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International Space Station Acoustics

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ABSTRACT

The International Space Station (ISS) presents a significant acoustics challenge considering all of the modules and equipment that make it an on-orbit laboratory workshop and home with long-term crew occupation. This challenge is further complicated by the fact that there are numerous suppliers of ISS hardware, including the international partners. This paper addresses how ISS acoustics are managed to ensure a safe and habitable environment by establishing requirements, providing oversight and design support, sharing lessons learned and information, testing for hardware compliance, predicting future acoustic levels, and performing on-orbit measurements and monitoring of actual acoustic levels. ISS acoustic requirements are classified in three categories by the type of hardware involved: modules; payloads, and Government Furnished Equipment. The current status of overall ISS acoustics for each of these hardware categories will be discussed. In addition, examples will be discussed where NASA design support was used to aid in obtaining compliance, where difficulties were encountered, and where areas of concern were addressed.

1. INTRODUCTION

The International Space Station (ISS) is an on-orbit laboratory workshop and a home with long-term crew occupation. Mission duration for the crews in ISS is currently from four months nominally to six months maximum. The ISS acoustics environment is important to maintain at reasonable levels from a standpoint of crew safety (temporary or permanent hearing loss), crew comfort and habitability, communications between crew and the ground and among each other, and crew performance. The ISS presents a significant acoustics challenge because of obvious difficulties with controlling a number of connected, operating modules with payloads and equipment to perform ISS functions and experiments, sustaining crew, and keeping them in good physical condition. Modules have equipment such as fans, pumps, compressors, avionics, and other noise producing hardware or systems to serve their functional and life support needs. Payload racks with operating equipment create continuous or intermittent noises, or combinations of both. Payload rack contributions to the total on-orbit noise can be and has been shown to be significant. Payload racks or sub-rack payloads are added or changed out over time. The crew exercises on a treadmill and with other conditioning devices, which generate noise. Communications between crew and ground, which are raised to communicate over the background environment, adds to the overall crew noise exposure. The crewmembers have to work and live in the resultant acoustic environment. The acoustics challenge is further complicated by the fact that there are numerous suppliers of ISS modules, hardware, and payloads from across and outside the United States. Management becomes more intricate by resolving variations in documentation of the requirements, ensuring that the requirements are consistent and appropriate, reconciling differences in planning and oversight to ensure that the hardware is designed to meet requirements, and coordinating the design experiences and approaches.

This paper addresses how ISS acoustics are managed to ensure a safe and habitable environment. Included are the management and technical structure; the current ISS module, payload and Government Furnished Equipment (GFE) requirements; oversight provision and design support; lessons learned and information shared; hardware compliance measurements; and acoustic compliance status of ISS modules. Predictions of future acoustic levels; on-orbit measurements; and monitoring of actual acoustic levels are covered in a separate paper by Allen and Goodman [1].

2. IMPORTANCE OF CONTROLLING NOISE TO ACCEPTABLE LEVELS

There are three basic criteria that should be met by the acoustics levels throughout the ISS: (1) they must not present a health hazard to the crew; (2) they should not present any significant impact or degradation on crew performance and operations; and (3) they should provide a habitable, comfortable work and sleep environment. Crew health hazards of most concern are temporary or permanent hearing loss, although other psychological or physiological effects can be significant. Crew performance concerns include inability to effectively communicate and understand what is being said or what is going on around them (e.g., intelligibility, speech interference, inability to hear alarms or other important auditory cues such as an equipment item malfunctioning, inability to concentrate, strain in vocal cords). A STS–40 Shuttle crew member reported ending up with headaches, constant gritting of teeth and furrowing of brow, and indicated that noise was very difficult to deal with all day and night. [2] Because of concerns with the effects of high noise levels, early in 1992, the Shuttle Acoustics Working Group and the Astronaut Office conducted tests in varying dBA exposures while performing simulated Orbiter flight deck operational tasks. [3] Astronauts commented that 70 dBA was a level where: ear protection was recommended; communications were more difficult, but acceptable for 1-2 hours a day; levels were at the limit for normal speech; levels were fatiguing, but tolerable for multiple brief periods; and this level was initially irritating. At the 75 dBA level: levels were tolerable for 10-20 minutes maximum and hearing protection was required; levels were very loud from a communications standpoint and it was difficult to concentrate; recommend limit to one or two hour periods of exposure; and level inhibits communications and requires raised voice. Note that these tests took place in a simulated Orbiter mid-deck area and were related to Shuttle flight duration. In May 2000, the Washington Post reported, “The noise problem is more serious, in the view of some. It exists not only on the orbiting Zarya module, but also on the service module awaiting launch. Clattering fans and other systems create a 75-decibel racket that rivals that of city traffic and could cause health problems for crews over the long term. Analysts also warn that excessive noise can dangerously mask other problems, such as the hiss of an air leak.” [4]

A recent example of problems with hearing signals on ISS is with difficulties in hearing an atmospheric monitoring device’s low battery warning signal. Inability to communicate or understand voice or signals could result in loss of science or have serious consequences, if the information was important. A habitable environment is important to ensure proper crew rest, relaxation, and health. These concerns are sometimes considered in descending priority, although crew performance and operations can lead to more serious circumstances, including problems with the mission or crew health. One of the first ISS crewmembers related that communications were the biggest acoustic concern. The World Health Organization (WHO) indicated the following about noise: “Noise can cause hearing impairment, interfere with communication, disturb sleep, cause cardiovascular and psycho-physiological effects, reduce performance, and provoke annoyance responses and changes in social behavior. The main social consequence of hearing impairment is the inability to understand speech in normal conditions, which is considered a severe social handicap.” [5]

Noise Criterion (NC) curves are used to establish safe and comfortable acoustic levels in rooms and workplaces where people have reasonable communications, including good intelligibility. NASA- Manned Spacecraft Center (MSC) (now the Johnson Space Center) originally specified NC-50 to be the integrated systems requirement for the continuous noise limits during all manned spacecraft. [6] In the Shuttle Orbiter Program, attempts were made to not exceed the NC-50 level, but a specification level in octave bands equivalent to NC- 63 (assuming the worst case limit in an octave band defines the NC value) and 68 dBA were settled on for Orbital Flight Test for the mid-deck. This level was later adopted in the Shuttle Program for all elements including the Orbiter mid-deck and flight deck, and Spacelab module. Measurements on Orbiters revealed acoustic levels ranging from 61 to 64 dBA. Since crews normally spent 10 to 14 days in space these levels were accepted.

The ISS started out with the NC-50 requirement, but this ended up to be for modules only, with payloads and any GFE covered by their own requirements. Generally, payloads are limited to a module complement level of NC-48, so full up continuous integrated systems noise became controlled to the combination of NC-50 for modules plus the NC-48 for the payload complement. The combination of NC-50 and NC-48 is termed herein the NC-52 total specification. This results in a derived systems limit curve of this combination, which carries a value of 60 dBA (versus 58 dBA for NC-50). (Figure 1) Studies and assessments made during Shuttle development and the early ISS program indicated that NC-50 was a good limit for full up systems. However, the overriding view was that module suppliers in ISS were not providing or controlling the payloads or GFE, and therefore should not be responsible for ensuring NC-50 compliance with inclusion of this hardware. The NC-50 plus NC-48 systems derived requirement has been challenged as too restrictive, and recently the ISS Program, has asked an Independent Assessment Team to review the ISS Acoustic requirements to determine if requirements are too stringent and can be relaxed. Response to the ISS was that current requirements are good and appropriate. These requirements have not been changed, but there always seem to be questions about whether we could allow higher levels and if so, what would they do to crew hearing loss and performance.

There has been a lot of discussion about the need to concentrate on hearing protection and conservation for ISS crews. This is necessary because the noise dosage and levels in some locations are excessive, but the best and primary method to obviate hearing loss should be to establish good standards for acoustic levels and ensure their compliance (keep the noise at reasonable levels). The MSC Standard [6] was intended to control levels, such as to preclude the need to wear hearing protection during normal work and sleep. Hearing protection provisions need to be available in event noise levels get too high and especially for use during short-term operations, such as the actuation of module equalization or depressurization valves. Even wearing hearing protection might introduce other complications, e.g., discomfort caused by wearing them (pressure points, irritability); possible ear infection (especially with plug type devices); and impeded/complicated communications when devices are kept in place, have to be removed, or set aside. The author is concerned that availability of hearing protection makes it too easy to allow higher noise levels because the hearing protection safeguards can be called on to remedy the situation and can be used to alleviate efforts to quiet hardware.

3. ISS ACOUSTIC REQUIREMENTS

Acoustical noise requirements need to be setup early in a program, be treated as requirements, and compliance watched over and assured. A lesson learned in the Shuttle Program was that limits must be applied to the specific hardware that goes into modules, to ensure control of the resultant levels and give the hardware a standard to comply with. The MSC Design Standard 145 [6] referred to earlier specified an integrated systems level only, and did not effectively sub-allocate requirements to hardware that made up the system. As a result, some hardware items used the systems limits for lack of any definition of hardware requirements and because these limits were higher and easier to meet. To ensure that the overall full-up system noise is controlled, it was determined that all elements contributing to the systems noise had to have appropriate limits. A summary of ISS acoustic limits for all ISS modules, payloads, and Government Furnished Equipment (GFE), is shown in Table 1 and 2. Similar limits for the U.S. Segment modules are shown in Figure1, which were derived from the basic requirements of SSP 41000 [7]. Russian Segment specification limits for modules are shown relative to NC curves, Figure 2 and documented in Table 3. Payloads and GFE requirements contain definitions for continuous and intermittent noise. A continuous noise source is a significant noise source, which exists for a cumulative total of 8 hours or more in any 24-hour period; and an intermittent noise source is a significant noise source, which exists for a cumulative total of less than 8 hours in any 24-hour period.

Intermittent noise limits for payload racks are shown in Table 1. Similar limits apply to GFE. There are no U.S. Segment module intermittent noise limits, because these limits were thought to be implemented better on payload and GFE hardware which is either in defined locations in the modules or can be controlled by crew operations, if necessary. Also, the module surrounds the crew and noise can come from a multitude of uncontrolled locations. The Russian Segment includes intermittent noise limits relative to full up systems operation, as shown in Table 4. These Russian requirements deal with the permissible increase in the overall system levels and thus are not applied to the hardware, but their result on the environment. If there are several items on-board that are intermittent, then there is no sub-allocation defined for individual hardware items. The other concern with these limits is when noise levels are at these limits most of the time, then the crew would have to vacate the area, since the limits would dictate the crew vacate the module.

4. MANAGEMENT, SUPPORT OF DESIGN/DEVELOPMENT, AND COMPLIANCE

NASA Johnson Space Center (JSC) has an Acoustics Office managing and working the following areas: acoustics requirements; ISS and hardware oversight; participation in the design process (design and development) of hardware; hardware emission testing; hardware compliance with requirements; acoustic consultation; providing materials information to hardware groups and International Partners; working resolution of which payloads should be manifested together on a future mission; evaluating the acceptability of acoustics from a flight readiness standpoint for each flight or a group of flights (called an Increment in ISS); disposition of waivers/exceptions; and mission monitoring and support. The four areas concentrated on are modules, payloads, GFE, and the integration of all hardware in a Module. A prime objective of this group is to ensure noise levels from modules and hardware within them are compliant with the established requirements, which in turn should ensure a safe and habitable environment.

At times when hardware items are shown to be in need of design or consultant support, or in serious non-compliance, special focus and efforts are marshaled to help remedy the situation. Examples of these efforts are: quieting an Airlock Module depressurization pump and develop a heat exchanger muffler; developing muffler approaches for Express Racks and recommending their implementation; supporting efforts to quiet the Micro-gravity Glove Box, a German provided payload; supporting efforts to test and quiet the Minus Eighty-degree Laboratory Freezer (MELFI) payload rack and provide materials to support initial flight hardware needs; developing a muffler design for the Russian Functional Cargo Block Module; developing fan wrap and muffler design concepts to support Russian fan quieting; providing design and materials support of the Temporary Early Sleep Station which is now being used in ISS; developing a Noise Abatement Kit for ISS use; and numerous other design support and consultation efforts. These efforts were intended to, and have aided, the hardware to obtain compliance.

An Acoustics Working Group (AWG), chaired by the Acoustics Office is made up of representatives from the following organizations: ISS Program Office; the Astronaut Office; Payload Engineering & Integration Office; the Space Medicine and Health Care Systems Office; and Boeing acoustics and payloads support. Representatives from other areas are also included as required, for example the Marshall Space Flight Center acoustics specialists are often included in discussions. The functions of this group are: to serve as a focal point for JSC acoustics; review all aspects of the ISS acoustic environment; review acoustic effects on the crew, determine safety issues related to acoustics; establish and resolve an individual or group position on concerns, waivers/exceptions, and provide recommendations to the ISS Program; perform oversight and support to the ISS.

5. STATUS OF COMPLIANCE OF MODULES AND WITH FULL-UP SYSTEMS

Recent flight data taken in the U.S Segment is shown in Figure 3. The U.S. Laboratory when first flown exceeded the NC-50 module requirement and initially was waived predicated on planned modification of three hardware items: the pump package assembly (PPA), the Carbon Dioxide Removal Assembly (CDRA) and the medium rate outage recorder (MCOR). The CDRA and MCOR have been modified, and the PPA modification is now under assessment. The U.S. Lab is reasonably close to the total module systems requirement of NC- 52 (Figure 1), except it has been higher in the aft end of the module. Bay 6 levels are shown high. The Node and Airlock are shown to be at acceptable levels.

The Russian Segment consists of the Functional Cargo Block (FGB), Service Module (SM), and the Docking Compartment (D.C.). Measurements taken in these modules are shown (Figure 5). These modules exceed the Russian Segment specification limits. (Table 3). A waiver has been granted for the FGB and an exceedance has been granted to the D.C. The SM compliance has been waived, with the intent to implement modifications as soon as feasible. The SM levels, although improved by modifications, are still excessively high. Additional SM on-orbit measurement data in various locations are shown (Figures 6, 7). Results of acoustic dosimeter measurements of the crew exposure (time-weighted average) and levels measured at fixed module locations are shown in Table 5.

The acoustic levels measured in ground testing of other international partner (IP) modules are shown in Figure 8. Levels in these modules are expected to be acceptable.

6. LESSONS LEARNED

A summary of lessons learned in the ISS are as follows: noise requirements for programs need to well founded, and specify full up systems limits and limits for hardware types provided; acoustics needs to be dealt with early in the design process; acoustics requirements need to be treated seriously as requirements, not goals; complicated hardware systems like modules and payload racks, need to implement acoustical noise control plans that layout items such as identification and rating of all noise sources, proposed development and verification testing; and an appropriate level of consulting, design support, and oversight needs to be applied ; and common testing and verification needs to be applied for all ISS modules; a small team of experienced personnel, such as the NASA acoustics team has numerous advantages and benefits to the ISS.

7. AREAS OF CONCERN

This writer's experience is that not until ISS, did acoustics gain adequate acceptance or attention as a technical discipline, compared to other standard technical areas, such as structures, thermal control, environmental control, and others. Early attention to acoustics is necessary in design of ISS hardware, especially considering the complexity of modules and payloads.[8]. Attending to acoustics early and being proactive better ensures compliance and minimizes expenditures and schedule impacts. A relatively small group such as the Acoustics Office has been effective in taking proactive steps to help hardware suppliers achieve compliance [9, 10, 11, 12 and 13]. Utilizing a team such as this is effective from a cost standpoint, helps ensure compliance, minimizes schedule impacts, and maintains a valuable knowledge and technical capability for hardware suppliers and for the technical base of NASA's space program.

The tendency is to consider hearing loss in evaluations of excessive levels, rather than communications and habitability, as noted earlier. The Navy, in their Guide for Crew Habitability for Ships, [14] calls out the following noise criteria. To meet normal and high standards (termed HAB+): cabin, state rooms, berthing and sanitary space levels shall not exceed a maximum acceptable noise level of 50 dBA. Navigation and control rooms, including wheelhouse, pilothouse, chart room, radio and radar rooms, and ships offices. However, this guide also includes maximum acceptable sound pressure levels, as follows: cabin, staterooms, berthing and sanitary spaces levels shall not exceed the "maximum acceptable level" of 80 dBA navigation and control spaces listed above are allowed a maximum of 85 dBA. The areas where communications are important only goes up to 55 dBA, an increase 5 dBA from normal and high standards. (limits for communications are especially important and are not granted much leeway when standards are eased). NC-50 is equivalent to 58 dBA and the modified NC-52 is equivalent to 60 dBA. According to NASA-STD-3000, "for satisfactory communication of most voice messages in noise, 75% intelligibility is required" [15]. NASA-STD-3000 also indicates that the 75 % value falls within the lower part of the very good to Excellent range of intelligibility (range is 0.7 to 1.0) Using this 75% figure and data from a 1975 report by Pearsons, the maximum noise environment level would be NC-50.2 to obtain this level of intelligibility when using normal voice level at 5-8 feet distances between crew [16]. In this report NC-55 noise level would drop the intelligibility to 30%. These references indicate our ISS specifications are allowing some loss in intelligibility, and measured levels in the Service Module shown above, are of concern. The World Health Organization (WHO) in one report [17], gives guideline values for industrial, commercial, shopping and traffic areas, indoors and outdoors as 70 dBA for a 24 hour time base (exposure). The listed critical health effect is hearing impairment. In addition to the Shuttle data on dBA we have discussed in Section 2, we have Russian Mir program results, which show significant hearing loss on long duration missions. This information and previous discussion indicates that levels at or close to 70 dBA should be considered ISS daily exposure limits and that SM levels measured and documented in Table5 are problematic. It is frequently discussed that long- term studies are required to substantiate limits. This author's opinion is that these limits are justified in view of crew experience noted herein, especially considering the variability in crew member physiological and psychological response to noise.

8. CONCLUDING REMARKS

The ISS presents numerous challenges in acoustics. JSC's Acoustics Office and the AWG perform valuable management oversight over acoustic activities. The JSC acoustics team provides beneficial support of module, payloads, and GFE requirements definition, design and development, consultation, and applies proactive efforts to help hardware providers achieve compliance. The acoustic team also manages predictions for flight readiness, on-orbit measurements, and maintains a database of measurements, and distributes reports and assessments of the data. It is important that the ISS noise be in compliance with current specifications. This is important to ensure acceptable crew communications, health, and well-being. The communications aspect of ISS acoustics needs to be further addressed. Current ISS Module meet or are close to meeting the NC-52 defined in this document. The acoustic levels in the Russian Segment are high, but acceptable considering crew operations. The SM levels and crew exposure readings are too high, and further effort is needed to lower them.

9. ACKNOWLEDGEMENTS

The author would like to acknowledge the support of Dr. Ferdinand Grosveld and the efforts of Dr. Punan Tang, James Warnix, and Robert Hill, who made significant contributions discussed in this paper. In addition, acknowledgement is order for efforts of the acoustics team who also made major contributions to these efforts.

10. REFERENCES

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[16] Gregory D. Pilkinton, "ISS Acoustics Mission Support," *Noise-Con 2003, the 2003 National Conference on Noise Control Engineering*, Cleveland, Ohio, 2003 June 23-25.

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11. TABLES

Table 1. Acoustic design requirements

Design Requirements		U.S. Specifications SSP 50005	Russian Specifications SSP 50094	GFE, Payloads, and Non-Integrated H/W
Continuous Noise (more than 8 hours)	Awake Hours	NC-50	60 dBA (approximately NC-55)	NC-40
	Sleep Hours	NC-40	50 dBA	Not Specified
	Hazardous Limit	85 dBA	Not Specified	Not Specified
Intermittent Noise (8 hours or less)	Hazardous Limit	Not Specified	Variable based on duration 65 dBA for 4 hr up to 80 dBA for ½ hr	Variable based on duration 49 dBA for 8 hr up to 79 dBA for 1 min
Impulse noise (one second or less	Hazardous Limit	140 dBA	Not Specified	Not Specified

Table 2. Acoustics requirements references

1. SSP 41000 3.3.10.2 and SSP 50021, 3.2.6.1 The integrated acoustic environment in habitable areas shall not exceed the U.S. NC-50 criterion for noise sources averaged over any 10 second time interval (as specified in SSP 50005, paragraph 5.4).
2. SSP 50005, 5.4.3.2.3.1 sound pressure levels from all operating systems and subsystems considered at a given time shall not exceed the NC 50 contour for work periods and the NC 40 contour for sleep compartments
3. SSP 50094, 6.5.2.4 This equivalent level for crew activity shall not exceed 60 dBA.
4. SSP 50094, Table 6.5.2.4.2-1 Maximum daily allowable sound levels in habitable volumes during the operation of additional noise sources as a function of exposure time
5. SSP 28484, 3.3.6.4.1 A GFE continuous noise source shall not exceed the limits provided in Table 3.2.1-1, for all octave bands. This is equivalent to NC40.
6. SSP 50021, 3.2.6.2 and JSC 28322, 3.2.1 All non-integrated hardware to be flown in the ISS Modules shall not exceed NC-40 as measured at 0.6 meters from the noisiest point on the hardware as in accordance with JSC 28322.
7. SSP 50005, 5.4.3.2.1.1 Noise of constant sound levels of 85 dB(A) and greater are considered hazardous regardless of the duration of exposure.
8. SSP 50005, 5.4.3.2.1.4 Impulse sound is a change in sound pressure level of more than 10 dB in one second or less. Impulse noise shall not exceed 140 dB peak pressure level to meet hearing conservation criteria for unprotected ears.
9. SSP 28484, 3.3.6.4.1 A significant noise source that exists for a cumulative total of less than eight hours in any 24-hour period is considered an intermittent noise source. A GFE intermittent noise source shall comply with the limits provided in Table 3.2.2-1.

Table 3. Allowable sound and sound pressure levels in habitable volumes of space vehicles

Flight duration over 30 days	Octave-band Sound Pressure Levels, dB								A-weighted Sound Pressure Level, dBA
Geo. mean, Hz	63	125	250	500	1000	2000	4000	8000	
WORK	79	70	63	58	55	52	50	49	60
REST	71	61	54	49	45	42	40	38	50

Table 4. Maximum daily allowable sound levels in habitable volumes during the operation of additional noise sources as a function of exposure time

Maximal exposure time, hours	Permissible increase in exposure levels, dBA
4	+5
2	+10
1	+15
0.5	+20

Table 5. On-Orbit Dissymmetry Summary – February 11-12th, 2003

		Serial No.	24-Hour Equivalent, (Leq, dBA)	Crew Member/ Location	RECORDED PARAMETERS Lavg/Leq, dBA	SLM, dBA	Lmax, dBA	Time, hours:min.
Crew Worn	02/11/2003	1006	67	Work	69.2	56.3	99.4	13:32
				Sleep	50.9	66.4	87.4	11:03
		1005	70	Work	70.5	67	99.4	13:30
				Sleep	66.8	58.5	90.1	11:03
		1003	67	Work	69.3	57.3	ofl	13:31
				Sleep	57.5	58.4	87.3	11:03
Static	02/12/2003	1003	69	LAB1P6 (w)	68.5	62.5	89.8	13:05
				LAB1P6 (s)				
		1005	71	Cent Post (w)	71.3	60.1	98.4	13:05
				Cent Post (s)				
		1006	70	SM table (w)	70.3	60.4	90	13:04
				SM table (s)				

12. FIGURES

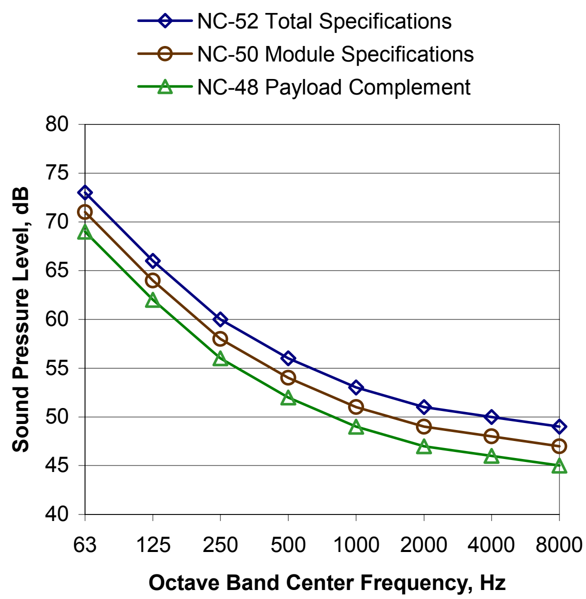

Figure 1. U.S. Lab continuous noise specifications

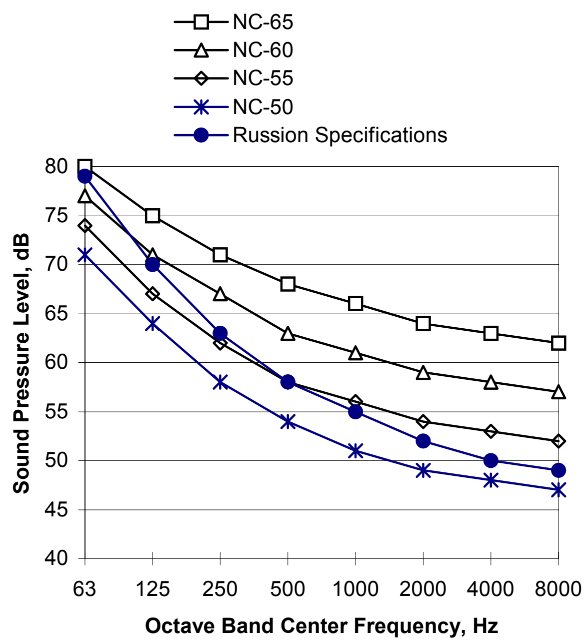

Figure 2. Russian continuous noise specifications

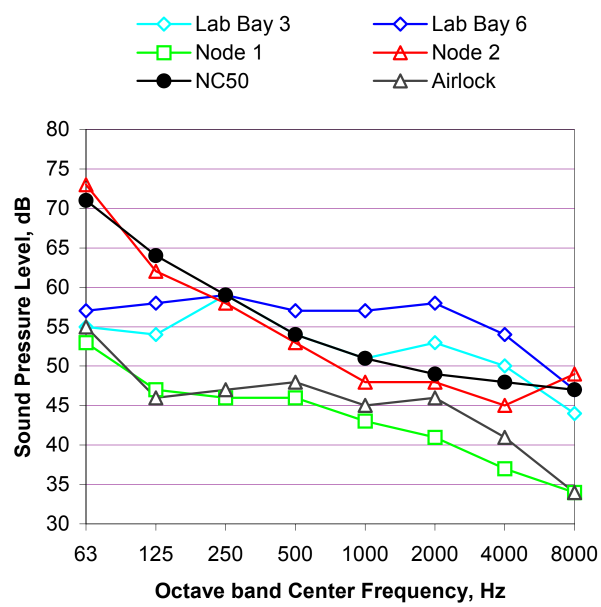

Figure 3. U.S. Segment sound pressure level measurements

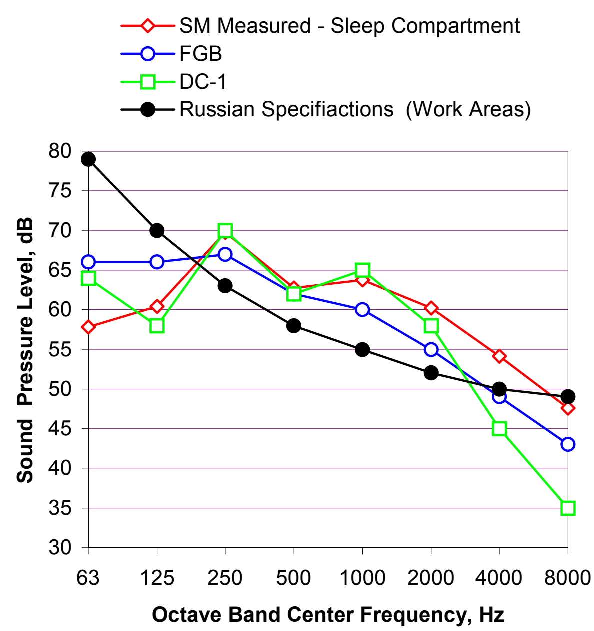

Figure 4. Russian Segment sound pressure level measurements

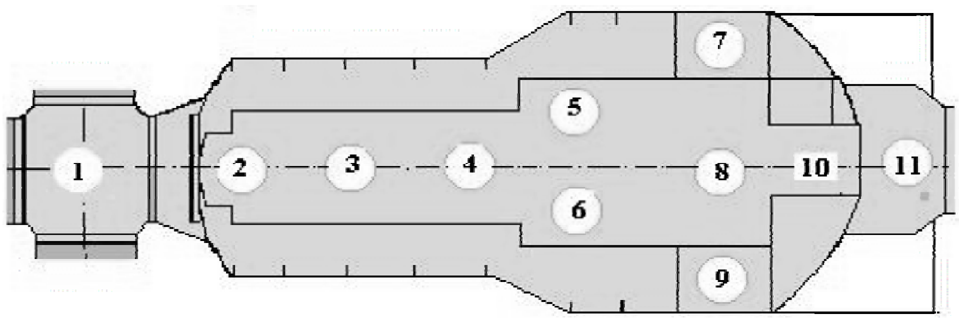

Figure 5. Service Module measurement locations

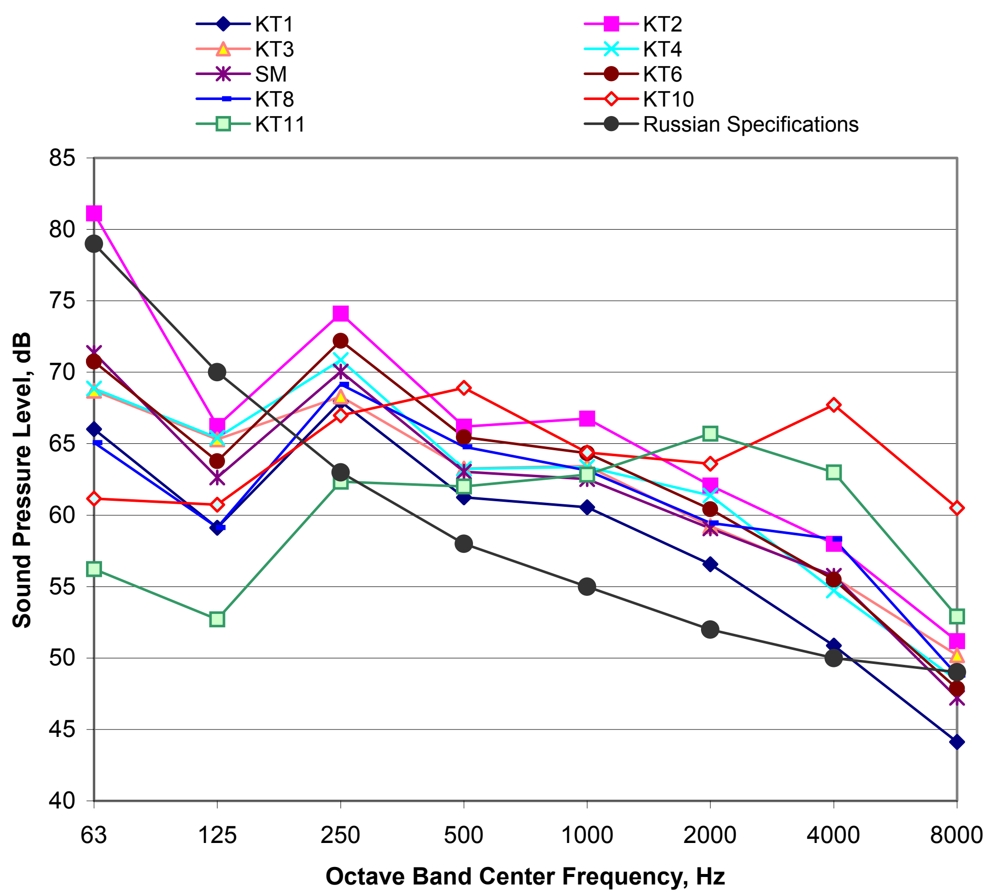

Figure 6. Service Module sound pressure level measurements

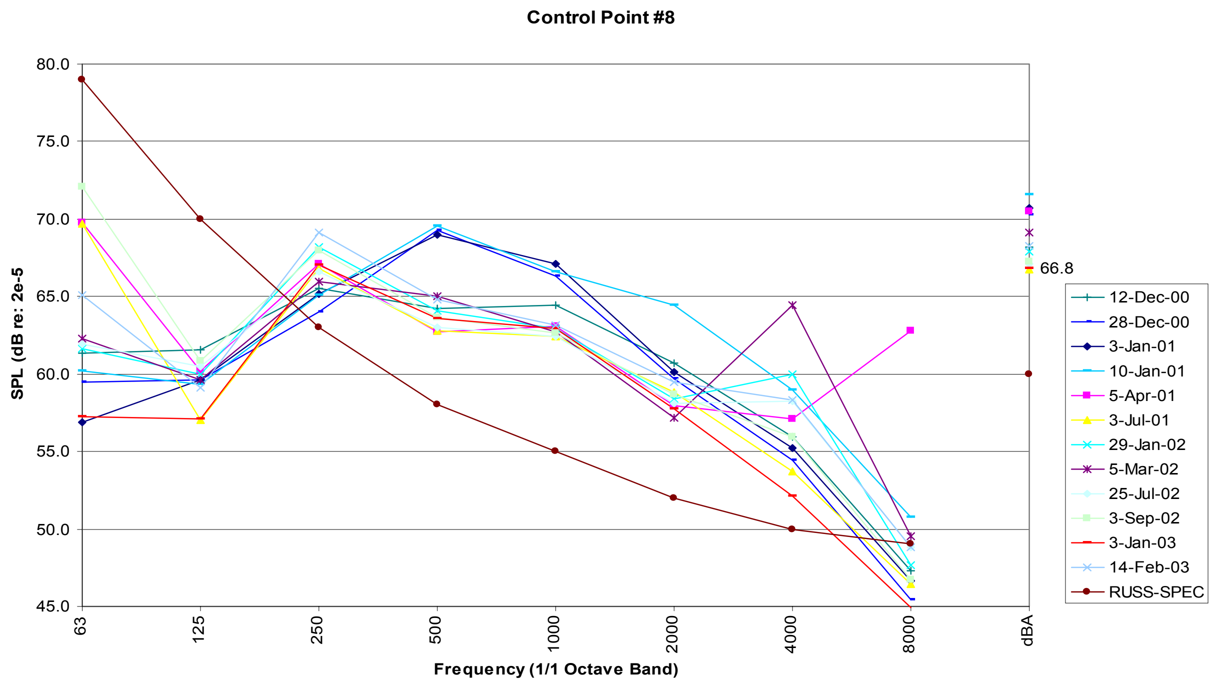

Figure 7. Sound pressure level measurements at control point number 8

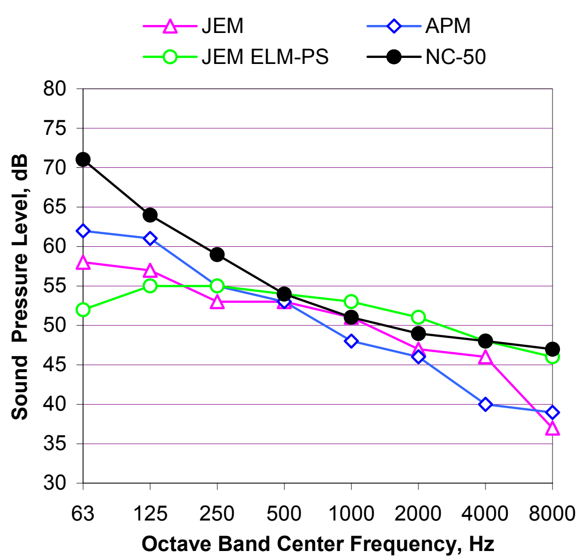

Figure 8. IP Elements