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NASA Technical Memorandum 104775

An Evaluation of Noise and its Effects on Shuttle Crewmembers During STS-50/USML-1

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SUMMARY

High noise levels can lead to physiological, psychological, and performance effects in man. These effects may range from irritability, annoyance, and sleep interference at low levels to interference with verbal communication and fatigue at moderate levels, to temporary threshold shift and permanent threshold shift at more extreme levels. Long-term noise also reduces tolerance for stress, resulting in frustration. During certain STS-40 inflight operations, the flight crew experienced noise levels that they considered "unacceptable."

The current study evaluated the acoustic environment of the STS-50/USML-1 mission. The major objectives were to gain subjective assessments of the STS-50 noise levels, document any impacts of noise upon crewmember performance, collect in-flight sound level measurements, compare noise levels (objectively and subjectively) across missions, evaluate the current Shuttle acoustic criterion, and to make recommendations regarding noise specifications for SSF and other long duration manned space missions.

Sound level measurements indicated that background noise levels were the lowest on the Orbiter middeck (about 60 decibels), followed by Spacelab (61 decibels) and the Orbiter flightdeck (64 decibels). All values in this paper represent decibels on the A-weighted scale unless otherwise specified.

The current Orbiter flightdeck noise limit of 63 decibels appears to be completely acceptable. A background noise limit of no greater than 65 decibels is recommended for the middeck specification (the current limit is 68 decibels). Maintaining the current SSF acoustic specifications of Noise criterion curve (NC) 50 in work areas and NC 40 in sleep areas is recommended—NC curves impose limits at several frequencies while overall decibel values apply only to the total energy.

The STS-50 crew found the flightdeck noise level to be completely acceptable, with the single exception of "significant" air movement noise on the aft flightdeck. Middeck background noise levels were rated as acceptable. When the Ergometer Vibration Isolation System was in use on the middeck, noise levels reached 68 decibels but it was still considered to be acceptable by most crewmembers. The Spacelab acoustic environment was rated the most favorably of all areas.

All crewmembers reported being awakened by crew activity on the middeck—one astronaut estimated that this occurred 5-8 times per night. The sleep stations afforded attenuation from airborne noise sources, although the opening and closing of lockers disturbed sleep. "Ringing in the ears" was briefly experienced by one individual as a result of a loud squeal emitted by the Waste Control System during an anomaly. Three crewmembers reported that noise had, on occasion, interfered with their ability to concentrate and relax. The entire crew indicated that speech interference had occurred between decks and, to a much lesser degree, on the same deck. Four of them also noted that noise had interfered (at least "rarely") with their ability to monitor the air-to-ground voice communication loop. The crew stated that they had experienced no difficulty hearing a caution or warning alarm during the mission.

Based on each of the sound level measurements collected, acceptable speech communications were graphically depicted within models of the spacecraft by Graphics Analysis Facility personnel. This tool offers a unique and flexible method of visually evaluating the likelihood of impaired verbal communications.

Future evaluations, such as the one planned for the STS-57/SH-1 mission, will: 1) further define the acoustic characteristics of manned spacecraft and their impact on astronaut performance; 2) investigate individual differences in the reaction to noise; and 3) apply this data to aid in the design of safe and habitable space vehicles.

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ACRONYM LIST

dBA	Decibels with the A-weighted network applied
DOD	Department of Defense
DPM	Drop Physics Module
DSO	Detailed Supplementary Objective
DTO	Detailed Test Objective
ECLSS	Environmental Control and Life Support System
EDO	Extended Duration Orbiter
EVIS	Ergometer Vibration Isolation System
GBX	Glovebox
GRAF	Graphics Analysis Facility
HDRR	High Data Rate Recorder
ISO	International Standards Organization
JSC	Johnson Space Center
MIL-STD	Military Standard
NASA	National Aeronautics and Space Administration
NC	Noise Criterion
OVEI	Orbiter Vehicle End Item Specification
SAMS	Space Acceleration and Measurement System
SH	SpaceHab
SILs	Speech Interference Levels
SLS	Spacelab Life Sciences (STS-40 mission)
SPAWG	Spacelab/Payloads Acoustic Working Group
SSF	Space Station Freedom
STDCE	Surface Tension Drive Convection Experiment
STS	Space Transportation System
USML	United States Microgravity Laboratory (STS-50 mission)
WCS	Waste Control System

INTRODUCTION

Background

During the 13-day United States Microgravity Laboratory (USML-1) mission that was launched on Space Transportation System (STS)-50 on June 25, 1992, the Flight Crew Support Division[1] at Johnson Space Center (JSC) conducted a human factors evaluation. This evaluation, performed as a detailed supplementary objective (DSO 940), concentrated on several interfaces between the crew and their spacecraft. DSOs present an opportunity for investigators to work directly with Shuttle crewmembers to evaluate various interfaces. The three areas investigated during STS-50 were the glovebox and associated hardware, the Lower Body Negative Pressure experiment hardware, and the acoustic environment. This paper assesses the impact of noise on crewmembers during STS-50, the first of the extended duration orbiter (EDO) missions, and presents implications for SSF and other longer duration missions.

USML-1 was dedicated to scientific and technological investigations of materials, fluids, and biological processes in a manned space laboratory environment; performing scientific test bed experiments and demonstrations of technological feasibility; and exploring the potential applications of the space environment for commercial processes and products. The laboratory was housed in Spacelab, a modular payload that can be assembled in various configurations for mission-specific requirements. During STS-50 it offered a shirt-sleeve working environment that was approximately 7 meters (or 23 feet) in length; 4 meters (13.5 feet) in outside diameter; and was replete with experiments dedicated to understanding the mysteries of material behavior in the microgravity environment.

Because of center-of-gravity concerns, Spacelab is carried toward the rear of the Shuttle inside the payload bay, as represented in figure 1. This makes it necessary for a tunnel to be used to link the lab to the middeck. As is typical of all Shuttle missions, the Orbiter payload bay doors were opened during all but the launch and reentry phases of flight.

Recently much attention has been focused on the issue of noise (unwanted sound) onboard the Orbiter. This is due, at least in part, to the occasional "unacceptable" levels that the flight crew experienced during STS-40/Spacelab Life Sciences-1 (Koros, Adam, and Wheelwright, 1992). National Aeronautics and Space Administration (NASA) administrators, realizing the very real consequences of excessive noise levels to crew safety and operations, particularly during EDO missions, convened the multi-disciplinary Spacelab/Payloads Acoustics Working Group (SPAWG) to study the issue of excessive noise and to propose solutions.

The success of all manned space missions is dependent upon near perfect performance of all those onboard. Research indicates that excessive noise may result in effects that range from irritability, annoyance, and sleep interference at low levels;

[1] Formerly the Man-Systems Division

Figure 1. Representation of United States Microgravity Laboratory-01 (USML-1) in Columbia's payload bay (picture generated by NASA Graphics Analysis Facility).

to interference with verbal communication and/or fatigue at moderate levels; to temporary threshold shift and, at more extreme levels, permanent threshold shift. Noise also reduces tolerance for frustration (Glass & Singer, 1972). A summary of the major physical and performance effects and the thresholds at which they typically occur is presented in figure 2.

The acoustic requirements for the Orbiter are presented in section 3.4.6.1.3. of the Orbiter Vehicle End Item Specification (OVEI) (NASA, 1986); the levels for Spacelab are contained in the Spacelab Payload Accommodations Handbook (NASA, 1985), section 5.1.1.4.1. Currently the noise limits are 63 dBA on the Orbiter flight deck, 68 dBA on the Orbiter middeck, and 59 dBA in Spacelab. Originally, the noise limits for both the Orbiter and Spacelab were specified as NC (noise criterion curve) 50 (equivalent to a level of 59 dBA); however, these limits were increased due to hardware and implementation costs.

In a survey of 33 Shuttle astronauts, researchers found that approximately 60 percent of respondents reported that Orbiter noise disturbed their sleep, led to annoyance, and interfered with relaxation and speech (Willshire and Leatherwood, 1985). Clearly, these consequences hold severe implications for mission success. Therefore, noise limits have been imposed. These limits are usually expressed in overall decibels on the A-weighted scale (dBA). Leo Beranek (1988) explains that "the A-weighting of a sound level meter discriminates against sound pressure signals at frequencies below 1000 Hz and above 6000 Hz, and enhances levels between 1000 Hz and 6000 Hz." This scale is used because it approximates human hearing perception.

Several sources document the many adverse effects of noise on human performance. In the *Handbook of Human Factors,* it is noted that in loud noise, comprehension suffers, reading takes longer, and memory of contents is poor (Salvendy, 1987). The authors state that writing efficiency may also be diminished because of the difficulty of retrieving material from the part of long-term memory concerned with the meaning of words, the so-called semantic memory. These and other associated performance effects have been noted by Shuttle crewmembers in the spacecraft environment. Six of the seven STS-40 astronauts indicated that their concentration was impaired at least occasionally by noise during the mission (Koros, 1992).

Additional concerns over high noise levels are raised by evidence that noise also affects performance in other ways. Smith (1989) states that "any task involving auditory information is likely to be impaired by the presence of noise" and that merely "listening in a noisy environment may also produce impairments in performance because of the additional effort involved." One STS-40 crewmember considered the noise to be possibly the major contributor to fatigue during the mission (Koros, 1992).

According to Smith, the three types of tasks most susceptible to the deleterious effects of continuous noise are

1) Monitoring tasks, if
   a. the noise level is over 86 dB

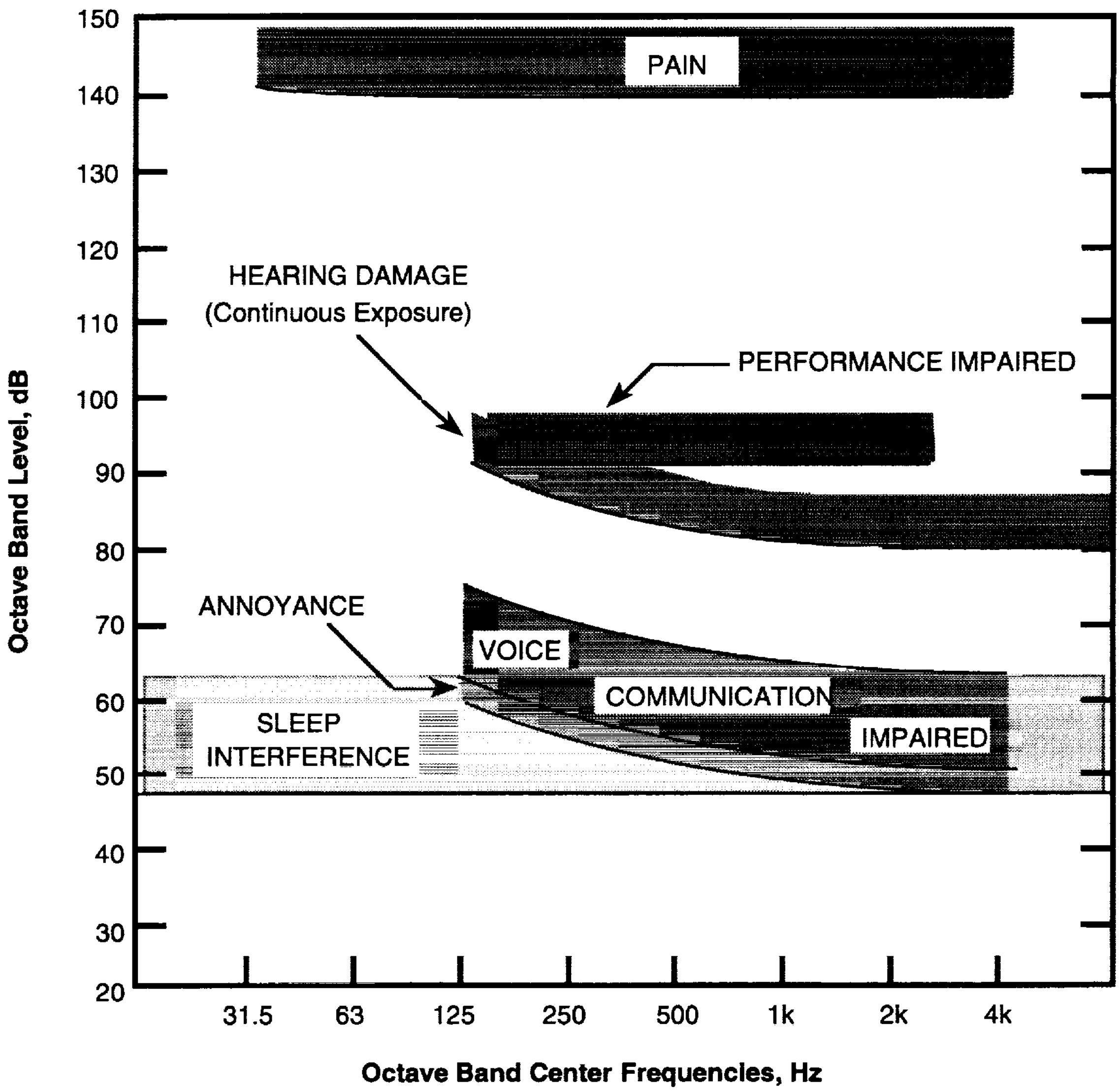

Figure 2. Physical and performance thresholds for noise effects. Scale adapted from Willshire (1984).

b. the length of the watch is long
c. the signals are hard to see
d. the situation is not one that encourages caution

2) Continuous tasks, since noise appears to increase momentary inefficiency interspersed with normal performance
3) Multiple tasks or tasks with several subcomponents. Noise often leads to increased concentration upon the dominant or high probability component at the expense of other features.

Based on Shuttle astronauts' experience from previous missions and consideration of the types of tasks in which crewmembers are required to engage, noise impacts on performance were anticipated for the USML mission Specifically, it was believed that crewmembers may find noise levels to be intrusive during sleep periods, and that verbal communication would be hampered during operation of noisy payloads, such as the vacuum cleaner.

Objectives

The objectives of the current study were to

1) Gain subjective assessments of the STS-50 noise levels
2) Document any impacts of noise upon crewmember performance
3) Collect inflight one-third-octave sound level measurements
4) Interpret the subjective assessments based upon the sound level data
5) Compare noise levels (objectively and subjectively) across missions
6) Evaluate the current Shuttle acoustic criterion
7) Make recommendations regarding noise specifications for Space Station Freedom (SSF) and other long duration manned space missions

METHOD

Subjects

The participants in this evaluation were the seven crewmembers assigned to the STS-50/USML-1 mission. The crew was composed of five males and two females.

Apparatus

Questionnaire. Two versions of the questionnaires were developed for the current study—one inflight and the other postflight. Each consisted of five-point anchored Likert scales, yes/no items, and open-ended questions, all of which had spaces provided for explanations. The questions were based on those previously administered to the STS-40/SLS-1 crew. Since crewmember time was limited, the inflight questionnaire was kept slightly shorter—containing only 18 questions compared to 24 for the postflight version. Certain items in the questionnaires were identical so that a comparison could be made between inflight and postflight responses.

The degree to which noise impacted the crew was assessed in two ways. First, the crew was asked to rate the acceptability of the overall noise levels and the levels from various payloads. Second, questions were asked regarding whether physiological effects (such as fatigue, headaches, or "ringing ears"), psychological effects (for example, annoyance, sleep interference, or speech interference), or performance effects (such as difficulty monitoring air-to-ground loop or caution/warning alarm) had occurred during the mission due to noise.

Sound Level Meter. The Shuttle's noise sources primarily emit constant continuous noise (for example, ventilation systems, pumps, electric motors) and intermittent sources (for example, air compressors and machinery with varying work cycles), thus one-third-octave analysis is valid and offers much useful data (Foreman, 1990). Therefore, a Brüel & Kjær (B & K) Type 2231 Modular Precision Sound Level Meter (serial number 1624553), B & K Octave Filter Set Type 1625 1/3-1/1 (serial number 1620800) and B & K Microphone Type 4155 were used in this study. This meter fulfills IEC 804 type 1, relevant sections of IEC 651 type 1 I, and ANSI S1.4-1983 type 1 specifications.

This sound level meter was originally selected for use during the STS-40 mission by DSO 904 personnel because it required minimum preflight training and inflight time, was highly versatile, met the weight and volume restrictions, was similar to the Orbiter sound level meter that had already passed space qualification tests, and was capable of measuring and storing one-third-octave band data.

The B & K Loudness Calculation Module (BZ 7111) firmware was used to automate the measurement procedure to minimize crew demands. This module also enabled storage of up to 10 one-third-octave spectra measurements and information on various parameter settings in nonvolatile memory so that it could be downloaded to an IBM PC-compatible computer after the flight. Field calibration was performed at JSC 6 weeks before launch using a B & K Type 4228 piston phone (serial number 1570787) and DP 0776 adapter. The meter was then shipped to the Cape for stowage in Columbia.

During launch the meter was stored in locker MF 57 M in three separate pieces—the sound level meter, the octave filter set, and the input stage (with the microphone already attached). Just prior to the first scheduled measurement, the sound level meter was assembled. When assembled, the meter measured 47 centimeters (18.5 inches) long, 8 centimeters (3 inches) wide, and 5 centimeters (2 inches) deep. Figure 3 shows the meter in its stowed and operational configurations. After each use, the meter was temporarily stowed on the middeck wall by means of a velcro pad until the next scheduled measurement. When all measurements were completed, the meter was dismantled into its three components and returned to the assigned locker.

Based on the characteristics of the Shuttle's acoustic environment—highly reverberant with several relatively steady sources and no single discernible source—the sound level meter was set to "diffuse" sound incidence correction factor and "slow" time weighting (in compliance with MIL-STD-1474B specifications [DOD, 1979]). Time weightings are necessary because without them neither the display of the measuring instrument nor the human operator can follow rapid sound level fluctuations. The standardized rise time and decay time for slow weighting is 1 second—effectively averaging over about 1 second. The frequency weighting factor was set to "linear" as required by the loudness calculation firmware (BZ 7111) that was loaded.

Preflight Procedures

Documentation. The mission-specific information required for the development of this evaluation was gained from the USML mission brochure and the L-9 month EDO/DSO Flight Projects Office presentation made to the crew. Specific information regarding scheduled crew activities were contained in timelines in the STS-50 Flight Plan (NASA, 1992a). DSO 904 crew procedures, identical to those used inflight, were available in the biomedical DSO/detailed test objective (DTO) checklist section of the Flight Data File (NASA, 1992b).

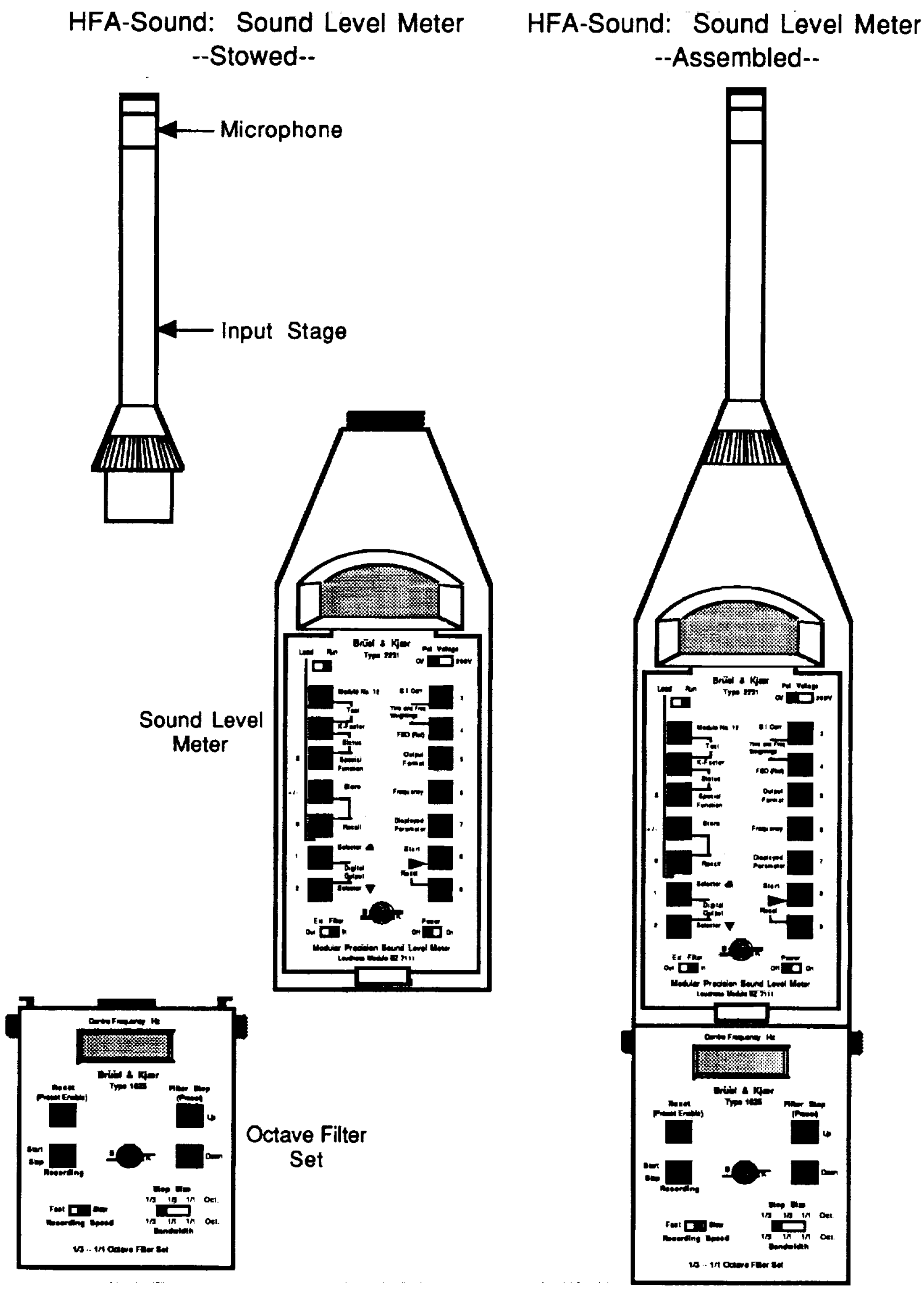

Figure 3. Diagram of the sound level meter and octave filter set used in DSO 904.

Measurement Methodology. Data was required to evaluate two different conditions: background noise levels and levels during payload operation. To determine the minimum background noise level, data was collected when no major noise sources other than essential life support equipment—primarily consisting of the Environmental Control and Life Support System (ECLSS)—were operating. Four measurements were taken during this condition (referred to as "nominal operations" in this DSO)—one each in the middeck and flightdeck, and two in Spacelab. These measurements were collected in the center of each volume.

Estimates of the noise levels experienced by crewmembers while operating noise-generating equipment were collected by scheduling measurements during time periods when only the payload of interest (and essential life support equipment) were operating. In compliance with MIL-STD-1474B(MI) (DOD, 1979) guidelines, these measurements were taken 6" to the right of the operator's right ear, midway between the operator and the rack. The presence of the body in a sound field does influence measurement results—the literature indicates that the difference between sound measured with and without a person present ranges from -1 to +5 dB (Harris, 1991)—however, this range was considered well within acceptable limits for the current evaluation. Furthermore, this influence was believed to be highly representative of the sound field to which the person would be exposed while operating the payload.

Candidates for the DSO 904 noise measurements were drawn from the list of USML payloads requiring acoustic waivers and from consultations with various personnel associated with the mission. Six major sources were identified (3 relatively constant sources and 3 intermittent short-term sources):

1) Ergometer Vibration Isolation System (EVIS)
2) Drop Physics Module (DPM)
3) Glovebox (GBX) Circulation System
4) Surface Tension Convection Experiment (STDCE)
5) Space Acceleration Measurement System (SAMS) recorder
6) High Data Rate Recorder (HDRR)

From this group the first four were chosen since they represented relatively continuous noise sources. Continuous noise sources were selected because they represented long-term sources and because the instrumentation selected used a step filter, requiring the source to continue uninterrupted for at least 3 minutes. In addition to these sources, the vacuum cleaner was selected for measurement (even though it did not operate for extended periods of time) because STS-40 crew comments indicated the noise levels it generated were unacceptable (ranging from 89 to 97 dB). The SAMS recorder and HDRR were not selected because the noisy events were not timelined (intermittent) and they were too short-lived for measurement with a step filter. Therefore, the equipment selected for measurement was: EVIS (Spacelab/locker), DPM (Spacelab/Rack8), GBX (Spacelab/Rack12), STDCE (Spacelab/Rack3) and the vacuum cleaner (middeck/locker). Figure 4 shows the layout of the USML and the major payloads.

A summary of all the measurement locations, measurement conditions, microphone locations, and scheduled measurement times is given in table 1. The numbers in parentheses refer to the nine sound level meter memory locations used in this evaluation (0 through 8). The source and conditions for the final measurement (memory location number 9) were left to the crew's discretion.

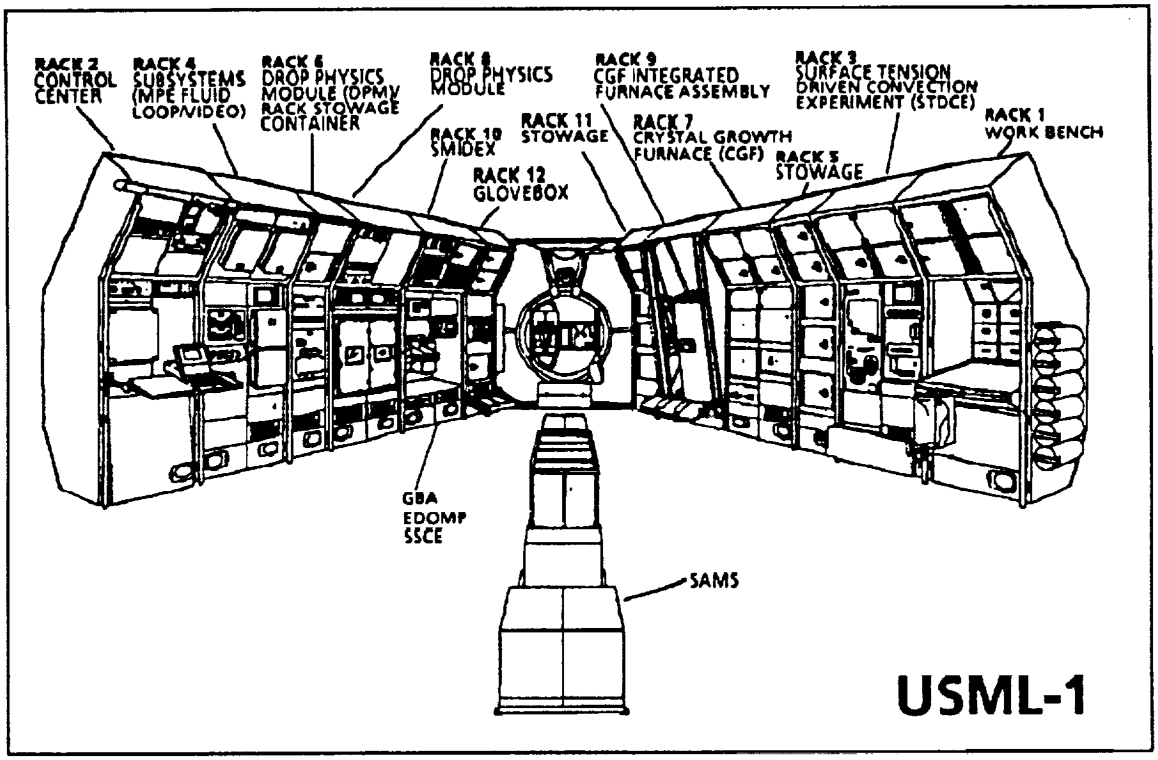

Figure 4. USML-1 Spacelab Rack Configuration. (NASA, 1992c)

TABLE 1. USML-1 DSO 904 NOISE MEASUREMENTS—SOURCES, MICROPHONE LOCATIONS AND SCHEDULED MEASUREMENT TIMES

Measurement Location (Memory Number)	Condition (Primary Noise Source)	Microphone Location	Scheduled Time (MET)
Flightdeck, Center (7)	Nominal Operations (ECLSS)	Module center	3/00:40
Middeck, Center (5)	Nominal Operations (ECLSS)	Module center	1/07:45
Middeck, Center (4)	Payload Operations (EVIS)	Module center	2/20:15
Middeck, Center (8)	Payload Operations (Vacuum)	Module center	0/23:30
Spacelab, Center (3)	Nominal Operations (ECLSS)	Module center	0/18:30
Spacelab, Center (6)	Nominal Operations (ECLSS)	Module center	4/02:30
Spacelab, Rack 8 (0)	Payload Operations (DPM)	1' from source	10/13:45
Spacelab, Rack 12 (1)	Payload Operations (GBX)	1' from source	7/15:15
Spacelab, Rack 3 (2)	Payload Operations (STDCE)	1' from source	8/14:30

Briefings. Crew briefings were conducted at L-6 months and L-2 months. Due to scheduling difficulties, the L-6 month briefing was presented to different representatives of the nine crewmembers (seven prime and two alternate) on three separate occasions beginning in early January 1992 and ending later that same month. At each presentation general information on the DSO and human factors was presented and then each of the investigators involved presented more specific information regarding his/her study. The crew was informed that the goal of the noise evaluation was to understand the effects of noise on Shuttle crewmembers and operations. Additionally, they were made aware of the need for a subjective questionnaire and noise measurements.

The L-2 month briefing was scheduled as two separate sessions due to difficulty scheduling the entire crew for a single briefing period. These briefing sessions afforded the opportunity to reiterate the procedures and goals of the assessment and to answer any crew questions. Copies of the inflight questionnaire and Sound Level Meter Training form were circulated and briefly reviewed.

Sound Level Meter Training. Sound level meter training took place at L-6 months (January 1992) at the Full Fuselage Trainer in Building 9B at JSC. The two crewmembers assigned to use the meter were present, and each was given a brief summary of the general methodology to be pursued and the locations of the proposed measurements. Copies of the sound level meter operating procedures (identical to those available inflight in the Flight Data File) were circulated and the crewmembers performed each of the procedures.

At L-1 month the two crewmembers assigned to taking the DSO 904 measurements participated in a brief retraining session addressing sound level meter operating procedures. Arrangements were made for the crew to have access to the meter during the quarantine period and it was delivered to them at that time.

Inflight Procedures

Questionnaires. All seven crewmembers were scheduled to complete the inflight Human Factors questionnaire on Flight Day 10. It was classified as an easycap item in the Crew Activity Plan to allow the crew flexibility in their hectic work schedule.

Mission Monitoring. Mission monitoring took place in the Customer Support Room in Building 30 at JSC. The area is provided to groups sponsoring payloads, DSOs or DTOs on a Shuttle flight. Groups are assigned to one of four desks at which downlinked video, air-to-ground channels 1 and 2, subsystem management screens, uplink packages, and mission updates are provided. DSO personnel were available to Customer Support representatives at all times, including outside of regular business hours, but the support was never required.

Postflight Procedures

Questionnaires. Postflight questionnaires were furnished to each of the crew at the landing site. Since this DSO broached several topics in addition to noise, the questionnaires were tailored to each individual so that they would not be required to respond to areas that did not apply to them. All crewmembers were asked about the noise levels.

Debriefings. Debriefing sessions were held with crewmembers at JSC on an individual basis within about 2 months of landing. The purpose of these sessions was to gain insight into crewmembers' ratings on various questions contained in the questionnaire and to learn additional information that could not easily be conveyed through the pencil and paper format.

Sound Measurements. The data from each of the noise measurements was downloaded to an IBM PC computer for graphing and analysis using the B & K loudness calculation software (BZ 7113). The meter and software used in this evaluation was designed for measurement of stationary sound phenomena such as fan noise, ventilator noise, noise from air conditioning units, refrigerators, household appliances and business machines.

RESULTS

Questionnaires

Results of the 3 inflight and 6 postflight questionnaires that were completed are presented below. Due to time constraints only 3 crewmembers were able to complete the inflight questionnaire. Two crewmembers completed both the inflight and postflight versions. The questions were categorized into 2 groups: subjective ratings of the overall noise levels and payload levels, and their effects (physiological, psychological and performance).

Noise Level Ratings. Table 2 contains a frequency count (tally) of the crew's assessment of the acoustic environment. It includes ratings of the overall noise level, and of noise during nominal and experiment operations, sleep periods and from anticipated "noise offending" payloads. In rating the flightdeck, 2 responses fell between anchors and were included in the more favorable category in order to retain all available information.

Although no source was considered unacceptable by the crew, several sources exceeded background levels. These included the Reaction Control System jets, Waste Control System (WCS) fan separators when the "coffee can bag was removed," air movement on the aft flightdeck, EVIS, STDCE water pump, vacuum cleaner, and crew activities during sleep periods (particularly locker opening and closing).

The USML-1 crewmembers also rated the acceptability of the mission's acoustic environment for longer duration missions and these results are presented in table 3. One individual mentioned becoming desensitized to noise as the mission went on, only noticing how quiet it was when the fans stopped. It was also stated that "as the flight went on, others often couldn't hear calls from the flightdeck to the middeck unless you shouted at them." Based on the comment, it could not be determined whether this was due to prolonged noise exposure or perhaps a larger number of scheduled activities.

Noise Effects. This category of question offered an objective method by which to assess the impact of noise. The crew was asked whether certain physiological, psychological, or performance effects had occurred which they could attribute to the noise levels during the mission. A summary of the crew's ratings regarding the physiological effects is presented in table 4.

TABLE 2. CREW RATINGS OF THE STS-50/USML-1 ACOUSTIC ENVIRONMENT

	Crew Postflight Rating, Tally (Inflight Rating)				
Question	Completely Acceptable	Moderately Acceptable	Borderline	Moderately Unacceptable	Extremely Unacceptable
1. Noise overall	2 (1)†	4 (2)			
2. Noise in the Orbiter Flightdeck:					
___during nominal operations	4	2 (3)			
___during experiment operations	4	1			
3. Noise in the Orbiter Middeck:					
___during nominal operations	2 (1)	4 (2)			
___during experiment operations		4	2		
4. Noise in Spacelab:					
___during nominal operations	5 (2)	1 (1)			
___during experiment operations	3	2			
5. Noise during sleep periods	2	1 (1)	2 (1)	(1)	
6. Noise from:					
___DPM	4 (3)				
___EVIS		2	2	1	
___GBX	2	2			
___STDCE	3		1		

†Numbers in parentheses represent inflight responses.

TABLE 3. CREW RATINGS OF THE LONG-TERM ACCEPTABILITY OF THE STS-50/USML-1 ACOUSTIC ENVIRONMENT

	Crew Postflight Rating, Tally (Inflight Rating)				
Question	Disagree Strongly	Disagree	Undecided	Agree	Agree Strongly
14. Noise levels became increasingly bothersome as the mission progressed.	2 (1)†	4 (1)		(1)	
15. If I were on a 30-day mission, noise like that on this mission would be unacceptable.	2	4 (3)			
16. If I were on a 6-month mission, noise like that on this mission would be unacceptable.	2	3	1 (1)	(1)	

†Numbers in parentheses represent inflight responses.

All sleeping crewmembers were awakened by crew activities on the middeck—this occurred 5 to 8 times per night according to one astronaut's estimation. Another experienced "ringing in the ears" due to the WCS squeal that occurred early in the mission. However, once the system was repaired the symptom disappeared.

TABLE 4. STS-50/USML-1 CREW RESPONSE TO ITEMS REGARDING THE OCCURRENCE OF PHYSIOLOGICAL EFFECTS DUE TO NOISE

Question	Crew Postflight Rating, Tally (inflight)	
	No	Yes
17. Did noise wake you up?	(1)†	6 (2)
18. Did noise result in fatigue?	6 (1)	
19. Did noise result in headaches?	6 (2)	
20. Did noise result in "ringing ears"?	4 (2)	2

†Numbers in parentheses represent inflight responses.

Tables 5 and 6 show responses to the questions regarding the occurrence of certain psychological and performance effects. Half the crew indicated that they had experienced interference in their ability to relax and concentrate. Comments revealed that this interference was predominantly limited to periods during which exercise equipment was in use. One individual found the noise levels during exercise periods to be particularly detrimental to his concentration.

TABLE 5. STS-50/USML-1 CREW RATINGS OF THE OCCURRENCE OF PSYCHOLOGICAL EFFECTS ATTRIBUTED TO NOISE

Question	Crew Postflight Rating, Tally (Inflight Rating)				
	Never	Rarely	Occasionally	Frequently	Always
11. How often did noise interfere with your concentration?	3 (1)†	3 (1)	(1)		
12. How often did noise interfere with your ability to relax?	3 (1)	2 (1)	1	(1)	

†Numbers in parentheses represent inflight responses.

From table 6 it is apparent that speech interference was common, and that noise did interfere with air-to-ground communications. No crewmember expressed having any difficulty hearing a caution or warning alarm. Impaired task performance was noted only by one individual.

Sound Measurements

In all, nine one-third-octave sound level measurements were made and stored with the DSO 904 meter during this mission. Postflight, the data was downloaded to an IBM PC-compatible computer loaded with B & K loudness calculation software (BZ 7113). The software, which complies with ISO 532 Method B (Zwicker) standards, determines the overall A-weighted sound pressure and loudness level (in sones and phons). Since acoustic specifications are not written according to loudness levels, this data will not be presented here. The overall dBA for each measurement is presented in table 7, along with the applicable acoustic specification for that location. The middeck

TABLE 6. STS-50/USML-1 CREW RATINGS OF THE OCCURRENCE OF PERFORMANCE EFFECTS ATTRIBUTED TO NOISE

Question	Crew Postflight Rating, Tally (Inflight Rating)				
	Never	Rarely	Occasionally	Frequently	Always
7. How often did you have difficulty hearing another crewmember's speech without the use of an intercom between decks?		2		2 (3)†	2
8. How often did you have to raise your voice to be heard by another crewmember on a different deck?		1	1	2	1
9. How often did you have difficulty hearing another crewmember's speech without the use of an intercom on the same deck?	2 (2)	3 (1)		1	
10. How often did you have to raise your voice to be heard by another crewmember on the same deck?	1	5			
13. How often did noise interfere with your ability to monitor the a/g loop?	2	3		1	

	Crew Postflight Rating, Tally	
	No	Yes
21. Did noise ever cause you to have difficulty hearing a caution or warning alarm?	6	
22. Did noise ever interfere with your performance on a task? If so, briefly explain when and how it interfered.	5	1

†Numbers in parentheses represent inflight responses.

TABLE 7. COMPARISON OF MEASURED OVERALL A-WEIGHTED VALUES FOR DSO 904 DURING USML-1 AND APPLICABLE ACOUSTIC SPECIFICATION

Measurement Location (Memory Number)	Condition (Primary Noise Source)	A-Weighted Decibels	
		Measured Value	Acoustic Specification
Flightdeck, Center (7)	Nominal Operations (ECLSS)	64.0	63
Middeck, Center (5)	Nominal Operations (ECLSS)	59.9	68
Middeck, Center (4)	Payload Operations (EVIS)	67.9	68
Middeck, Center (8)	Payload Operations (Vacuum)	79.9	128†
Spacelab, Center (3)	Nominal Operations (ECLSS)	61.6	59
Spacelab, Center (6)	Nominal Operations (ECLSS)	61.2	59
Spacelab, Rack 8 (0)	Payload Operations (DPM)	64.7	59
Spacelab, Rack 12 (1)	Payload Operations (GBX)	61.0	59
Spacelab, Rack 3 (2)	Payload Operations (STDCE)	63.8	59

†Maximum acceptable noise level for a duration of 7 minutes. A source with a frequency spectrum similar to that of the vacuum cleaner would most likely not be able to meet the octave band limits if it exceeded 105 decibels.

and flightdeck specification values represent the acceptable overall A-weighted decibels as presented in the OVEI, while the Spacelab acoustic specification values were derived from the NC 50 curve. The numbers in parentheses refer to the memory locations for the eight spectra stored for this evaluation (numbers 0 through 8) and correspond to the conditions presented in table 1.

Octave sound pressure levels were calculated for each of the measurements from the one-third-octave data collected. This data is graphed by location in figures 5 through 8. The memory locations (in parentheses) are directly comparable to those presented in tables 1 and 7. Figure 7 depicts Spacelab background noise levels, while noise levels during specific payload operation are presented in figure 8. The NC 50 curve of the U.S. Noise Criteria Standard is included on the graphs to allow comparison with "acceptable" noise levels and because the current SSF noise specification is NC 50 for habitable elements (NC 40 for individual payloads).

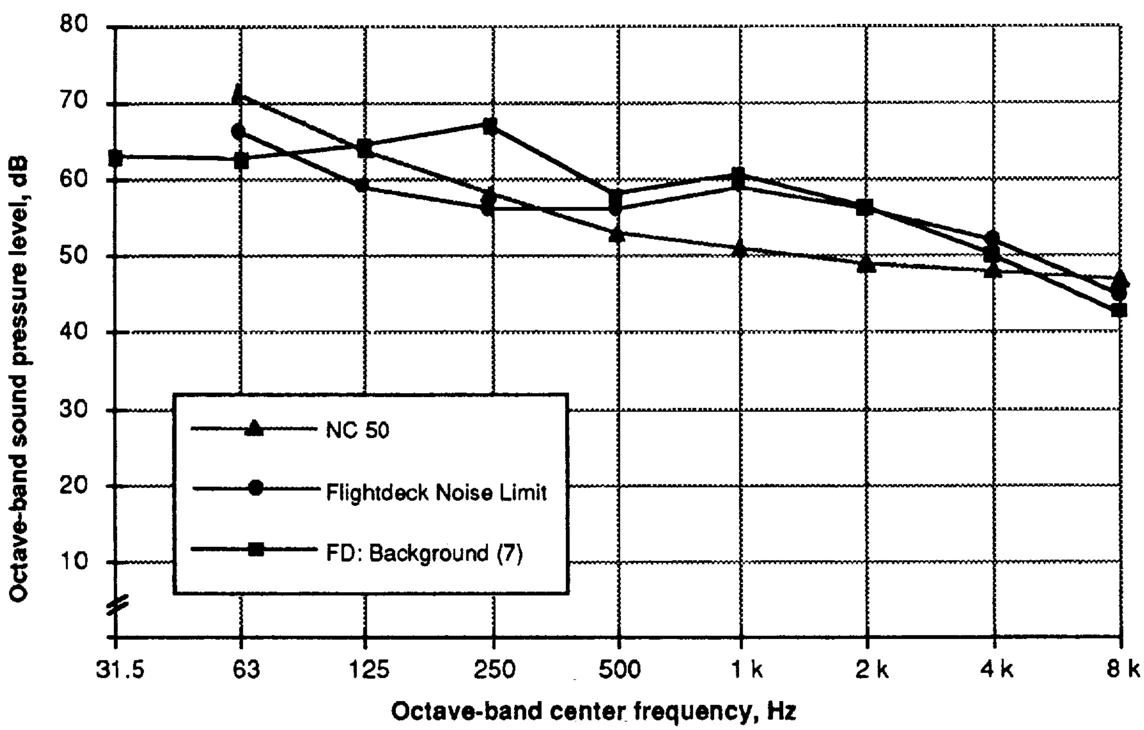

Figure 5. Graph of the DSO 904 sound level measurement made on the flightdeck during STS-50 and the applicable acoustic specification.

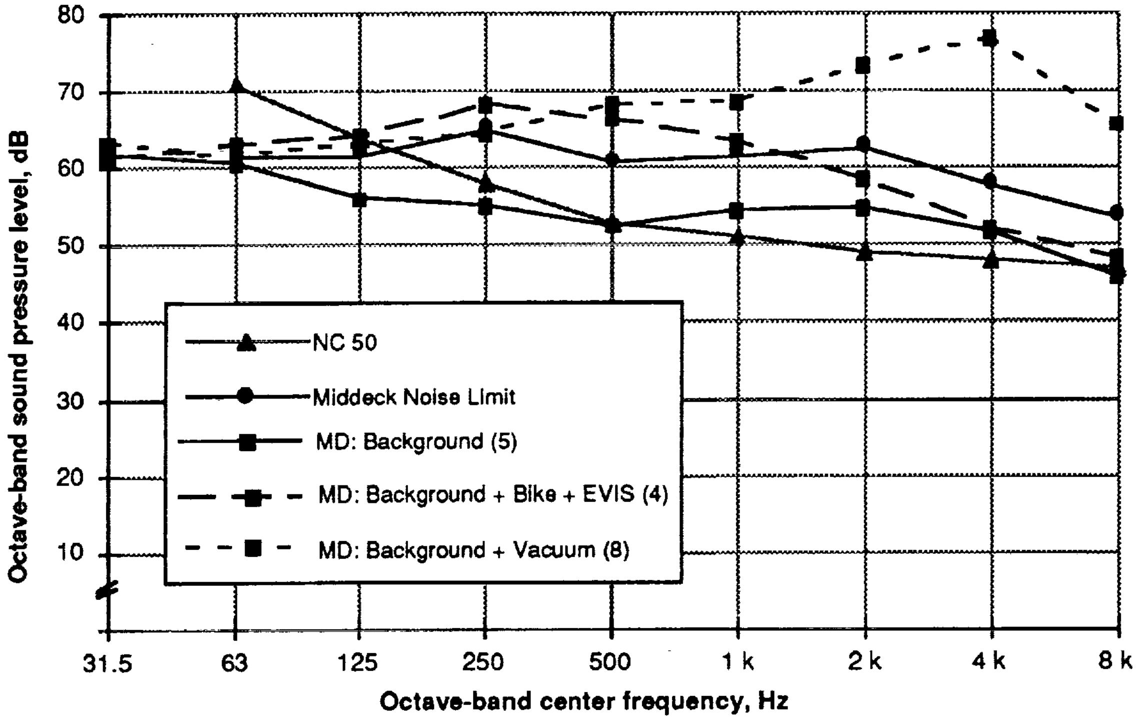

Figure 6. Graph of the DSO 904 sound level measurements made on the middeck during STS-50 and the applicable acoustic specification.

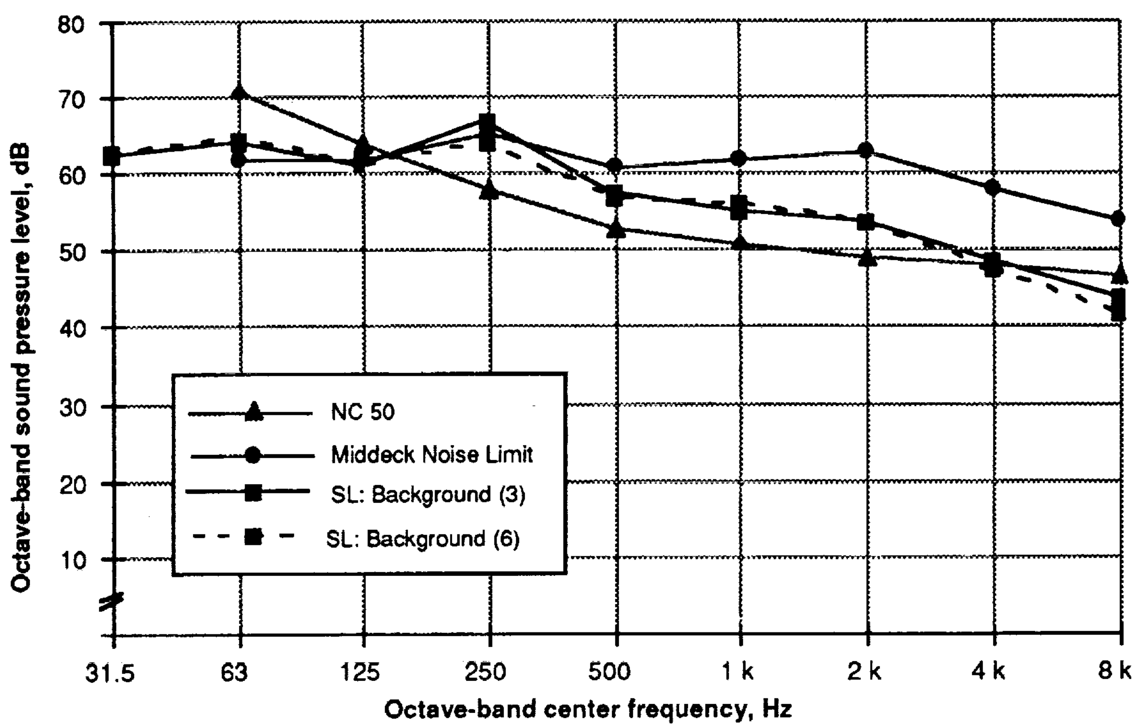

Figure 7. Graph of the DSO 904 background sound level measurements made on Spacelab during STS-50 and the applicable acoustic specification.

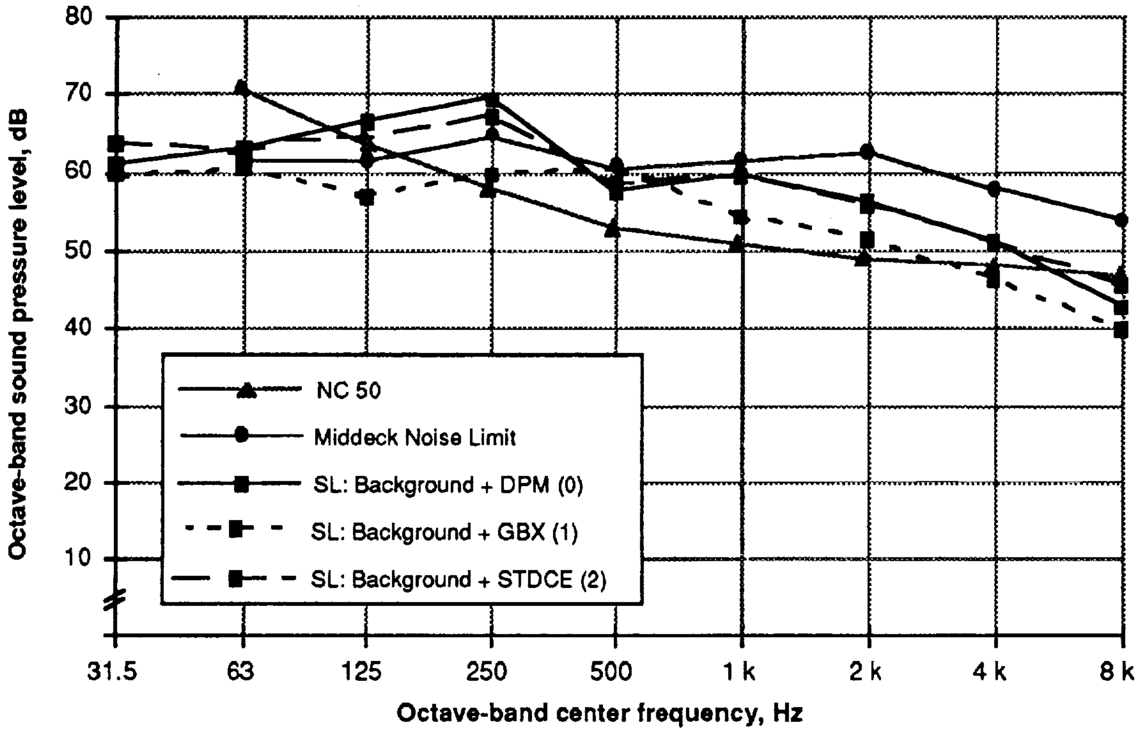

Figure 8. Graph of the DSO 904 sound level measurements made on Spacelab during STS-50 during payload operation and the applicable acoustic specification.

DISCUSSION

Noise Levels

Human reaction to noise is highly individualistic; however, the ratings exhibited a great deal of consistency across all items in the questionnaire. In assessing the overall acoustic environment, all crewmembers indicated that the levels were acceptable (table 2). Although most areas were considered "completely acceptable," overall noise was rated as "moderately acceptable" by four of the six postflight respondents. Evaluation of the data suggests that the only sources of concern were noise during sleep periods and on the middeck, particularly during experiment operations.

The overall rating (table 2) is believed to reliably represent the global impact of the acoustic environment on the crew across the entire mission because, when ratings were averaged across all modules (flightdeck, middeck and Spacelab) and conditions (nominal and experiment operations), the results were virtually identical to the overall rating. On a scale with "5" representing the positive anchor and "1" the negative, the values were 1.56 overall vs. 1.67 when questions 2 through 4 were averaged.

A summary of the postflight responses to questions 2 through 4 and noise data collected during the mission is given in figure 9. The figure represents a comparison of crew ratings and DSO 904 sound level measurements across both noise conditions for each module. Solid bars represent nominal or background conditions. The error bars indicate values for the experimental operating condition (i.e., when the selected payload was being operated). Two error bars are presented in the figure for the middeck because the loudest source (vacuum cleaner) was operated on a short-term basis for only about 5 minutes.

The crew rated background noise in Spacelab as the most acceptable, with the flightdeck a close second, as shown in figure 9. Though the middeck background noise levels were rated as acceptable, they were rated less favorably than the other areas, particularly during the experiment operating conditions. The crew's evaluation of the noise levels for each module will be addressed in turn.

Flightdeck. The noise measurement taken on the flightdeck during this evaluation returned an overall A-weighted sound pressure level 1 decibel above the 63 dBA specification for that volume. Crew ratings and comments suggest that this level is acceptable, with the single exception of "significant" air movement noise on the aft flightdeck. The crew indicated that this source did not impact their performance. Since the noise measurement was taken in the center of the flightdeck, the air movement noise is not apparent in the data.

All crewmembers maintained the same rating for both the nominal and experimental conditions. Since no payloads were deployed in this volume, the identical ratings between the two conditions justifies some confidence in the validity of the responses.

Middeck. It is apparent from figure 9 that the highest sound level measurements taken during this evaluation took place in the middeck. The shorter error bar represents noise levels on the middeck during operation of EVIS. EVIS was most likely the loudest sustained noise source used in this volume. The taller error bar (vacuum cleaner) is included to allow comparison of the range of noise on the middeck; however, it cannot be compared directly to the other measurements since it is the only short-term (less than 5 minutes) source represented. Of the three habitable volumes, the middeck was rated as the least acceptable during both the nominal and experiment conditions. Even so, at their worst (experiment operations) the levels were rated no worse than borderline. The crew indicated that the primary offender was EVIS.

The measurements made on the middeck suggest that noise levels were approximately 60 dBA during USML-1, rising to 68 dBA during exercise (i.e., when EVIS was operating)—both complying with the middeck's 68 dBA limit. During vacuum operation overall sound pressure levels reached 80 dBA, but it was not identified as a problem by the crew. This may be explained in part by two factors. First, the differences in the duration of operation—the vacuum was used for short periods (about 5 minutes), while EVIS was in use for several hours per day. Secondly, attitude toward the source significantly impacts whether one will experience annoyance or not. In everyday life we have learned to accept vacuum cleaners as loud pieces of equipment and so little thought is given to the noise they generate.

Comparison of the frequency spectra from the background (nominal operations) middeck and flightdeck noise measurements indicates that the middeck was lower at all

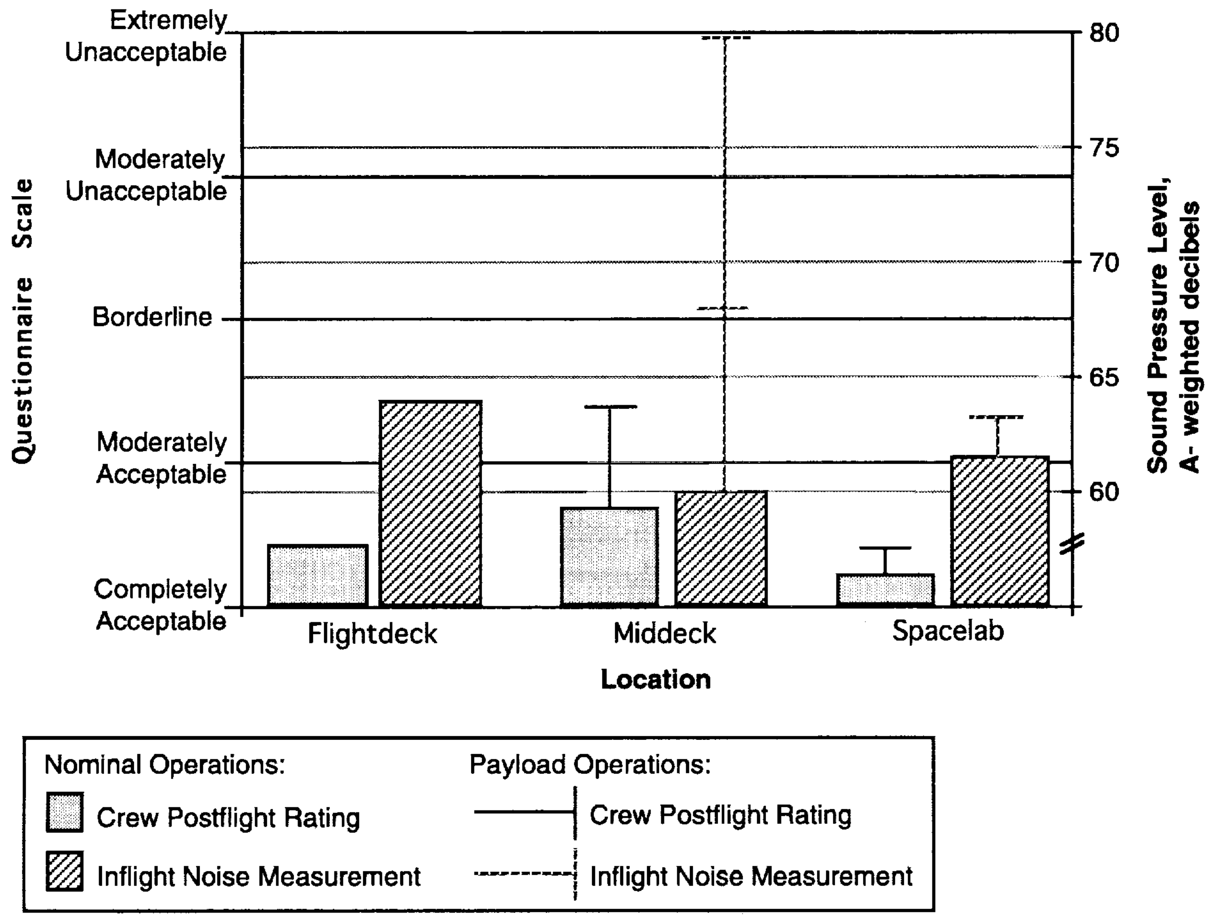

Figure 9. Comparison of DSO 904 sound level measurements and crew postflight ratings of noise for nominal (background) and experiment operations by location.

frequencies except 8 000 hertz—and at this point it exceeded the flightdeck curve by only 2 decibels. Nevertheless, crewmembers rated the flightdeck more favorably than the middeck for nominal operations (table 2). Possible explanations include that the measurement locations and/or measurement times may not have truly reflected the astronauts' acoustic environment, that ratings may have been influenced by a carry over effect from the much louder middeck experiment conditions, or that the differences may be due to the temporal displacement between when the conditions were experienced and when the questionnaire was completed. The noise measurements represent (as do all non-continuous measurements) single "snap shots" of the environment and rely on the principle of random sampling to ensure the representativeness of the data. The data collected in this DSO is believed to be a reasonable estimate of the noise levels because it was highly consistent with previous measurements of the flightdeck and middeck. The influence of time on ratings and the possibility of a carry over effect will be more closely evaluated during the upcoming SpaceHab-01 mission.

Spacelab. Although the DSO 904 measurements collected in Spacelab exceeded the NC 50 acoustic specification at most frequencies (250, 500, 1k, 2k and 4k hertz), the module was rated the most favorably of all three habitable volumes (figure 9). All respondents considered it acceptable. Five of the six respondents found background levels "completely acceptable," and three of them maintained this rating for payload operation conditions. Crew ratings of background and experiment operation conditions showed minimal range—mirroring the objective measurements. The change between background sound level measurements and the loudest measured payload (GBX) was around 3 decibels which, according to the *Human Factors Design Handbook,* is barely perceptible (Woodson, 1981).

Although the NC 50 was exceeded, the background (nominal operations) met the middeck noise limit at all but the lower frequencies (63 and 250 hertz). It is important to note that the ACW recently forwarded the recommendation that the Spacelab module specification be relaxed to comply with the middeck noise limit.

The background measures were taken in the center of Spacelab in order to assess the reliability of the DSO measurement procedures and instrumentation. Although the data were collected on 2 different days (flightdays 1 and 5) by 2 different crewmembers, the values exhibited exceptional agreement across all frequencies (see figure 7). The difference between the overall A-weighted sound pressure levels was 0.4—affording confidence in the reliability of the current procedure.

The second set of measurements made in Spacelab was intended to represent the maximum acoustic levels to which the crew was exposed in that volume, and so was taken just in front of the operator near the ear position. Overall values are presented in table 7, and the frequency spectrums in figure 8. Few differences were apparent in the octave frequency analysis between the DPM and STDCE. Data collected during use of the GBX proved to be lower than both these payloads (about 10 decibels at the lower frequencies and 5 decibels at the higher frequencies), except at 500 hertz where it peaked slightly above the DPM and STDCE. The loudest measurement taken in Spacelab for this evaluation was 65 dBA—just bordering on levels considered intrusive.

Direct comparisons cannot be made between the two sets of data since they were collected in different locations and because the presence of an object (person) in the sound field significantly affects the results. However, since all three payloads' measurements returned values close to background levels, it does suggest that the sources identified did not contribute significantly to overall noise levels (i.e., they were not major sources at the crewmember's working position possibly due either to being "quiet" sources or to receiving significant attenuation from the rack).

Long-Term Acceptability. In the postflight questionnaire, the entire crew indicated that the USML-1 acoustic environment would be acceptable for both the 30-day and 6-month time periods (table 3). Responses remained consistent in all but 2 of the 8 cases (2 inflight and 6 postflight) in which the item was completed. The acceptability of the current noise levels for longer durations is further supported by the crew comments suggesting they became desensitized to the levels. In addition, responses to the questionnaire indicated that the noise levels did not become more intrusive as the mission progressed (table 3).

Effects on Crewmembers

One method of assessing the impact of the acoustic environment on an individual is to determine the extent to which certain physiological, psychological and performance effects occur as a result of the noise exposure. These are each addressed below.

Physiological Effects. Typically the dimensions included in this category are fatigue, headaches, "ringing ears," and number of times one is woken up. Sleep has been included as a physiological effect; however, it clearly holds severe repercussions on performance. None of the crew reported experiencing fatigue or headaches as a result of noise. Two crewmembers did encounter "ringing ears." One case does not appear to be due to exposure to severe noise levels, but instead to a normal physiological reaction due to the use of ear plugs. The other report does represent a situation in which the symptom may well have been caused by being exposed to a high noise condition. Based on the crewmember's account, a loud squeal was emitted by the WCS due to an anomaly within the system. The individual stated that the anomaly was quickly rectified and the "ringing" quickly dissipated.

The most significant physiological impact noise had on the USML-1 crew was the interruption of sleep. The entire crew reported being woken up as a result of noise—one individual estimated it occurred about 5-8 times per night. Typically, crew activity on the middeck was specified as the source of the disturbance because, like most Spacelab missions, it followed a 24-hour work day (with 2 shifts) and therefore tasks were required to be performed around the clock.

Utilization of the sleep stations does appear to have attenuated airborne noise sources; however, they afforded little protection from structure-borne sources. In fact, crew comments suggest that the bunks served as paths along which this energy was readily directed. Indicative of this phenomenon are the following comments:

"The worst noise was the locker clicking and banging against the bunks."

"(I was awoken by) lockers closing near my sleep station. Metallic noise was the most problem."

"Sharp noise (aft lockers opening/closing) were occasionally disturbing."

Still, noise during sleep periods was considered to be acceptable by three crewmembers (two of whom rated it "completely acceptable") and "borderline" by another two of them.

Based on the crew's comments regarding the sleep stations, it was determined that they afford significant attenuation from airborne sources because the panels separate them from the activity and because the noise generated by the fresh air ducts in the sleep stations serves to mask unwanted sounds. Beyond the acoustic benefits of the sleep stations, the crew affirmed the sleep stations' importance as being one of the few areas that afforded privacy.

Psychological Effects. Although the current levels were considered acceptable, three crewmembers indicated that noise interfered with their concentration (table 5, question 11). All three stated that the occurrence was rare. One of them stated that concentration was affected when attempting to locate experiment samples within various lockers, and that it was especially difficult to concentrate during exercise periods.

The performance impacts of this impairment in concentration will be addressed in more detail in the next section.

Three of the crew reported that noise had led to interference in their ability to relax during the mission. Of these, two indicated that this had occurred "rarely." Noise conditions were rated favorably by all, suggesting that the crew was willing to accept the noise levels even though some experienced physiological effects. This suggests that, in the future, the program should consider the acoustic environment to ensure that significant compromises are not being made.

Performance Effects. The performance implications selected for the current study included whether the following were noted: masking of caution and warning alarms, difficulty monitoring the air-to-ground voice loop, speech interference, and impaired task performance. Sleep interruption, which also holds serious implications for performance, has already been addressed under physiological effects.

No crewmember reported experiencing difficulty hearing a caution or warning alarm (table 6). This would only be anticipated under the most extreme noise conditions and not likely to occur during any mission; however, its consequences are so severe that it was included in this questionnaire.

Four of the six respondents indicated that noise had, at times, interfered with their ability to monitor the air-to-ground voice communication loop. Two crewmembers reported that they had never experienced any such difficulty.

The third area of performance effects addressed was the degree to which speech interference occurred. Beyond disrupting potentially critical information, noisy environments also caused individuals to raise their voice, contributing to fatigue and hampering verbal communication (see table 6). Every crewmember indicated that speech interference had occurred between decks. When on the same deck, the majority still noted some difficulty in hearing another crewmember's speech, but to a much lesser degree. It was apparent that the crew never considered the interference to have significantly impacted them in the performance of their assigned duties.

The likelihood of speech interference was also confirmed by the noise measurements. All eight sound level measurements collected for this evaluation exceeded the 50 dBA at which speech interference typically begins. The extent to which speech interference takes place can be determined by evaluating the frequency range between 300 hertz and 6,000 hertz. To do this, Speech Interference Levels (SILs) were calculated for each measurement following the American National Standards Institute (1977) standard. This standard defines the SIL as the average unweighted noise levels of the octave band center frequencies at 500, 1 000, 2 000, and 4 000 hertz.

"Preferred distances" and "maximum distances" for communication were determined for each of the noise conditions based upon information presented in the *Handbook of Acoustical Measurements and Noise Control* (Harris, 1991). Preferred distances were determined using the overall dBA values. They represent typical distances for conversational communication. As noted in the handbook, in a noisy environment people tend to adopt shorter talker-to-listener distances for more comfortable face-to-face communication. The maximum distances were based upon the SILs for each noise measurement. Maximum distance refers to talker-to-listener distances for just-reliable (i.e., greater than 90% intelligibility for sentences) speech communication. When in a noisy environment, speakers typically raise their voice 3 to 6 decibels to compensate for each 10-decibel increase in noise level. Therefore, an average increase in vocal level was required. This was determined by passing a "line of best fit" through the range of typical increases.

Once the communication distances were determined, individuals at the JSC Graphics Analysis Facility (GRAF) used the PLAID software to generate computer views. Figures 10 through 17 present the maximum and preferred distances for verbal communication based upon the noise conditions. Note that there is variability in the noise level in any space and therefore the communication distances depicted represent the conditions for the measurement location at the time the measurement was taken. However, the values do appear to be good estimates of levels the crew typically encountered during STS-50. For more information on the exact locations and conditions of the noise measurements consult table 1.

Figure 10 presents the distance at which a crewmember would most likely be able to communicate on the flightdeck at the time that the sound level measurement was taken. Based on the figure, it appears unlikely that the crew would have any difficulty understanding one another. Crew comments suggest this was the case, except for the aft flightdeck where air movement noise was present.

Figures 11, 12 and 13 depict the likely communication distances in the middeck. Background noise (figure 10) clearly would not present verbal communication difficulties. During operation of EVIS, depicted in figure 12, crewmembers would most likely not be able to communicate reliably across the middeck. Vacuum cleaner operation could be expected to severely impair voice communication, as suggested in figure 13. In the postflight questionnaire, several crewmembers commented adversely about noise during operation of EVIS.

Verbal communication distances in Spacelab during background noise conditions, and operation of the DPM, GBX, and STDCE, respectively, are presented in figures 14 through 17. Little difference in the distances is evident between the conditions. Even during background conditions, the maximum reliable non-aided communication distances in Spacelab were most likely around three quarters of the 7-meters (22.97 feet)-long module. Regardless of this, the crew found the noise environment in Spacelab to be completely acceptable. It is therefore likely that the crew compensated for the noise environment by speaking louder, listening intently to each other and/or moving closer together whenever communication was required.

The GRAF offers a unique and flexible method of graphically representing acceptable speech communication distances within relatively high fidelity models of the flightdeck and middeck. Further enhancement of the basic Spacelab model developed

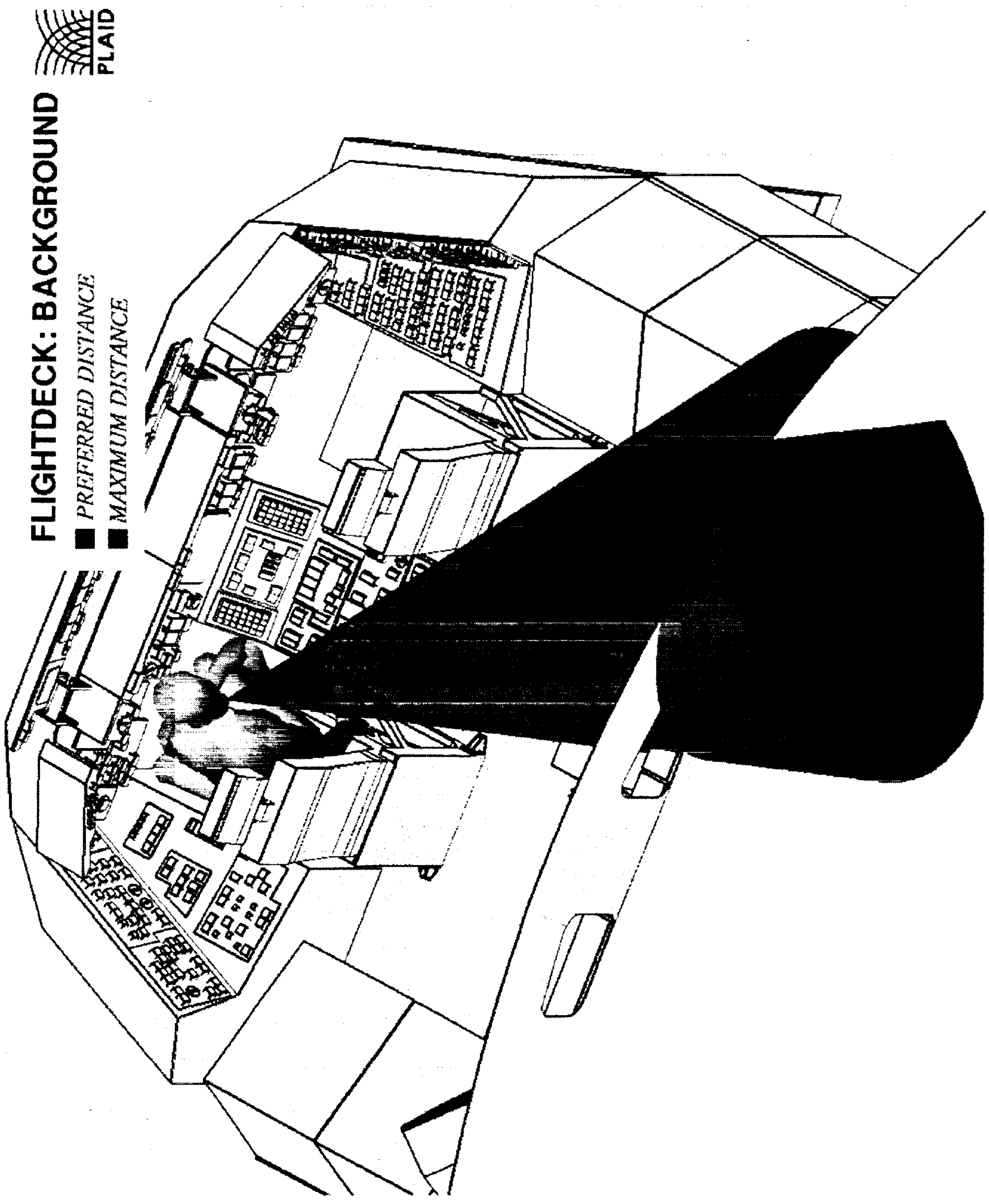

Figure 10. Verbal communication distances on the flightdeck during STS-50/USML-1 background noise only. (picture generated by GRAF)

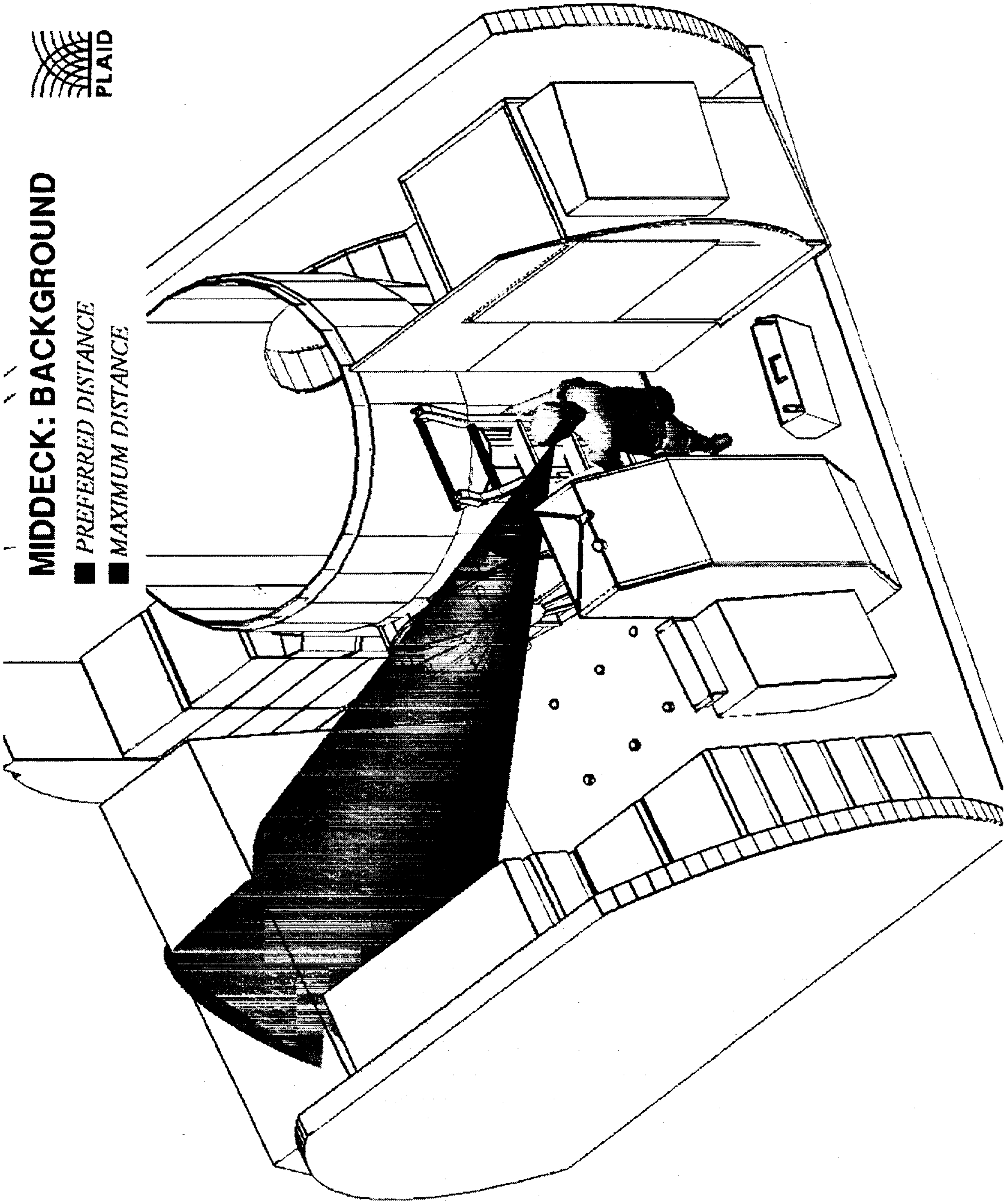

Figure 11. Verbal communication distances on the middeck during STS-50/USML-1 background noise only. (picture generated by GRAF)

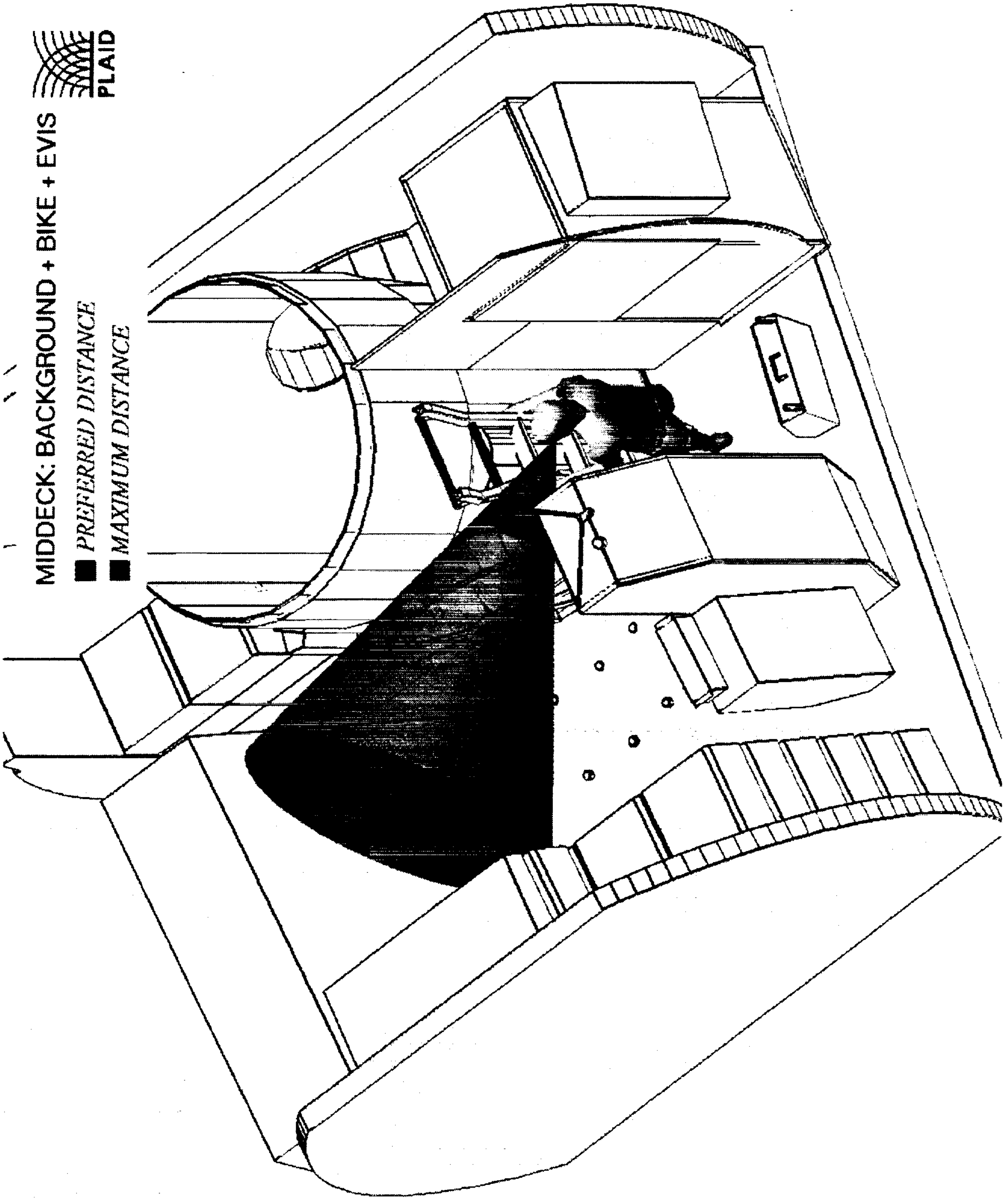

Figure 12. Verbal communication distances on the middeck during STS-50/USML-1 with bike and EVIS operating. (picture generated by GRAF)

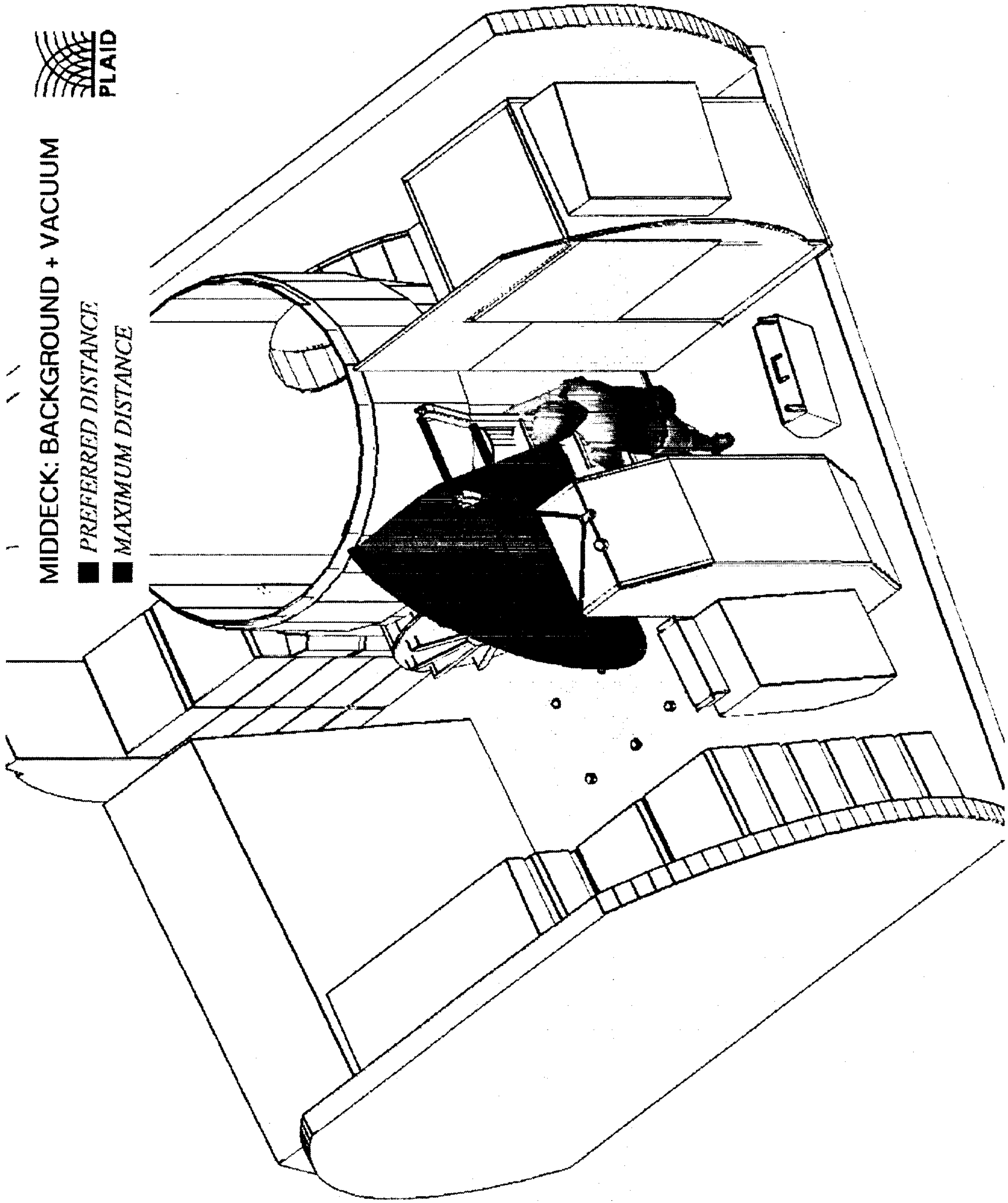

Figure 13. Verbal communication distances on the middeck during STS-50/USML-1 with vacuum cleaner operating. (picture generated by GRAF)

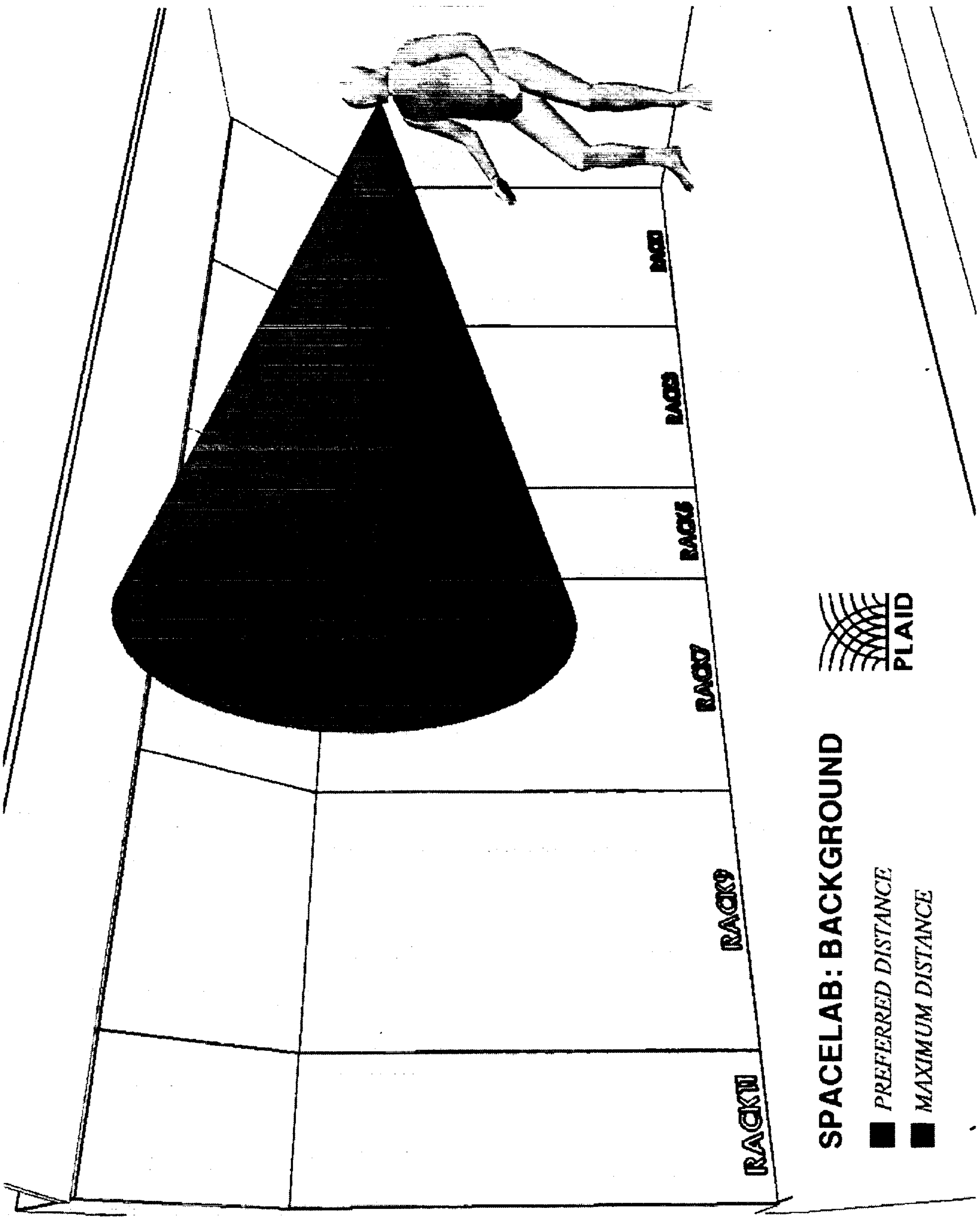

Figure 14. Verbal communication distances in Spacelab during STS-50/USML-1 background noise only. (picture generated by GRAF)

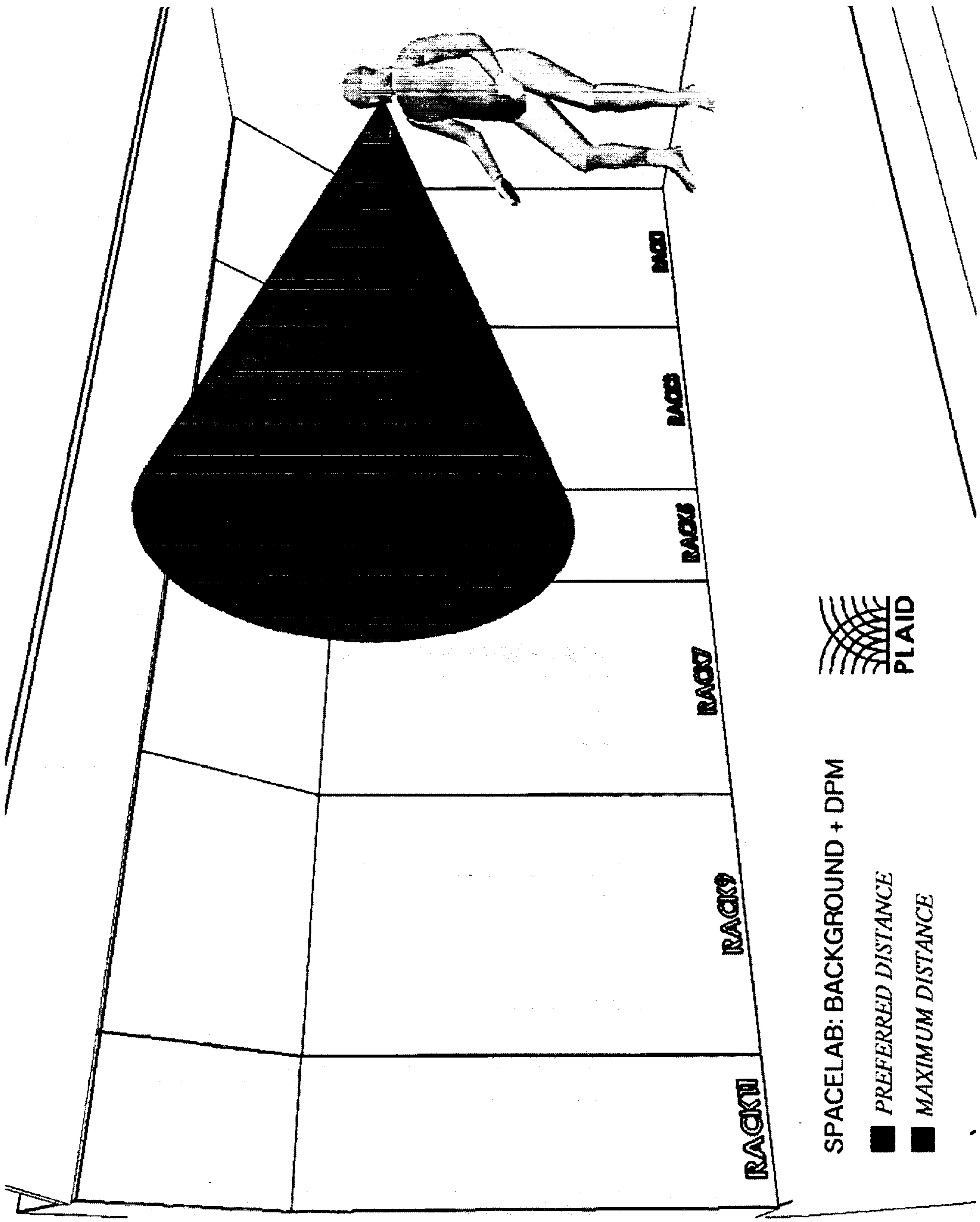

Figure 15. Verbal communication distances in Spacelab during STS-50/USML-1 with DPM operating. (picture generated by GRAF)

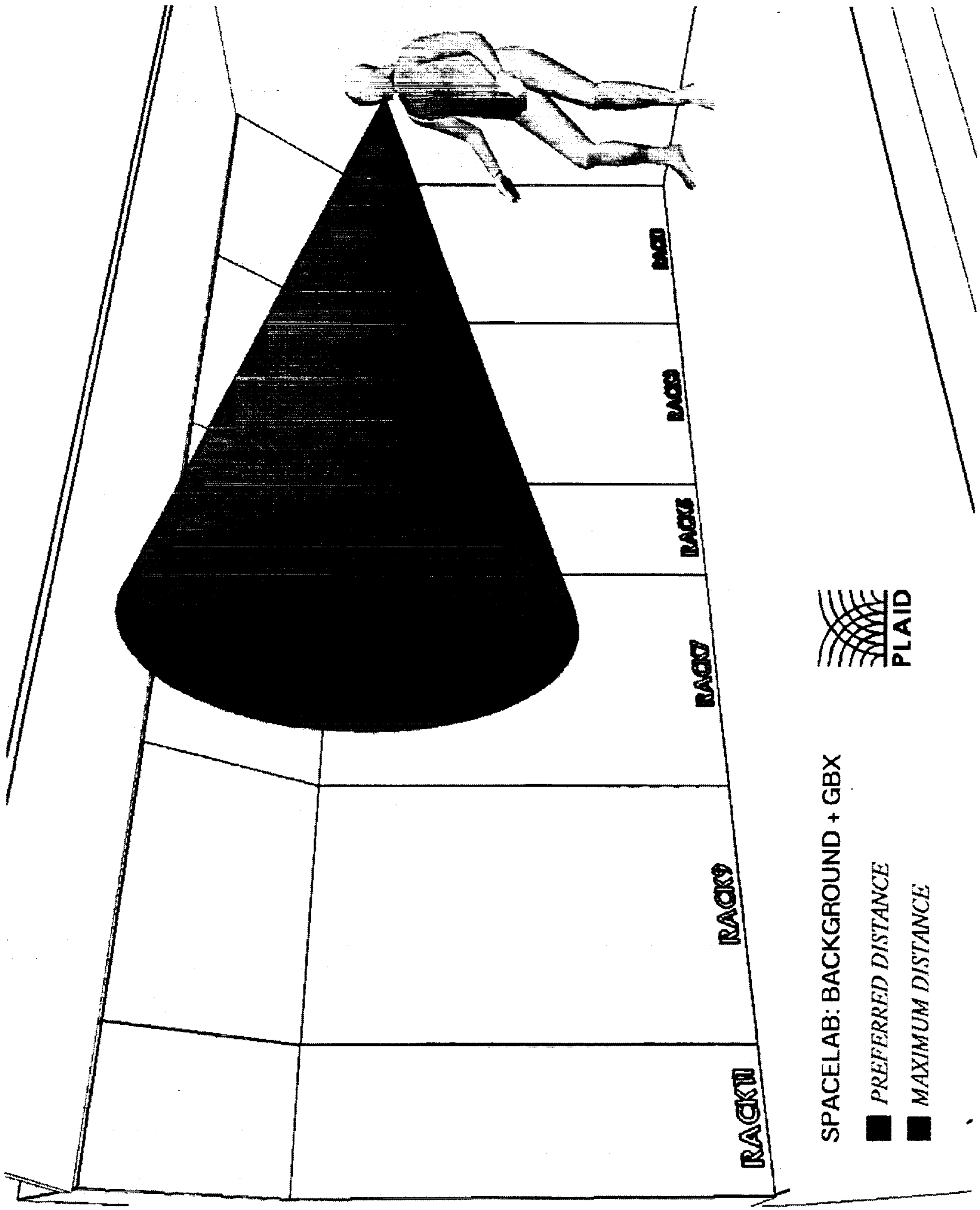

Figure 16. Verbal communication distances in Spacelab during STS-50/USML-1 with GBX operating. (picture generated by GRAF)

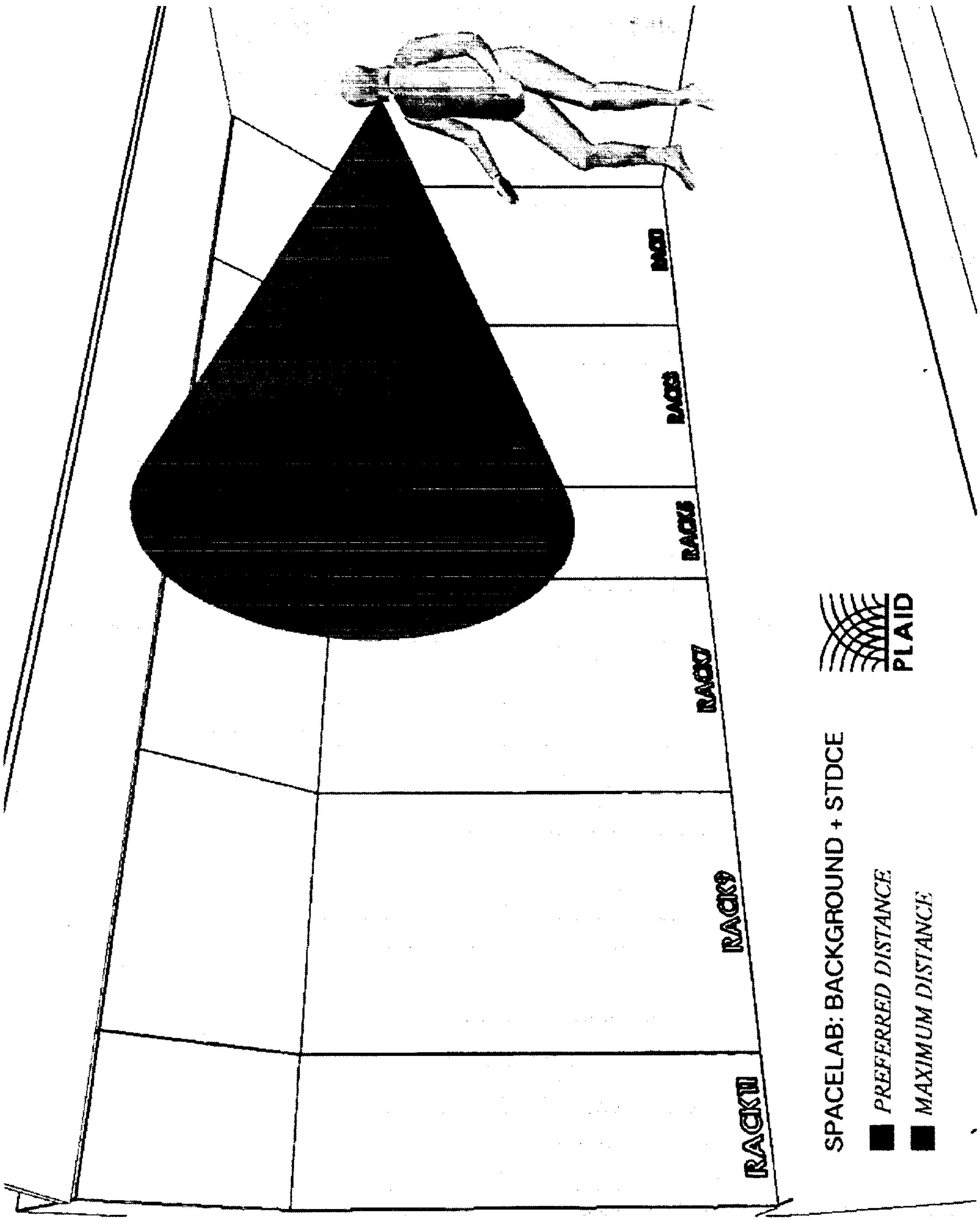

Figure 17. Verbal communication distances in Spacelab during STS-50/USML-1 with STDCE operating. (picture generated by GRAF)

for this evaluation could offer the same fidelity for this module as well. In addition, the use of this methodology as an assessment tool based on known (measured) noise levels also offers promise as a technique for predicting future speech communication problems from predicted levels.

With predicted noise levels for a specific mission, various crewmember locations and work scenarios could be evaluated to identify situations in which verbal communication might be impaired. For example, if a payload necessitated that crewmembers speak to one another from opposite ends of the middeck for extended periods of time during noise conditions similar to those experienced during operation of EVIS (68 dBA), speech interference could be anticipated. To avoid the added consequence of crew fatigue, a recommendation to minimize verbal communications at these times or to move the speaker and listener closer together could be forwarded. This technology would be most efficiently employed as a method of determining impairment of major communication paths in larger volumes (such as Spacelab or SSF) during high noise periods.

Finally, five of the six crewmembers noted no impairment in their performance on any task. The individual who noted an impact stated that this occurred while attempting to locate experiment samples within various lockers, and that it was especially difficult to concentrate when exercise equipment was in use. This could be anticipated since it falls within one of the categories of high risk tasks identified by Smith (1989)—multiple tasks or tasks with several subcomponents. In order to perform this task, the crewmember was required to read the Flight Data File to determine the next sample and its location. Then the crewmember had to pass down the Spacelab tunnel into the middeck, locate the locker, select the appropriate sample from a host of candidates (often while the ergometer was in use), return down the tunnel and then conduct the test. Based on the work Smith cites, it is likely that the individual concentrated upon the more dominant component of the task (possibly the name of the sample) at the expense of other less critical features, such as the locker number.

By far the most significant performance impact was in the area of speech interference. All crewmembers experienced some impairment in verbal communications, yet none of them considered it to be critical to their successful performance on any task. Even so, the STS-50 noise levels did result in the need for raised voices and presumably forced repeats of instructions as well. It seems likely that the additional vocal effort contributed to crewmember fatigue, and that the need to repeat oneself resulted in some tasks taking longer to complete than expected.

Inflight and Postflight Questionnaires

Since only two crewmembers completed both the inflight and postflight versions of the questionnaire a conclusive finding cannot be presented. However, the data does suggest a trend toward rating the acoustic environment more favorably after the flight than during it. The combined average for these two crewmembers' responses varied from 2.75 inflight to a slightly more favorable 2.45 postflight (on a scale with "1" representing the most positive rating and "5" the most negative). Especially noteworthy is that on 3 questions (5, 12, and 14) both respondents rated the levels more leniently postflight. These questions dealt with the acceptability of noise levels during sleep periods, the degree to which noise interfered with concentration, and whether noise became increasingly bothersome as the mission progressed. Therefore, it appears that responses to postflight noise questionnaires may be more lenient than inflight versions, particularly in these areas. Further evaluation into whether ratings are significantly influenced by this variable is recommended and will be pursued during STS-57/SpaceHab-1.

Responses to whether noise became more bothersome differed with each crewmember. Three of the seven STS-40 crewmembers indicated that noise did become more bothersome as the mission progressed, while, postflight, none of the STS-50 astronauts agreed with this statement. Both STS-40 and STS-50 crewmember ratings on this item were highly consistent with their ratings of the acceptability of the quietest area (combined correlation of about 0.7) and with how often one had difficulty hearing another crewmember (combined correlation of 0.63). Based upon these findings it is likely that noise becomes more bothersome if one considers the quietest area to be intrusive, and if one is required to raise one's voice to communicate verbally. If, on the other hand, the quietest area is considered acceptable and the individual does not have to raise his voice to communicate, it is likely that the individual will no longer be aware of the noise at all. Although the threshold to different events is highly individualistic it appears to remain consistent within the individual. It is evident from this data that the amount of annoyance experienced by an individual cannot be predicted based upon the physical parameters of the noise environment alone.

Accurate assessment of the acoustic environment is critical since noise presents significant ramifications for crewmember performance. Once the differences between inflight and postflight ratings are quantified, it can be determined whether inflight data collection is required to gain accurate subjective assessments, or whether the evaluation can be performed postflight—thereby avoiding taxing already overburdened inflight resources and crew time.

Comparison of Spacelab Missions

Background noise levels on Spacelab varied greatly between STS-9, STS-40, and STS-50. The levels range from a low of 61 dBA during STS-50, to 64 dBA for STS-9, and reached a high of 70 dBA on STS-40. Figure 18 presents overall A-weighted noise levels against a scale of common noise sources. The Shuttle and Spacelab values presented are based on measurements taken in the center of each acoustic space for DSO 904 during STS-40 and STS-50. It should be noted that the levels experienced by the STS-40 crew on the middeck and Spacelab, and those experienced by the STS-50 on the flightdeck, exceeded the level at which noise begins to be considered intrusive (62 dBA).

The flightdeck was considered completely acceptable by both the STS-40 and STS-50 crews. Sound level measurements made in the volume were within 2 decibels. The only comment that the crew made regarding the flightdeck was the presence of air movement noise at the aft flight station. The middeck was somewhat quieter on STS-50 (60 dBA) than STS-40 (64 dBA) during nominal operations. Both crews recommended that noise levels be reduced on the Orbiter middeck. During both flights, exercise

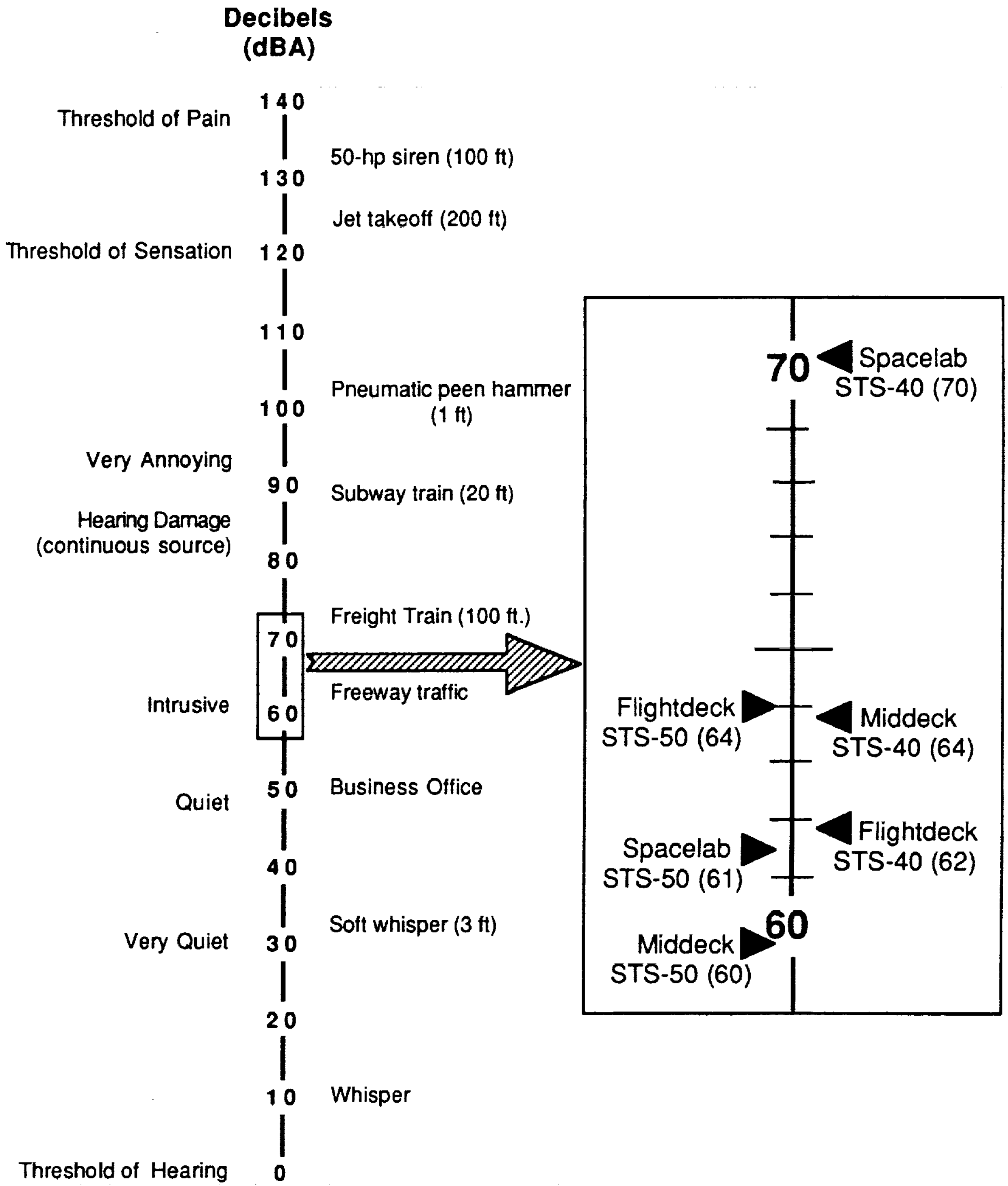

Figure 18. Comparison of DSO-904 background noise measurements (overall A-weighted decibels) on STS-40 and STS-50. The scale depicts the levels in relation to common noise sources (Scale adapted from Thumann and Miller, 1986, p. 17). On the left side of the scale are various psychological and physiological reactions to noise.

equipment was listed as the main cause of dissatisfaction with the acoustic environment. The treadmill and the EVIS were identified as the primary offender for STS-40 and STS-50, respectively.

In Spacelab, background noise levels varied widely between missions. Figure 19 presents the results of sound level measurements made during each of the missions (STS-9, STS-40 and STS-50). During STS-50 the 61 dBA level was considered acceptable. In fact, the volume was rated more favorably than the Orbiter middeck or flightdeck. The STS-9 crew found the general noise level of Spacelab to be low, and on-orbit noise measurements supported this with a value of 64 dBA overall (Eilers, 1987). In contrast, the 70 dBA background level of STS-40 compelled the entire crew to state that reductions in the noise level of Spacelab were mandatory. The majority of crewmembers also reported experiencing losses in the ability to sleep, concentrate, and relax. The high noise levels were attributed to mission-specific payloads for which acoustic waivers were granted. Since this mission, the waiver process has been reviewed and changes implemented to ensure that similar background levels do not occur in the future.

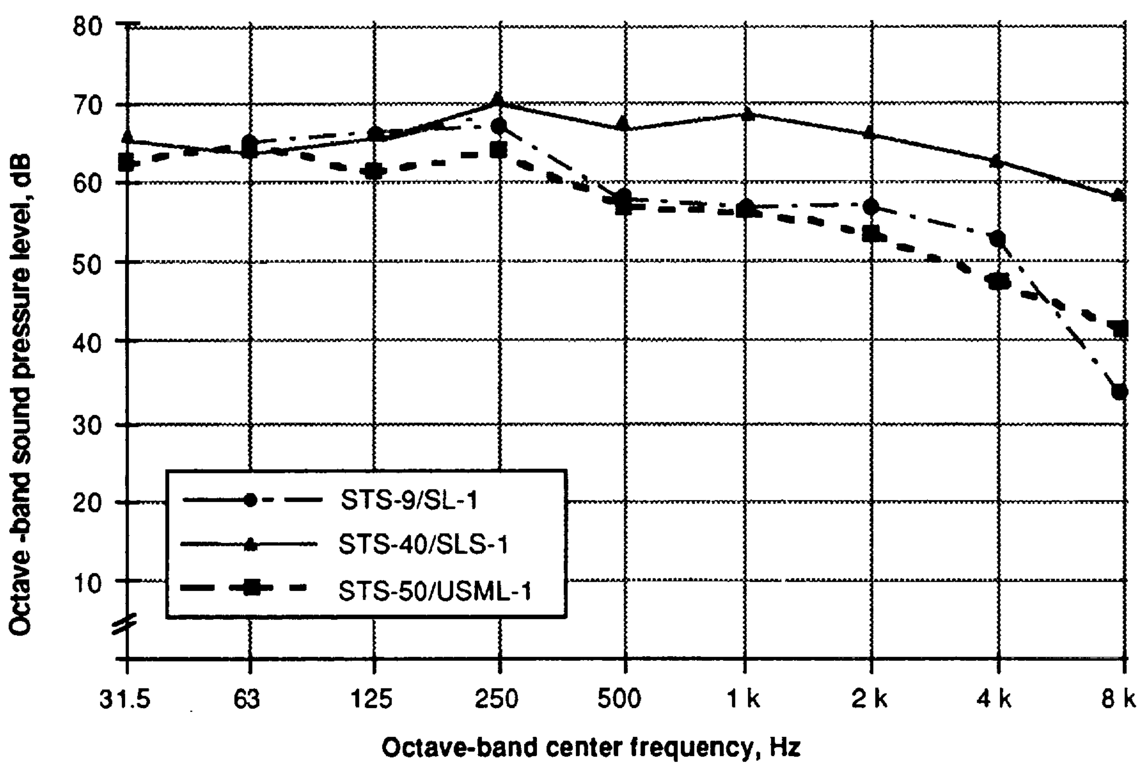

Figure 19. Octave-band sound pressure levels on STS-9, STS-40, and STS-50.

Acoustic Guidelines

Evaluating the crew's comments in conjunction with literature on the subject of noise and its effects on man, the most appropriate criterion appears to be the following (Harris, 1991):

> In work spaces where speech communication is essential, the background noise should not exceed an A-weighted sound level of 60 to 65 dBA; those levels permit satisfactory communication at a distance of up to 2 meters (6.5 feet).

As noise levels increase they may interfere with verbal communications and even cause significent losses in speech intelligibility. EVIS, which emitted levels of about 68 dBA, was identified as a significant noise source and was rated more unfavorably than other payloads by the crew. The STS-40 crew stated that improvements in background noise levels in Spacelab were mandatory—its level during the mission was 70 dBA.

It appears that the current Orbiter flightdeck noise limit of 63 dBA represents a completely acceptable level for current Shuttle mission durations. The middeck specification of 68 dBA appears to be higher than desirable—even for moderate periods of time this level leads to crew accounts of speech interference, and impairments in the ability to relax and concentrate. Two of the crewmembers rated noise levels during operation of EVIS as borderline (one found it unacceptable)—yet the levels it emitted (68 dBA) met the current overall acoustic specification for continuous sources. Since current Shuttle missions are relatively short-term ventures, the compromise in performance is likely to be slight and cause little impact to mission objectives. However, as mission duration increases and performance tasks become longer and more complicated, the current level may lead to more significant impairment in performance and more critical crewmember comments.

The current module acoustic limit for habitable volumes of SSF during work periods is NC 50[2]. Though the proposed criterion is somewhat more stringent than the 68 dBA recommendation just forwarded, it is an appropriate goal since mission durations will be significantly longer on the Space Station and the volume in the modules is much greater. Based on the Shuttle's acoustic environment, an NC 50 curve allows nearly 80% of key words to be understood correctly at a distance of five to eight feet (Pearsons, 1975). As levels increase to the NC 55 level (about 63 dBA), the percent of key words understood correctly falls to near 30%. Further, in conditions similar to those currently existing on the Shuttle, roughly equivalent to an NC 60, the percent of key words correctly understood at a distance of five to eight feet plummets to less than 10%. Any task relying upon verbal communication will be severely compromised in such a situation.

Sleep and rest periods represent times when the individual is particularly susceptible to noise. Therefore, the SSF maximum background noise level for sleeping, resting, and relaxing is NC 40. Levels of 47 dBA (roughly equivalent to the NC 40) have

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[2] The NC 50 is equivalent to 59 dBA; however, other noise spectrums of 59 dBA do not follow the NC-50 noise spectrum.

also been recommended in order to minimize crewmember annoyance and sleep interference (Beranek, Blazier, & Figwer, 1971).

In situations where these guidelines are not practical, it is necessary to be aware of potential human limitations and then to design equipment, allocate responsibility (human versus machine), and create procedures with these factors in mind. Smith (1989) states that monitoring tasks, continuous tasks, and tasks with several subcomponents are especially susceptible to performance decrement in the presence of noise. Clearly, crewmembers are often required to engage in these types of tasks. To minimize the likelihood or degree of decrement, the following types of tasks should be minimized during especially noisy periods:

1) Monitoring tasks
2) Continuous tasks that are critical in nature
3) Tasks that are cognitively burdensome (i.e., unpredictable or require evidence to be accumulated or collected from a number of sources)

However, if monitoring tasks cannot be avoided the following steps should be taken:

1) Keep the length of the watch short.
2) Make sure signals are easy to detect.
3) Do not allow noise levels to exceed 86 dBA.
4) Avoid using crewmembers to monitor situations that require caution.

A final point to be made is that human performance is generally more adversely affected by intermittent noise than by noise that is continuous, and that these negative effects are greatest when the intermittent noise occurs at irregular intervals (Holohan, 1982). Therefore, acoustic limits for intermittent sources are critical and should be stringently enforced.

CONCLUSIONS

The conclusions that can be forwarded based upon the inflight sound level measurements and the STS-50 crew comments fall into two categories—general conclusions regarding methodological issues and individual reactions to noise, and findings regarding the STS-50 acoustic environment.

General

1) The DSO measurement methodology and instrumentation is highly reliable and represents a repeatable data acquisition technique.

2) Inflight and postflight responses to noise questionnaires appear to differ significantly in some areas. Further evaluation into this effect is warranted.

3) The GRAF software (PLAID) offers a unique and highly flexible method of visually evaluating the impact of noise and crewmember location on acceptable speech communications.

4) The amount of annoyance experienced by an individual is highly individualistic and cannot be predicted based upon the physical parameters of the noise environment alone.

5) Whether noise becomes more bothersome as mission duration increases is highly correlated to the rating of the acceptability of the quietest area and with how often one has difficulty hearing another crewmember. This effect was noted across questionnaires completed by both the STS-40 and STS-50 crew.

STS-50 Shuttle Noise Environment

1) Noise levels on the flightdeck were approximately 64 dBA during this mission (1 decibel above its specification). The crew indicated that this level was acceptable, with the single exception of "significant" air movement noise on the aft flightdeck.

2) The current Orbiter flightdeck noise limit of 63 dBA appears to be totally acceptable for current mission durations.

3) Middeck background noise levels were about 60 dBA, rising to 68 dBA during exercise (i.e., when EVIS was operating). The middeck was rated the least acceptable volume during both the nominal and experiment conditions. During even the noisiest conditions the levels were rated no worse than "borderline." The crew indicated that the primary offender was EVIS.

4) The Spacelab acoustic environment was rated as the most acceptable. Five of the six respondents found background levels "completely acceptable," and three of them maintained this rating for payload operation conditions. Noise levels during background and payload operations were 61 dBA and 64 dBA, respectively.

5) Physiological effects were reported by the USML-1 crew. All crewmembers reported being woken up. One individual estimated that they were woken up 5-8 times per night by crew activity on the middeck. Ringing in the ears was briefly experienced by one crewmember as a result of a loud squeal emitted by the WCS during an anomaly.

6) Psychological effects occurred as a result of the noise levels. Three crewmembers indicated that noise interfered with their concentration on occasion. Three of the astronauts also reported that noise had led to interference in their ability to relax during the mission.

7) Crewmembers reported experiencing performance effects as a result of the STS-50 noise environment. Every crewmember indicated that speech interference had occurred between decks and, to a much lesser degree, on the same deck. Four of them indicated that noise had interfered with their ability to monitor the air-to-ground voice communication loop. No crew member reported experiencing difficulty hearing a caution or warning alarm.

8) Sleep stations afforded attenuation from airborne noise sources; however, they may also have served as pathways along which structure borne energy was directed.

9) The noise being emitted by the fresh air ducts inside the sleep stations is significant but serves to mask other unwanted sources.

RECOMMENDATIONS

1) Revise the middeck background noise limit to be no greater than 65 dBA. The current middeck acoustic limit (68 dBA) can be expected to impact crew performance on occasion—particularly during long duration missions, and when tasks rely upon verbal communication or entail several subcomponents.

2) Structurally isolate the Orbiter sleep stations from the middeck lockers to minimize the number of times that sleeping crewmembers are disturbed by crew activities on the middeck.

3) When vigilance tasks must be performed, do not allow noise levels to exceed 86 decibels, keep the length of the watch short, make sure signals are easy to detect, and do not require crewmembers to monitor tasks for which the consequences of poor performance are severe.

4) Minimize the scheduling of monitoring tasks, continuous tasks, and tasks with several subcomponents during peak noise periods.

5) Enforce NC 50 as the acoustic limit for all long duration space missions in work areas where speech communication is essential.

6) Enforce NC 40 as the background noise limit for times when crewmembers are sleeping, resting, and relaxing.

7) Stringently enforce acoustic limits for intermittent sources.

8) Maintain the current SSF acoustic specifications of NC 50 for work periods and NC 40 for sleep periods.

FUTURE STUDIES

Further studies into the effects of the acoustic characteristics on astronaut performance will be pursued on the Shuttle and other manned spacecraft. Sound level measurements and crew questionnaires are already planned for the STS-57/SH-1 mission. These data, along with that already collected, will serve to further define the acoustic characteristics of manned spacecraft and their impact on astronaut performance, as well as to enable investigation of individual differences in the reaction to noise, and apply this knowledge to the design of safe and habitable space vehicles. The GRAF models created will be further refined to include crewmember locations during various activities so that acceptable verbal communication distances can be evaluated.

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High noise levels can lead to physiological, psychological, and performance effects in man, ranging from irritability, annoyance, and sleep interference to interference with verbal communication and fatigue, and to temporary or permanent threshold shift at more extreme levels. The current study evaluated the acoustic environment of the STS-50/USML-1 mission. The major objectives were to gain subjective assessments of the STS-50 noise levels, document impacts of noise upon crewmember performance, collect in-flight sound level measurements, compare noise levels across missions, evaluate the current Shuttle acoustic criterion, and to make recommendations regarding noise specifications for SSF and other long-duration manned space missions.

Sound measurements indicated that background noise levels were 60, 64, and 61 A-weighted decibels, respectively, on the Orbiter middeck, flightdeck, and Spacelab. All levels were rated acceptable, with the Spacelab environment rated the most favorably. Sleep stations afforded attenuation from airborne noise sources, although all crewmembers reported being awakened by crew activity on the middeck. Models of distance for acceptable speech communications were generated, identifying situations of compromised verbal communications to be avoided.

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