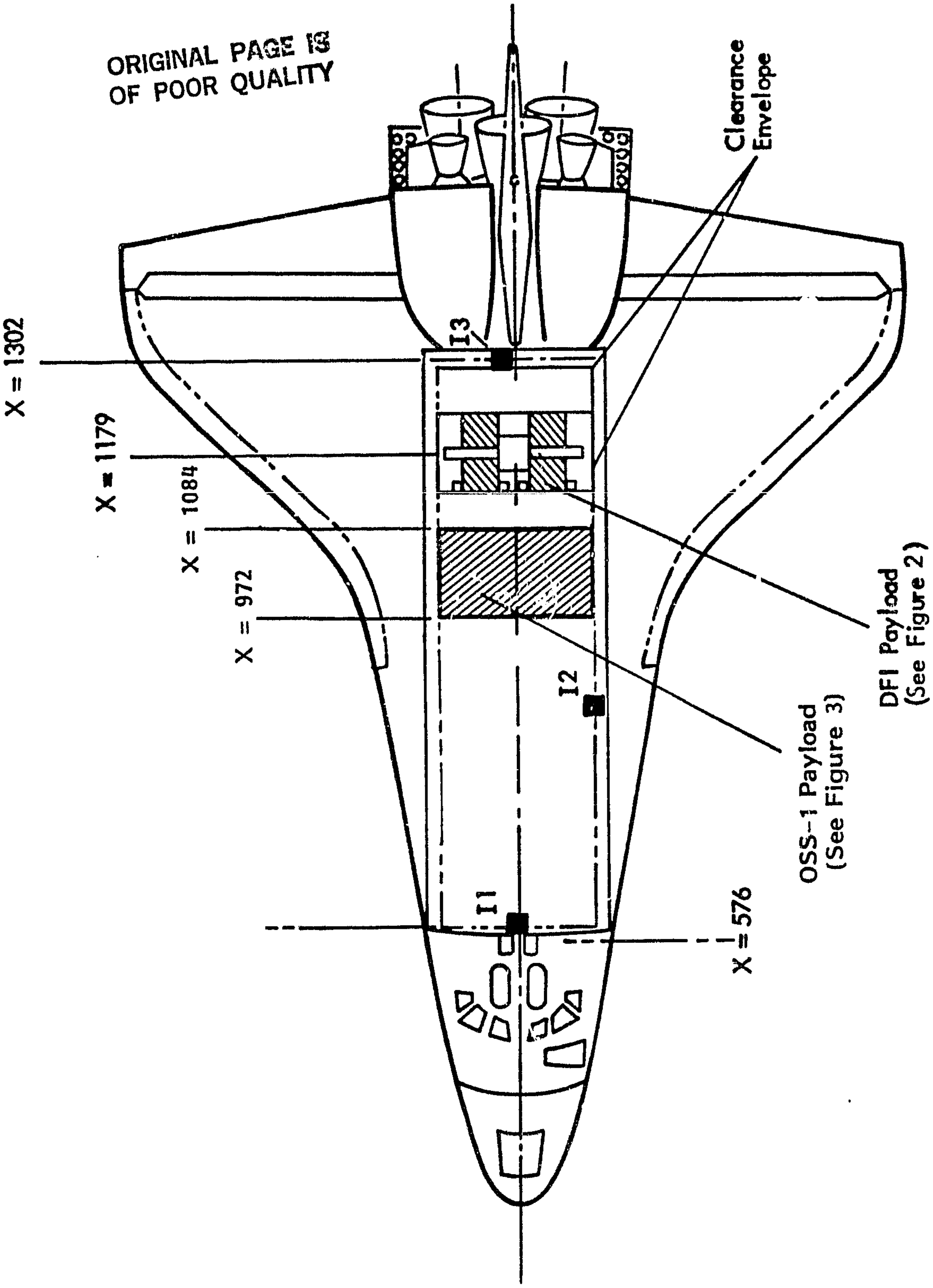

FIGURE 1. PAYLOAD BAY CONFIGURATION FOR STS-3

in Figure 2, and the three located on the OSS-1 payload (I19, I20, and I22) are identified in Figure 3. Note that the detailed locations given in Table 1 are taken directly from the NASA "30-Day Report" [5]* covering the STS-3 flight and are different in some cases from the tentative locations presented in the report covering the preflight bias error correction study [6]. Hence the bias error corrections originally presented in [6] have been recomputed using the actual microphone locations for STS-3 detailed in Table 1. These recomputed bias error corrections for STS-3 are presented in Appendix A to this report.

2.2 Exterior Microphones

A number of flush mounted microphones were installed on the exterior of the orbiter vehicle fuselage, and data from six of these microphones were available for analysis. One final microphone located in the aft fuselage section also provided data. The locations of these exterior microphones are illustrated in Figure 4. The frequency range of the exterior and aft fuselage microphones was stated in [5] to be 20 Hz to 8 kHz.

* With corrections provided verbally by NASA

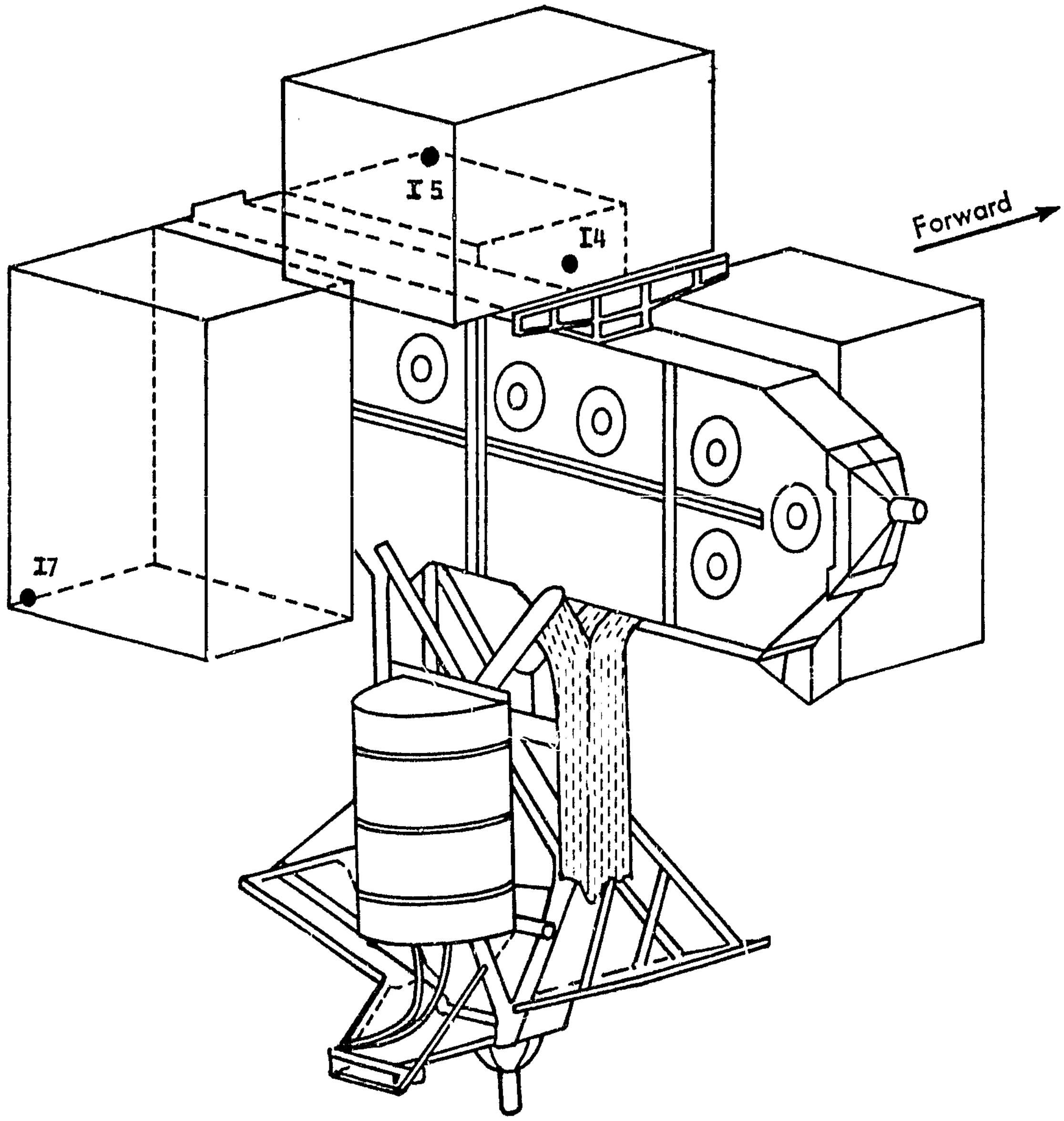

FIGURE 2. MICROPHONE LOCATIONS ON DFI PAYLOAD FOR STS-3

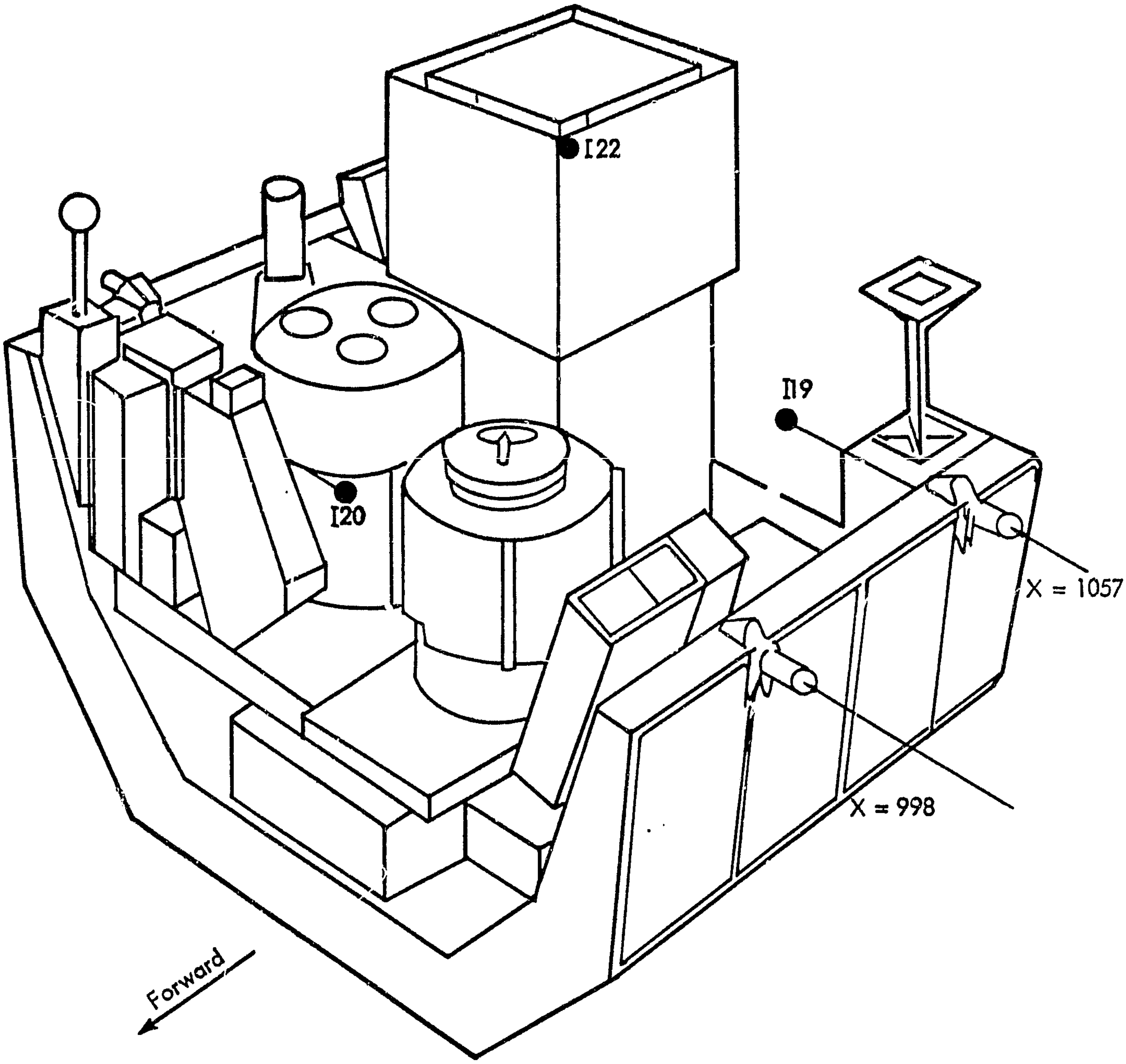

FIGURE 3. MICROPHONE LOCATIONS ON OSS-1 PAYLOAD FOR STS-3

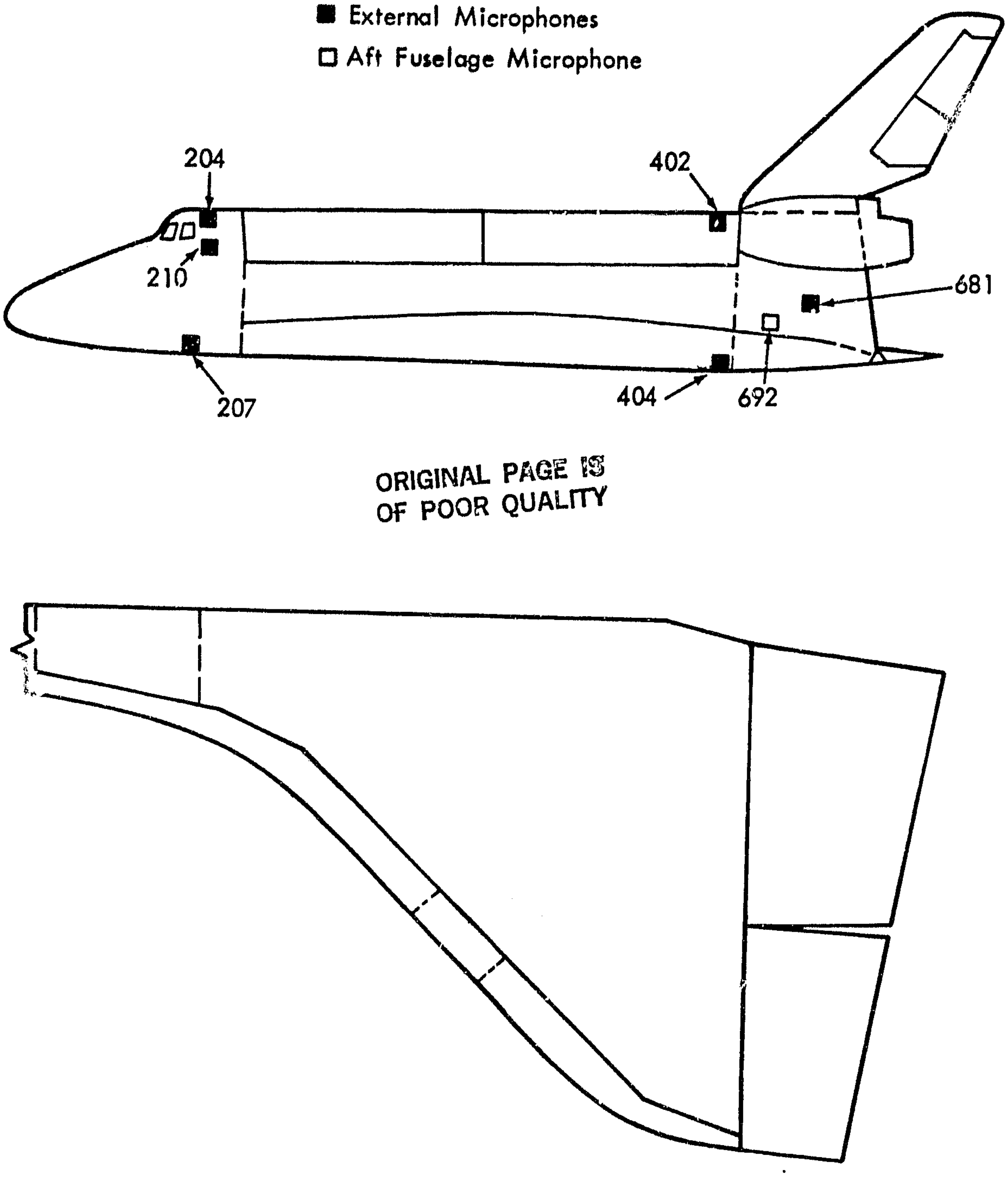

FIGURE 4. LOCATIONS OF MICROPHONES WHICH PROVIDED DATA ON EXTERIOR SOUND FIELD FOR STS-3

3. GENERAL ASSESSMENT OF ACOUSTIC DATA

As for the STS-1 and STS-2 data [3,4], the STS-3 data presented in the "30-Day Report" and provided separately by NASA are of marginal quality. One critical exterior microphone mounted at the forward end of the payload bay doors (V08Y9401 in [5]) as well as one interior microphone on the DFI payload (V08Y9280A in [5]) and a second interior microphone on the OSS-1 payload (V08Y9233A in [5]) produced unusable data during lift-off. All the interior microphones revealed a poor signal-to-noise (S/N) ratio at high frequencies, and there is evidence that the exterior microphones also have this problem. Inspection of the data indicates that the S/N ratio is worse for microphones with an upper frequency limit of 2 kHz than it is for those with an upper frequency limit of 8 kHz. The cause of the poor S/N ratio has not been identified positively, although NASA personnel believe it may be due to intermodulation effects. Since it was not possible to develop a correction procedure with any degree of certainty , the decision was made to exclude, for present purposes, data at frequencies above 800 Hz for microphones with an upper frequency limit of 2 kHz, and above 1600 Hz for all the other microphones (internal and external).

3.1 Forward Bulkhead Measurements

At frequencies below 125 Hz, the interior levels measured at the forward bulkhead (I1) are generally higher than the levels measured at all other locations including the aft bulkhead. This result is contrary to analytical expectations [1] and the results of acoustic experiments performed on OV101 and the Rockwell 1/4 scale model of Space Shuttle [6]. However, the high levels at the forward bulkhead in this same frequency range appeared on the STS-1 and STS-2 flights as well [3,4], and the signals from the forward bulkhead microphone during all three flights reveal no anomalies. Furthermore, the high levels at the forward bulkhead cannot be explained away based upon reflection effects since the influence of reflections in this frequency range on I1 is similar to that experienced by the mid-sidewall (I2) and aft bulkhead (I3) microphones, as computed in Section 3.4 of [6]. These observations tend to support the conclusion that the low frequency sound pressure levels in the forward region of the payload bay probably are higher than in other regions of the bay, contrary to earlier expectations.

3.2 Data Analysis Procedures

The data analysis procedure was the same as followed for STS-1 [3] and STS-2 [4]. Specifically, the data were analyzed in terms of rms values in one-third octave bands expressed in dB referenced to 20 μPa. The one-third octave band levels were determined from the maximum value of continuous rms levels in each one-third octave band computed with an averaging time of 0.5 seconds over the time interval from T = 0 to T + 10 seconds (T = 0 is the time of the SRB ignition). In almost all cases, the maximum one-third octave band levels during lift-off occurred within this time interval, usually around T + 5 seconds. The one-third octave band levels were also computed at T + 120 seconds to establish a noise floor for the instrumentation (at T + 120 seconds, the flight altitude is about 50 km and airborne acoustic noise is negligible).

3.3 Noise Floor Corrections

The one-third octave band levels used for the analyses in this report were corrected for background noise by the following procedures.

1. If the maximum level during lift-off is at least 10 dB above the background noise, no correction is applied to the data.

2. If the maximum level during lift-off is at least 3 dB but less than 10 dB above the background noise, the data are corrected for background noise using the relationship,

$$\text{corrected dB} = 10 \log \left[10^{(dB_r/10)} - 10^{(dB_b/10)}\right] \qquad (1)$$

   where dB_r is the sound pressure level as read during lift-off and dB_b is the background noise level.

3. If the maximum level during lift-off is less than 3 dB above the background noise, the data are considered too contaminated by noise to be useful and are discarded.

This method of correcting for background noise assumes that the signal designated as "background" has a constant level which is independent of test condition. The validity of the assumption is not known for the present situation. Consequently, the "corrected" data have to be regarded with some caution.

3.4 Data Frequency Range

As discussed previously, the microphones have frequency ranges of 5 Hz to 2 kHz or 20 Hz to 8 kHz, and, for present purposes, the corresponding "effective" upper frequency limits for useful data are taken to be 800 Hz and 1600 Hz, respectively. At low frequencies, since NASA presents data over a frequency range starting with the 12.5 Hz one-third octave band for all microphones, it has been assumed in this report that all microphones provide acceptable data down to the 12.5 Hz band.

4. EVALUATION OF INTERIOR ACOUSTIC DATA

The initial plan for the evaluation of the STS-3 data was based upon the bias error correction study in [6]. However, due to the forward bulkhead measurements discussed in Section 3.1, an alternate analysis procedure was introduced in the evaluations of the STS-2 data [4] and is used for the STS-3 data as well.

4.1 Planned Evaluation of STS-3 Data

The maximum one-third octave band sound pressure levels measured during the STS-3 lift-off phase (T = 0 to T + 10 seconds) by the nine microphones inside the payload bay are detailed in Table 2. The energy-average of these measurements is computed in Table 3. Also shown in Table 3 is the bias error correction factor, the estimated space-average level and 95% confidence limits on the true space-average computed for each frequency band. The bias error corrections account for the fact that the nine measurement locations in the bay are not fully representative of the entire bay volume. These bias errors were computed in [6] for assumed microphone locations, and are recomputed in Appendix A herein for the actual locations on STS-3. The space-average estimate is obtained by adding the bias error to the energy-average. The 95% confidence limits for the true space-average levels are defined by

$$\text{Upper 95\% Limit} = 10 \log \left[\bar{\ell}_{ea} + \frac{t_{m;0.025}}{\sqrt{n}} s_{\ell} \right] + \Delta \qquad (2a)$$

$$\text{Lower 95\% Limit} = 10 \log \left[\bar{\ell}_{ea} - \frac{t_{m;0.025}}{\sqrt{n}} s_{\ell} \right] + \Delta \qquad (2b)$$

Table 2. Measured Sound Pressure Levels in Payload Bay During STS-3 Lift-Off

Freq. (Hz)	Measured Sound Pressure Levels, dB (ref: 20 μPa) by Location								
	I1 9405	I2 9219	I3 9403	I4 9220	I5 9275	I7 9281	I19 9232	I20 9234	I22 9231
12	118.5	112.0	120.5	112.0	114.0	118.5	110.5	110.0	114.0
16	120.5	114.5	114.0	106.5	108.5	111.5	114.0	116.5	116.0
20	118.5	114.5	114.5	107.0	109.5	109.0	111.5	114.0	111.5
25	120.0	119.5	120.5	119.0	120.0	116.0	122.0	114.5	121.5
31	122.0	118.5	111.5	112.5	114.5	110.0	113.5	113.0	114.0
40	127.0	122.5	115.0	117.5	119.5	111.5	117.5	119.0	117.0
50	130.0	123.0	115.0	119.0	119.5	115.0	122.0	117.5	122.0
63	130.5	124.0	117.5	119.0	123.5	119.0	122.5	120.0	124.5
80	127.5	128.0	122.5	120.0	121.5	119.0	121.0	124.5	123.5
100	127.5	127.0	124.5	122.5	124.0	123.0	119.0	124.0	126.0
125	127.5	130.0	122.0	120.5	122.5	123.0	119.5	122.5	128.0
160	125.5	125.5	124.5	122.5	124.0	120.0	122.0	120.0	127.0
200	127.0	123.5	123.0	124.0	123.5	122.5	120.0	122.0	127.5
250	123.5	122.0	124.5	123.0	123.5	120.5	122.0	121.0	126.0
315	120.5	121.0	124.5	120.0	122.5	120.0	119.5	118.0	123.0
400	118.5	119.5	119.5	117.5	120.0	116.5	117.5	116.0	121.5
500	117.0	118.5	116.5	114.0	118.0	115.0	114.5	115.5	118.5
630	115.0	118.5	118.5	110.5	116.0	115.0	113.0	114.5	115.0*
800	113.5	116.0	111.5	110.0	114.0*	111.5	111.5*	111.5	**
1000	113.0	114.5	109.0	108.0	**	109.0	**	111.0	**
1250	111.5	115.0	107.0*	107.5	**	107.0	**	109.5	**
1600	110.0	113.5	105.0*	105.5*	**	107.0*	**	107.5	**

* Corrected for instrumentation noise

** Instrumentation noise too large for accurate correction

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Table 3. Space Average Sound Pressure Levels in Payload Bay during STS-3 Lift-Off, Estimated using Bias Corrections on Energy Average

Freq. (Hz)	Sound Pressure Levels in dB (ref: 20 μPa)				
	Energy-Average	Bias Correc.	Space-Average	95% Conf. Limits Lower	Upper
12	116.0	+1.7	117.7	112.4	120.0
16	115.2	-0.6	114.6	108.7	117.1
20	113.5	-0.1	113.4	108.3	115.7
25	119.7	+1.5	121.2	119.4	122.5
31	116.1	+1.3	117.4	107.5	120.3
40	120.7	+1.3	122.0	101.3	125.0
50	123.0	+0.7	123.7	*	127.1
63	124.2	+1.7	125.9	110.8	128.9
80	124.1	0.0	124.1	120.1	126.2
100	124.8	+0.3	125.1	122.8	126.5
125	125.4	-0.1	125.3	120.1	127.6
160	124.0	-0.3	123.7	121.5	125.2
200	124.3	-0.4	123.9	121.2	125.5
250	123.2	+0.3	123.5	121.8	124.7
315	121.4	0.0	121.4	119.3	122.8
400	118.8	-0.1	118.7	117.0	119.9
500	116.7	-0.8	115.9	114.4	117.1
630	115.7	-0.5	115.2	112.8	116.8
800	112.8	-0.5	112.3	110.0	113.9
1000	111.4	-0.4	111.0	106.4	113.2
1250	110.7	-0.3	110.4	98.9	113.2
1600	109.2	-0.8	108.6	97.0	111.2

* Standard deviation too large to define a lower confidence limit

where

$$\bar{\ell}_{ea} = 10^{L_{ea}/10}$$

$$s_\ell = \left[\frac{1}{n-1}\sum_{i-1}^{n}\left(\ell_i - \bar{\ell}_{ea}\right)^2\right]^{\frac{1}{2}}$$

$$\ell_i = 10^{L_i/10}$$

n = sample size = 9

$t_{m;0.025}$ = 0.025 percentage point of Student "t" variable with $m = n - 1 = 8$ degrees-of-freedom

Δ = bias correction factor.

The resulting space-average sound pressure level estimates with 95% confidence intervals are shown in Figure 5. Note that the lower 95% confidence limits are sometimes undefined. This occurs because the term $t_{m;0.025}s_\ell/\sqrt{n}$ in Eq.(2b) sometimes exceeds $\bar{\ell}_{ea}$, producing the logarithm of a negative number. The practical interpretation here is that the sample size of $n = 9$ is not sufficient relative to the scatter in the data to provide a meaningful estimate of the space-average levels, at least in terms of a lower bound.

At frequencies above 800 Hz the sample size is reduced from 9 to 6 because of the contamination from instrumentation noise in three of the data channels (see Table 2). The lower bound of the 95% confidence limits is still defined at these frequencies, although the confidence interval is large.

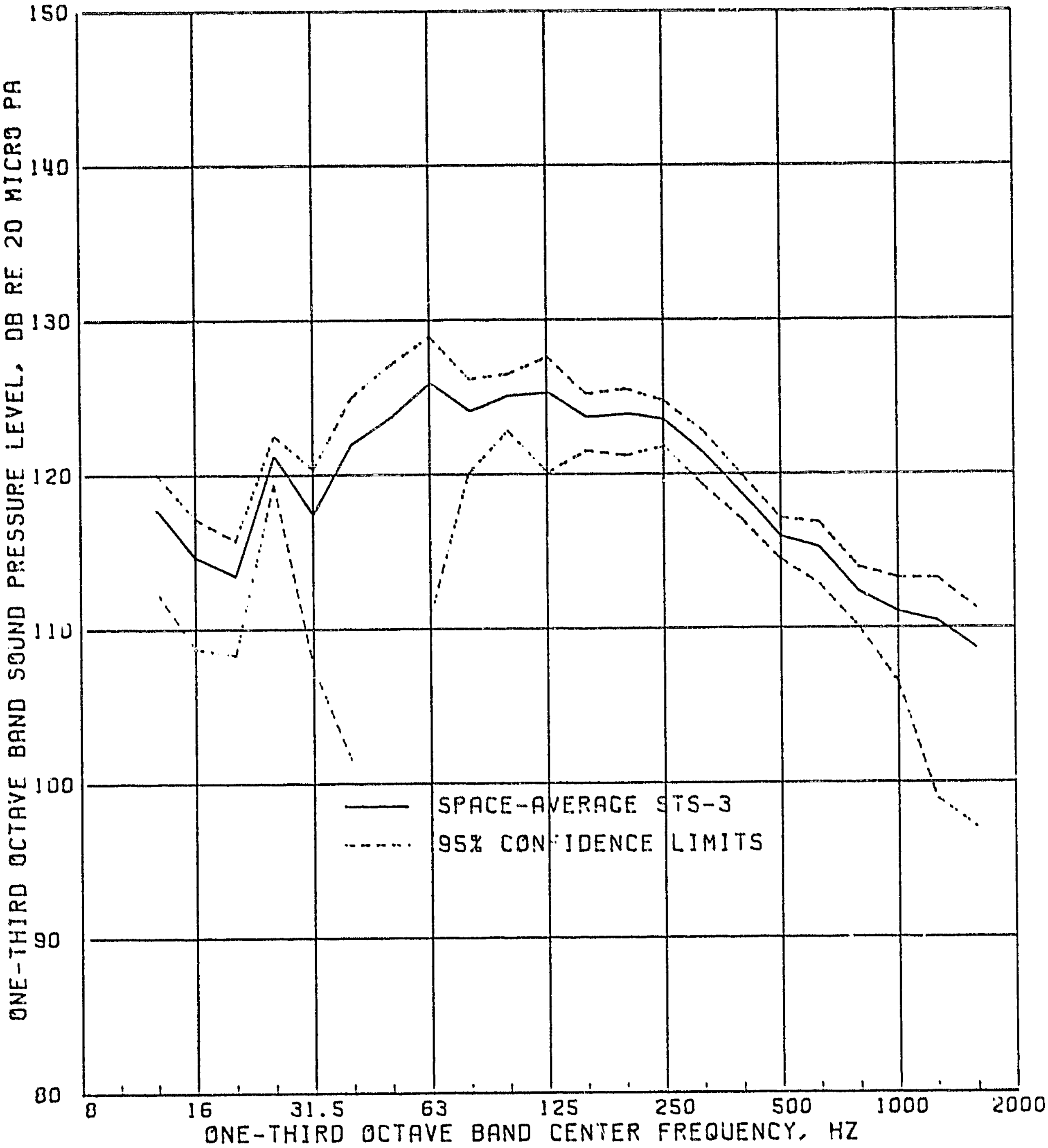

FIGURE 5. ESTIMATE OF SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY FOR STS-3 LIFT-OFF

4.2 Alternate Evaluation of STS-3 Data

Referring back to the discussions concerning the forward bulkhead measurement in Section 3.1, there is now strong evidence that the sound pressure levels in the forward region of the payload bay are generally higher than in other regions of the bay. This was not observed in the data from the OV101 and 1/4 scale model experiments used to derive the bias error correction factors in [6] and Appendix A herein. Hence, there is some reason to doubt the validity of the space-average estimates in Figure 5, computed using the bias error corrections.

For the STS-2 data [4], this situation was dealt with by introducing an alternate estimation procedure as follows:-

1. Divide the payload bay longitudinally into four regions of equal length.

2. Compute the energy-average of the sound pressure levels measured in each region.

3. Estimate the space-average for the entire payload bay from the energy-average of the average levels computed in the four regions.

This alternate procedure is believed to provide more accurate estimates of the payload bay space-average levels and, hence, is applied here to the STS-3 data.

The microphone locations for STS-3 which fall in each of the four regions of the payload bay are detailed in Table 4. The energy-average levels in each region and the estimated space-average levels in the payload bay are presented in Table 5. The space average levels from Table 5 are plotted in Figure 6

Table 4. Microphone Locations in Various Regions of the Payload Bay for STS-3

Region Identification	Region Bounds (Station Nos.)	Measurement Locations In Region
1st 1/4	576- 758	I1
2nd 1/4	759- 941	I2
3rd 1/4	942-1124	I19,I20,I22
4th 1/4	1125-1307	I3,I4,I5,I7

along with the 95% confidence limits on the true space-average computed using Eq.(2) with n = 4. Note that the confidence limits are relatively wide with the lower limit often being undefined because the variance of the data in the four regions is computed assuming the sample average for each region constitutes a single sample value. Conventional variance calculations for stratified sampling [7], which would probably yield a narrower confidence band, are complicated here since two of the regions contain only one sample value.

4.3 Comparisons to STS-1 and STS-2 Data

The estimated space-average sound pressure levels in the payload bay for STS-3 are shown in comparison to the STS-1 and STS-2 estimates in Figure 7. For STS-2 and STS-3, the space-average levels are estimated by the alternate procedure outlined in Section 4.2. For STS-1, there was insufficient data to apply the alternate procedure so these levels were estimated using bias error corrections as detailed in [3].

Table 5. Space Average Sound Pressure Levels in Payload Bay During STS-3 Lift-Off, Estimated using Energy Averages of Subdivided Bay.

Freq. (Hz)	Sound Pressure Levels in dB (ref: 20 μPa)						
	Energy-Average by Quarters				Space Average	95% Conf.Limits	
	1st 1/4	2nd 1/4	3rd 1/4	4th 1/4		Lower	Upper
12.5	118.5	112.0	111.9	117.5	116.0	*	119.3
16	120.5	114.5	115.6	111.0	116.8	*	120.7
20	118.5	114.5	112.5	111.0	115.1	*	118.7
25	120.0	119.5	120.4	119.2	119.8	118.8	120.6
31.5	122.0	118.5	113.5	112.4	118.3	*	122.3
40	127.0	122.5	117.9	116.8	122.9	*	127.3
50	130.0	123.0	120.9	117.6	125.4	*	130.2
63	130.5	124.0	122.7	120.4	126.2	*	130.7
80	127.5	128.0	123.2	121.0	125.8	*	128.9
100	127.5	127.0	123.9	123.6	125.8	120.3	128.2
125	127.5	130.0	124.8	122.1	127.0	*	130.4
160	125.5	125.5	124.0	123.1	124.6	122.3	126.1
200	127.0	123.5	124.4	123.3	124.8	119.5	127.1
250	123.5	122.0	123.6	123.1	123.1	121.8	124.1
315	120.5	121.0	120.7	122.2	121.1	119.6	122.3
400	118.5	119.5	118.9	118.6	118.9	118.1	119.6
500	117.0	118.5	116.5	116.1	117.1	114.9	118.6
630	115.0	118.5	114.2	115.8	116.2	110.1	118.7
800	113.5	116.0	111.5	112.0	113.6	106.4	116.2
1000	113.0	114.5	111.0	108.7	112.3	104.2	115.0
1250	111.5	115.0	109.5	107.2	111.8	*	115.3
1600	110.0	113.5	107.5	105.9	110.2	*	113.8

* Standard deviation too large to define a lower confidence limit

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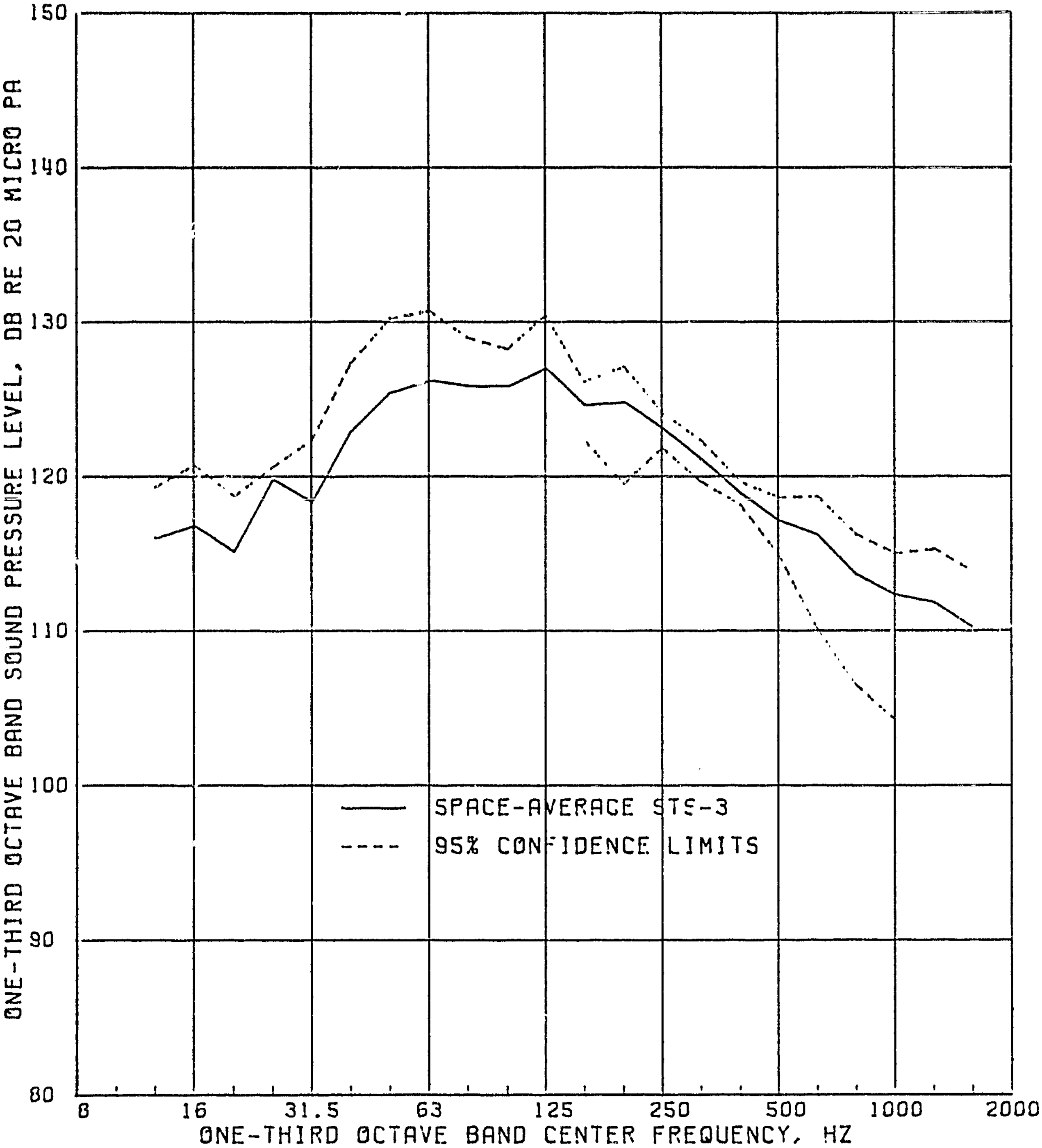

FIGURE 6. ALTERNATE ESTIMATE OF SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY FOR STS-3 LIFT-OFF

In the case of the STS-2 data the results from [4] have been modified at frequencies above 800 Hz to incorporate the "effective" upper frequency limits of 800 Hz or 1600 Hz introduced in Section 3. These limits were not applied in [4] and large differences were observed between space-average sound pressure levels for STS-1 and STS-2 at high frequencies (see, for example, Figure 9 of [4]).

The results in Figure 7 show good agreement among the estimated space-average sound pressure levels for the three launches in the frequency range 31.5 to 1600 Hz. The differences at frequencies below 31.5 Hz undoubtedly reflect normal estimation errors due to the large scatter in the measurements at the very low frequencies. Above 800 Hz the sound pressure levels show much better agreement than was the case for the comparison of STS-1 and STS-2 data in [4] prior to the introduction of the effective upper frequency limits. For example, in Figure 7 the maximum difference between sound pressure levels above 800 Hz is about 2 dB, whereas in [4] the levels differ by about 4 dB.

4.4 Final Estimate of Space-Average Levels

With payload bay sound pressure levels now available from three Space Shuttle launches (STS-1 through STS-3), it is appropriate to estimate space-average levels using all available data. This is done using the alternate procedure outlined in Section 4.2. The various measurement locations from the first three launches are listed by payload bay region in Table 6.

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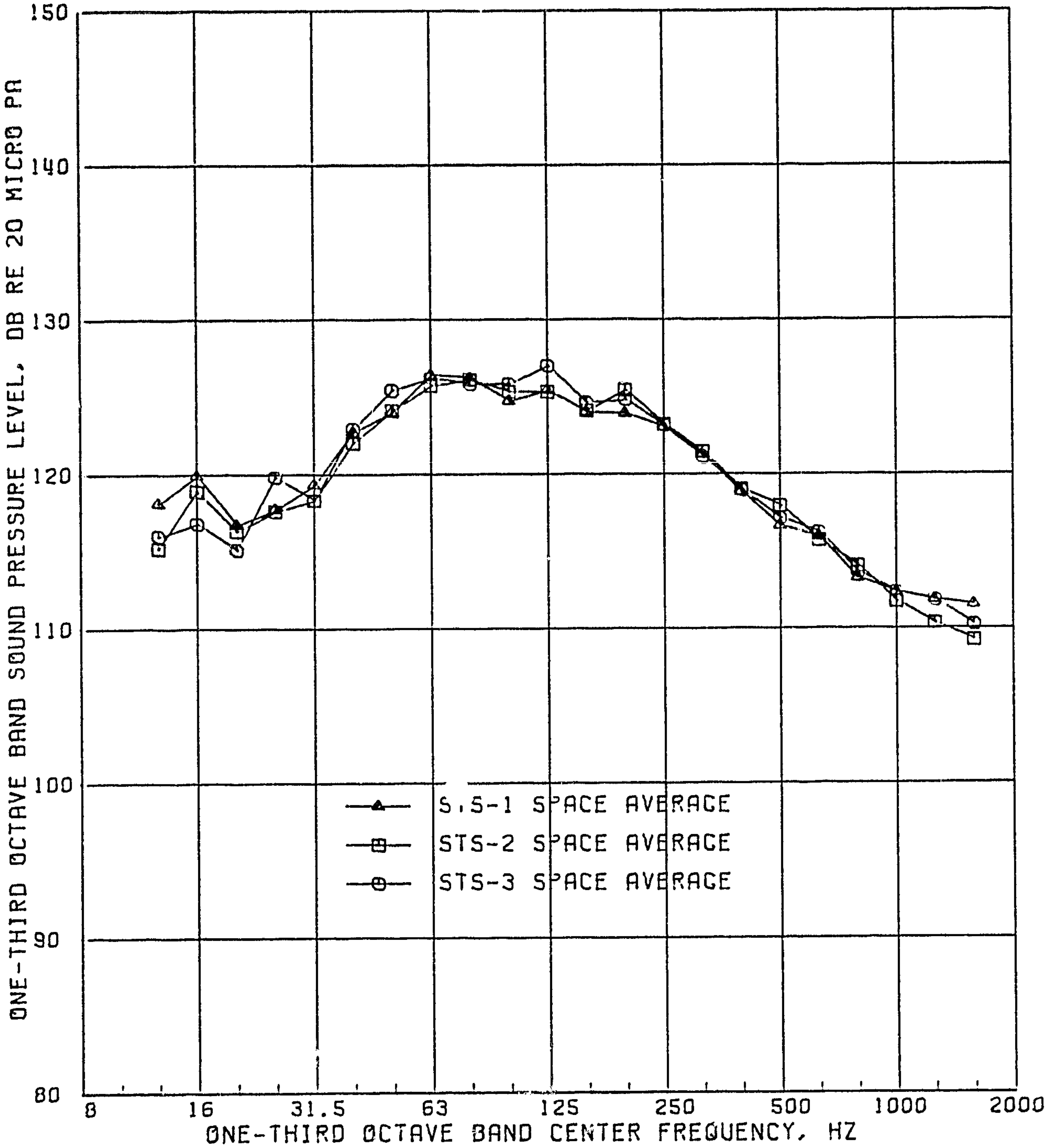

FIGURE 7. COMPARISON OF SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY FOR STS-1, STS-2 AND STS-3 LIFT-OFF

Table 6. Microphone Locations in Various Regions of the Payload Bay for STS-1 through STS-3

Region Identification	Region Bounds (Station Nos.)	Measurement Locations In Region
1st 1/4	576- 758	I1*
2nd 1/4	759- 941	I2*,I13,I15
3rd 1/4	942-1124	I4(1),I12,I14,I16-I20, I22
4th 1/4	1125-1307	I3*,I4(2,3)**,I5(2), I5(3), I6, I7**, I8-I11

* Same location on all three flights
** Same location on STS-2 and STS-3

Note that microphones I1-I5 and I7 were flown on more than one mission. Specifically;

(a) I1-I3 were installed at the same location on all three flights,

(b) I4 was installed at the same location on STS-2 and STS-3, and at a different location on STS-1,

(c) I5 was installed at two different locations on STS-2 and STS-3, and was not present on STS-1, and

(d) I7 was installed at same location on STS-2 and STS-3, and was not present on STS-1.

Previous studies [4] established that the primary source of variance in the acoustic data is due to spatial variability. The variation in sound pressure level from flight to flight at a given location is relatively small. Hence to estimate a final space-average level for the payload bay, measurements made at the same location on more than one flight are averaged together and counted as one sample in the calculations. From Table 6, the sample size for the final calculations is n = 23 divided among the four regions such that

$$n_1 = 1;\ n_2 = 3;\ n_3 = 9;\ n_4 = 10 \tag{3}$$

The mean and standard deviation of the energy values in each region is computed from

$$\bar{\ell}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} \ell_{ij};\ s_i^2 = \frac{1}{n_i-1}\sum_{j=1}^{n_i}\left(\ell_{ij} - \bar{\ell}_i\right)^2\ ;\ i=1,2,3,4 \tag{4}$$

where

$$\ell = 10^{L/10} \tag{5}$$

and L is the sound pressure level in dB.

The overall mean and standard deviation of the payload bay energy values are then calculated using stratified sampling statistics [7] from

$$\bar{y} = \sum_{i=1}^{4} \bar{\ell}_i/4\ ;\quad s_{\bar{y}}^2 = \sum_{i=1}^{4} s_i^2/16 \tag{6}$$

The final space-average sound pressure level is given by

$$\text{Space-average SPL} = 10 \log \bar{y} \tag{7}$$

and 95% confidence limits are computed from

$$\text{Upper 95\% Limit} = 10 \log \left[\bar{y} + t_{m;0.025}\, s_{\bar{y}}\right] \qquad (8a)$$

$$\text{Lower 95\% Limit} = 10 \log \left[\bar{y} - t_{m;0.025}\, s_{\bar{y}}\right] \qquad (8b)$$

where $\bar{y}$ and $s_{\bar{y}}$ are as defined in Eq.(6) and $t_{m;0.025}$ is the 2.5 percentage point of the student "t" variable with m = n-1 = 22 degrees-of- freedom*.

The above calculation procedure poses one problem in that only one sample value is available for the first 1/4 region, meaning that a variance s_1^2 from Eq.(4) cannot be calculated for this region. To circumvent this problem, the average variance of the other three regions is used to estimate the variance of the first 1/4 region; i.e.,

$$s_1^2 = (s_2^2 + s_3^2 + s_4^2)/3 \qquad (9)$$

The final space-average sound pressure level estimates with 95% confidence limits computed using Eqs.(4) through (9) are presented in Table 7 and plotted in Figure 8. Note that the confidence interval about the space-average estimate is relatively narrow at most frequencies. This is expected since all the data from the first three Space Shuttle launches are used to arrive at the space-average estimate. Above 800 Hz the spread in the confidence interval is due in part to the reduced number of data samples.

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* At frequencies above 800 Hz, n = 10 and m = 9 due to the elimination of data believed to be contaminated by noise.

Table 7. Space-Average Sound Pressure Levels in Payload Bay during Space Shuttle Lift-Off, Estimated Using all Data from STS-1 through STS-3

Freq. (Hz)	Sound Pressure Levels in dB (ref: 20 μPa)								
	Energy Average by Quarters				Space Average	95% Conf. Limits		Range of Values	
	1st 1/4	2nd 1/4	3rd 1/4	4th 1/4		Lower	Upper	Minimum	Maximum
12.5	119.2	109.7	111.7	115.2	115.5	113.0	117.0	106.4	119.2
16	122.3	114.8	117.6	112.3	118.4	116.9	119.5	104.0	122.3
20	119.4	114.2	115.1	110.5	115.9	114.0	117.3	106.1	119.4
25	119.9	117.8	117.8	115.5	118.0	114.3	120.0	109.7	122.0
31.5	121.1	116.5	116.2	114.1	117.8	115.3	119.3	110.0	121.1
40	126.1	119.6	118.5	117.2	121.9	120.2	123.1	112.0	126.1
50	128.2	121.6	122.7	118.0	124.2	121.1	126.0	114.7	128.8
63	129.9	123.4	123.1	119.5	125.7	124.0	127.0	116.4	129.9
80	128.1	124.7	124.1	121.0	125.2	121.7	127.1	118.0	128.5
100	127.2	124.2	123.9	122.9	124.9	122.8	126.3	119.0	127.2
125	126.6	126.0	125.5	122.3	125.4	119.8	127.7	119.5	130.4
160	125.5	124.2	124.1	122.3	124.2	120.9	126.0	118.0	128.5
200	127.1	122.6	125.2	122.8	124.8	121.1	126.8	120.0	130.0
250	123.5	122.3	123.4	122.5	123.0	120.0	124.7	119.8	127.3
315	121.2	120.5	121.3	121.2	121.1	117.9	122.9	117.9	125.6
400	118.8	118.2	119.5	118.8	118.8	115.6	120.7	115.9	123.5
500	117.4	117.1	117.9	117.0	117.3	114.0	119.2	114.0	122.0
630	114.4	115.9	115.6	116.2	115.5	112.4	117.4	111.2	119.0
800	113.3	113.3	114.4	114.0	113.8	107.8	116.2	109.4	118.0
1000	112.7	113.1	110.6	109.4	111.7	108.4	113.6	108.0	114.5
1250	111.5	112.2	110.0	108.5	110.8	105.6	113.1	106.6	114.0
1600	110.3	111.3	109.4	107.7	109.9	105.0	112.1	106.1	113.0

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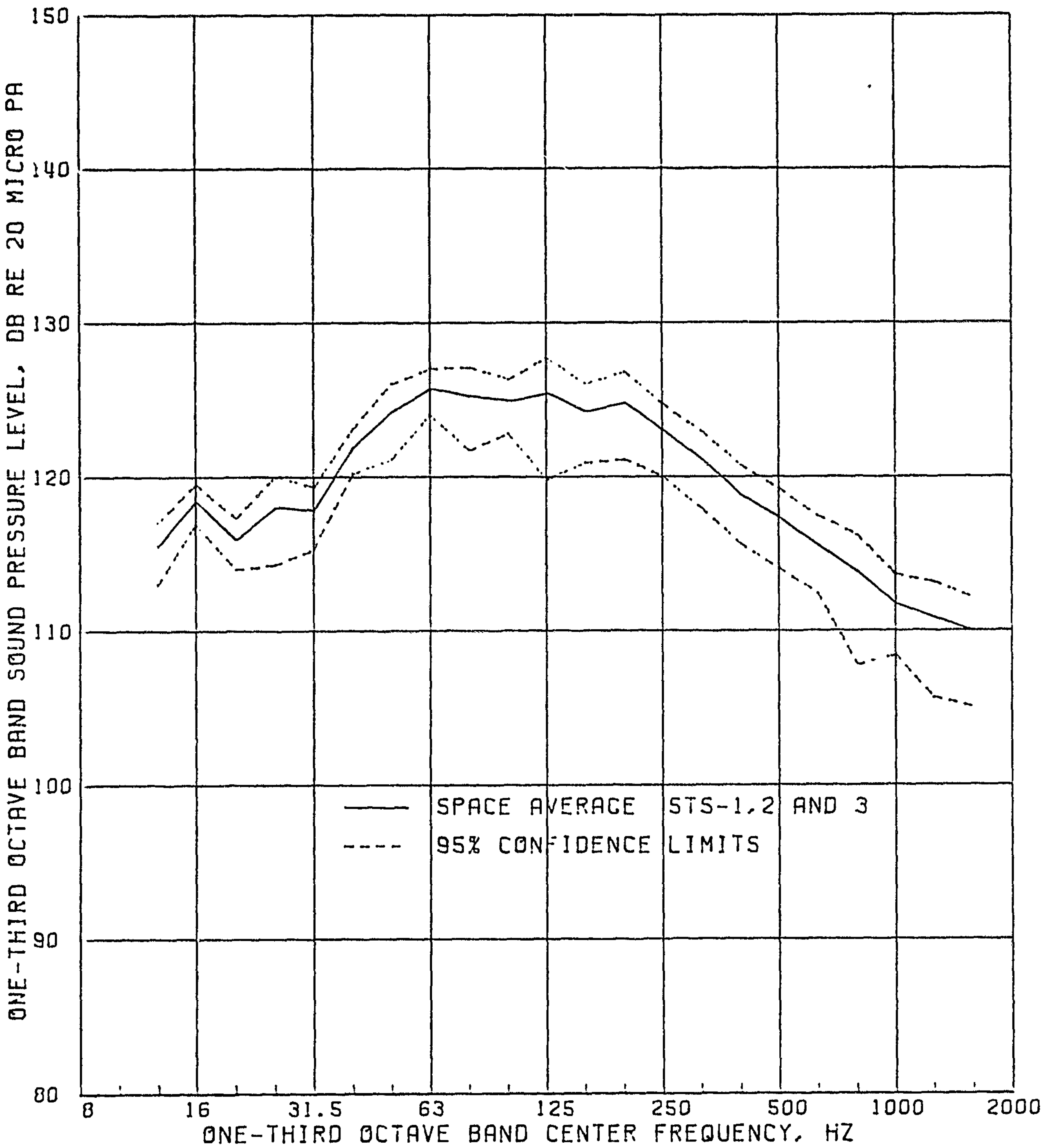

FIGURE 8. ESTIMATED SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY AT LIFT-OFF (BASED ON STS-1, STS-2 AND STS-3 LAUNCHES)

4.5 Tolerance Limits on Spatial Variability

Beyond the space-average estimates in Figure 8, the variation of sound pressure levels from one point to another within the payload bay is also of interest, particularly for payload design and test criteria. The most easily formulated statistical bounds on the spatial variation of payload bay levels are given by the maximum and minimum sound pressure levels measured in each one-third octave band during the first three launches (STS-1 through STS-3). These maximum and minimum measured values for the first three launches are shown in Figure 9 and listed in Table 7. As in Section 4.4, measurements made at the same location on two or more of the launches are averaged together and counted as a single sample value. The total sample size is then n = 23, as detailed in Table 6 except at frequencies above 800 Hz where the sample size is reduced due to the elimination of data believed to be contaminated by instrumentation noise. At high frequencies, n = 10.

If it is assumed that the measurement locations on the first three launches constitute a representative sample of the payload bay volume, the maximum and minimum values in Figure 9 can be interpreted as a statistical tolerance interval on payload bay levels using the nonparametric equation [8]

$$1 - \beta^{n} - n(1-\beta)\,\beta^{n-1} = \gamma \qquad (10)$$

where n = sample size = 23

β = fractional portion of additional measurement which will be less than the largest value and greater than the smallest value in the sample.

γ = confidence coefficient associated with the statement that at least β portion of additional measurements will fall between the maximum and minimum values in the sample.

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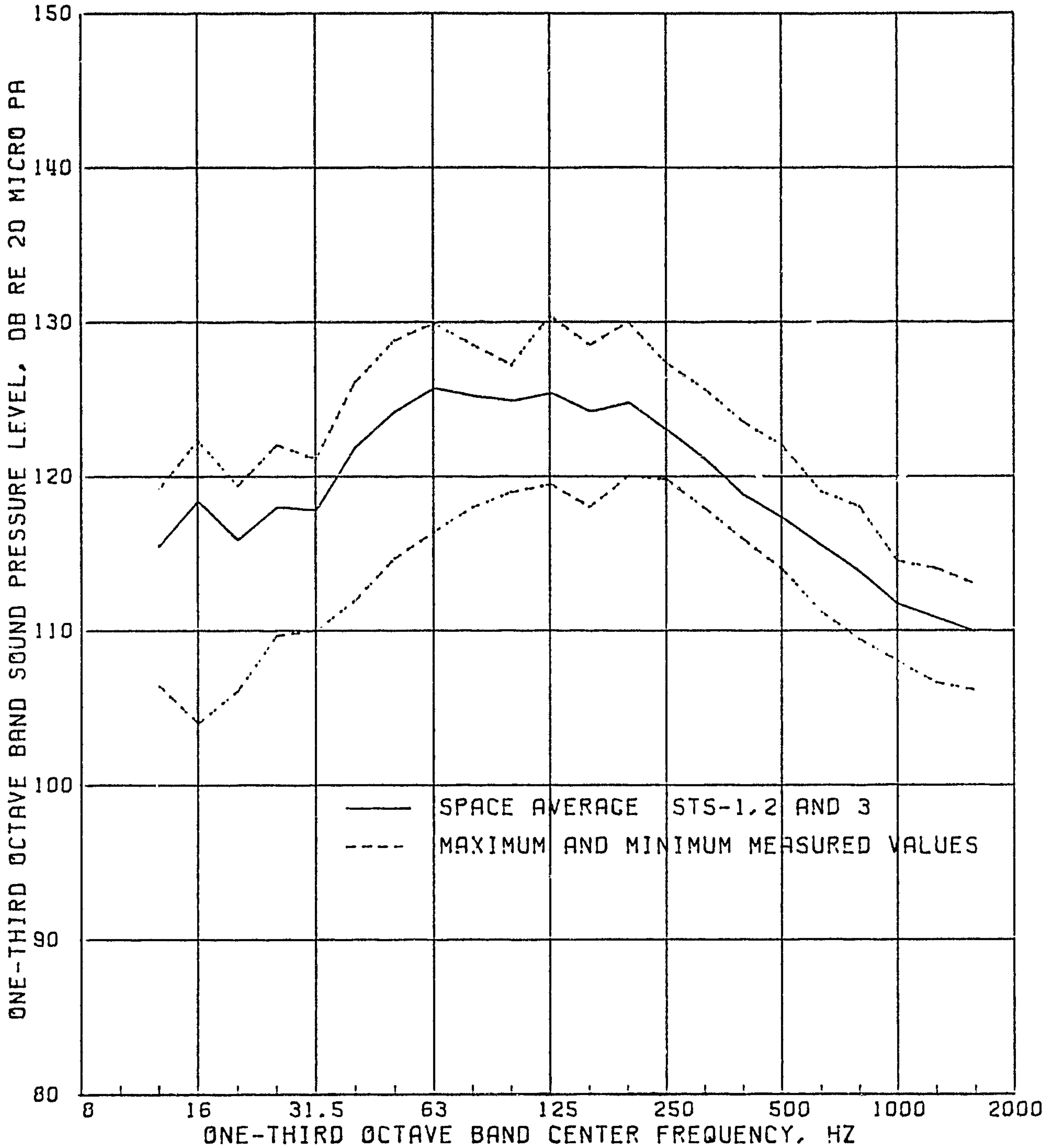

FIGURE 9. LIMITS ON SPATIAL VARIATION OF SOUND PRESSURE LEVELS IN PAYLOAD BAY AT LIFT-OFF (BASED ON STS-1, STS-2 AND STS-3 LAUNCHES)

For $\gamma = 0.95$, Eq.(10) is satisfied by $\beta = 0.81$. Hence it can be said with 95% confidence that at least 81% of all additional measurements would fall between the limits shown in Figure 9*.

In terms of an upper bound only on the sound pressure levels in the payload bay, the applicable equation is [8]

$$\gamma = 1 - \beta^n \tag{11}$$

where n = sample size = 23

β = fractional portion of additional measurements which will be less than the largest value in the sample.

γ = confidence coefficient associated with the statement that at least β portion of additional measurements will fall below the maximum values in the sample.

Again for $\gamma = 0.95$, Eq.(11) is satisfied by $\beta = 0.88$ meaning it can be said with 95% confidence that at least 88% of all additional measurements would fall below the upper limit shown in Figure 9*. Based upon these conclusions, it is believed the upper limit in Figure 9 might be used as a conservative upper bound on sound pressure levels in the payload bay for design and test criteria purposes.

* As noted earlier, n = 10 at frequencies of 1000 to 1600 Hz. In this frequency range it can be said with 95% confidence that at least 61% of all additional measurements would fall between the limits shown in Figure 9 and at least 74% of all additional measurements would fall below the upper limit shown in Figure 9.

5. EVALUATION OF EXTERIOR ACOUSTIC DATA

5.1 Summary of STS-3 Data

The maximum one-third octave band levels were measured during the lift-off phase (T = 0 to T + 10 seconds) by the six exterior microphones and the aft fuselage microphone shown in Figure 4. For two of these microphones (402 and 404), the analysis was performed using an averaging time of 0.5 second and for the remaining five an averaging time of 0.2 second was used.

To obtain a consistent set of data, based on the 0.5 second averaging time used for the STS-1 and STS-2 data, an estimate was made of the effect of the averaging time on the levels. Maximum levels were available for both 0.2 second and 0.5 second averaging times for STS-1 microphones 202 and 681 and for STS-2 microphones 204 and 207. The difference in levels due to averaging time was calculated for each one third octave band for the 4 cases and averaged to give a correction for averaging time shown in Table 8. This correction was applied to the STS-3 maximum levels for microphones 204, 207, 210, 681 and 692 to give estimated maximum levels for an averaging time of 0.5 second, shown in Table 8.

5.2 Comparisons to STS-1 and STS-2 Data

The six exterior microphones plus the aft fuselage microphone on STS-3 also provided data during STS-1 and STS-2 (except for STS-2 Microphone 681). Direct comparisons of the one-third octave band sound pressure levels measured at these common exterior and aft fuselage locations during STS-1, STS-2 and STS-3 lift-offs are shown in Figure 10. An estimated value for STS-2 microphone 681, as developed in [4], has been included. It is seen from Figure 10 that the measured levels during the three launches are broadly similar with a few exceptions as follows:

Table 8. One-Third Octave Band Sound Pressure Levels Exterior to the Payload Bay during STS-3 Lift-Off

Freq. (Hz)	Correction Factor, dB (0.2 secs -0.5 secs)	One-Third Octave Band Sound Pressure Level, dB re 20 μPa						
		Measured (0.2 secs) - Correction Factor					Measured (0.5 secs)	
		204	207	210	681	692	402	404
12	2.4	130.5	136.0	131.0	138.5	119.0	134.0	140.0
16	2.3	131.0	135.0	134.5	135.0	117.5	133.0	140.0
20	1.9	132.0	136.5	133.5	136.0	119.0	134.5	135.0
25	1.6	132.5	139.0	133.5	138.0	125.0	134.5	137.0
31	1.1	135.0	140.0	134.5	139.0	119.0	135.0	140.0
40	1.5	137.0	139.5	135.5	138.5	123.5	137.5	140.5
50	0.7	138.0	139.0	138.5	142.0	124.5	138.0	140.0
63	1.5	138.0	139.0	140.0	143.0	123.5	139.5	141.0
80	1.1	136.5	140.5	138.0	142.5	120.0	139.0	143.5
100	1.3	137.5	138.0	139.0	143.5	120.5	140.0	143.5
125	1.1	139.5	138.0	141.0	143.0	122.0	139.5	143.5
160	0.6	140.5	138.5	141.5	147.0	123.5	140.5	145.5
200	0.5	140.0	140.5	141.0	148.5	122.0	140.5	147.0
250	0.7	138.0	139.5	142.0	147.5	120.0	139.5	145.5
315	0.6	138.0	139.5	141.5	148.5	119.5	140.0	144.5
400	0.6	137.5	141.5	142.0	147.0	118.0	139.5	142.0
500	0.7	138.0	140.5	140.5	146.5	119.5	139.0	143.0
630	0.6	137.0	140.0	139.0	146.0	120.5	137.5	144.0
800	0.5	135.5	139.5	138.0	146.5	120.5	136.5	144.0
1000	0.6	134.5	138.5	138.0	145.0	118.5	135.0	143.5
1250	0.5	133.5	138.0	137.5	144.5	119.0	135.0	143.0
1600	0.5	132.5	136.5	137.0	142.0	120.5	133.5	142.0

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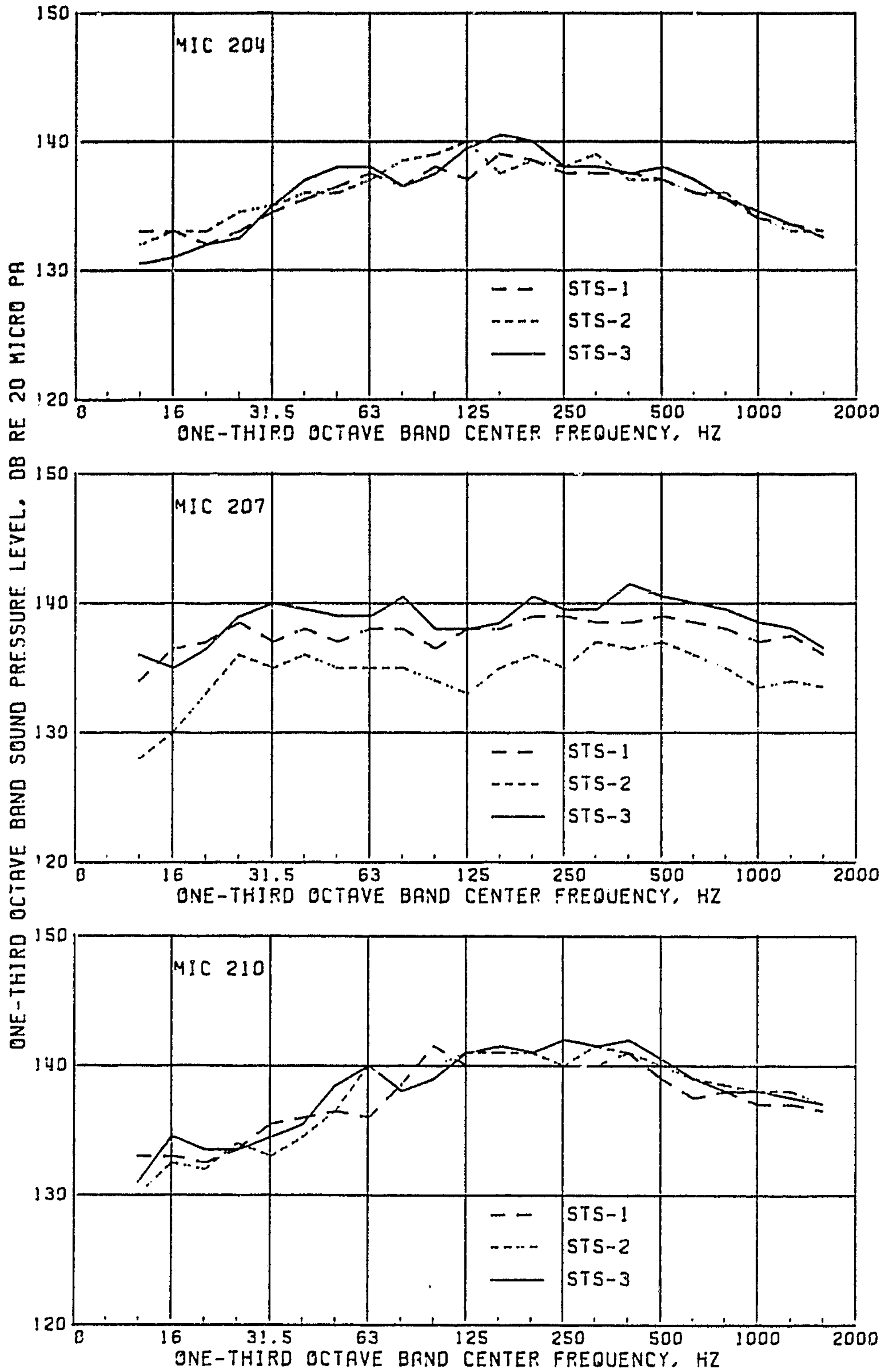

FIGURE 10. COMPARISON OF SOUND PRESSURE LEVELS AT EXTERIOR LOCATIONS FOR STS-1, STS-2 AND STS-3 LIFT-OFF

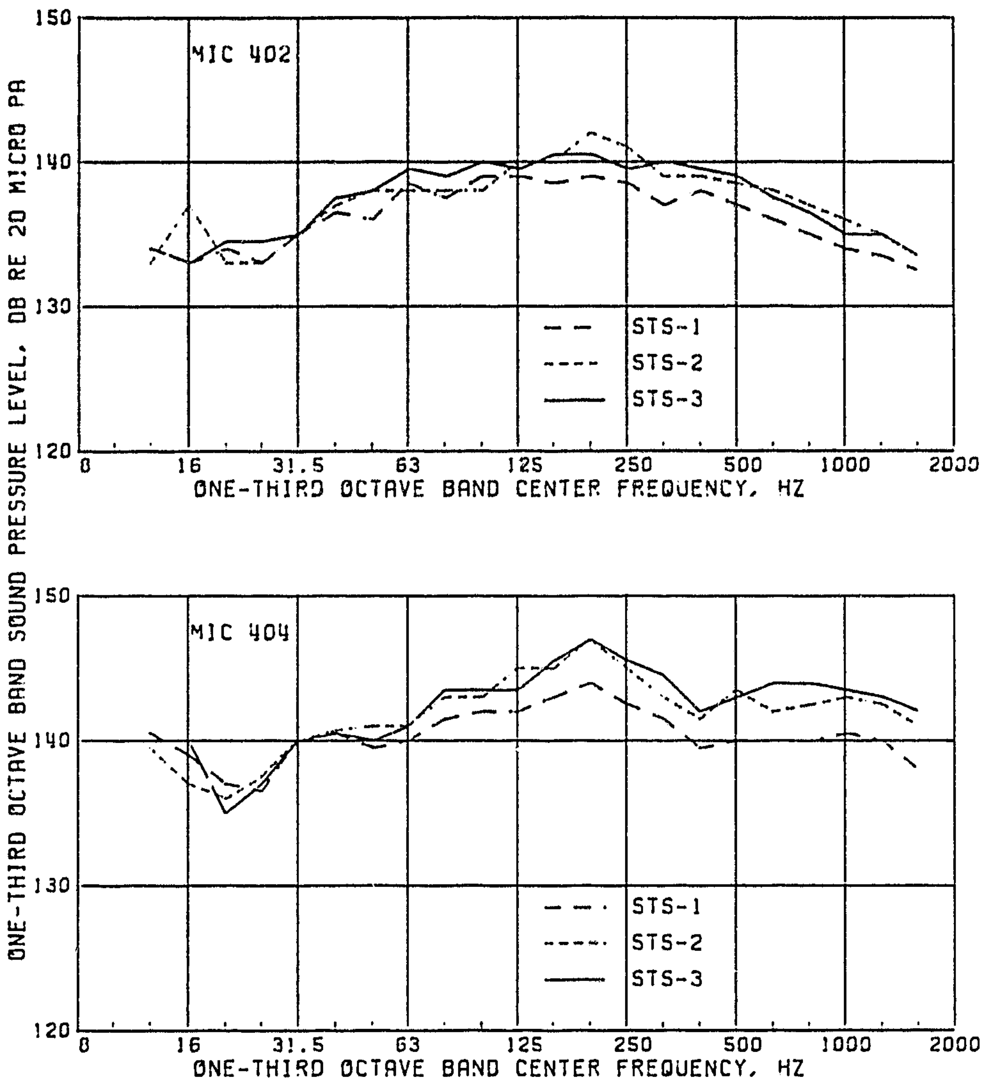

FIGURE 10. (CONTINUED)

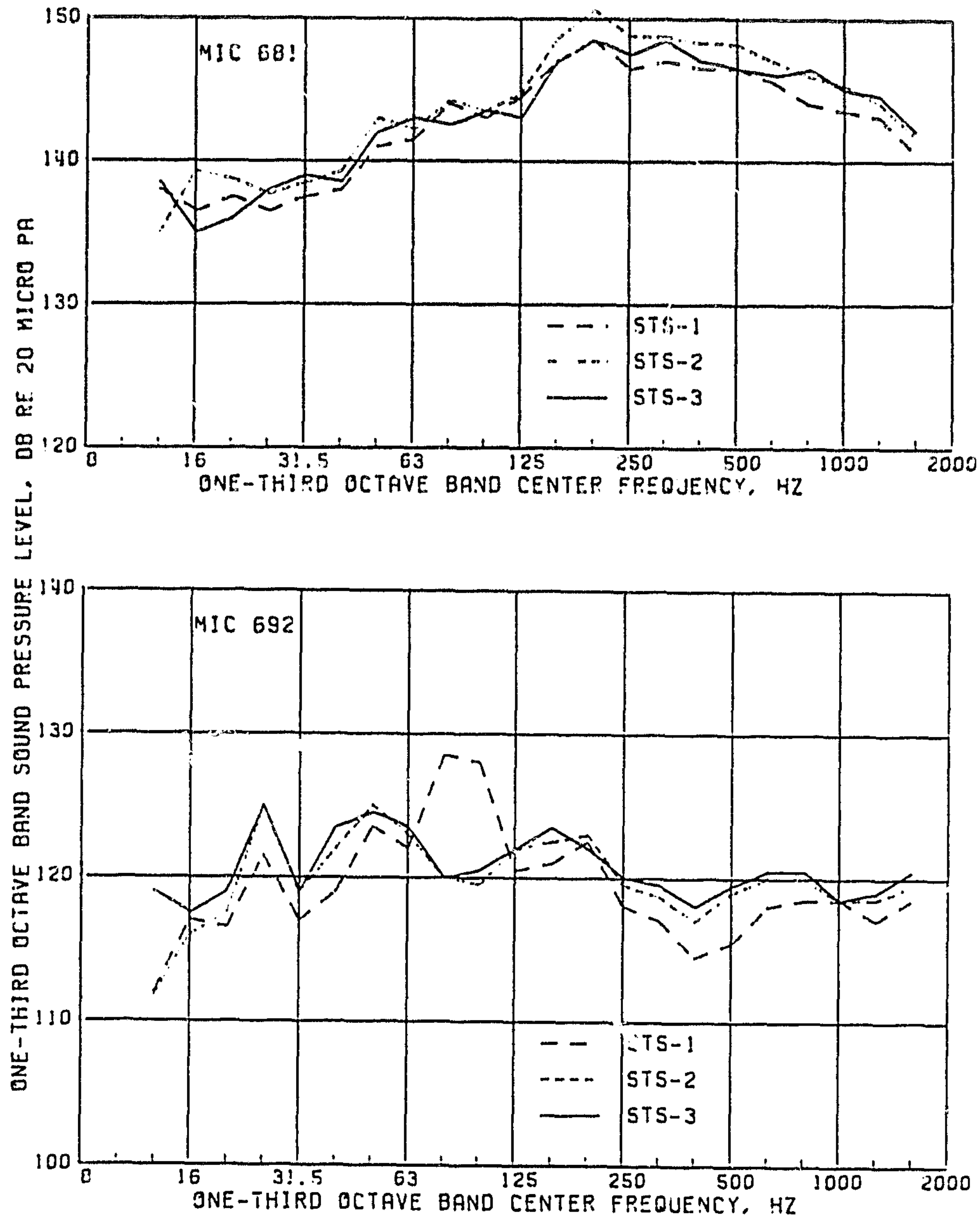

FIGURE 10. (CONTINUED)

1. Microphone 207 on the forward bottom of the orbiter shows the STS-2 levels to be consistently lower (by 3 to 5 dB) than the STS-1 levels in all frequency bands while the STS-3 levels are higher (by up to 2 dB) than the STS-1 levels in most bands.

2. Microphones 402 and 404 on the exterior aft fuselage show that the STS-1 levels are consistently lower (by up to 3 dB) in most one-third octave bands above 125 Hz.

5.3 Estimation of Space-Average Sound Levels

The objective of the evaluation of the measured exterior sound levels is to generate data input information for use in the computation of payload bay sound levels using the PACES computer program. The exterior structure of the payload bay of the orbiter vehicle is modeled as six regions in PACES. These regions are:

(1)	Payload bay doors	Sta 582 to 1307
(2)	Bottom structure (forward region)	Sta 582 to 1191
(3)	Bottom structure (aft region)	Sta 1191 to 1307
(4)	Sidewall (forward region)	Sta 582 to 1040
(5)	Sidewall (aft region)	Sta 1040 to 1307
(6)	Aft bulkhead	Sta 1307

(It is assumed that there is no acoustic power flow through the forward bulkhead of the payload bay). The analytical model for PACES requires that a space-average sound pressure level spectrum, in one-third octave frequency bands, be provided for each region. These spectra are used as data inputs to the computer program. The evaluation of the STS-3 exterior sound levels has to be performed in order to determine estimates for these six spectra. The approaches used in determining these spectra are described briefly in the following discussion.

Payload Bay Door:

Data are available for microphone locations 402 (Microphone No. V08Y9402A at X = 1300) at the aft end of the payload bay door and 204 (Microphone No. V08Y9204A at X = 520) on the top of the forward fuselage just forward of the payload bay. A comparison of the one-third octave band levels shows that the values are very similar for the two locations, as is shown in Figure 11. Thus, space-average sound levels were computed by taking the energy average of the sound levels at the two locations.

This approach makes two assumptions. Firstly, it is assumed that the similarity of the sound levels at locations 204 and 402 implies that there is no significant variation in sound level along the length of the door. Secondly, it is assumed that the sound levels along the door centerline are typical of the levels in the circumferential direction. The only information regarding the circumferential distribution of sound levels on the door is provided by location 210 (Microphone No. V08Y9210A at X = 540, Z = 420). This location is on the side of the forward fuselage, at approximately the same longitudinal station as location 204. The sound levels at 210 are similar to those at 204, for frequencies below 100 Hz, but at higher frequencies the sound levels are 2 to 5 dB higher than those at 204 (see Figure 10). However, if data for locations 204 and 210 were energy-averaged to obtain an estimate of the sound levels at the forward end of the door, the net effect on the door space-average sound level would be 1.5 dB at the most. Furthermore, the coordinate for location 210 corresponds roughly to the hinge line of the payload bay door and to a region of the door which is highly-curved and, thus, stiff.

Consequently the higher sound levels measured at location 210 will probably have a negligible effect on the acoustic power transmitted through the door, and the data were not included in the computation of the space-average sound levels on the door.

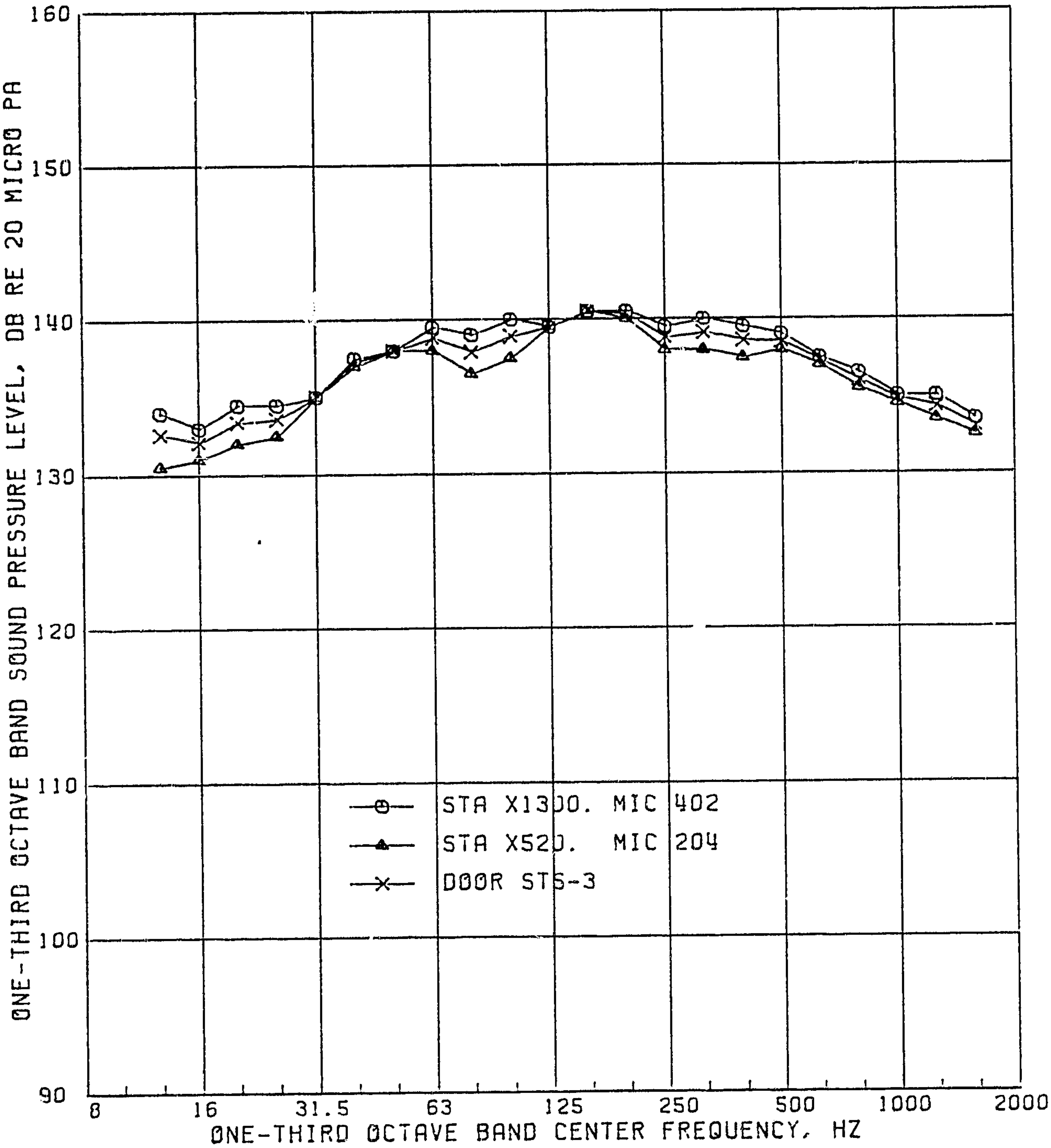

FIGURE 11. SOUND LEVELS ON PAYLOAD BAY DOOR FOR STS-3 LIFT-OFF

Figure 12 shows the comparison between the space-average sound levels for STS-1, STS-2 and STS-3, with the STS-1 levels 1-2 dB lower at frequencies above 100 Hz.

Sidewall:

Data are available for microphone locations 210 (Microphone No. V08Y9210A at X = 540) on the forward fuselage, and 681 (Microphone No. V08Y9681A at X = 1420) on the aft fuselage. There was no microphone location on the sidewall of the mid--fuselage. Consequently, some method has to be devised to interpolate between the two measurement locations.

As can be seen in Figure 13, the sound levels at the two locations differed by up to 8.5 dB, in contrast to the sound levels at the forward and aft ends of the door where the levels were within 3 dB. Furthermore, it is required to obtain space-average sound levels for two different areas on the sidewall. It is thus not possible simply to take the energy average of the sound levels at the two measurement locations. Two alternative approaches were tried. In the first approach it was assumed that the mean square pressure varied inversely with the square of the distance from the source (i.e. free field of a point source) and in the second method the mean square pressure was assumed to vary inversely with distance (i.e. a line source). The inverse square law was finally adopted because the effective source locations were more acceptable from physical considerations. At low frequencies the effective source locations were 50 to 170 feet aft of the orbiter vehicle and at high frequencies, 40 to 75 feet.

Applying the inverse square law to the sound levels at X = 540 and 1420, an effective source location was determined at each one-third octave band center frequency. The inverse square law

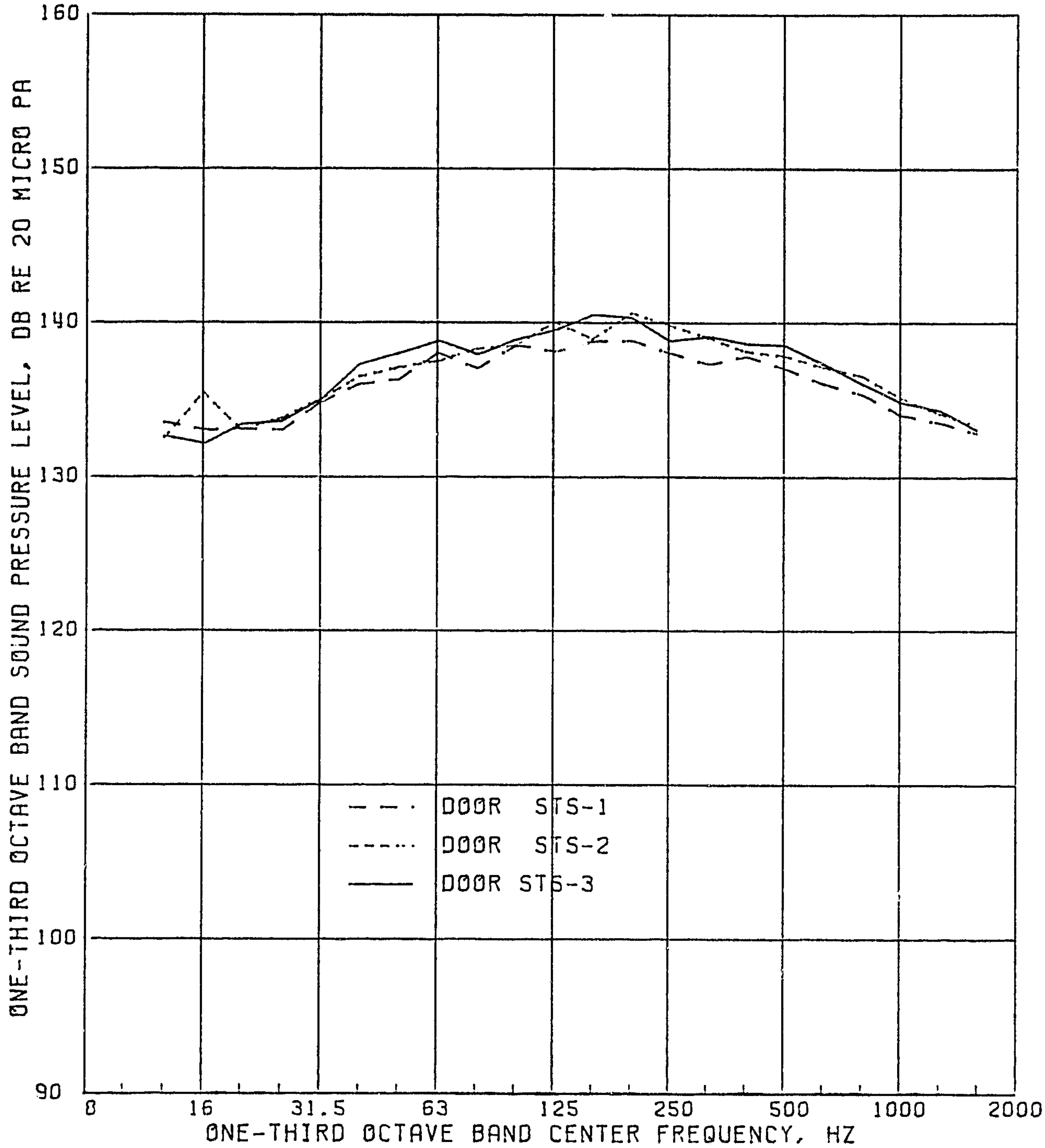

FIGURE 12. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON PAYLOAD BAY DOOR FOR STS-1, STS-2 AND STS-3 LIFT-OFF

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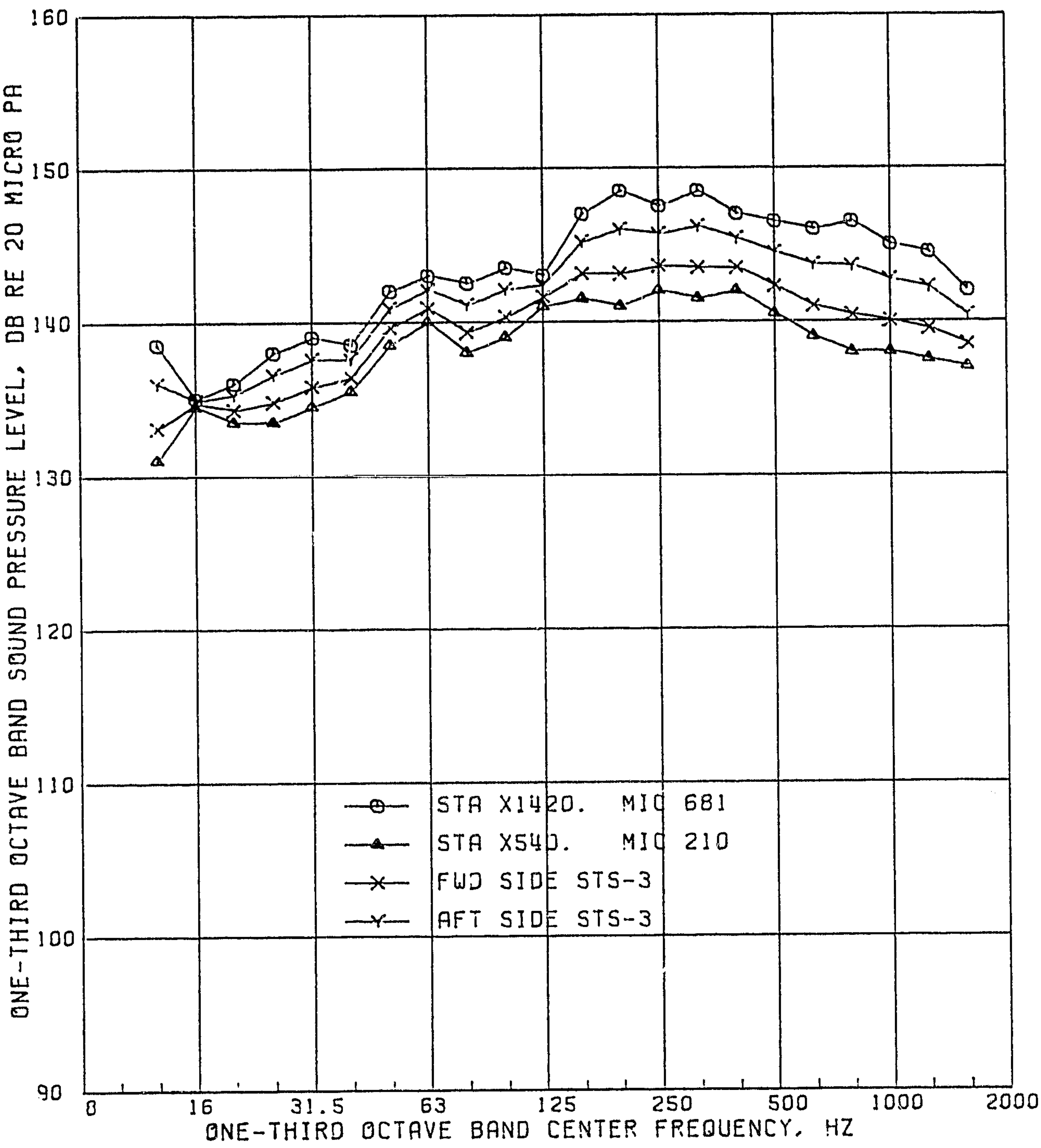

FIGURE 13. SOUND LEVELS ON MID-FUSELAGE SIDEWALL FOR STS-3 LIFT-OFF

was then used to estimate sound levels at the forward (X = 582) and aft (X = 1307) ends of the sidewall, and at X = 1040, the boundary between the forward and aft regions of the sidewall. Finally, the sound levels at X = 582 and X = 1040 were averaged on an energy basis to obtain space-average levels for the forward region, and a similar process was applied to sound levels at X = 1040 and 1370 for the aft region.

The estimated space-average sound levels for the forward and aft regions of the sidewall are plotted in Figure 13, and the levels are compared in Figures 14 and 15 with corresponding spectra predicted for STS-1 and STS-2. The STS-2 and STS-3 data are similar to the STS-1 data below 160 Hz, but are approximately 1 dB greater at higher frequencies, for both forward and aft regions. The assumptions implicit in the estimation of space-average sound levels on the sidewall for STS-3 are the same as those for the door. These assumptions are (a) that the sound level varies monotonically in the longitudinal direction and (b) the sound level is essentially constant in the lateral direction. The same assumptions will also be adopted for the bottom structure.

Bottom Structure:

Data are available for microphone locations 404 (Microphone No. V08Y9404A at X = 1300) on the aft region of the mid-fuselage bottom structure, and 207 (Microphone No. V08Y9207A at X = 500) on the bottom structure of the forward fuselage. No microphone was located on the forward region of the mid-fuselage bottom structure. Consequently, it was again necessary to apply an interpolation procedure, and, for consistency, the inverse square law adopted for the sidewall was again used.

Sound levels measured at locations 404 and 207 are shown in Figure 16, where it is seen that the differences between the forward and aft locations are smaller than is the case for the

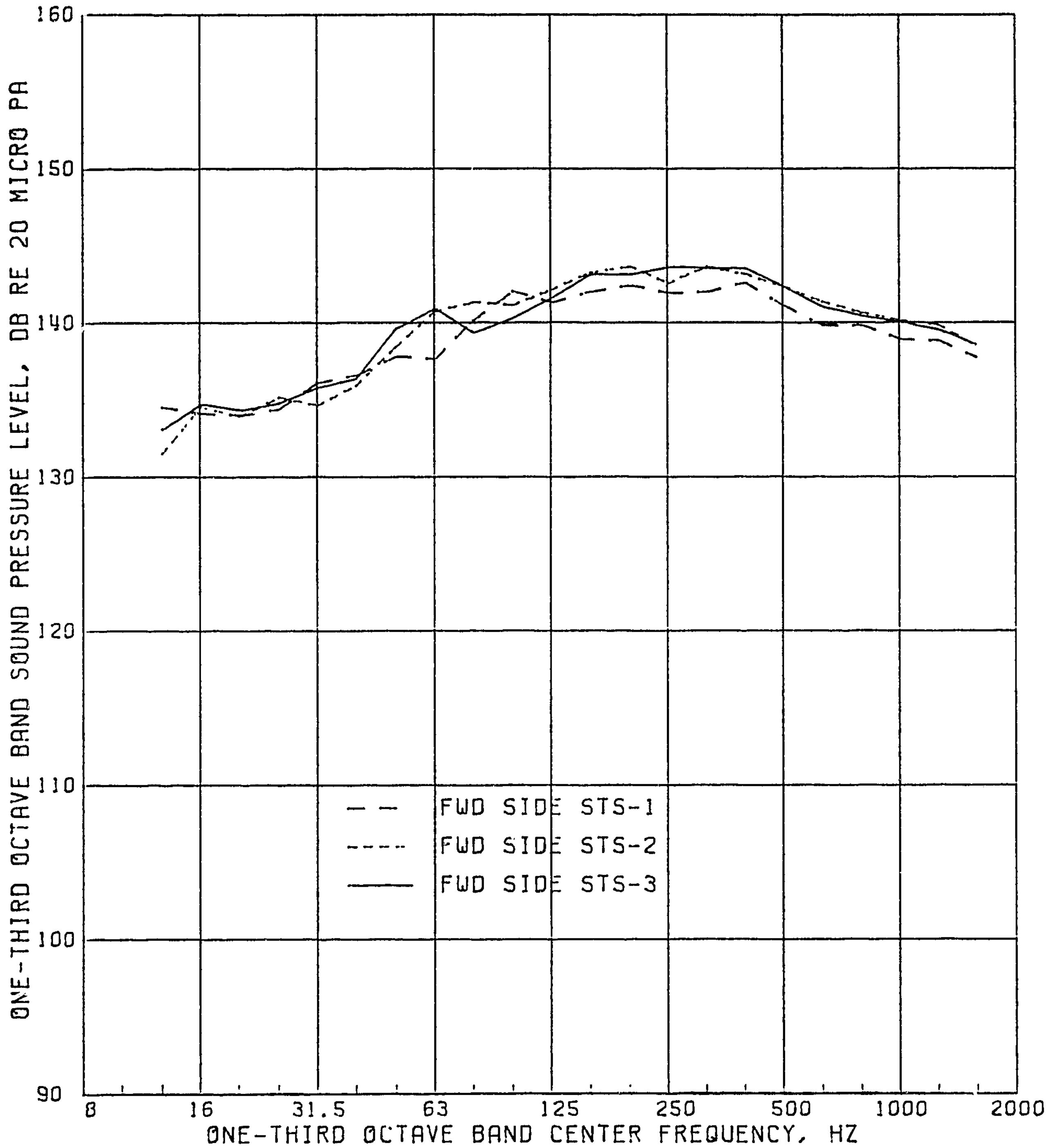

FIGURE 14. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON FORWARD REGION OF MID-FUSELAGE SIDEWALL FOR STS-1, STS-2 AND STS-3 LIFT-OFF

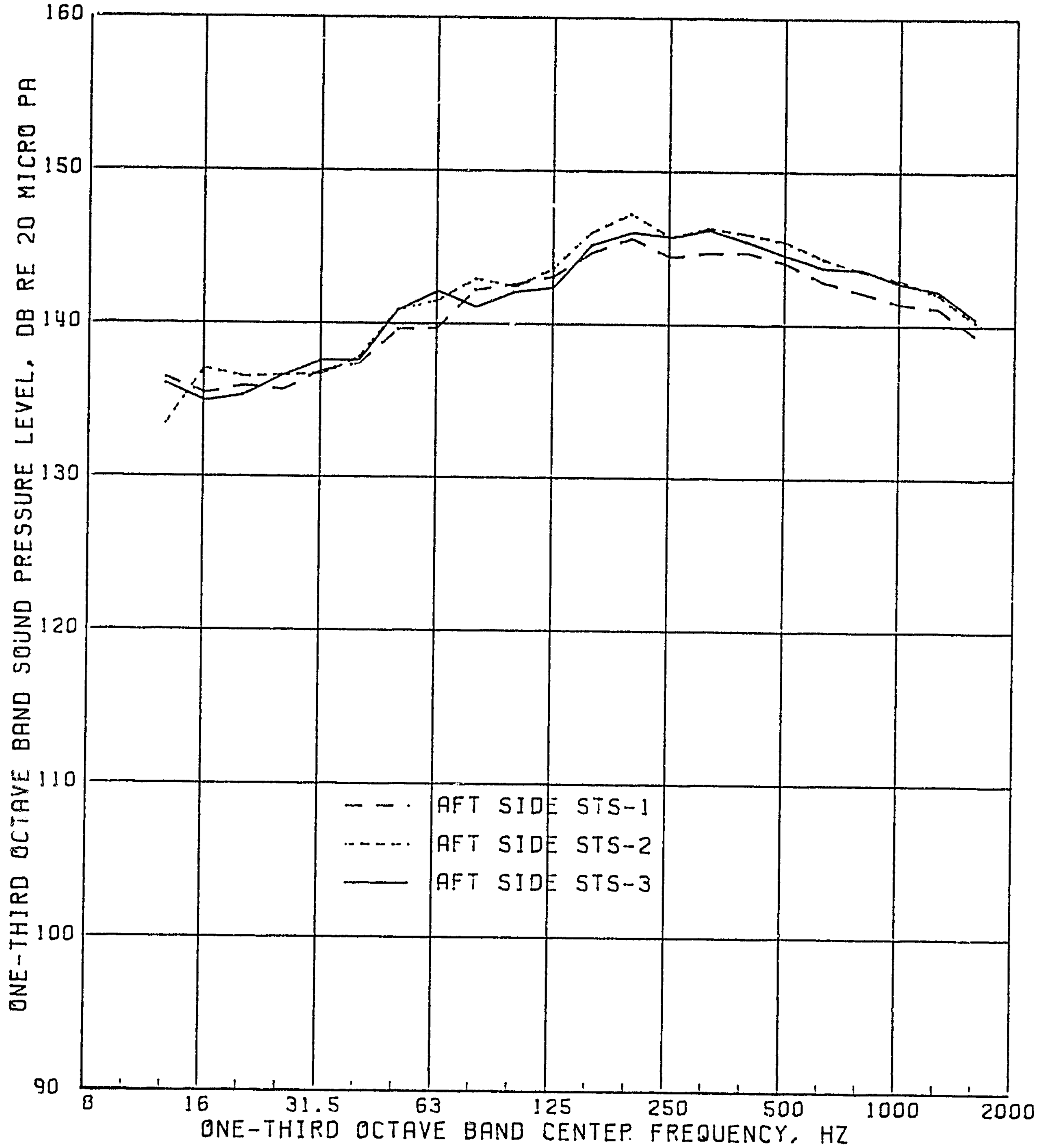

FIGURE 15. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON AFT REGION OF MID-FUSELAGE SIDEWALL FOR STS-1, STS-2 AND STS-3 LIFT-OFF

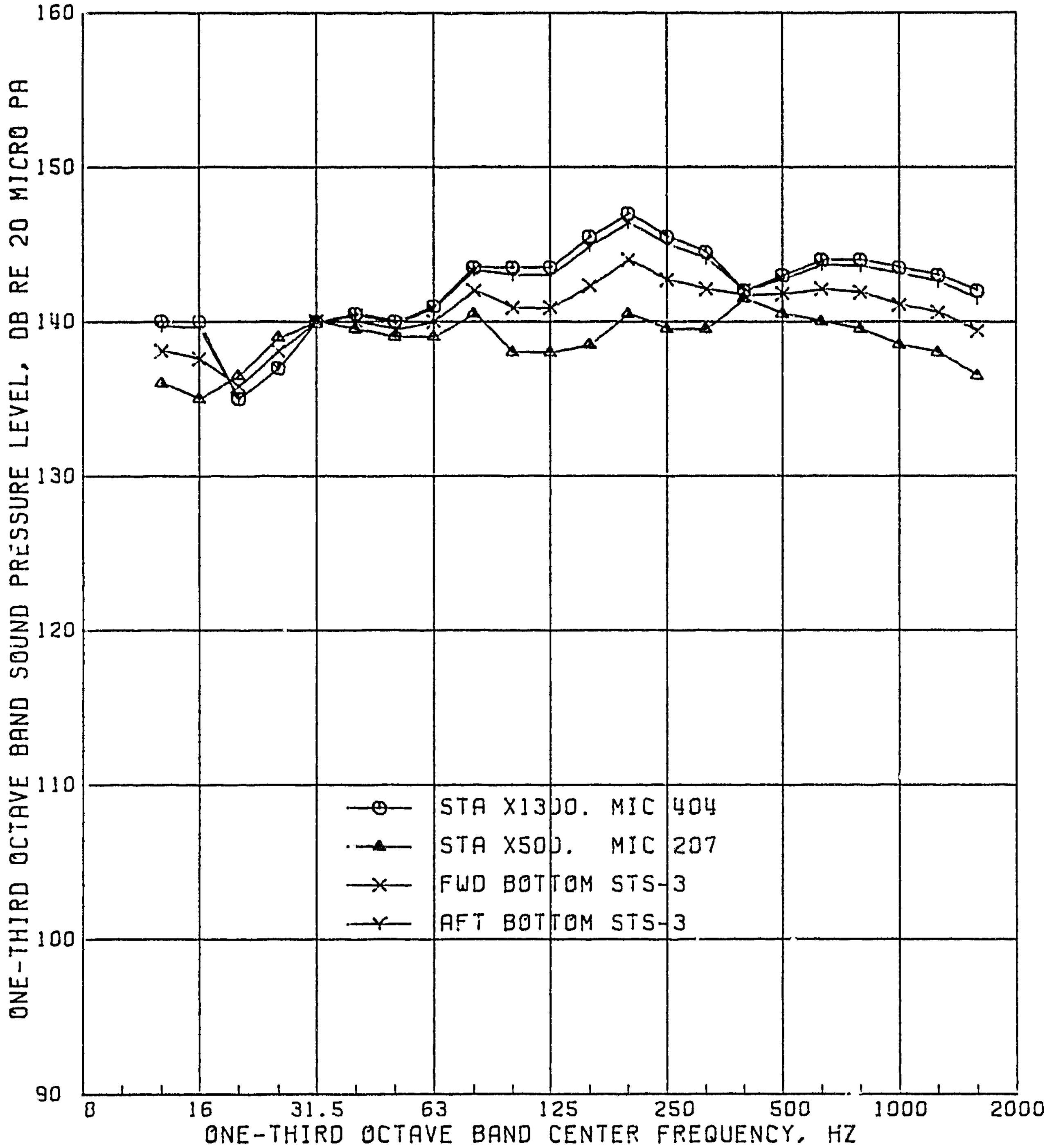

FIGURE 16. SOUND LEVELS ON MID-FUSELAGE BOTTOM STRUCTURE FOR STS-3 LIFT-OFF

sidewall (Figure 13). Thus the precise nature of the interpolation procedure is less critical with regard to the accuracy of the estimates. Using microphones 207 and 404, the same interpolation and averaging procedure was performed as for the sidewall. The estimated space-average levels for the forward and aft regions are shown in Figure 16, and are seen to be strongly influenced by the high levels at Station 404. Figures 17 and 18 compare the estimated space-average levels for the forward and aft regions of the bottom structure for STS-1, STS-2 and STS-3. For the forward region, STS-3 levels are typically 2 to 3 dB higher than the STS-1 and 2 levels. For the aft region, STS-1 levels are typically 2.5 dB lower than the STS-2 and STS-3 levels for frequencies above 100 Hz.

Bulkhead:

Sound levels in the aft fuselage were measured at only one location, 692 (Microphone No. V08Y9692A) shown in Figure 4. In the absence of any other information, it is therefore assumed that the sound levels measured at that location are representative of the space-average values on the aft bulkhead of the payload bay. The sound pressure level spectra measured at location 692 are shown in Figure 19 for STS-1, STS-2 and STS-3. The spectra are similar except at 80 Hz and 100 Hz for STS-1.

5.4 Data Input for PACES

The space-average sound levels calculated for the six structural regions bounding the Space Shuttle payload bay are required as data input for the PACES computer program in order to calculate interior sound levels for STS-3 lift-off. The six one-third octave band spectra, contained in Figures 11 through 19, are collected together in Figure 20 and tabulated in Table 9.

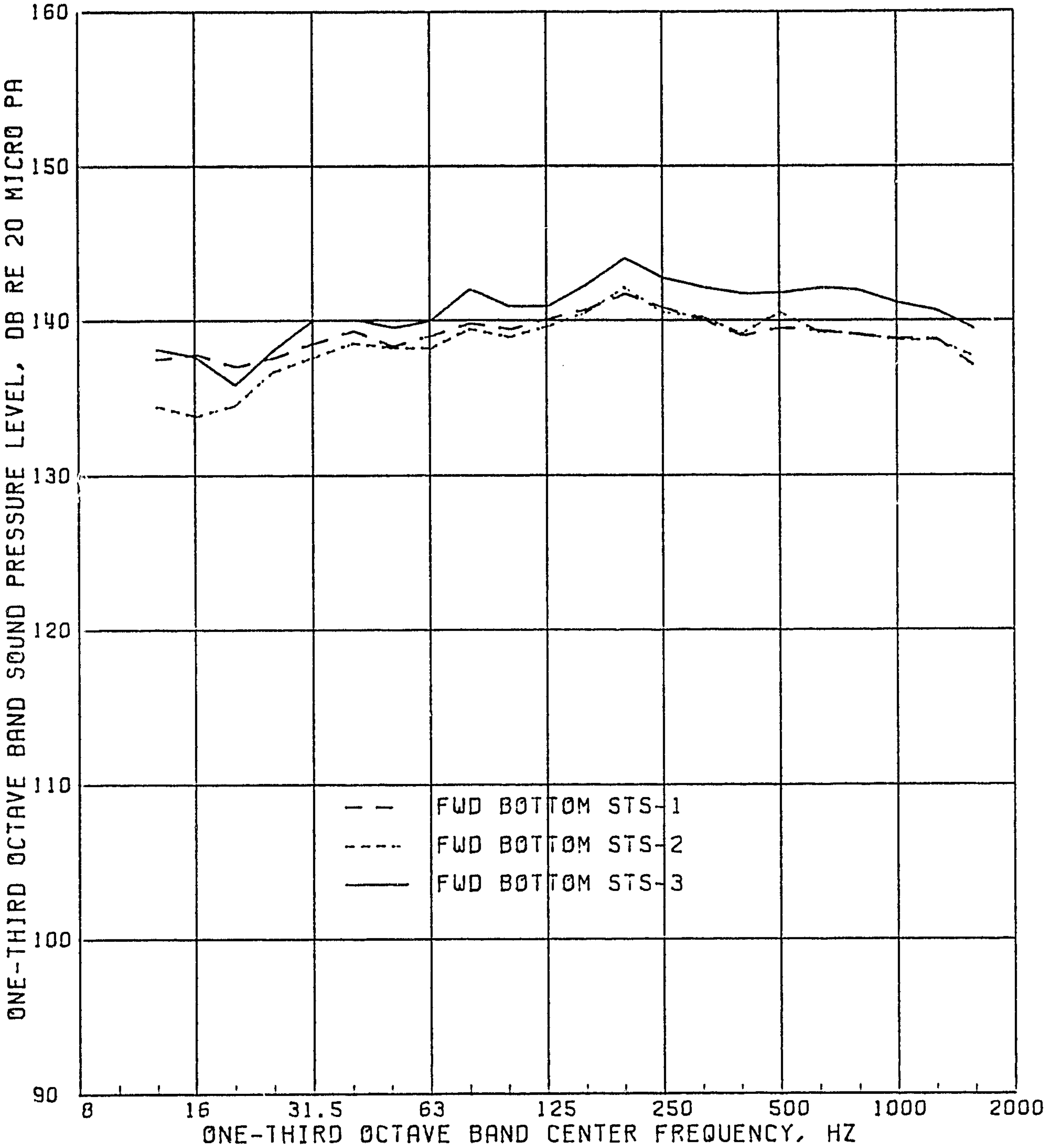

FIGURE 17. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON FORWARD REGION OF MID-FUSELAGE BOTTOM STRUCTURE FOR STS-1, STS-2 AND STS-3 LIFT-OFF

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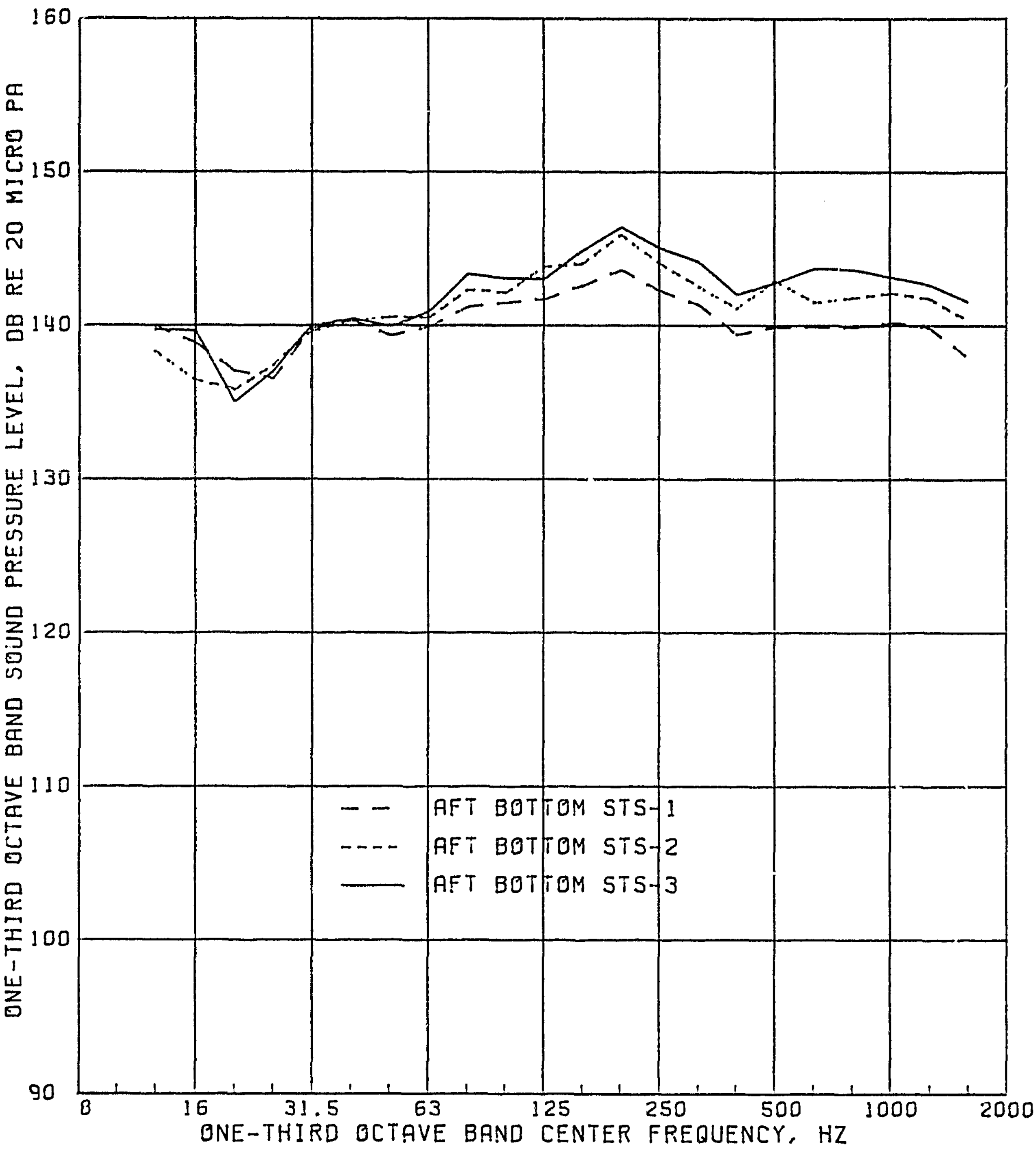

FIGURE 18. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON AFT REGION OF MID-FUSELAGE BOTTOM STRUCTURE FOR STS-1, STS-2 AND STS-3 LIFT-OFF

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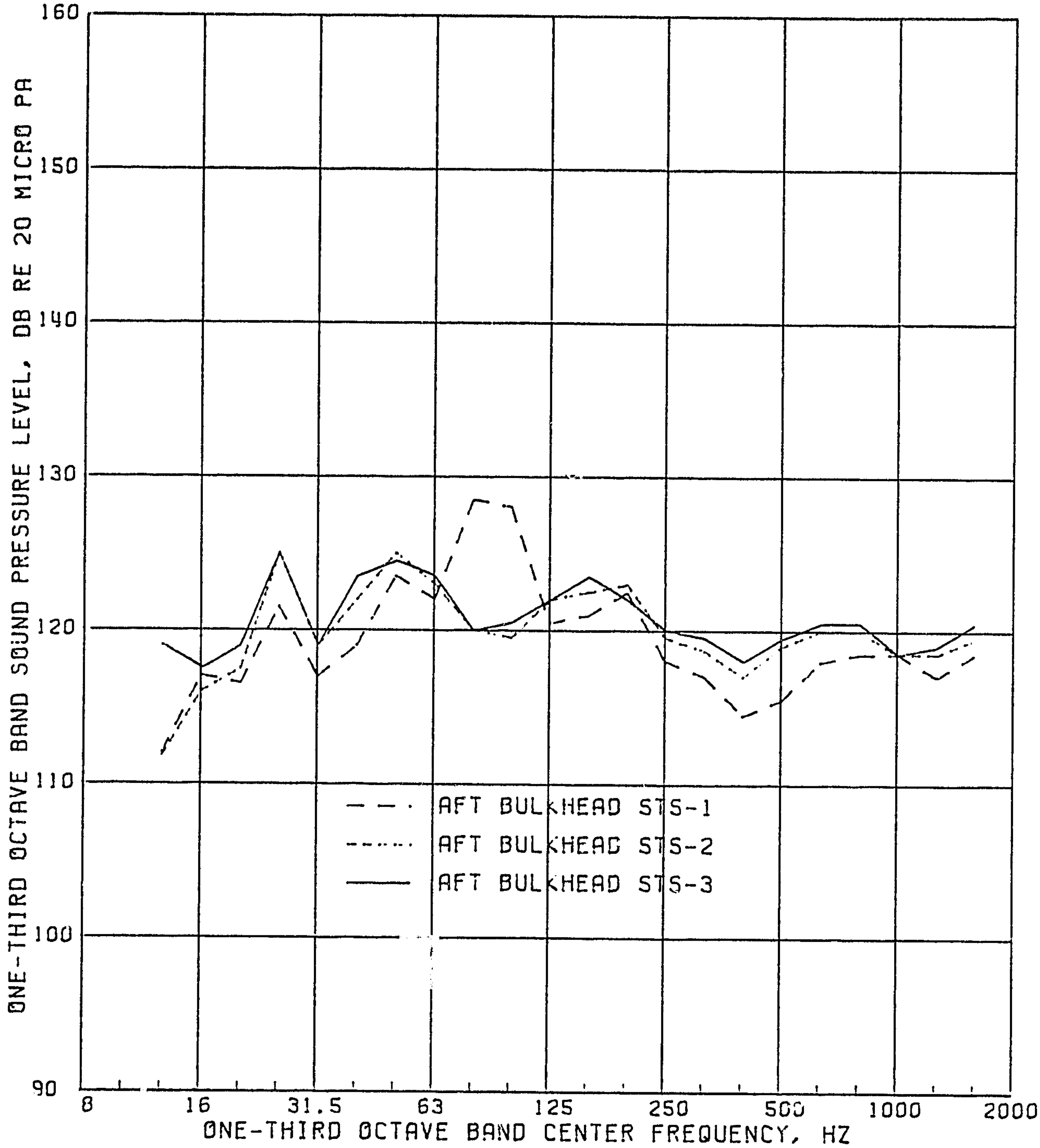

FIGURE 19. COMPARISONS OF SOUND LEVELS ON PAYLOAD BAY AFT BULKHEAD FOR STS-1, STS-2, AND STS-3 LIFT-OFF

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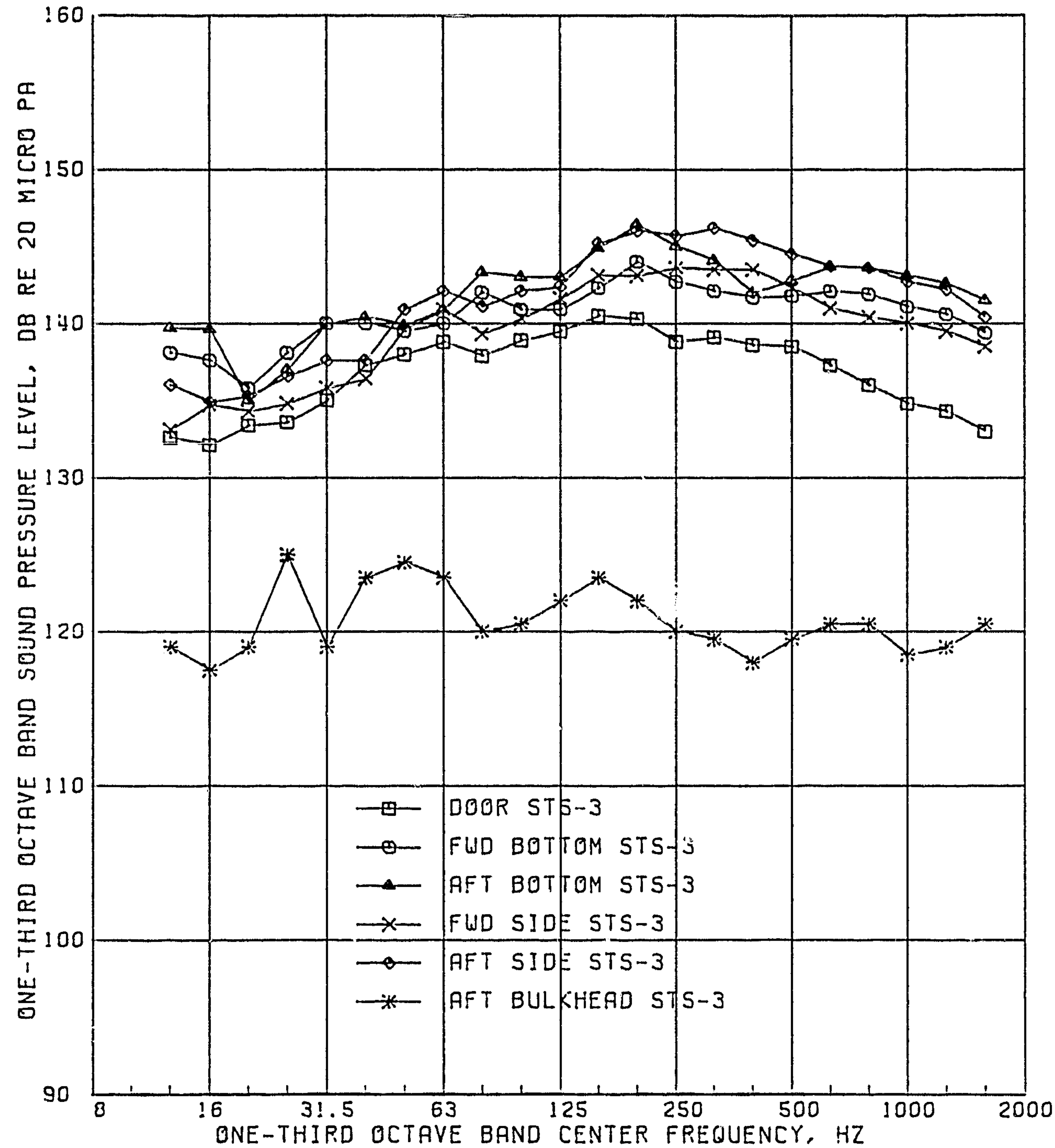

FIGURE 20. SPACE-AVERAGE SOUND LEVELS FOR EXTERIOR OF PAYLOAD BAY ESTIMATED FROM STS-3 LIFT-OFF DATA

Table 9. Exterior Space-Average Sound Pressure Levels for STS-3 Lift-Off (dB re 20 μPa)

Frequency Hz	Door	Bottom STA 582 -1191	Bottom STA 1191 -1307	Sidewall STA 582 -1040	Sidewall STA 1040 -1307	Aft Bulkhead
12.5	132.6	138.1	139.7	133.1	136.0	119.0
16.0	132.1	137.6	139.6	134.7	134.9	117.5
20.0	133.4	135.8	135.0	134.3	135.3	119.0
25.0	133.6	138.1	137.0	134.8	136.6	125.0
31.5	135.0	140.0	140.0	135.8	137.6	119.0
40.0	137.3	140.0	140.4	136.4	137.6	123.5
50.0	138.0	139.5	139.9	139.6	140.9	124.5
63.0	138.8	140.0	140.9	140.9	142.1	123.5
80.0	137.9	142.0	143.3	139.3	141.1	120.0
100.0	138.9	140.9	143.0	140.3	142.1	120.5
125.0	139.5	140.9	143.0	141.6	142.4	122.0
160.0	140.5	142.3	144.9	143.1	145.2	123.5
200.0	140.3	144.0	146.4	143.1	146.0	122.0
250.0	138.8	142.7	145.0	143.6	145.7	120.0
315.0	139.1	142.1	144.1	143.5	146.2	119.5
400.0	138.6	141.7	142.0	143.5	145.4	118.0
500.0	138.5	141.8	142.8	142.3	144.5	119.5
630.0	137.3	142.1	143.7	141.0	143.7	120.5
800.0	136.0	141.9	143.6	140.4	143.6	120.5
1000.0	134.8	141.1	143.1	140.0	142.7	118.5
1250.0	134.3	140.6	142.6	139.5	142.2	119.0
1600.0	133.0	139.4	141.5	138.5	140.4	120.5

The STS-1 and STS-2 spectra in Figures 21 and 22 can be compared with the STS-3 spectra in Figure 20. The STS-2 levels show an increase of 1 to 1.5 dB at frequencies above 100 Hz, but otherwise the levels are similar.

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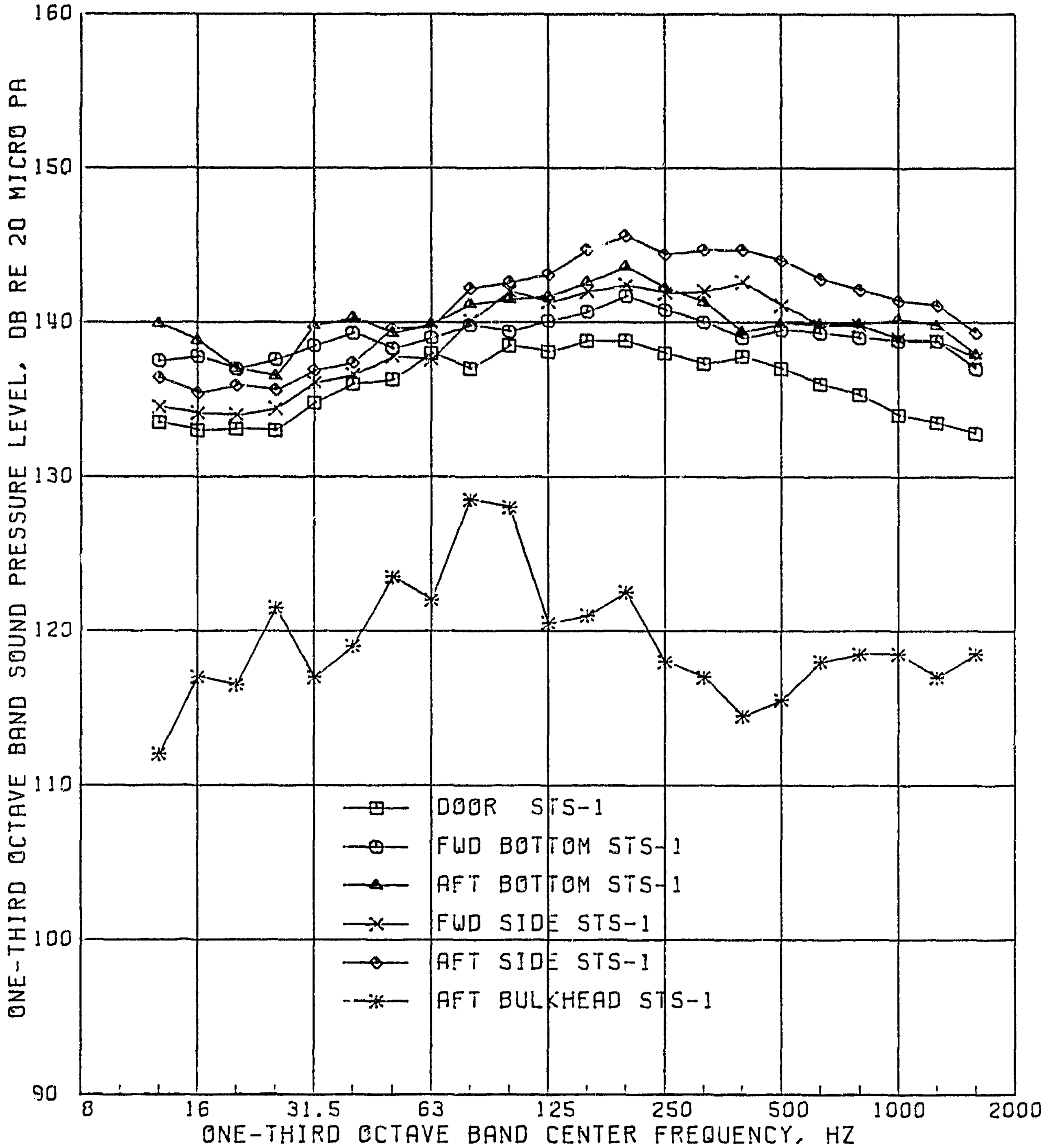

FIGURE 21. SPACE-AVERAGE SOUND LEVELS FOR EXTERIOR OF PAYLOAD BAY ESTIMATED FROM STS-1 DATA

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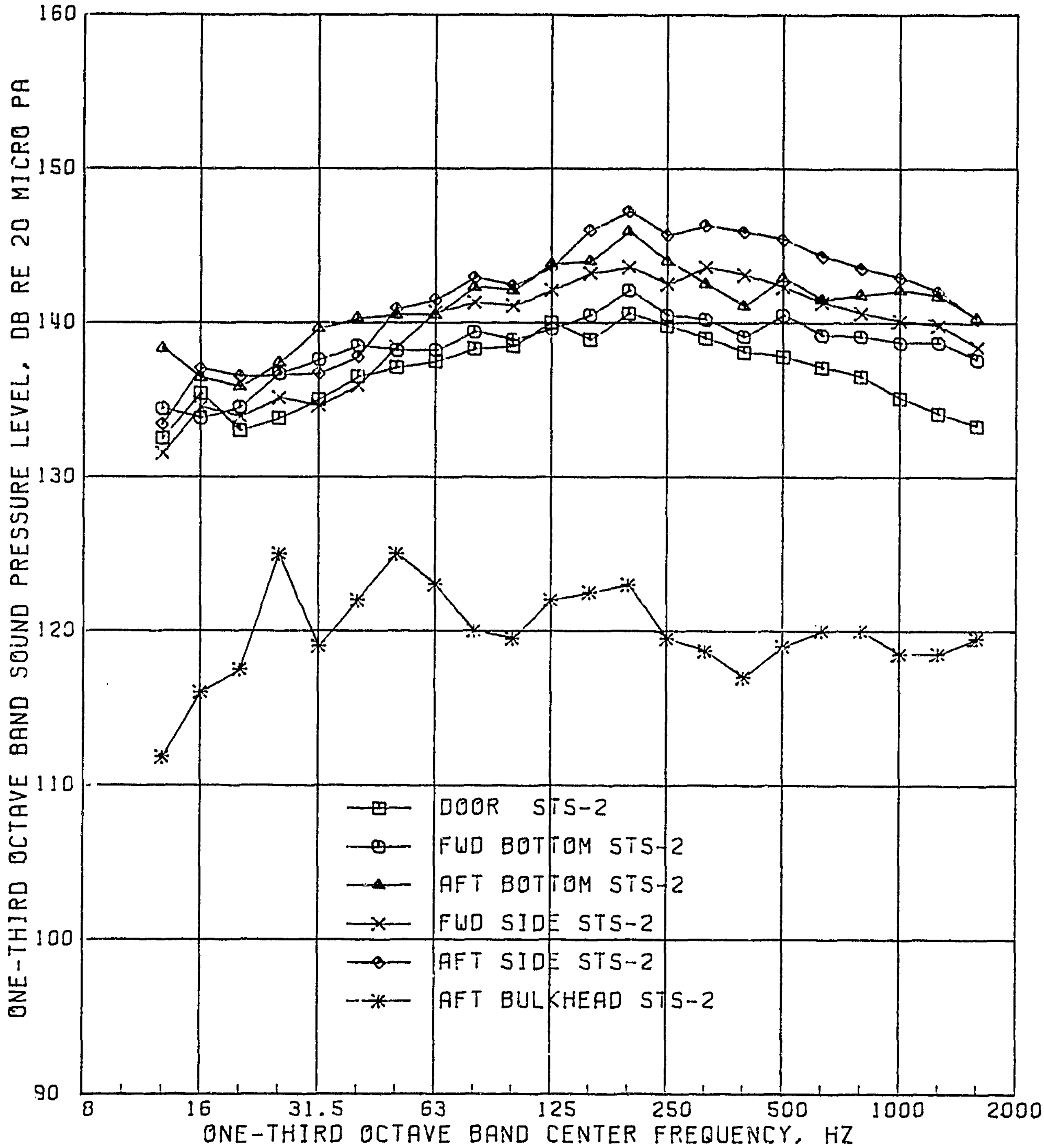

FIGURE 22. SPACE-AVERAGE SOUND LEVELS FOR EXTERIOR OF PAYLOAD BAY ESTIMATED FROM STS-2 DATA

6.0 PACES CALCULATIONS

6.1 Interior Space-Average Sound Levels

The STS-3 space-average exterior sound levels plotted in Figure 20 have been used as input data to the PACES computer program in order to predict space-average sound levels in the payload bay at lift-off. Three different payload bay configurations have been considered. In the first case the bay was considered to be completely empty. Then, for the second case, the OSS-1 and DFI payloads were modeled as a single volume-displacing (non-bounding) payload, such as that described in Volume II of [1] for the DSP/IUS payload. Finally, in the third case, the bay was modeled as two subvolumes with the DFI payload forming the bounding surface between the two regions. The OSS-1 payload was modeled as a volume-displacing payload in the forward subvolume.

These three cases were considered in order to explore the effects of the different idealizations and to provide a reasonable simulation of launch conditions. The results from the analyses are contained in the following three sections. Similar analyses were performed in [4] for STS-2 payloads.

6.2 Empty Bay Representation

In [3] the space-average sound levels in the payload bay for STS-1 were estimated under the assumption that there was no payload in the bay. The DFI payload was assumed to have zero volume and zero sound absorbing area. As the payload size increased from STS-1 to STS-2 and STS-3, the assumption lost its validity. However, for comparative purposes, the first prediction for the STS-3 launch assumes that there is no payload in the bay. Acoustic absorption coefficients for the payload bay surfaces are those given in Table 10, which includes TCS material

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Table 10. Estimated Absorption Coefficients for Payload Bay

Frequency (Hz)	Door	Bulkhead	Sidewall & Bottom (Base)	Sidewall with TCS			Bottom with TCS			TCS Beneath Payload	Payload Without TCS
				STA582-919	STA919 1307	Average	STA582-919	STA919-1307	Average		
12.5	0.100	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.175
16	↓	0.043	0.040	0 043	0.065	0.054	0.043	0.065	0.054	0.065	↓
20		0.045	0.040	0.045	0.090	0.068	0.045	0.090	0.068	0.090	
25		0.048	0.040	0.048	0.114	0.081	0.048	0.114	0.081	0.115	
31.5		0,050	0.040	0.050	0.140	0.095	0.050	0.140	0.095	0.140	
40		0.055	0.040	0.055	0.140	0.098	0.060	0.140	0.100	0.140	
50		0.060	0.040	0.060	0.145	0.103	0.065	0.145	0.105	0.145	
63		0.065	0.040	0.065	0.150	0.108	0.075	0.155	0.115	0.155	
80		0.075	0.050	0.075	0.165	0.120	0.095	0.170	0.133	0.170	
100		0.085	↓	0.085	0.180	0.133	0.110	0.195	0.153	0.205	
125		0.100		0.100	0.200	0.150	0.125	0.230	0.178	0.260	
160		0.105		0.105	0.240	0.173	0.140	0.280	0.210	0.360	
200		0.115		0.115	0.280	0.198	0.165	0.375	0.270	0.500	
250		0.125		0.125	0.370	0.248	0.220	0.480	0.350	0.570	
315		0.210		0.210	0.460	0.335	0.310	0.540	0.425	0.605	
400		0.305		0.305	0.505	0.405	0.415	0.565	0.490	0.615	
500		0.400		0.400	0.525	0.463	0.480	0.570	0.525	0.615	
630		0.400		0.400	0.530	0.465	0.505	0.570	0.538	0.595	
800		0.400		0.400	0.530	0.465	0.520	0.570	0.545	0.570	
1000		0.400		0.400	0.520	0.460	0.530	0.565	0.548	0.550	
1250		0.400		0.400	0.510	0.455	0.535	0.560	0.458	0.530	
1600		0.400		0.400	0.505	0.453	0.535	0.550	0.543	0.510	
2000		0.400		0.400	0.490	0.445	0.535	0.540	0.538	0.500	
2500		0.395		0.395	0.470	0.433	0.525	0.530	0.525	0.490	
3150		0.390		0.390	0.455	0.423	0.520	0.520	0.520	0.480	
4000		0.390		0.390	0.430	0.410	0.510	0.510	0.510	0.470	

on the fore and aft bulkheads. The calculated space-average interior sound levels for STS-3 are compared in Figure 23 with corresponding results for STS-1 and STS-2 launches. Differences in predicted interior levels can be attributed mainly to the changes in the door exterior sound pressure levels shown in Figure 12, since the acoustic power transmitted through the door dominates the predicted interior sound pressure level spectrum.

6.3 Representation with a Single Payload

In this representation the DFI and OSS-1 payloads are combined and modeled as a single, volume-displacing payload with non-bounding surfaces. This is the representation recommended in Volume II of [1] for a payload whose volume is small relative to the volume of the payload bay. This idealization is discussed in Volume II of [1] with reference to the DSP/IUS payload. For the case of STS-3 it is estimated that the sound-absorbing area of the DFI payload is 25.8 sq.m (40,000 sq.in) and of the OSS-1 payload, 53.6 sq.m (83,000 sq.in). It is assumed that the total area of the DFI is covered with TCS material but only 30% of OSS-1 is covered with the material. The volumes of the DFI and OSS-1 payloads are estimated to be 10.5 cu.m (640,000 cu.in) and 19.5 cu.m (1,190,000 cu.in) respectively. The total payload volume is only 6% of the volume of the empty bay.

Absorption coefficients presented in Table 10 for typical payloads were obtained in [1] from test data for several shrouded and unshrouded spacecraft launched prior to the introduction of the Space Shuttle. Since the payloads launched on STS-1 through STS-3 were covered, at least in part, by TCS material it is appropriate to include the sound absorbing properties of that material when determining the acoustic characteristics of the payload. Furthermore, it is also appropriate to assume that at low frequencies the absorption coefficients of the payloads should be typical of relatively flexible spacecraft structures.

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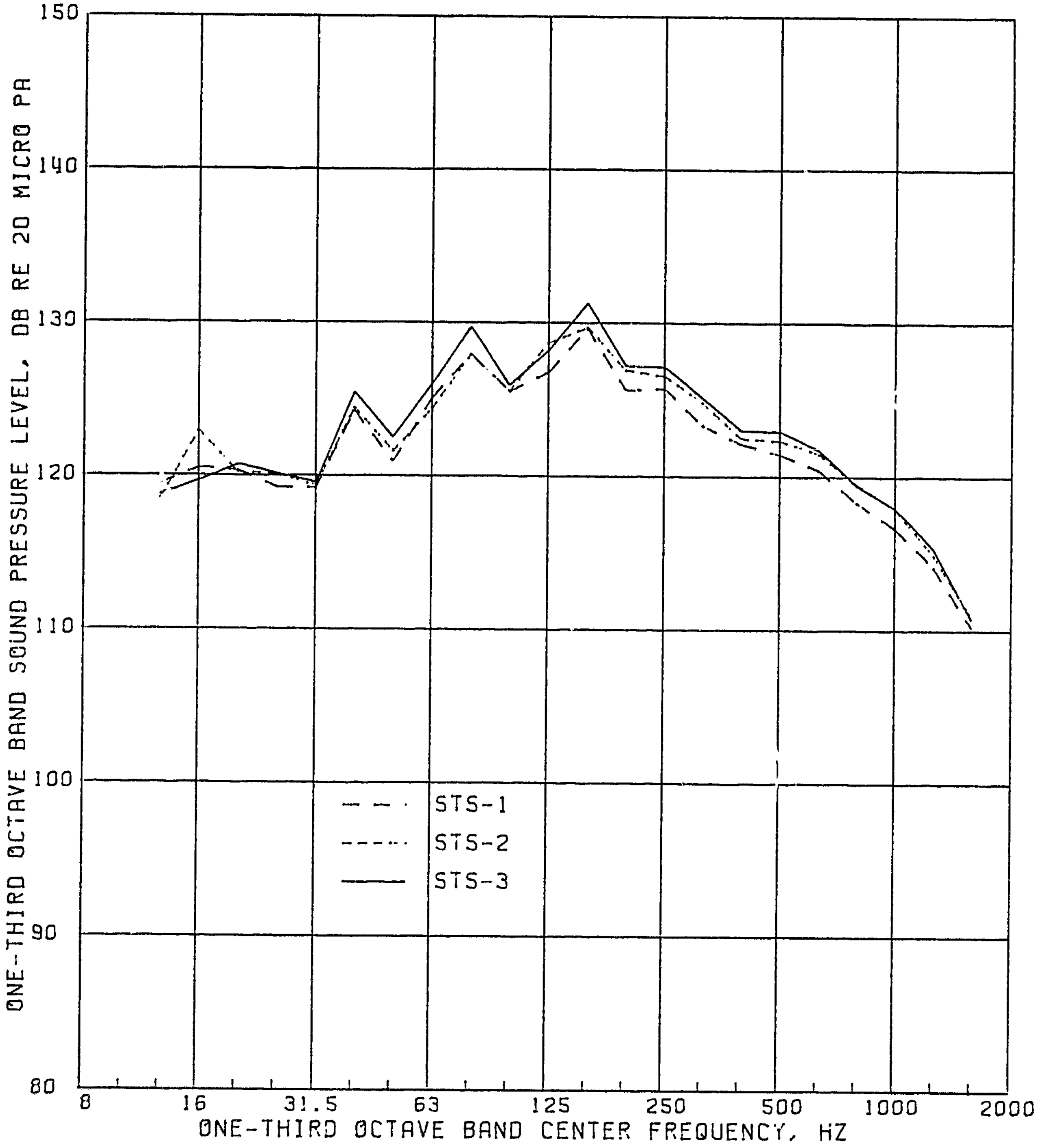

FIGURE 23. SPACE-AVERAGE SOUND PRESSURE LEVELS PREDICTED BY PACES FOR EMPTY PAYLOAD BAY AT LIFT-OFF (STS-1 THROUGH STS-3)

The resulting composite absorption coefficient spectrum for the combined DFI/OSS-1 payload is given in Table 11.

Table 11. Assumed Absorption Coefficients for Payload Surfaces

Frequency (Hz)	Absorption Coefficient			
	Payload Without TCS	Payload With TCS (DFI)	Combined DFI/OSS-1 Payload	OSS-1 Payload
12.5	0.175	0.175	0.175	0.175
16				
20				
25				
31.5				
40				
50				
63				
80				
100				
125				
160				
200		0.175	0.175	0.175
250		0.220	0.198	0.193
315		0.310	0.243	0.229
400		0.415	0.295	0.271
500		0.480	0.328	0.297
630		0.505	0.340	0.307
800		0.520	0.348	0.313
1000		0.530	0.353	0.317
1250		0.535	0.355	0.319
1600		0.535	0.355	0.319
2000		0.535	0.355	0.319
2500		0.525	0.350	0.315
3150		0.520	0.348	0.313
4000	0.175	0.510	0.343	0.309

The predicted space-average sound pressure levels in the payload bay with a non-bounding payload are compared in Figure 24 with corresponding spectra for STS-1 and STS-2. In all cases the spectra are very similar in shape and level to the corresponding spectra in Figure 23 predicted for an empty payload bay. The effect of the payload is to reduce the one-third octave band space-average sound pressure levels by, on the average, 0.6 dB for STS-3, 1.1 dB for STS-2 and 0.3 dB for STS-1.

6.4 Representation with Two Subvolumes

When payloads have small volumes, the PACES computer program procedure recommends that the payloads be modeled as volume-displacing payloads in a single volume. Such an idealization is discussed in Section 6.3. One important reason for adopting such an idealization is that any arbitrarily selected subvolume around a small payload would artificially create acoustic modes which could not occur in practice. These modes distort the PACES predictions. However, it was of interest for STS-2 to assume that the payload bay was divided into two subvolumes, with the DFI payload forming the boundary between the two regions [4]. A similar model is used here for the STS-3.

To achieve this idealization without the introduction of spurious modes, the DFI payload is represented as an inward deformation of 1.0m (40 inches) to the rear x-surface (X = 1184) of the forward subvolume and a similar inward deformation to the forward x-surface (X = 1184) of the aft subvolume. In this manner the DFI payload volume is introduced without forming a small sub-volume around the payload. The OSS-1 payload is modeled as a non-bounding payload in the forward subvolume. (Approximate area and volume for OSS-1 are given in Section 6.3). Acoustic absorption coefficients used for the DFI and OSS-1 payload surfaces are given in Table 11, and are based on the discussion in Section 6.3.

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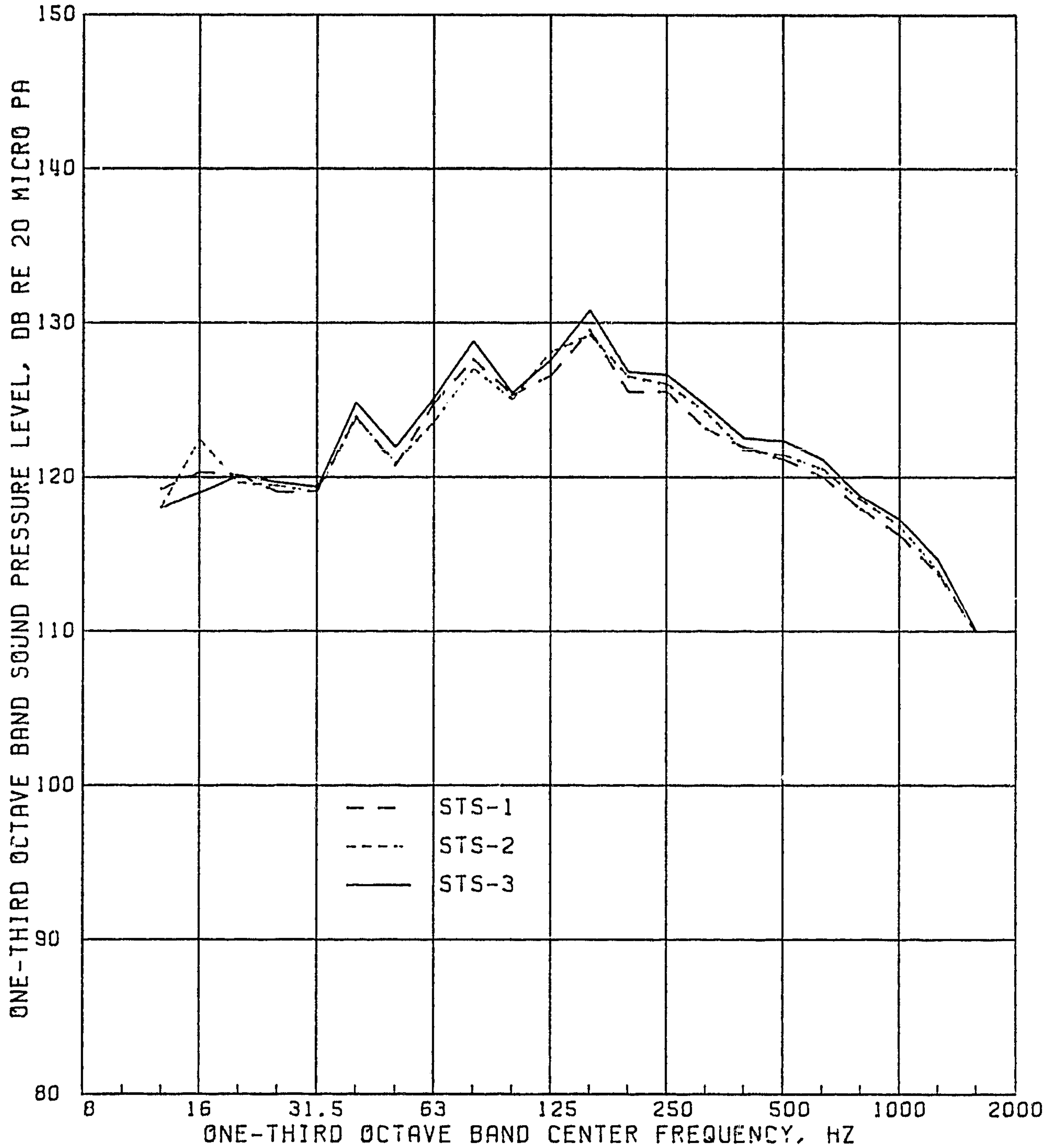

FIGURE 24. SPACE-AVERAGE SOUND PRESSURE LEVELS PREDICTED BY PACES FOR PAYLOAD BAY WITH SINGLE VOLUME-DISPLACING PAYLOAD (STS-1 THROUGH STS-3)

The predicted space-average sound pressure level spectra for the two subvolumes are plotted in Figure 25, where the results are compared with those calculated on the basis of the single non-bounding payload discussed in Section 6.3. There are only small differences in predicted sound level between the two payload idealizations, and the general trends are similar to those for STS-2 [4]. Firstly, with the exception of only three frequency bands, the sound levels predicted for the two-subvolume idealization are equal to, or lower than, the corresponding levels predicted for the single volume representation. Averaging over all one-third octave bands the differences are 1.1 dB for the forward subvolume and 1.5 dB for the aft subvolume. Secondly, for the two-volume idealization the predicted sound pressure levels are higher in the forward subvolume than in the aft; the differences are small, however, being only 0.4 dB on the average, and 2.0 dB as a maximum.

6.5 Comparison with Measured Data

The space-average sound presssure levels predicted in Section 6.3 for a payload bay with a volume-displacing payload can be compared with corresponding levels determined from the STS-3 launch measurements. As is discussed in Section 4.0 there are two alternative values of the "measured" space-average sound pressure level. The first "measured" spectrum is based on the bias error correction method of [6], as described in Section 4.1. This spectrum, with the associated 95% confidence limits, is compared with the PACES predicted spectrum in Figure 26. A similar comparison is shown in Figure 27, where the measured values are now based on the four-volume average described in Section 4.2.

In both cases the spectrum levels predicted by PACES are slightly higher than the corresponding measured values, with the predictions showing better agreement with the four-volume average than with the average based on the bias error correction method. For

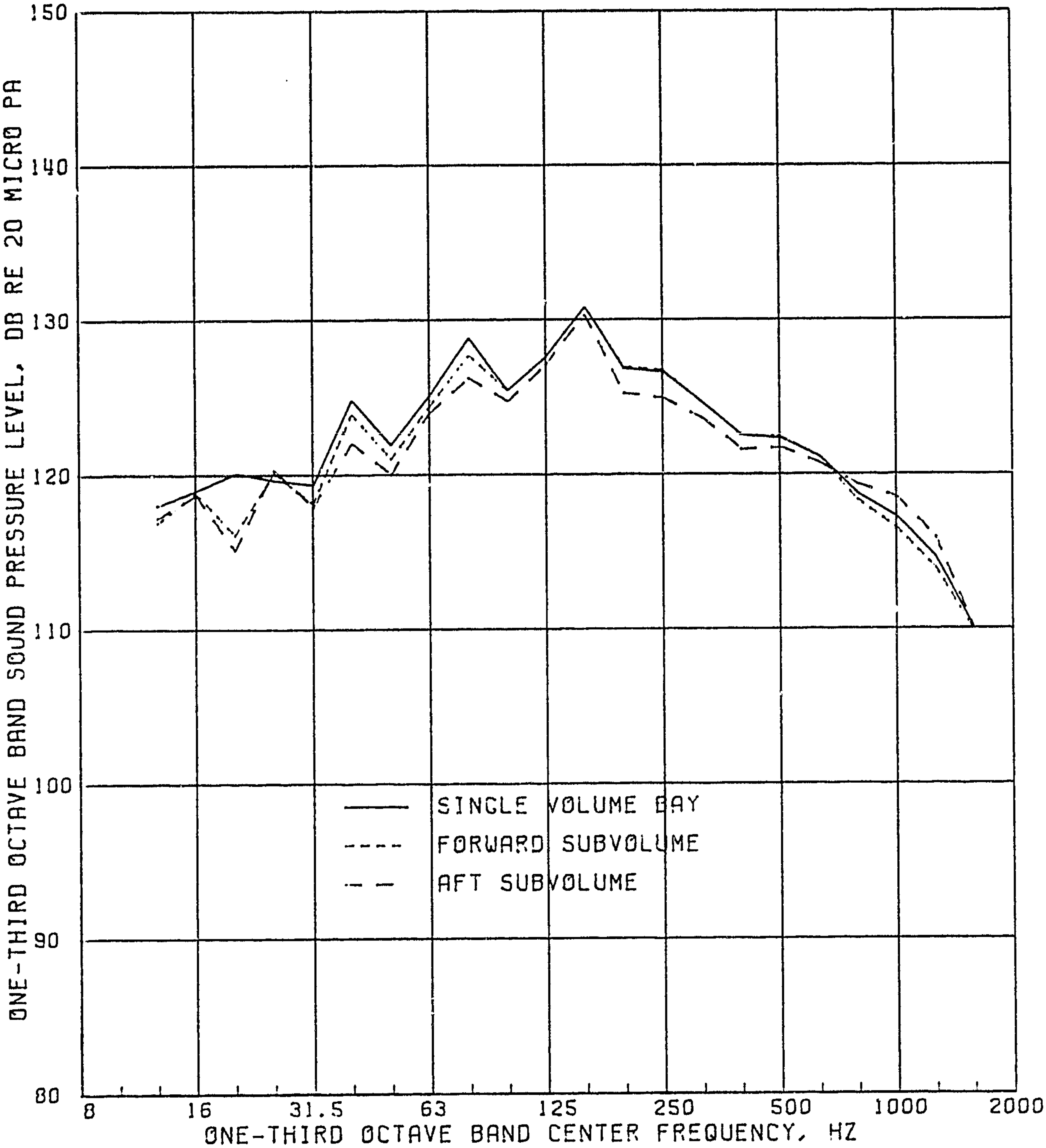

FIGURE 25. PAYLOAD BAY SOUND PRESSURE LEVELS PREDICTED BY PACES FOR SINGLE VOLUME AND TWO-SUBVOLUME PAYLOAD BAY REPRESENTATIONS WITH VOLUME-DISPLACING PAYLOADS (STS-3)

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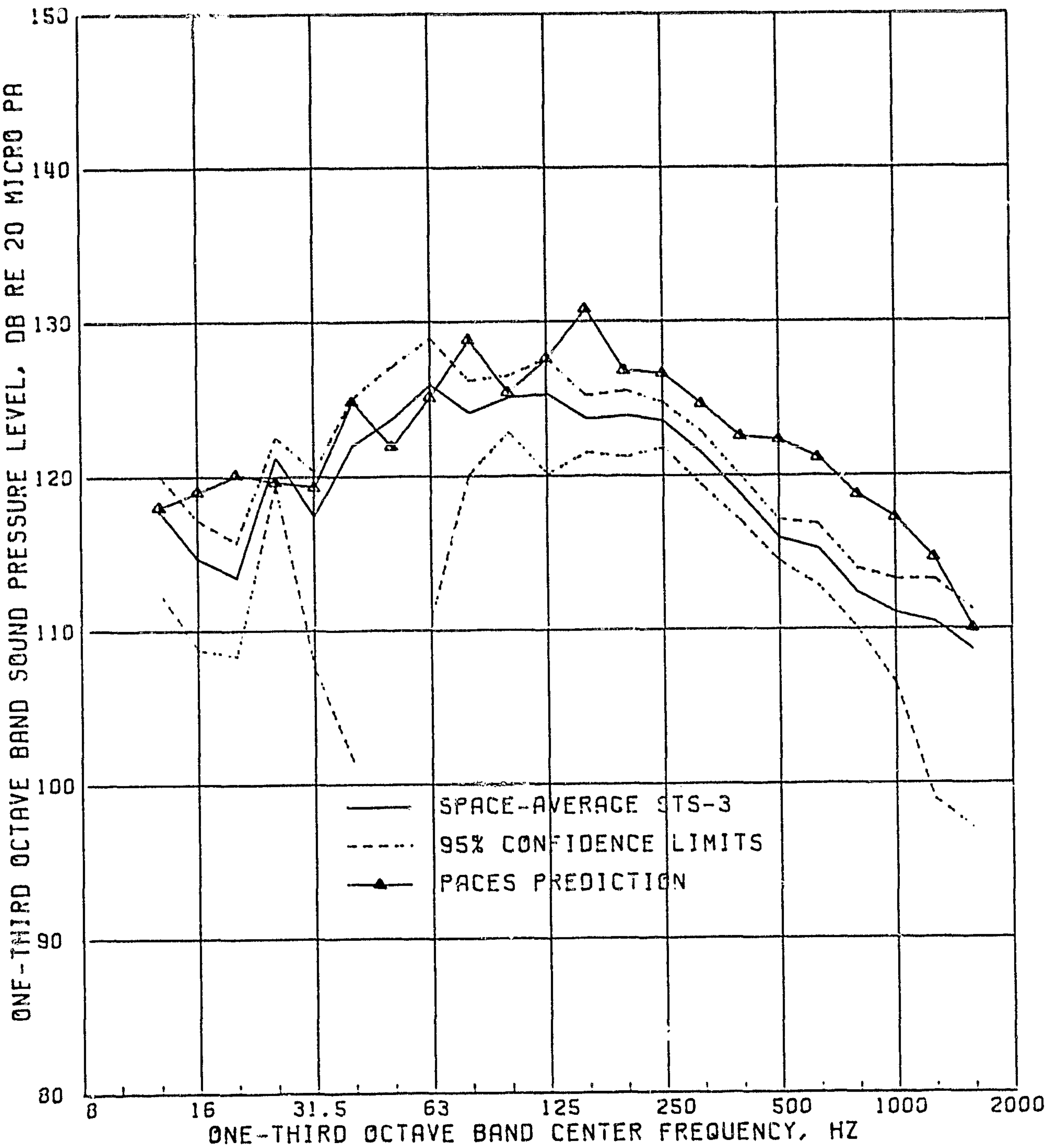

FIGURE 26. COMPARISON OF PREDICTED (SINGLE VOLUME WITH PAYLOAD) AND MEASURED (BIAS ERROR CORRECTION METHOD) PAYLOAD BAY SPACE-AVERAGE SOUND PRESSURE LEVELS FOR STS-3

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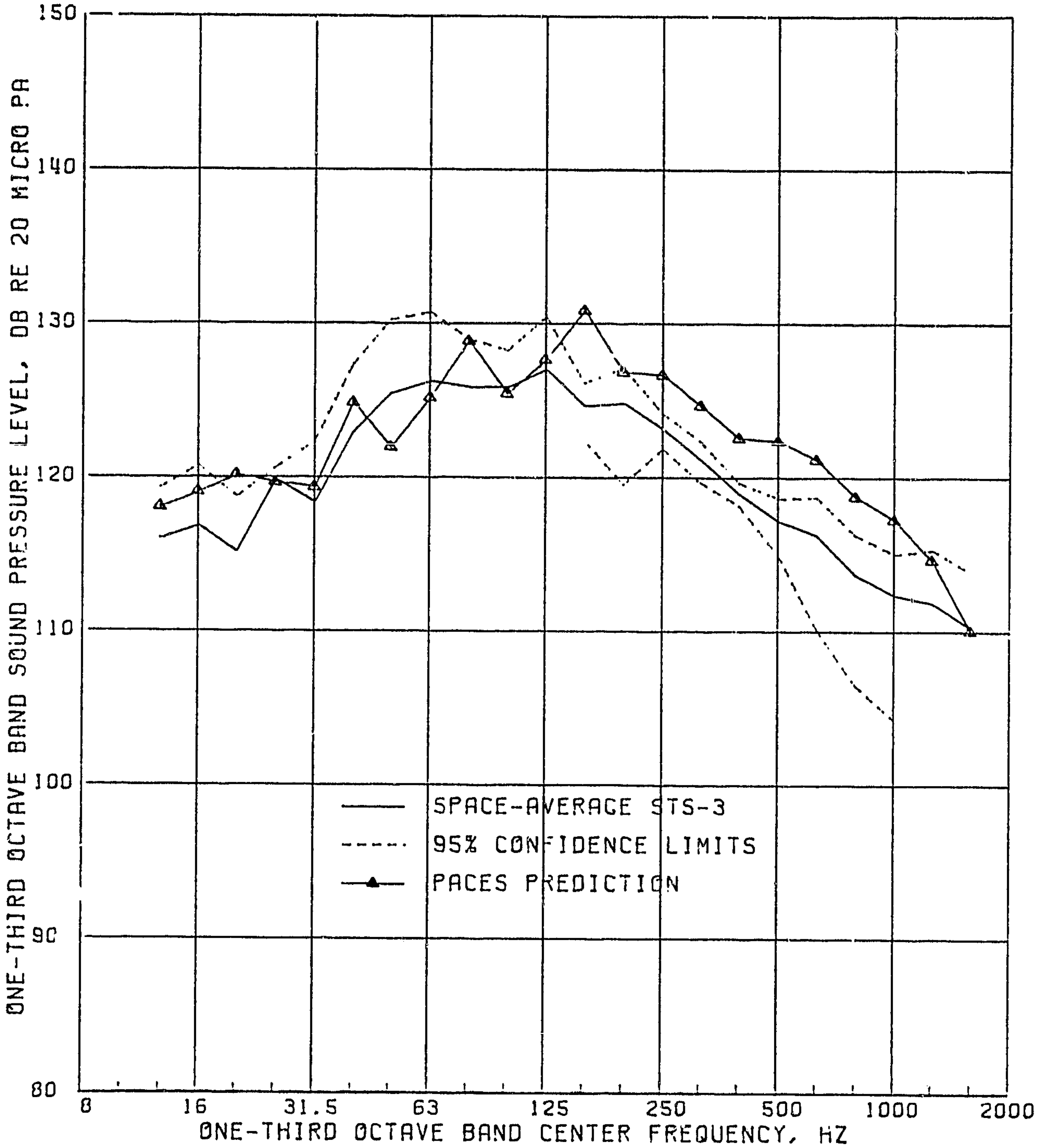

FIGURE 27. COMPARISON OF PREDICTED (SINGLE VOLUME WITH PAYLOAD) AND MEASURED (FOUR-VOLUME AVERAGE) PAYLOAD BAY SPACE-AVERAGE SOUND PRESSURE LEVELS FOR STS-3

example, if the differences between measured and predicted space-average one-third octave bands sound pressure levels are averaged for the frequency range 12.5 Hz to 1600 Hz, the PACES program predicts sound levels which are about 2.4 dB higher than measured values based on four-volume averaging, and 3.2 dB higher than those obtained following the bias error correction method of [6].

Inspection of Figures 26 and 27 (and of similar figures for STS-1 [3] and STS-2 [4]) suggests that the spectra can be subdivided into two frequency ranges, 12 to 125 Hz and 160 to 1600 Hz. In the upper frequency range the predicted sound pressure levels are consistently higher than the measured values, with the average difference for the one-third octave bands being 3.5 to 4.5 dB. At lower frequencies the predicted and measured spectral curves cross several times with the predicted levels in some bands being higher than measured values, while in other bands the converse is true. Thus in the frequency range 12.5 to 125 Hz the predicted one-third octave band levels are, on the average, only 1 dB higher than the measured values.

The comparison between measured and predicted space-average sound pressure levels can be carried further by means of the predicted levels for the two-subvolume idealization discussed in Section 6.4. For this comparison, predicted space-average sound pressure levels for the whole bay are obtained from volume-weighted energy averages for the two subvolumes. The average levels are compared in Figure 28 with measured four-volume averages. It is seen that in the high frequency range (160 to 1600 Hz) the agreement between predicted and measured levels is essentially no better than for the single volume idealization (Figure 27). In the low frequency range (12.5 to 125 Hz) the predicted spectrum shows closer agreement with measured values, with the average difference between predicted and measured

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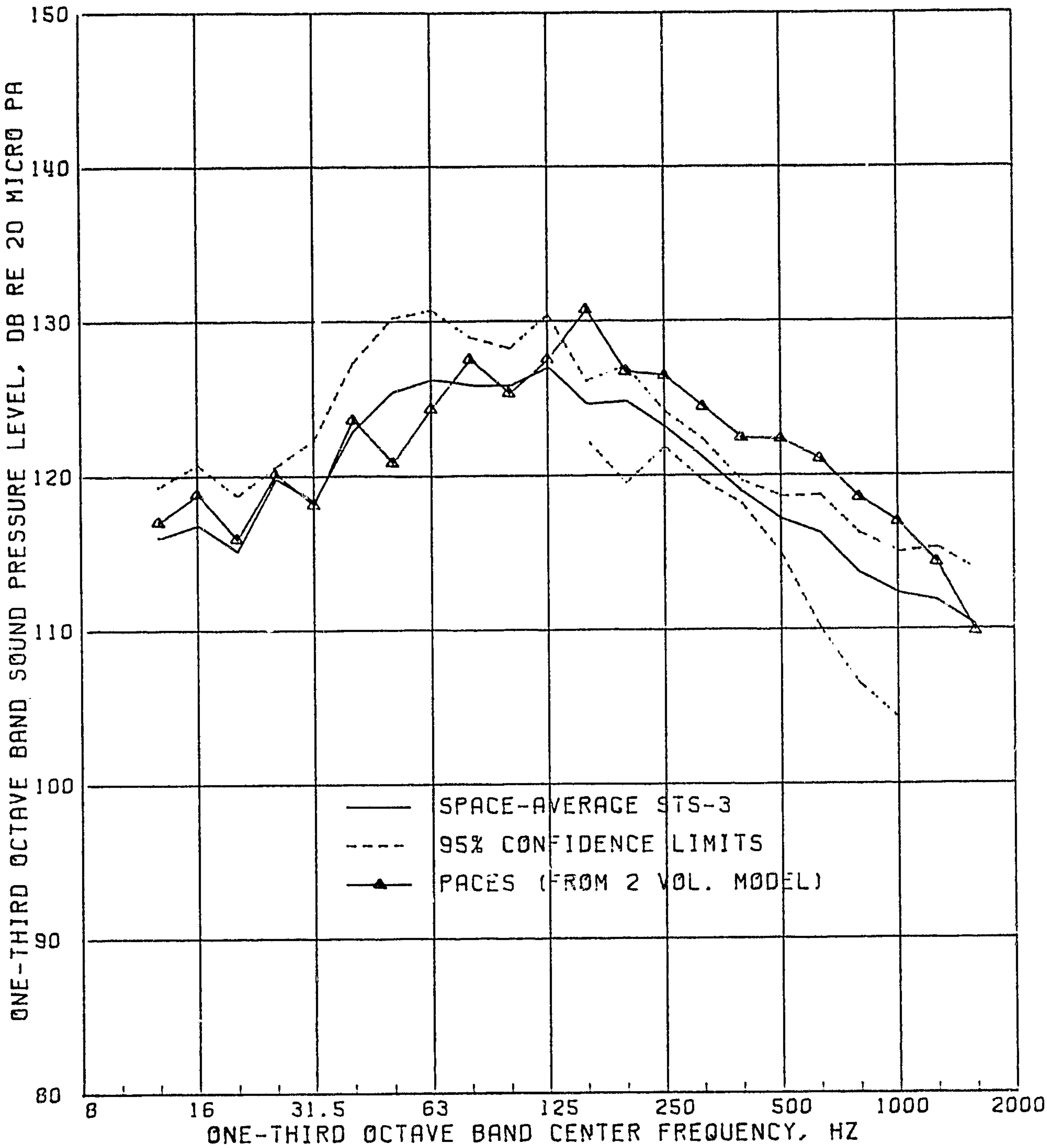

FIGURE 28. COMPARISON OF PREDICTED (TWO-VOLUME MODEL) AND MEASURED (FOUR-VOLUME AVERAGE) PAYLOAD BAY SPACE-AVERAGE SOUND PRESSURE LEVELS FOR STS-3

levels for the eleven one-third octave bands being 0 dB. A more-detailed comparison based on sound levels in individual subvolumes does not seem worthwhile because, as discussed in Section 6.4, the two-subvolume idealization is not necessarily appropriate for such a small payload.

6.6 Influence of Vents

In the analysis of STS-1 data [3], a crude model was developed to represent the noise transmission through the open vents. The effect of the open vents was to increase the acoustic power flow into the bay and, consequently, increase the space-average sound levels in the bay. However, since the model is crude and the accuracy of the estimates for the exterior sound pressure levels at the vent locations is poor, no PACES predictions have been made for STS-3 payload bay interior sound levels with vents open. It is highly desirable that measurements be made in the payload bay to determine the acoustic power being transmitted through the open vent. This is particularly important for large diameter payloads.

7.0 CONCLUSIONS

Space-average sound pressure levels computed from measurements at 9 locations in the payload bay of the Space Shuttle orbiter vehicle during STS-3 launch have been compared with predicted levels obtained using the PACES computer program. The comparisons have been performed in the frequency range 12.5 to 1600 Hz, since the test data at higher frequencies may be contaminated by instrumentation background noise.

One important factor in the evaluation of the PACES analytical model is the measured spatial variation of the sound pressure levels in the payload bay. The data show higher sound levels in the forward part of the bay than in the aft. This is in contrast to the spatially uniform data from the OV-101 and one-quarter scale tests on which the bias error correction procedure [6] was based. To compensate for this spatial variation an alternative procedure for estimating the space-average sound pressure levels was introduced in [4] for the analysis of STS-2 data. The same procedure, whereby the bay is divided into four equal subvolumes and the sound pressure levels averaged for each subvolume before obtaining an overall average for the bay, has been used for the STS-3 measurements.

In general the PACES analytical model tends to overpredict the space-average sound pressure levels in the payload bay, although the magnitude of the discrepancy is usually small. Furthermore the discrepancy depends to some extent on the manner in which the payload is modeled analytically, and the method used to estimate the space-average sound pressure levels from the measured data. When making the comparison between measured and predicted sound levels it is convenient to consider upper (160 to 1600 Hz) and lower (12.5 to 125 Hz) frequency ranges separately. In the upper frequency range the comparison seems to be essentially independent of the analytical model and the estimation method applied to the measurements. The difference between predicted and measured levels, averaged over the eleven one-third octave frequency bands in the frequency range 160-1600 Hz, is about 4 dB.

At lower frequencies the difference between predicted and measured space-average sound pressure levels does depend on the analysis methods used, although even so the predicted levels are, on the average, higher than the measured values. These differences, averaged over the eleven one-third octave bands from 12.5 to 125 Hz, range from 0 to 2 dB.

Although the intent of this investigation, and preceding studies [3,4] for STS-1 and STS-2, was to evaluate the PACES analytical model for an empty payload bay, several payload idealizations were studied. Since the payload volume is so small (about 6% of the total payload volume) the recommended idealization [1] for use in PACES would be that of a non-bounding, volume-displacing payload. Other idealizations utilizing two- and four-subvolumes were tried, and the results for the two-subvolume idealization are given in this report. Results for the four-subvolume idealization were omitted since the analysis introduced spurious acoustic modes. This limitation on the PACES program is discussed in detail in [1], and arises when subvolumes constructed in the payload idealization do not have boundaries which provide strong acoustic reflections.

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APPENDIX A

Recomputed Bias Error Corrections for Payload Bay Sound Pressure Level Measurements During STS-3 Lift-Off

(See [6] for general principles and procedures)

Table A-1. Paired Microphones from OV101 and 1/4 Scale Model Tests for STS-3*.

General Location	STS-3 Microphone Locations (Figs 1-3)	OV101 Test Microphone Locations (Ref.6)	1/4 Scale Model Microphone Locations (Ref.6)
Forward Bulkhead	I1	M16-A	M3-A
Mid Sidewall	I2	M19-B	M4-C
Aft Bulkhead	I3	M15-A	M3-F
DFI Payload	I4	M12-A	M3-E
	I5	M12-B	M2-E
	I7	M15-B	M4-F
OSS-1 Payload	I19	M11-B	M3-E
	I20	M11-A	M3-D
	I22	M11-A	M1-D

* Replaces Table 8 in Reference 6.

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Table A-2. Sound Pressure Levels at STS-3 Measurement Locations from OV101 Jet Noise Tests

Freq. (Hz)	Sound Pressure Level, dB (ref: 20 μPa)							
	M11-A (2)*	M11-B (1)*	M12-A (1)*	M12-B (1)*	M15-A (1)*	M15-B (1)*	M16-A (1)*	M16-B (1)*
12.5	71.3	71.8	73.3	73.9	73.9	73.7	74.8	75.3
16	82.8	83.4	75.8	75.7	82.0	82.0	81.5	83.9
20	84.1	85.0	76.4	74.9	84.7	86.2	83.1	85.2
25	90.0	89.0	87.2	90.1	86.6	84.7	89.1	91.6
31.5	88.7	95.1	86.2	89.2	81.1	89.4	87.0	94.5
40	89.9	95.6	90.3	97.1	81.7	97.4	84.9	101.9
50	93.5	101.3	89.8	100.3	92.9	98.8	89.8	105.5
63	106.0	105.7	101.2	107.6	103.9	103.3	105.3	113.0
80	104.4	103.2	104.0	112.2	106.3	108.7	100.3	109.0
100	109.3	109.5	107.8	112.3	110.9	108.0	109.7	114.2
125	109.0	110.4	108.7	112.4	106.3	110.0	105.6	112.1
160	108.8	110.3	107.3	108.1	110.9	108.4	110.1	107.8
200	110.6	108.5	112.1	108.4	109.6	111.9	110.2	107.9
250	110.3	111.7	110.6	106.5	110.7	110.3	112.3	109.8
315	109.2	110.4	109.0	111.1	110.3	110.7	109.1	111.1
400	111.2	113.0	113.2	113.5	113.5	113.2	108.9	113.0
500	108.1	110.7	109.5	112.7	109.2	111.2	108.7	111.4
630	110.1	108.6	107.8	107.4	111.3	108.3	107.0	107.7
800	106.4	106.8	106.6	106.4	106.8	107.7	104.3	106.8
1000	105.7	106.6	105.3	107.0	107.2	107.9	103.3	106.2
1250	104.1	104.4	102.3	104.3	104.8	104.6	102.8	104.7
1600	102.2	101.1	101.0	101.2	103.0	101.0	99.9	100.0
2000	97.8	97.7	96.9	97.2	97.7	97.8	96.3	98.5

* Numbers in parentheses denote number of STS-3 measurements which pair with OV101 measurement location.

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Table A-3. Sound Pressure Levels at STS-3 Measurement Location From 1/4 Scale Model Tests - With TCS Blankets

Freq. (Hz)	Sound Pressure Level, dB (ref: 20 μPa)							
	M3-A (1)*	M4-C (1)*	M3-D (1)*	M3-F (1)*	M4-F (1)*	M3-E (2)*	M1-D (1)*	M2-E (1)*
12.5	70.8	66.9	72.7	76.7	76.6	69.9	74.8	67.5
16	76.4	76.8	77.5	79.0	78.4	77.2	79.4	84.0
20	79.4	80.5	83.5	83.2	83.1	80.5	84.4	80.3
25	71.0	73.6	70.6	72.7	74.2	67.6	70.5	70.3
31.5	72.3	74.4	73.1	75.6	81.9	73.3	78.4	75.7
40	74.4	78.6	74.3	78.7	85.8	77.3	76.2	79.3
50	74.0	74.4	75.7	69.7	78.1	82.9	79.1	81.8
63	69.5	73.6	70.9	69.1	75.9	72.1	74.8	75.1
80	70.2	73.8	71.3	70.7	70.4	76.5	72.9	78.8
100	71.4	73.8	72.4	72.0	75.6	73.4	72.4	75.1
125	75.3	73.8	72.9	77.9	73.8	75.7	75.4	77.1
160	72.9	72.4	73.2	72.9	72.3	72.9	74.2	72.6
200	74.6	73.5	75.7	75.3	74.0	73.9	77.1	75.3
250	72.2	69.9	73.7	72.8	74.4	74.1	77.2	74.4
315	72.1	67.9	72.1	72.7	71.5	71.4	72.2	72.2
400	70.5	69.6	72.2	73.1	71.9	71.2	72.2	72.4
500	71.3	69.6	68.8	75.7	71.3	72.2	71.9	74.7
630	69.7	68.0	70.9	69.5	70.2	71.1	72.6	73.8
800	67.0	65.2	66.7	68.6	67.6	68.8	68.8	70.2
1000	66.0	65.0	66.5	68.7	68.4	67.0	67.7	70.7
1250	66.6	65.0	67.8	69.5	68.5	67.4	68.6	69.6
1600	66.4	65.7	68.0	69.7	69.6	68.4	70.2	72.0
2000	64.7	63.7	66.2	66.7	66.3	65.2	67.7	68.8

* Numbers in parenthesis denote number of STS-3 measurements which pair with each 1/4 scale model.

Table A-4. Sound Pressure Levels at STS-3 Measurement Location From 1/4 Scale Model Tests - No TCS Blankets

Freq. (Hz)	Sound Pressure Level, dB (ref: 20 μPa)							
	M3-A (1)*	M4-C (1)*	M3-D (1)*	M3-F (1)*	M4-F (1)*	M3-E (2)*	M1-D (1)*	M2-E (1)*
12.5	73.3	67.3	67.8	73.5	73.0	67.7	69.8	67.5
16	79.9	86.4	77.4	78.9	79.5	84.0	76.6	84.0
20	82.1	79.4	84.9	85.4	85.1	79.8	84.1	80.3
25	70.2	71.3	70.5	71.1	73.4	69.8	71.9	70.3
31.5	71.7	74.1	73.0	70.8	76.8	73.8	78.0	75.7
40	73.9	79.3	73.2	73.5	82.0	74.6	73.4	79.3
50	69.8	82.9	72.0	66.6	75.1	80.8	74.2	81.8
63	68.8	75.5	71.6	69.0	73.2	71.8	73.3	75.1
80	70.5	79.6	70.4	73.8	71.0	75.7	72.8	78.8
100	73.2	77.7	72.9	73.7	75.9	74.5	74.9	75.1
125	78.3	77.3	74.9	76.4	76.9	75.4	74.8	77.1
160	74.9	75.5	76.6	76.5	76.1	76.1	73.4	72.6
200	76.1	75.8	76.1	75.4	75.3	75.5	75.6	75.3
250	76.1	73.5	74.4	76.4	77.1	73.2	75.5	74.4
315	74.6	73.1	73.1	76.3	74.6	74.9	73.6	72.2
400	74.4	74.0	74.6	75.1	75.2	75.9	73.4	72.4
500	74.6	72.5	73.5	72.9	73.4	74.5	73.3	74.7
630	73.5	71.8	73.1	73.9	72.8	72.0	73.9	73.8
800	69.4	69.2	71.0	70.7	70.4	70.2	69.3	70.2
1000	68.5	68.8	70.4	70.5	70.9	69.2	69.8	70.7
1250	68.8	69.8	70.4	70.6	71.3	69.9	71.1	69.6
1600	70.2	70.0	70.8	71.5	71.4	70.4	71.0	72.0
2000	67.3	66.9	68.2	67.4	66.8	68.3	67.6	68.8

* Numbers in parentheses denote number of STS-3 measurements which pair with each 1/4 scale model measurement location.

Table A.5 Summary of Bias Correction Factors for STS-3 Payload Bay Acoustic Levels

Freq. (Hz)	Sound Pressure Level, dB (ref: 20 μPa)										
	1/4 Scale Model - TCS			1/4 Scale Model - No TCS			Average 1/4 S.M.	OV101 Jet Noise Test			Average
	9 Point Average	Space Average	Correct. Factor	9 Point Average	Space Average	Correct. Factor	Correct. Factor	9 Point Average	Space Average	Correct. Factor	Correct. Factor
12.5	73.1	75.7	+2.6	70.5	71.2	+0.7	+1.7	73.5	75.3	+1.8	+1.7
16	79.1	77.1	-2.0	82.4	82.2	-0.2	-1.1	81.9	81.7	-0.2	-0.6
20	82.1	81.8	-0.3	83.0	82.7	-0.3	-0.3	83.8	83.9	+0.1	-0.1
25	71.4	75.2	+3.8	71.1	72.8	+1.7	+2.8	89.1	89.4	+0.3	+1.5
31.5	76.5	76.9	+0.4	74.7	75.7	+1.0	+0.7	90.6	92.5	+1.9	+1.3
40	79.6	79.7	+0.1	77.2	78.0	+0.8	+0.5	95.6	97.8	+2.2	+1.3
50	79.4	77.8	-1.6	78.8	79.4	+0.6	-0.5	99.2	101.2	+2.0	+0.7
63	73.2	73.9	+0.7	72.8	74.0	+1.2	+1.0	107.2	109.6	+2.4	+1.7
80	74.5	72.5	-2.0	75.5	75.5	0	-1.0	107.2	108.1	+0.9	0
100	73.5	72.7	-0.8	74.9	74.3	-0.6	-0.7	110.6	112.0	+1.4	+0.3
125	75.6	74.4	-1.2	76.4	76.0	-0.4	-0.8	109.7	110.3	+0.6	-0.1
160	73.0	72.4	-0.6	75.5	74.7	-0.8	-0.7	109.1	109.1	0	0.3
200	75.0	74.3	-0.7	75.6	75.4	-0.2	-0.5	110.2	109.9	-0.3	-0.4
250	74.0	73.9	-0.1	75.1	75.6	+0.5	+0.2	110.5	111.0	+0.5	+0.3
315	71.7	71.6	-0.1	74.3	73.6	-0.7	-0.4	110.1	110.6	+0.5	0
400	71.7	71.3	-0.4	74.7	73.5	-1.2	-0.8	112.6	113.1	+0.5	-0.1
500	72.5	70.6	-1.9	73.8	73.0	-0.8	-1.4	110.3	110.5	+0.2	-0.8
630	71.1	69.6	-1.5	73.1	72.5	-0.6	-1.1	109.1	109.2	+0.1	-0.5
800	68.2	67.0	-1.2	70.1	69.1	-1.0	-1.1	106.6	106.7	+0.1	-0.5
1000	67.7	66.3	-1.4	69.9	69.4	-0.5	-1.0	106.2	106.3	+0.1	-0.4
1250	68.0	67.0	-1.0	70.2	70.0	-0.2	-0.6	104.0	104.0	0	-0.3
1600	69.1	67.1	-2.0	70.9	70.0	-0.9	-1.5	101.4	101.2	-0.2	-0.8
2000	66.3	65.3	-1.0	67.8	67.0	-0.8	-0.9	97.6	97.6	0	-0.4